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Novel PDL/PDG compensator for transmission optical devices using Sagnac interferometer

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Abstract: We describe a novel scheme for complete suppression of polarization-dependent loss/gain (PDL, PDG) for transmission-type optical devices (LPG, SOA) via a $\lambda/2$ -shifted all-fiber Sagnac loop interferometer. The results are explained theoretically and demonstrated experimentally.

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1. Introduction

Intrinsic and fabrication-induced polarization-dependent loss (PDL) and polarization-dependent gain (PDG) in optical components have been recognized as a major source of transmission impairment in optical fiber communications, sensors, and biomedical diagnostics [1,2]. A simple way to compensate for these effects does not exist and polarization diversity or polarization scrambling scheme is typically the only viable solutions [3]. In this paper, a novel PDL/PDG compensation scheme is demonstrated for bi-directional transmission-type optical components exhibiting either PDL or PDG, by inserting them inside an all-fiber Sagnac loop interferometer. The elimination of polarization-dependency is first theoretically explained with a Jones matrix analysis. This is followed by experimental verification of this compensation method using a broadband linear polarizer (LP), a semiconductor optical amplifier (SOA) and a narrowband fiber acousto-optic tunable filter (AOTF). Since the all-fiber Sagnac interferometer can be easily constructed and wholly integrated into all-fiber devices, the new method alleviates a major hindrance for a number of fiber-optic devices.

2. Theory of polarization compensation

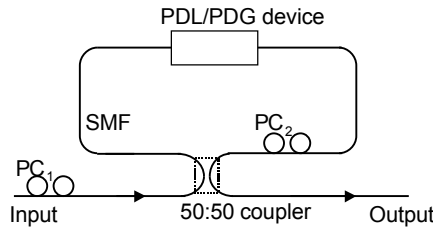


Fig. 1. The schematic diagram of the PDL/PDG compensator based on an all-fiber Sagnac interferometer and consists of a 50:50 power coupler and a polarization controller.

The schematic diagram for the PDL/PDG compensator for transmission-type device is shown in **Fig. 1**, where the PDL/PDG element is inserted inside a Sagnac interferometer loop that comprises of a 50:50 coupler and a polarization controller (PC_2) all connected by a section of single-mode fiber (SMF). The all-fiber Sagnac interferometer can be easily constructed from off-the-shelf components and unlike other fiber-based interferometers; it has low temperature sensitivity since the two interfering paths always have equal length [4]. Following an analysis procedure outlined in Ref. 5, but including the presence a PDL/PDG element with Jones matrix $[J_p] = \begin{bmatrix} a(l) & 0 \\ 0 & b(l) \end{bmatrix}$, where $a(l)$ and $b(l)$ are transmission factors (< 1 for loss and > 1 for gain) for x and y-polarized electric fields at l , respectively, the transmission matrix at the output port $[T(l)]$ for this loop configuration can be expressed as:

$$\begin{aligned}
 [T(l)] &= [K_{//}][R][J_{PC}][J_P][J_{SMF}][K_{//}] + [K_X][J_{SMF}]^T [J_P]^T [J_{PC}]^T [R][K_X] \\
 &= j \frac{1}{2} (a(l) + b(l)) \sin \frac{\Gamma(l)}{2} \sin 2\alpha \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \quad (1)
 \end{aligned}$$

where $[J_{SMF}] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and $[J_{PC}] = \begin{bmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{bmatrix} \begin{bmatrix} e^{i\Gamma(l)/2} & 0 \\ 0 & e^{-i\Gamma(l)/2} \end{bmatrix} \begin{bmatrix} \cos q & \sin q \\ -\sin q & \cos q \end{bmatrix}$ are Jones matrices of single mode fiber (SMF) and the PC inside the Sagnac loop, respectively, $[R] = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$ is a coordinate conversion matrix for the folded loop, $[K_{//}] = \begin{bmatrix} \sqrt{0.5} & 0 \\ 0 & \sqrt{0.5} \end{bmatrix}$ and $[K_{\times}] = \begin{bmatrix} j\sqrt{0.5} & 0 \\ 0 & j\sqrt{0.5} \end{bmatrix}$ are the parallel and cross-coupling matrices, respectively for the 50:50 power coupler. Here, $\Gamma(l)$ and q are the retardance and the orientation of the PC. For an input field, $E_m = [E_x \ E_y e^{j\beta}]^T$, where E_x and E_y are the electric field amplitudes in x and y directions respectively, and j is the phase delay between them, the transmitted intensity at the output port can be expressed as:

$$I_{trans}(l) = \frac{1}{4} (a(l) + b(l))^2 \sin^2 \frac{\Gamma(l)}{2} \sin^2 2q (|E_x|^2 + |E_y|^2), \quad (2)$$

which is clearly polarization-independent. At $q = \pi/4$, the transmittance is equal to $(a(l) + b(l))^2/4$ modulated by $\sin^2(\Gamma(l)/2)$. The transmittance is maximum when $\Gamma(l) \approx \pi$, that is, when the PC acts as a half-wave ($l/2$) plate at the wavelength band of interest. For an ideal linear polarizer where $a(l) = 0$ and $b(l) = 1$, a maximum polarization-independent transmittance of 25% (-6 dB) can be expected. When the transmittance reaches its maximum value, the corresponding reflectance is zero. The general expression for reflectance can be worked out similarly. Unlike the transmitted light, the intensity of the reflected light is polarization-dependent. Finally, it should be noted that the compensator works only when the back reflection from the PDL/PDG element is low so as not to cause residual Michelson interferometer like action.

3. Suppression of PDL and PDG in linear polarizer and SOA

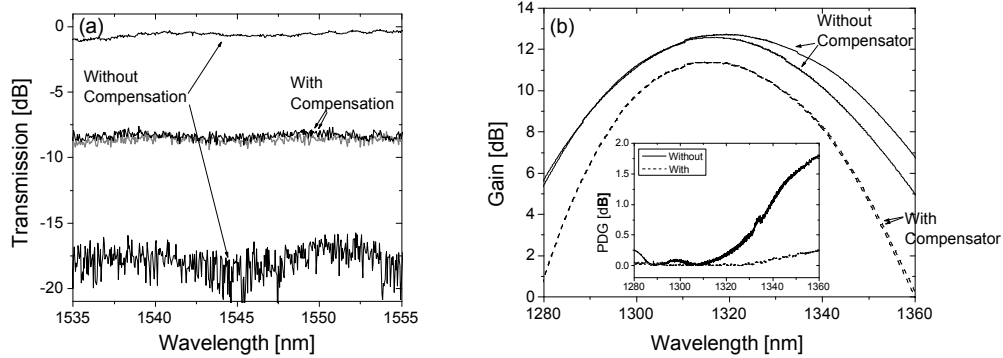


Fig. 2. (a) Transmission spectra of the linear polarizer (LP) for two extreme input SOPs with and without PDL compensation; (b) Gain spectra of the semiconductor optical amplifier (SOA) for two extreme input SOPs with and without PDG compensation. The drastic reduction of PDG in each case is also shown in the inset of the figure.

To test the PDL/PDG compensator, we first examined the polarization dependency of a passive broadband linear polarizer (LP) and an active semiconductor optical amplifier (SOA) by placing them inside (e.g. with compensation) and outside (e.g. without compensation) the Sagnac interferometer. The PDL effect is measured using a polarized broadband source and the transmission spectra are recorded using an optical spectrum analyzer. When the LP is placed outside the Sagnac loop, the transmission spectra show a large polarization extinction ratio of 20 dB over a wavelength range between 1535 and 1555 nm, see **Fig. 2 (a)**. However, when the LP is inserted inside the Sagnac loop, as shown in **Fig. 1**, the transmission spectra become polarization-independent irrespective of the settings of PC₂. **Fig. 2 (a)** shows the transmission spectra at maximum transmittance when input state of polarizations (SOPs) are varied. At this condition, the insertion loss is about 7.5 dB (with polarization-dependent ripple of <0.5 dB), of which 6 dB (25% transmission) is attributed to the intrinsic transmittance of the Sagnac interferometer and 1.5 dB is associated with insertion loss of the same interferometer. A return loss > 20 dB is measured.

We used the same configuration and procedure to investigate the PDG compensation in a SOA. The solid lines in **Fig. 2 (b)** correspond to the gain spectra at two extreme input SOPs that yield the largest PDG when the SOA is biased at a current of 200 mA. The gain spectra become nearly polarization-independent when the SOA is inserted inside the Sagnac interferometer as shown in the dashed lines in **Fig. 2 (b)**. In **Fig. 2 (b)**, the PC is adjusted (i.e. acting as a $\lambda/2$ plate) to achieve maximum gain near 1315 nm. The gain penalty of ~1.5 dB near 1315 nm is attributed to the insertion loss of the Sagnac interferometer itself. This penalty can in principle be reduced by

optimizing all components used to construct the PDL/PDG compensator. The higher gain penalty that appears at both ends of the gain spectra is caused by the fact that PC_2 can no longer be maintained as a $1/2$ plate at these wavelengths [4]. The corresponding PDG spectra for each configuration based on the gain spectra of **Fig. 2 (b)** are also shown in the inset of the same figure. The near elimination of the PDG (from 1.7 dB to 0.2 dB at 1360 nm) of the SOA using the Sagnac interferometer is clearly evident. The residual PDG is likely caused by the polarization dependency of the polarized broadband light source itself.

4. Suppression of polarization mode splitting in acoustic flexural-wave induced LPG

Next, we test the polarization compensation scheme on a narrowband transmission-filter device, namely a long-period fiber grating (LPG). While conventional UV-inscribed LPGs have low PDL [6], a CO_2 laser / micro-bending induced LPGs and a flexural wave induced fiber-AOTFs are intrinsically polarization-dependent since the mode coupling in these devices involves a symmetrical core mode and an asymmetrical cladding modes [6,7]. The combination of this polarization-dependent mode coupling and narrow coupling bandwidth lead to a polarization splitting of the filtering (loss) spectra in these filters. We used 28 cm long dispersion compensating fiber (OFS EHS100) since this type of fiber shows a large polarization-dependent mode splitting [8]. **Fig. 3 (a)** shows the filtering spectra for five different input SOPs. Spectrally resolved and polarization-dependent coupling to each of the cladding TE_{01} , TM_{01} , and HE_{21} modes are clearly observed. The polarization-dependent mode splitting is completely eliminated when the fiber-AOTF is placed inside the Sagnac interferometer as shown in **Fig. 3 (b)**.

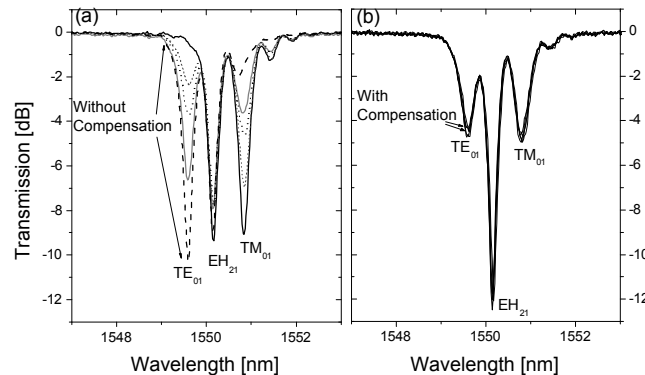


Fig. 3. Loss spectra of the fiber AOTF for five different input SOPs (a) without and (b) with PDL compensation. A dispersion compensating fiber (OFS EHS 100) with a length of 28 cm is used in this experiment.

5. Conclusion

In summary, we analyze the transmission characteristics of a Sagnac loop interferometer containing a PDL/PDG element and a PC using Jones matrices. We show that polarization independence in the transmission mode can be achieved in such a configuration and maximum transmittance occurs when the PC is adjusted to function as a half wave ($1/2$) plate. The result is verified experimentally for a linear polarizer, semiconductor optical amplifier, and a narrowband flexural-wave induced fiber AOTF. This new method provides a powerful means to alleviate PDL/PDG impairment for transmission-type devices irrespective of the origin of their polarization dependencies.

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