First Demonstration of an Integrated Photonic Phase-Sensitive Amplifier

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Abstract: For the first time, an integrated photonic phase-sensitive amplifier is reported. Approximately 6.3 dB extinction of on-chip phase-sensitive gain based on a signal-degenerate dual pump four-wave mixing architecture has been achieved.

OCIS codes: (190.4380) Nonlinear optics, four-wave mixing; (190.4410) Nonlinear optics, parametric processes; (250.5300) Photonic integrated circuits; (250.5980) Semiconductor optical amplifiers

1. Introduction

Optical phase-sensitive amplifiers (PSAs) have been attracting increasing research attention in the past few years [1] due to its well-known advantage of realizing noiseless amplification and potential 0 dB noise figure (NF). Compared to conventional phase-insensitive amplifiers (PIAs) featuring 3-dB quantum-limited NF, PSAs' noise-free amplification could significantly improve the performance of the optical amplifier and provide a wide range of applications, such as optical telecommunication, optical sensing, optical spectroscopy, and LIDAR. Although PSAs have been demonstrated using parametric down-conversion in $\chi^{(2)}$-based nonlinear material [2], and using four-wave mixing (FWM) in $\chi^{(3)}$-based nonlinear media like optical fibers [3] and semiconductor optical amplifiers (SOAs) [4], in all demonstrated PSAs so far, their implementations are based on bulky bench-top systems, which makes it difficult to use them in real-world scenarios. Photonic integration that enables the combination of key optical components and reduction in scale would great benefit the implementation of PSAs for practical applications.

In this paper, for the first time, we report an integrated photonic signal-degenerate dual pump PSA based on a highly nonlinear SOA (NL-SOA) and demonstrate its 6.3 dB extinction of on-chip phase-sensitive gain. To the best of our knowledge, it is also the first time to use an SOA for non-degenerate phase-sensitive amplification.

2. Principle

Figure 1 and Figure 2 show respectively the schematic and the photo of the signal-degenerate dual pump PSA. The coherent input light waves, which are coupled into the chip, consist of two pumps and one signal to be amplified, and are here generated based on external modulation. The modulator can also be integrated on the photonic IC.

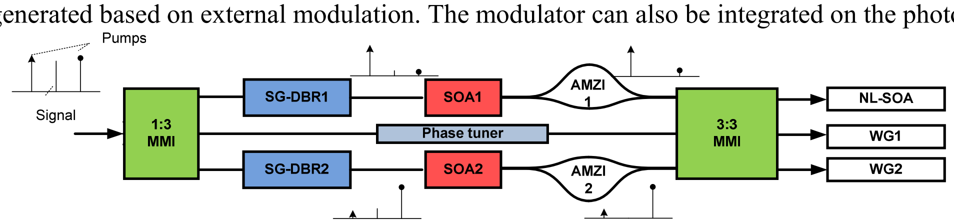

Fig.1 Schematic of the signal-degenerate dual-pump PSA

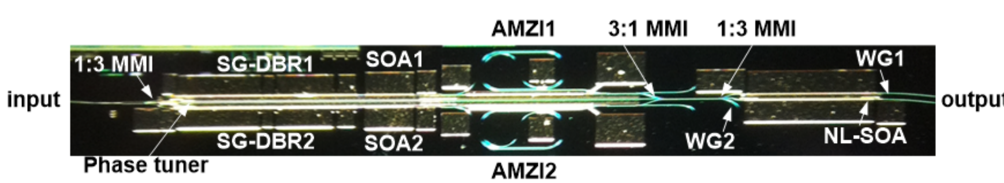

Fig. 2 Photo of the fabricated photonic integrated circuit of the proposed PSA

To achieve low NF, wavelength selective switches should be used to split and combine signal and pumps. However, to reduce the complexity of the chip in this first demonstration, the input light waves are here split into three paths via a 1 by 3 multimode interference (MMI) coupler. Among two of three paths, there are two sampled grating distributed Bragg reflector (SG-DBR) lasers, each of which is injection locked by the corresponding pump that is then selectively amplified. After further amplified by the followed SOA, the pump is filtered by an asymmetric Mach-Zehnder interferometer (AMZI) to remove the residual signal and the noise falling in the signal's spectrum, which avoids signal interference among three paths and enables the signal to be shot-noise limited. Along the third path, there is a phase tuner to phase shift the signal based on quantum-confined stark effect, therefore, the adjustable and stable phase relationship among the signal and two pumps can be achieved for observing the variation in signal power after phase sensitive amplification as a function of signal's phase. The light waves along three paths are combined together and split again by a 3-by-3 MMI coupler to a NL-SOA where phase-sensitive amplification occurs, a long passive waveguides (WG) as potential alternative and a short WG as a reference. The SOA is particularly used as a PIA and its PIA gain caused by population inversion maybe interfere with the nonlinear parametric process and undermine the phase-sensitive amplification. To overcome or minimize this issue, the NL-SOA would be saturated to optimize the FWM and suppress the amplified spontaneous emission noise.

To monolithically integrate the single-chip PSA, we have chosen an InP/InGaAsP centered quantum well (CQW) platform with 10 quantum wells. Quantum well intermixing (QWI) technology [5] is used to define active and passive areas. CQW platform maximizes the mode overlap with the QWs, and therefore more significant nonlinear effect has been achieved. Moreover, the passive waveguide with intermixed quantum wells still have quite strong quantum stark effect, which is ideal for low-loss phase tuner. On the chip, both surface ridge waveguide and the deeply etched ridge waveguides are defined. Surface ridge is used for the SG-DBR laser for better heat dissipation and single-mode operation. Deeply etch waveguide is used for rest of the chips, which leads to better flexibility for waveguide routing and better SOA nonlinear efficiency due to higher confinement factor.

3. Experimental results

Coherent incident light waves are generated via external modulation with a RF frequency of about 10 GHz, which is half of the free spectral range of the AMZIs. Each SG-DBR laser is configured properly to be injection locked by the corresponding pump. The output power of each SG-DBR is about 12 dBm, and each AMZI is configured to maximize the pumps and suppress the signal along the path. The current applied to the phase tuner is tuned from 0 to 4 mA and the relative phase of the signal is measured as shown in Figure 3. The total power of the pump and signal waves sent to the NL-SOA is about 0 dBm, which is enough to enable the NL-SOA saturated. Given that the injection locking is enabled or not, the signal power at the output of the NL-SOA is measured as the current applied to the phase tuner is swept from 0 to 4 mA, which is shown and compared in Figure 3 as well.

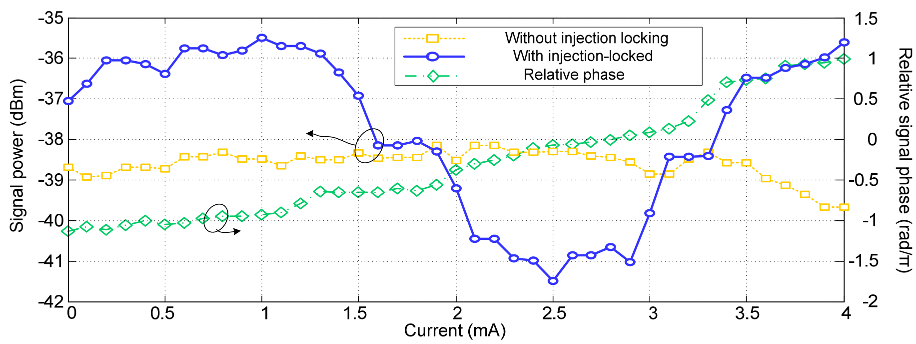

Fig. 3 Measured signal power at the output of the NL-SOA with and without injection locking, and measured relative phase change of the signal as the current applied to the phase tuner is increasing from 0 to 4 mA.

As can be seen in Figure 3, when two SG-DBR lasers run independently, there is no phase-sensitive amplification due to random phase drifting among the pump and signal waves. The measured average signal power is about -38.5 dBm with approximate ±0.4 dB fluctuation when the current is lower than 3.5 mA. Once the injection locking is enabled, the pump and signal waves become as coherent as the incident light waves and phase sensitive amplification is realized, the signal power goes up to -35.3 dBm and decreases to -41.6 dBm, exhibiting a sine-curve like change as the signal phase is swept over 2π. Approximately 6.3 dB extinction of phase-sensitive on-chip gain is demonstrated. This is to the best of our knowledge the demonstration of a fully integrated photonic PSA.

4. References

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