

Optical delay interferometer based on phase shifted fiber Bragg grating with optically controllable phase shifter

Tae-Young Kim¹, Masanori Hanawa², Sun-Jong Kim³, Swook Hann⁴, Yune Hyoun Kim⁵,
Won-Taek Han¹, and Chang-Soo Park¹

¹Department of Information and Communications, Gwangju Institute of Science and Technology, 1, Oryong-dong,
Buk-Gu, Gwangju 500-712 Korea

²University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan

³Research Center COM, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

⁴Strategic Technology Group & Photonics System Laboratory, Korea Photonics Technology Institute, 971-
35, Wolchul-Dong, Buk-Gu, Gwangju 500-460, Korea

⁵Industrial Materials R&D, LG Chem. Ltd., Research Park, 104-1 Moonji, Yuseong, Daejeon 305-380, Korea

csp@gist.ac.kr

Abstract: We propose a novel optical delay interferometer (ODI) with an optically controllable phase shifter. The proposed interferometer is implemented by using a phase shifted fiber Bragg grating and an Yb³⁺/Al³⁺ co-doped optical fiber. The phase of the delayed optical signal is linearly controlled by adjusting the induced pumping power of a laser diode at 976 nm. Polarization dependent loss, polarization dependent center wavelength shift and temperature induced center wavelength shift of the ODI are 0.044 dB, 6 pm, and 9.8 pm/°C, respectively.

©2006 Optical Society of America

OCIS codes: (060.2340) Fiber optics components; (060.2310) Fiber optics; (060.2330) Fiber optics communications; (060.4510) Optical communications.

References and links

1. H. Dong, G. Zhu, Q. Wang, H. Sun, N.K. Dutta, J. Jaques, and A.B. Piccirilli, "Multiwavelength fiber ring laser source based on a delayed interferometer," *IEEE Photon. Technol. Lett.* **17**, 303-305 (2005).
2. D. Stowe and Hsu Tsung-Yuan, "Demodulation of interferometric sensors using a fiber-optic passive quadrature demodulator," *J. Lightwave Technol.*, **1**, 519-523 (1983).
3. E. Swanson, J. Livas, and R. Bondurant, "High sensitivity optically preamplified direct detection DPSK receiver with active delay line stabilization," *IEEE Photon. Technol. Lett.* **6**, 263-265 (1994).
4. M. Hanawa, T. Fujimoto, and K. Nakamura, "Simple clock extraction method from NRZ signals by π -phase shifted fiber Bragg gratings," *OECC 2005, Tech. Dig.* 8D2-5, 820-821, (2005).
5. J. W. Arkwright, P. Elango, T. W. Whitbread, and G. R. Atkins, "Nonlinear phase changes at 1310 nm and 1545 nm observed far from resonance in diode pumped ytterbium doped fiber," *IEEE Photon. Technol. Lett.* **8**, 408-410, (1996).
6. P. Elango, J. W. Arkwright, P. L. Chu, and G. R. Atkins, "Low-power all-optical broad-band switching device using ytterbium-doped fiber," *IEEE Photon. Technol. Lett.* **8**, 1032-1034 (1996).
7. M. J. F. Digonnet, R. W. Sadowski, H. J. Shaw, and R. H. Pantell, "Resonantly enhanced nonlinearity in doped fibers for low-power all-optical switching: A review," *Opt. Fiber Technol.* **3**, 44-64 (1997).
8. Y. H. Kim, N. S. Kim, Y. Chung, U. Paek, and W.-T. Han, "All-optical switching application based on optical nonlinearity of Yb³⁺ doped aluminosilicate glass fiber with a long-period fiber gratings pair," *Opt. Express* **12**, 651-656 (2004).
9. Y. H. Kim, U. Paek, and W.-T. Han, "All-optical 2 × 2 switching with two independent Yb³⁺-doped nonlinear optical fibers with a long-period fiber grating pair," *Appl. Opt.* **44**, 3051-3057 (2005).
10. M. Janos, J. Arkwright, and Z. Brodzeli, "Low power nonlinear response of Yb³⁺-doped optical fiber Bragg gratings," *Electron. Lett.* **33**, 2150-2151 (1997).

11. Y. Lai, W. Zhang, L. Zhang, J. Williams, and I. Bennion, "Optically tunable fiber grating transmission filters," *Opt. Lett.* **28**, 2446-2448 (2003).
12. Y. H. Kim, B. H. Lee, Y. Chung, U. C. Paek, and W.-T. Han, "Resonant optical nonlinearity measurement of $\text{Yb}^{3+}/\text{Al}^{3+}$ codoped optical fibers by use of a long-period fiber grating pair," *Opt. Lett.* **27**, 580-582 (2002).
13. M. K. Davis, M. J. F. Digonnet, and R. H. Pantell, "Thermal effects in doped fibers," *J. Lightwave Technol.* **16**, 1013-1023 (1998).
14. T. Iwashima, A. Inoue, M. Shigematsu, M. Nishimura, and Y. Hattori, "Temperature compensation technique for fibre Bragg gratings using liquid crystalline polymer tubes," *Electron. Lett.* **33**, 417-419 (1997).

1. Introduction

An optical delay interferometer (ODI) has been developed for a variety of applications including a multi-wavelength laser [1], an optical sensor [2], and a demodulator for an optical differential phase-shift keyed signal [3]. In general, the ODI has been realized by an imbalanced Mach-Zehnder interferometer (IMZI) or an asymmetric Michelson interferometer (AMI), in which an interferometric time delay was introduced by changing the lengths of two lightwave paths in two arms of the devices. Performance of the conventional ODI is intrinsically affected by environmental perturbations such as temperature and acoustic interference, thus an additional circuit is needed to compensate them.

In a previous work, a π -phase shifted fiber Bragg grating (π -PSFBG) was used as an ODI with a fixed phase shift of π [4]. The PSFBG, in which a single lightwave path is shared to generate an interferometric delay, has been recognized as an effective configuration to mitigate the environmental perturbations. The amount of the phase shift, however, was fixed in the fabrication process.

In general, a phase controlling function is required in the ODI for the adaptive phase control of the delayed optical signal. This function is usually used to compensate for the center wavelength offset of the incoming optical signal, to make setting the desired initial phase of the ODI easier, or to precisely adjust the phase. Therefore, an optical phase control function is needed for practical application. Moreover, the phase control speed, precise phase controllability, and remote controllability are important factors, hence some methods, to optically control the phase using nonlinearities in special optical fibers, were investigated [5-10].

In this paper, we propose an optically phase-controllable ODI using a PSFBG and an $\text{Yb}^{3+}/\text{Al}^{3+}$ co-doped optical fiber (YDF). The proposed ODI is more tolerable to environmental perturbations owing to a shared interferometric lightwave path. It is also compact, accurate, and cost-effective due to the fiber-based grating technology. It was experimentally demonstrated that the phase of the delayed optical signal through the ODI was linearly controlled by changing the induced optical power from a pump laser diode at 976 nm. We also investigated polarization dependencies and temperature effect of the proposed ODI.

2. Principle of optically controllable optical delay interferometer

The working principle of the proposed PSFBG based ODI is shown in Fig. 1. The PSFBG consists of two sub FBGs and one piece of YDF between the FBGs [11]. Although it has the same configuration as that proposed in Ref. [4], the difference being that the ability to optically change the phase of the delayed optical signal by the YDF introduced between the FBGs.

The two sub FBGs each with length of L_1 are serially placed with a gap of length L_2 including the YDF of length L_3 . The optical signal is sent to the ODI through an optical circulator. Then a part of the incoming optical signal is reflected by the first FBG (FBG1) and another part of the optical signal is reflected by the second FBG (FBG2) with a certain time delay and a phase shift. The output of the device is an interfered optical signal of the above two reflected signals.

There is a time delay of Δt and a phase difference of $\Delta\phi$ between the two reflected optical signals from the two sub FBGs. The delay time, Δt , and the phase difference, $\Delta\phi(\lambda)$, at a wavelength λ are given by the following equations,

$$\Delta t = \frac{2((n_0 + \delta n_1)L_1 + n_3L_3 + n_0(L_2 - L_3))}{c}, \quad (1)$$

$$\Delta\phi(\lambda) = \frac{2\pi((c\Delta t) \bmod \lambda)}{\lambda}$$

$$= \frac{2\pi((2((n_0 + \delta n_1)L_1 + n_3L_3 + n_0(L_2 - L_3))) \bmod \lambda)}{\lambda}$$

where c is the velocity of light in vacuum, n_0 and n_3 are the refractive indices of the optical fiber core and the YDF core, δn_1 is the refractive index change of FBG1, $a \bmod b$ is a remainder of a/b . In both equations, the first and the second terms correspond to the time delay or the phase change, respectively in FBG1 and the YDF.

A desired time delay can be achieved by adjusting the interval between the two sub FBGs, i.e. $L_1 + L_2$. When the initial phase difference of the proposed ODI is to be tuned, the refractive index on the second term in equation (1) can be changed by pumping power.

For a symmetric ODI, in which two interfering optical signals have the same power, the reflectivities of the two sub FBGs should follow equation (2) to allow the reflected optical signal powers from the two sub FBGs to be the same, assuming low reflectivities.

$$R_1 = R_2(1 - R_1)^2, \quad (2)$$

where R_1 and R_2 are the reflectivities of FBG1 and FBG2, respectively.

In the proposed ODI, the YDF of length L_3 is inserted between the two FBGs to implement an optically controllable phase shifter which controls the phase of the delayed optical signal reflected by FBG2. It enables us to precisely set the phase difference between the two reflected lights from the two FBGs. The phase change is the result of both radiative and non-radiative transitions occurring in the absorption band of the YDF, as a pumping light from a laser diode (LD) with center wavelength of near 980 nm is launched into the YDF. The radiative transitions enhance the nonlinear coefficient of the YDF, resulting in the refractive index change in the YDF [12]. This eventually introduces a phase shift for the propagating optical signal. In addition, the non-radiative transitions cause a thermal-induced index change, also introducing the phase shift of the delayed optical signal [13].

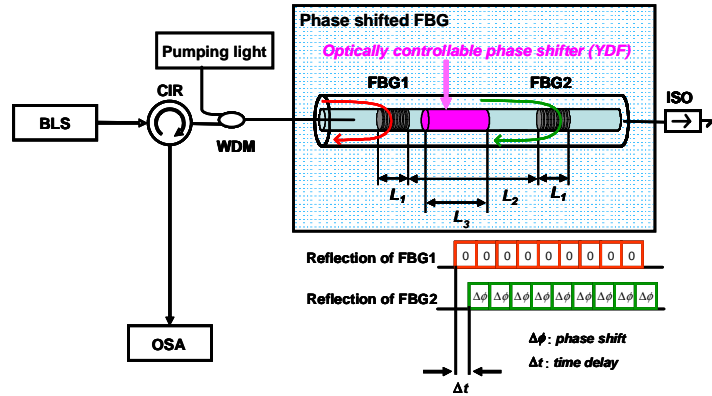


Fig. 1. Working principle and experimental setup. BLS: broadband light source, CIR: optical circulator, WDM: 980/1550-nm wavelength-division multiplexer, Pumping light: 976 nm laser diode, FBG: fiber Bragg grating, YDF: Yb³⁺/Al³⁺ co-doped optical fiber, ISO: optical isolator, OSA: optical spectrum analyzer.

3. Experiments and discussion

Some trial devices were fabricated for the proof-of-principle experiments. A piece of YDF with 7 mm length, i.e. $L_3=7$ mm, was spliced between two photosensitive single-mode fibers (PSFs). The concentration of Yb^{3+} ions and Al^{3+} ions in the used YDF was about 0.82 and 3.02 at% measured by the electron probe microanalysis, respectively. In addition, the absorption coefficient was 2.8 cm^{-1} at 976 nm.

After the splicing, two FBGs were written on the PSF by irradiating a KrF excimer laser beam through a uniform phase mask. Those two FBGs were placed with an interval of almost 10.25 mm so that the time delay, Δt , was to be 100 ps. Therefore the FBG length L_1 and the gap length L_2 were set to be 1 and 9.25 mm, respectively. The index changes of the FBGs were not so strong and with an order of 10^{-4} because the PSFs were used without any hydrogen loading. Their reflectivities were about 0.31 and 0.66, respectively. The ODI inherently has multiple reflections from its cavity structure. And, this cavity effect can be decreased for low reflectivities. To show feasibility as an ODI, we chose reflectivities with low insertion loss. It could be chosen depending on the applications. The used device has multiple reflections of less than -10 dB.

The optical spectrum of the ODI with the 100 ps interferometric delay was measured by an optical spectrum analyzer (OSA) with 0.01-nm resolution. The experimental setup is also shown in Fig.1. Under no pumping light, both measured and theoretically calculated spectra are shown in Fig. 2. The fine interference fringe pattern appeared with 0.08 nm of the free spectral range (FSR) at around 1553 nm, corresponding to the interferometric delay of 100 ps. Both measured and calculated data are in good agreement with each other near the center wavelength.

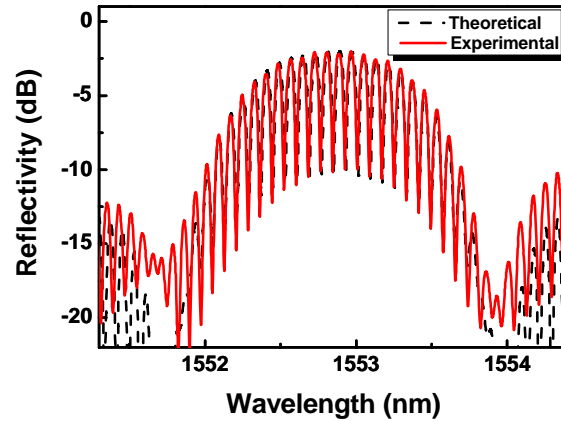


Fig. 2. Theoretically calculated and experimentally measured optical spectra of the ODI.

In our experiments, a pumping light at 976 nm was used to control the phase shift of the proposed ODI. As the pumping power increase, the fringes shift to the longer wavelength preserving the envelope of the fringe pattern determined by the FBG itself. The inset of Fig. 3(a) shows optical spectra of the ODI for pumping power of 0 and 6.9 mW. This is a clear evidence of phase shift of the delayed signal, obviously attributing to the index change in the YDF due to the launched pumping light. The amount of the phase shift, $\Delta\phi$, was calculated by the following equation from the wavelength shift, $\Delta\lambda$, of one narrow peak in the fringe pattern.

$$\Delta\phi = \frac{2\pi}{S} \Delta\lambda, \quad (3)$$

where S is the FSR of the fringe pattern.

The result is shown in Fig. 3(a). The amount of phase shift increased linearly as the pumping power was increased. Moreover, to obtain a phase shift of 2π , only a few milli-watts of pumping power were required. It means that the device proposed can readily be controlled with very low power consumptions. On the other hand, as mentioned previously, the phase shift in the YDF is partly supported by the thermal-induced index change. However, as seen in Fig. 3(b), only the fringe pattern was changed by the thermal-induced index change while the entire spectral envelope of the FBGs was almost unchanged. It reveals that the heat conduction from the YDF to the FBGs is negligible.

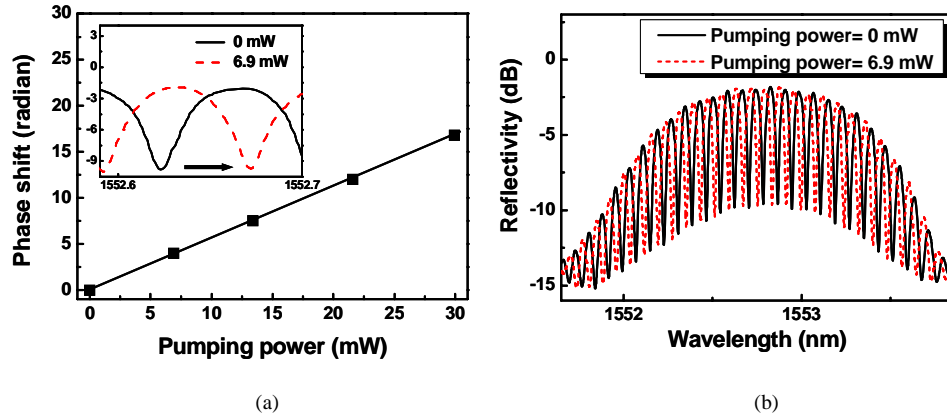


Fig. 3. (a) Pump-induced phase shift of the ODI (inset: enlarged optical spectra for pumping power of 0 and 6.9 mW), (b) measured optical spectra for pumping power of 0 and 6.9 mW.

The polarization dependencies of the ODI, namely polarization dependent loss (PDL) and polarization dependent center wavelength shift (PDCW) were investigated by using a polarization scanning method. Two optical spectra corresponding to both fast and slow axes of the polarization state were measured, as shown in the lower part of Fig. 4, showing that PDL and PDCW were 0.044 dB and 6 pm at the operating wavelength, respectively. The polarization dependencies, originating from an asymmetric inscription on the gratings during fabrication, should be studied further to be lowered.

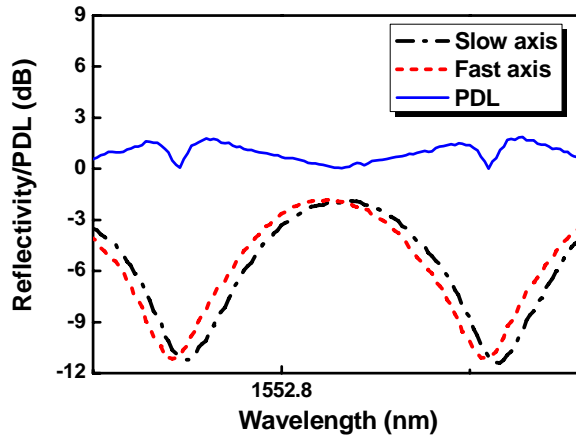


Fig. 4. Measured polarization dependent loss and polarization dependent center wavelength shift.

The temperature effect of the proposed ODI was also investigated by observing its optical reflection spectra. The temperature was controlled from 30 up to 45 °C by using a thermoelectric controller (TEC). As shown in Fig. 5(a), the center wavelength of the ODI was shifted to longer wavelength as the temperature was increased. The sensitivity was ~ 9.8 pm/°C, as shown in the inset of Fig. 5(a), which is well matched with those of the other FBG-based devices (~ 10 pm/°C). Hence, the temperature compensation schemes using a temperature controller or an athermal package [14] should be considered for a practical application.

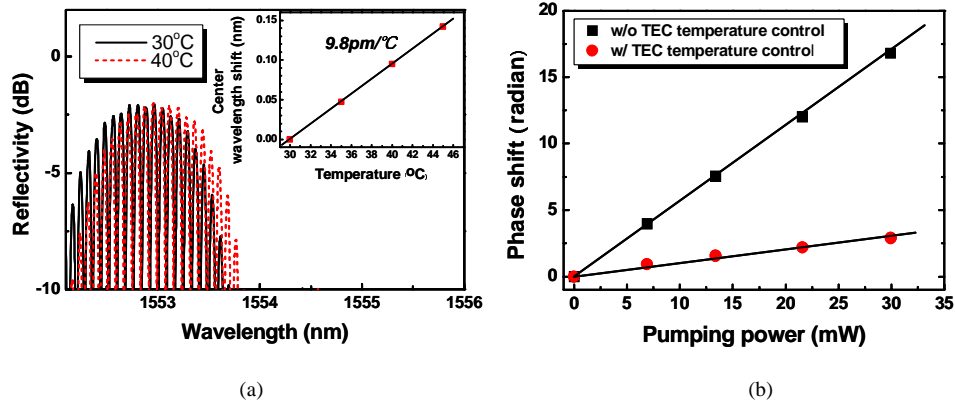


Fig. 5. (a) Measured optical spectra of the ODI to see its temperature effect (inset: center wavelength shift measured as a function of the temperature), (b) compared phase shift efficiency for the ODI with and without the TEC temperature control.

On the other hand, the temperature management using the TEC for the ODI might affect on its phase shift efficiency. As shown in Fig. 5(b), the amount of phase shift was measured for the case of using the TEC. And this was compared with that not using the TEC. When the TEC was used, the gradient of phase shift to the pumping power was ~ 0.1 radian/mW and it was about 5.6 times lower than that (i.e., ~ 0.56 radian/mW) for the case of not using the TEC. It is because the pump-induced thermal effect, namely non-radiative transition in the YDF, was decreased. The reduced phase shift efficiency can be avoided by using the TEC only on the two FBGs, retaining the YDF with a material having low heat conductivity.

4. Conclusion

We have proposed a novel optical delay interferometer based on a phase shifted fiber Bragg grating and an $\text{Yb}^{3+}/\text{Al}^{3+}$ co-doped optical fiber in which the phase of a delayed optical signal can be optically controlled. The phase controllability for the delayed optical signal was experimentally demonstrated, showing that the phase was linearly shifted by controlling the pumping power at around 980 nm. Polarization dependent loss and polarization dependent center wavelength shift were 0.044 dB and 6 pm at the operating wavelength, respectively. It is believed that the proposed optical delay interferometer is not only cost-effective but also promises a stable operation against external perturbations.

Acknowledgments

This work was supported by KOSEF through grant No. R01-2004-000-10846-0 from the Basic Program.