Low-loss SiN waveguides for efficient and broadly tunable nonlinear frequency conversion

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Abstract: We report on the use of low-loss Si₃N₄ waveguides for efficient frequency conversion tunable from the near infrared to the short-wave infrared. We achieve -15 dB conversion efficiency for 200 mW coupled pump power. © 2020 The Author(s)

1. Introduction

Nowadays, integrated photonics structures are widely used both for their linear and nonlinear properties. Owing to high optical confinement and strong intrinsic nonlinear material properties, we can efficiently exploit nonlinear phenomena while keeping the size of the device at the chip level. Several platforms appear suitable for nonlinear integrated optics such as silicon (Si), silica (SiO₂), silicon nitride (Si₃N₄), chalcogenide glasses and III-V semiconductors [1]. They all present their specific advantages and drawbacks. While silicon and chalcogenides offer some of the highest intrinsic nonlinearity, the former suffers from high nonlinear losses at telecommunication wavelengths while the latter is not CMOS fabrication compatible and still lacks reliability. Silica has weak nonlinearity and starts strongly absorbing beyond 2 microns. Regarding III-V approaches, high performance devices such as low-loss dispersion engineered waveguides are still difficult to realize. Therefore, Si₃N₄ appears to be a good compromise thanks to its CMOS fabrication compatibility, low linear losses, relatively high nonlinearity, and larger bandgap compared to silicon which allows operation from the visible to the middle infrared with very low two-photon absorption and free carrier absorption. A specifically challenging task is still however the realization of broadband and efficient continuous wave (CW) four-wave mixing (FWM) in CMOS fabrication compatible waveguides. This comes from the trade-off between bandwidth and efficiency when pump power is limited, as is often the case in CW regime: while efficiency can be improved by increasing the interaction length, it leads to a reduction of the bandwidth for a constant pump power. In such platforms, dispersion optimization also becomes particularly critical.

Here we show efficient FWM with CW pumping in low-loss Si₃N₄ waveguides, reaching -15 dB with 200 mW pump. Operation at both 1550 nm and 2000 nm is possible, with 30 nm and 60 nm 3dB bandwidth, respectively, despite the use of cm-long waveguides. The waveguides have low loss in combination of large cross sections, which allows for dispersion engineering.

2. Experiments and results

Figure 1. (a) Theoretical dispersion of the $2 \times 0.78 \mu\text{m}^2$ waveguide. Inset schematic of the waveguide cross-section (b) Spectrum at the output of the 32.2 cm waveguide for 200 mW of coupled pump power. (c) Idler power (I_1 and I_2) as a function of the power of P for constant signal power. We have a quadratic and linear dependence, respectively.

The waveguides used in this study have a cross section of $2.0 \times 0.78 \mu\text{m}^2$. Their estimated propagation loss is around 0.05 dB/cm allowing for the design of long waveguides. The waveguides are folded in spirals and we tested two different lengths of 16.5 cm and 32.2 cm. The dispersion of the waveguide is tailored as to provide a relatively low and flat anomalous dispersion between 1 and 2.2 μm as seen in Fig.1(a). Combined with the enhanced transparency window, this design is suitable for FWM process in the telecom and short-wave infrared

simultaneously as opposed to previous work [2,3]. The experimental pump-probe setup operates both at 1.5 and 2 μm . For the former, we couple two tunable amplified sources through a wavelength-division multiplexer. For the later, a fixed laser diode at 2004 nm is amplified and serves as the pump while a home-made Thulium doped fiber laser tunable from 1800 nm to 2000 nm serves as the signal. On both cases, light is injected into the waveguides using micro-lensed fibers with an estimated coupling loss around 8 dB per facet.

Fig. 1(b) shows the spectrum at the output of the 32.2 cm waveguide for 200 mW of pump power coupled (P) together with a signal (S) both in the telecom band. We measure -15 dB conversion efficiency (CE), which is, to the best of our knowledge, the highest value reported for CW-pumped frequency conversion in a non-resonant Si_3N_4 waveguide. We varied power of P keeping the power of S constant as to measure the growth dependence of idler I_1 and idler I_2 (Fig.1(c)). As expected we observe a quadratic dependence for the CE to I_1 (since P acts as the pump) and linear for I_2 (since P acts as a signal).

Figure 2: CE curves as a function of pump-signal detuning for (a) pump at 1550 nm in a 16.5 cm long waveguide, (b) pump at 1550 nm in a 32.2 cm long waveguide, (c) pump at 2004 nm in a 16.4 cm long waveguide and (d) pump at 2004 nm in a 32.2 cm long waveguide. Points: experimental data; Line: theoretical fit.

In Fig.2, we plot the CE as a function of the pump-signal detuning. The results for the telecom band are shown in Fig.2 (a,b), for the waveguide of length 32.2 cm and 16.5 cm, respectively. We estimate the pump power near 100 mW. Similarly, the results for the 2.04 micron pump are in Fig. 2(c,d) and a pump power of approximately 79 mW. Based on measurements obtained with a signal located a few nm from the pump, we estimate the nonlinear coefficient $\gamma = 0.62 \text{ W}^{-1}\text{m}^{-1}$, in agreement with theoretically predicted value. We note that as expected, the CE decreased by close to 6 dB in the shorter waveguides (half the length) while the bandwidth increased. By fitting the experimental data, we can extract the expected dispersion at the pump wavelength. We observe that the 3dB bandwidth is wider in the 2 microns band, going from approximately 30 nm to 60 nm (two sided), an indication of a lower dispersion value. The extracted dispersion values $\beta_{2_1550\text{nm}} = -0.304 \pm 0.044 \text{ fs}^2/\mu\text{m}$ at 1550 nm and $\beta_{2_2004\text{nm}} = -0.206 \pm 0.02 \text{ fs}^2/\mu\text{m}$ at 2004 nm. While the extracted values are slightly higher than the expected ones (see Fig. 1(a)), the trend is similar and we estimate the zero-dispersion-wavelength to be between 2.2 and 2.3 μm .

To conclude, we show continuous-wave conversion efficiency of -15 dB with 200 mW of telecom pump power and -35 dB with 79 mW at 2 microns, over a large bandwidth. Owing to the low loss features of our Si_3N_4 waveguides, the CE could be further increased by using longer waveguides. In addition, our waveguides have a large cross section, which allows for further dispersion engineering, which was not possible in other low loss waveguides [2]. Flattening of the dispersion would enable wider bandwidth without sacrificing efficiency.

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