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Continuous-wave nonlinear optics in low-stress silicon-rich nitride waveguides

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Abstract: We demonstrate CW-pumped wavelength conversion in low-stress silicon-rich nitride waveguides. The ability to grow thick silicon-rich layers simultaneously enables high-field confinement, dispersion engineering and handling high-power levels without two-photon absorption effects.
OCIS codes: (130.4310) Integrated optics: Nonlinear; (130.7405) Integrated optics: Wavelength conversion devices

1. Introduction

Silicon nitride is gaining significant attention for realizing nonlinear optics at a chip scale [1]. The appeal of this platform is its full compatibility with CMOS fabrication processes. In contrast to its all-silicon counterparts, it has an ultra-broadband transparency window extending all the way up to the visible and ultraviolet regions. At the telecommunications wavelength, there is no sign of two-photon absorption even when operating at high power levels [2, 3]. The nonlinear coefficient is lower than silicon-based devices, but the propagation loss in the waveguide can be made sufficiently low, allowing for practical nonlinear phase shifts [4].
In order to achieve broadband phase matching, dispersion engineering (by tailoring the dimensions of the waveguide) is critical. One problem however of silicon nitride waveguides is the difficulty of growing layers thicker than 400nm owing to large tensile stress, which results in cracking and hence low fabrication yield [5, 6]. Notwithstanding, achieving thick layers is desirable in order to get anomalous dispersion in micrometer-scale waveguides [7] as well as higher field confinement (hence higher nonlinearity) and minimize the impact of scattering loss at the surfaces [5]. A promising solution to minimize the impact of cracking consists of inscribing trenches in the oxide layer before depositing the nitride film. Silicon nitride waveguides as thick as 800nm have been fabricated using this approach [5]. Another possibility that completely avoids crack formation is to vary the stoichiometry of the silicon nitride layer. This has been shown in [8], with silicon-rich nitride waveguides fabricated with thicknesses 800nm. In this work, we follow a similar manufacturing process and grow silicon-rich nitride channel waveguides with thickness 700nm. We provide a detailed characterization of the linear and nonlinear properties. The waveguides feature linear absorption losses in the order of $1-3$dB/cm and show no evidence of nonlinear absorption in the telecommunications region.

2. Fabrication

The low stress silicon nitride film was deposited in a Low Pressure Chemical Vapor Deposition (LPCVD) process on top of 2μm thermal oxidized silicon wafer. The gas flow ratio of amonia (NH_3) and dichlorsilane (SiH_2Cl_2) in the LPCVD process can be carefully set to vary on demand the relative proportion of silicon and nitride. After contact lithography with DUV light of 220nm wavelength, the patterned photoresist was used as a etching mask for the silicon nitride. To harden the resist and reduce the resist roughness, a descum in oxygen plasma and a postbake of 20min in 220°C was performed. A strip of silicon nitride was created by dry etching in CHF_3 and O_2. On the Scanning Electron Microscopy (SEM) picture in Fig. 1(a), a crack free silicon nitride strip waveguide of 700nm height and 1.65μm width is presented. We measure the relative content of silicon using Energy Dispersive X-ray spectroscopy (EDX), yielding a relative content of 65% silicon and 35% nitrogen. The top cladding of 2μm was deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD).

3. Optical properties

Embedded in SiO_2, high index contrast is achieved within the SiN core, which leads to a high confinement of the optical field inside the waveguide. This is clearly illustrated in Fig. 1(b), which shows a COMSOL simulation of the fundamental TE-mode. The relevance of growing thick layers is further illustrated in Fig. 1(c), which indicates that the waveguide can enter in the anomalous regime at 1550nm wavelength by controlling the height of the channel. The linear loss measurements are assessed using the cut-back method. Low propagation loss of $1-3$dB/cm at 1550nm for TE-polarization were measured in 10 different waveguides. The results for several wavelengths are summarized in Fig. 1(d). The estimated coupling loss of $5dB$ per facet (Fig. 1(e)) is achieved by direct side coupling to the waveguide

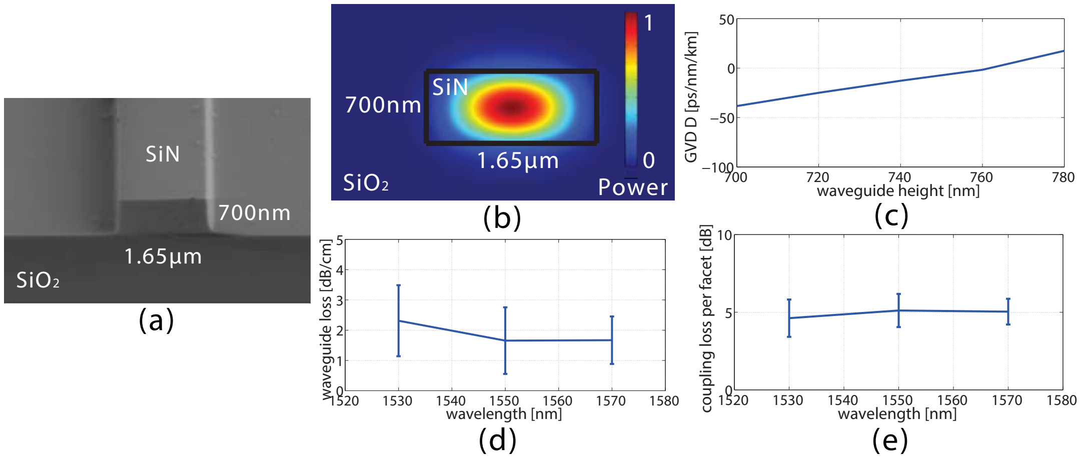

Fig. 1. (a) SEM picture of SiN strip waveguide after etching. (b) Simulated power distribution of fundamental TE-mode. (c) Simulated dispersion versus waveguide height. (d) Measured waveguide propagation loss versus wavelength. (e) Measured coupling loss per facet versus wavelength.

over lensed fibers (spot size $2\mu m$).

Next, we provide a characterization of the nonlinear properties in a dual CW-pumped experiment with varying power levels, as in [9, 10]. In short, two CW tunable lasers are aligned in polarization and amplified with a high-power amplifier. Two narrow bandpass filters are used to reduce the out of band spontaneous emission noise. The power of the generated idler in the 0.94cm long waveguide is analysed with the aid of an optical spectrum analyzer. The power of the idler depends on the amount of nonlinear phase shift according to:

$$\frac{I_0}{I_1} = \frac{J_0^2(\varphi_{SPM}/2) + J_1^2(\varphi_{SPM}/2)}{J_1^2(\varphi_{SPM}/2) + J_2^2(\varphi_{SPM}/2)}, \tag{1}$$

$$\varphi_{SPM} = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}} L_{eff} P_{in} = \gamma L_{eff} P_{in}, \tag{2}$$

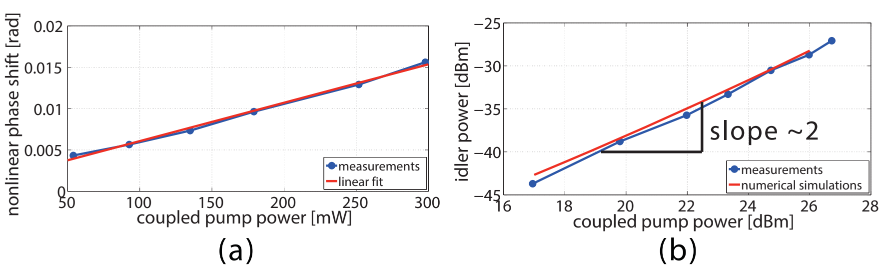

Fig. 2. (a) Nonlinear phase shift φ_{SPM} versus coupled pump power. (b) outcoupled idler power over launched pump power.

Here I_0 and I_1 are the intensities of the pump wave and the first order idler wave. J_i is the $i-th$ order Bessel fuction. The ratio of nonlinear phase shift φ_{SPM} versus coupled pump power P_{in} into the waveguide is $4.64 \cdot 10^{-5}$/mW and shown by the slope in Fig. 2(a). Following Eq. 2 and using a calculated effective length L_{eff} of $0.76cm$, yields a nonlinear parameter $\gamma = 6.1$/W/m. This is 20 times higher than for the ultra-low loss Si_3N_4 waveguide presented in [4]. A natural concern when dealing with a silicon-enriched waveguide is whether the device displays some carrier effects induced by two-photon absorption. We carry out another experiment, where a CW signal with constant power of 18.9dBm at 1562nm was combined with a CW pump of variable power at 1563nm, aligned in polarization, and launched together into the waveguide. The generated idler versus launched pump power is presented in Fig. 2(b). An

absolute output idler power of −27dBm at a launched pump power of 30dBm has been achieved. This corresponds to an output conversion efficiency ($P^{out}_{idler}/P^{out}_{signal}$) of −37.6dB. The curve in Fig. 2(b) shows a very good match with the numerical even up to hundreds of mW coupled power. The slope being close to a factor of 2 indicates absence of nonlinear loss by two-photon absorption and carrier effects. The numerical simulation accounts for pump depletion considering the linear loss parameters obtained from Fig. 1(d) and is obtained by solving the nonlinear Schrödinger equation with the split-step Fourier method. In the simulations a waveguide dispersion value of −16.5ps/nm/km was used. The discrepancy with respect to the dispersion predicted in Fig. 1(c) is likely due to a difference in the actual refractive index dispersion profile of the silicon nitride layer.
To investigate further the effect of waveguide dispersion, we assess the bandwidth of the conversion efficiency in the four-wave mixing process. Using the same experimental setup as before, we detune the signal in wavelength away from the pump. The power levels are maintained constant at 18.8dBm for the signal and 30.8dBm for the pump.The results are presented in Fig. 3. The 3dB bandwidth of the conversion efficiency is around 8nm, limited by the dispersion amount in the waveguide (−16.5ps/nm/km). The relatively close agreement between measurements and simulations confirm the dispersion and nonlinear coefficient estimations from the measurements in Fig. 2.

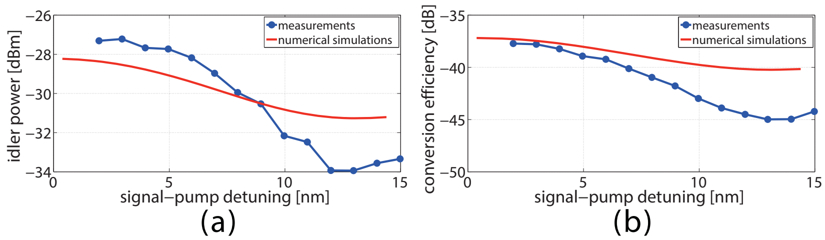

Fig. 3. (a) generated idler power versus signal-pump detuning. (b) conversion efficiency versus signal-pump detuning.

4. Conclusion

We have presented a low-stress silicon rich waveguide that shows low linear losses (1 − 3dB/cm), high nonlinearities (6/W/m) and absence of two-photon absorption. The fabrication with DUV contact lithograph and the high optical confinement makes this platform suitable for large-scale highly integrated nonlinear optics. Further improvements of the propagation losses inside the waveguide are under investigation by adding an annealing step in the manufacturing. Another improvement is expected from using a deposition of a higher quality SiO_2 top cladding using LPCVD.
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