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Time-continuous Travelling-Wave Optical Parametric Amplification in a Photonic Circuit

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Abstract *We demonstrate a traveling wave parametric amplifier in a photonic Si_3N_4 integrated spiral waveguide of 2.0 m length with footprint 3x5 mm. We achieve net gain of 7 dB on-chip and 2 dB fiber-to-fiber in the optical C-band. ©2022 The Author(s)*

Introduction

The amplification of optical signals is pivotal across science and technology. The invention of doped-fiber travelling wave amplifiers has revolutionized optical communications systems and is one of the cornerstones of the modern information infrastructure[1]. Optical amplification can also be achieved by harnessing the intrinsic nonlinearities of optical media such as the optical Kerr effect. Such parametric amplifiers can achieve gain at virtually any wavelength within the optical transparency window, can operate very close to the fundamental quantum noise limit of 3 dB for a linear phase insensitive amplifier, can achieve noiseless amplification via phase sensitive amplification, and are inherently non--reciprocal, i.e. they amplify unidirectional laser signals only. In the microwave domain such traveling wave parametric amplifiers (TWPA) are a key technology for low noise broadband amplification.

These properties have made parametric amplifiers pivotal for signal regeneration and wavelength conversion, and the most promising candidates to extend optical communication systems to new wavelength ranges (see Figure 1 a,b). Achieving net-gain requires that the weak parametric gain overcomes the waveguide propagation loss, mandating tight confinement and exceptionally low loss.

In highly optical fibers, impressive performance and gain has been achieved [2], [3]. Yet the use of fiber-based parametric amplifiers has been impeded by the weak light confinement and low Kerr nonlinearity of silica fibers, which requires 100s of meters of specialty fiber and high pump power to achieve optical net-gain. For this reason fiber based parametric amplifiers remained impractical.
Parametric net-gain has also been achieved in mechanically diced periodically poled lithium

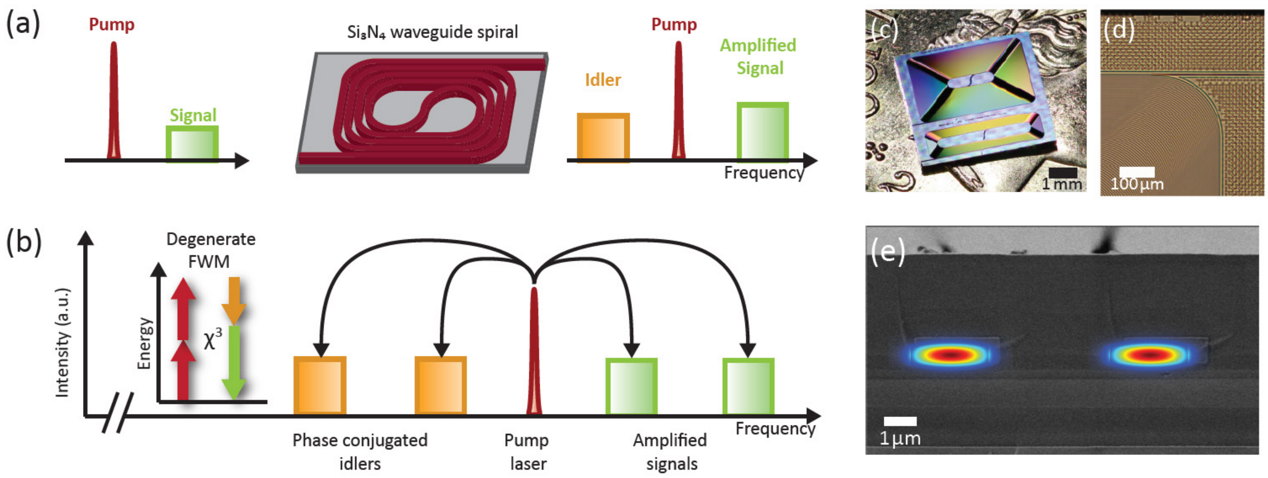

Figure 1: Principle of a traveling wave optical parametric amplifier (TWOPA) and Si_3N_4 waveguide spiral (a) Pump (red) and signal (green) lasers are injected into the optical waveguide spiral. At the output, the signal is amplified and a phase-conjugated idler is generated. (b) Degenerate four-wave mixing transfers optical power from the pump laser to the signal (gain) and a phase-conjugated idler (frequency conversion) that is generated at a symmetric frequency offset from the pump. (c) Photograph of a Si_3N_4 photonic chip containing two waveguide spirals of lengths more than a meter. (d) Optical microscope image showing the corner of the waveguide spiral corner and the coupling taper for fiber coupling. (e) Scanning electron microscope image of the chip cross-section showing two parallel Si_3N_4 waveguides in the spiral.

niobate waveguides[4], [5]. Device performance is ultimately limited by wafer size as no waveguide bends can be cut using mechanical dicing and co-integration with laser sources and photonic integrated waveguides remains challenging. True sub-micron optical waveguides bear the potential to overcome these limitations[6]–[8] and achieve parametric net-gain in a photonic integrated circuit, yet the elusive goal of a non-resonant parametric gain exceeding the propagation loss was not possible until recently [9], [10].

Continuous parametric net-gain in photonic integrated circuits

Here we report our work on a photonic circuit-based travelling-wave optical parametric amplifier with net signal gain in the continuous-wave regime. Our amplification medium is a 2.0 m long Si_3N_4 waveguide spiral with a low footprint of 3x5 mm (see Figure 1 c,d,e) which is enabled by the exceptionally low losses of Si_3N_4 photonic Damascene waveguides of 0.5~dB/m in ring resonators and 1.5 dB/m in spirals that were reported recently**[11]**. Our waveguide cross-section is 910x2450nm, which results in anomalous group velocity dispersion of -134 fs^2mm^{-1}. The waveguide loss and dispersion were measured with a custom ultra-wideband optical frequency domain reflectometer. The optical setup for parametric amplification measurements is depicted in Figure 2a. Experimental pump on-off parametric gain spectra and numerical simulations of the gain are depicted in Figure 2 b,d, respectively. We achieve net-gain of 2 dB fiber-to-fiber (7 dB on-chip net gain) at a pump power of 6.2 W at the input fiber facet in fiber (~4 W on-chip). Our numerical calculations of the small signal gain agree with the experimental findings assuming a area A_{eff} as small as 1.67 μm² and the effective nonlinearity γ of our waveguide as 0.51 $W^{-1}m^{-1}$. This takes into account recent measurements of Gao et al. who find a reduced nonlinear refractive index of high quality Si_3N_4 films grown at EPFL**[12]**.

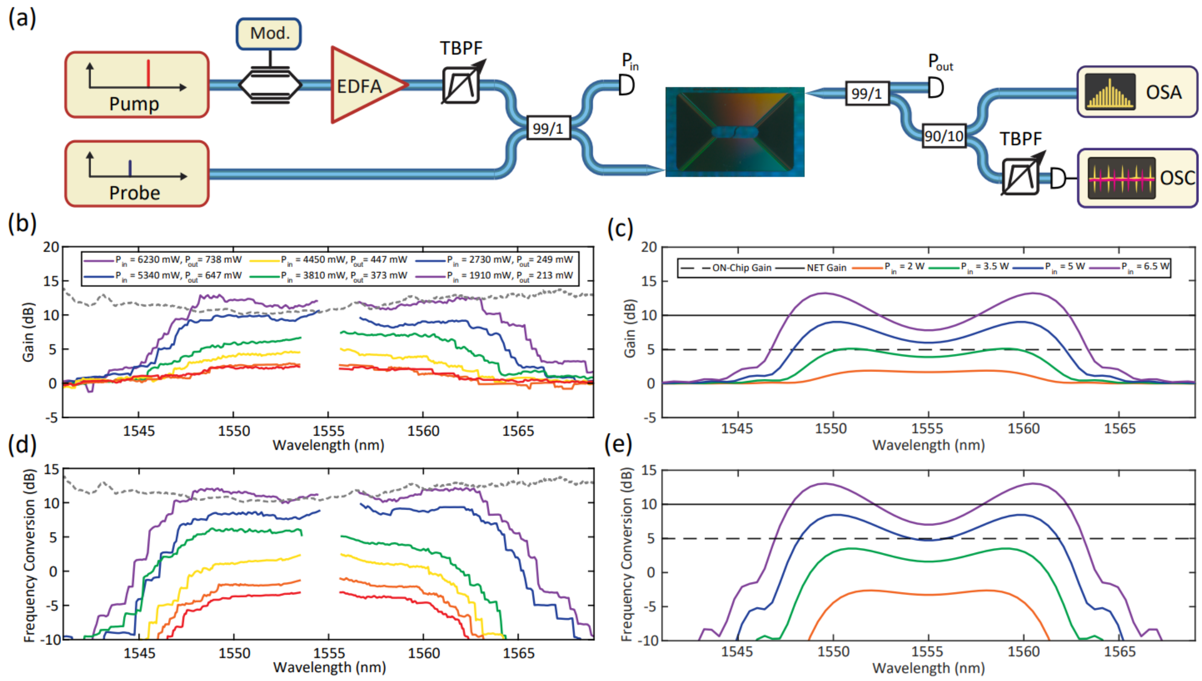

Figure 2: Photonic chip-based, continuous-travelling-wave optical parametric amplification and frequency conversion. (a) Schematic of experimental setup. The pump laser can be modulated (Mod.) in phase and amplitude before amplification in a highpower EDFA. Amplified spontaneous emission noise is suppressed using a tunable bandpass filter (TBPF). The pump and signal lasers are combined using a 20 dB directional coupler (99/1) before coupling into the photonic chip using lensed fibers The output light is sent to an optical spectrum analyzer (OSA). The amplified and modulated signal light is filtered, detected with a photodiode, and analyzed using a digital oscilloscope (OSC). (b) Wavelength and power dependent gain of the system. Measured input (P_{in}) and output powers (P_{out}) using two power meters are marked in the legend. Dashed grey line is the total loss including the fiber-chip coupling losses (c) Simulated gain spectra for the 2-meter-long waveguide spiral. Black dotted line indicates threshold for on-chip gain. Black solid line indicates threshold for off-chip gain. (d,e) Same as (b,c) but indicating the idler frequency conversion efficiency from the pump to the idler.

We also measure the parametric gain by fast modulation of the pump laser modulating the pump laser amplitude with a 50 MHz square wave with a duty cycle of 50%. The instantaneous nature of parametric amplification mediated by the optical Kerr effect imprints the pump modulation directly on the amplified signal and generated idler. The measurement results are depicted in Figure 3. The pump laser is tuned to 1544.5 nm for this measurement, and the signal laser is tuned to 1548.5 nm. Figure 3c depicts the extracted gain values as a function of the input peak power that is seen at the tip of the lensed fiber used to couple light into the chip. The results are in agreement with numerical calculations of the gain up to a peak input power of 5 W where we see a deviation up to 2.5 dB, which might be related to was recently attributed to a temporary increase of Si_3N_4 propagation loss after high power operation[10]. However, we do not observe a reduction in the pump transmission at any of the used optical power levels. Still, the parametric gain is able to compensate the total losses of our photonic chip including fiber-to-chip coupling.

Conclusions

In summary, the reported breakthrough of achieving net gain in photonic waveguide parametric amplifiers bears great potential to improve overall device performance, footprint, and design freedom. The fundamental absorption loss**[11]** of stoichiometric Si_3N_4 waveguides was measured as low as 0.15 dB/m, which would facilitate parametric gain above 70 dB according to our simulations using as little as 500~mW of optical pump power in a single stage 30~m waveguide spiral amplifier that can be fabricated on a 20x20 mm^2 photonic chip, exceeding the performance of the best fiber-based parametric amplifiers.

Acknowledgements

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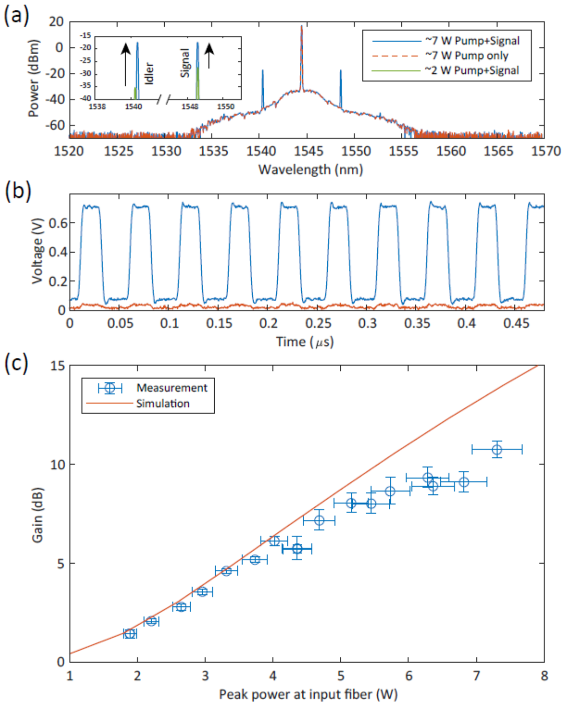

Figure 3: Parametric gain measurement using pump modulation. (a) Optical spectrum showing the pump, signal, and idler. Inset: change of signal and idler power levels with the increase of pump from about 2 W (green line) to maximum value of 7 W (blue line). (b) Measurement of signal modulation due to parametric gain (blue). Small modulation observed without the signal (red) is obtained from modulation instability of the strong pump laser and finite bandwidth of the bandpass filter used to reject the pump light. (c) Measured optical signal gain extracted from the modulation measurement (blue). A simulated gain curve is depicted in red.

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