An Integrated Gallium Phosphide Travelling-Wave Optical Parametric Amplifier

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Abstract: We demonstrate optical continuous-travelling-wave parametric amplification in a 5.55-cm-long integrated gallium phosphide waveguide, achieving up to 35 dB of gain and significantly surpassing the bandwidth of erbium-doped fiber amplifiers.

1. Introduction

Optical amplification, particularly through the use of erbium-doped fiber amplifiers (EDFAs), is crucial in modern optical communication systems. EDFAs effectively boost the strength of optical signals, allowing transmission over long distances, extending network reach, and compensating for signal losses [1–3]. They have revolutionized telecommunications by enabling high-speed data transmission and supporting bandwidth-intensive applications. Despite all the advantages, the amplification bandwidth of EDFAs is limited and can not be made broader. An efficient viable alternative has not yet been found. A promising solution is parametric amplification – a nonlinear process that utilizes the intrinsic properties of materials to amplify optical signals [4–7]. In this process, as shown in Fig. 1(a,b), the pump wave interacts with a nonlinear medium, leading to the transfer of energy from the pump wave to the signal wave, resulting in low-noise unidirectional signal amplification, while simultaneously generating the idler wave. To date, optical parametric amplifiers (OPAs) have been implemented using various methods, including optical fibers [5–7], bulk crystals or diced waveguides [8–11], and photonic integrated circuits (PICs) [12–18]. Here we develop integrated optical continuous-travelling-wave parametric amplifiers that significantly surpass the amplification bandwidth of traditional EDFAs. We achieve up to 35 dB of parametric gain in the small-signal regime, and more than 10 dB of net gain in the wavelength window spanning approximately 140 nm and centered at 1550 nm, with the maximum value of net gain reaching 25 dB. This is, to our knowledge, the first demonstration of such a large and broadband continuous-wave net gain in a photonic integrated waveguide.

2. Device description

Our device comprises a 5.55-cm-long gallium phosphide (GaP) spiral waveguide (Fig. 1(c)) [19, 20]. GaP is a semiconductor material with exceptional optical and electronic properties. It boasts a high refractive index ($>$ 3), transparency across a wide spectral range from visible to long-infrared wavelengths (0.55–11 μm), and a substantial nonlinear coefficient $\chi^{(3)}$, making it an attractive choice for various photonics applications and offering compact and space-efficient solutions. Precise patterning of GaP photonic circuits is performed using electron-beam lithography, while high-efficiency optical coupling is achieved by defining the chip facets via laser dicing. We fabricate an array of sprials with various waveguide widths on a 7×7 mm^2 chip. The average GaP layer thickness is 299 nm. The designed waveguide width of the device in Fig. 1(a) is 780 nm. The length of our spirals is only a few centimeters, which is a major step in device miniaturization compared to meter-long parametric amplifiers utilizing silicon nitride waveguides [21, 22] or hundred-meter-long fiber-based devices [6, 7]. Using optical frequency-domain reflectometry, we determine the average linear optical propagation loss of the spiral waveguide to be 1 dB/m at a wavelength of 1550 nm.

3. Gain measurements

We measure the parametric gain using a conventional amplification measurement with a strong pump and a weak signal (Fig. 1(f)), coupled into and collect from the chip using lensed fibers. To obtain the amplification spectra, we scan the signal laser wavelength and record the output spectra of our amplifier using an optical spectrum analyzer (OSA) in max-hold operation mode (Fig. 1(g)). The signal power is set to 1.5 μW, and the pump power

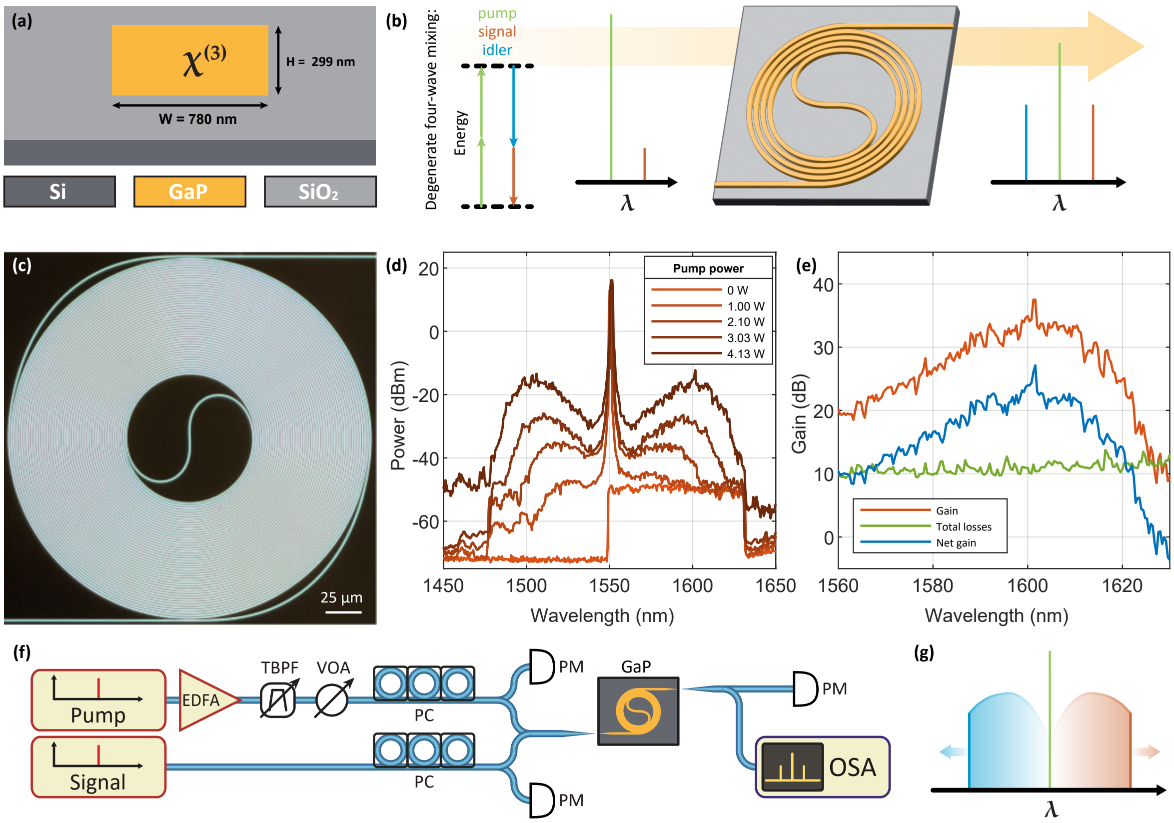

Fig. 1. GaP parametric amplifier. (a) Material stack of the device and waveguide dimensions. (b) Schematic of degenerate four-wave mixing process occurring in a spiral waveguide. (c) Microscope image of the fabricated spiral waveguide. (d) Optical spectra measured with an OSA using max-hold mode to record the maximum signal at various pump powers. (e) Evaluated gain and net-gain spectra corresponding to the highest pump power. (f) Schematic of a conventional experimental setup for amplification measurements. (g) Schematic of an OSA max-hold measurement; with every sweep OSA captures and displays the highest optical power level within a set wavelength range.

is increased up to 4 W in 1-W steps (Fig. 1(d,e)) using an EDFA. We observe strong optical parametric gain reaching 35 dB, providing a net gain up to 25 dB (accounting for both the on-chip optical propagation loss and the fiber–chip–fiber coupling losses) in a spectral window 140-nm-wide observing the typical signal and idler parametric gain lobes characteristic of the optical Kerr effect. The scanning range is limited by the available tunable lasers in our laboratory. We scan the signal wavelength only in one direction from 1550 nm to 1630 nm. Symmetric signal gain and idler conversion efficiency lobes are observed due to the nature of degenerate four-wave mixing.

4. Discussion and conclusion

Integrated parametric amplifiers hold significant promise for a wide array of future applications in the field of photonics and optical communication. Their compact and integrated nature makes them highly desirable for space-constrained systems. With the ability to provide broadband, high-gain and low-noise amplification, these devices are poised to address the ever-growing demand for increased data rates and long communication distances using extended spectral bandwidth. Indeed, our present demonstration of gain covers not only the C- and L-bands addressed by conventional EDFAs, but also the optical S-band. Further dispersion engineering to increase the bandwidth is still possible. As the need for faster and more efficient data transmission continues to grow in various domains, from telecommunications to healthcare and beyond, integrated parametric amplifiers are playing a pivotal role in shaping the future of optical technologies and revolutionizing how we communicate and process information.

5. Acknowledgments

The sample was fabricated at the Binnig and Rohrer Nanotechnology Center (BRNC) at IBM Research Europe, Zurich. This work was supported by the European Union Horizon 2020 Programme for Research and Innovation under grant agreement No. 812818 (Marie Curie ETN MICROCOMB), by the Swiss National Science Foundation (SNF) under grant number 192293, and by the Air Force Office of Scientific Research under award number FA9550-19-1-0250. J. R. acknowledges funding from the SNF Ambizione grant No. 201923 (UNPIC).

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