Thesis for the Degree of Doctor of Philosophy

Integrated Nonlinear Optics in Silicon Nitride Waveguides

Clemens Krückel

Photonics Laboratory
Department of Microtechnology and Nanoscience (MC2)
Chalmers University of Technology
Göteborg, Sweden, 2017
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Göteborg, May 2017

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Doktorsavhandlingar vid Chalmers Tekniska Högskola
Ny serie 4235
ISSN 0346-718X

Technical Report MC2-356
ISSN 1652-0769

Photonics Laboratory
Department of Microtechnology and Nanoscience (MC2)
Chalmers University of Technology, SE-412 96 Göteborg, Sweden
Phone: +46 (0) 31 772 1000

Front cover illustration: From top left to bottom right. SEM image of a silicon nitride strip waveguide after dry-etching (width 1.65 µm, height 0.7 µm). Optical spectrum of the four-wave mixing process. Simulation of the optical power distribution in a silicon nitride strip waveguide.

Printed by Chalmers reproservice, Chalmers University of Technology
Göteborg, Sweden, May, 2017
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Clemens Krückel

Chalmers University of Technology
Department of Microtechnology and Nanoscience (MC2)
Photonics Laboratory, SE-412 96 Göteborg, Sweden

Abstract

Current nanofabrication techniques allow patterning of optical waveguides with sub-micron cores. This results in strong confinement of light, which leads to high optical intensities. If the waveguides are fabricated with materials that display a large nonlinear Kerr coefficient, then nonlinear optical phenomena can take place in a very efficient manner.

Silicon nitride is a very well-studied material in the electronics industry. The material has a large transparency window, from the ultraviolet to the short-wave infrared, and its fabrication is completely compatible with standard techniques formerly developed by the semiconductor industry. Silicon nitride strip waveguides can also confine light, and diverse applications based on nonlinear optics have been demonstrated before. However, these applications required core thickness above 300 nm and they are very challenging to fabricate in a reliable manner with standard deposition techniques.

In this thesis, we have studied unconventional silicon nitride waveguides that are more robust for fabrication. The first layout corresponds to a thin strip waveguide with low optical confinement and propagation losses of only 6 dB/m. This technology was originally developed at the University of California, Santa Barbara. We used the technology to demonstrate wavelength conversion of high-speed data. In this thesis, we developed another silicon nitride technology that allowed for high light confinement. We discovered that by modifying the stoichiometry of the film during the deposition process, one could drastically change the optical and mechanical properties of the material. With this technology we demonstrated octave-spanning supercontinuum generation in collaboration with the Technical University of Denmark and XPM-based all-optical processing in collaboration with McGill University. These results indicate that this platform is very suitable for nonlinear integrated optics.

The long-term goal of our research is being able to attain an optical parametric amplifier on chip using a continuous-wave pump laser source. In this thesis we benchmarked the losses of high-confinement waveguides for the realization of 10 dB parametric net-gain on chip and identified silicon nitride as the most plausible technology to achieve this goal in the near future.

Keywords: four-wave mixing, integrated optics devices, nanostructure fabrication, nonlinear optical signal processing, nonlinear optics materials, wavelength conversion devices
This thesis is based on the following appended papers:


Related publications and conference contributions by the author not included in the thesis:


doi.org/10.3993/jo00.00.00.00.00.00.00

Journal papers


Conference presentations and papers


Acknowledgement

I would like to thank Prof. Peter Andrekson for giving me the opportunity to gain experience and improve my professional skills in the research environment in the photonics laboratory. I acknowledge Prof. Magnus Karlsson for sharing his expertise and answering questions about nonlinear optics.

I want to thank my supervisor Dr. Victor Torres-Company for being a thorough and talented leader.

I would like to thank Prof. John Bowers, Dr. Jared Bauters, Dr. Martijn Heck and Dr. Daryl Spencer from the University of California Santa Barbara for the collaboration and for providing waveguide samples. I also thank Dr. Morten Bache from DTU as well as Mohammad Dizaji and Dr. Lawrence Chen from the McGill University for the collaboration.

In order to establish our own processing line, I was highly supported with expertise from the MC2 cleanroom staff. I would like to thank in particular Johan Andersson, Mats Hagberg, Karin Hedsten, Göran Alestig and Ulf Södervall for their valuable support.

I thank my colleague Dr. Erik Haglund for sharing his snus with me but more importantly his profound knowledge about nanofabrication. Attila Fülöp deserves acknowledgment for fruitful discussions about integrated optics and letting me utilize his mature computer skills now and then.

I have to thank my three office mates gratefully. Dr. Josué Parra Cetina for being a great fellow, Dr. Samuel Olsson for his organized manner of answering any question and Dr. Vicente Durán Bosch for his Spanish education and positive approach towards Mondays. Special thanks are also directed to Dr. Aleš Kumpera, Dr. Tobias Eriksson and Tamás Lengyel for being around and making work more harmonic and joyful.
Furthermore, I extend thanks to Jeanette Träff for being supportive and I acknowledge of course all the rest of the photonics laboratory members for being great colleagues. Finally, I want to express gratitude to all my family and friends.

Clemens Krückel

Göteborg
May 2017

This work was financially supported by the European Research Council Advanced Grant PSOPA (291618) and the Swedish Research Council (VR).
Abbreviations

ChGs chalcogenide glasses
CMOS complementary metal-oxide-semiconductor
CVD chemical vapor deposition
CW continuous wave
DFB distributed feedback
DUV deep ultraviolet
ebeam electron-beam
EUV extreme ultraviolet
FCA free-carrier absorption
FWM four-wave mixing
GVD group-velocity dispersion
HNLF highly nonlinear fiber
IC integrated circuit
IR infrared

LPCVD low-pressure chemical vapor deposition
MBE molecular beam epitaxy
MEMS micro-electro-mechanical systems
MOCVD metalorganic chemical vapor deposition
MOSFET metal-oxide-semiconductor field-effect transistor
NA numerical aperture
PECVD plasma-enhanced chemical vapor deposition
RF radio-frequency
RIE reactive-ion etching
SBS stimulated Brillouin scattering
SEM scanning electron microscopy
SHG second-harmonic generation
SOA semiconductor optical amplifier
SOI silicon-on-insulator
SPM self-phase modulation
SSMF standard single-mode fiber
THG third-harmonic generation
TPA two-photon absorption
UV ultraviolet
VCSEL vertical-cavity surface-emitting laser
XPM cross-phase modulation
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Chapter 1

Introduction

Our society displays a huge demand for high-speed internet. This demand is satisfied, in part by the technological achievements made in the field of optical communication. This field involves the transmission of digital information via light over fibers of glass. Thereby, light is routed through a global network of optical fibers in order to connect computers and data centers all over the world. The advent of fiber technology in 1966 [1] enabled a revolution in modern communication leading to the present fiber links with outstanding data rates beyond 1 Tb/s.

The optical fiber is the standard medium used to transmit data in long distance connections of metro and long-haul links between cities and continents. Furthermore, the fiber is also essential in connections of shorter range, like in data centers or supercomputers. Indeed, the fiber has progressively replaced most metal-based transmission lines (e.g. copper) for distances down to 1 m [2]. Interestingly, it was already predicted in 1984 [3] that the optical connection is the best solution to connect silicon electronic components. The reason for this is that an optical connection has about six orders of magnitude lower loss at high data rates compared to an electrical connection [4].

Data centers are huge facilities for data storage and data processing driven by social media platforms or search engines. The large number of servers in a data center are commonly linked by fiber-based optical interconnects [2]. Currently there are two methods to realize an optical interconnect, based on either vertical-cavity surface-emitting lasers (VCSELs) or silicon photonics. The VCSEL, based on III-V materials, is a laser source that offers high-speed direct on-off switching to modulate binary optical data [5, 6]. Companies like TE connectivity utilize the VCSEL technology in their optical interconnects to reach data rates of 4×25 Gb/s [7]. The silicon photonics approach on the
other hand utilizes an laser in combination with a silicon based modulator integrated on a microchip. There are many companies developing silicon photonic interconnects for datacenters. For example, Sicoya has presented their $4 \times 25$ Gb/s transceiver based on silicon photonics technology [8]. The major requirements for the platforms used in data centers are low-cost fabrication, low-power consumption, high reliability and simple scalability to higher data rates. In [9] both platforms, VCSEL and silicon photonics, are compared from a technological and economic perspective. The prediction foresees that silicon photonics is favored for longer transmission distances (>300 m) with single-mode fibers and VCSELs continue its domination for data centers due to economical benefits.

In the context of this thesis, it is meaningful to present the field of silicon photonics in more detail. Silicon photonics is the integration of optical devices on a silicon microchip. For the integration of optical devices the same nanofabrication facilities are utilized as for the high-volume integration of silicon microelectronics. Silicon microelectronics, more precisely the complementary metal-oxide-semiconductor (CMOS) transistor logic, is a central key figure leading to the information revolution in the last 50 years. Especially noticeable is the massive size reduction and performance increase of electronic devices. With the demonstration of the first optical waveguide in silicon in 1986 [10], it was proven that the fabrication environment for silicon electronics can also be utilized to manufacture optical devices. In 1996 a rib waveguide was presented using the silicon-on-insulator (SOI) platform with low losses of 0.1 dB/cm showing the potential of light guiding on chip [11]. This shows that within silicon photonics even optical interconnects between processor cores at the microchip level are possible [2]. Unfortunately, silicon has no efficient light emission so by now hybrid solutions are available where III-V lasers are bonded on the silicon photonics chip [12]. An alternative solution was recently proposed in [13] where a III-V distributed feedback (DFB) laser structure was grown directly on silicon.

Nevertheless, thanks to the compatibility with CMOS fabrication facilities, tailored for high-volume low-cost processing, the fabrication of silicon photonic circuits in the same process line offers many advantages. Additionally it offers the opportunity to bring together optics and electronics on the same microchip [8]. One interesting change in recent years is the offered access to silicon photonic systems for researchers without fabrication facilities in the context of multi-project wafer runs [14]. Here production costs are shared by combining designs on the same wafer that is manufactured for all users. With multi-project wafer runs, the fabless access to silicon photonics components becomes more affordable [14]. Crystalline silicon has become a common material of choice for integrated optics. Over the past years the research output in the field of silicon photonics
1.1. THIS THESIS

for linear optical applications has increased. However, it turns out that silicon is also a very promising material for nonlinear optics applications [15]. A high refractive index and huge nonlinearities are the major advantages of this material for nonlinear integrated optics. The small core dimensions achievable with modern fabrication techniques together with the index contrast to the cladding material leads to remarkably high optical confinement, with huge intensities that enable efficient nonlinear processes. Although the market for volume production of nonlinear devices is missing, CMOS-compatible fabrication provides high yield, reproducibility and the flexibility to fabricate in existing CMOS fabs. The nonlinear optical effects can be utilized for applications like signal regeneration [16], broadband wavelength conversion [17] or supercontinuum generation [18]. However, nonlinear loss contributions that occur for wavelengths in the telecommunication band limit the performance of this material platform [19, 20].

A material platform that overcomes these challenges and does not show nonlinear losses at telecommunication wavelengths because of its large optical bandgap is silicon nitride [21]. Silicon nitride is also a CMOS-compatible material [22] and offers the same potential for mass production. Similar to silicon, silicon nitride is accessible for the broader research community through multi-project wafer runs. In its stoichiometric composition, Si$_3$N$_4$, waveguides with extraordinary low-loss performance down to 0.001 dB/cm have been demonstrated [23]. Another essential difference to silicon is the transparency window of silicon nitride. In contrast to silicon, silicon nitride is transparent down to ultraviolet (UV) wavelengths thus enabling devices for visible light processing [24] and sensing [25] applications. Silicon nitride also has a fairly high nonlinear Kerr coefficient [26]. In the past years this materials has been explored for nonlinear optics with impressive results including octave spanning comb generation [27] and ultra-broad supercontinuum generation [28]. However, fabrication challenges to achieve thick waveguides constrains the important capabilities for dispersion engineering as thick films show cracks due to high tensile stress [29]. As silicon nitride is a compound dielectric, unlike silicon, its stoichiometry can be modified during the deposition process. The change in deposition parameters allows to move from stoichiometric silicon nitride Si$_3$N$_4$ to its non-stoichiometric form by increasing the silicon content. This comes along with various advantages for nonlinear photonics.

1.1 This thesis

In this thesis we present two silicon nitride based waveguide designs. One shows thin waveguides with low-confinement and the other one thick waveguides with high confinement. For the first design we use the low-loss character-
istic to reach good nonlinear performance that leads to the first demonstration of wavelength conversion of high speed data in this platform. With the second design of high-confinement waveguides we explore the impact of the core material on the waveguide properties. As a waveguide core material we use different LPCVD based silicon nitride compositions reaching from stoichiometric to silicon enriched. We show the first holistic study that connects fabrication and film characterization with an analysis of linear and nonlinear performance on system level. With the good nonlinear properties of the silicon rich nitride waveguide, we demonstrate supercontinuum generation and XPM-based all-optical processing.

In a theoretical analysis we compare thick waveguides based of stoichiometric silicon nitride with silicon waveguides. In the study we emphasize the impact of nonlinear absorption and set benchmarks to reach a performance target of 10 dB parametric net-gain on-chip that has not been achieved yet.

**Thesis outline**

In chapter 2 the basics of nonlinear optics are summarized with a focus on $\chi^{(3)}$-based Kerr nonlinearities like four-wave mixing (FWM). Chapter 3 covers the basics about waveguide theory including information about mode properties, loss and coupling mechanisms of waveguides. In chapter 4 common material platforms for integrated nonlinear optics are introduced. The platforms are compared in terms of linear and nonlinear performance and benchmarked with the highly-nonlinear fiber (HNLF) technology. Chapter 5 includes the presentation of CMOS-compatible fabrication techniques that are used to manufacture optical waveguides. In Chapter 6 possible future projects are discussed.
Chapter 2

Nonlinear Kerr optics

For high optical intensities the interaction of light and matter becomes nonlinear, meaning that the optical radiation after propagation through a medium is not a linear superposition of the radiation before the medium. Especially when working with integrated optics, a very high confinement of light can be achieved, leading to very high intensities. The resulting nonlinear effects can be utilized for useful applications. In this chapter the fundamental physical principles for nonlinear interaction of light and matter are explained with a focus on nonlinear Kerr optics, the dominant nonlinear effect in materials used for integrated optics.

2.1 Material polarization and refraction

The propagation of electromagnetic radiation is described by Maxwell’s equations. In a transparent medium with no free charges Maxwell’s equations become

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
\[ \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \]  
\[ \nabla \cdot \mathbf{D} = 0 \]  
\[ \nabla \cdot \mathbf{B} = 0, \]  

(2.1)  
(2.2)  
(2.3)  
(2.4)
where $E$ and $H$ are the electric and magnetic field vectors, and $D$ and $B$ are the electric and magnetic flux densities. The interaction of light with the medium is described by the electric displacement of charges $D$ given by

$$D = \epsilon_0 E + P,$$

where $\epsilon_0$ is the vacuum permittivity and $P$ is the induced polarization by the medium. The polarization of the material describes the reorientation and relocation of charges and dipoles in response to the presence of an electric field. As the light has a vectorial nature, the susceptibility terms are tensors and the material response depends on its orientation and isotropy. To provide a simple physical insight, a scalar mathematical description is chosen from here on.

### 2.1.1 Linear material properties

For a low electric-field strength in an isotropic medium, the polarization follows a linear dependence

$$P_{\text{lin}} = \epsilon_0 \chi E,$$

where $\epsilon_0$ is the vacuum permittivity and the susceptibility $\chi$ is the proportionality factor. The susceptibility $\chi$ is related to the relative electrical permittivity of the medium $\epsilon_r$ by $\chi = \epsilon_r - 1$ which accounts for the various fundamental polarization mechanisms of the material. The excitation of the individual polarization mechanisms depends on the frequency of the present electric field therefore $\epsilon_r$ is given by a dielectric function. This frequency dependent function fully describes the optical properties of the material. The relative permittivity is a complex value

$$\epsilon_r = \epsilon_r' - i\epsilon_r'',$$

where the real part defines the strength of the polarization and the imaginary part accounts for material absorption mechanisms that occur during the polarization process. Both parts are physically linked via the Kramers-Kronig relation. Figure 2.1 illustrates the contributions to the complex permittivity (dipolar, ionic and electronic polarization mechanisms). At various frequencies the polarization of the material becomes significant and the figure shows the relation between the real and imaginary part in a simplified manner. Here, we focus on the material response at high-frequency electromagnetic radiation that is relevant for materials used in the field of optics. The transparency window of these materials is given by the wavelength range in which the material absorption is negligible which is mainly restricted to the frequency spectrum between UV-radiation and IR-radiation. One way to characterize the complex dielectric function and describe the optical properties of a material is by using
2.1. MATERIAL POLARIZATION AND REFRACTION

Figure 2.1: Illustration of the electrical permittivity ($\epsilon_r'$ real part, $\epsilon_r''$ imaginary part).

ellipsometry as described in chapter 5.2. For many common optical materials like crystalline silicon or stoichiometric silicon nitride the optical constant has been studied in detail. The refractive index $n_0$ of the material is connected to the relative permittivity together with the relative permeability $\mu_r$ according to

$$n_0 = \sqrt{\epsilon_r \mu_r}.$$  \hspace{1cm} (2.8)

In nonmagnetic materials $\mu_r = 1$ thus $n_0 = \sqrt{\epsilon_r}$. Similar to the relative permittivity, the refractive index is a complex parameter where the imaginary part accounts for material absorption. In Paper F we utilize the ellipsometer technology to explore the complex refractive index for various silicon nitride compositions in the UV wavelength range (more details in 5.2). This study not only gives information about one end of the transparency window, but it also defines its optical bandgap that causes linear material absorption for UV and visible light and nonlinear absorption at longer wavelengths.

2.1.2 Nonlinear material properties

For intense electrical fields a saturation of the polarization takes place and the polarization response of the material becomes nonlinear. The nonlinear polarization behavior at high intensities has its origin in the nonlinearity of the motion of molecular bound electrons in the material. The description of the polarization including nonlinear behavior is described by a pertubative approach [30]

$$P = P_{\text{lin}} + P_{\text{nl}} = \epsilon_0 \chi E + \epsilon_0 \chi^{(2)} E^2 + \epsilon_0 \chi^{(3)} E^3 + \ldots$$ \hspace{1cm} (2.9)
CHAPTER 2. NONLINEAR KERR OPTICS

Here $\chi^{(2)}$ and $\chi^{(3)}$ are the second and third-order susceptibility leading to the second and third-order nonlinear polarization terms. As the higher-order susceptibility terms are in general several orders of magnitude smaller than the linear susceptibility, they only become effective at high intensities. Different susceptibility terms contribute to particular optical effects and have influence on the interaction of radiation with matter. For example, the linear susceptibility $\chi$ is included in the refractive index $n_0$ of the material and accounts for the change of optical phase. The second-order susceptibility $\chi^{(2)}$ leads to effects like second-harmonic generation, sum-frequency generation or the linear electro-optic effect (Pockels’ effect). The third-order susceptibility $\chi^{(3)}$ results in third-harmonic generation or the quadratic electro-optic effect (Kerr effect) [31].

The Kerr effect is of great interest in this thesis. It is common to describe the strength of this effect with the nonlinear Kerr coefficient $n_2$ that is related to the real part of the third-order susceptibility by $n_2 = \frac{2}{n_0} \Re(\chi^{(3)})$ [32]. The imaginary part of the Kerr coefficient accounts for nonlinear losses in the presence of high intensity fields (i.e. TPA) originating from the optical bandgap. In [32] Sheik-Bahae et al. relate $n_2$ to the optical bandgap via

$$n_2 = K' \frac{G_2(h\omega/E_g)}{n_0^2 E_g^2},$$  \hspace{1cm} (2.10)

where $K'$ is a constant, $n_0$ is the refractive index, $h\omega$ is the photon energy, $E_g$ is the bandgap energy and $G_2$ is a smooth function accounting for wavelength dependency with values between -0.05 and 0.1. This equation allows to predict the nonlinear Kerr coefficient from ellipsometer measurement data. In Paper [1] we studied this relation for different silicon nitride compositions as each composition displays a different optical bandgap $E_g$ and a different refractive index.

The Kerr effect causes nonlinear refraction, where the refractive index of a material changes in the presence of light with high intensities. This intensity dependence of the refractive index can be described as [30]

$$n(|E|^2) = n_0 + n_2 |E|^2.$$  \hspace{1cm} (2.11)

As the phase shift of a wave is dependent on the refractive index given by equation [2.11] both the linear and the nonlinear part contribute to the total phase shift of a wave in a medium. In terms of nonlinear phase shift one distinguishes between self-phase modulation (SPM) and cross-phase modulation (XPM). SPM is when the nonlinear phase shift of a wave is induced by its own intensity. XPM is the nonlinear phase shift induced by the intensity of light at other frequencies or polarization. Thus the intensity modulation at a strong intensity wave leads to the phase modulation of light at a different frequency.
This can lead to practical nonlinear signal processing schemes, as studied in Paper [D] and [E].

The nonlinear polarization of a material can give rise to generation of light at frequencies different from the one of the excitation field. Nonlinear polarization takes place in various materials of liquid, gaseous or solid state where solids may have amorphous or crystalline composition. It is important to mention that materials with molecular inversion symmetry do not possess even order susceptibility terms. This means that in materials like silicon or silicon dioxide the lowest nonlinear susceptibility term is $\chi^{(3)}$. In this thesis we refer to these materials as $\chi^{(3)}$-materials. The polarization response of the medium excited with a monochromatic electric field is illustrated in Fig. 2.2. Here an excitation field of $E(t) = E_0 \cos(\omega_1 t)$ was used for convenience. For low intensity fields the polarization $P$ follows the present field linearly without showing nonlinear behavior as shown in Fig. 2.2.a. The frequency of the output field only contains the component at $\omega_1$ in relation to the excitation field. Increased intensities trigger the nonlinear response of the material polarization accounting for higher-order polarization terms. For a $\chi^{(2)}$-material the second-order polarization produces nonlinear distortion of the polarization. As shown in Fig. 2.2b, the induced polarization does not follow the excitation field. This results in a new frequency component at $2\omega_1$ resulting from the squared field component in Eq. 2.9. The process in $\chi^{(3)}$-materials is similar, where a third-harmonic component is produced at $3\omega_1$ driven by the third-order susceptibility illustrated in Fig. 2.2c [33].

### 2.2 Four-wave mixing

In $\chi^{(3)}$-materials the polarization is given by

$$ P = \epsilon_0 \chi E + \epsilon_0 \chi^{(3)} E^3, $$

(2.12)

where the third-order polarization term is included. This term involves the nonlinear interaction of four waves and leads to the phenomenon of four-wave mixing (FWM). This phenomenon results from the radiation-induced modulation of the refractive index as shown in Eq. 2.11 and causes the generation of light at new frequencies. In this context, the material is mediating the nonlinear interaction among optical waves with the conservation of photon energy. In order to exemplify the four-wave-mixing process and the generation of new frequency components, we consider the input to a $\chi^{(3)}$-material as a superposition of three monochromatic waves at different frequencies as shown in Fig. 2.3a. The mixing term of the input waves is given by $E(t) = E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t) + E_3 \cos(\omega_3 t)$ that is inserted into Eq. 2.12.
Figure 2.2: Illustration of material polarization $P$ and frequency generation in dependence of the input field amplitude $E$ and material susceptibility $\chi$. a) Linear polarization of material. b) Nonlinear material polarization based on $\chi^{(2)}$ susceptibility. Second-harmonic frequency generation at $2\omega_1$. c) Nonlinear material polarization based on $\chi^{(3)}$ susceptibility. Third-harmonic frequency generation at $3\omega_1$.

The triple product of $E$ results in multiple new frequency components at the output. All possible new frequencies (only first order) at the output of the medium are combinations of the input frequencies given by

\[(\omega_1 + \omega_2 - \omega_3), (\omega_1 + \omega_3 - \omega_2), (\omega_2 + \omega_3 - \omega_1),\]
\[(2\omega_1 \pm \omega_2), (2\omega_1 \pm \omega_3),\]
\[(2\omega_2 \pm \omega_1), (2\omega_2 \pm \omega_3),\]
\[(2\omega_3 \pm \omega_1), (2\omega_3 \pm \omega_1),\]
\[3\omega_1, 3\omega_2, 3\omega_3, (\omega_1 + \omega_2 + \omega_3).\]
2.3 WAVELENGTH CONVERSION

The frequency components that are generated in the FWM process are illustrated in Fig. 2.3b (components around the third-order harmonics are not included in the figure). The efficiency of each of the above wave interactions depends on the phase-matching conditions which will be explained in section 2.4. During the FWM process the photon energy of the four-waves interacting is conserved. To illustrate this, we focus on the generated frequency component at $\omega_4 = \omega_1 + \omega_2 - \omega_3$ as shown Fig. 2.3c. Given the photon energy of $E_{\text{photon}} = \hbar \omega$, with $\hbar$ as the reduced Planck constant, the energy is conserved if energy is transferred from two photons at frequencies $\omega_1$ and $\omega_2$ to photons at the frequencies $\omega_3$ and $\omega_4$ satisfying $\omega_1 + \omega_2 = \omega_3 + \omega_4$.

2.3 Wavelength conversion

Let us consider a common case in nonlinear optics in which the input to a $\chi^{(3)}$-material consists of a strong wave at $\omega_P$, called the pump, and a weak one at $\omega_S$ called the signal. As the waves propagate through the medium, the signal wave may be amplified and a wave at $\omega_1$, called the idler, is generated, as illustrated in Fig. 2.4. This scenario is referred to as pump-degenerate FWM. The FWM process here is similar to the example given before where the generated new frequency at $\omega_4$ satisfies the relation $\omega_4 = \omega_1 + \omega_2 - \omega_3$. In the pump-degenerate process both photons $\omega_1$ and $\omega_2$ are at the same wavelength, $\omega_1 = \omega_2 = \omega_P$, and the signal wave is at $\omega_3 = \omega_S$. This means that the energy conservation in the pump-degenerate FWM process is given by

$$\omega_1 = 2\omega_P - \omega_S$$

(2.13)

considering $\omega_4 = \omega_1$. The interaction between the pump, signal and idler waves
as propagating along the $z$-direction is described via three coupled differential equations given by \[ \text{(30)} \]

\[
\frac{dE_P}{dz} = i\gamma \left( \left| E_P \right|^2 + 2 \left( \left| E_S \right|^2 + \left| E_I \right|^2 \right) \right) E_P + 2E_SE_IE_P^* \exp (i\Delta \beta z), \tag{2.14} \]

\[
\frac{dE_S}{dz} = i\gamma \left( \left| E_S \right|^2 + 2 \left( \left| E_P \right|^2 + \left| E_I \right|^2 \right) \right) E_S + E_I^* E_P^2 \exp (-i\Delta \beta z), \tag{2.15} \]

\[
\frac{dE_I}{dz} = i\gamma \left( \left| E_I \right|^2 + 2 \left( \left| E_P \right|^2 + \left| E_S \right|^2 \right) \right) E_I + E_S^* E_P^2 \exp (-i\Delta \beta z). \tag{2.16} \]

The coupling between the waves is facilitated by the nonlinear parameter $\gamma$ and the mismatch of the propagation constant between the waves $\Delta \beta$. It is assumed that the waves have the same optical polarization and optical field overlap. The nonlinear parameter $\gamma$ includes the nonlinear effects in $\chi^{(3)}$-materials and the field confinement, which is explained in more detail in section 3.5. The mismatch of the propagation constant for pump, signal and idler wave is given by $\Delta \beta = 2\beta_P - \beta_S - \beta_I$ where the propagation constants of pump, signal and idler are given by $\beta_P$, $\beta_S$ and $\beta_I$. The propagation constant $\beta$ gives information about the velocity of a wave (more detail in section 3.3).

### 2.4 Phase-matching condition

For efficient energy transfer between the waves in the FWM process, the conservation of momentum is required. This means that the efficiency with which power is transferred depends on the relative phase among the interacting waves. This is described within the nonlinear phase-matching condition

\[
k \equiv \Delta \beta + 2\gamma P_P = 0, \tag{2.17} \]
where the linear part $\Delta \beta$ comes from the mismatch of the propagation constant between the waves and the nonlinear part $2\gamma P_p$ accounts for the nonlinear phase shift. This equation is valid under the assumption that no pump depletion takes place and the pump power is much larger than the signal and idler power so that the main contribution to the nonlinear phase shift comes from the pump. The factor of two accounts for the pump-degenerate FWM as both annihilated pump photons are located at the same frequency. In the coupled differential equations [2.14, 2.16] the nonlinear and linear phase shifts are included in the first and second terms in the parenthesis [30]. In order to compensate for the positive nonlinear phase shift, the linear phase shift has to be negative, which requires in general anomalous dispersion of the medium (dispersion is described in more detail in section 3.3.2). To achieve phase matching, the relation between power levels, propagation constants and frequencies is essential.

The efficiency of energy transfer between pump, signal and idler, when the frequency separation between pump and signal is increased, depends on the dispersion properties of the $\chi^{(3)}$-medium. One way to assess this is by evaluating how the conversion efficiency changes with the wavelength separation of signal and pump. This is exemplified in Fig. 2.5 for a waveguide system with various group-velocity dispersion (GVD) values ($\beta_2$, see section 3.3.2). For smaller GVD values the conversion efficiency is maintained for a larger signal-pump detuning. The numerical simulations leading to Fig. 2.5 and ex-

![Figure 2.5: Numerical simulations of the output conversion efficiency of a 5 cm waveguide as a function of signal-pump detuning. The impact of the group-velocity dispersion (GVD) on the conversion bandwidth is shown for four different $\beta_2$ values. (Waveguide parameter: $\gamma = 5 \text{ (W} \cdot \text{m)}^{-1}$, propagation loss = 0.5 dB/cm, Pump power = 27 dBm)\n
\[^{1}\text{Here the conversion efficiency is defined as the ratio of idler power and signal power after propagation through the } \chi^{(3)}\text{-medium.}\]
experiments similar to the simulations were performed in Paper A and B. This behavior can be summarized with the conversion bandwidth $\Omega_{\text{FWM}}$. The conversion bandwidth is defined as the signal-pump frequency separation at which the signal gain decreases by 3 dB and is given by [17]

$$\Omega_{\text{FWM}} \approx \left[ \frac{4\pi}{|\beta_2| z} \right]^{\frac{1}{2}},$$

(2.18)

where $\beta_2$ is the GVD coefficient.

With either low GVD or short interaction length $z$, the conversion bandwidth can be increased. One huge advantage of integrated optical systems is the potential for strong light confinement that results in the possibility to tailor the dispersion properties in a reliable manner. In combination with the short length of these systems, it is possible to achieve a very large conversion bandwidth. To give an example, by dispersion engineering the waveguide, broadband wavelength conversion over $\sim 200$ nm has been shown in an integrated silicon waveguide [17].
Chapter 3

Waveguide theory

Integrated optical systems offer the opportunity to tailor the dispersion and achieve high confinement in small structures, therefore leading to high optical intensities at moderate power levels. These are ideal conditions for the realization of nonlinear optics with high efficiency and over broad bandwidth. In this chapter wave guiding structures and their basic physical properties are introduced.

3.1 Confined-wave propagation

The propagation of an optical beam in free space or bulk media is accompanied by the phenomenon of diffraction. This phenomenon describes the spatial broadening of optical radiation upon propagation. Waveguiding structures provide a means to avoid the divergence associated to this effect and guide light in a confined manner over distance. Waveguides are composed of mainly two distinct regions, a core medium enclosed by a cladding. The two areas are distinguished by a refractive index difference, where the core displays a higher refractive index than the surrounding cladding. Crucial for wave guiding is the behavior of light at the interface of the two regions. The confinement upon propagation can be understood from a ray-optics picture, where the energy of the wave confined in the core experiences total internal reflection at the interface with the cladding [34]. The propagation of light in a waveguide is described by the wave equation [30]

\[ \nabla^2 E = \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 (P_{\text{lin}})}{\partial t^2} - \mu_0 \frac{\partial^2 (P_{\text{nl}})}{\partial t^2}. \]  (3.1)
CHAPTER 3. WAVEGUIDE THEORY

The wave equation is derived from Maxwell’s equations. The electric field and the material polarization are given by $E$ and $P$, the speed of light in vacuum is $c$ and the vacuum permeability is $\mu_0$. The Nabla-operator $\nabla$ represents the differential operation $\left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$ for the spatial directions $x, y$ and $z$.

3.2 Waveguide designs

The light guiding by total internal reflection requires a refractive index difference between the core and cladding materials. In order to achieve this index contrast, the proper materials have to be chosen. Several different platforms provide the required refractive index features, and various different waveguide designs have been developed that offer confined light propagation. One important design, essential for the success of optical communication, is the optical fiber where core and cladding are circular rods presented in Fig. 3.1.a. In the figure, $z$ indicates the propagation direction of the optical wave. The material of choice for typical optical fibers is fused silica with slightly different composition of core and cladding. The refractive index difference is only around 0.01 and a common core diameter of a standard single-mode fiber (SSMF) used for telecommunications is around 10 $\mu$m.

It is important to distinguish the fiber design from designs suitable for inte-

![Figure 3.1](thegif)
3.3. MODE PROPERTIES

3.3.1 Mode field

As light propagates in a waveguide, only specific transverse field distributions of the electromagnetic field can be propagated. These field distributions are termed the modes of the waveguide. Information about the modes is obtained by solving the wave equations (Eq. 3.1) for the concrete combination of waveguide design and material distribution. Only a few structures, such as the cylindrical geometry and the slab waveguide allow for an analytical treatment. Otherwise, this equation needs to be solved numerically given the boundary conditions and specific material information. The number of modes in the waveguide varies, depending on the optical wavelength, the waveguide dimensions and the used materials. If only the fundamental mode propagates, the waveguide is called single mode. In order to simplify matters, a solution of
the wave equation is approximated with a uniform transverse-field distribution propagating in the $z$ direction as given by

$$E(x, y, z) = E(x, y)\exp(i\beta z).$$  (3.2)

Here $E(x, y)$ represents the spatial field distribution transverse to the propagation direction and $\beta$ indicates the propagation constant of the mode. Both parameters are characteristic for the mode and describe the propagation of the electromagnetic field completely. Only a single frequency component of the electrical field is considered, and the harmonic term $\exp(-i\omega_0 t)$ is dropped for simplicity.

How well the optical field is confined inside the core area is described by the effective area parameter

$$A_{\text{eff}} = \left( \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x, y)|^2 \, dx \, dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x, y)|^4 \, dx \, dy} \right)^2.$$  (3.3)

As can be seen in the equation, the field distribution $E(x, y)$ is what determines the effective area. The modal field distribution is dictated by the waveguide design and the index contrast between the core and the cladding. Paper 30 shows how $A_{\text{eff}}$ changes with a different refractive index of the waveguide core. In general, higher-order modes and longer wavelengths result in larger effective areas. As a comparison, a typical SSMF has an effective area of around 100 $\mu$m$^2$, whereas a silicon strip waveguide can reach an effective area of 0.054 $\mu$m$^2$ as reported in 35.

### 3.3.2 Dispersion

The propagation of light in bulk media is affected by the refractive index $n_0$ of the medium. The dependence of the refractive index on the wavelength is the chromatic dispersion of the material. In integrated waveguides the optical phase shift of light can be different from the one occurring in bulk media. This is accounted for by introducing the effective index $n_{\text{eff}}$ as

$$n_{\text{eff}} = \frac{\beta}{k_0},$$  (3.4)

where $k_0 = \frac{2\pi}{\lambda_0}$ is the wavenumber with $\lambda_0$ the wavelength of light in vacuum. Different modes and modes at different polarization have different effective indices $n_{\text{eff}}$. The effective index accounts for the influence of core and cladding.
3.3. MODE PROPERTIES

The effective index of a guided mode has a value in between the refractive index of the cladding \( n_{cl} \) and the core \( n_{cl} < n_{eff} \leq n_{co} \). As \( n_{eff} \) is wavelength dependent, both the material dispersion and the waveguide contribute to the total dispersion. More detailed information about dispersion in the waveguide is revealed when writing \( \beta \) as a Taylor expansion around a center frequency \( \omega_0 \):

\[
\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \ldots
\]

(3.5)

The terms \( \beta_m \) account for different contributions to the propagation constant and are calculated by

\[
\beta_m = \left( \frac{d^m \beta}{d\omega^m} \right)_{\omega = \omega_0}
\]

(3.6)

The parameter \( \beta_0 \) is connected to the phase velocity of a monochromatic wave by \( v_p = \frac{\omega_0}{\beta_0} \). The group velocity of a pulse is related to \( \beta_1 \) by \( v_g = \frac{1}{\beta_1} \). Information about how pulse broadening is affected upon propagation is connected to the amount and sign of the group-velocity dispersion (GVD) coefficient \( \beta_2 \). The broadening comes from the different propagation speeds of the individual frequency components forming a pulse. One distinguishes between normal dispersion when the GVD is positive (\( \beta_2 > 0 \)) and anomalous dispersion when the GVD is negative (\( \beta_2 < 0 \)). Sometimes this is called normal GVD and anomalous GVD. In the anomalous dispersion regime the higher frequency (blue-shifted) components propagate faster than the lower frequency (red-shifted) components of an optical pulse. The reverse is true for the normal dispersion regime. The sign of the GVD coefficient is important for phase-matching in nonlinear optics (sec 2.4). It is highly relevant to re-emphasize that for high confinement waveguides the GVD depends on the waveguide parameters, and the dispersion can be tailored e.g. by changing the dimensions of the waveguide. In Paper B and F simulations were presented, that show the dependence of the GVD on the waveguide dimensions of a strip waveguide. It is common to describe the GVD with the dispersion parameter \( D \) where

\[
D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2
\]

(3.7)

and the units are typically expressed in ps/(nm·km).

3.3.3 Polarization

The electromagnetic wave description assigns a direction of oscillation to the electric and magnetic field component as it propagates in time and space. In isotropic media the propagation behavior, more precisely the propagation constant, is independent on the electromagnetic field oscillation. However,
in anisotropic media the refractive index is dependent on the orientation of the electric field, leading to birefringence. It is common to define the electric field as the superposition of two polarization states, the TE and the TM polarization modes. For the TE polarization the electrical field component in propagation direction is zero and for TM polarization the magnetic field component in propagation direction is zero [36].

Although the materials forming a waveguide are mostly isotropic, the waveguide itself can however show anisotropic optical properties. This can be the case in rectangular waveguides. As the field components along the propagation direction are only close to zero, one talks about quasi-TE and quasi-TM modes. In addition, for structures with a small refractive index difference between core and cladding, the two polarization states (quasi-TE and quasi-TM) have dominant electric field components either in the horizontal x-direction or vertical y-direction labeled by $E_{pq}^x$ and $E_{pq}^y$, where $p$ relates to the mode-order in the x-direction and $q$ relates to the mode-order in y-direction. In order to exemplify the difference of the effective index on the mode order and polarization, the modes that are present in an integrated strip waveguide with dimensions of 1000 nm in width and 500 nm in height are compared in Fig. 3.2. A mode-solver was used to calculate the modes. The simulations were carried out using COMSOL Multiphysics where Maxwell’s equations are solved using a finite element method. The waveguide, here silicon nitride as the core material and silicon dioxide as the cladding material, has two guided modes for both states of polarization at 1.55 $\mu$m wavelength. The figure shows the power distribution in the propagation direction and it can be seen that the effective index changes with the state of polarization and mode order. In applications, the birefringent dependence of the waveguide design has been utilized to build integrated photonic systems like polarization rotators and polarization splitters [37, 38], as well as polarizers [39]. Even polarization independent designs have been demonstrated [40].

3.4 Loss mechanisms

3.4.1 Linear loss

The propagation loss in integrated optical waveguides has three fundamental linear contributions which are material absorption, scattering loss and radiation loss [41]. The origin of material losses and the resulting transparency window of optical materials has been introduced in section 2.1.1 and studied for silicon nitride in Paper 1. The loss contributions are accounted for in the
Figure 3.2: Mode-solver simulations of the power distribution in propagation direction $z$ for a strip waveguide with dimensions of 1000 nm in width and 500 nm in height. The core and cladding materials are silicon nitride and silicon dioxide. a) Fundamental quasi TE-mode ($E_{00}^x$). b) Second-order quasi TE-mode ($E_{10}^x$). c) Fundamental quasi TM-mode ($E_{00}^y$). d) Second-order quasi TM-mode ($E_{10}^y$).

The loss parameter $\alpha$ that leads to an exponential power decay along propagation distance $z$

$$P = P_0 \exp(-\alpha_{\text{lin}} z),$$

where $P_0$ is the initial power before propagation and $\alpha_{\text{lin}}$ is the linear attenuation coefficient. In nonlinear optics, the propagation loss plays a significant role. In calculations of nonlinear processes the total physical length of the waveguide $L$ is commonly replaced by the effective length $L_{\text{eff}}$ given by

$$L_{\text{eff}} \equiv \frac{1 - \exp(-\alpha_{\text{lin}} L)}{\alpha_{\text{lin}}}. \quad (3.9)$$

The effective length represents the waveguide length before the power attenuation becomes significant. With a longer physical length $L$ the effective length increases according to Eq. 3.9 and reaching a maximum that is given by $1/\alpha_{\text{lin}}$.

\[ ^1 \text{The conversion from attenuation in dB/m to linear attenuation is given by the relation } \alpha \approx 4.343 \cdot \alpha_{\text{lin}}. \]
In Fig. 3.3 a this is illustrated for different loss values.

The origin of material absorption lies in the interaction of optical waves with the medium during propagation as introduced in 2.1.1. Impurities in the material can lead to additional absorption. A known example for a molecular-bond-related absorption wavelength is the nitrogen-hydrogen bond (N-H) whose oscillation behavior absorbs light around telecom wavelengths. In Paper F, we show that a high-temperature annealing step can remove this absorption mechanism as has been demonstrated before.

Another contribution to the propagation loss is the scattering loss that occurs at the interfaces between the core and the cladding. The amount of scattering loss is related to the mean value of the surface roughness and its statistical variance [42]. The confinement of light, and thus the interaction with the sidewall, changes with core-cladding index contrast, mode order, wavelength and polarization. Waveguides with very thin sidewalls of only 40 – 50 nm lead to record low propagation loss [23]. A similar core thickness has been used in the work of Paper A. In Paper B, the roughness of the waveguide sidewalls and top surface has been analyzed in order to characterize the scattering loss. Another origin of scattering loss are imperfections in the core material.

The third contribution to propagation loss, the radiation loss, becomes relevant when waveguides are bent. In a curved waveguide the optical field is distorted in comparison to a straight waveguide which can lead to radiation of optical energy into radiating modes. The radiation loss becomes larger for shorter bending radii and waveguides with lower light confinement [43]. Therefore, in Figure 3.3: a) Impact of linear propagation loss on the effective length ($L_{\text{eff}}$).

b) Impact of linear propagation loss, two-photon absorption (TPA) and free-carrier absorption (FCA) on the maximum effective length as a function of optical power (More details in text).
3.4. LOSS MECHANISMS

integrated optical systems, the minimum achievable bending radius is mainly limited by radiation loss rather than by processing tolerances \( [41] \). For high-density integrated photonics a high optical confinement is essential in order to implement waveguides with short bending radii \( (\leq 10 \mu m) \).

3.4.2 Nonlinear loss

Nonlinear loss contributions become relevant in certain materials. In the presence of nonlinear loss, the total loss coefficient changes to

\[
\tilde{\alpha} = \alpha + \alpha_{\text{NL}}(|E|^2),
\]

(3.10)

where \( \alpha \) describes the linear contribution to the loss and \( \alpha_{\text{NL}} \) accounts for nonlinear loss. Examples of nonlinear loss is interband absorption like two-photon absorption (TPA) that occurs in materials like silicon or chalcogenide glasses (ChGs) at telecommunication wavelengths owing its small optical bandgap \( [19, 44] \). During the TPA process the energy of two photons is absorbed in order to bridge the bandgap energy and excite electrons from the valence band to the conduction band. This nonlinear loss has intensity dependence according to

\[
\alpha_{\text{NL(TPA)}} = \alpha_2 |E|^2,
\]

(3.11)

where \( \alpha_2 \) is the TPA absorption coefficient. The free charge carriers generated by TPA give rise to another nonlinear loss mechanism, the free-carrier absorption (FCA). In this process photon energy is transferred to free carriers in the conduction band or holes in the valence band. The impact of TPA and FCA on the maximum effective length is illustrated for a silicon waveguide\(^2\) in Fig. 3.3.b. In the scenario of nonlinear loss the maximum effective length is defined as the length at which the power decayed by 4.343 dB. The figure shows the dependence on the optical power and a comparison to materials without nonlinear loss. The optical confinement defines the intensity for a given power according to \( |E|^2 = P/A_{\text{eff}} \). The emerging free-carrier loss is proportional to the free-carrier concentration \( [11] \) and reduced with the duration it takes for carrier recombination (free-carrier lifetime). A possible way to counteract the FCA and effectively reduce the free-carrier lifetime is the removal of free carriers from the waveguide region. This has been shown in devices based on a reverse biased p-i-n structure in rib waveguides \( [15] \). How the nonlinear absorption in silicon waveguides (with or without carrier removal) changes the achievable nonlinear phase shift (see 3.5) has been studied theoretically in Paper [11].

\( ^2 \)The following parameters were used for simulations: \( \gamma = 200 \text{ (W·m)}^{-1}, A_{\text{eff}} = 0.09 \mu m^2, \alpha_2 = 7000 \times 10^{-15} \text{ m/W, free-carrier lifetime} = 800 \text{ fs}. \)
CHAPTER 3. WAVEGUIDE THEORY

3.4.3 Coupling loss

The coupling of light from an optical fiber to an integrated waveguide is commonly done by the direct focusing (end-fire) approach or by grating couplers. In the end-fire coupling approach light is focused directly from the fiber to the bare integrated waveguide. The coupling efficiency is dependent on the overlap integral of the field of the incident beam and the mode field of the waveguide and is calculated by (3.12)

\[ \eta_m = \frac{\left( \int A(x)B_m^*(x)dx \right)^2}{\int A(x)A^*(x)dx \int B_m(x)B_m^*(x)dx}. \]

To simplify the equation only the transverse direction is considered, where \( A(x) \) and \( B_m(x) \) are the field distributions of the incident beam and the \( m \)-th mode of the waveguide. The equation shows that improved coupling is achieved by matching the two fields \( A(x) \) and \( B_m(x) \).

Spot size converters at the end of the waveguides are commonly used to tailor the mode field in the integrated system to match the one of the incident beam. In [46] a coupling loss of 0.2 dB per facet has been demonstrated using a spot size converter. In this thesis, we used direct side-coupling into the waveguides via tapered lensed fibers.

Grating couplers are periodic grating structures that allow coupling of light from an oblique angle to the direction of the waveguide [47]. The advantage of grating couplers in comparison to end-fire coupling is that cleaving of the wafer is not needed, thus making on wafer testing possible. A drawback is the limited bandwidth and polarization dependence. In [48] a grating coupler design with a coupling loss of 0.62 dB and a 1-dB bandwidth of 40 nm has been shown.

3.5 Nonlinear parameter

It is convenient to write the nonlinear behavior of an integrated waveguide in the nonlinear parameter \( \gamma \) as

\[ \gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}, \]

where \( n_2 \) is the Kerr coefficient of the material, \( \lambda \) is the wavelength and \( A_{\text{eff}} \) is the effective area. The equation shows that both the nonlinear Kerr properties of the material and the field confinement have significant contributions to \( \gamma \). With a given nonlinear parameter \( \gamma \), power \( P \) and effective length \( L_{\text{eff}} \), the maximum nonlinear phase shift in a waveguide is

\[ \theta_{\text{nl}} = \gamma PL_{\text{eff}}. \]
This was presented in Paper [F] where both the increase in nonlinear Kerr coefficient and the reduction of effective area leads to a larger nonlinear parameter.
Chapter 4

Materials for integrated nonlinear optics

In this chapter we present and compare material platforms that are established in the field of integrated nonlinear optics. The materials are classified into three different groups: Chalcogenides, III-V materials and CMOS-compatible materials. In the following, linear and nonlinear optical properties are presented and afterwards the materials are compared to one of the most common widespread solutions for nonlinear optics, i.e. a highly nonlinear fiber (HNLF) of silicon-doped glass that is commercially available.

4.1 Chalcogenides

The family of chalcogenide glasses (ChGs) is based on the chalcogen elements from group VIa of the periodic table presented in Fig. 4.1. In particular the elements sulphur, selenium and tellurium form glass compounds with elements like phosphorous, germanium or arsenic. To form the glass compounds, deposition techniques like thermal evaporation, sputtering or chemical vapor deposition (CVD) can be used, followed by a post-deposition annealing step. ChGs are amorphous semiconductors and by tailoring the atomic composition of the glasses the optical properties can be changed. For instance the transparency of the ChGs is affected by the used chalcogen element, and the transparency window can enter into the mid-infrared wavelength region (sulphides 11 µm, selenides 15 µm, tellurides 20 µm). With a linear refractive index of ~ 2 – 3 at 1.55 µm wavelength, these glasses can be used as the core medium in an integrated optical waveguide with different surrounding cladding materials, such as SiO₂.

Examples for ChGs are the selenium based compound GeAsSe and the sulphur-
based compound As$_2$S$_3$. The glass GeAsSe has very high Kerr nonlinearities of up to $9 \times 10^{-18} \text{m}^2/\text{W}$ with a very low two-photon absorption (TPA) coefficient [49, 50]. Waveguides created with this material have been used to demonstrate FWM and supercontinuum generation [49]. A more common chalcogenide material in the field of integrated nonlinear optics is As$_2$S$_3$. Although it has a three times lower Kerr coefficient than GeAsSe, the lower waveguide losses achieved while having similar low TPA make it the more suitable ChGs for applications in the telecommunication band [51]. Waveguides based on As$_2$S$_3$ have been fabricated with 5 dB/m propagation loss compared to 250 dB/m for GeAsSe (see Table 4.1). Using rib waveguides made from As$_2$S$_3$, several nonlinear applications have been shown, like FWM [52, 53] or supercontinuum generation [51], and applications like wavelength conversion based on XPM [54] and FWM [55] as well as SPM-assisted signal regeneration [56].

### 4.2 III-V materials

The group of III-V materials is based on compounds formed between elements from group IIIa (aluminum, gallium or indium) and group Va (nitrogen, phosphorous, arsenic) in the periodic table shown in Fig. 4.1. Due to the direct bandgap in III-V materials they are commonly used in amplifiers (semiconductor optical amplifiers (SOAs)) or light emitting devices, including lasers. The
4.3 CMOS-COMPATIBLE MATERIALS

Crystalline semiconductor materials are mainly grown by molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD) in order to achieve layer by layer growth of crystalline morphology. This epitaxial growth requires a crystalline substrate and misses flexibility of stacked deposition on top of non-crystalline materials. Using III-V materials in CMOS-process lines is strictly avoided due to contamination of the fabrication line as III-V elements serve as dopants for silicon.

III-V materials like GaAs or AlGaAs are transparent through the communication bands and are utilized for nonlinear integrated optics. As the materials form compounds, the optical properties can be varied by changing the atomic composition of the compound. For instance, both the refractive index and bandgap increases by adding Aluminum to GaAs, hence becoming AlGaAs. The nonlinear coefficient of these materials is very high with $16 \cdot 10^{-18} \text{m}^2/\text{W}$ for GaAs [57] and even $26 \cdot 10^{-18} \text{m}^2/\text{W}$ for AlGaAs [58]. However, in the compound of GaAs, large nonlinear loss $\sim 100000 \cdot 10^{-15} \text{m}/\text{W}$ [20] limits the amount of power that can be sent to the device. A significant reduction of nonlinear loss by more than one order of magnitude is achieved with increased content of aluminum in AlGaAs [59] because of the increase in bandgap. The high nonlinearities and moderate linear propagation losses enable nonlinear experiments in AlGaAs like FWM [59, 60]. Wavelength conversion assisted by XPM has been shown in waveguides [57] as well as in resonators [61]. Even microresonator based comb generation has been shown [58]. In AlGaAs outstanding performance has been achieved by demonstrating a FWM conversion bandwidth of 750 nm [62] and a very low power threshold (7 mW) for comb generation [63].

4.3 CMOS-compatible materials

The manufacturing facilities for CMOS electronics have matured over the last decades and allow for low cost and mass production of electronic devices. Silicon, a group IV element, is the base material for CMOS components [64] but it is also attractive for nonlinear integrated optics [15] due to its large transparency window between 1 and 9 µm wavelength and its large nonlinear Kerr coefficient. A description of CMOS-compatible processing is given in more detail in the next chapter. In the field of nonlinear integrated optics, pure silicon is used both in crystalline and amorphous morphology. Silicon is also used in a compound with nitrogen (group V), forming silicon nitride, which is another CMOS-compatible material widely used for nonlinear integrated optics.
4.3.1 Silicon

Crystalline silicon

Integrated silicon waveguides are mainly based on the commercially available silicon-on-insulator (SOI) platform. This platform, originating from CMOS electronics, offers a single-crystalline silicon film separated by a layer of silicon dioxide from the bulk substrate. This layer combination is not possible to fabricate by deposition, but achieved by wafer bonding and is most suitable for the fabrication of waveguides. Crystalline silicon (c-Si) offers a large Kerr coefficient of \( 4 - 9 \cdot 10^{-18} \, \text{m}^2/\text{W} \) \[19, 20\]. A high refractive index contrast is given when silicon (3.5 at 1.55 \( \mu \text{m} \) wavelength) is embedded in silicon dioxide (1.45 at 1.55 \( \mu \text{m} \) wavelength). Under this condition the light guided in the silicon core is highly confined which leads to high optical intensities. The drawback of silicon as a material for nonlinear optics is the low optical bandgap of 1.2 eV leading to a TPA coefficient of \( \sim 5000 \cdot 10^{-15} \, \text{m/W} \) in the telecommunication band \[19, 20\]. Upon TPA, free carriers are generated in the waveguide which causes further absorption loss and a shift in dispersion. The resulting free-carrier absorption sets a limit on the maximum intensity level where efficient nonlinear processes are possible. The nonlinear absorption becomes less critical at longer wavelengths where the photon energy is reduced (e.g. 0.62 eV at 2 \( \mu \text{m} \) wavelength). For nonlinear optics in the mid infrared (IR), silicon is a very suitable material.

Free carriers can be removed from the waveguide core with an applied electric field \[66, 67\]. In order to apply the electric field, a reverse-biased p-i-n diode design is used in a rib waveguide structure. Nonlinear experiments that have been presented in SOI-based silicon waveguides with and without carrier removal design include, among others, signal regeneration \[16, 68\], supercontinuum generation \[18\] and third-harmonic generation (THG) \[69\]. Furthermore FWM has been demonstrated in nonresonant structures \[70, 72\] as well as in microring resonators \[73, 74\]. Wavelength conversion with data rates up to 40 Gb/s has been shown in \[75, 76\]. It is worth highlighting that in crystalline silicon the highest continuous wave (CW) FWM conversion efficiency (-1 dB) has been achieved among all waveguide platforms by using a biased p-i-n diode for carrier removal \[45\]. In Paper G we theoretically compared silicon waveguides (with and without carrier removal) in terms of their nonlinear performance and compared it to stoichiometric silicon nitride.

Amorphous silicon

Low-temperature-deposited silicon in amorphous form has raised interest in recent years because of its increased nonlinear Kerr coefficient and reduced TPA coefficient compared to crystalline silicon. The deposition in a plasma-enhanced chemical vapor deposition (PECVD) step (further information in \[5.5.2\]) allows processing temperatures as low as 200 – 400°C. The possibility
of deposition, that is not given for crystalline silicon, allows the fabrication of multiple layer designs and possible vertical coupling between waveguides. Deposited amorphous silicon has dangling bonds\(^1\) that are commonly saturated with hydrogen leading to hydrogenated amorphous silicon (a-Si:H) suitable for integrated optics \([77]\). One drawback of amorphous silicon is its temporal instability. Although material degradation can be reversed by annealing, a variation of system performance can be expected \([78]\). Indeed, reported nonlinear Kerr coefficients for a-Si:H vary in the range of \(0.5 - 74.3 \cdot 10^{-18} \text{m}^2/\text{W} \) \([79, 84]\) indicating a large dependence of the material on the processing parameters. TPA coefficients of around \(1000 - 3000 \cdot 10^{-15} \text{m/W} \) have been presented \([79, 82]\) that is roughly a factor of two below crystalline silicon. The potential for nonlinear optics has been shown in e.g. FWM experiments \([81, 85]\) and FWM based wavelength conversion \([80]\). Additionally spectral broadening induced by SPM \([83]\) and XPM \([79]\) has been presented, as well as supercontinuum generation \([86, 87]\).

### 4.3.2 Silicon nitride

Another CMOS-compatible material that is widely used to integrate nonlinear photonic systems is silicon nitride. In the CMOS fabrication process silicon nitride is used as a thermal and electrical insulator. Silicon nitride can be deposited in low-pressure chemical vapor deposition (LPCVD) and plasma-enhanced chemical vapor deposition (PECVD) process steps (details about both processes are provided in 5.5) as well as by sputtering. With these different techniques the material deposition can be performed at various temperatures giving large flexibility of fabrication. The material has in general amorphous morphology. The elementary material composition is crucial when characterizing its optical properties. In the field of nonlinear photonics three main groups of silicon nitride have been presented: stoichiometric silicon nitride \(\text{Si}_3\text{N}_4\) with a given atomic Si:N ratio of 3:4 studied in Paper A, F and G; silicon nitride in a non-stoichiometric composition with varying atomic ratios summarized with \(\text{Si}_x\text{N}_y\), studied in Papers B – F; and a proprietary material named Hydex, whose properties are similar to silicon oxynitride SiON \([22]\). In the following all three material platforms are presented in detail.

#### Stoichiometric silicon nitride

Stoichiometric silicon nitride has a transparency window ranging from below 0.3 to above 6 \(\mu\)m wavelength, and it has potential as a core material for integrated optics, including visible light applications. The refractive index of stoichiometric silicon nitride is \(\sim 2\) at 1.55 \(\mu\)m wavelength. Waveguides

\(^1\)Dangling bonds are unsaturated material bonds that have energy states within the bandgap of the material resulting in strong absorption in the near IR \([77]\).
manufactured with Si$_3$N$_4$ and SiO$_2$ as core and cladding materials show low
propagation losses and good optical confinement reaching high intensity and
long interaction lengths. Among all presented materials, this platform pro-
vides waveguides with the lowest propagation loss of 0.001 dB/cm [23] and
ring resonators with the highest Q-factors (∼80 million) [88]. The large optical
bandgap of Si$_3$N$_4$, more than three times larger than silicon, allows for
neglecting TPA at wavelengths in the telecommunication band. This, together
with the low propagation loss, is the key aspect for nonlinear optics. The non-
linear Kerr coefficient however is $\sim 0.2 \cdot 10^{-18}$ m$^2$/W [26], roughly two orders
of magnitude lower than silicon. In Paper [F] we give a detailed analysis of the
optical properties of Si$_3$N$_4$.

The main fabrication challenge when depositing thick layers of Si$_3$N$_4$ is an
increased tensile stress in the film that leads to cracking of the layer above
$\sim 300$ nm [89]. A larger thickness is required for optimal dispersion engineer-
ing and light confinement. To overcome this challenge, different strategies have
been investigated including thermal cycling [90], PECVD frequency alterna-
tion [91], mechanical stress barriers [29, 92] and deposition in trenches [93, 94].
With thin waveguides (40–50 nm) the cracking problem is avoided completely
and in addition ultra-low propagation loss properties are achieved by reducing
the sidewall scattering losses [23] but it is not possible to attain high nonlinear
parameters nor low dispersion in this waveguide design. In thick high-
confinement waveguides, the nonlinear capability of this material has been
shown in experiments like supercontinuum generation [95], harmonic genera-
tion in a microring cavity (second-harmonic generation (SHG) and third-
harmonic generation (THG)) [96] and resonator based Kerr frequency comb
generation [90, 97–99]. In thin waveguides with very low propagation loss
FWM-based wavelength conversion has been demonstrated in Paper [A]. Over
all presented platforms the broadest supercontinuum generation (495 THz) [28]
has been achieved in stoichiometric silicon nitride as well as coherent octave-
spanning microresonator combs [100]. In Paper [C] we theoretically evaluated
the propagation loss that is required to achieve 10 dB signal net-gain in this
platform.

**Silicon-rich nitride**

The variation of the ratio between silicon and nitrogen in non-stoichiometric
silicon nitride, Si$_x$N$_y$, gives a degree of freedom to change the optical and me-
chanical properties of the material. This enables for instance modifying the
refractive index and optical bandgap between the one achieved for Si$_3$N$_4$ and
silicon as shown in Paper [F]. The material with an increased silicon content in
comparison to Si$_3$N$_4$ is often referred to as silicon-rich nitride. The material
brings a relaxation of the tensile stress that is achieved when growing these
layers [101, 102], allowing to achieve thick cores in a single deposition step.
A flexible and reliable deposition with variable compositions of Si$_x$N$_{y}$ is given within the CMOS fabrication environment explored in detail for LPCVD deposition in Paper F and for PECVD deposition in [103]. Lately, research has been carried out to explore the impact of the composition on the nonlinear Kerr coefficient in more detail. Using PECVD nonlinear Kerr coefficients of $\sim 2 \cdot 10^{-18}$ m$^2$/W has been reported in [103] and up to $\sim 28 \cdot 10^{-18}$ m$^2$/W in [104]. Using LPCVD we showed Kerr coefficients of up to $\sim 1.1 \cdot 10^{-18}$ m$^2$/W in Paper F where we also related the increased nonlinearities to a reduced optical bandgap. The nonlinear performance in silicon-rich nitride has been presented in a FWM experiment in Paper B and supercontinuum generation in Paper C. Furthermore, we demonstrated XPM-based all-optical processing in Paper D and E.

**Hydex**

Hydex, invented by the company Little Optics, is a high-index doped silica glass with a refractive index between 1.5 and 1.9 (at 1.55 $\mu$m wavelength) close to silicon oxynitride. It has a nonlinear Kerr coefficient of $0.1 \cdot 10^{-18}$ m$^2$/W [105] which is slightly below the one for Si$_3$N$_4$. Waveguides with very low propagation loss have been fabricated in this platform, which enables a long effective length. Nonlinear experiments have been performed in order to show the potential of Hydex waveguides for nonlinear optics including FWM [106], wavelength conversion in non-resonant waveguides [107] and microrings [108] as well as supercontinuum [105] and comb generation [109, 110].

### 4.4 Comparison to HNLF

In order to compare these nonlinear platforms between each other, the maximum achievable nonlinear phase shift $\theta_{nl} = \gamma P_{max} L_{eff}$ (see section 3.5) is calculated. The results will be benchmarked to the HNLF. At the moment HNLF is the best platform for nonlinear optics in terms of maximum nonlinear phase shift. For each platform representative waveguide systems are chosen. The calculations of the nonlinear phase shift are based on the detailed information shown in Table 4.1. Crucial for the calculation of the maximum nonlinear phase shift is the maximum effective length but also the maximum possible power that is launched into the system. For platforms that do not show TPA a reasonable power of 2 W is taken and for HNLF a stimulated Brillouin scattering (SBS) limited maximum power of 500 mW is assumed. In general, the SBS threshold is increased by straining the HNLF, changing its material composition or by modulating the CW pump. For platforms that display TPA the maximum launched power was chosen as the value when the nonlinear TPA loss reaches either 10% (Fig. 4.2a) or 1% (Fig. 4.2b) of the linear loss according to Eq. 3.11. The TPA parameter and effective area used
Figure 4.2: (a) Maximum nonlinear phase shift with nonlinear loss restricted to 10% of linear loss. (b) Maximum nonlinear phase shift with nonlinear loss restricted to 1% of linear loss. (The platforms are evaluated according to the parameters provided in Table 4.1.)

for the calculations are provided in Table 4.1. This means that we restrict the analysis to the linear loss regime to simplify the comparison, as max $L_{\text{eff}}$ is calculated for all materials as $1/\alpha_{\text{lin}}$. Fig. 4.2 a shows the higher nonlinear phase shift is obtained for chalcogenides, III-V, amorphous silicon and HNLF. Crystalline silicon and silicon nitrides show in general a similar performance. For the more stringent demand in the maximum launched power, the result changes. Still ChGs, AlGaAs and HNLF show the largest nonlinear phase shift. Here, the material suffering from TPA shows worse performance. Silicon nitride becomes better in comparison to silicon and becomes the best CMOS-compatible platform for nonlinear optics. This is a rough estimation of the nonlinear phase shift as three-photon absorption and FCA have not been considered thus resulting in similar performance of silicon with and without p-i-n structure. As shown in Fig. 3.3 the FCA becomes the dominant nonlinear loss contribution at higher power levels. Therefore, a more detailed consideration of the nonlinear absorption effects is required that also accounts for the reduction of nonlinear loss with decaying power. This was done for silicon waveguides as presented in Paper C. The paper shows the impact of TPA and free-carrier lifetime on the nonlinear phase shift and illustrates that there is an optimum power level to maximize the nonlinear performance. In order to implement devices that allow nonlinear operations over a broad bandwidth, the dispersion becomes relevant as discussed before. This point is not included in the discussion but the relevant information about the achieved dispersion
4.5 Conclusion

It becomes clear after the presentation and comparison of the material platforms in this chapter, that there is no platform that combines low loss, high nonlinearities and the absence of nonlinear absorption. In distinct platforms, different record performances have been achieved, which indicates that each platform can outperform each other in terms of selected features. To conclude this chapter, the major advantages and disadvantages of each material platform are briefly summarized.

Chalcogenides offer good nonlinear performance. However, the chalcogenide glasses are not CMOS-compatible.

III-V compounds have demonstrated flexibility when it comes to tailoring material properties. Especially AlGaAs combines high refractive index and high nonlinearities, leading to highly efficient nonlinear processes. Missing CMOS-compatibility and the required epitaxial growth brings fabrication disadvantages.

Crystalline silicon has high nonlinearities and is a highly mature (CMOS-compatible) platform with easy access through commercially available SOI-wafers or multi-project wafer runs. Potential for monolithic co-integration with electronic components is another strong advantage of this platform. Nevertheless, crystalline silicon shows nonlinear loss constraints limiting the used power levels, and silicon can not be deposited in crystalline form on top of amorphous wafer substrates like silica.

Amorphous silicon shows high nonlinear Kerr coefficients and the low temperature deposition technique allows for flexible deposition with potential layer stacking. Reported temporal instability is the drawback.

Silicon-rich nitride offers CMOS-compatibility and has the possibility to be deposited flexibly on amorphous substrates. Furthermore low propagation losses are reported within this platform. The moderate nonlinearities and the high tensile stress in thick films are the drawback.

Nonstoichiometric silicon nitride is a CMOS-compatible material and offers flexible processing of thick layers suitable for dispersion engineering. The optical properties of the compound can be engineered by changing the composition of silicon and nitrogen. High propagation losses are the drawback.

Hydex has very low propagation losses. The low nonlinearities and the low refractive index are drawbacks. The platform is not widely available.
Table 4.1: Comparison of material platforms for nonlinear optics regarding the Kerr coefficient $n_2$, two-photon absorption TPA, effective area $A_{\text{eff}}$, nonlinear parameter $\gamma$, propagation loss, group-velocity dispersion (GVD) $\beta_2$ and waveguide design. The main reference is given in the last column. Material information taken from other references are marked accordingly.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Material</th>
<th>$n_2$ [10$^{-18}$ m$^2$/W]</th>
<th>TPA $\alpha_2$ [10$^{-15}$ m/W]</th>
<th>$A_{\text{eff}}$ [µm$^2$]</th>
<th>$\gamma$ [(W·m)$^{-1}$]</th>
<th>Loss [dB/m]</th>
<th>GVD $\beta_2$ [ps$^2$/m]</th>
<th>design</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNLF</td>
<td>SiO$_2$ based</td>
<td>0.026</td>
<td>-</td>
<td>9</td>
<td>0.01</td>
<td>0.0009</td>
<td>zero-GVD at 1541 nm</td>
<td>fiber</td>
<td>[111]</td>
</tr>
<tr>
<td>ChGs</td>
<td>Ge$<em>{11.5}$As$</em>{24}$Se$_{64.5}$</td>
<td>8.6</td>
<td>100</td>
<td>0.24</td>
<td>136</td>
<td>250</td>
<td>-84</td>
<td>strip</td>
<td>[49]</td>
</tr>
<tr>
<td></td>
<td>As$_2$S$_3$</td>
<td>2.92</td>
<td>6.2 [44]</td>
<td>7.1</td>
<td>1.7</td>
<td>5</td>
<td>433</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-V</td>
<td>GaAs</td>
<td>15.9</td>
<td>102 000 [20]</td>
<td>1.8</td>
<td>36</td>
<td>600</td>
<td>n.i. [b]</td>
<td>strip</td>
<td>[57]</td>
</tr>
<tr>
<td></td>
<td>Al$<em>{0.17}$Ga$</em>{0.83}$As</td>
<td>26</td>
<td>300-500 [59]</td>
<td>0.16</td>
<td>660</td>
<td>140</td>
<td>-127</td>
<td>strip</td>
<td>[58]</td>
</tr>
<tr>
<td>CMOS-</td>
<td>c-Si (with p-i-n)</td>
<td>4.5 [20]</td>
<td>5 000</td>
<td>0.06</td>
<td>280</td>
<td>100</td>
<td>n.i. [b]</td>
<td>rib</td>
<td>[68]</td>
</tr>
<tr>
<td>compatible</td>
<td>c-Si</td>
<td>4.5 [20]</td>
<td>5 000</td>
<td>0.006</td>
<td>360</td>
<td>360</td>
<td>-3445</td>
<td>strip</td>
<td>[66]</td>
</tr>
<tr>
<td>materials</td>
<td>a-Si:H</td>
<td>21</td>
<td>2 500</td>
<td>0.07</td>
<td>1 200</td>
<td>45</td>
<td>-0.42</td>
<td>strip</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>Si$_3$N$_4$ (low conf.)</td>
<td>0.09 [a]</td>
<td>-</td>
<td>1.28</td>
<td>0.1-0.3</td>
<td>6</td>
<td>0.7</td>
<td>strip</td>
<td>[113], Paper A</td>
</tr>
<tr>
<td></td>
<td>Si$_3$N$_4$ (high conf.)</td>
<td>0.26</td>
<td>-</td>
<td>0.88</td>
<td>1.2</td>
<td>40</td>
<td>zero-GVD at 1560 nm</td>
<td>strip</td>
<td>[22]</td>
</tr>
<tr>
<td></td>
<td>Si$_x$N$_y$ (LPCVD)</td>
<td>0.6</td>
<td>-</td>
<td>0.81</td>
<td>3</td>
<td>140</td>
<td>-77</td>
<td>strip</td>
<td>Paper B</td>
</tr>
<tr>
<td></td>
<td>Si$_x$N$_y$ (PECVD)</td>
<td>1.6</td>
<td>-</td>
<td>0.4</td>
<td>16</td>
<td>150</td>
<td>n.i. [b]</td>
<td>strip</td>
<td>[103]</td>
</tr>
<tr>
<td></td>
<td>Si$_x$N$_y$ (PECVD)</td>
<td>28</td>
<td>-</td>
<td>0.23</td>
<td>500</td>
<td>450</td>
<td>n.i. [b]</td>
<td>strip</td>
<td>[104]</td>
</tr>
<tr>
<td></td>
<td>SiON (Hydex)</td>
<td>0.11</td>
<td>-</td>
<td>2</td>
<td>0.2</td>
<td>4</td>
<td>10</td>
<td>strip</td>
<td>[108]</td>
</tr>
</tbody>
</table>

[a] effective $n_2$ for low-confinement waveguide
[b] no information available in reference
Chapter 5

CMOS-compatible micro- and nanofabrication

To understand the manufacturing processes that enable silicon-based integrated optical systems, in this chapter relevant CMOS-compatible micro- and nanofabrication steps are introduced.

5.1 CMOS-compatible photonics

Electronic components, such as microprocessors, have evolved tremendously in performance during the last decades, while keeping price low and even reducing footprint size. The reasons for this can be found in the development of the micro- and nanofabrication techniques and infrastructure for electronics. Mass production and miniaturization led to a tremendous improvement of integrating functionalities on microchips referred to as integrated circuits (ICs). One key component for integrated logic is the metal-oxide-semiconductor field-effect transistor (MOSFET) which forms the building block for CMOS technology. In general, the term CMOS-compatible defines fabrication techniques and materials that may be used in a CMOS processing line without risk of contamination or other adverse effects. Materials that are compatible with the CMOS fabrication infrastructure benefit from a mature processing platform that offers ideal conditions for low-cost mass production. The CMOS fabrication infrastructure can be used as leverage to manufacture optical waveguides. With the first silicon-based optical waveguide \[10\] the path of silicon photonics began \[14\] \[15\]. The integration of silicon photonics enables major advantages in communication systems \[16\]. With modern multi-project wafer runs, the high volume processing of CMOS fabs can be used to give fairly low-cost access to integrated photonic systems \[14\] \[17\].
5.2 Ellipsometry

5.2.1 Introduction

Ellipsometry is a widespread measurement technique to characterize material properties of thin films and surfaces in wavelength ranges from the near-UV to the far-IR. Properties like the dielectric function of a material (see 2.1) or the thickness of a deposited film are measured with the ellipsometer in an indirect manner by analyzing the interaction of polarized light with the sample under test.

In detail, the ellipsometer directs a beam of linearly polarized light to the sample where the material changes the polarization state of the light beam that is then detected and analyzed. The relative change in state of polarization, the complex ellipsometer parameter \( \rho \), is described by

\[
\rho = \tan(\psi)e^{i\delta}
\]

(5.1)

with \( \psi \) and \( \delta \) as change in magnitude and phase of light before and after the sample. The polarized light is expressed by a superposition of the orthogonal basis vectors p-polarization and s-polarization that allows to define every state of polarization. The interaction of light with matter is theoretically described according to the Fresnel equations yielding two independent complex Fresnel coefficients for light with p- and s-polarization \( R_p \) and \( R_s \) according to

\[
\rho = \frac{R_p}{R_s}.
\]

(5.2)

The Fresnel equations are based on Snell’s Law and include film thickness and refractive indices (complex permittivity, see section 2.1) to define the relative polarization change induced by the material.

In an iterative process the parameters of the Fresnel equations are used as fitting parameters to match the measured ellipsometer parameter described by Eq. 5.1.

5.2.2 Tauc-Lorentz Model

In this work we studied the optical properties of silicon nitride films. For the characterization we performed a simple approach where the silicon nitride was deposited directly on a silicon substrate with known properties. For the silicon nitride film we defined a theoretical model that represents the complex permittivity of the material. It is common to refer to this model as the general oscillator model as it includes the pole information (see Fig. 2.1) as oscillator functions. In the model the complex permittivity is expressed by

\[
\epsilon_r = \text{offset} + \epsilon_{UV} + \epsilon_{IR} + \epsilon_{TL},
\]

(5.3)
where offset is a constant of 1, $\epsilon_{UV}$ is the UV pole contribution, $\epsilon_{IR}$ the pole contribution at IR frequencies and $\epsilon''_{TL}$ is the Tauc-Lorentz oscillator term. The first three terms are real functions thus not including material absorption. The Tauc-Lorentz oscillator term is complex and models the material absorption close to the band gap. The three oscillator functions are

$$
\begin{align*}
\epsilon_{UV} &= \frac{A_{UV}}{E_{UV}^2 - E^2} \\
\epsilon_{IR} &= \frac{A_{IR}}{E_{IR}^2 - E^2} \\
\epsilon''_{TL} &= \left[ \frac{A_{TL}E_{TL}(E - E_g)^2}{(E^2 - E_{TL}^2) + C^2E^2} \cdot \frac{1}{E} \right].
\end{align*}
$$

(5.4)

In the equations, $E$ is the photon energy, $A_{xx}$ and $E_{xx}$ describe the strength and location of the corresponding oscillators, $C$ is a broadening term and $E_g$ is the optical bandgap. All these parameters and the thickness of the film are used as fitting parameters to match the ellipsometer measurement data. The shown $\epsilon''_{TL}$ in Eq. (5.4) is the imaginary part of the complex dielectric function $\epsilon_{TL}$. The real part is obtained via the Kramers-Kronig relation. For the material characterization carried out in Paper [1] we used the complete analytical solution of the Kramers-Kronig integral provided in [118].

5.3 Optical lithography

One of the most important manufacturing steps in the environment of semiconductor fabrication is the lithography process. This step combines the reproducible transfer of patterns for dedicated functionality onto the wafer. The patterns are geometries dedicated to produce structures as e.g. electrical contacts, passivation areas, areas for localized doping or etching of ridges, trenches or mesas. It is important to mention that during the lithography step the geometries are only structured and prepared for further processing steps such as etching. Optical lithography offers high throughput and comes with relatively affordable equipment.

In the lithography process the system design is projected via a photomask onto a photosensitive polymer on the wafer. The photomask contains transparent parts (glass) and opaque parts (chromium). As the photomask is aligned in between the light source and wafer (with photoresist), the optical radiation passes through the photomask and exposes only the selected areas of the resist where the photomask is transparent. The photosensitive resist then undergoes a chemical change when exposed to radiation. An example of the exposure step during the lithography process is illustrated in Fig. 5.1a. Light sources used for optical lithography are in the regime of UV, deep ultraviolet (DUV)
or extreme ultraviolet (EUV), reaching wavelengths from 400 nm down to around 100 nm. The resolution in terms of the minimum feature size that can be exposed scales with wavelength. In the case of optical contact lithography where photomask and wafer are in contact, the minimum resolved feature is described by \[ W_{\text{min}} \approx \sqrt{k\lambda g}, \] (5.5) where \( \lambda \) is the wavelength, \( k \) is the resist specific technology parameter (often around 1) and \( g \) is the gap between photomask and wafer. As an example, a gap of 2 \( \mu \)m and a light source with 300 nm wavelength would give a minimum feature size of around 800 nm. In the case of projection lithography the minimal feature size is described by \[ W_{\text{min}} \approx k \frac{\lambda}{\text{NA}}. \] (5.6) Here an objective with a numerical aperture (NA) is placed between the mask and wafer in order to project a smaller image of the mask onto the wafer and achieve a scaling down of the mask geometries. The use of optical projection lithography at 193 nm wavelength is the standard in industry and waveguide fabrication has been reported in [43]. Both equations show that lithography using shorter wavelengths yields a smaller minimum feature size that can be resolved during exposition. After exposure the photoresist is developed where exposed parts are removed for positive photoresists, while unexposed parts are removed for negative photoresists. The exposing radiation activates a different photosensitive chemistry in positive and negative resists. In positive resist the radiation triggers a scission of polymer chains leading to the reduction of its molecular weight that makes it easier to be resolved during development. The opposite effect takes place in a negative resist where cross polymerization leads to a reduced dissolution behavior. The remaining resist structures can serve as an etchmask or define openings for other processing steps like metal deposition with lift-off. The developed positive photoresist of the lithography example is illustrated in Fig. 5.1b.

Higher resolution than optical lithography can be achieved using electron-beam (ebeam) lithography. A shorter wavelength compared to optical radiation is achieved by the acceleration of electrons to high energies. Electron-sensitive resist is exposed by a focused electron beam. This technique is used to create photomasks or write masks directly on the wafer for very small features. Although writing features well below 100 nm are possible [64], the ebeam lithography has a serial writing procedure making the process time consuming, and the equipment is expensive and complex. This lithography technology is therefore unsuitable for mass production and in that sense not CMOS compatible.

The fabrication processes utilized in Papers A−F make use of optical contact
5.4 Thermal oxidation

The success of silicon as the primary semiconductor material in the field of electronics is based on its high-quality oxide [64]. A low amount of defects and an easy fabrication process makes the combination of silicon and silicon dioxide a powerful alliance in integrated circuits with fast switching MOSFETs with low power consumption. The oxide is formed during an oxidation process in which silicon undergoes a chemical reaction with oxygen in order to create silicon dioxide according to [64]

$$\text{Si(solid) + O}_2(\text{gas}) \rightarrow \text{SiO}_2 .$$  \hspace{1cm} (5.7)

It is important to mention that the oxidation reaction only takes place at the silicon surface. As a layer of SiO$_2$ builds up on top of the silicon wafer, oxygen atoms have to diffuse through the oxide layer in order to react at the silicon surface to form the SiO$_2$. At room temperature a silicon wafer oxidizes by only 2.5 nm and further oxidation is halted as the mobility of oxygen atoms is too low to diffuse through the oxide layer. Therefore thermal oxidation is carried out at process temperatures around 700 – 1200°C for increased diffusion of oxygen towards the silicon surface. Silicon oxidation is commonly done under atmospheric pressure (760 Torr) and a distinction
is made between dry oxidation with molecular oxygen (O\textsubscript{2}) as oxidant and wet oxidation with water vapor (H\textsubscript{2}O) as oxidant. Dry oxidation has the advantage of a denser oxide with higher quality whereas in wet oxidation a higher oxidation rate is achieved. The oxidation reaction takes place at the interface between silicon and silicon dioxide. Gaseous water molecules have to diffuse from the wafer environment through the silicon dioxide to reach the interface. The oxidation rate becomes important when growing thick oxides as the rate decreases significantly with increasing oxide thickness. The increased oxidation rate in the wet oxidation compared to dry oxidation comes from the higher diffusivity of H\textsubscript{2}O through the oxide layer in comparison with O\textsubscript{2}. The difference in rate becomes clear when oxidizing a 1 \(\mu\)m layer of SiO\textsubscript{2} as dry oxidation takes 48 hours while wet oxidation takes 2 hours. In optical waveguide systems, typical oxide thicknesses of around 1 – 4 \(\mu\)m are used in order to avoid leakage of light from the waveguide to the substrate. In the fabrication processes of Papers A\textsuperscript{[A]}\textsuperscript{[E]} thermal wet oxidation was used. An oxide around 3 \(\mu\)m was grown in Papers B\textsuperscript{[B]}\textsuperscript{[F]} where high confinement waveguides were fabricated. For the unconventional low confinement waveguide presented in Paper A\textsuperscript{[A]} an oxide thickness of 15 \(\mu\)m was grown in order to avoid substrate leakage \[23\].

### 5.5 Thin-film deposition

In order to deposit thin films of dedicated materials, several deposition techniques are available in the CMOS library of micro- and nanofabrication. The principle of all techniques is based on the transition of materials from a molecular movable state (gaseous or liquid) to the solid state to form a deposition on top of a wafer substrate. To prepare molecules for precipitation on a substrate, physical or chemical reactions can be utilized. Common physical deposition processes are evaporation and sputtering where the vaporized material condensates on a substrate. Vaporization of the deposition material is done by thermal heating of the source (evaporation) or by energetic ion bombardment (sputtering). A thin-film deposition technique based on chemical reactions is called chemical vapor deposition (CVD). In the CVD process gaseous chemicals react at the wafer surface to start a chemical deposition process. The activation energy for the chemical reaction to happen is commonly thermal or plasma assisted, naming the CVD process either low-pressure chemical vapor deposition (LPCVD) or plasma-enhanced chemical vapor deposition (PECVD).

#### 5.5.1 LPCVD

In LPCVD processes the chemical reaction is driven by temperature. Typical temperature values in the LPCVD reaction chamber are around 700 – 800°C.
The atomic composition of the precursor gases pumped into the reaction chamber defines the material composition of the deposited film. Changing the gas flow of the individual precursor gases can change the atomic composition of the deposit. This also enables in-situ doping of films by adding other gaseous chemicals. The precursor gases are introduced into the reaction chamber in non-reactive form and start to decompose once reaching the hot substrate region in the reactor where the decomposed reaction products are deposited. The benefit of having a low pressure in the chamber of around 0.1–1.0 Torr is that gas phase nucleation is minimized resulting in formation of solid clusters of atoms only on the wafer surface. This leads to a high uniformity of the deposited film. Two different types of reactors are used, cold-wall and hot-wall reactors. In cold-wall reactors the deposition reaction only takes place at the surface of the wafer. Hot-wall reactors on the other hand have a more uniform distribution of temperature and reduced convection effects, but a film is deposited at the reactor wall leading to a memory effect of the chamber.

Common materials deposited with LPCVD are silicon nitrides and silicon dioxide. In the manufacturing process of Papers A–F the deposition of silicon nitride was done using LPCVD.

### 5.5.2 PECVD

The primary nonthermal energy source which is used to drive a CVD-based process is the radio-frequency (RF) plasma. Therefore the PECVD process offers the advantage of distinct reduction of process temperatures in comparison to LPCVD. Typical deposition temperatures for PECVD processes are around 200–400°C. These fairly low temperatures feature an increased substrate protection and allow film deposition on top of temperature-critical substrates (e.g. metalization layers). Common materials for deposition in a PECVD system are silicon-based oxides and nitrides that are mainly used for passivation. Furthermore, the RF power of the plasma is an additional parameter that offers control over the deposited film properties.

### 5.5.3 Silicon nitride deposition by LPCVD and PECVD

The deposition of silicon nitride as a material for waveguide cores has been shown in both LPCVD [119] and PECVD [26] processes. The film quality of LPCVD nitride is in general higher compared to a PECVD nitride. This comes from the 15–30% higher hydrogen content in PECVD nitrides resulting in larger optical absorption at telecom wavelengths [120]. The stress in thick films of deposited stoichiometric silicon nitride (indicated in section 4.3.2) used for optical waveguides and micro-electro-mechanical systems (MEMS) devices [121] can give rise to cracks in the layers. One approach to avoid film cracks is to change the content of silicon and nitrogen from stoichiometric (Si$_3$N$_4$)
to silicon enriched. This has been shown with LPCVD in Papers B−F and [101] and also with PECVD in [122]. Another alternative to reduce the film stress in silicon nitride film is by depositing different layers at alternating RF frequencies of the plasma [91, 123, 124].

5.6 Reactive ion etching

To transfer the pattern from an etch mask into the substrate, an etching procedure is required. In general, etching can be carried out in dry or wet form. Wet etching is mostly isotropic\(^1\) and performed in an etch bath where the pure chemical process can offer a high etch selectivity between materials. Dry etching on the other hand provides an anisotropic etch. This enables better control over the process in comparison to wet etching because there are more available process parameters in dry etching. One special form of dry etching is ion milling where ionized molecules are accelerated in an electric field towards the target substrate. The bombardment of ions with high kinetic energy towards the wafer surface leads to the constant sputtering of surface molecules. This pure physical process has the advantage of a high degree of anisotropy, but typically has low selectivity [64].

A dry etching process that can provide both selectivity and anisotropy simultaneously is reactive-ion etching (RIE) by supporting both chemical and physical etching properties. RIE is commonly used to etch silicon-based materials (e.g. Si, SiO\(_2\), Si\(_x\)N\(_y\)) with halogen-based etch-chemicals (e.g. CHF\(_3\), CF\(_4\)). The physical component of the etching comes from electric-field-assisted acceleration of ionized species toward the surface of the wafer similar to the ion milling process. The chemical component comes from the gaseous etching chemicals used in the process that are ionized and broken down by the plasma inside the etch chamber to form chemically reactive species. The radical species undergo a chemical reaction and break the bonds of surface atoms on the wafer. In this process the binding of surface atoms to reactive radicals becomes energetically favored so that volatile reaction products are formed that are exhausted from the etching chamber. The chosen carbon containing etch chemicals leave reaction by-products like carbon that form polymer coatings on the wafer. This carbon deposition is removed by physical collisions with incident ions. As the impact of ions is lower on vertical sidewalls, the polymer sidewall passivation assists anisotropic etching. In Papers B−F the etching of the silicon nitride layers was performed in an RIE process.

\(^{1}\)An isotropic etching process is characterized by the same etching speed in all directions. Exception for this etch behavior is the wet etching in materials like silicon where the etching can be directed by the crystal planes allowing to wet etch in anisotropic manner.
Chapter 6

Future outlook

As presented in Paper G, in order to realize parametric signal net-gain of \(\sim 10\) dB, propagation losses of 0.05 dB/cm are required in a silicon nitride waveguide. In comparison to this value, our present waveguides fabricated from Si\(_3\)N\(_4\) show losses of around 0.4 dB/cm (Paper F). Thus, in order to reach the net-gain target, a further reduction of the propagation losses are necessary. The recommended changes of our established fabrication process that may lead to a reduction of the waveguide propagation losses are the following: In Paper B, we estimated losses occurring from the scattering at the waveguides sidewalls to be around 0.2 dB/cm. In order to reduce these losses, it is essential to minimize the roughness of the core sidewalls. Assuming that the roughness is translated from the etch mask, it is required to improve the existing lithography process. One option for improvement is to study the reflow properties of the resist at different temperatures during the hardbake step. The temperature is to be optimized so that the best resist smoothness is achieved. In Paper F, we reported the increase of waveguide propagation losses for silicon nitride compositions with increased silicon content. The loss measurements were carried out in the wavelength range between 1510 and 1610 nm. However, according to the ellipsometer measurements, we estimated material transparency for all compositions at wavelengths above 600 nm. This discrepancy may originate from increased material scattering in the material. It was observed throughout this work that a reduction in furnace pressure led to a reduction in propagation loss for the silicon rich nitride compositions. One potential explanation is the relation between furnace pressure and gas phase nucleation [64] that could be related to increased material scattering. Knowledge about the correlation between the furnace pressure and the propagation
losses could lead to loss improvements in all silicon nitride compositions.
Chapter 7

Summary of papers

Paper A


This paper presents the linear and nonlinear characterization of low-loss low-confinement waveguides fabricated from stoichiometric silicon nitride. These waveguides were fabricated by the group of John Bowers (University of California Santa Barbara). The 100 nm thin waveguide core leads to low optical confinement and results in low propagation loss of 0.06 dB/cm. In a nonlinear FWM experiment, wavelength conversion 10 Gb/s OOK data has been demonstrated. This paper shows that a similar conversion efficiency to SOI waveguides could be achieved with Si$_3$N$_4$, despite the inherently lower nonlinear coefficient.

My contribution: This experimental work was performed in joint collaboration with the group of John Bowers at UCSB, which provided the waveguides. At Chalmers I developed and built the measurement environment for the waveguide characterization, prepared and performed the measurements. I implemented and performed the simulations. I presented the results at CLEO 2014 and wrote the first draft of the paper.
Paper B


This paper presents the fabrication, simulation and characterization of high-confinement waveguides based on non-stoichiometric silicon nitride. This waveguide platform was developed at Chalmers. The propagation and coupling losses have been shown in a wavelength-resolved manner and the contribution of the scattering loss evaluated. In mode-solver simulations the dispersion and confinement properties in terms of the waveguides dimensions has been studied. Nonlinear FWM experiments has been shown and the functionality of a microring resonator has been presented, displaying high-quality factors $\sim 10^5$ in the 1.5 $\mu$m wavelength regime. We showed that this platform has similar nonlinear performance compared to Si$_3$N$_4$ with the additional advantage of a high yield fabrication process.

My contribution: I developed the waveguide fabrication process and performed the complete waveguide fabrication. I expanded the previously implemented measurement environment for waveguide characterization and developed the wavelength-resolved loss measurement technique. I prepared and performed the measurements. I assisted in developing the mode solver and performed parts of the simulations. I presented the results at OFC 2015 and wrote the first draft of the paper.

Erratum: In the erratum we corrected the measured nonlinear Kerr coefficient. The mistake originated from underestimating the coupled power in the dual-pump experiment. The correction does not impact the conclusions drawn in the paper.

Paper C


In this paper we use the high-confinement silicon-rich nitride waveguides to generate a more than octave-spanning supercontinuum. The experiments were conducted by the group of Morten Bache (DTU) using the waveguides developed and fabricated at Chalmers. The supercontinuum was generated from sub-kW 130 fs pulses. The results demonstrate that this platform enables sim-
ilar nonlinear performance as low-loss stoichiometric silicon nitride waveguide with the direct advantage of having a simplified fabrication process.

**My contribution:** I contributed to the waveguide design and performed the waveguide fabrication. I conducted the material characterization that provided the information for the waveguide simulations. I assisted in writing the paper.

**Paper D**


In this paper we showed all optical signal processing based on cross-phase modulation. The experiments were performed by the group of Lawrence Chen (McGill University) using the waveguides developed and fabricated at Chalmers. The dimensions of the waveguides were engineered in order to achieve flat anomalous dispersion across the C- and L-band. The performed interferometer-based measurements confirmed the simulated dispersion values. With the dispersion engineered waveguides we showed ultra-broad band wavelength conversion based on XPM. The broad-band nonlinear performance was demonstrated by wavelength conversion of 10 Gb/s RZ-OOK data across the C-band.

**My contribution:** I contributed to the waveguide design and performed the waveguide fabrication. I conducted the material characterization that provided the required parameters for the waveguide simulations. I assisted in writing the paper.

**Paper E**

“All-optical radio frequency spectrum analyzer based on cross-phase modulation in a silicon-rich nitride waveguide,” *IEEE International Topical Meeting on Microwave Photonics (MWP)*, Long Beach, USA, paper ThM1.5, Nov. 2016.

In this paper we demonstrated an all optical radio frequency spectrum analyzer based on cross-phase modulation. This work was carried out in collaboration with the group of Lawrence Chen at McGill University using the waveguide fabricated at Chalmers University. We explored XPM-based spectral broadening of a cw probe to analyze the RF spectrum of the intensity-modulated signal in the optical domain. In the dispersion engineered waveguides we mea-
sured the bandwidth of the RFSA to be above 560 GHz. In experiments we demonstrated the performance of this all-optical spectrum analyzer with resolved spectral characterization of modulation rates up to 160 GHz.

**My contribution:** I contributed to the waveguide design and performed the waveguide fabrication. I assisted in writing the paper.

**Paper F**


This paper presents the impact of the silicon nitride composition of a high-confinement waveguides on its linear and nonlinear properties. With a focus on low-pressure chemical vapor deposition (LPCVD) it was shown how the gas flow ratio during deposition serves as a way to change optical and mechanical properties of the material. Measurements of linear loss and material-specific nonlinear Kerr coefficients were carried out for five silicon nitride composition ranging from stoichiometric (Si$_3$N$_4$) to silicon-rich. In mode-solver simulations waveguide geometries were presented that led to desired anomalous group-velocity dispersion and increased nonlinearities. The measured nonlinear Kerr coefficient of the five compositions was compared with theoretical expectations and other platforms for nonlinear integrated optics. This was the first holistic characterization of the nonlinear performance of LPCVD silicon nitride for various compositions.

**My contribution:** I expanded the previously developed fabrication process and performed the fabrication of the waveguides. I implemented the ellipsometer model for the silicon nitride film characterization. I conducted the mode solver simulations. I presented the results at OFC 2017 and wrote the paper with support from the co-authors.

**Paper G**


In this work we theoretically discuss performance requirements to achieve 10 dB on-chip net-gain in three popular CMOS-compatible platforms for nonlinear integrated optics. We discussed the material platforms silicon nitride (Si$_3$N$_4$) and silicon (c-Si) where the silicon waveguide also included a hypo-
theoretical waveguide design with carrier removal. We highlighted the relevant tuning parameters in all three platforms in order to maximize the achievable nonlinear phase shift. This study sets benchmark requirements to reach the targeted 10 dB net-gain on chip.

**My contribution:** I implemented and performed the numerical simulations. I wrote the paper with support from the co-authors.
Bibliography


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BIBLIOGRAPHY


Appendix A

Clean room processes

In this appendix, we describe the clean room recipes used to manufacture the optical waveguides presented in Paper B−F.

Recipe for optical waveguide fabrication

1. Growth of silicon dioxide in Centrotherm oxidation furnace

<table>
<thead>
<tr>
<th>Silicon substrate</th>
<th>3-inch, p-doped/Boron, &lt;100&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1100°C</td>
</tr>
<tr>
<td>Gas flow</td>
<td>O\textsubscript{2} 5 l/min, H\textsubscript{2} 8 l/min</td>
</tr>
<tr>
<td>Oxidation time</td>
<td>1 200 min</td>
</tr>
<tr>
<td>Thickness SiO\textsubscript{2}</td>
<td>3 ( \mu )m</td>
</tr>
</tbody>
</table>

2. Deposition of silicon nitride in Centrotherm LPCVD furnace

<table>
<thead>
<tr>
<th>Si\textsubscript{3}N\textsubscript{4} - DCS:NH\textsubscript{3} 0.27</th>
<th>770°C, 250 mTorr, DCS 98.1 sccm, NH\textsubscript{3} 360 sccm growth rate center 4.02 nm/min, growth rate edge 4.24 nm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si\textsubscript{x}N\textsubscript{y} - DCS:NH\textsubscript{3} 4</td>
<td>770°C, 200 mTorr, DCS 240 sccm, NH\textsubscript{3} 60 sccm growth rate center 4.06 nm/min, growth rate edge 4.21 nm/min</td>
</tr>
<tr>
<td>Si\textsubscript{x}N\textsubscript{y} - DCS:NH\textsubscript{3} 8</td>
<td>770°C, 200 mTorr, DCS 126 sccm, NH\textsubscript{3} 15.8 sccm growth rate center 2.93 nm/min, growth rate edge 3.11 nm/min</td>
</tr>
<tr>
<td>Si\textsubscript{x}N\textsubscript{y} - DCS:NH\textsubscript{3} 12</td>
<td>770°C, 200 mTorr, DCS 240 sccm, NH\textsubscript{3} 20 sccm growth rate center 3.07 nm/min, growth rate edge 3.23 nm/min</td>
</tr>
<tr>
<td>Si\textsubscript{x}N\textsubscript{y} - DCS:NH\textsubscript{3} 16.67</td>
<td>770°C, 200 mTorr, DCS 250 sccm, NH\textsubscript{3} 15 sccm growth rate center 2.43 nm/min, growth rate edge 2.55 nm/min</td>
</tr>
</tbody>
</table>
CHAPTER A. CLEAN ROOM PROCESSES

3. Photolithography to define etchmask in mask aligner Sucss MJB3 DUV

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer cleaning</td>
<td>Rinse in Acetone, Isopropanol, Water and blowdry with N₂</td>
</tr>
<tr>
<td>Adhesion promotion</td>
<td>HDMS primer</td>
</tr>
<tr>
<td>Spin photosresist UV60-0.75</td>
<td>3,500 rpm, 45 s, 1,000 ms acceleration/deceleration</td>
</tr>
<tr>
<td>Softbake on hotplate</td>
<td>130°C, 4 min</td>
</tr>
<tr>
<td>Exposure settings</td>
<td>800 ms, DUV (200 – 260 nm wavelength), vacuum-mode</td>
</tr>
<tr>
<td>Post-exposure bake on hotplate</td>
<td>130°C, 1 min</td>
</tr>
<tr>
<td>Development in MF-CD-26</td>
<td>45 sec (rinse in water and blowdry with N₂)</td>
</tr>
<tr>
<td>Descum in oxygen plasma</td>
<td>150 W, 2 min</td>
</tr>
<tr>
<td>Hardbake in oven</td>
<td>130°C, 15 min</td>
</tr>
</tbody>
</table>

4. Reactive-ion etching of silicon nitride in Oxford Plasmalab 100

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Generator power</td>
<td>50 W</td>
</tr>
<tr>
<td>ICP power</td>
<td>150 W, 16.5 MHz</td>
</tr>
<tr>
<td>Pressure</td>
<td>95 mTorr</td>
</tr>
<tr>
<td>Gas flow</td>
<td>CHF₃ 50 sccm, O₂ 10 sccm</td>
</tr>
<tr>
<td>Etch rate</td>
<td>~ 45 nm/min</td>
</tr>
<tr>
<td>Resist removal</td>
<td>Acetone 5 min, MR-rem 400 55°C 5 min + ultrasonic 5 min, Isopropanol 3 min, rinse in water and blowdry with N₂</td>
</tr>
</tbody>
</table>

5. Polymer removal in standard clean process (SC1 + SC2)

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1 (H₂O₂+NH₃+H₂O)</td>
<td>80°C 10 min (rinse in water)</td>
</tr>
<tr>
<td>HF</td>
<td>1 min (rinse in water)</td>
</tr>
<tr>
<td>SC2 (H₂O₂+HCl+H₂O)</td>
<td>70°C 10 min (rinse in water and blowdry with N₂)</td>
</tr>
</tbody>
</table>

6. Deposition of silicon dioxide in STS PECVD chamber

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>550 mTorr</td>
</tr>
<tr>
<td>Gas flow</td>
<td>SiH₄ 400 sccm, N₂O 1,420 sccm</td>
</tr>
<tr>
<td>Deposition rate</td>
<td>44 nm/min</td>
</tr>
</tbody>
</table>

Recipe for crack barrier fabrication

1. Laser lithography to define crack barriers in Heidelberg Instruments DWL 2000

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer cleaning</td>
<td>Rinse in Acetone, Isopropanol, Water and blowdry with N₂</td>
</tr>
<tr>
<td>Adhesion promotion</td>
<td>HDMS primer</td>
</tr>
<tr>
<td>Spin photosresist S1813</td>
<td>3,500 rpm, 45 s, 1,000 ms acceleration/deceleration</td>
</tr>
<tr>
<td>Soft bake on hotplate</td>
<td>115°C, 2min</td>
</tr>
<tr>
<td>Exposure parameters</td>
<td>Focus offset 0, Intensity 100, Transmission 100</td>
</tr>
<tr>
<td>Development in MF-319</td>
<td>60 sec (rinse in water and blowdry with N₂)</td>
</tr>
</tbody>
</table>

2. Etching of silicon dioxide in HF bath

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>37.5 min</td>
</tr>
<tr>
<td>Etch rate</td>
<td>80 nm/min</td>
</tr>
</tbody>
</table>
Recipe for annealing of silicon nitride

1. Annealing of silicon nitride film in Thermolyne M. 59340 furnace

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1200°C</td>
</tr>
<tr>
<td>Gas flow</td>
<td>N₂ 20 s.u.</td>
</tr>
<tr>
<td>Duration</td>
<td>3 h</td>
</tr>
</tbody>
</table>
Continuous wave-pumped wavelength conversion in low-loss silicon nitride waveguides


(Also presented at the Conference on Lasers and Electro-Optics (CLEO), San Jose, USA, paper SW3M.4, June 2014)
Continuous wave-pumped wavelength conversion in low-loss silicon nitride waveguides

Clemens J. Krückel,1,* Víctor Torres-Company,1 Peter A. Andrekson,1 Daryl T. Spencer,2 Jared F. Bauters,2 Martijn J. R. Heck,2 and John E. Bowers2

1Photons Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
2Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA

*Corresponding author: kruckel@chalmers.se

Received December 16, 2014; revised January 26, 2015; accepted January 28, 2015; posted January 28, 2015 (Doc. ID 230655); published March 3, 2015

In this Letter we introduce a complementary metal-oxide semiconductor (CMOS)-compatible low-loss Si3N4 waveguide platform for nonlinear integrated optics. The waveguide has a moderate nonlinear coefficient of 265 W/km, but the achieved propagation loss of only 0.06 dB/cm and the ability to handle high optical power facilitate an optimal waveguide length for wavelength conversion. We observe a constant quadratic dependence of the four-wave mixing (FWM) process on the continuous-wave (CW) pump when operating in the C-band, which indicates that the waveguide has negligible high-power constraints owing to nonlinear losses. We achieve a conversion efficiency of ~26.1 dB and idler power generation of ~10.6 dBm. With these characteristics, we present for the first time, to the best of our knowledge, CW-pumped data conversion in a non-resonant Si3N4 waveguide. © 2015 Optical Society of America

OCIS codes: (190.3120) Integrated optics devices; (190.4360) Nonlinear optics, devices; (190.4380) Nonlinear optics, materials; (190.4390) Nonlinear optics, integrated optics.

http://dx.doi.org/10.1364/OL.40.000875

Photonics integration can lead to drastic reductions in power consumption and the size of optical systems. The integration of photonic systems showing nonlinear phenomena such as four-wave mixing (FWM) enables useful applications for all-optical signal processing such as wavelength conversion [1] or signal regeneration [2] at the chip level. Material platforms suitable for nonlinear integrated optics, including silicon-based compounds (Si, Si3N4, SiON, SiO2) [3–6], chalcogenide glasses [7], and III–V semiconductors (AlGaAs) [8], have been extensively studied for decades. In addition, some of the above materials could be hybridized with extra layers, such as organic composites [9], to further improve the nonlinear performance.

Using the mature technologies of the complementary metal-oxide semiconductor (CMOS) processing platform for integrated optics enables the option for mass production and thus tremendously reduces processing costs. To better understand why silicon nitride is our chosen material, let us turn our attention to the nonlinear phase shift $\Phi_{NL} = \gamma P L_{eff}$. This product of nonlinear coefficient $\gamma$, power level $P$, and effective length $L_{eff}$ must be maximized to achieve high FWM efficiency. As the nonlinear Kerr coefficient of Si3N4 is one order of magnitude greater than the one in SiO2 [10], a higher $\gamma$ and a more efficient Kerr process is achieved in Si3N4. Although Si has even higher nonlinearities, the nonlinear losses originating from two-photon absorption (TPA) and free carrier absorption at telecom wavelengths limit the maximum power levels $P$ that can be sent in this material. The need to operate at moderate power levels means that the energy in the wavelength-converted signal will not be high, regardless of the conversion efficiency (CE). It is of course possible to remove the photogenerated carriers in silicon waveguides by applying an electric field across the structure [11], but this requires additional manufacturing steps. These limitations do not exist in silicon nitride owing to its larger bandgap, providing a transparency window that extends to the ultraviolet [12]. In addition, the high index contrast to SiO2 allows for high optical confinement with the option to tailor waveguide dispersion [13].

Indeed, wavelength conversion by FWM in Si3N4 waveguides has been presented previously. But in order to achieve high CE, a pulsed pump with high peak power has been used in straight waveguides [14]. Alternatively, cavity enhancement of a continuous-wave pump has been shown in resonating structures [15]. Comb generation by cascaded FWM has been demonstrated in [15–17]. These examples clearly indicate the potential of this material for nonlinear integrated optics. However, CW wavelength conversion in non-resonant silicon nitride waveguide structures has not been investigated thoroughly. In this Letter we present CW-pumped wavelength conversion using the waveguides previously developed in [18]. This work extends the research presented in [19] by providing additional measurements and a more detailed comparison with numerical simulations. These original waveguide designs featured low propagation loss [18] so that a large effective length $L_{eff}$ of up to a few meters could be achieved in a compact platform. Larger interaction length results in an increased nonlinear phase shift and thus a higher FWM efficiency. We critically test the performance of these devices in a data conversion experiment that shows for the first time, to the best of our knowledge, CW-pumped wavelength conversion in a non-resonating Si3N4 waveguide.

The low propagation loss of this platform is achieved by using very thin waveguide dimensions. In this Letter we use a Si3N4 waveguide core cross section with a height of 100 nm and a width of 2.8 μm. The propagation loss is only 0.06 dB/cm. The waveguide cross section of the Si3N4 core and SiO2 cladding is shown in Fig. 1(a). Waveguides with similar dimensions have been used previously for linear applications; design and fabrication were first presented in [18]. The weak field confinement

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in our design (only around 12% of the optical power is guided in the Si$_3$N$_4$ core) leads to low scattering interaction of the optical field with the thin waveguide sidewalls.

The waveguide has single mode properties; simulations of the power distribution of the fundamental TE-mode are shown in Fig. 1(b). Since most of the power is in the cladding, we investigated the impact of having a change in its refractive index. A 5% variation of the cladding refractive index modifies the power confinement by less than 1.5%.

In the experiments, light is launched into the waveguide over tapered fibers with a coupling loss of 2.8 dB per facet. The propagation and coupling losses were evaluated with the cutback method. Waveguides of several meter lengths were coiled in spiral form with a minimum bending radius of 1 mm on a chip with a reduced footprint of 1.5 cm $\times$ 1.5 cm. As the waveguide has a polarization extinction ratio of more than 40 dB, we optimized the launched light for the lower-loss TE-polarization in all experiments. It is worth mentioning that even a 5% variation of the cladding refractive index modifies the power confinement by less than 1.5%.

The dispersion properties of this design were studied experimentally in a 6 m long waveguide by measuring the time delay versus wavelength using the time-of-flight technique. The results are presented in Fig. 1(c). From the measurement data we extracted a normal group velocity dispersion (GVD) of $-0.4$ ps/nm/m at 1550 nm and a dispersion slope of $1.4$ ps/nm$^2$/nm. The GVD is in fair agreement with the expected value of $-0.56$ ps/nm/m computed from mode solver simulations. We measured a nonlinear coefficient $\gamma$ of 285 W/km for this low-loss Si$_3$N$_4$ waveguide in a dual pump experiment [21]. Compared to other techniques, the dual pump experiment amplifies the two pumps independently.

Nonlinear effects occurring in the amplifiers become irrelevant. The results are in agreement with [10], where nonlinearities of different core thicknesses were investigated. To determine the optimal waveguide length for the following nonlinear experiments, we simulated the FWM-based idler generation by solving the nonlinear Schrödinger equation (NLSE) with the split-step Fourier method. As waveguide parameters for the simulations, we used the measured values of losses, dispersion, and nonlinear coefficient stated above. The simulated idler power as a function of waveguide length (Fig. 2) indicates that there is an optimum waveguide length of around 0.8 m. Above this length, a clear impact of the linear loss on the nonlinear FWM process is visible. For the theoretical model we used 33.3 dBm for the pump (1563 nm) and 18.9 dBm for the signal (1562 nm), which correspond to the power values used in the measurements. Next, we assessed the CE of the waveguides in an FWM experiment by launching a signal-pump pair into the waveguide in a degenerate pump configuration. A waveguide of 1 m length was used in this nonlinear measurement. To minimize the impact of dispersion, a detuning of 1 nm between the waves was chosen. Signal and pump were amplified independently and combined in a wavelength-division multiplexing coupler before launching into the waveguide. While keeping the signal at a constant 18.9 dBm, the pump power was varied. At the output of the chip, we analyzed the CE, optimistically defined as $P_{\text{idler}}/P_{\text{signal}}$, and the absolute idler power as a function of launched pump power. As expected, the maximum CE was $-26.1$ dB, corresponding to a launched pump power of 33.3 dBm as shown in Fig. 3(a). This results in a converted idler power of $-19.6$ dBm for the launched signal power of 18.9 dBm [Fig. 3(a)]. In the figure, measurement data are compared with the theoretical model, which shows a constant quadratic dependence on the pump power even up to 33.3 dBm. This indicates that the saturation effects owing to TPA or carrier effects are negligible. These CE results offer incomplete information about the absolute generated idler power. In spite of a relatively low CE, the advantage of our platform is that it can handle high CW power, thus allowing us to achieve high idler powers. The results presented here provide a 5.5 dB improvement with respect to the work in [19], where a 2 m long waveguide was used instead. This is in agreement with the simulations shown in Fig. 2.

An important aspect of any FWM-based wavelength converter is the impact of chromatic dispersion. We assess this by changing the wavelength spacing of the

![Fig. 1. (a) Schematic of waveguide cross section. (b) Simulation of power distribution of the fundamental TE-mode. (c) Measurement of time delay relative to 1550 nm versus wavelength.](image)

![Fig. 2. Numerical simulation of maximum generated idler power versus length of waveguide.](image)
signal-pump pair. Detuning signal and pump results in an additional phase mismatch that reduces the FWM CE. The launched power levels of signal and pump were kept constant at 18.9 and 33.3 dBm. The signal wavelength was decreased from 1562 nm while keeping the pump wavelength at 1563 nm. In Fig. 3(b), the results of the measured converted idler power versus signal-pump detuning are plotted. The 3 dB-bandwidth of the idler power is reached at a signal-pump spacing of 2.7 nm. We compared the measurements with the theoretical model of the system as shown in Fig. 3(b). Each point in the simulation curve is an independent solution of the NLSE for a different wavelength separation of signal and pump. The value of the GVD in the simulations is tuned to match the locations of the minimums in the measurement ripples.

Finally, to assess the performance of the waveguide in a more practical scenario, we carried out a wavelength data conversion experiment. The setup for this measurement is shown in Fig. 4(a). The signal wave is modulated with 10 Gb/s non-return-to-zero (NRZ) on-off keying (OOK) data, amplified, and then launched together with the amplified pump wave into a 2 m long waveguide. After the chip, the idler is filtered out from the spectrum with an optical bandpass filter (OBF) and launched into the receiver stage at different power levels, controlled with a variable optical attenuator (VOA). We use a pre-amplifier-based receiver stage in which the idler is optically amplified and filtered, and then amplified after the photo detector in the electrical domain. To evaluate the bit-error rate (BER) of the data conversion, we compared the data at the idler wavelength with the original generated bit sequence in front of the chip. Figure 4(b) shows the BER as a function of launched power into the pre-amplified receiver. Error-free (BER of $10^{-9}$) data conversion is achieved at a receiver power of $-34.6$ dBm for up to 6 nm conversion width. A receiver penalty of 0.8 dB of converted data with respect to back-to-back (b2b) transmission can be seen. In comparison to data conversion in other platforms such as Si, where dispersion-engineered waveguides have been used [22], in our experiments the high normal dispersion significantly limits our conversion bandwidth. However, the waveguide dimensions in our design have not been optimized for high-bandwidth wavelength conversion.

In summary, we have shown that the CMOS-compatible low-loss Si$_3$N$_4$ waveguide presented in [18], originally developed for linear optics applications, is also well suited for nonlinear optics applications (particularly FWM-based wavelength conversion). Although the nonlinear coefficient (285 W/km) is small compared to other integrated nonlinear platforms, we achieved an output CE of $-26.1$ dB and an absolute idler power of $-19.6$ dBm. Our experiments illustrate the relevance of having a long effective length and high power-handling capabilities. With these characteristics we present, for the first time, CW data conversion in a non-resonant Si$_3$N$_4$ waveguide.

This work is supported by the European Research Council under grant agreement ERC-2011-AdG-291618 PSOPA and the Wallenberg Foundation. Victor Torres-Company gratefully acknowledges funding from the Swedish Research Council (VR).

References

Linear and nonlinear characterization of low-stress high-confinement silicon-rich nitride waveguides

C. J. Krückel, A. Fülöp, T. Klintberg, J. Bengtsson, P. A. Andrekson, and V. Torres-Company

*Optics Express*, vol. 23, no. 20, pp. 25828–25837, Sept. 2015


(Also presented at the *Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, paper W1K.4, March 2015)
Linear and nonlinear characterization of low-stress high-confinement silicon-rich nitride waveguides

Clemens J. Krückel,∗ Attila Fülöp, Thomas Klintberg, Jörgen Bengtsson, Peter A. Andrekson, and Víctor Torres-Company

Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

∗kruckel@chalmers.se

Abstract: In this paper we introduce a low-stress silicon enriched nitride platform that has potential for nonlinear and highly integrated optics. The manufacturing process of this platform is CMOS compatible and the increased silicon content allows tensile stress reduction and crack free layer growth of 700 nm. Additional benefits of the silicon enriched nitride is a measured nonlinear Kerr coefficient $n_2$ of $1.4 \cdot 10^{-18} \text{m}^2/\text{W}$ (5 times higher than stoichiometric silicon nitride) and a refractive index of 2.1 at 1550 nm that enables high optical field confinement allowing high intensity nonlinear optics and light guidance even with small bending radii. We analyze the waveguide loss ($\sim 1 \text{dB/cm}$) in a spectrally resolved fashion and include scattering loss simulations based on waveguide surface roughness measurements. Detailed simulations show the possibility for fine dispersion and nonlinear engineering. In nonlinear experiments we present continuous-wave wavelength conversion and demonstrate that the material does not show nonlinear absorption effects. Finally, we demonstrate microfabrication of resonators with high $Q$-factors ($\sim 10^5$).

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OCIS codes: (130.3120) Integrated optics devices; (130.7405) Wavelength conversion devices; (160.6000) Semiconductor materials; (190.4380) Nonlinear optics, four-wave mixing; (220.4241) Nanostructure fabrication; (230.5750) Resonators.

References and links

1. Introduction

Silicon nitride (Si$_3$N$_4$) waveguides constitute a very attractive platform for integrated photonics applications. Similar to silicon-on-insulator (SOI) devices, their fabrication process is fully compatible with CMOS fabrication standards, and they render suitable for hybrid integration with other active components, such as modulators, amplifiers and detectors, both with silicon
and III/V materials [1–3]. A key difference with respect to SOI is that the transparency window of Si₃N₄ reaches into the visible and ultraviolet regions, which opens up new opportunities for integrated optics in life science applications [4, 5]. Ultra-low propagation losses of ~0.1 dB/m in the optical telecommunication window have been reported for thin (40–50 nm), low confinement, Si₃N₄ waveguides [6]. This has enabled the fabrication of high-performance passive devices, such as arrayed waveguide gratings [7] and ultra-high Q resonators [8] of relevance in fiber-optics applications.

Thicker waveguides provide higher optical confinement inside the waveguide core. High confinement allows for shorter curvature radii and, as a result, a higher density of photonic integration. In addition, the relatively high index contrast with respect to the silica cladding allows for engineering the dispersion of the waveguide (see e.g. [9]). This is crucial to achieve broadband phase matching in nonlinear optics applications [10]. Indeed, supercontinuum generation [9, 11], parametric frequency comb generation [12–14] and wavelength conversion [12] have been reported in thick Si₃N₄ waveguides. In contrast to SOI waveguides, Si₃N₄ shows no sign of two-photon absorption in the optical telecommunications band [10], which allows one to leverage the high-power erbium-doped fiber technology.

A challenge with Si₃N₄ waveguides is that films thicker than ~300 nm suffer large tensile stress and, in consequence, the waveguides tend to crack [15]. However, for a rectangular waveguide geometry, it is necessary to have very thick waveguides in order to get the zero dispersion wavelength in the telecommunications C-band [16]. Recent works address this manufacturability issue in different ways [16, 17]. In [17], mechanical trenches are inscribed in the oxide layer before the waveguide structures are fabricated. The trenches prevent further propagation of mechanical shock waves that initiate near the edge of the wafer. In this way, a crack-free region where devices can be safely fabricated, is cleared at the center of the wafer. With this method, stoichiometric Si₃N₄ (i.e. Si₃N₄) waveguides as thick as 900 nm have been fabricated recently. Epping et al. [16] proposed an alternative method that consists of filling inscribed trenches in the oxide layer with silicon nitride. Hence the filled trench becomes the waveguide’s core. Using Si₃N₄, they achieve propagation losses in the order of 0.4 dB/cm for waveguides of similar thickness.

An interesting feature of Si₃N₄ films is that the relative content of Si and N can be precisely adjusted during the deposition process. A different composition in the film has a dramatic effect in the stress [18]. In particular, films with lower stress can be deposited by increasing slightly the content of silicon [19], resulting in crack-free, thick (>500 nm) waveguides as reported e.g. in [20]. In this work, we present a detailed analysis of the linear and nonlinear properties of our thick non-stoichiometric SiₓN₄ waveguides [21]. Although the propagation losses (~1 dB/cm) are above the values reported by others [16, 17], the nonlinear Kerr coefficient is ~5 times higher than stoichiometric Si₃N₄ waveguides [22], resulting in notable nonlinear effects even when operating with continuous-wave (CW) lasers. We provide an in-depth study of the dispersion and nonlinear characteristics and detail our fabrication process. We observe no sign of detrimental two-photon absorption effects in the telecommunications C-band. The high mode confinement allows for manufacturing high-quality factor resonators (Q ~10⁵) with a free spectral range in the order of several nanometers, a record-high value for non-stoichiometric SiₓN₄ waveguides. In essence, the presented structure combines in a single platform the beneficial features of stoichiometric silicon nitride (absence of two-photon absorption) with those of SOI waveguides (large nonlinear coefficient), making it very promising for integrated nonlinear optics applications.

The remaining of the work is structured as follows. In Section 2 we describe the fabrication process. Section 3 covers the loss characterization and the simulation results of group velocity dispersion, and the nonlinear coefficient are presented in section 4. In Section 5 nonlinear
experiments are presented, and in Section 6 we summarize the performance of our high-$Q$ microresonators.

2. Fabrication

The manufacturing of the silicon-enriched nitride waveguides is compatible with the mature processing platform to fabricate complementary metal-oxide-semiconductor (CMOS) systems, which gives the option for mass production of integrated optics devices. A detailed schematic of the fabrication procedure of our Si$_x$N$_y$ waveguides is presented in Fig. 1(a). To simplify matters, only the upper part of the wafer processing is shown so that the symmetric layer growth on the backside is not part of the schematic. Starting from a plain silicon wafer (P-doped/Boron, <100> orientation) in the first step, a 2 µm layer of buried-oxide is grown in a thermal wet oxidation process in H$_2$O environment. On top of the silicon dioxide film a layer of silicon-enriched nitride is deposited in a low-pressure chemical vapor deposition (LPCVD) process. By varying the gas composition of the film forming reactants NH$_3$ and SiH$_2$Cl$_2$ injected into the reaction chamber, the ratio of the silicon and nitrogen content in the Si$_x$N$_y$ film can be adjusted. The recipe we used results in a ratio of around 65% silicon to 35% nitrogen that enables a tensile stress reduced growth of Si$_x$N$_y$ films with a thickness of 700 nm. The film

![Fig. 1. (a) Schematic of fabrication process for silicon-enriched nitride waveguides. Only the processing of the top part of the wafer is presented. (I) Silicon wafer as initial condition. (II) Thermal wet oxidation of 2 µm SiO$_2$. (III) LPCVD deposition of 700 nm silicon-rich nitride in a gas mixture of NH$_3$ and SiH$_2$Cl$_2$. (IV) Patterning of the photoresist based etching mask by DUV lithography. (V) Dry etching of Si$_x$N$_y$ in CHF$_3$ and O$_2$ and remaining etch mask removal. (VI) PECVD deposition of 2 µm SiO$_2$ in SiH$_4$ and N$_2$O. (b) SEM picture of patterned Si$_x$N$_y$ strip after etching. Magnification of 70 000. (c) Experimental results of spectrally resolved waveguide loss and coupling loss in Si$_x$N$_y$ waveguide (700 nm height, 1.65 µm width). The dark lines show the mean value, the bright shadowed areas the standard deviation and the brown curve shows the propagation loss for one sample waveguide; (see details in the text).]
composition was measured with energy dispersive X-ray spectroscopy. In order to transfer the transverse waveguide pattern into the Si$_x$N$_y$ layer we used a photoresist based soft mask during etching which is structured via deep-ultraviolet (DUV) contact lithography. This lithography technique readily enables to resolve feature sizes down to around 200 nm. The smoothness and durability of the etch mask is improved by a descum procedure and a heat treatment at 130 °C for 20 min. In a CHF$_3$ and O$_2$ based dry etching step, a Si$_x$N$_y$ strip is etched with nearly smooth and vertical sidewalls as can be seen in the scanning electron microscope (SEM) picture in Fig. 1(b). The picture reveals that the 700 nm thick silicon-enriched nitride strip is crack free. With our DUV lithography and etching process a 400 nm gap between two waveguides can clearly be resolved as shown in Fig. 2(a). Finally, the 2 µm upper SiO$_2$ cladding of the waveguide is deposited in a plasma-enhanced vapor deposition (PECVD) step with SiH$_4$ and N$_2$O as the reactive gas mixture.

3. Loss characterization

To specify dominant loss contributions in our silicon-enriched nitride waveguides, we combined spectrally resolved transmission scans with the cut-back method. The transmission scans are measured by launching light from a tunable laser into the waveguide and sweeping the wavelength in synchronization with a photodetector to measure the system throughput for individual wavelengths. By calibrating the transmission scans, the fiber-to-fiber loss of the device under test were separated from additional setup loss. The wavelength scans with 189 data points were performed for three different waveguide lengths (1.98, 3.03, 5.01 cm). The transmission loss from three different lengths allows the fitting of a first-order polynomial, to extract propagation loss and coupling loss from the slope and offset of the polynomial. Performing an individual polynomial fit for each wavelength, results in a spectrally resolved characterization of the coupling and propagation loss. In Fig. 1(c) the waveguide propagation loss of one waveguide with 189 wavelength data points is shown. The noise of the curve, resulting from spurious reflection artifacts in the waveguide, was cleaned up using a moving average filter.

Fig. 2. (a) SEM picture of the coupling region between the bus waveguide and the microring resonator at a magnification of 25 000. The inset shows the indicated rectangular area for the analysis of sidewall roughness, with the SEM image intensity converted to color code. The black line going from top to bottom is the identified edge of the waveguide wall used to extract the roughness parameters. (b) Atomic force microscopy picture of the Si$_x$N$_y$ surface.
average filter over 20% of the data points. In total, seven different waveguide systems at
different locations in the same wafer were evaluated to calculate the mean value and standard
deviation for the spectrally resolved propagation and coupling loss as presented in Fig. 1(c).
It can be seen that the coupling loss is fairly constant over wavelength with a mean value
of around 4.8 dB per facet owing to Fresnel reflections and modal field mismatch between
the tapered fiber (spot size 2.5 µm) and the waveguide. The propagation loss decreases from
around 1.8 dB/cm at 1510 nm down to 1.2 dB/cm above 1570 nm. This trend indicates
dominant material loss over losses from scattering locations in the waveguide boundaries as
the higher confinement at shorter wavelength increases the optical wave interaction with the
material. The material losses in the C-band could be caused by higher-order vibrational modes
of N-H bonds.

We support the claim of dominant material loss at lower wavelength by an estimation of the
scattering losses which was done in two steps. First, the surface roughness of the waveguide
sidewalls and the top surface was measured for the Si$_x$N$_y$ waveguide strip after etching. The
sidewall roughness was obtained from image processing the top-view SEM pictures of the
straight waveguide; a result can be seen as the inset in Fig. 2(a) where the black meandering
line indicates the detected position of the sidewall. For the top surface a two-dimensional
surface profile was obtained with atomic force microscopy (AFM) and the results are presented
in Fig. 2(b). From these measurements we calculated as indicators of the roughness feature size
both the root mean square (rms) $\sigma$ of the roughness height variations and the (auto-)correlation
$L_c$ of the fluctuations along the plane of surface. The extracted roughness parameters were ($\sigma$, $L_c$) = (5, 45) nm for the sidewall and ($\sigma$, $L_c$) = (0.5, 30) nm for the top surface. The bottom
surface of the waveguide was not accessible for roughness measurements but it was assumed
to have similar roughness parameters as for the top surface. In the second step the parameters
were inserted into an expression for the scattering loss originally derived for slab waveguides
[23]. It has, however, been widely used also for rectangular waveguides, with some reasonable
though not entirely rigorous reinterpretation of the entities in the formula. Since our aim is to
qualitatively compare the scattering losses to the total waveguide losses the precision in this
approach should be more than sufficient. In addition to the surface roughness parameters, the
scattering loss formula also contains some entities for the undisturbed waveguide - without
surface roughness - which were obtained from numerical simulations as mentioned in the
next section. The loss formula then yielded a total loss from the two sidewalls of $\sim$0.2 dB/cm
and from the top and bottom interfaces of less than 0.01 dB/cm. The sidewall scattering
loss is thus not insignificant but clearly smaller than the absorption loss, judging from the
measurements of the total waveguide loss. The strong wavelength dependence of the total
loss further underscores that absorption is the dominant loss mechanism, since the scatter-
ing loss is virtually independent of the wavelength; the simulations show that increasing the
wavelength from 1500 to 1600 nm the sidewall scattering loss decreases by merely 0.01 dB/cm.

4. Simulation of group velocity dispersion and nonlinear coefficient

In order to receive realistic results from mode solver simulations the refractive indices of all
three materials forming the waveguide were determined using spectroscopic ellipsometry over
the wavelength range from 245 to 1690 nm. The measurements were taken from one point in
the middle of the wafer. The measured refractive indices at 1550 nm for the thermally grown
and PECVD deposited SiO$_2$ were around 1.44 and 1.46, and for the silicon-enriched nitride
layer it was 2.1. Simulations were then carried out with a finite element method based solver
(COMSOL). The high index contrast between core and cladding results in a power distribu-
tion mainly confined in the core as presented in Fig. 3(a), here presented for the fundamental
TE-mode at 1550 nm wavelength. The high confinement of this mode translates into a small effective area $A_{\text{eff}}$ of around 0.9 µm$^2$ for a waveguide with dimensions of 700 nm in height and 1.65 µm in width. It is important to mention that for this cross-section dimension, both the fundamental and second order TE- and TM modes are guided for wavelengths above the L-band. For efficient nonlinear processes over a wide spectrum a low and anomalous dispersion in the waveguide structure is essential. By tailoring the dimensions of the core medium, it is possible to change the waveguide dispersion in order to overcome the normal material dispersion to obtain the desired chromatic dispersion in the waveguide. For our material combination we studied the impact of the height and width of the waveguide on the dispersion $D$ in detail. We varied the core dimensions with steps of 30 nm for the height and in steps of 90 nm for the width and interpolated the data to achieve fine resolved dispersion information for different waveguide cross sections as presented in Fig. 3(b) for the fundamental TE-mode at 1550 nm. The plot reveals that anomalous dispersion, $D > 0$, is achieved at waveguide dimensions thicker than 600 nm. With our stress reduced Si$_x$N$_y$, those thicknesses can be manufactured without film cracking, leading to high yield and reproducibility of the processed waveguides. The dimensions of the waveguides used in this work (1.65 µm width, 700 nm height) result in anomalous dispersion of around 60 ps/(nm·km) according to the simulations. Nonlinear processes are enhanced with higher nonlinear parameter $\gamma$ that is related to the nonlinear Kerr coefficient $n_2$, the wavelength $\lambda$ of the optical field and the $A_{\text{eff}}$ of the waveguide.
Table 1. Comparison of nonlinear Kerr coefficient $n_2$ and optical band gap energy $E_g$ for silicon, silicon-enriched nitride and stoichiometric silicon nitride.

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>$n_2$ (at 1.5 µm) [m$^2$/W]</th>
<th>$E_g$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si [24, 25]</td>
<td>(100% Si)</td>
<td>$\sim 4 \cdot 10^{-18}$</td>
<td>1.12</td>
</tr>
<tr>
<td>Si$_x$N$_y$</td>
<td>(65% Si)</td>
<td>$1.4 \cdot 10^{-18}$</td>
<td>2.3</td>
</tr>
<tr>
<td>Si$_3$N$_4$ [22, 27]</td>
<td>(43% Si)</td>
<td>$0.24 \cdot 10^{-18}$</td>
<td>$\sim 5$</td>
</tr>
</tbody>
</table>

by

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}.$$  \hfill (1)

Consequently, $\gamma$ is enhanced by reducing the effective area and/or by increasing the nonlinear Kerr coefficient $n_2$ of the materials. We measured a nonlinear Kerr coefficient $n_2$ of $1.4 \cdot 10^{-18}$ m$^2$/W for the silicon-enriched nitride (see section 5). The comparison of our silicon-enriched nitride composition (65% Si, 35%N) to pure silicon (100% Si) and stoichiometric silicon nitride (43% Si, 57%N) shows that the value of our material falls in between the other two as shown in Table 1 [22, 24, 25]. This is expected taking into account that the increased content of silicon comes along with an increase in nonlinearities. But one should be aware of the drawback when increasing the silicon content in a Si$_x$N$_y$ compound as the optical bandgap of the material is reduced. This increases the risk of two photon absorption (TPA) and the related carrier effects when working with high optical intensities.

The ellipsometry data of the Si$_x$N$_y$ material absorption serves as the basis to fit a theoretical model based on the Tauc-Lorentz dispersion relationship as described in [26]. From the model a bandgap of 2.3 eV was inferred, which is between reported values for Si and Si$_3$N$_4$ presented in Table 1 [25, 27]. To bridge an optical bandgap energy of 2.3 eV with two photons of the same wavelength, each photon needs a wavelength of 1100 nm or shorter. This provides an indirect indication that in our material, TPA should be negligible in the C-band.

Utilizing the measured $n_2$ for Si$_x$N$_y$ and the $n_2$ for silica available in the literature, the nonlinear parameter $\gamma$ was simulated for different waveguide dimensions as presented in Fig. 3(c), which shows results for the fundamental TE-mode at 1550 nm. From the mode solver data the $A_{\text{eff}}$ is calculated as in [28]. As can be seen in the plot, the maximum $\gamma$ is achieved at waveguide dimensions of around 0.9 µm width and 450 nm height, where the optical field confinement leads to the smallest effective area. Comparing the simulations of the dispersion with the simulations of the nonlinear parameter indicates that there is a tradeoff between achieving anomalous dispersion and the highest nonlinearities. This tradeoff is highlighted by including the line of zero dispersion in the $\gamma$ simulation graph in Fig. 3(c).

5. Nonlinear experiments

Next we show the potential of our platform in integrated optics by realizing a set of experiments with CW-pumped waveguides. The setup shown in Fig. 4(a) contains two tunable CW lasers where both waves are amplified independently and controlled in polarization. In this way we ensure that no nonlinear interaction occurs in the amplifiers but only in the integrated waveguide. The amplified spontaneous emission (ASE) of the signal after the amplifier is filtered out by an optical bandpass filter (OBF), whereas the ASE of the pump is removed in the 200 GHz bandwidth common port of the wavelength-division multiplexing (WDM) coupler. After combining signal and pump in the WDM coupler both waves are launched over a tapered fiber
into the microchip containing a straight waveguide of 0.94 cm length. The polarization of both waves is optimized for maximum throughput in the nonlinear experiments. After the chip the conversion efficiency (CE), defined as $\frac{P_{\text{out idler}}}{P_{\text{out signal}}}$, is analyzed with respect to signal and pump waves at the input. We experimentally demonstrate that the FWM conversion efficiency is directly proportional to the pump power, even at high power levels where the increased silicon content may raise the concern of TPA happening. In the experiments, signal and pump waves were placed with 1 nm wavelength separation (signal 1562 nm, pump 1563 nm) to minimize the impact of dispersion in the FWM process. The signal power was kept constant at 19 dBm as the pump power was increased. At the output the idler and signal power were tracked with an optical spectrum analyzer (OSA) and the conversion efficiency is displayed in Fig. 4(b). The agreement with the numerical simulation indicates that the nonlinear measurement results follow the theoretical dependence on the pump power. The deviation from a quadratic dependence is explained by the strong signal that saturates the FWM process slightly. The numerical simulations are realized by solving the nonlinear Schrödinger equation with the split-step Fourier method. Coupling loss variations are considered in the simulations.

The group velocity dispersion was studied in a second experiment. Here, the separation of signal and pump wavelength is changed by setting the pump to 1563 nm and detuning the signal away to shorter wavelengths. Both waves were launched into the waveguide at constant power levels (signal 19 dBm, pump 30 dBm). The change in CE over signal-pump detuning is plotted in Fig. 4(c). The graph indicates a 3 dB conversion bandwidth of around 8 nm. This corresponds to a dispersion value of $\sim 15 \text{ ps/(nm km)}$. The difference with respect to the simulation results [Fig. 3(b)] could be due to slight variations in the waveguide geometry that are within fabrication tolerance.

Fig. 4. (a) Schematic of experimental setup for four-wave mixing experiments. Continuous wave (CW) tunable laser. Polarization controller (PC). Erbium doped fiber amplifier (EDFA). Optical bandpass filter (OBF). Wavelength-division multiplexing (WDM) coupler. (b) Outcoupled conversion efficiency as a function of launched pump power into the waveguide. (c) Outcoupled conversion efficiency as a function of wavelength separation between signal and pump wave. (d) Nonlinear phase shift $\phi_{\text{SPM}}$ as a function of coupled pump power.
Next, we provide a characterization of the nonlinear properties in a dual CW-pumped experiment with different launched power levels, as in [29, 30]. Two CW tunable lasers are copolarized and amplified with high-power amplifiers. The generated idler power in the waveguide with a length of 0.94 cm depends on the amount of nonlinear phase shift $\varphi_{SPM}$ according to:

$$
\frac{I_0}{I_1} = \frac{J_0^2(\varphi_{SPM}/2) + J_2^2(\varphi_{SPM}/2)}{J_1^2(\varphi_{SPM}/2) + J_2^2(\varphi_{SPM}/2)}
$$

(2)

$$
\varphi_{SPM} = \gamma L_{eff} P_{in},
$$

(3)

Here $I_0$ and $I_1$ are the intensities of the pump wave and the idler wave of first order. $J_i$ corresponds to the $i$-th order Bessel function. The ratio of nonlinear phase shift $\varphi_{SPM}$ versus coupled pump power into the waveguide is $4.64 \times 10^{-5}$ (mW)$^{-1}$ as shown by the slope in Fig. 4(d). Following Eq. (3) and using a calculated effective length $L_{eff}$ of 0.76 cm, a nonlinear coefficient $\gamma$ of 6.1 (W m)$^{-1}$ is evaluated. With an effective area $A_{eff}$ of around 0.9 $\mu$m$^2$ the Kerr coefficient $n_2$ is thus $1.4 \times 10^{-18}$ m$^2$/W using Eq. (1).

### 6. Compact microstructures: ring resonator

The high index contrast between the SiO$_2$ cladding and the silicon-enriched nitride core facilitates the fabrication of ring resonator systems with small bending radii. We manufactured a ring resonator with 20 $\mu$m bending radius as shown in the SEM picture in Fig. 5(a) taken prior to the top cladding deposition. We characterized the ring by scanning a tunable laser across a broadband window (1520-1620 nm). Optimizing the polarization for maximum throughput leads to the transmission scan shown in Fig. 5(b). The measured free spectral range of the transmission data is $\sim$150 000. (d) $Q$-factor evaluation of resonances from 1520 to 1620 nm wavelengths.

Fig. 5. (a) SEM picture of microring resonator with 20 $\mu$m bending radius at a magnification 7 000. (b) Wavelength dependent transmission spectrum of a 20 $\mu$m radius microring resonator system. (c) High-resolution scan of microring resonance at $\sim$1617.4 nm. The quality factor is $\sim$150 000. (d) $Q$-factor evaluation of resonances from 1520 to 1620 nm wavelengths.
resonances is 8.3 nm. A zoom-in on one of the resonances measured with 0.1 pm resolution is displayed in Fig. 5(c) indicating a quality factor of around 150 000 by fitting a Lorentzian curve and evaluating the full-width half maximum in linear scale. An evaluation of the quality factor for resonances in the wavelength regime between 1520 and 1620 nm is presented in Fig. 5(d) and shows \( Q \)-factors up to 165 000. These loaded quality factors are in agreement with the measured transmission loss in Fig. 1(c).

7. Conclusion

We have presented silicon enriched nitride waveguides with a composition of 65\% silicon and 35\% nitrogen and discussed the advantages of having enhanced silicon content in Si\(_x\)N\(_y\) with respect to Si\(_3\)N\(_4\). The reduced tensile stress in the film allows thick film deposition and dispersion engineering towards anomalous dispersion, one important requirement for broadband wavelength conversion. Nonlinear characterization revealed a nonlinear Kerr coefficient \( n_2 \) of \( 1.4 \times 10^{-18} \) m\(^2\)/W and an optical bandgap of 2.3 eV that shows the potential for high power nonlinear optics as demonstrated experimentally. High confinement in the presented waveguides and propagation loss of \( \sim 1 \) dB/cm enable high \( Q \)-factor \( (\sim 1.5 \times 10^5) \) ring resonators with small bending radii for high density of photonic integration. The waveguide loss has been evaluated to be dominated by material loss.

Acknowledgments

This work was supported by the European Research Council under grant agreement ERC-2011-AdG-291618 PSOPA, the Wallenberg Foundation and the Swedish Research Council (VR).

The authors would like to thank Seyed Ehsan Hashemi for helping out with taking the AFM picture.
Linear and nonlinear characterization of low-stress high-confinement silicon-rich nitride waveguides: erratum

CLEMENS J. KRÜCKEL, ATILIA FÜLÖP, THOMAS KLINTBERG, JÖRGEN BENGTSSON, PETER A. ANDREKSON, AND VICTOR TORRES-COMPANY

Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

*kruckel@chalmers.se


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OCIS codes: (130.3120) Integrated optics devices; (130.7405) Wavelength conversion devices; (160.6000) Semiconductor materials; (190.4380) Nonlinear optics, four-wave mixing; (220.4241) Nanostructure fabrication; (230.5750) Resonators.

In [1], we presented an experimental study of the linear and nonlinear properties of silicon-rich nitride waveguides fabricated via low-pressure chemical vapor deposition (LPCVD). Owing to an error in the estimated coupled power in the two-pump experiment, we have overestimated the nonlinear Kerr parameter of the waveguide. The corrected Fig. 4(d) should be:

![Figure 1](https://example.com/figure1.png)

Fig. 1. Nonlinear phase shift $\phi_{SPM}$ as a function of coupled pump power.

From this figure we infer a nonlinear parameter $\gamma = 3 \text{ (W} \cdot \text{m})^{-1}$ leading to a nonlinear coefficient $n_2 = 0.6 \cdot 10^{-18} \text{ m}^2/\text{W}$.

The Table 1 should therefore look as follows:

<table>
<thead>
<tr>
<th>Coupled pump power [mW]</th>
<th>Nonlinear phase shift [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0.005</td>
</tr>
<tr>
<td>200</td>
<td>0.011</td>
</tr>
<tr>
<td>300</td>
<td>0.017</td>
</tr>
<tr>
<td>400</td>
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<tr>
<td>500</td>
<td>0.030</td>
</tr>
<tr>
<td>600</td>
<td>0.036</td>
</tr>
<tr>
<td>700</td>
<td>0.042</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement data</th>
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<tr>
<td>Linear fit</td>
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</tbody>
</table>

References and links

Table 1. Comparison of nonlinear Kerr coefficient $n_2$ and optical band gap energy $E_g$ for silicon, silicon-enriched nitride and stoichiometric silicon nitride.

<table>
<thead>
<tr>
<th></th>
<th>$n_2$ (at 1.5 µm) [m$^2$/W]</th>
<th>$E_g$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si [24,25]</td>
<td>$\sim 4 \cdot 10^{-18}$</td>
<td>1.12</td>
</tr>
<tr>
<td>Si$_x$N$_y$</td>
<td>$0.6 \cdot 10^{-18}$</td>
<td>2.3</td>
</tr>
<tr>
<td>Si$<em>{3/4}$N$</em>{4/3}$ [22,27]</td>
<td>$0.24 \cdot 10^{-18}$</td>
<td>$\sim 5$</td>
</tr>
</tbody>
</table>

The main conclusion in [1] is still valid. Varying the relative composition between silicon and nitride during LPCVD deposition provides a higher Kerr coefficient than what is possible with stoichiometric silicon nitride.
Octave-spanning supercontinuum generation in a silicon-rich nitride waveguide

X. Liu, M. Pu, B. Zhou, C. J. Krückel, A. Fülöp, V. Torres-Company, and M. Bache

We experimentally show octave-spanning supercontinuum generation in a nonstoichiometric silicon-rich nitride waveguide when pumped by femtosecond pulses from an erbium fiber laser. The pulse energy and bandwidth are comparable to results achieved in stoichiometric silicon nitride waveguides, but our material platform is simpler to manufacture. We also observe wave-breaking supercontinuum generation by using orthogonal pumping in the same waveguide. Additional analysis reveals that the waveguide height is a powerful tuning parameter for generating mid-infrared dispersive waves while keeping the pump in the telecom band.  

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OCIS codes: (130.2790) Guided waves; (130.2755) Glass waveguides; (190.7110) Ultrafast nonlinear optics; (320.6629) Supercontinuum generation.

http://dx.doi.org/10.1364/OL.41.002719

Supercontinuum generation in photonic crystal fibers pumped with a mode-locked laser oscillator allowed generating octave-broadened coherent spectra without an amplifying stage [1]. This remarkable achievement paved way for self-referencing in laser frequency combs [2] and key advances in biophotonics [3].

There is a growing interest in supercontinuum generation in photonic integrated waveguides. This offers the prospect of supercontinuum generation in different regions of the electromagnetic spectrum with extremely low pump pulse energies delivered by near-IR ultrafast femtosecond fiber lasers. One of the most promising waveguide platforms that has demonstrated near-IR-pumped octave-spanning supercontinua is silicon nitride [4–9]. Silicon nitride waveguides can be manufactured directly on an oxidized silicon wafer. Unlike silicon, silicon nitride has negligible two-photon absorption in the near-IR. The nonlinear Kerr coefficient is comparatively lower than other integrated waveguide technologies, but this is offset by lower linear propagation loss. As a result, large nonlinear phase shifts can be obtained at modest pump powers. The broadest supercontinuum generated on chip has been measured on a silicon nitride waveguide pumped with an Yb mode-locked fiber laser [6]. Carefully engineered silicon nitride waveguides provided highly coherent supercontinua [7], suitable for detecting the carrier envelope offset frequency of frequency combs [8].

Thick waveguides are needed to achieve suitable dispersion engineering and high mode confinement. However, silicon nitride films tend to crack above 400 nm thickness. Advanced fabrication methods utilize crack barriers and in-trench growth to overcome film cracking [10,11], which recently enabled the supercontinua reported in [6–8]. An octave-spanning spectrum in nonstoichiometric silicon nitride waveguides was recently reported, but it required a complex multi-cladding structure for dispersion engineering [9]. A simpler approach to circumvent cracking is to reduce film stress by slightly increasing the silicon content during deposition. This allows thick crack-free film growth in a single deposition step with minimized process complexity. The resulting so-called silicon-rich nitride [12] shows a higher refractive index and an increased material absorption loss than stoichiometric silicon nitride, but this is compensated for by a higher nonlinear Kerr coefficient [13,14].

Here we report octave-spanning supercontinuum generation in a 10 mm long silicon-rich nitride waveguide [14] pumped in the quasi-TE mode with a mode-locked femtosecond Er-fiber laser in the telecom C band. The key waveguide aspects are that an increased nonlinearity compensates for the higher propagation loss, and that thick waveguides can be made with a simple, single-cladding, CMOS-compatible structure suitable for dispersion engineering at telecom wavelengths. This gives a supercontinuum performance similar to stoichiometric silicon nitride waveguides made with advanced fabrication techniques [4–8]. When pumping in the quasi-TM mode, spectral broadening from optical wave breaking is observed for the first time in silicon nitride waveguides, which we show is caused by the TM pump mode experiencing normal dispersion.

Our silicon-rich nitride film is fabricated in a low-pressure chemical vapor deposition (CVD) process [14]. The waveguide patterns are transferred by standard deep UV contact lithography followed by dry etching. The silica top cladding is done in a plasma-enhanced CVD process. The waveguides feature a Kerr parameter of \( \gamma \approx 5.7 \pm 0.5 \text{ (Wm)}^{-1} \) around 1.55 \( \mu \text{m} \), which...
is a slightly modified value to that of [14] owing to an improved linear propagation loss estimate (1.35 ± 0.3 dB/cm). Importantly, two-photon absorption is absent at 1.55 μm. The waveguide dimensions are displayed in Fig. 1(a). The waveguide height was around 700 nm, with about 5% variation across the wafer. This uncertainty translates into a range of group velocity dispersion (GVD) profiles bounded by the shadow areas in Fig. 1(a). The dispersion is calculated using finite-element simulations (COMSOL) and includes both the dispersion of the material in bulk and the waveguide’s geometry. The dispersion of the film is measured up to 1.7 μm and extrapolated up to 2.4 μm using empirical relations from the bulk material dispersion. The slight tilt in the waveguide’s wall is a consequence of the etching process. The COMSOL calculations include this tilt, and showed that tilt variations have a negligible effect in the GVD, compared to the uncertainty in the waveguide height or material dispersion. For the TE mode, the resulting GVD has two zero-dispersion wavelengths (ZDWs) giving a broad region (spanning 700 nm) with flat and moderate anomalous dispersion, centered on 1550 nm, as desired for an efficient supercontinuum generation.

The experimental setup is shown in Fig. 1(b). (Please see the acronyms in the caption.) An Er femtosecond fiber laser centered at 1555 nm produces a 90 MHz pulse train; each pulse has a 33 nm bandwidth (FWMH) supporting a transform-limited 105 fs (FWMH) Gaussian pulse. The pulses were coupled by an objective lens into a DCF to compensate for the accumulated chirp before the waveguide. NDFs were used to control the pulse energy, and an FPC controlled the polarization, followed by a piece of single-mode fiber spliced to a tapered, lensed fiber (OZ Optics, based on SMF-28), which focused to a 2.0 μm FWHM spot size. We used an intensity autocorrelator to estimate the pulse duration to 130 fs FWHM (assuming a Gaussian shape) at the waveguide entrance, revealing some remaining chirp in the pulse. The maximum total power before the waveguide was 42 mW. The output from the waveguide was collected with a tapered lensed fiber.

To record the supercontinuum, we used two OSAs with spectral ranges 600–1700 nm and 1200–2400 nm, whose spectra were overlapped to get the final spectrum. The coupling loss is estimated at 6.5 ± 1.0 dB/facet (TE) and 5.3 ± 1.0 dB/facet (TM), providing a maximum input pulse energy of 105 pJ (TE) and 140 pJ (TM) coupled into the waveguide.

The measured power spectral density (PSD) in the TE case is shown in Fig. 2(a) for a range of pulse energies. The spectra for low pulse energies are clearly dominated by self-phase modulation (SPM), i.e., early stage broadening before soliton formation occurs. At 78 pJ, the soliton has formed, accompanied by two soliton-induced dispersive waves [15], one on each side of the two ZDWs. The strongest dispersive wave is found at low wavelengths, peaked around 820 nm, while the mid-IR dispersive wave, peaked around 2250 nm, is less powerful and changes significantly when increasing the pulse energy further to the maximum value of 105 pJ (9 mW average power).

The results are verified with numerical simulations using the so-called nonlinear analytic envelope equation (NAEE) [16], which resolves subcycle carrier-wave dynamics and includes a full expansion of the cubic nonlinearity. We only model the waveguide fundamental mode (FM). The mode-effective index and effective area from the COMSOL calculations were extrapolated directly to the NAEE grid without polynomial expansions and were carefully extended beyond the COMSOL modeling domain to avoid unphysical dispersion scenarios. The frequency dependence of the effective mode area was modeled as shown in [17]. A constant propagation loss was used, and noise was included as a half-photon per temporal mode in the input, modeling quantum vacuum fluctuations in the Wigner representation [18]. An extended NAEE model was used to include the Raman effect [19], which empirically

![Fig. 1](image1.png)

**Fig. 1.** (a) Numerically calculated GVD for the TE and TM modes for h = 695 nm. The shadowed area indicates the variations from changing the waveguide height h = 650–740 nm; this changes the second ZDW from 1.7 to 2.1 μm (see also Fig. 3). (Inset) Cross-sectional geometry and modal confinement of power for the fundamental quasi-TE mode. (b) Experimental setup for supercontinuum generation. NDF, neutral density filter; DCF, dispersion compensating fiber; FPC, fiber polarization controller; OSA, optical spectrum analyzer.

![Fig. 2](image2.png)

**Fig. 2.** (a) Experimental spectra in the TE case, showing the PSD at the end of the waveguide (corrected for end-facet coupling loss). The numbers show the estimated input pulse energies in picojoules. (b) Results of numerical simulations of the TE FM using h = 660 nm. The spectra show the total PSD at the waveguide end averaged over 50 noise realizations. The pulse was prechirped using GDD = +3500 fs².
included the Si-N asymmetric stretching mode centered at 410 cm$^{-1}$ [20], having a broadband 70 cm$^{-1}$ linewidth and a relative Raman strength $f_R = 0.2$, both typical values for amorphous materials. Generally, the Raman effect gave minor contributions, in line with previous studies of silicon nitride waveguides. This might be due to the moderate anomalous dispersion range of the waveguide in which the Raman effect can influence the soliton by redshifting it.

Figure 2(b) shows corresponding numerical simulations where the major features of the experimental spectra are reproduced in the power sweep, except for the precise location of the dispersive waves. This is likely due to the uncertainty of the mid-IR dispersion and to the precise soliton wavelength (i.e., how much it is frequency shifted by Raman or self-steepening effects). The dispersive waves also seem to be narrower in the experimental case. The simulations only model the FM but, from the higher-order modes (HOMs) given by the COMSOL simulations, we estimate that around 55% of the input energy will be coupled to the FM, and the rest goes into the HOMs. The HOMs will not show any spectral broadening due to their lower peak powers, higher GVD, and larger mode areas. In the numerical spectra shown in Fig. 2(b), we have therefore added the equivalent energy of the HOMs at the end of the simulation as 45% of the total input spectrum. Additionally, combining the 33 nm bandwidth of the input pulse with the measured value of 130 fs FWHM corresponds to a group delay dispersion of GDD $= \pm 3500$ fs$^2$. The simulations used positive chirp, but similar results were found with negative chirp. We note that the simulations used lower energies than the experiments, which can be attributed to uncertainties in coupling efficiencies, waveguide nonlinearity, dispersion, input pulse pre-chirp, etc.

Figure 3 shows that the waveguide height is a powerful dispersion tuning parameter. At the pump wavelength, the TE mode has anomalous dispersion for all considered heights, while the GVD for the TM mode changes sign at $h = 675$ nm. The simulations show the best match to the experimental results for $h = 660$ nm. With this parameter, the long- and short-wavelength dispersive waves (DW 1 and 2) agree well with the experiments. This height is within the 5% variation margin across the wafer, as mentioned above. Similar results were observed for $h = 650–675$ nm while, beyond this range, the simulations did not match the experiments well.

Figure 4 shows a representative simulation for the supercontinuum propagation dynamics. The pulse energy is 40 pJ, corresponding to the green curve in Fig. 2(b). In Fig. 4(a), the soliton forms as a single-cycle spike (5 fs FWHM) and, after this self-compression point ("max"), the temporal trace shows interference oscillations. These are due to the two dispersive waves phase matched to the soliton, all temporally overlapping, but located at different wavelengths. In the spectral evolution (e), the dispersive waves are seen to be present at the soliton formation point ("max") and, after this, they grow significantly; see also (d). In (c), the shot-to-shot coherence is shown, as calculated from the first-order coherence function $g^{(1)}(\lambda)$ [21]. This excellent coherence pertains for lower powers, while we found it degrades for higher levels (which is quite typical).

Figure 5(a) shows the TM case. While less broadening was observed, the spectrum broadens sufficiently to enter the important 1600–1850 nm wavelength range for three-photon absorption microscopy [22]. The spectral shapes are indicative of optical wave breaking [23], which happens when the pump dispersion is normal, so no soliton can form. The spectral broadening is typically much weaker than in the soliton case because no dispersive waves are formed, and the pulse does not self-compress. Instead, the pulse becomes highly chirped and eventually develops steep temporal shock fronts. In frequency domain, this is accompanied by highly coherent SPM-induced spectral broadening. To understand when TM has normal GVD at 1555 nm, we refer to Fig. 3, which shows that the TM mode has normal GVD at 1555 nm when the waveguide height is taken well below 700 nm. Indeed, the numerical simulations shown in Fig. 5(c) agree well with the experimental results using the exact same parameters as in the TE case.
concerning waveguide height and pulse pre-chirp. In time domain (not shown), the pulses were chirped, but the powers were too low to observe severe shock front formation. The experimental data show extremely symmetrical SPM broadening, which could only be observed in the simulations when using a transform-limited pump with only 20 pJ energy, over 2 octaves of coherent supercontinuum generation in an easily manufacturable CMOS-compatible waveguide.

Fig. 5. (a) Experimental spectra for various TM pump pulse energies; The ZDWs are those calculated for the TM mode using a 660 nm waveguide height. TM mode numerical simulations showing (b) the coherence function and (c) the average spectra. The simulations used the same waveguide specs (width, height) and input pulse prechirp as in Fig. 2(b).

Fig. 6. Simulations showing the spectral coherence and average PSD for a 750 nm waveguide height and using a transform-limited TE-polarized pump pulse.

femtosecond pulses (80–140 pJ) from an Er-fiber laser. In the TE case, a soliton and two dispersive waves were excited to give a 1.5 octave supercontinuum (820–2250 nm at –30 dB). In the TM case, a continuum was generated by optical wave breaking as the TM mode had normal dispersion at the pump wavelength. Numerical results indicate an excellent coherence of the supercontinua and that they could extend into the mid-IR with a slightly thicker waveguide. These results are promising for short-range near-IR and mid-IR coherent supercontinuum generation in an easily manufacturable CMOS-compatible waveguide.

Funding. Vetenskapsrådet; Teknologi og Produktion, Det Frie Forskningsråd (FTP, DFF) (11-106702); European Research Council (ERC) (ERC-AdvG 291618).

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Cross-phase-modulation-based wavelength conversion in low-stress silicon-rich nitride waveguide

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Optical Fiber Communication Conference (OFC), Anaheim, USA, paper Tu2K.4, March 2016
Cross-Phase-Modulation-Based Wavelength Conversion in Low-Stress Silicon-Rich Nitride Waveguide

Mohammad Rezagholipour Dizaji¹, Clemens J. Krückel², Attila Fülöp³, Peter A. Andrekson², Victor Torres-Company², and Lawrence R. Chen¹

¹ Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec, Canada, H3A0E9
² Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, 41296 Gothenburg, Sweden
mohammad.rezagholipourdizaji@mail.mcgill.ca

Abstract: We report cross-phase-modulation-based wavelength conversion of 10 Gb/s RZ-OOK using a low-stress silicon-rich nitride waveguide. The waveguide is engineered to display flat and low dispersion over the entire C+L bands.

OCIS codes: (130.3120) Integrated optics devices; (130.7405) Wavelength conversion devices; (060.4510) Optical communications; (060.2330) Fiber optics communications; (190.3270) Kerr effect.

1. Introduction

Silicon nitride (Si₃N₄) is becoming an attractive platform for integrated nonlinear optics [1]. In spite of a lower nonlinear refractive index compared to silicon-on-isolator [2] and chalcogenides [3], the propagation loss can be made sufficiently low (0.1 dB/m in thin waveguides [4]), and it can handle high-power levels. Si₃N₄ has a wide transparency window from UV to SWIR and as such can support ultra-broadband operation. In contrast with silicon [2], Si₃N₄ is not expected to have nonlinear loss and two-photon absorption (TPA) in the telecommunication range, due to its larger bandgap energy [1]. The relatively high refractive index difference between a Si₃N₄ core and silicon dioxide (SiO₂) cladding enables integration of photonic lightwave circuits [5].

A challenge for Si₃N₄ in nonlinear optics is dispersion engineering. For rectangular waveguide geometry, it is necessary to increase the thickness to > 600 nm and such thick films have very high tensile stress and tend to crack. This issue has been partly alleviated in recent works [6-8]. In [8], we reported fabrication of Si₃N₄ waveguides thicker than 700 nm in a single deposition step. The key was varying the stoichiometry of the Si₃N₄ film during the deposition process (in particular increasing the relative content of silicon). Our results indicated a higher nonlinear coefficient than stoichiometric silicon nitride (Si₃N₄) and the possibility to achieve anomalous dispersion albeit at the expense of increased propagation loss ~ 1-1.5 dB/cm. In this paper, we report wavelength conversion based on cross-phase modulation (XPM) using a dispersion engineered silicon-rich nitride waveguide. BER measurements show error free operation. Measurements also show no evidence of nonlinear loss in the telecommunication range. Although further work has to be done with regards to improving the linear loss, these results indicate the waveguides are highly functional for broadband nonlinear optics applications.

![Fig. 1. (a) Cross section of the Si₃N₄ waveguide, (b) dispersion measurement and simulation results, (c) simplified schematic representation of pump and probe nonlinear interaction through the Si₃N₄ waveguide; the probe at the output is further filtered to induce phase-to-amplitude conversion (see details in text), (d) output vs. input power measurement results.](image)

2. Optical characteristics of the low-stress silicon-rich nitride waveguide

The Si₃N₄ waveguide is displayed in Fig. 1(a). It is engineered with dimensions 0.7×1.65 μm² and 2 cm in length. The waveguide is embedded in SiO₂, resulting in high confinement of the optical field inside the Si₃N₄ core with an effective area A_eff ~ 0.9 μm² [8]. The dispersion of the quasi TE mode is flat and anomalous over the entire C and L bands. The overall insertion loss is ~ 14.5 dB using edge coupling into and out of the waveguide with lensed fibres
of 2 µm spot size. Figure 1(b) shows the measured group-velocity-dispersion coefficient ($\beta_3$) using commercially available dispersive virtual reference interferometer technology [9]. The blue line is the simulation result using the commercial FEM-based mode solver COMSOL. The dispersion constants of the bulk materials used in the simulation were set to match those of the real device, which had been previously measured using ellipsometry.

In order to confirm the absence of nonlinear absorption for the Si$_3$N$_4$ waveguide in the telecommunications band, we measured the output power vs. input power into the waveguide (see Fig. 1c). The input light is an amplified pulse train at 10 GHz, centered at 1550 nm, with a pulse width of 2 ps. We can see that a linear relationship is preserved, even for higher input power values. This is expected since the bandgap energy of the Si$_3$N$_4$ film is too large (2.3 eV or a corresponding wavelength of 539 nm [8]) for TPA to occur at 1.5 µm.

3. Experimental setup

Figure 2 shows the experimental setup for XPM-based wavelength conversion using the Si$_3$N$_4$ waveguide. XPM occurs between a 10 Gb/s data signal acting as pump and a CW signal as probe. The pump data signal is generated by modulating a 10 GHz pulse train from a fibre-based mode-locked laser (MLL) generating 2 ps FWHM pulses at 1550 nm with a 2$^{31}$ - 1 PRBS data from a LiNbO$_3$ Mach Zender modulator (MZM). The average optical power at the output of the MZM (point A) is 2 dBm, and the corresponding extinction ratio (ER) and timing jitter are ~ 20 dB and ~240 fs. The modulated data signal is amplified using a 23 dBm erbium doped fibre amplifier (EDFA).

![Diagram](Tu2K.4.pdf)

Fig. 2. (a) XPM-based wavelength conversion experiment setup. (b) optical spectra after the Si$_3$N$_4$ waveguide while varying the probe laser. PPG: pulse pattern generator. DCA: digital communication analyser. PM: power meter. PF: programmable filter. PD: photo detector. BERT: bit error rate tester.

The probe signal is a CW signal generated using an external cavity tunable laser source. The CW is then amplified using a 23 dBm EDFA followed by a 0.3 nm band pass filter (BPF) to reduce out-of-band amplified spontaneous emission noise; the power level at the output of the 0.3 nm BPF is 16.7 dBm. Both pump and probe signal pass through separate polarization controllers and are combined using a wavelength division multiplexer (WDM); the pump signal passes through the transmission port with a pass band of 5 nm centered at 1550 nm. The combined signal passes through the Si$_3$N$_4$ waveguide, and the output of the waveguide is then filtered using a programmable filter (PF) with 10 GHz resolution.

Figure 2(b), shows the optical spectra at the output of the Si$_3$N$_4$ waveguide (point B in Fig. 2(a)) for CW probe centered at different wavelengths, while the pump data signal is fixed and is centered at 1550 nm. The CW wavelength is varied to cover a range of wavelength on both sides of the pump data signal. The spectrum is broadened significantly around the CW, due to XPM caused by the high power pump data signal at 1550 nm. Information content of the original data signal is printed on the broadened parts of the spectrum centered at the CW wavelength, therefore wavelength conversion happened. The PF is set as a notch filter and has a bandwidth of 5 nm (0.3 nm bandwidth of the notch and 2.5 nm bandwidth of each of the sidebands). Right after the PF there is a variable optical attenuator (VOA), and then the receiver, comprising a highly sensitive EDFA, a BPF, a
photodetector, and the error detector. The highly sensitive EDFA operates at constant output power mode (19.5 dBm). The BPF2 is a tunable bandwidth wavelength filter centered at the wavelength of the CW with a bandwidth set to 5.3 nm.

4. Results and discussion

Figure 3(a) shows the spectra at 4 different points of the experiment setup (Fig. 2(a)) for the CW centered at 1562 nm. These points are the following: (1) output of the Si$_3$N$_4$ waveguide (point B), (2) output of the PF (point C), (3) output of the highly sensitive EDFA (point D), and (4) output of the BPF2 (point E).

BER measurements are done for 4 CW wavelengths (see Fig. 3(b)). The wavelength range is limited by the range of operation of the optical equipment (the BPF, the PF and the EDFA) not by the waveguide.

![Image](Tu2K.4.pdf)

**Fig. 3.** (a) Optical spectra at different points in Fig. 2. (a), for CW at 1562 nm, (b) BER measurement results; insets: two electrical eye diagrams.

Figure 3(b) shows the BER results. The power penalty at 10$^{-9}$ varies in the range between 1.6 dB and 3.4 dB, for different CW wavelengths. The difference in the power penalty is mostly due to the difference in the gain profile of the EDFA at different CW wavelengths. The insets in Fig. 3(b) show the electrical eye diagrams at BER = 10$^{-9}$ for 1562 nm, and the back-to-back (B2B) case. The electrical eye diagrams are captured using a 30 GHz electrical sampling module.

5. Conclusion

We performed wavelength conversion of a 10 Gb/s RZ-OOK data signal based on XPM using a novel silicon-rich nitride waveguide platform. BER measurements show error-free operation for the wavelength-converted signal. The waveguide is engineered to have flat and low anomalous dispersion, supporting broadband operation. Our measurements show absence of nonlinear loss in the telecommunications band. Although further work needs to be done in improving the waveguide’s propagation loss to increase the conversion efficiency, these results illustrate the potential of Si$_3$N$_4$ waveguides for high-speed ultra-broadband nonlinear optics applications.

6. References


Acknowledgment

This work was supported by the Swedish Research Council (VR).
All-optical radio frequency spectrum analyzer based on cross-phase modulation in a silicon-rich nitride waveguide

M. Rezagholipour Dizaji, C. J. Krückel, P. A. Andrekson, V. Torres-Company, and L. R. Chen

*IEEE International Topical Meeting on Microwave Photonics (MWP)*, Long Beach, USA, paper ThM1.5, Nov. 2016
All-Optical Radio Frequency Spectrum Analyzer Based on Cross-Phase Modulation in a Silicon-Rich Nitride Waveguide

M. Rezagholipour Dizaji, C. J. Krückel, P. A. Andrekson, V. Torres-Company, and L. R. Chen

1 Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec, Canada, H3A0E9
2 Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, 41296 Gothenburg, Sweden
Mohammad.rezagholipourdizaji@mail.mcgill.ca

Abstract—We report RF-spectrum analysis of optical signals based on cross-phase-modulation in a silicon-rich nitride waveguide. Measurements show a bandwidth of at least 560 GHz for our RF-spectrum analyzer. RF-spectra measurements for pulse trains at rates from ~ 10 GHz to ~ 160 GHz are demonstrated.

Keywords—Radio frequency spectrum analysis, cross phase modulation, integrated optics, silicon nitride.

I. INTRODUCTION

The increasing demand for high speed data processing requires devices and techniques that are not limited by the speed of electronics. One of the microwave photonic applications that highlights the potential of nonlinear optical effects to overcome the bandwidth limitation of electronics is the monitoring of the radio frequency (RF) of an optical signal. Traditionally, the RF spectrum of an optical signal is measured by using a combination of a high bandwidth photodetector and an electrical RF spectrum analyzer (RFSA). However, the bandwidth of signals that can be characterized using this approach is limited by the available bandwidth from the photodetectors and/or RFSA, unless some form of mixing technique (down-conversion) is used. Optical techniques can overcome this bandwidth limitation and include intensity autocorrelation and the use of cross-phase modulation (XPM) to implement a photonic RFSA [1]. In the latter, owing to the nonlinear interaction between the signal under test and a continuous wave (CW) probe, the phase of the CW probe will be modulated by the intensity of the signal under test. This results in XPM-based spectral broadening about the CW probe’s wavelength. This newly generated optical spectrum centered at the CW probe, uniquely represents the RF spectrum of the signal under test and can be recorded with an optical spectrum analyzer. The bandwidth of this technique is limited by the nonlinear effect and the nonlinear medium, and the resolution is limited to the resolution of the optical spectrum analyzer (OSA) that is used to record the XPM spectrum.

XPM-based RFSA can be performed in a variety of nonlinear media, however integrated optical signal processing and microwave photonics by reducing the overall size and easier control of dispersion compared to nonlinear fibres have been of particular interest during the past years. Integrated photonic RFSA was first demonstrated using chalcogenide waveguides [2] and shortly after using silicon nanowires [3]. In [4] photonic RFSA with higher bandwidth using CMOS compatible platforms (Hydex) is reported. Implementation of microwave photonic modules in silicon nitride has also attracted many attentions in the past decade [5,6] but photonic RFSA has not been implemented in this platform yet.

Si3N4 has a wide transparency window from UV to short-wavelength infrared and therefore can operate over an ultrabroad wavelength range. For example, Si3N4 is more suitable for applications at 850 nm compared to SOI as the latter has high absorption at wavelengths below 1100 nm. While Si3N4 has a lower nonlinear refractive index compared to chalcogenide [7] and SOI [8], the possibility of reducing the propagation loss (a loss as low as 0.1 dB/m in thin waveguides was demonstrated in [9]) and the capability of handling high power levels makes it an attractive platform. Most importantly, in contrast with SOI, Si3N4 is not expected to have nonlinear loss and two-photon absorption (TPA) in the telecommunication range due to its larger bandgap energy [10]. This is valid for Hydex as well [4].

Proper dispersion engineering of Si3N4 by varying the geometry of the waveguide will be needed to optimize nonlinear effects such as self-phase modulation, XPM, and four wave mixing (FWM) [11]. For rectangular waveguides in order to obtain proper phase matching condition over the desired wavelength range of operation, a thickness of more than ~ 600 nm is required. Increasing the thickness of the waveguide will increase the chance of cracking during film deposition. We resolved this problem, by increasing the relative content of silicon and changing the stoichiometry of the Si3N4 film during the deposition process. Using this process we obtained a crack-free silicon-rich nitride (SRN) waveguides with a thickness > 700 nm using a single deposition step. Our SRN waveguides have a nonlinear coefficient that is 5 times greater than that for stoichiometric silicon nitride (Si3N4) as well as the possibility to achieve anomalous dispersion [12]. In [13] we used this SRN waveguides to perform all-optical wavelength conversion based on XPM, and recently demonstrated 1.5 octave supercontinuum generation using femtosecond pulses directly obtained from a fiber oscillator [14].

Our silicon rich nitride platform offers the opportunity of performing nonlinear optics, and implementation of microwave processing applications such as XPM-based RFSA. Indeed, further optimization of the waveguide’s design needs to be done for any particular signal processing and microwave photonics application. In the case of photonic RFSA, the
absence of nonlinear absorption in silicon rich-nitride material systems (similar to Hydex [4]) makes this platform a suitable candidate as the frequency response of the photonic RFSA will not be dependent to the power level of the input signal. Also the broadband operation range of silicon nitride gives us this freedom to be able to obtain XPM that is used for RF spectrum analysis, over a very broader wavelength range. However, proper dispersion engineering for the required phase matching is needed. We report the first operation of an XPM-based RFSA using an integrated silicon nitride waveguide. Measurements of electrical spectra for optical pulse trains with repetition rates from ~10 GHz to ~160 GHz are demonstrated. The measurements show a bandwidth of greater than 560 GHz for our photonic RFSA.

II. EXPERIMENTS AND RESULTS

Our SRN waveguide has dimensions 0.7 µm × 1.65 µm, with a length of 2 cm. The increased thickness of 700 nm without cracking was achieved by enriching the silicon content to 65% (and 35% of nitrogen) in the Si₃N₄ film. The waveguide is buried in silicon dioxide and the contrast in the refractive index results in a high confinement of the optical field inside the SRN core with an effective area A_eff ~ 0.9 µm². The nonlinear coefficient γ at 1550 nm is 4.5 (W.km)⁻¹. The waveguide supports both quasi-TE and quasi-TM modes and the overall fiber-to-fiber loss for the quasi-TE mode is 11 dB which gives an estimated propagation loss of ~ 1 dB/cm (given a coupling loss of ~ 4.5 dB/facet [12]) using edge coupling into and out of the waveguide with lensed fibers of 2.5 µm spot diameter. The waveguide has a relatively flat and anomalous dispersion over the entire C- and L-bands: the measured dispersion is 67 ps/(nm.km) with a dispersion slope of 0.015 ps/(nm².km) at 1550 nm [13].

Fig. 1. Experimental setup for the all-optical RF spectrum analyzer, CW: continuous wave, BPF: band pass filter, OSA: optical spectrum analyzer.

The XPM-based RF spectrum analysis technique has an intrinsic bandwidth which depends on the Kerr effect’s response time. Other than that, the dispersion profile of the nonlinear medium in which XPM occurs affects the bandwidth of the RF-spectrum analyzer. More specifically, the group velocity mismatch between the CW probe and the signal under test causes a walk off which limits the operation bandwidth. Considering all these limitations, the operation bandwidth of the photonic RFSA is still far beyond the speed of the state of the art electronics. In order to quantify the bandwidth limitation of our photonic RFSA, we use the method proposed by [1] which is based on mixing two beating CW signals with a frequency separation Δf (around a center frequency f_c) that interact with a CW probe centered at the frequency f_p. The beating waves form a modulated envelope centered at the CW probe frequency with a detuning of Δf on both sides. By varying Δf and measuring the corresponding power amplitude of the tones at f_p ± Δf we can determine the operation bandwidth.

The experimental setup of the photonic RFSA is shown in Fig. 1. The same setup is used to estimate the bandwidth of the photonic RFSA, such that in this case the ‘signal under test’ comprises two tunable laser sources (TLS), with a frequency offset with respect to each other which are then combined together using a 50/50 coupler. The combined signal is amplified using a high power EDFA (EDFA 2) that can provide a maximum output power of 33 dBm. The CW probe signal is generated using a DFB laser source at 1538.9 nm which is amplified to 18 dBm followed by a 0.4 nm band pass filter (BPF) to remove the out of band amplified spontaneous emission (ASE) noise. The signals on the two branches are then combined using a WDM coupler with a transmission band of 5 nm centered at 1550 nm. The signal generated from the two TLS lasers passes through the transmission port of the WDM coupler. The combined signal is then launched into the SRN waveguide. The power of the signal launched into the waveguide, as well as the output signal power from the waveguide are monitored using two power meters. The optical spectra of the output of the waveguide for different frequency detuning Δf were captured using an OSA. Frequency detuning Δf is varied by symmetrically varying the frequency of the two TLS lasers around f_c which results in varying the frequency of the XPM-RF tones (f_p ± Δf). The optical spectrum and the peak power of the XPM-RF tones were recorded over a broad range of detuning.

Fig. 2. Bandwidth measurement results for the photonic RFSA showing the XPM-tone peak power as a function of frequency detuning Δf. The inset is the recorded OSA spectrum for Δf = 562 GHz, showing that the generated XPM-tone, and the FWM idler are about to overlap.

Figure 2 shows the bandwidth measurement results for the photonic RFSA showing the XPM-tone peak power as a function of frequency detuning Δf. For this measurement the output power of the EDFA 2 is set to ~27 dBm. The minimum output power of the EDFA 2 for which the peak power of the generated XPM-tones will be still above the noise floor over the 3 dB bandwidth range of the photonic RFSA is ~23 dBm. This results show that at a frequency detuning Δf = 562 GHz the peak power reduction is 2.2 dB which is still within the 3-
dB bandwidth range of our all-optical RF spectrum analyzer. For the RFSA bandwidth measurement we were limited by the frequency range of the devices that we used, such as C-band limited laser sources and the available WDM coupler with a transmission band of only from 1547.5 nm to 1552.5 nm. As we can see in the inset of the Fig. 2, at $\Delta f = 562$ GHz the generated XPM-tone which its peak power needs to be measured for the purpose of bandwidth measurement, is very close (almost overlapping) with the FWM idler generated from the interaction of the two TLSs. Further increasing the frequency detuning results in overlapping the XPM-tone that we measure with the FWM idler. Therefore, a minimum bandwidth of 560 GHz is shown, whereas the actual bandwidth of our RF spectrum analyzer is > 560 GHz. Other factors that influence in limiting the bandwidth measurement are (1) the dispersion induced walk-off between the probe signal and the TLS signals, (2) the wavelength dependent propagation loss of the waveguide (see Fig. 3 (c) of [12]), which results in power drop variation at the wavelength range that is used for the bandwidth measurement. However, due to the equipment restriction the measurements were performed in this wavelength range: and (3) the polarization dependent loss that results in power drop variation over the wavelength range in which the bandwidth measurement is done. Optimization of the wavelength dependent propagation and polarization loss can be done by further investigations of the SRN waveguide’s design.

We use our photonic RFSA to demonstrate monitoring of the RF spectrum of signals at rates of up to ~160 GHz. The experimental setup of the all-optical RFSA is shown in Fig. 1. The signal under test is generated using a mode-locked laser (MLL) operating at 9.95 GHz, and 1550 nm with a pulse duration of 2 ps, and then passively multiplied by 4, 8, and 16 times (equivalent of 39.8 GHz, 79.6 GHz, and 159.2 GHz, respectively) using an optical multiplexer (OMUX). The output of the OMUX passes through a polarization beam splitter in order to obtain a uniform polarization for all of the pulses at its output. This is due to the fact that the pulses which are generated using the OMUX have different polarizations from one pulse to another (in any period of $T=1/f_0$, $f_0 = 9.95$ GHz). The multiplexed signal is then amplified to ~27 dBm. The probe signal is formed by generating a CW signal from a distributed feedback laser, which is then amplified to ~18 dBm followed by a 0.4 nm BPF to remove the out of band ASE noise. The signal under test and the CW probe are combined together using a WDM coupler with a transmission band of 5 nm, centered at 1550 nm. The output signal of the WDM coupler is then launched into the SRN waveguide. The output spectrum of the waveguide is measured using the OSA around the wavelength of the CW probe (XPM generated signal), which is the RF spectrum of the signal under test. We use two different OSAs with different resolutions in order to compare the results of the measurements: a high resolution OSA with a resolution as low as 20 MHz, and a conventional OSA with a resolution of 12.5 GHz. Figure 3 shows the recorded RF spectra of the signals at ~ 10 GHz, 40 GHz, 80 GHz, and 160 GHz, using the two mentioned OSAs. The insets show a zoomed version of the spectral lines.

Figure 3 (a) – (d) show the measured RF spectra using a conventional OSA with a 12.5 GHz resolution for the pulse trains with repetition rates of 9.95 GHz, 39.8 GHz, 79.6 GHz, and 159.2 GHz, respectively. The information that can be received from the RF spectrum of a signal depends on the resolution of the OSA. As can be seen, the resolution is not high enough in Fig. 3 (a) to distinguish the spectral tones at multiples of 9.95 GHz, as the separation between the spectral tones is smaller than the resolution of the OSA. For the pulse trains shown in the Figs. 3 (b) – (d) the repetition rate is larger than the resolution of the OSA, making it possible to see some spectral content around the desired frequencies, but further details of the frequency content of the signal cannot be seen due to the coarse resolution of the OSA. Using a higher resolution OSA can provide further details of the RF spectrum of the signal. Figure 3 (e) shows the measured spectrum using the OSA with a 20 MHz resolution for the pulse train with repetition rate of 9.95 GHz (the OMUX is not used in this case). As can be seen the separation between the spectral lines is 9.95 GHz as expected and equal to the repetition rate of the MLL. Figures 3 (f) – (h) show the measured spectra using the high resolution OSA for the pulse trains with

![image]

Fig. 3. Measured RF spectrum of pulse trains at (a) / (e) 9.95 GHz, (b) / (f) 39.8 GHz, (c) / (g) 79.6 GHz, and (d) / (h) 159.2 GHz using a conventional OSA with 12.5 GHz resolution / a high resolution OSA with 20 MHz resolution.
repetition rates of 39.8 GHz, 79.6 GHz, and 159.2 GHz, respectively (the OMUX is used in these cases). The spectral tones representing the corresponding desired frequencies are highlighted in the figures, demonstrating the feasibility of all-optical RF spectrum analysis at these frequencies. Measurement of RF spectrum of pulse trains or data signals at higher bit rates (up to the operation bandwidth of the all-optical RFSA) are also possible, which require components capable of generation of signals at those frequencies. RFSA’s results for the pulse trains in Figs. 3 (f) – (h) show the existence of spurious tones at some other frequencies in addition to the desired spectral tones of the corresponding pulse trains. This is due to the principal of operation of the OMUX. The OMUX passively multiplies the repetition rate of the intensity of its input data signal using an interferometric structure. It is designed to receive an PRBS optical data signal with a pattern length of $2^7$ at the bit rate of 9.95 GHz and multiply the data rate by either 4, 8, or 16 at the output while preserving the pseudo randomness nature of the data signal, such that the output data signal will remain PRBS with a pattern length of $2^7$, regardless of its frequency. However, in our experiment we used a pulse train (instead of data signal) at repetition rate of 9.95 GHz as the input of the OMUX and therefore, the output is not a pure multiplied version of the input pulse train. This makes the corresponding spectrum of the output of the OMUX to include spurious tones at other frequencies, which will also be reflected to the recorded RF spectrum.

Comparing the spectra in Figs. 3 (a) – (d) with the corresponding spectra in Fig. 3 (e) – (h) we can see that the presence of the spurious tones is not explicitly clear in the OSA with a poorer resolution and therefore using an OSA with higher resolution will be advantageous. We need to mention that the resolution which can be achieved using the conventional electrical spectrum analyzers is in the order of tens of Hertz which provides a lot further details of the spectral content of the signal, whereas, using the all-optical RF spectrum analysis technique the best resolution of ~ 1 GHz is provided using the highest available resolution OSAs.

We see in the Fig. 3 that the spectral tones are vanished at frequencies > ~300 GHz, whereas, the bandwidth measurement results in Fig. 2 demonstrate presence of spectral tones at frequencies > 560 GHz. This is due to the fact that the two tones in the bandwidth measurement experiment receive full amplification provided by the EDFA 2, but in the RFSA measurement of pulses the optical power provided by the EDFA 2 is distributed between all the spectral contents of the pulse source and the desired spectral tone (equal to the repetition rate of the output of the OMUX) does not receive full amplification. This can be resolved by either higher power allocation to the signal under test, or increasing the nonlinearity of the SRN platform to generate XPM peaks with higher power levels.

III. CONCLUSIONS

Performing integrated microwave photonics can reduce the overall footprint of the microwave photonic circuit. Silicon-based platforms such as SOI and silicon nitride have attracted lots of attention in the past decade, where many works have investigated microwave photonics application using silicon nitride platforms. The potential of reducing the insertion loss, broadband operation, and the absence of nonlinear loss make silicon nitride a suitable candidate for optical signal processing and microwave photonics applications. This work shows the potential of using SRN platforms for performing photonic RFSA.

In this paper we report the first demonstration of an XPM-based RFSA using an integrated silicon nitride waveguide. The measurements show a bandwidth of more than 560 GHz for our photonic RFSA. Measurements of RF spectra for the pulse trains at repetition rates from ~ 10 GHz to ~ 160 GHz are demonstrated. By further optimization of the design of our SRN waveguide such as increasing the nonlinearity of the waveguide and more appropriate dispersion engineering, larger operation bandwidth for the photonic RFSA can be obtained.

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Optical bandgap engineering in nonlinear silicon nitride waveguides

C. J. Krückel, A. Fülöp, Z. Ye, P. A. Andrekson, and V. Torres-Company

Submitted, March 2017

(Also presented at the Optical Fiber Communication Conference (OFC), Los Angeles, USA, paper M3F.6, March 2017)
Optical bandgap engineering in nonlinear silicon nitride waveguides

Clemens J. Krückel,* Attila Fülöp, Zhichao Ye, Peter A. Andrékson, and Victor Torres-Company

Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

*kruckel@chalmers.se

Abstract: Silicon nitride is a well-established material for photonic devices and integrated circuits. It displays a broad transparency window spanning from the visible to the mid-IR and waveguides can be manufactured with low losses. An absence of nonlinear multi-photon absorption in the erbium lightwave communications band has enabled various nonlinear optic applications in the past decade. Silicon nitride is a dielectric material whose optical and mechanical properties strongly depend on the deposition conditions. In particular, the optical bandgap can be modified with the gas flow ratio during low-pressure chemical vapor deposition (LPCVD). Here we show that this parameter can be controlled in a highly reproducible manner, providing an approach to synthesize the nonlinear Kerr coefficient of the material. This holistic empirical study provides relevant guidelines to optimize the properties of LPCVD silicon nitride waveguides for nonlinear optics applications that rely on the Kerr effect.

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OCIS codes: (130.3120) Integrated optics devices; (160.4330) Nonlinear optics materials; (190.4390) Nonlinear optics, integrated optics; (220.4241) Nanostructure fabrication.

References and links


1. Introduction

Silicon nitride is a well-established material in the microelectronics industry, where it has been used as electrical and thermal insulator in electric circuits. This material can be processed using the mature fabrication lines for electronic integration. Silicon nitride also features a set of optical properties that makes it an ideal choice for many applications that require integration of photonic devices on chip. Examples include ultra-high-Q resonators [1] and filters based on ultra-low-loss waveguides [2]. Silicon nitride can also be co-integrated with active components such as amplifiers [3], modulators and detectors [4]. The broad transparency window extends towards the blue wavelength range, which allows for processing visible light on chip [5,6] and biophotonic sensing applications [7].

Another important feature of silicon nitride is that in its stoichiometric form (Si$_3$N$_4$), it has a nonlinear Kerr coefficient ten times higher than silica [8]. Its large optical bandgap and high thermal damage threshold permit high optical intensities to build up in the system without suffering from nonlinear losses in the near infrared. The potential of this material for nonlinear optics has been demonstrated with the generation of microresonator based frequency combs [9–11], octave-spanning supercontinuum [12,13] and wavelength conversion [14,15].

The optical properties of silicon nitride depend on the conditions under which the material is deposited. There is a wealth of empirical studies that demonstrate that varying the flow ratio of the precursor gases during chemical vapor deposition modifies the stoichiometry of the film [16,17]. This results in a change of refractive index, optical bandgap and film stress [16,18,19]. Increasing the relative content of silicon vs nitride yields a silicon-rich nitride film [17]. This is highly relevant for nonlinear optics applications because waveguides fabricated from silicon rich nitride tend to have a higher nonlinear Kerr coefficient [20–22]. Lacava et al. recently demonstrated that the Kerr coefficient can be enhanced by an order of magnitude in silicon nitride waveguides fabricated via plasma-enhanced chemical vapor deposition (PECVD) by varying the silicon content of the film [21]. However, most nonlinear optic applications are based on silicon nitride deposited via low-pressure chemical vapor deposition (LPCVD) [9,13,23,24]. Despite the popularity of this platform, the impact of the film stoichiometry on the nonlinear properties of LPCVD silicon nitride is not well known.

In this paper, we focus on the full characterization of the nonlinear properties of LPCVD silicon nitride waveguides. We fabricated waveguides with five different compositions, from stoichiometric to the maximum silicon content that is allowed in our furnace. We show that the gas flow ratio modifies the optical properties of the material but in a highly reproducible fashion. We present a holistic empirical study, highlighting how the gas flow ratio can be used to engineer the optical properties of the waveguide for broadband nonlinear optic applications.

The remainder of this work is as follows. In section 2 we present the characterization of the optical properties of the film and the waveguide fabrication process. Section 3 covers the impact of the silicon nitride composition on waveguide propagation loss and group velocity dispersion engineering. In section 4 we focus on the evaluation of material dependent Kerr nonlinearities and assess the impact of waveguide confinement on the nonlinear Kerr parameter. In section 5 we compare the measured Kerr nonlinear coefficients with theoretical expectations and establish a comparison between LPCVD and PECVD silicon nitrides as well as other material platforms used for nonlinear optic applications.
2. Fabrication and material properties

We fabricated high-confinement strip waveguides with a silicon nitride core surrounded by a silicon dioxide cladding. For the deposition of silicon nitride (SiN), we used dichlorosilane (DCS) and ammonia (NH$_3$) as precursor gases in an LPCVD furnace (Centrotherm). In order to form the waveguide core, the SiN film was patterned by optical contact lithography (DUV) and dry etching (CHF$_3$+O$_2$). The process steps were similar to the ones presented in [20] and further advanced by including a standard cleaning step after etching.

Throughout the fabrication and characterization process, it became clear that the ratio between the two precursor gases DCS and NH$_3$ is the most relevant parameter to control the properties of the SiN film. The ratio DCS:NH$_3$ directly impacts the atomic composition of the material. It yields an increase in silicon content with increased gas ratio [16]. We have confirmed this trend with measurements based on X-ray diffraction [20]. Throughout this paper we will however use the ratio DCS:NH$_3$ to describe the composition because it provides a more accurate means to control the fabrication process. The relation between gas flow ratio and atomic composition in LPCVD SiN has been reported in the literature [16].

We fabricated five different SiN compositions. The chosen gas ratios DCS:NH$_3$ reached from 0.3 for stoichiometric silicon nitride (Si$_3$N$_4$) to non-stoichiometric silicon nitride (Si$_x$N$_y$) with a maximum gas ratio of 16.7 given by the gas flow limits of the furnace. For deposition of Si$_3$N$_4$ we used the recipe provided by Centrotherm. All films were deposited under similar temperature conditions around 800$^\circ$C and the pressure was optimized to reach both stable deposition conditions and best possible film uniformity.

The target height and width of the fabricated waveguide core were 700 by 1650 nm for all compositions. Stoichiometric Si$_3$N$_4$ films display cracks at this thickness, so we etched crack barriers following a similar process to [25,26] into the bottom oxide using a laser writer tool followed by a wet-etch step in order to minimize waveguide imperfections. The patterned structures increased the crack-free area of the wafer to several cm$^2$ as cracks originating from wafer handling were stopped. However, full control of cracks was not achieved. Etching into the silicon substrate was suggested in [27] to get rid of this issue. It is worth emphasizing that films deposited using gas ratios above $\sim$4 had no cracks at the fabricated thickness of 700 nm owing to a decrease in stress for silicon-rich nitride. As an example, the measured stress in stoichiometric Si$_3$N$_4$ films (DCS:NH$_3$ 0.3) lied above 1200 MPa whereas films from DCS:NH$_3$ 12 had values around $\sim$500 MPa.

We used spectroscopic ellipsometry for the analysis of the refractive index properties of the materials. We fitted the measurement data using a Tauc-Lorentz oscillator model [28]. This model yields the resonance pole information and optical bandgap. Figure 1(a) shows the real part of the refractive index for all fabricated compositions within the wavelength range of the ellipsometer (245-1000 nm) and the extrapolation up to 2000 nm. One can observe that, at a fixed wavelength, the refractive index increases with higher gas flow ratio. This is consistent with an increase of silicon content in the film [16]. Figure 1(b) illustrates the variation of the optical bandgap of the material with the gas flow ratio. It is clear that by increasing the gas flow ratio, the optical bandgap of the film decreases, but it always remains above the energy level for two-photon absorption to take place at 1550 nm, as indicated by the dotted red line. Physically the measured optical bandgap corresponds to the photon energy at which the imaginary part of the refractive index, $\kappa$, becomes non-zero, as shown in the figure inset. The absence of material loss for wavelengths above 350-600 nm clearly indicates the ultra-broad transparency window of silicon nitride.

We studied the uniformity of the SiN films by realizing repeated ellipsometer area scans. The uniformity was measured with 137 points across the 3-inch wafer with an x-y-position change of 0.5 cm. For illustration purposes we used a SiN film fabricated with the gas ratio 8 in Fig. 1(c), but similar results were obtained for the other compositions and over independent fabrication.
Fig. 1. a) Measured refractive index as a function of wavelength for different SiN compositions. The shadowed area shows extrapolated data from the measurements. b) Optical bandgap as a function of gas flow ratio. The two-photon absorption limit indicates twice the photon energy at 1550 nm wavelength. The inset shows a zoomed in part of the measured imaginary refractive index $k$ as a function of wavelength for the fabricated compositions. c) Area scan of the film thickness with 139 points showing the uniformity of the deposited SiN film on a 3-inch wafer (DCS: NH$_3$ 8). d) Reproducibility of the refractive index at 850 nm carried out over 22 points on a single wafer and between 3 independent deposition runs.

A maximum deviation from target (700 nm) below 3% can be observed. Such non-local change in film height should be considered when designing waveguide dimensions for dispersion engineering. Next, we studied the reproducibility of the film composition by first comparing the refractive index change across a single wafer (22 measurement points) and second by comparing the average refractive index of 3 wafers from independent deposition runs. The results are shown in Fig. 1(d). A deviation below 0.15% is reached in both cases when measuring ~200 nm thick films. Thin films were chosen here to reduce processing time. This study shows that the gas flow ratio in an LCPVD furnace provides a reliable way to control the optical properties and composition of the SiN films.
3. Linear waveguide properties

3.1. Waveguide propagation loss

We evaluated waveguide propagation losses and coupling losses using the cut-back method with 3 different lengths. The loss measurements were done in a spectrally resolved manner from 1510 to 1610 nm and the polarization was optimized for maximum system throughput. In order to present representative data, we performed the measurements over 5 waveguides. The averaged values and standard deviation per wavelength are presented in Fig. 2. Since we used the same cross-section geometry for all waveguide compositions, any change in measured waveguide propagation loss is likely caused by the material properties of the SiN waveguide core.

For the waveguides with gas flow ratio 4 to 16.7 the three cut-back lengths were 4, 3 and 1 cm. The waveguides fabricated from Si$_3$N$_4$ had lengths of 2.2, 1.3 and 0.9 cm because we had to restrict ourselves to the crack-free area of the wafer. Instead of the straight waveguides used in this work, a space saving design (spiral, meander) is recommended if film cracks cannot be avoided.

We used horizontal coupling directly into the waveguide core via tapered lensed fibers with 2.5 µm spot size diameter. Coupling losses $\sim$4 dB per facet were obtained for all compositions. The larger uncertainty in the Si$_3$N$_4$ waveguide losses is due to the shorter cut-back lengths, resulting in lower measurement precision. We observe a reduction in waveguide loss with decreasing gas flow ratio. The typical absorption resonance around 1.53 µm is visible for all compositions with DCS:NH$_3$ $\geq$4. This is likely due to the existence of N-H bonds that remain from the use of ammonia as precursor gas. This fact alone however cannot explain the increase absorption observed in the L band. Interestingly, we could get rid of the absorption resonance for DCS:NH$_3$ 0.3 by realizing an annealing step at 1200°C over 3 h in nitrogen atmosphere. The final losses after annealing for Si$_3$N$_4$ were around 0.4 dB/cm at 1550 nm wavelength, a value comparable to other reported values in the literature using waveguides with similar dimensions [13]. We estimate the scattering losses contribute 0.2 dB/cm [20]. Additional steps, such as the use of a higher quality LPCVD top oxide layer could further improve the propagation losses [27]. How well the annealing step can be applied to the other composition requires further investigations.

For example the same annealing recipe caused an increase in waveguide loss for the silicon-rich composition DCS:NH$_3$ 8. We suggest that the losses are caused by the formation of silicon clusters, since a similar effect has been reported in the literature when annealing silicon-rich nitride films [29]. Whether the losses of the silicon-rich nitride films can be decreased with a different annealing recipe deserves further investigation because, as we shall show in the next section, these materials display very high nonlinear Kerr coefficient.

![Fig. 2. Waveguide propagation loss as a function of wavelength for waveguides with 5 different silicon nitride compositions corresponding to different DCS:NH$_3$ ratios. The darker colored line shows the mean value and the brighter shadowed areas illustrates the standard deviation of the loss measurements. The inset shows the waveguide core after etching.](image-url)
3.2. Numerical analysis of waveguide dispersion

Here we look into the dispersion engineering possibilities of the SiN waveguides. The waveguide dispersion can be engineered over a broad wavelength range by tailoring its dimensions [30] or in the case of a silicon nitride waveguide by changing its material composition [31].

The simulations were performed with a modesolver based on COMSOL-Multiphysics using the refractive index data for the core and cladding materials extracted from ellipsometer measurements. First, we show how the waveguide width and height individually impact the group velocity dispersion profile $\beta^2$. This is exemplified in Fig. 3(a) for the SiN composition fabricated using the gas ratio 16.7 for the fundamental quasi TE-mode. The left illustration shows that an increase in waveguide height is required (fixed width of 1.65 $\mu$m) in order to reach anomalous GVD. In the right illustration it can be seen that varying the waveguide width allows to shift the second zero dispersion wavelength to lower optical frequencies.

The impact of both waveguide width and height together is studied in Fig. 3(b) in more detail. Here, we show how the GVD changes for all geometry combinations for a width from 0.4 to 2 $\mu$m and a height from 0.25 to 1 $\mu$m. This allows relating the dispersion profile to the optical

![Image of waveguide dispersion graphs](image-url)

Fig. 3. a) Impact of height and width variation on the group velocity dispersion (DCS:NH$_3$ 16.7, quasi-TE-mode). b) Group velocity dispersion coefficient $\beta^2$ as a function of waveguide width and height of the silicon nitride waveguide considering the material corresponding to DCS:NH$_3$ 16.7 (1550 nm wavelength, quasi-TE-mode). The black line indicates the dimensions at which zero GVD occurs. The circle indicates the dimensions of the fabricated waveguides. c) Waveguide dimensions at which crossing from normal to anomalous dispersion occurs (1550 nm wavelength, quasi-TE-mode). The circle indicates the dimensions of the fabricated waveguides.
confinement. The illustration is valid for the fundamental quasi-TE-mode at wavelength of 1550 nm. Waveguide dimensions that lead to $\beta_2$ values of zero are lying along the black line. Thus, anomalous dispersion is achieved for the dimensions on the right side of this line. We compared the dimensions required to cross from normal to anomalous dispersion for all fabricated SiN compositions, see Fig. 3(c). The larger refractive index of the silicon rich compositions causes in general a shift of the anomalous GVD crossing towards thinner and narrower dimensions. This trend is expected, since a higher silicon rich composition provides higher refractive index contrast and allows for higher mode confinement in the core. This result will be further discussed in the next subsection in the context of optimization of the nonlinear parameter. It can be seen that for the fabricated dimensions, anomalous dispersion at 1550 nm is achieved for all compositions except for Si$_3$N$_4$.

4. Nonlinear properties

In this section we illustrate that the nonlinear Kerr coefficient of silicon nitride strongly depends on the gas flow ratio utilized during deposition. First, we evaluate the nonlinear parameter $\gamma$ in measurements based on a dual-pump experiment [20,32] where the nonlinear phase shift is measured as a function of optical pump power, i.e. $\theta_{nl} = \gamma P L_{eff}$, with $L_{eff}$ being the effective length of the waveguide. The measurements were carried out around 1563 nm. This experiment also served as a means to verify the absence of multi-photon absorption at telecom wavelengths up to several hundreds of mW continuous-wave (CW) pump power coupled into the waveguide. The slope in the linear fit of $\theta_{nl}$ vs $P$ provides an estimation of the nonlinear parameter $\gamma$ of the waveguide with knowledge of $L_{eff}$. The results of the measurements are summarized in Fig. 4(a) by the circular symbols. The calculation of the errors includes both the error in the slope and the error in $L_{eff}$ provided by the uncertainty in the losses (Fig. 2). It is clear that increasing the flow ratio yields a higher nonlinear parameter. This however does not necessarily mean that the nonlinear Kerr coefficient increases. To verify this, we calculated the Kerr coefficient as $n_2 = \gamma \lambda A_{eff}/2\pi$. The effective area can change even if the cross-section is identical for all compositions. This fact is illustrated in Fig. 4(b). The effective area decreases for larger DCS:NH$_3$.
Fig. 5. a) Nonlinear parameter for different width and height of the waveguide core fabricated from DCS:NH$_3$ ratio 16.7. The simulations are made for the fundamental quasi TE-mode at 1550 nm wavelength. The plot indicates the fabricated waveguide dimensions, the dimensions that lead to a maximum nonlinear parameter, and the dimensions that result in a maximum nonlinear parameter with the requirement of zero GVD. b) Maximum relative nonlinear phase shift $\gamma \cdot \text{max } L_{eff}$ achieved for the fabricated waveguide dimensions of 700 nm height and 1650 nm width.

ratios, which results from the higher optical confinement owing to the increase in refractive index. Figure 4(c) shows the estimated $n_2$ for each of the measured SiN compositions. It is clear that the Kerr coefficient can be modified by roughly a factor of 4 by controlling the gas flow ratio during film deposition; from $n_2 = (0.31 \pm 0.04) \cdot 10^{-18} \text{ m}^2/\text{W}$ for Si$_3$N$_4$ (DCS:NH$_3$ 0.3) to $n_2 = (1.13 \pm 0.13) \cdot 10^{-18} \text{ m}^2/\text{W}$ for DCS:NH$_3$ 16.7.

The results in Fig. 4(a) (circles) correspond to the nonlinear Kerr parameter measured for different compositions with identical cross-section. This parameter could be further enhanced by optimizing the waveguide dimensions for each composition. This is illustrated in Fig. 5(a) using the composition corresponding to DCS:NH$_3$ 16.7. The parameter $\gamma$ is maximized for a waveguide whose dimensions provide the highest optical confinement. The dimensions correspond to 0.82 $\mu$m width and 0.4 $\mu$m height (highlighted by the diamond symbol in Fig. 5(a)). This maximum value is almost double the value we measured for the fabricated geometry. However, comparing this plot with Fig. 3(b), it becomes clear that this cross-section geometry does not yield anomalous dispersion. This conclusion is generally valid for all compositions. One could instead calculate the geometry that provides the maximum nonlinear parameter within the zero GVD contour in Fig. 3(b) (plotted again in Fig. 5(a)). This point is defined by the square symbol in Fig. 5(a). This analysis is carried out for all compositions and the results are presented in Fig. 4(a), where the measured nonlinear parameter for each composition is compared to what could be obtained if the waveguide dimensions were optimized. The nonlinear parameter could be enhanced by almost an order of magnitude by varying the stoichiometry of the film with respect to the measured value in stoichiometric silicon nitride.

Of course, the relevant parameter for most nonlinear optics applications in absence of multiphoton absorption is the amount of nonlinear phase shift per unit power, i.e. $\theta_{nl}/P = \gamma L_{eff}$. This figure of merit is important, as the nonlinear parameter alone does not provide the whole picture. In order to include propagation losses, we considered the case of maximum achievable effective length,
max $L_{\text{eff}}$, as $1/\alpha$ with $\alpha$ being the linear loss. The results for our materials are shown in Fig. 5(b). Surprisingly, the plot indicates two optimum compositions that yield maximum nonlinear phase shift. Composition DCS:NH$_3$ 0.3 is stoichiometric silicon nitride and it benefits from very low propagation losses. Composition DCS:NH$_3$ 8 corresponds to the results previously reported in [20,33]. This material reaches a similar nonlinear phase shift due to its increased nonlinear coefficient and moderate linear loss. The large uncertainty in the standard deviation for the Si$_3$N$_4$ material comes from the high uncertainty of the low waveguide losses, which has a larger impact when calculating max $L_{\text{eff}}$. It is important to emphasize that this comparison is not fundamental. Further decrease in propagation losses for one or another composition could dramatically change this picture.

5. Theoretical comparison and discussion

In order to understand the fundamental limitations of the Kerr effect in our platform and to validate our experimental results, we compare our measured values of the nonlinear Kerr coefficient $n_2$ with theoretical expectations. A useful theoretical approach developed by Sheik-Bahae et al. [34] links $n_2$ directly to the optical bandgap of the material according to

$$n_2 = K' G_2 \left( \frac{\hbar \omega}{E_g} \right) \frac{n_0^2}{E_g^2}.$$  

(1)

This equation is developed under the assumption that there is a Kramers-Kronig relation between the real and imaginary parts of the nonlinear refractive index and that the nonlinear absorption is dominated by two-photon absorption [34]. The relation is valid for a broad range of photon frequencies, even when they are far below the optical bandgap. This is taken into account by the function $G_2$. In the equation above, $n_0$ is the refractive index and $K'$ is a constant. The function $G_2$ is maximized for photon energies close to $E_g/2$ thus suggesting that highest Kerr nonlinearities are attained when using a wavelength close to the TPA limit. The formulation is valid for solids provided the assumptions above hold. In such case, it gives reasonable estimates for a broad range of oxides and glasses [35].

Figure 6 indicates that the properties of our materials follow reasonably well the Sheik-Bahae relationship. The photon energy and refractive index were taken at 1563 nm, the wavelength of the dual-pump experiment. Uncertainties from the Kerr coefficient evaluation are not considered here. For comparison, other widely used nonlinear materials are included in Fig. 6 based on data of refractive index, nonlinear Kerr coefficient and bandgap provided in the references. The way the
bandgap is defined is not explicitly mentioned in the publications. This may lead to a discrepancy in $E_g$. At the two extremes of the bandgap scale, we find crystalline silicon (c-Si) [36, 37] and silicon dioxide (SiO$_2$) [38, 39]. These materials display different Kerr nonlinearities in comparison to our silicon nitride compositions but they follow qualitatively the scaling $1/E_g^4$. It is interesting to note that the two low bandgap materials deposited with PECVD, namely hydrogenated amorphous silicon (a-Si:H) [40, 41] (refractive index of 3.5 was assumed) and Si$_7$N$_3$ [22] display a huge increase in nonlinearities but a significant deviation from the Sheik-Bahae relation. Our LPCVD Si$_3$N$_4$ display a Kerr coefficient value $n_2 = (0.31 \pm 0.04) \cdot 10^{-18} \text{ m}^2/\text{W}$ in agreement with previously reported values in the literature [42]. This value is also compatible with the value reported for PECVD Si$_3$N$_4$ [8, 43].

6. Conclusion

We have demonstrated that the gas flow ratio in the LPCVD process to synthesize silicon nitride can be used to control the nonlinear characteristics of an integrated waveguide. Essentially, the gas flow ratio modifies the frequency location of the optical bandgap, which in turn varies the refractive index and Kerr coefficient. These parameters increase with higher gas flow ratios. We did not observe nonlinear absorption in the erbium telecommunications band up to hundreds of mW of optical power coupled into the waveguide. The nonlinear Kerr coefficient of LPCVD silicon rich nitride follows qualitatively a Sheik-Bahae relationship. We found two compositions yielding an optimum nonlinear phase shift per launched power, one was stoichiometric silicon nitride (Si$_3$N$_4$) and the other one a composition with slightly increased silicon content [20]. The performance of the former is due to the relatively low linear losses, whereas the latter provides an increase in nonlinear parameter. The possibility to modify the refractive index of the waveguides in a highly reproducible fashion opens up a new way to engineer the dispersion of silicon nitride waveguides and enhance their nonlinear characteristics.

Funding

This work was supported by the European Council under grant agreement ERC-2011-AdG-291618 PSOPA, the Wallenberg Foundation and the Swedish Research Council (VR).
Towards on-chip net-gain in CMOS-compatible waveguides

C. J. Krückel, P. A. Andrekson, and V. Torres-Company

Accepted to the Conference on Lasers and Electro-Optics (CLEO) Europe, Munich, Germany, paper CD-P.14, June 2017
Towards On-Chip Net-Gain in CMOS-compatible Waveguides

Clemens J. Krückel, Peter A. Andrekson, and Victor Torres-Company

Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

On-chip optical parametric gain was first demonstrated in a silicon waveguide using a pulsed pump source [1]. However, the realization of optical net-gain with a continuous-wave (CW) pump remains a challenge in integrated platforms. Highly nonlinear fibers can provide parametric gain with CW pump [2]. The key advantage of this low-loss platform is its long effective length $L_{\text{eff}}$, which results in a huge nonlinear phase shift, $\Theta_{\text{NL}} = \gamma P L_{\text{eff}}$ using moderate power levels, $P$, in spite of the relatively low nonlinear parameter $\gamma$. The question we address in this contribution is: How far are we from obtaining net gain in a CMOS-compatible platform under CW pumping?

Fig. 1 Nonlinear phase shift vs. pump power in (a) Si, $\text{Si}_x\text{N}_y$ (no TPA, no FCA), (b) Si (TPA, FCA with $\tau$ 800 ps) and (c) Si with carrier removal (TPA, low FCA, linear power of 100 dB/m [3]). For all three cases, we consider $L_{\text{eff}}$ as the propagation length at which the pump power decays by 4.3 dB. Note that this magnitude becomes power-dependent for the structures shown in (b) and (c). (d) Signal net-gain vs. signal-pump detuning. The GVD was chosen to cover a similar gain spectrum in the three cases. The signal power is chosen to be -60 dBm.

We focus on high-confinement strip waveguides based on silicon nitride ($\text{Si}_x\text{N}_y$) [4] (that can achieve low propagation losses and have moderate nonlinear coefficient) and silicon (Si) nanowires [5] (that can achieve high nonlinear coefficient but have relatively high linear propagation losses). We restrict the study to the 1.5 μm region. As silicon displays nonlinear losses (TPA and FCA), we also present a ridge waveguide design that reduces FCA by free carrier removal [6]. In the upper row figures, we analyze the nonlinear phase shift as a function of power. The nonlinear parameter is kept at a reasonable value with today's technology (see Table). In absence of nonlinear loss, the nonlinear phase shift scales linearly with optical pump power, with a slope increasing for lower linear losses. The silicon waveguide shows nonlinear loss at higher power levels (TPA coefficient of 0.7 cm/GW, FCA coefficient of $1.45 \times 10^{-6}$ (λ/1.55)2 AN [6]). This results in an optimum launched power that maximizes the nonlinear phase shift. This maximum can be increased and shifted to lower power levels by reducing the propagation losses. In a waveguide with carrier removal, a reverse biased pin-diode reduces the free-carrier lifetime, which gives another tuning parameter to increase the nonlinear phase shift. In Fig. 1.c this is illustrated for three different $\tau$ and constant propagation losses of 1 dB/cm.

In Fig. 1.d, we analyze the minimum amount of linear loss that would be necessary in order to achieve 10 dB net gain. For Si, we choose the power that maximizes the nonlinear phase shift and for the pin diode structure we select 10 ps of carrier lifetime, similar to state of the art structures [6]. Our conclusion is clear: linear loss is the major challenge to overcome in order to obtain parametric net gain. With today’s technology, we envision it is more realistic to achieve net gain in silicon nitride waveguides than in silicon structures. Silicon nitride microresonators with low anomalous dispersion and losses equivalent to <1 dB/m have been fabricated [7]. The challenge to fabricate spiral structures with a physical length of 1 m seems to be more feasible than decreasing the propagation losses of Si pin diode structures by an order of magnitude in a platform that simultaneously displays anomalous dispersion [3].

References