Cross-Phase Modulation Efficiency in Offset Quantum-Well and Centered Quantum-Well Semiconductor Optical Amplifiers

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***Abstract*—We conduct an experimental study of cross-phase modulation efficiency for semiconductor optical amplifiers with two different active regions—offset quantum-well (OQW) stack and centered quantum-well (CQW) stack. OQW devices exhibit less than 100° phase change, whereas CQW devices are 60% more efficient for the same pump input power, with more than 200° phase change possible. The input wavelength degrades the phase change significantly outside the 30-nm gain bandwidth window.**

***Index Terms*—Cross-phase modulation (XPM), photonic integrated circuits (PICs), semiconductor optical amplifier (SOA), wavelength conversion, wavelength converter.**

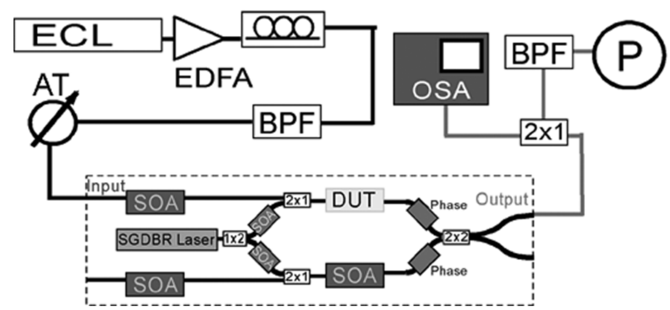

Fig. 1. Experimental setup.

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) represent one of the key components of modern photonic integrated circuits (PIC). These devices are used to perform a variety of functions on a chip, such as linear signal preamplification [1], boosting of the signal level of integrated sources [2], optical gating [1], as well as nonlinear functions used in PICs like SOA-based wavelength converters [1]–[4]. Quantification of the SOA nonlinear behavior is presented in this letter, for two commonly used SOA active region structures/integration platforms, employing centered and offset quantum wells (OQWs) [4], [5]. The choice of the SOA active region design depends on the desired application, and will influence the SOA properties such as achievable gain, saturation power, and nonlinearity. The main difference between the offset and centered quantum-well (CQW) platforms is in the extent of overlap of the mode with the active region. Larger overlap, for the case of CQWs, increases the gain and nonlinearity of an SOA, while also reducing the SOAs output saturation power. More details about this can be found elsewhere [1].

Application of SOA nonlinearities is particularly of interest in SOA integrated wavelength converters [2]–[6], which are good candidates for deployment into the future optical networks. These wavelength converters exploit the nonlinear interactions between pump and probe photons at two different wavelengths in the SOA active medium in order to transcribe the original input information onto a new wavelength.

Some of the most promising integrated wavelength converters utilize the effect of cross-phase modulation (XPM) in an SOA. XPM in an SOA is caused by the input bit stream which reduces the carrier density in the active region, compressing the gain of the active region, thereby causing a temporal refractive index change, and as a consequence a temporal optical phase change. This phase change will be imprinted onto a probe continuous-wave signal concurrently propagating through the same SOA [1], [2]. For wavelength conversion of intensity modulated signals, the phase change in the SOA needs to be converted to an amplitude change. This is achieved by using optical filtering, either through an SOA interferometric structure [2], or by using a bandpass filter after the SOA [3].

Despite the popularity of integrated XPM-based SOA wavelength converters, detailed examination of the XPM efficiency of different integration platforms, to the best of our knowledge, has not been reported. This efficiency will directly impact the output power, optical signal-to-noise ratio, and extinction ratio of the SOA based wavelength converters.

We perform a thorough comparison of XPM efficiencies, measured by the amount of achievable optical probe phase change caused by the pump signal power change, for SOAs fabricated in two widely used integration platforms using an OQW active region [6], and using a CQW active region [5].

II. Measurement Method

The phase change measurements are performed indirectly, utilizing two different monolithically integrated widely tunable Mach–Zehnder interferometer (MZI)-SOA wavelength converters (Fig. 1), realized in the OQW platform [4], [6], and also

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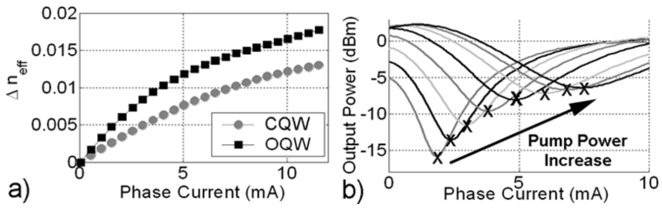

Fig. 2. (a) Effective index change in function of phase current (b) OERC family of curves for increasing pump power.

in the CQW platform that employs quantum-well intermixing [5]. For both device types, OQW and CQW, all SOAs and active regions on chip are realized in the same platform, respectively. The chips also contain a number of passive sections, where the quantum wells have either been etched off (OQW) [4] or intermixed (CQW) [5].

Data about the effective index change as a function of a passive waveguide section's electric bias current can be obtained by observing the shift in the reflected amplified spontaneous emission from the sampled-grating distributed Bragg reflector (SGDBR) laser mirror peaks, while pumping the SGDBR mirror with different current densities [7]. This data is shown in Fig. 2(a), for both OQW and CQW cases.

MZI-SOA interferometer on each device contains the same type of passive waveguide phase section, which enables the interferometer phase control through current injection [4], resulting in a characteristic interferometer optical–electrical response curve (OERC) [4], [6].

Measuring OERC for different optical power levels of the pump signal in the device under test (DUT) yields a family of curves shown in Fig. 2(b). The minima of the curves, as a function of phase electrode current, are shifted due to the different amounts of index change caused by the external pump signal in the DUT. This index change is proportional to the phase electrode current at the minimum of the OERC. Using the relationship between the phase electrode current density and effective index change (Fig. 2(a)) previously obtained, we can relate the total phase change to the optical power level of the pump signal.

III. Experimental Procedure

The XPM efficiency is measured in one of the MZI-SOAs of these integrated devices (labeled DUT in Fig. 1 [6]), which makes the measurements stable and reproducible. The experimental setup is shown in Fig. 1. The input pump signal is generated by an external cavity laser, amplified by an erbium-doped fiber amplifier (EDFA), filtered using a tunable bandpass filter (BPF), and its power is controlled using an optical attenuator. The polarization of the light is controlled before the light is coupled to the input waveguide of the device. The light from the SGDBR laser is equally split on-chip between the two branches of the MZI, and amplified by the booster SOAs before reaching the MZI-SOAs (Fig. 1) [4]. The bias of the DUT (Fig. 1), is controlled by a high precision source meter, which allows for both forward and reverse biasing of the DUT while measuring the current with a precision greater than 1 μA. The output of the interferometer is coupled to a lensed fiber and then split and led to an optical spectrum analyzer, and through an optical BPF to an optical power meter (Fig. 1). Optical power level for the pump signal is controlled by the on-chip preamplifier SOA bias, whereas the probe power level is controlled by the on-chip booster SOA bias [4]. Before each OERC is taken, probe and pump power levels are measured (individually) by reverse biasing the DUT, which then acts as a photodiode with 100% quantum efficiency, and recording the photocurrent. Knowing the quantum efficiency and the responsivity of this photodiode allows for translation of this photocurrent into the optical power. Finally, families of OERCs are taken for different power level, DUT bias, and pump–probe wavelength combinations. The other MZI-SOA's bias current is kept constant, as well as the probe power, throughout the given measurement. This data is analyzed and converted into the phase change data as explained in the Section II.

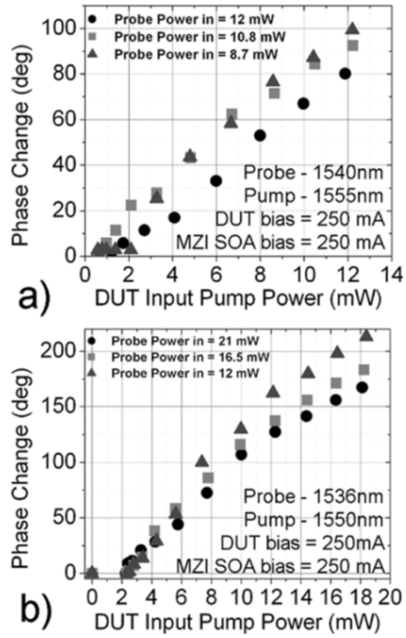

Fig. 3. XPM efficiency as function of probe power (for varied pump powers) (a) OQW (b) CQW.

IV. Results

Fig. 3 shows the results for the DUT phase change as a function of the pump (input signal) power entering the DUT, for different probe (SGDBR) powers coupled into the DUT. Higher probe power results in the lower initial carrier concentration in the DUT, thereby setting the amount of gain compression attainable for the given pump signal power, and thus limiting the maximum phase change. For high-speed wavelength conversion, on the other hand, high photon density caused by the high SGDBR probe power in the DUT is desirable in order to reduce the gain recovery time [1]–[4]. Therefore, a tradeoff exists in order to optimize the speed of operation while maximizing the conversion efficiency. The OQW device experiences a maximum phase change of 100°, whereas the CQW device exhibits a phase change of up to 160° for the same pump power (Fig. 2(a) and (b), respectively). The input pump signal power is limited by the maximum attainable gain in the preamplifier SOA (Fig. 1). Due to higher confinement of about 12% (compared to 7% for the OQW), CQW-based preamplifiers provide more gain at a given amplifier length, thus, phase change data for higher power levels exists for the CQW SOA.

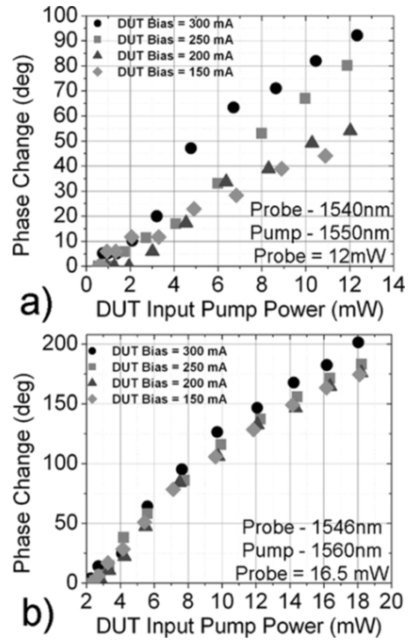

Fig. 4. XPM efficiency as function of DUT bias current (for varied pump power) (a) OQW (b) CQW.

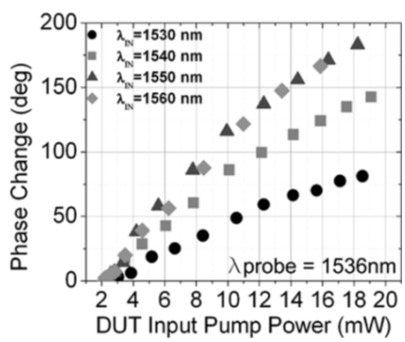

Fig. 5. XPM efficiency wavelength dependence (CQW).

The refractive index change primarily occurs in the active region of the SOA. The modal index then is proportional to this index change and the confinement factor of the mode.

Higher phase change of the CQW SOAs compared to OQW SOAs can be explained by two effects: higher confinement factor, which then increases the modal index change, and higher available gain (over the given SOA length), which allows for more gain compression and more nonlinear behavior of the CQW SOAs.

Fig. 4 shows the XPM efficiency measurements for varying DUT bias current. OQW SOAs exhibit more dependence, primarily due to their higher input saturation power when compared to the CQW SOAs. Increased DUT bias current increases the amount of phase change possible.

High bias current of the DUT is compatible with the high-speed operating conditions of the MZI-SOA WC [1]–[4], so in this case, both efficiency and high-speed operation conditions are satisfied simultaneously.

Wavelength dependence of the XPM of the quantum-well stack used was studied as well, and the results are shown in Fig. 5. The reasons for this dependence is in the wavelength dependence of the quantum-well gain [7]. Since both device realizations utilize the same quantum-well designs, the wavelength dependence will be similar. The results shown are for the CQW case. The XPM efficiency decreases significantly with wavelength change (25% over 20 nm), and is maximum at the gain peak of the quantum wells (1555 nm in this case). The same dependence is expected of the longer wavelength side of the gain peak, but could not be measured due to limited gain bandwidth of the EDFA used.

V. Summary and Conclusion

In this letter, we have reported on the comprehensive investigation of the XPM efficiency for two different types of SOAs, fabricated in two commonly used integration platforms in InP, based on OQW and CQW active regions. The measurements were performed using an interferometric phase measurement method enabled by employing integrated tunable wavelength converter devices [4], [5]. With carrier and photon densities in the DUT set equivalent to conditions that would allow for high-speed wavelength conversion [6], OQW devices exhibit less than 100° phase change, whereas CQW devices are 60% more efficient for the same pump input power, with more than 200° phase change possible. The input wavelength dependence is significant, and the XPM efficiency is limited by the DUT gain bandwidth window. Overall, CQW SOAs are better candidates for realization of the XPM-based wavelength converters [5]. However, OQW devices can provide more linear gain with higher saturation powers due to their lower optical confinement factor [6].

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