Ultralow-loss Silicon Nitride Waveguides for Parametric Amplification

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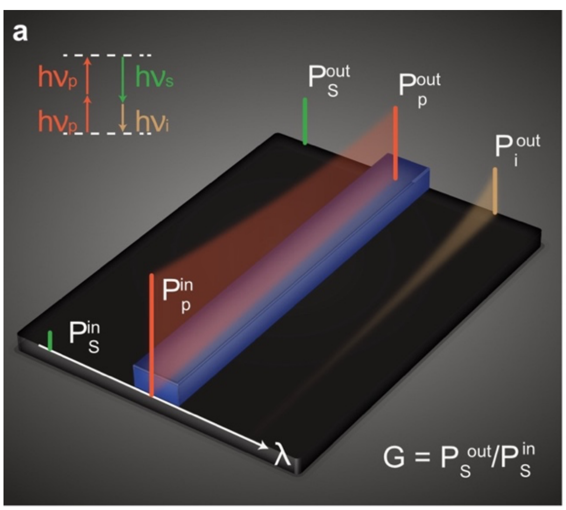
Abstract: We report net gain in a continuous-wave-pumped parametric amplifier implemented in a meter-long dispersion-engineered silicon nitride waveguide. These results are enabled by the record-low loss (1.4dB/m) of the waveguide. © 2022 The Author(s)

1. Introduction

Fiber-optic parametric amplifiers [1] (FOPAs) exploit four-wave-mixing in a nonlinear fiber to attain unique characteristics, differing from conventional amplifiers that rely on stimulated emission of radiation. For example, they have an ultrafast (fs) response time, their gain bandwidth is controlled by the dispersion of the fiber, and when implemented in phase-sensitive mode, they could in principle attain a noise figure of 0dB, that is below the conventional quantum limit [2]. FOPAs have enabled myriad applications in optical communications and signal processing [3], including record receiver sensitivity [4] and compensation of nonlinear impairments in the transmission link [5]. Nonlinear fibers with Ge-doped small cores have been the workhorse for the above-mentioned applications. These specialty fibers are commercially available and have a nonlinear coefficient ~10x higher than standard single-mode fiber, allowing for efficient parametric amplification in lengths of a few hundred meters. Highly nonlinear fibers have negligible losses but have other drawbacks, including polarization mode dispersion and uncontrollable changes in group velocity dispersion along the propagation length. In addition, for practical applications, a FOPA must be implemented with a continuous-wave high-power laser (> 1W). At such high average power levels, other nonlinear effects like stimulated Brillouin or Raman scattering degrade the performance of the FOPA. These drawbacks have motivated the quest for alternative waveguide platforms in the past couple of decades.



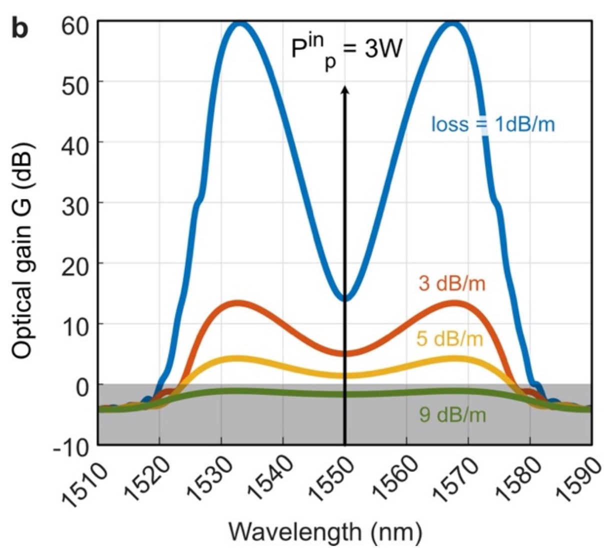


Figure 1. **a**, Illustration of continuous-wave pumped phase-insensitive parametric amplification in a (Kerr) nonlinear waveguide. **b**, Simulated optical gain for a fixed input pump power (3W) for different propagation losses. The waveguide length is assumed to be equal to the effective length (hence different for every loss value), and the nonlinear Kerr parameter and group-velocity dispersion coefficient are 1 $(W.m)^{-1}$ and -20 ps^2/km. These values are representative of what can be obtained with strong-confinement silicon nitride waveguides.

The pioneering demonstration of parametric amplification in silicon nano-waveguides using a pulsed pump [6] sparked a bulk of research in integrated nonlinear optics using materials with large nonlinear Kerr coefficient, such as

silicon, AlGaAs and others. The underlying motivation is to benefit from the large refractive index difference between core and cladding materials to attain high optical intensity (large nonlinear Kerr parameter), resulting in a decrease in waveguide length or pump power, or both (Fig. 1a). However, strong field confinement and large refractive indices exacerbate the waveguide susceptibility to scattering losses, –an aspect that has been largely overlooked. It is important to stress that linear losses cause a twofold penalty by attenuating both the pump that supplies the energy and the signal which is intended to be amplified [7]. Hence, excessive linear losses place a disproportional requirement in pump power and nonlinear parameter, and can decrease the noise figure of the parametric amplifier [8].
A different line of research has focused on decreasing linear losses in silicon nitride waveguides [9]. Silicon nitride is an outstanding material for Kerr nonlinear optics as it has a broad transparency window, negligible two-photon absorption in the near infrared, a high threshold for stimulated Brillouin scattering, high-power handling capability, a nonlinear Kerr coefficient ten times larger than silica, and its dispersion can be engineered with the core geometry. Figure 1b presents the requirements in terms of linear losses in order to attain net gain considering a pump power of 3W coupled into a dispersion-engineered silicon nitride waveguide. Clearly, linear losses in the order of 1-3 dB/m are needed to enable the myriad applications of CW-pumped parametric amplifiers. Advanced manufacturing techniques have been developed over the past decade that result in equivalent losses at this level in ring resonator structures [9] but attaining <3dB/m loss in meter-long dispersion-engineered waveguides is much more difficult and has only been achieved recently [10]. In this invited contribution, we report record-low loss silicon nitride waveguides featuring strong optical field confinement and the first CW-pumped parametric amplifier in an integrated Kerr nonlinear waveguide [11].

2. Waveguide characteristics

Our silicon nitride waveguides (Fig. 2) are fabricated using the subtractive processing method described in [12]. The waveguides are patterned with e-beam lithography. The waveguide has a rectangular cross-section geometry of 2000 nm (width) x 690 nm (thickness), supporting in theory three quasi-TE modes. A multi-pass strategy is implemented that results into smooth sidewalls with 1nm rms sidewall roughness and 450 nm autocorrelation length. Waveguides with lengths beyond a meter are fabricated by concatenating multiple spirals. Importantly, the waveguides feature adiabatic bend designs that minimize coupling to higher order modes. Stitching errors are calibrated prior patterning and intentionally offset during electron beam exposure.

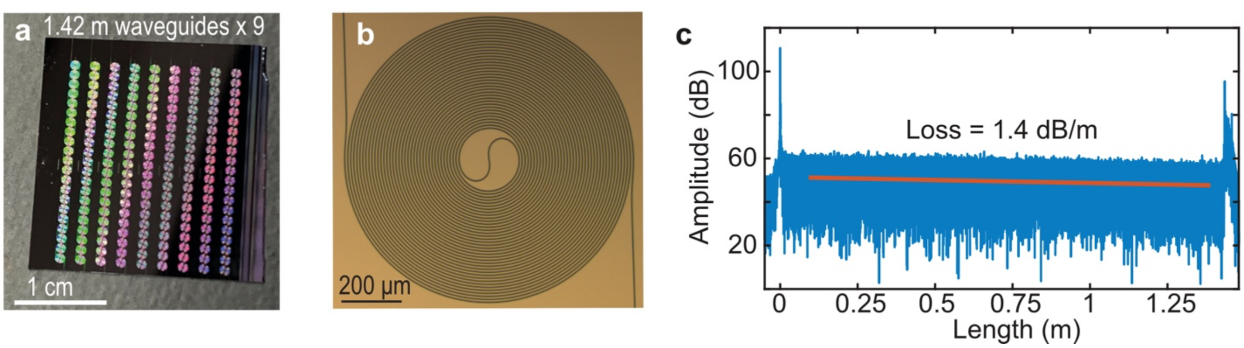


Figure 2. **a**, Photography of a ~2x2 cm^2 chip containing 9 optical waveguides, each 1.42 m long. The waveguides are fabricated by concatenating a sequence of spirals, with one example presented in **b**. **c**, Reflection amplitude of a comb-calibrated optical frequency domain reflectometer, indicating a propagation losses of 1.4 dB/m for the quasi TE mode.

Waveguide losses are measured via optical frequency-domain reflectometry using a rapidly tunable laser calibrated to a self-referenced frequency comb [13]. The calibration of the optical frequency axis enables the precise calculation of the impulse responses at the waveguide interfaces, and from this the group velocity dispersion of the fundamental mode can be retrieved (approximately -36 ps^2/km). Our waveguides feature losses of 1.4 dB/m and are fabricated with an intrawafer yield of ~60% (12 out of 20 waveguides presented no defects, resulting in a mean propagation loss of 1.7dB/m). These results correspond to the lowest loss ever attained in a dispersion-engineered silicon nitride waveguide. Lower losses have been reported in low-confinement waveguides [14], which feature normal dispersion and are unsuitable for phase matching and parametric amplification.

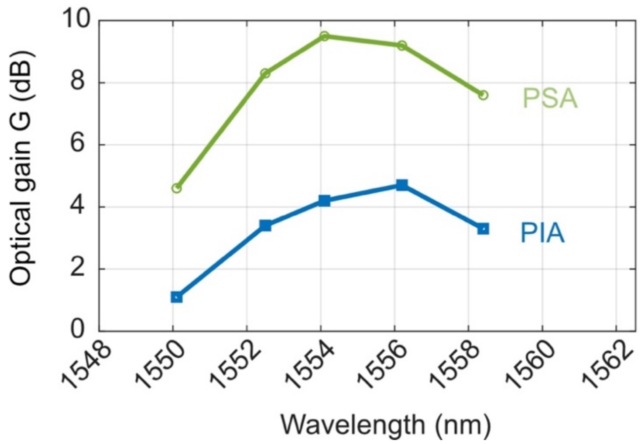


Figure 3. Measured on-chip CW gain using a 1.4m long silicon nitride waveguide when pumped with 34.4 dBm optical power (on chip). The gain is defined as in Fig. 1, i.e. the ratio between the output signal power to the input. In phase-sensitive mode, an idler wave is also input to the waveguide, resulting in about 5.2dB additional gain.

3. CW-pumped optical parametric amplification in silicon nitride waveguides

The waveguides described above are used in a CW-pumped parametric amplification experiment. First, the phase-insensitive mode of operation is assessed. For this, a laser at 1563nm is used as the pump source. The laser is amplified with an erbium-doped fiber amplifier, and 34 dBm is coupled to the chip (which has 2.5 dB loss per facet). The signal gain G is defined as the ratio between the output signal power to the input. From Fig. 3, it can be seen that 4.3 dB gain is obtained at the peak wavelength. The optimal gain is slightly lower than the value predicted by our simulations [11] and we believe this is due to the fact that a non-negligible fraction of the pump power is exciting higher-order modes that do not contribute to providing gain to the signal. Next, we explore the parametric amplifier in its phase-sensitive modality. Here, a copier stage [2] is assembled to create a conjugated idler wave at the input of the waveguide. The relative phase among signal, pump and idler are controlled with a programmable optical processor, then combined with a WDM coupler and coupled to the silicon nitride waveguide with a lensed fiber. In this case, the signal gain increases up to 9.5 dB when the phase difference among waves is correctly aligned [1]. The normalized phase sensitive gain is ~ 20dB, and the estimated on-chip noise figure 1.2 dB, i.e. with coupling losses deducted [11].

4. Conclusion

The first CW-pumped parametric amplifier in an integrated Kerr nonlinear waveguide is reported. Gain up to 9.5 dB (4.3dB) in phase-sensitive (phase-insensitive) mode are achieved with 34 dBm pump power. The results are enabled by record-low-loss (1.4 dB/m) dispersion-engineered silicon nitride waveguides.

5. References

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We gratefully acknowledge the Swedish Research Council (VR-2020-00453, VR-2015-00535) and the KA Wallenberg foundation for support.