Non-linear polarization orthogonality loss in a semiconductor optical amplifier

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Polarization-based optical communications are attracting more attention recently, where the crucial points are polarization features and their measurements. Based on the Müller matrix method, we obtain measurable expressions for the polarization-dependent gain (PDG) and the loss of polarization orthogonality (LPO), while give the boundary of the LPO for any PDG devices. We experimentally demonstrate that non-linear LPO can be created in a semiconductor optical amplifier and find that the LPO will slightly skim over the boundary near the threshold of the injected current. Furthermore, an empirical formula is achieved to gauge the LPO-induced power penalty, which is proven to be valid in differential polarization shift-keying transmission by executing a bit error rate measurement. Our conclusions are applicable to non-orthogonal polarization cases and valuable to polarization-related communications, even orbital angular momentum multiplexing.

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Optical communication based on states of polarization (SOPs) has prominent advantages, such as power equalization, better polarization characteristics, and less power penalty (PP), which further suppress the polarization mode dispersion (PMD) and improve the spectrum efficiency[1,2]. For example, increasing the polarization alternation of optical signals can efficiently prevent non-linear degradation[3]. At present, to enhance the capacity expansion of existing optical communication systems, there has been increasing interest in polarization division multiplexing (PolDM) and polarization shift keying (PolSK)[4–9]. Generally, orthogonal SOPs are utilized to multiply or modulate the optical signals. To perform SOP-based communications, there is the key point that the polarization correlations such as the orthogonality should be preserved well in the transmission. In a linear optical system with polarization-dependent loss (PDL), the SOPs will keep their orthogonality for a long distance, for example, orthogonal SOPs preserve well after transmitting in a fiber with a length longer than 50 km[10].

However, we have found, for the first time to our knowledge, that the orthogonality will be lost or trimmed down in a non-linear semiconductor optical amplifier (SOA), whose refractive nonlinearity is 10^8 times larger than an equivalent length of optical fiber[11]. Further analysis shows that the loss of polarization orthogonality (LPO) is non-linearly related to the polarization-dependent gain (PDG) of the SOA. Based on Müller matrix (MM) method, we derive the measurable expressions for the PDG and the LPO while obtaining the LPO boundary for any devices with PDG, and we experimentally demonstrate it by MM-based measurements. Moreover, we investigate the impact of LPO on the bit error rate (BER) of the PolSK signals while indicating how much PP the LPO creates and how the BER varies when they pass through the SOA.

In Stokes space, any optical system such as an SOA can be described by a 4×4 MM $M=\{m_{ij}\}_{4\times4}$. Therefore, the SOPs for input and output optical fields described by Stokes vectors $\vec{S}_\mathrm{i}$ and $\vec{S}_\mathrm{o}$ are related by $\vec{S}_\mathrm{o}=M\vec{S}_\mathrm{i}$. Similar to the PDL, the PDG can be completely determined by the first row of matrix M as follows[12]:

$$\mathrm{PDG}=10\ \log\frac{m_{11}+\sqrt{m_{12}^2+m_{13}^2+m_{14}^2}}{m_{11}-\sqrt{m_{12}^2+m_{13}^2+m_{14}^2}}. \qquad (1)$$

Accordingly, to gauge the PDG of an SOA, one needs to obtain the MM M in the first step. In general, by inputting into an SOA four kinds of linear-independent SOPs producing an invertible matrix $S_\mathrm{in}=[\vec{S}_\mathrm{i1},\vec{S}_\mathrm{i2},\vec{S}_\mathrm{i3},\vec{S}_\mathrm{i4}]$ and by simultaneously measuring the corresponding output SOPs, we can get another matrix, $S_\mathrm{out}=[\vec{S}_\mathrm{o1},\vec{S}_\mathrm{o2},\vec{S}_\mathrm{o3},\vec{S}_\mathrm{o4}]$. Since $S_\mathrm{out}=MS_\mathrm{in}$, the MM M can be achieved by

$$M=S_\mathrm{out}S_\mathrm{in}^{-1}. \qquad (2)$$

Due to the noticeable PDG, when two optical waves with orthogonal SOPs are launched into an SOA, they cannot remain orthogonal anymore, which means an evident LPO caused by the SOA. According to Ref. [10], the

LPO is dependent on the maximum and minimum power transfer coefficients of the SOA and can be further derived and expressed in terms of MM elements[13]:

$$\mathrm{LPO} \le \left| \arccos \frac{\sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}}{m_{11}} - \frac{\pi}{2} \right|. \tag{3}$$

By substituting Eq. (1) into Eq. (3), we get

$$\mathrm{LPO} \le \left| \arccos \frac{10^{\mathrm{PDG}/10} - 1}{10^{\mathrm{PDG}/10} + 1} - \frac{\pi}{2} \right|, \tag{4}$$

in which the unit of PDG is decibels (dB). It can be seen that the maximum LPO is non-linearly connected with the PDG.

To demonstrate the validity of our above analysis, we firstly measure the PDG of the SOA by the MM method, which is shown in Fig. 1.

A tunable semiconductor laser (TSL 210, Santec) emits a stable, continuous wave with a fixed SOP, which goes into the polarization state generator (PSG). Subsequently, four kinds of linear-independent SOPs are produced one by one from the PSG and measured by an in-line polarimeter (POD-101, General Photonics). Then they are launched into the SOA (SOA-XN-OEC-1550, CIP Technologies) with length of ~2 mm, which has a polarization sensitivity of ~1 dB around 1550 nm and is supplied by a homemade driver with current and temperature control. The corresponding SOPs outputting from the SOA are measured by polarimeter 2 (PA-530, Thorlabs).

Once we get four pairs of input and output SOPs, according to Eq. (2), we can obtain the MM of the SOA. In general, the matrix is dependent on the injected current of the SOA, while it is also related to the wavelength and power of the input laser. Therefore, we investigate in detail the influence of these parameters and get the corresponding matrixes. Afterwards, we are able to compute the PDG of the SOA based on Eq. (1). To reduce the disturbance and improve the computation accuracy, we apply the differential rotation method, which we have demonstrated before[14]. After a large amount of measurement and calculation, the PDGs have been achieved for the SOA under different conditions. The results are partly shown in Fig. 2.

Due to the highly non-linear properties of the SOA, all of the curves in Fig. 2 are far away from straight lines. When the injected current increases while the input power

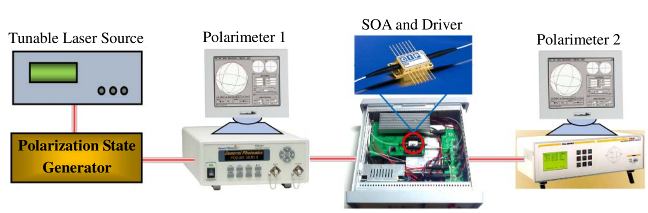

Fig. 1. Experimental setup for measuring the PDG and LPO in the SOA.

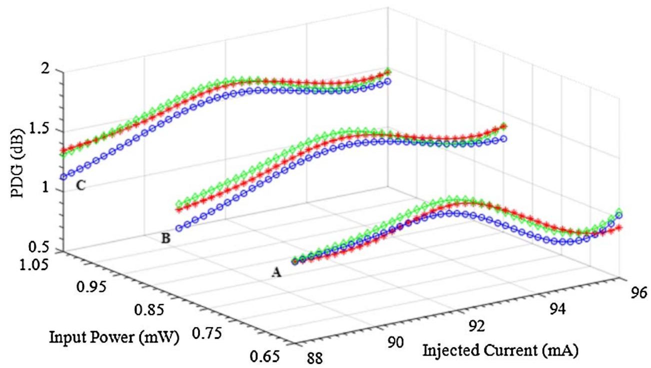

Fig. 2. PDG versus injected current of the SOA for inputs with 3 fixed powers (A curves: 0.65 mW, B curves: 0.85 mW, and C curves: 1.05 mW) and 3 fixed wavelengthes (blue circles: 1547 nm; green diamonds: 1557 nm; red stars: 1567 nm)

and wavelength are fixed, the PDG rises up first and then goes down. The peak values (~1.5 dB) respond to the currents around 92 mA in our experiment. As the injected current is fixed, the PDG changes much less when the input power varies between 0.65 and 1.05 mW or the wavelength increases from 1547 to 1567 nm. These results satisfy the theoretical analysis, because the PDG is mainly dependent on the amount of carriers in the SOA, which is mostly determined by the injected current.

After measuring the PDG, we can calculate the maximum LPO according to Eq. (4). To further confirm its reliability, we measure the practical LPO as two polarization-orthogonal optical signals going through the SOA. The experimental setup is same as that in Fig. 1, while the PSG generates two orthogonal polarization signals. By analyzing the SOPs of signals before and after the SOA, we can get the real LPO, according to Ref. [15]. The results are illustrated in Fig. 3, where we can find that most of the measured LPOs are less than their corresponding maxima. However, when the injected currents are close to the threshold value (~85 mA) of the SOA, the difference is smaller between the measured and calculated LPOs, while at a lower input power, even a few experimental data are a bit higher than the calculated ones. This is an interesting phenomenon. We believe the reason for this is that around the threshold current, the carriers fluctuate too violently in the SOA, which makes the PDG vary greatly, so some of the measured LPOs jump a little beyond the boundary. But at a higher input power, the carriers are easily saturated, so the PDG becomes relatively steady as well as the LPO.

For PolSK communications that utilize orthogonal SOPs, the LPO will be detrimental to the performance and cause a detection penalty. To know how much the penalty will be, we investigate the BER of the differential PolSK (DPolSK) signals through the SOA with different PDG/LPO. The experimental setup is schematically shown in Fig. 4.

The pulse pattern generator (MP1800A, Anritsu) is set to produce pseudo-random bit sequences at 10 Gbit/s,

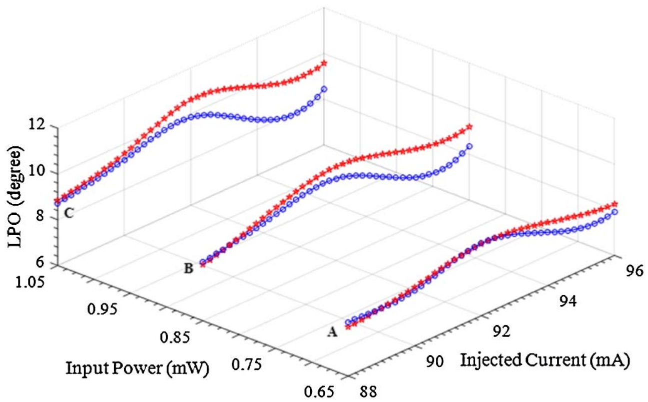

Fig. 3. Experimental (blue circles) and calculated (red pentagrams) LPOs of the SOA for different currents and 3 fixed input powers (A curves: 0.65 mW, B curves: 0.86 mW, and C curves: 1.05 mW) at 1567 nm.

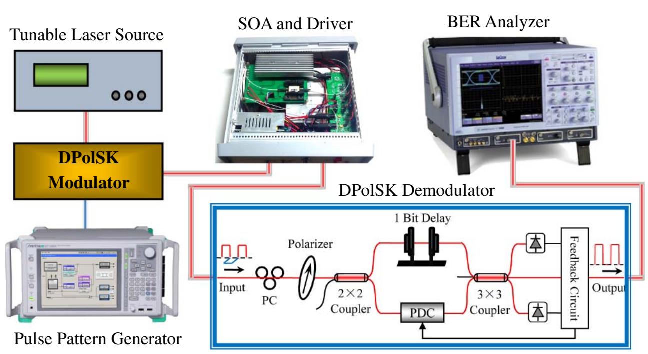

Fig. 4. BER measurement scheme for DPolSK signals going through the SOA under different injected currents. PC, polarization controller; PDC, phase-drift compensator.

which modulate the laser through the differential polarization modulator and generate orthogonal DPolSK optical signals. Subsequently, the signals are launched into the SOA and further retrieved by the DPolSK demodulator (DPolD), and then they are finally observed and analyzed by a high-speed oscilloscope (WaveExpert 100H, LeCroy). The principle of the employed DPolD has been proposed and demonstrated in our previous work[16]. For this kind of demodulator, the PP introduced by the LPO alone can be derived from the above results and expressed as

$$PP = -10\log(1 - \sin(\mathrm{LPO})), \tag{5}$$

from which we can draw a conclusion that the PP will increase as the LPO goes up. In our experiment, the measured LPO has a maximum value of 10.6°; thus, the maximum PP is 0.86 dB according to Eq. (5).

Obviously, the LPO-induced PP will cause the deterioration of the demodulation and the detection as well, so the BER will increase when the LPO becomes greater. At a fixed input power of 0.85 mW and a wavelength of 1567 nm, we measure the BER when injecting the SOA with a current from 86 to 96 mA. The result is shown in Fig. 5, where we can find that the BER decreases first and then goes up as the current increases, which agrees well with above analysis. However, because the gain of the SOA also increases as the current goes up, this will compensate for the PP caused by LPO, thus making the BER curve relatively flat.

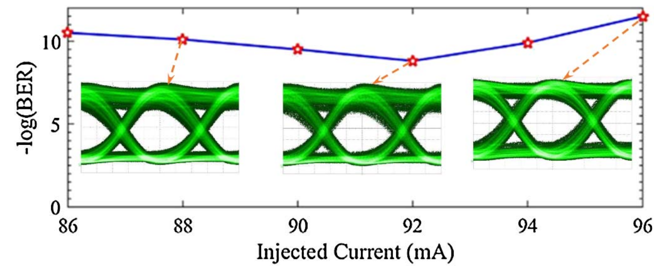

Fig. 5. BER measurement result with respect to injected current in the SOA.

In conclusion, based on the MM method, we demonstrate experimentally that the polarization orthogonality will be trimmed down or lost when signals pass through an SOA, while its LPO is non-linearly dominated by the PDG existing in the SOA. For easy measurements, the PDG and LPO are derived from the MM, and a boundary is given to the LPO for an SOA with any PDG. Our results are satisfied with the MM-based measurements, where we find that the LPO will break through the boundary a little as the injected currents approach the threshold. We further achieve an empirical formula that shows that the PP will increase as the LPO rises up, and we demonstrate it in DPolSK transmission by BER measurements. Our conclusions are valuable to polarization-related communications, such as PolDM, PolSK, and even orbital angular momentum multiplexing. They are applicable to non-orthogonal polarization cases as well.

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