Input polarization-independent multi-channel switching using cascaded long-period fiber grating and polarization-maintaining fiber

Chang-Seok Kim*[a], Young-Geun Han[b], Bernard Choi[a], J. Stuart Nelson[a], and Jin U. Kang[c]

[a]Beckman Laser Institute and Medical Clinic, University of California, Irvine, CA, 92612, USA
[b]Photonics Research Center, Korea Institute of Science and Technology, Seoul, 136-791, Korea
[c]Dept. of Electrical and Computer Eng., Johns Hopkins University, Baltimore, MD, 21218, USA
*Tel: 949-824-3754, Fax: 949-824-6969, E-mail: cskim@laser.bli.uci.edu

ABSTRACT

Novel multi-wavelength switching filters based on cascaded long-period fiber grating (LPG) and polarization-maintaining fiber (PMF) in a Sagnac loop configuration are proposed and experimentally demonstrated. While the multi-channel spectrum of PMF Sagnac loop filter is controlled by the polarization state in the loop, the polarization-independence of the LPG filter is used to drop one channel. The polarization-independence of the cascaded LPG filter is also used for the fixed periodic loss spectrum to drop multiple channels in the loop. Although the polarization state of the optical wave filter is switched by the electro-optic modulator in the loop, the device is independent of the polarization state of the input light due to the bi-directional polarization compensation of the Sagnac loop interferometer. This device can be used to achieve all-channel gating and odd/even-channel switching with fine channel selectivity and high speed response.

Keywords: Optical switches, Polarization, Birefringence, Long-period fiber grating, Polarization-maintaining fiber

1. INTRODUCTION

Multi-channel switching devices have received considerable attention in recent years for their applications in wavelength-division-multiplexed (WDM) communications, wavelength-domain biomedical imaging systems, and sensor applications [1-3]. Fiber-based interferometer, such as polarization maintaining fiber (PMF) Sagnac loop filter [4] and long-period fiber gratings (LPGs) filter [5], have been independently developed for multi-wavelength filtering applications. In the PMF Sagnac loop (PSL) filter, the spacing of multi-wavelength channels can be simultaneously controlled by the multiple PMF sections and relative polarization state in the loop although the Sagnac loop is independent of the polarization state of input light [4]. Multi-wavelength channel can be also achieved with cascaded LPGs pair. The spacing is controlled by the length of fiber in the middle of two LPGs [5]. In this research, unique advantages of both cascaded LPGs and PMF Sagnac loop are combined in novel configurations for polarization-independent multi-wavelength channel switching filter. The proposed device has a lot of advantages like the rapid response time and fine channel selectivity.

2. PMF SAGNAC LOOP FILTER

As shown in Fig. 1, the setup of PSL filter is composed of a polarization insensitive 50:50 fiber coupler, a PMF with a length of L_{PMF} and a birefringence of Δn_{eo}, and polarization controller (PC). The wavelength dependent phase difference between the clockwise and counter-clockwise beams in the loop produces a sinusoidal wavelength dependent filter transmission function. The spectral period of sinusoidal attenuation can be varied by changing the $\Delta n_{eo} \cdot L_{PMF}$ product value of PMF. For the precise and fast changing of polarization state in the loop, an $LiNbO_3$-based electro-optic polarization controller (EOPC) introduces an additional phase difference $\Delta\phi(V)$ between the two orthogonally polarized modes in the loop. The transmission function of PSL filter can be also derived using Jones matrixes [4] and can be written as Eq. (1)

Optical Components and Materials II, edited by Shibin Jiang, Michel J. F. Digonnet,
Proceedings of SPIE Vol. 5723 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.589710

$$T(V) = \cos^2\left(\frac{\pi}{\lambda}\Delta n_{eo}L_{PMF} + \frac{\phi(V)}{2}\right) \tag{1}$$

where λ is the operation wavelength and ϕ is the phase retardation between the two orthogonally polarized modes by driving voltage, *V*, applied to EOPC. By linearly inducing 22 V with the EOPC, the overall spectral shift of one channel period wavelength, $\Delta\lambda_{PSL}$, is achieved with small response time of fewer than 100 ns. The wavelength channel spacing, $\Delta\lambda_{PSL}$, of this PSL filter is determined by the birefringence, Δn_{eo}, and the effective length, L_2, of the PMF in the Sagnac loop [4], as given by Eq. (2).

$$\Delta\lambda_{PSL} \approx \frac{\lambda^2}{\Delta n_{eo} \cdot L_{PMF}} \tag{2}$$

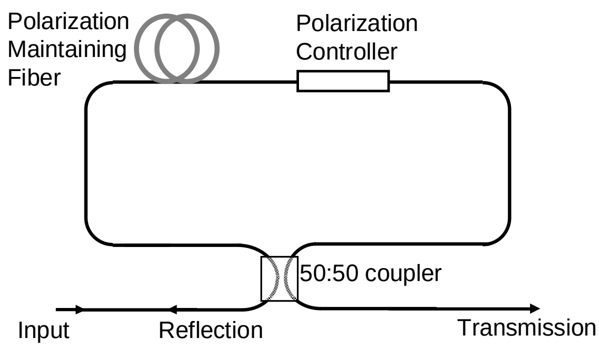

Figure 1: (a) Schematic setup of PMF Sagnac Loop (PSL) filter.

It is well known that a Sagnac interferometer is insensitive to the input polarization state although the optical wave filter is switched by the polarization state in the loop [6]. When a transmission-type device like PMF is combined with 50:50 fiber coupler to form a fiber Sagnac loop configuration, the output transmission becomes independent of the input-polarization states because the two counter propagating beams, of clockwise and counter-clockwise directions in the loop, can compensate the polarization dependency of the device. Transmission of the Sagnac loop only depends on the polarization state in the loop. Therefore, the input-light dependency of other transmission-type device can be easily eliminated when it is placed within a Sagnac loop configuration [7][8].

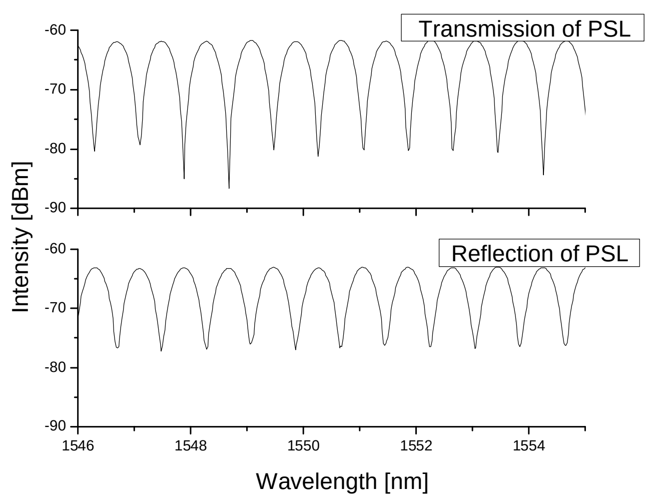

Figure 2: Each transmission and reflection spectrum of PSL filter with the channel spacing, $\Delta\lambda_{PSL}$, of 0.8 nm when L_{PMF} = 7.5m and Δn_{eo} = 0.0004.

As shown Fig. 2, transmission and reflection spectra shows an inverse relation due to the energy conservation. When the reflection beam is guided to the third port using a circulator, the transmission and reflection ports are suitable to generate even- and odd-channels at the same time. Since the transmission spectra of ϕ=0 and π also have inverse spectral relation each other, it can be easily induced that the reflection spectrum at ϕ=0 shows the same multi-channel characteristic with the transmission spectrum at $\phi=\pi$ with applied voltage of 11 V, which can be useful for the simultaneous multi-channel interleaver applications.

3. LONG PERIOD FIBER GRATING FILTER

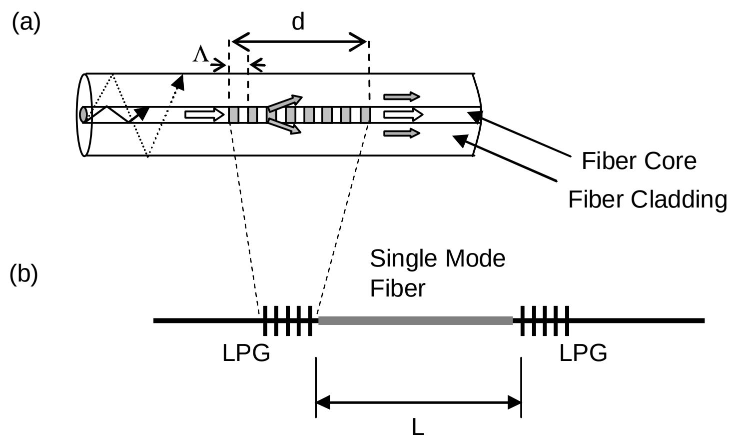

Figure 3: (a) Schematic figure of LPG filter with the grating period of Λ and length of d. (b) Configuration of cascaded LPGs filter with the separating fiber of length L.

Since a LPG, with length of d, couples light from a guided core mode into forward-propagating cladding modes through the phase matching condition due to the periodic index variation of core region, as shown in Fig. 3 (a) [5]. The coupled cladding modes are generally absorbed by the coating or scattered out and the transmission spectrum of the LPFG has a series of stop bands. The refractive index variation with period of Λ is, in general, induced with Excimer or Ar-ion laser exposure on the side of UV-photosensitivity fiber through the phase mask. Alternatively, CO2 laser or acousto-optic vibration is also used to induce the periodic refractive index variation in the fiber core.

The tunable single loss spectrum of Fig. 4 is generated with an acousto-optic modulation by piezo-electric transducer [10]. A traveling acoustic flexural wave induces a resonant coupling between core and cladding modes in a bare fiber. Power coupled to the cladding mode is eventually absorbed in the fiber jacket, inducing a loss filter spectrum. The resonance loss peak is tunable by changing the acoustic frequency. In Fig. 4, the cladding of Truewave fiber was etched to 75 μm in order to increase the acouso-optic coupling efficiency between core and cladding and to increase the corresponding cladding mode spacing over 200 nm. The length of bare fiber was 17.5 cm and frequency was 1557.5 kHz. As increasing the frequency to 1560.6 kHz, the resonance peak shifts with 0.4 nm lower. Owing to asymmetrical index perturbation, filter spectrum exhibits a polarization-dependency of ~0.1 nm in which the peak wavelength shifts with input polarization [10][11]. In measuring the transmission spectrum of LPG filter, we can tried to change the input and out ports for the comparison reason, and found out that the transmission spectrum is bi-directionally identical each other. Thus, it shows the directional-independent loss filtering characteristics when it is located in the Sagnac loop.

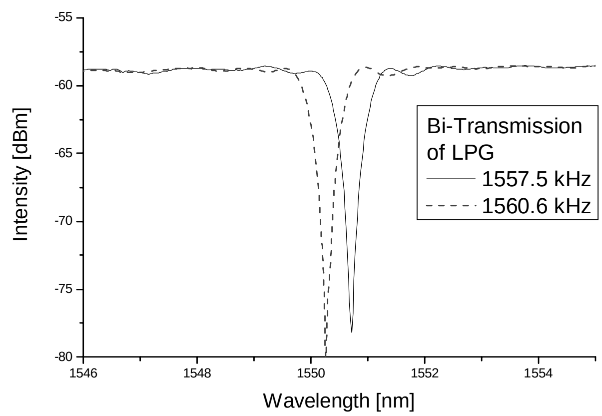

Figure 4: Transmission spectra of single LPG filter by aousto-optic modulations at the frequencies of 1557.5 and 1560.6 kHz.

In order to create multiple loss peaks for application in comb filter, Mach-Zehnder interference peaks are proposed within the profile of a single LPG loss bandwidth by cascading two twin LPGs [9]. The configuration of cascaded LPGs (CLPG) filter is shown in Fig. 3 (b). A part of the core mode intensity is coupled into a cladding mode in the first LPG, and the two core and cladding modes are combined in the second LPG, which results in sharp interference fringes within the profile of a single LPG loss peak. While two LPGs operate as two beam splitters, the two optical paths are the travelling core mode and one of the cladding modes. Since the phase delay between the core mode and propagating cladding modes is induced within the fiber between two cascaded LPGs, the wavelength spacing and the linewidth of the loss peaks can be controlled by the fiber length between LPGs [9].

In the theoretical research of Lee *et al* [10], the analytical expression for the transmission spectrum of CLPG can be presented in a closed form, shown as Eq. (3)

$$T = T_1 + R_1 - 2T_1R_1\cos^2\left(\frac{\pi}{\lambda}\Delta n_{cc}L_{SMF} + Kd + 2\tan^{-1}\left(\frac{\delta\beta}{2s}\tan sd\right)\right) \tag{3}$$

where

Δn_{cc} : effective index difference between the fiber core and cladding modes

L_{SMF} : separation length of SMF between adjacent gratings

K: grating constant given as $K = 2\pi / \Lambda$ where Λ is the grating period,

β_{co} : propagation constant of core mode

β_{cl} : propagation constants of cladding mode

$\delta\beta$: phase mismatch of propagation constants and grating constant given as $\delta\beta = \beta_{co} - \beta_{cl} - K$,

κ: coupling coefficient of a single LPG,

r : cladding mode amplitude after a grating given as $r = \left(\frac{\kappa}{s}\sin sd\right)$,

$R_1 = r_1 \cdot r_1$,

$T_1 = 1 - R_1$,

and $s^2 = \kappa\kappa^* + \left(\frac{\delta\beta}{2}\right)^2$.

Since the overall shape of multi-channel spectrum is determined by each LPG, and the channel spacing of the sinusoidal interference loss spectrum is dominantly governed by the grating-free SMF region between LPGs, we can approximately represent the channel spacing, $\Delta\lambda_{\text{LPFGs}}$, as Eq. (4)

$$\Delta\lambda_{LPFGs} \approx \frac{\lambda^2}{\Delta n_{cc} \cdot L_{SMF}} \qquad (4)$$

Fig 5 shows the spectra of CLPGs separated by a 0.78 m and 0.4 m SMF. Similar with single LPG filter, CLPG also shows identical filtering characteristics when both directions are used for transmission measurement. The polarization dependency of the transmission spectrum is almost negligible for the CLPG with SMF between gratings [8][11].

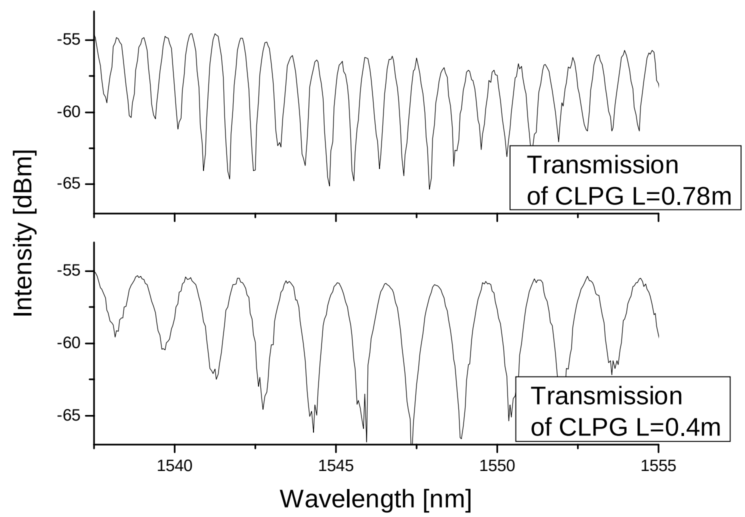

Figure 5: Each transmission and reflection spectrum of CLPG filter with the channel spacing, $\Delta\lambda_{CLPG}$, of 0.8 nm and 1.6 nm when L_{SMF} = 0.78 m and 0.4 m, respectively.

4. COMBINED FILTER

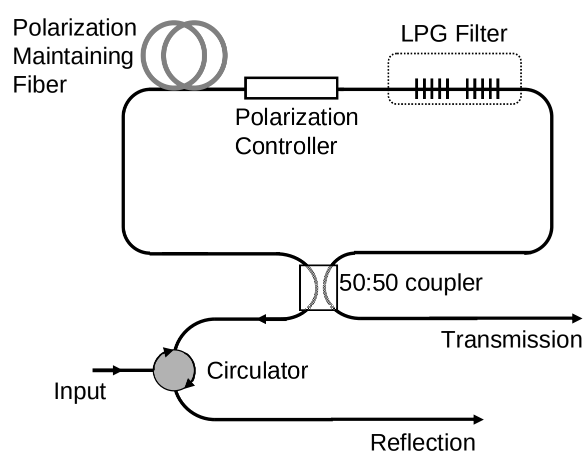

Figure 6: (a) Schematic setup of combined filter of PSL and LPG. Single LPG filter or CLPG filter is located in the dot line box. Reflection port is induced by circulator between input and 50:50 coupler.

While the multi-channel spectrum of PSL filter is controlled by the polarization state in the loop, the polarization-independence of the LPG filter can be used to drop one channel. The PSL channel spacing, $\Delta\lambda_{PSL}$, of 0.8 nm is determined with the length of PMF (L_{PMF} = 7.5m) and birefringence of PMF (Δn_{eo} = 0.0004) as shown in Fig. 2. The wavelength of single loss peak of acousto-optic LPG filter is selected with the applied frequency as shown in Fig. 4. Therefore, Fig. 7 shows the combination of these two unique characteristics. The switching of multiple even- or odd-channels in each port and the selection of drop channel can be precisely performed by two electrical signals into EOPC and LPG, respectively, in the loop. More than 30 dB of channel drop is monitored in the transmission port, but the loss peak does not affect the periodic multi-channel spectrum in the reflection port. The bandwidth of LPG loss peak can be further reduced by controlling the etched fiber diameter of acousto-optic LPG. Due to the polarization-insensitivity of Sagnac loop configuration, the modified multi-channel spectrum of the combined PSL and LPG filter is independent of the polarization variation of input-light.

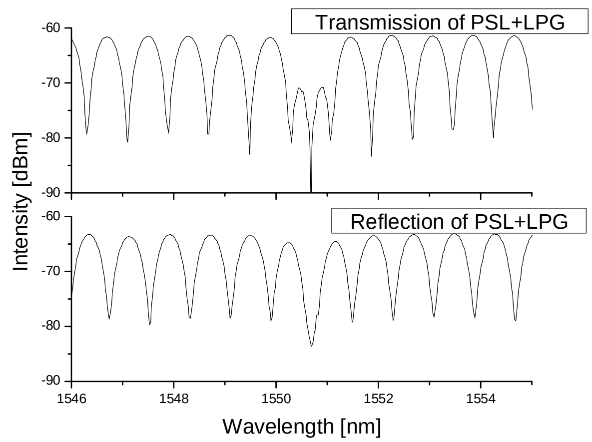

Figure 7: output spectra from transmission and reflection ports of the combined PSL and LPG filter.

The polarization-independence of the cascaded LPG filter is also used for the fixed periodic loss spectrum to drop multiple channels in the loop. When the low-birefringence SMF is located between the cascaded LPFGs, its sinusoidal loss spectrum is almost independent of the polarization states in the loop [11]. Fig. 8 shows that the loss peak wavelengths of CLPG (L_{SMF} of 0.34m) are suitable to select the multi-channels of PSL filter, which is linearly controlled by the polarization states of the EOPC [8]. While the PSL filter has the maximum intensity in the transmission port and minimum intensity in the reflection port for the same wavelength, the loss dips of the CLPG filter have the same spectrum in both transmission and reflection ports of the Sagnac loop configuration.

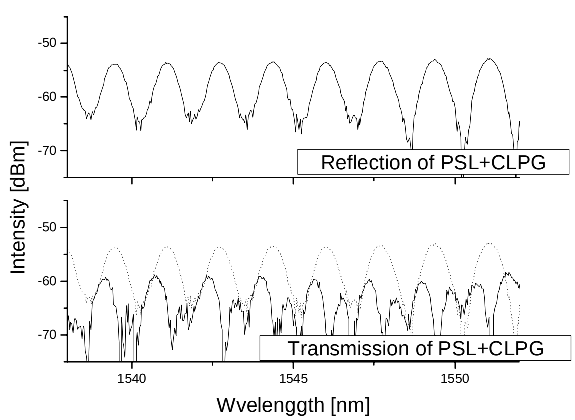

Figure 8: output spectra from transmission and reflection ports of the combined PSL and CLPG filter.

For LPG (length L_{SMF} of 0.34 m and effective index difference Δn_{cc} of 0.0042) and PSL (length L_{PMF} of 3.8 m and birefringence Δn_{eo} of 0.00038), both $\Delta\lambda_{Sagnac}$ and $\Delta\lambda_{LPFGs}$, are 1.68 nm and the transmission and reflection spectra become the superposition of the both identical sinusoidal spectra. Thus, the multi-channel band pass spectrum rapidly switches between the two gating states of all-ON / all-OFF by switching 0 V and 11 V to EOPC, respectively. The transmission spectra through Sagnac loop are still insensitive to the variation of polarized-input light. The finesse and selectivity of multi-channels can be further improved by the precise control of L_{SMF} and L_{PMF} in the loop.

5. CONCLUSION

Input-polarization-independent wavelength-selective switching devices based on cascaded LPG and PMF in a Sagnac loop configuration are proposed and successfully demonstrated. While the multi-channel spectrum of the PSL filter is controlled by the polarization state, the polarization-independency of the LPG filter is used for the fixed periodic loss spectrum in the loop. The channel spacing, number and selectivity are controllable by varying the fiber length in the loop.

Acknowledgement: The authors thank Dr. Qun Li and Prof. H. P. Lee of Dept. of Electrical and Computer Engineering, University of California, Irvine for their grateful helps in LPG experiment. The work was supported in part by the Arnold and Mabel Beckman Fellows Program and NIH grants AR47551, AR48458 and EB002495

REFERENCES

1. R. H. Qu, H. Zhao, Z. J. Fang, E. Marin, and J. P. Meunier, "Configurable wavelength-selective switch based on fiber grating and fiber loop mirror," *IEEE Photon. Technol. Lett.*, **12,** 1343-1345 (2000).
2. S. H. Yun, G. J. Tearney, B. E. Bouma, B. H. Park, and J. F. de Boer, "High-speed spectral-domain optical coherence tomography at 1.3 µm wavelength," *Opt. Express* **11,** 3598-3604 (2003).
3. X. Fang, H. Ji, L. J. Pelz, K. R. Demarest, and C. Allen, "A DC to multigigabit/s polarization-independent modulator based on a Sagnac interferometer," *J. Lightwave Technol.*, **15**, 2166-2171 (1997).
4. C. S. Kim, and J. U. Kang, "Multiwavelength Switching of Raman Fiber Ring Laser Incorporating Composite Polarization-Maintaining Fiber Lyot-Sagnac Filter," *Applied Optics*, **43**, 3151-3157 (2004).
5. Y. G. Han, C. S. Kim, J. U. Kang, U. C. Paek, and Y. Chung, "Multiwavelength Raman Fiber Ring Laser Based on Tunable Cascaded Long-Period Fiber Gratings", *IEEE Photon. Technol. Lett.,* **15,** 383-385 (2003).
6. A. Yu, and A. S. Siddiqui, "Optical modulators using fibre optic Sagnac interferometers," *IEE Proc. Optoelectron,* **141**, 1-7 (1994).
7. Y. W. Lee, J. Jung, and B. Lee, "Polarization-sensitive interference spectrum of long-period fiber grating pair separated by erbium-doped fiber," *IEEE Photon. Technol. Lett.*, **14**, 1312-1314 (2002).
8. C. S. Kim Y. G. Han, J. U. Kang, B. Choi, and J. S. Nelson, "Polarization-insensitive multi-wavelength switching based on polarization-selective long-period fiber gratings," *Opt. Express* **12,** 6082-6087 (2004).
9. X. J. Gu, "Wavelength-division multiplexing isolation fiber filter and light source using cascaded long-period fiber gratings," Optics Lett., 23, 509-510 (1998).
10. Qun Li, Amy A. Au, Chien-Hung Lin, I. V. Tomov, and H. P. Lee, "Performance Characteristics of a WDM Channel Monitor Based on an All-Fiber AOTF with an on-fiber Photodetector", *IEEE Photon. Technol. Lett.*, 15, 718-720 (2003).
11. S. T. Oh, W. T. Han, U. C. Paek, and Y. Chung, "Reduction of birefringence and polarization-dependent loss of long-period fiber gratings fabricated with a KrF excimer laser," *Opt. Express,* **11**, 3087-3092 (2003).