Single-chip dual-pumped SOA-based phase-sensitive amplifier at 1550nm

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Invited Paper

***Abstract*—A saturated semiconductor-optical-amplifier exhibited 6.3 dB of phase-sensitive gain using two tunable laser pumps coherently injection-locked from sidebands of a modulated tone, all integrated on a single InP chip.**

Keywords—phase sensitive amplifier, semiconductor optical amplifier, photonic integrated circuit, four wave mixing

I. INTRODUCTION

All optical signal processing based on noiseless phase-sensitive amplification (PSA) has been attracting increasing attention in recent years [1] and has been demonstrated in various bench-top systems using either parametric down-conversion in $\chi^{(2)}$-based nonlinear materials [2], or four-wave mixing (FWM), in $\chi^{(3)}$-based nonlinear mediums such as optical fibers [3] and semiconductor optical amplifiers (SOAs) [4]. However, it is difficult to use these bulky setups in practical scenarios. Photonic integration that enables the combination of key optical components and reduction in scale would greatly benefit the implementation of PSAs for practical applications.

In this paper, an integrated photonic signal-degenerate dual-pumped PSA at 1550 nm, based on a saturated SOA, is demonstrated. The performance of the SOA is characterized. Chip-scale PSA gain is theoretically analyzed, and a 6.3 dB extinction ratio of gain is realized.

II. CHIP-SCALE PSA

To monolithically integrate the single-chip dual-pumped PSA, an InP/InGaAsP centered quantum well (CQW) platform with 10 quantum wells (QWs), which can maximize the mode overlap with the QWs in an SOA and enhance the nonlinearity, is used. Quantum well intermixing (QWI) technology [5] is employed to define active and passive areas. Fig. 1 shows a schematic and a photo of the chip. Two pump sidebands and one signal generated from an external modulated tone are coupled into the chip and split into three paths via a 1-by-3 multimode interference (MMI) coupler. Along upper and lower paths, there are two sampled-grating distributed-Bragg-reflector (SG-DBR) lasers. Each laser is injection locked by one sideband, suppressing the other wavelengths. Each pump is amplified by an SOA, and noise is suppressed by an asymmetric Mach-Zehnder interferometer (AMZI). Along the middle path, there is a phase tuner to phase-shift the signal based on quantum-confined stark effect; therefore, an adjustable and stable phase relationship among the signal and the two pumps can be achieved for observing the phase-dependent gain of the signal. The light waves along the three paths are combined together in a 3-by-3 MMI coupler and split to a nonlinear SOA (NL-SOA) where PSA occurs, as well as long and short passive waveguides (WG) as references. The NL-SOA is saturated to optimize the FWM and suppress the amplified spontaneous emission noise.

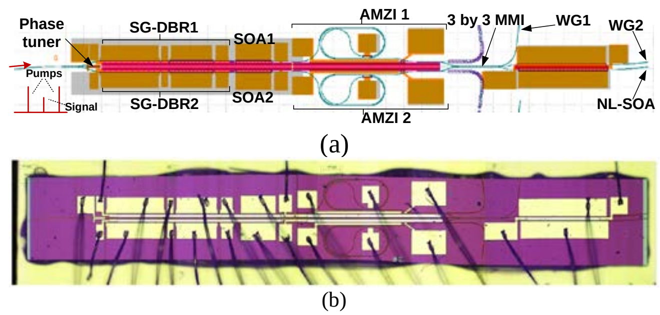

Fig. 1. Schematic and photo of the signal-degenerate dual-pumped PSA.

III. SOA CHARACTERIZATION

To theoretically investigate the chip-scale PSA in a NL-SOA, some identical SOAs with different lengths were made on the same wafer for characterization. Some of results are shown here. First of all, the gain profile of a 1-mm SOA, consisting of three cascaded 330-μm SOAs, was measured, which is shown in Fig. 2. The measured transparent current density is about 1 kA/cm^2. The peak gain is 47.5 dB/mm at 1560 nm when current density is about 9 kA/cm^2.

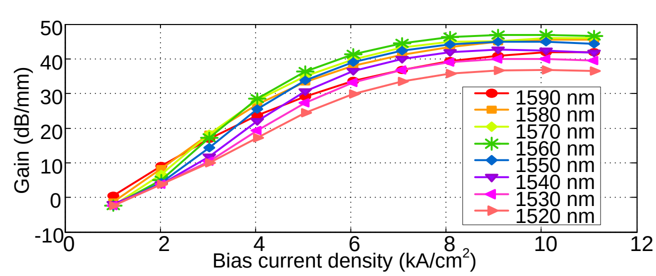

Fig. 2. Measured gain profile of a 1-mm SOA.

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The dispersion was measured as well using a 2.3-mm SOA based on a setup shown in Fig. 3. An intensity-modulated light wave is sent to the SOA. The RF signal is from a vector network analyzer (VNA). Due to the dispersion of the SOA, nonlinear phase shifts would be applied to incident tones and the recovered RF signal at the PD. From the recorded phase change obtained from the VNA when sweeping the wavelength of the carrier, we can calculate the total dispersion of the SOA as shown in Fig. 4. As we can see, dispersion is about 0 from 1550 nm to 1570 nm, and reaches -700 fs/nm near 1530 nm.

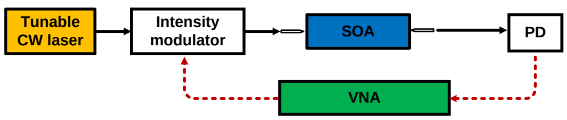

Fig. 3. Setup of the SOA dispersion measurement.

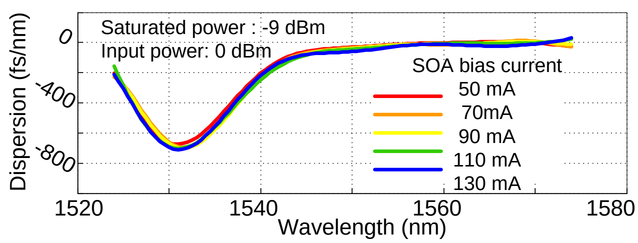

Fig. 4. Measured dispersion of a 2.3-mm SOA.

The SOA carrier lifetime was measured using a 50-µm SOA, which is shown in Fig. 5. The carrier lifetime decreases quickly as the input power goes up, and reaches about 180 ps at a high input power of 20 mW.

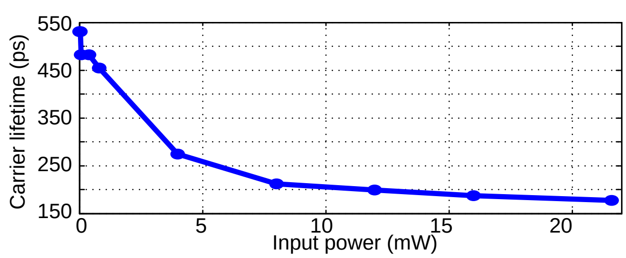

Fig. 5. Measured carrier lifetime with respect to input light wave power.

IV. Theoretical Simulation and Experimental Result

The injection current to the NL-SOA is set to be about 90 mA. The total power of the pump and the signal waves sent to the NL-SOA is set to be 0 dBm, saturating the NL-SOA. Using the parameters obtained from SOA characterization, a theoretical simulation of the PSA gain based on coupled differential equations [6] is presented in Fig. 6, showing a 6.5 dB extinction ratio of the phase-sensitive gain.

An experiment was performed to evaluate our simulation. Since the signal power after PSA varies with the signal phase, which should vary linearly with the square root of the injected current, the measured signal power at the output of the SOA with respect to the square root of the injected current was measured, which is shown in Fig. 7. For comparison, the signal power without injection locking and the relative phase change of the signal were measured, which are shown in Fig. 7 as well. The relative phase change was measured in a manner similar to that shown in Fig. 3. When two lasers are in free-running modes, there is no PSA due to random phase drifting. Once the injection locking is enabled, however, there is no obvious PSA or phase change of the signal until after the current is larger than 1 mA. Such a delay in phase shift has been observed in tunable lasers and could be caused by an N^+ sheet charge that occurs at the regrowth interface due to surface contamination. As the current is increased from 1 mA to 4 mA, there is a π phase shift to the signal and one cycle of signal power change is observed. Approximately 6.3 dB extinction of phase-sensitive on-chip gain is achieved, which agrees well with the simulation over this current and phase-shift range.

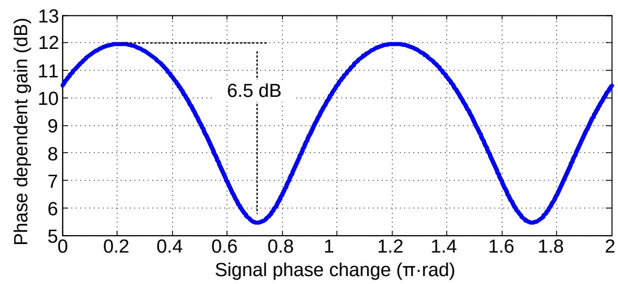

Fig. 6. Simulation result of the phase-sesitive gain of the chip-scale PSA.

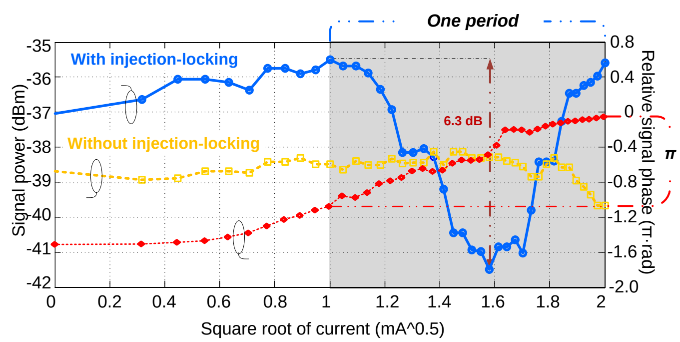

Fig. 7. Measured relationship among the signal power, the signal phase and the square root of the current applied to the phase tunner.

References

[1] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P.-O. Hedekvist, "Fiber-based optical parametric amplifiers and their applications," IEEE Select. Topics Quantum Electron. vol. 8, pp. 506–520, May/Jun. 2002.

[2] K. J. Lee, F. Parmigiani, S. Liu, J. Kakande, P. Petropoulos, K. Gallo, and D. J. Richardson, "Phase sensitive amplification based on quadratic cascading in a periodically poled lithium niobate waveguide," Opt. Express, vol. 17, pp. 20393–20400, Oct. 2009.

[3] Z. Tong, C. Lundström, P. A. Andrekson, C. J. McKinstrie, M. Karlsson, D. J. Blessing, E. Tipsuwannakul, B. J. Puttnam, H. Toda, and L. Grüner-Nielsen, "Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers," Nat. Photonics, vol. 5, pp. 430–436, Jun. 2011.

[4] A. D. Ellis and S. Sygletos, "Phase sensitive signal processing using semiconductor optical amplifiers," in OFC2013, paper OW4C.1

[5] E. Skogen, J. Barton, S. Denbaars, and L. Coldren, "A quantum-well-intermixing process for wavelength-agile photonic integrated circuits," IEEE J. Sel. Top. Quantum Electron. vol. 8, pp. 863–869, Jul. /Aug. 2002.

[6] J. Mørk and A. Mecozzi, "Theory of the ultrafast optical response of active semiconductor waveguides," J. Opt. Soc. Am. B, vol. 13, pp. 1803-1816, Aug. 1996.