Polarization-insensitive multi-wavelength switching based on polarization-selective long-period fiber gratings

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Abstract: Novel multi-wavelength switching filters based on cascaded long-period fiber gratings and polarization-maintaining fiber in a Sagnac loop configuration are proposed and experimentally demonstrated. The rapid wavelength switching is achieved by an electro-optic polarization controller. The device is independent of the polarization state of the input light due to the bi-directional polarization compensation of the Sagnac loop interferometer although the polarization state of the optical wave filter is rapidly switched by the electro-optic modulator in the loop. The proposed device can be useful for applications to all-channel gating and odd/even-channel switching devices with fine channel selectivity and high-speed response.

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OCIS codes: (120.5790) Sagnac effect, (060.1810) Couplers, switches, and multiplexers, (230.5440) Polarization-sensitive devices

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1. Introduction

Multi-wavelength-selective devices have become key components of various wavelength-division-multiplexed (WDM) communications, wavelength-domain biomedical imaging systems, and sensor applications [1-3]. Wavelength-selection by polarization-tuning is especially attractive in fiber interferometer filters due to fast tuning speed and all-fiber construction, compared to conventional tuning methods such as temperature [4], acousto-optic coupling [5] and mechanical strain [6]. So far various polarization-tunable all-fiber interferometers, such as Mach-Zehnder interferometers using cascaded long-period fiber gratings (LPFGs) [7] and Sagnac interferometers based on a polarization maintaining fiber (PMF) loop and 2×2 fiber coupler [8], have been independently developed for multi-wavelength filtering applications.

With cascaded LPFGs filters, a polarization-tunable multi-channel spectrum can be achieved when an elliptic erbium doped fiber (EDF) is inserted into the middle of two LPFGs [7]. The filter transmission spectrum has high spectral polarization sensitivity due to the birefringence of the EDF. The input light polarization state is used to modulate the transmission spectrum of the filter [7]. In contrast, the PMF Sagnac loop filter transmission spectrum is independent of the input light polarization state, and is instead modulated by the polarization state in the loop. The spacing and shape of multi-wavelength channels have been controlled in a limited fashion by the relative polarization states between multiple PMF sections [8].

In this paper, a multi-wavelength electro-optically switched filter that takes notable characteristics of both the cascaded LPFGs and PMF Sagnac loop is experimentally presented. Different functionality can be achieved by changing the intermediate medium between cascaded LPFGs in the Sagnac loop, such as PMF or single mode fiber (SMF). The proposed device has combined advantages like input-polarization insensitivity, rapid response time and fine channel selectivity.

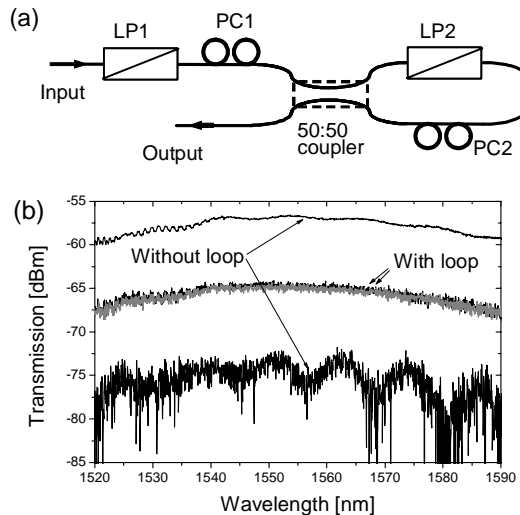## 2. Polarization-insensitive configuration

Fig. 1. (a) Schematic setup of a pair of LPs. A 50:50 coupler (enclosed by the dashed line) can be added to form a loop. (LP: Linear polarizer, PC: polarization controller) (b) For each configuration of without loop and with loop, maximum and minimum transmission spectra are shown for orthogonal input polarization states.

Before investigating the proposed configuration, the polarization independency of a general in-line fiber device within a Sagnac loop is experimentally examined by using a pair

of fiber linear polarizers (LP) since it is well known that a Sagnac interferometer is insensitive to the input polarization [9]. As shown in Fig. 1(a), two LPs (LP1 and LP2) and an all-fiber polarization controller (PC1) are connected in series (i.e., without forming a loop) after an unpolarized broadband light source. As the polarization state of PC1 between the two LPs is changed, the output transmission is varied by 20 dB for various angle positions of PC1 (Fig. 1(b)). However, when a 50:50 fiber coupler is inserted, as shown in Fig. 1(a) with dashed line, to form a fiber Sagnac loop configuration including the LP2, the output transmission becomes independent of the input-polarization states. The angle position of PC1 controls the state of polarized-input light into the Sagnac loop, but it does not affect the transmission spectrum, as shown in Fig. 1(b). It can be understood with the explanation that the two counter propagating beams, of clockwise and counter-clockwise directions in the loop, can compensate the polarization dependency of LP2 [9]. Therefore, when other in-line fiber devices, such as LPFG and PMF, are placed within the Sagnac loop, their transmission properties will not be affected by the polarization state of input light. Transmission of the Sagnac loop device only depends on the polarization state of PC2, which is placed in the loop [3].

In Fig. 2, the proposed Sagnac loop filter configuration is composed of cascaded LPFGs, two kinds of fibers ($L1$ and $L2$), all-fiber polarization controller (PC), a lithium-niobate electro-optic polarization controller (EOPC) and a polarization-independent 50:50 2×2 fiber coupler [8]. A birefringence modulating signal of 0~11 V can be used to change the phase of π for high-speed channel switching applications using the EOPC. The $L1$ fiber is located between two LPFGs, and the $L2$ fiber is placed elsewhere in the loop. Depending on the combination of 'PMF $L1$ and SMF $L2$' or 'SMF $L1$ and PMF $L2$' in the Sagnac loop, light at selected multi-wavelengths can be switched by an electro-optic birefringence modulation signal.
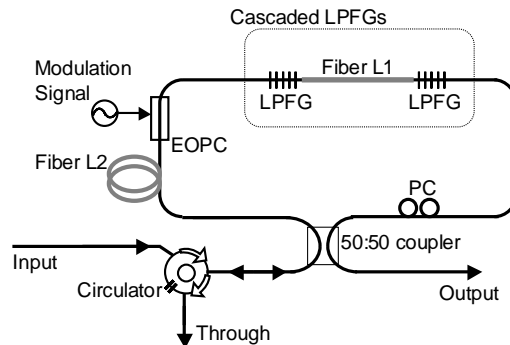

Fig. 2. Schematic setup of proposed experimental configuration. The cascaded LPFGs filter setup, in the dash line, is placed along the fiber Sagnac loop filter setup, out of the dash line. (LPFG: long-period fiber grating, EOPC: Electo-optic polarization controller, PC: polarization controller).

3. PMF L1 and SMF L2

The multi-channel spectrum of the cascaded LPFGs filter has been controlled by the enhanced birefringence fiber between two gratings, which induces a phase difference to modulate the transmission spectrum [7]. However, since spectral tuning is performed by the polarization state of the input signal, it is necessary to insert LP and PC elements at the front stage of the filter device. The dependency on the input-polarization state of such a device is not suitable for in-line wavelength-switching applications. Thus, using a similar configuration to Fig. 1(a), a Sagnac loop configuration is now applied to this polarization-dependent fiber device to make the multi-channel spectrum independent of the input-polarization state. Instead of spectral tuning by the polarized-input light [7], the electro-optic signal from the EOPC replaces the control function for multi-channel spectral tuning.
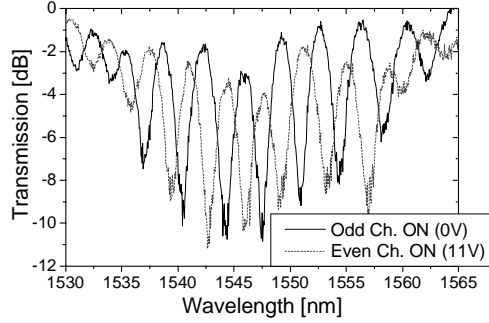
Fig. 3. Odd/Even-channel switching spectra at the output port of a Sagnac loop with cascaded LPFGs with a L1 = 0.14 m PMF.

Cascaded LPFGs separated by a 0.14 m PMF are placed in the Sagnac loop configuration shown in Fig. 2. The two LPFGs are fabricated on the photosensitive fiber with a KrF excimer laser and amplitude mask. The fabrication parameters are pulse energy of 180 mJ/pulse, grating period of 500 µm, and grating length of 2.0 cm. The channel spacing, $\Delta\lambda_{LPFGs}$, of the sinusoidal interference loss spectrum corresponds to the effective index difference between the fiber core and cladding modes, Δn_{cc}, and the separation length of fiber, L_1, of adjacent gratings, and the operating wavelength, λ, as shown in Eq (1) [4].

$$\Delta\lambda_{LPFGs} \approx \frac{\lambda^2}{\Delta n_{cc} \cdot L_1} \tag{1}$$

Figure 3 shows that the dips and peaks of spectral channels with a 3.6 nm period are switched by applying 11 V on the EOPC, which induces a π phase difference between the two orthogonal polarized states in the PMF [8]. Due to the polarization-insensitivity of Sagnac loop configuration, the multi-channel spectrum is independent of the polarization variation of input-light. High-speed odd/even channel switching is performed using the fast lithium-niobate birefringence modulator EOPC, which has a fast response time (less than 100 ns) [8]. An all-fiber PC inside the loop is manually positioned to optimize the transmission spectrum of the Sagnac loop interferometer. The non-uniform transmission and insertion loss result from the splicing loss between PMF and SMF and spectral inequality between two LPFGs [7]. When the excessive birefringence value is included in the loop, an uneven transmittance spectrum can be induced due to the wavelength-dependent phase difference in the short beat-length of fiber in the loop [8]. For the SMF, a low birefringence value of $\sim 1\times 10^{-7}$ is chosen for the short length of fiber $L2$. The birefringence of PMF $L1$ is selected with an optimum value of $\sim 2\times 10^{-5}$. The index difference between core and cladding of PMF $L1$ is known as 0.0047. Based on the low back-reflection loss of LPFGs, attenuator operation for the high-power optical signal (~ 1 W order continuous wave) is also available using the proposed devices when the phase modulation is performed by an all-fiber piezo-electric PC [1] instead of the lithium-niobate PC.

4. SMF L1 and PMF L2

Alternatively, when the low-birefringence SMF is placed between the cascaded LPFGs, its sinusoidal loss spectrum is almost independent of the polarization states in the loop [10]. Figure 4(a) shows that the loss peak wavelengths of cascaded LPFGs with a SMF (L1 of 0.34m length) are insensitive to the applied voltage of the EOPC. Thus, it is suitable to select the multi-channels of a sinusoidal spectrum due to the PMF $L2$ in the Sagnac loop, which is linearly controlled by the polarization states of the EOPC as shown in Figs. 4(b) and (c) [8].
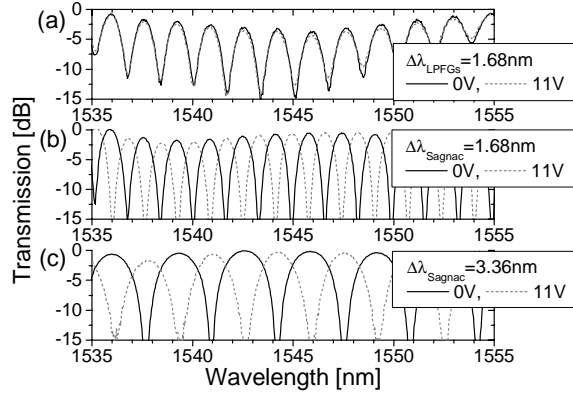
Fig. 4. Each transmission spectrum before combining together, at the applied voltages of 0 and 11 V, is measured for (a) cascaded LPFGs filter with a 0.34 m SMF only, (b) fiber Sagnac loop filters with a 3.8 m PMF only, and (c) fiber Sagnac loop filters with a 1.9 m PMF only.

The channel spacing, $\Delta\lambda_{Sagnac}$, of this PMF Sagnac loop filter is related to the birefringence, Δn_{eo}, and the effective length, L_2, of the PMF in the Sagnac loop, which can be written as Eq. (2) [8].

$$\Delta\lambda_{Sagnac} \approx \frac{\lambda^2}{\Delta n_{eo} \cdot L_2}$$

(2)

While the periodic maximum-peak wavelengths in the output port of the PMF Sagnac loop filter possess the same periodic minimum-dips as the through port [1], the periodic loss dips of the cascaded LPFGs have the same spectrum in both output and through ports of the Sagnac loop configuration. Figure 5 shows the combination of these two unique characteristics for all-channel gating and odd/even-channel switching applications. For $L1$ of SMF (length L_1 of 0.34 m and effective index difference Δn_{cc} of 0.0042) and $L2$ of PMF (length L_2 of 3.8 m and birefringence Δn_{eo} of 0.00038), both $\Delta\lambda_{Sagnac}$ and $\Delta\lambda_{LPFGs}$, are 1.68 nm as shown with Eq. (1) and (2), respectively. The transmission spectra of Figs. 4(a) and (b) become the spectral superposition of the both identical sinusoidal transmission spectra at the output port, as shown in Fig. 5(a). To overlap the two peak wavelengths of Fig. 4(a) and (b) perfectly at the input voltage 0 V, an initial adjustment of the manual PC in the Sagnac loop is required to shift the peak wavelength of Fig. 4(b). The transmission spectra through Sagnac interferometer are still insensitive to the variation of polarized-input light. Thus, by switching input voltage between 0 V to 11 V across the EOPC, the multi-channel band pass spectrum rapidly switches between the two gating states of all-ON / all-OFF, respectively. This results in more than a 20 dB center transmission difference at the output port. At the same time, the inverse gating states of the output-port are measured in the reflection spectrum at the through port, respectively.

When the length of $L2$ PMF is decreased to 1.9 m, the $\Delta\lambda_{Sagnac}$ (3.36 nm spacing) can be shifted by applied voltages, as shown in Fig. 4(c), such that the odd or even channels of the fixed $\Delta\lambda_{LPFGs}$ (1.68 nm spacing), as shown in Fig. 4 (a), can be chosen selectively. In Fig. 5(b), all the odd-channels can be switched ON and all the even-channels can be OFF simultaneously to the output port, or vice versa, depending on the switching signal of the EOPC between 0 V and 11 V. The manual PC adjustment is required to set the initial position of the PMF response. The complementary switching states of the output port are also routed at the through port at the same time. Compared with the conventional fiber Sagnac loop filter in Fig. 4(c), high channel selectivity between ON channels, and broad isolation width between

ON and OFF states can be achieved because the OFF channels are suppressed by the periodic loss channels of the cascaded LPFGs spectrum. The finesse and selectivity of multi-channels can be further improved by the precise control of fiber length in the loop.
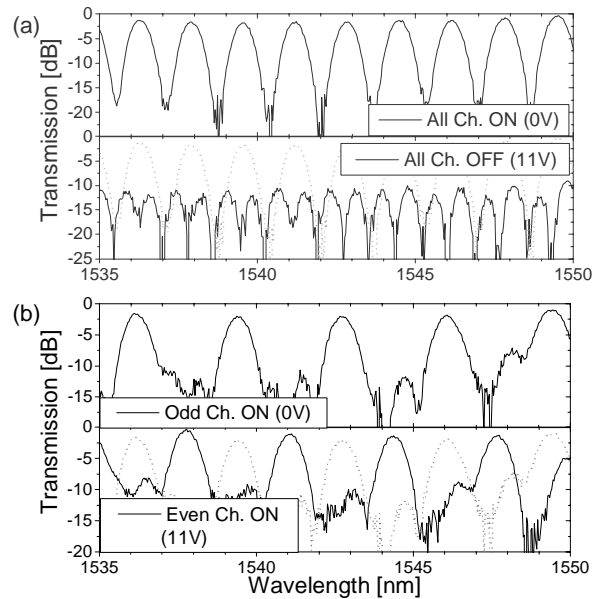

Fig. 5. (a) All-channel gating at the output port of a Sagnac loop when a L1 = 0.34m SMF and a L2 = 3.8 m PMF. (b) Configurable Odd/Even-channel switching at the output port of Sagnac loop when a L1 = 0.34 m SMF and a L2 = 1.9 m PMF. Inverse spectra are shown at the through port at the same time.

5. Conclusion

Polarization-insensitive wavelength-switching devices are successfully demonstrated based on cascaded LPFGs and PMF in a Sagnac loop configuration. The polarization-dependence of the cascaded LPFGs containing a PMF is used to switch between odd and even transmission channels in the Sagnac loop configuration. Alternatively, the polarization-independency of the cascaded LPFGs containing a SMF is used for the fixed periodic loss spectrum in the loop, while the multi-channel spectrum of the PMF Sagnac loop filter is controlled by the polarization state. With high-speed electro-optic modulation, the channel spacing, number and selectivity are easily controlled by varying the effective fiber length. The proposed device can be used for optical cross connects, interleaving routers, multiplexing components and multi-wavelength switching lasers in WDM optical system and biomedical diagnostic imaging systems.

Acknowledgments