Integrated Optical Parametric Amplifier with Record Gain

Junjie Xiao[1,2,#], Di Xia[1,2,#], Liyang Luo[1,2], Zhaohui Li[1,2,3], Bin Zhang[1,2,*]
1 Guangdong Provincial Key Laboratory of Optoelectronic Information Processing Chips and Systems, School of Electrical and Information Technology, Sun Yat-sen University, Guangzhou 510275, China.
2 Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, Guangzhou 510275, China.
3 Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, 519000, China.
** zhangbin5@mail.sysu.edu.cn*
 # These authors are equal contributions to this work

Abstract: We report an innovative phase-sensitive optical amplification using GeSbS microresonators, obtaining 31.5 dB gain with 8.5 mW CW-pump power in phase-insensitive mode, a 4.95 dB additional gain and 18.9 dB extinction ratio in phase-sensitive mode.

1. Introduction

Optical parametric amplifiers (OPAs) have garnered considerable interest for their abilities to mitigate the noise constraints imposed by traditional amplifiers, thereby enhancing the performance of classical and quantum communication, computation, and sensing [1, 2]. In contrast to conventional amplifiers relying on stimulated emission of radiation, OPAs can provide tailored, on-demand gain across a diverse range of wavelengths [3]. When operated in phase-sensitive amplifier (PSA) mode, OPAs can amplify an optical signal without introducing any excess optical noise [4].

Recently, on-chip OPAs have attracted significant attention because of their small footprint at the centimeter level and lithographically engineered dispersion properties [5]. However, the realization of high-gain OPAs (> 30 dB) in integrated waveguides has thus far been limited to femtosecond pump pulses [6, 7], rendering them unsuitable for many optical applications that require continuous wave (CW) operation. In the context of CW operation, impressive achievements have been demonstrated in ultralow-loss meter-long Si_3N_4 photonic integrated circuits, including an OPA with 12 dB parametric gain and a PSA with 5.2 dB additional gain and low noise figure [8, 9]. However, achieving significantly higher parametric gain and a low noise figure remains a challenge, particularly in the detection of weak-intensity optical signals for applications such as quantum remote sensing and long-distance quantum imaging [10, 11].

In this work, we demonstrate experimentally, for the first time, a microresonator-enhanced PSA system with a record high parametric gain of 31.5 dB at a low pump power of 8.5 mW. Our result unveils that the GeSbS chalcogenide glass enables greater parametric gain than Si_3N_4 at an equivalent pump power due to its prodigious nonlinear coefficient ($n_2 \sim 1.4 \times 10^{-18}$ m^2/W). Embracing its operation in the PSA mode, a remarkable additional gain of 4.95 dB, paired with a resolute phase-sensitive extinction ratio of 18.9 dB, is realized. Significantly, the phase noise of amplified signals remains pristine and unaffected by pump noise, underscoring the potential for enhanced noise reduction within the PSA operational framework.

2. High Gain Optical parametric amplification based on chalcogenide microresonators

Figure 1(a) illustrates the schematic of a microresonator-enhanced parametric amplifier, where the input waves are amplified via the degenerate four-wave mixing (dFWM) process. When the input signal, pump and idler are phase-correlated, the OPA can work in a PSA mode, giving rise to higher parametric gain and low noise figure. Optical microresonators play a pivotal role by significantly enhancing pump energy and lowering the threshold power for nonlinear effects. Moreover, materials with elevated nonlinear coefficients (n_2) further enhance parametric gain. In our theoretical exploration, we delved into the impact of heightened nonlinearity in microresonators on OPA performance based on the three-wave coupling mode equations. The GeSbS microresonator featured a parametric gain of approximately 8 dB higher than that of Si_3N_4 at the weak input signal power (100 nW), and such a gain difference can be larger for a smaller input signal power [12], see Fig. 1(c). Figure 1(d) elucidates the parametric gain concerning pump power for our GeSbS microresonator, revealing a remarkable 30 dB signal gain at a mere 3.5 mW pump power. Such results highlight the potential of the GeSbS photonic devices in facilitating compact, low pump power and high-gain parametric amplification.

In experiments, GeSbS microresonators were fabricated using the processing method described in [13]. The TM_{00} mode was deliberately chosen with an anomalous dispersion and over-coupled state. The loaded and intrinsic Q factors were 8.8×10^5 and 3.4×10^6, respectively. For the OPA experiment, we utilized two tunable lasers as the pump and signal sources. The measured optical spectrum in the OPA regime is shown in Fig. 1(e), where the orange line represents the input trace and the blue line depicts the output optical trace with the amplified signal wave. As expected from energy conservation in the dFWM process, an idler field of comparable strength was generated. Notably, a remarkable gain of 31.5 dB was achieved with a pump power of 8.5 mW and a signal power of approximately 100 nW. It is worth mentioning that the measured gain slightly deviated from the calculated result, which we attributed to minor variations in radii and coupling coefficients. We also measured the gain as a function of the pump power with a fixed input signal power (Fig. 1(f)). The gain increased rapidly as the pump power approached the OPO threshold of approximately 8 mW. By carefully choosing the pump detuning to prevent cavity oscillation, we achieved a higher gain at a pump power slightly above the OPO threshold. At higher pump powers, the peak gain wavelength shifts, leading to a reduction in gain at the original signal wavelength. Additionally, effectively suppressing optical parametric oscillation became more challenging at this stage. To further pursue high gain with a specific input signal power, the design and fabrication of considerably over-coupled microresonators, while maintaining high intrinsic Q factors, may be necessary.

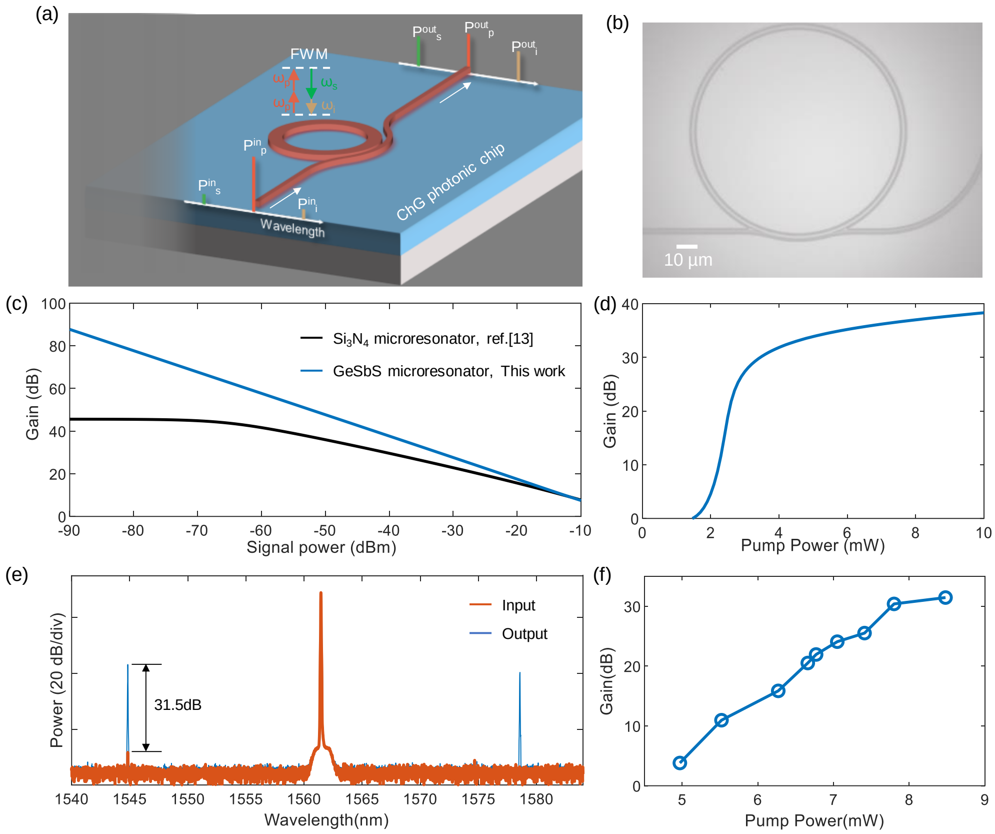

Fig. 1. (a) Schematic of PSAs based on dFWM. The orange, green, and yellow lines represent pump, signal, and idler waves, respectively. (b) Optical microscope image of the microresonator. The microresonator cross section is 2800 nm × 850 nm with a radius of 200 μm (FSR = 103 GHz), and a pulley waveguide coupler was implemented to finely tune the coupling coefficient (c) Simulated gain for different materials with 9 mW pump power. The numerical method is based on the three-wave coupling mode equations [12], in which only the γ has a slight difference for the GeSbS line. (d) Simulated gain versus pump power for a 100 nW input signal power (e) Input (red line) and output (blue line) spectra of the OPA system, the signal at 1544.8 nm was amplified by 31.5 dB. (f) Measured OPA gain as a function of pump power for a 100 nW input signal power.

Next, we explored the phase-sensitive mode of chalcogenide microresonators. Figure 2(a) illustrates the schematic of the PSA experimental setup. First, phase-correlated pump, signal, and idler waves were generated via FWM in a highly nonlinear fiber. Then, we utilized a programmable optical filter to balance the power of the signal and idler and control the relative phase among the three waves. After amplification by EDFA, the three waves were coupled in and out of the chalcogenide microresonators through two lensed fibers. The polarization states of the three waves were manually aligned to the TM_{00} mode using fiber polarization controllers (FPCs) and obtained a coupling loss of 5 dB/facet. The output spectra were recorded by an optical spectrum analyzer (OSA). In this experimental setup, we switched to OPA mode by blocking the idler wave using the programmable optical filter with the same pump power as PSA mode. Typical output spectra of the PSA (red line) and OPA (blue lines) are shown in Fig. 2(b). Due to the coherent superposition of the amplified signal and idler [4], it can be observed that the PSA provided an additional gain of 4.95 dB compared to OPA at 1534 nm while the noise floors remain the same. Figure 2(c) shows the normalized PSA gains with different signal phases, showing an extinction ratio of 18.9 dB between the maximum and minimum gain. Such results demonstrate high-extinction-ratio phase-sensitive characteristic properties with great potential in quantum optics and extremely weak light signals [14, 15]. We further characterized the frequency noise properties of the amplified signals under two modes by a delay self-heterodyne system. We chose the pump laser (Keysight 81606A) with higher noise than the signal laser (Toptica CTL 1550). The input signal was characterized at higher power and then attenuated to send into the chip. The frequency noise of the amplified signal was not affected by the pump noise and exhibited similar noises as the original signal, see blue line in Fig. 2(d). Furthermore, the PSA mode demonstrated additional noise compression of ~10 dB compared with the OPA mode (red line in Fig. 2(d)), particularly in the offset frequency range of 10 KHz to 1 MHz. We expect that a signal noise can be further suppressed with a higher PSA gain by further increasing the coupling coefficient and the intrinsic Q.

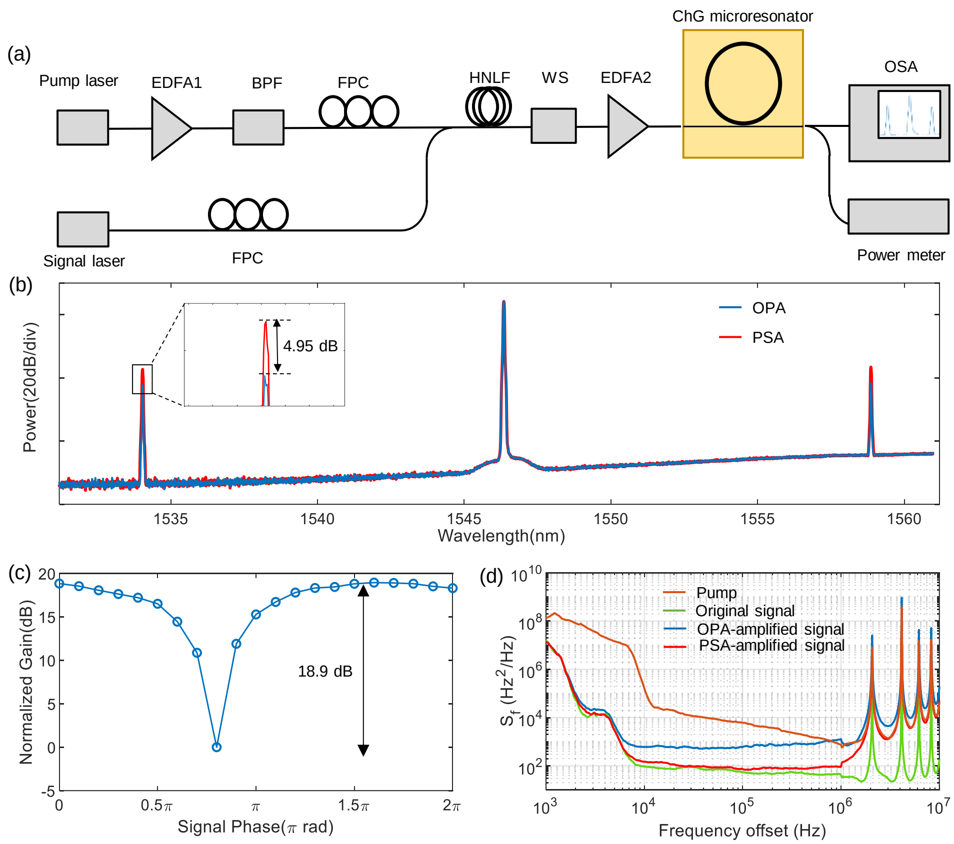

Fig. 2. (a) Schematic diagram of PSA experimental setup with a GeSbS chip. EDFA, erbium-doped fiber amplifier; BPF, band-pass filter; FPC, fiber polarization controller; HNLF, highly nonlinear fiber; POF, programmable optical filter; OSA, optical spectrum analyzer. (b) Output spectra for PSA (red line) and OPA (blue lines) modes. (c) Normalized PSA gains with different signal phases. (d) Frequency noise of the amplified signal under two modes.

3. Conclusions

We have successfully demonstrated a 31.5 dB parametric gain, even at a low pump power of 8.5 mW, within an integrated photonics microresonator. In addition, we achieved an additional 4.95 dB gain and an impressive 18.9 dB phase-sensitive extinction ratio in the PSA mode. PSA can be potentially extended to other wavelengths due to the ultra-wide transparency (from 0.5 to 10 μm) of chalcogenide microresonators. Leveraging the advantages of compact, low power requirements and substantial gain, GeSbS-based PSAs hold the promise of unlocking novel applications across a spectrum of fields.

4. References

[1] Z. Ou, et al.,APL Photonics **5**(2020).
[2] Z. Su, et al.,Photonics Res. **11**, 1861-1869 (2023).
[3] J. Hansryd, et al.,IEEE Photonics Technol. Lett. **13**, 194-196 (2001).
[4] P. A. Andrekson, et al.,Adv. Opt. Photonics **12**, 367-428 (2020).
[5] M. A. Foster, et al.,Nature **441**, 960-963 (2006).
[6] B. Kuyken, et al.,Opt. Lett. **36**, 4401-4403 (2011).
[7] K. Ooi, et al.,Nat. Commun. **8**, 13878 (2017).
[8] J. Riemensberger, et al.,Nature **612**, 56-61 (2022).
[9] Z. Ye, et al.,Sci. Adv. **7**, eabi8150 (2021).
[10] R. T. Glasser, et al.,Phys. Rev. A **78**, 012339 (2008).
[11] X. Ma, et al.,EPJ Quantum Technology **7**, 1-9 (2020).
[12] Y. Zhao, et al.,Optica **10**, 819-825 (2023).
[13] D. Xia, et al.,Laser Photonics Rev. **17**, 2200219 (2023).
[14] W. Yang, et al.,Opt. Lett. **42**, 4553-4556 (2017).
[15] T. Kashiwazaki, et al.,APL Photonics **5**(2020).

This work was supported by the National Key R&D Program of China under Grant (2019YFA0706301), the National Science Foundation of China (NSFC) (62375292, 61975242, 61525502), and the Natural Science Foundation of Guangdong Province for Distinguished Young Scholars (2023B1515020028), Sun Yat-sen University (23qnpy24).