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# Effect of a waist diameter of a polarization-maintaining fiber on ambient index sensitivity

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## ABSTRACT

We investigate the effect of a waist diameter of a polarization-maintaining fiber (PMF) on ambient index sensitivity by configuring a Sagnac loop interferometer. To make the PMF sensitive to external index change, a micro-tapering technique is exploited to fabricate the tapered PMF. The Sagnac loop interfoermeter is fabricated by using the tapered PMF with various waist diameters. The reduction of the PMF diameter results in the enhancement of the ambient index sensitivity of the tapered-PMF-based Sagnac interferometer.
**Keywords:** Refractive index measurement, Sagnac loop interferometer, Tapered polarization-maintaining fiber

## 1. INTRODUCTION

Optical fiber interferometers have been widely investigated due to their wide applications to fiber optic gyroscopes, optical communication system, and fiber sensors [1-3]. Especially, Sagnac loop interferometers have been of great interest for sensing applications because of their many advantages such as easy manufacture, flexibility, immunity to electromagnetic interference, high sensitivity, and great stability. Various sensing techniques based on the Sagnac interferometers have been proposed for measurement of temperature, strain, curvature, and pressure [4-7]. However, the conventional Sagnac interferometers do not have a sensing capability of external refractive index (RI) because the interference in the Sagnac interferometer is generated by using two counter-propagating core modes in the Sagnac loop. In order to measure an external RI, removal of the fiber cladding is required to increase the evanescent field interaction with the surrounding environment. This concept has been recently demonstrated by using the side-polishing or etching process [8, 9]. In both case, fabrication processes are rather complicated as well as the durability for the sensing application is severely degraded. In this paper, a simple RI sensing method based on a Sagnac loop interferometer incorporating a tapered polarization-maintaining fiber (PMF) is proposed and experimentally investigated. To make the Sagnac interferometer sensitive to the external RI, the PMF was tapered by using a micro-tapering technique. The reduction of the waist diameter of the PMF improve the sensitivity of the tapered PMF-based Sagnac interferometer to ambient index change. Various tapered PMFs with different waist diameters of 57 μm, 44 μm, and 36 μm, are fabricated and their transmission characteristics will be measured as the ambient RI is changed.

## 2. EXPERIMENTS AND RESULTS

Figure 1 shows the scheme for the fabrication technique of the tapered PMF by using a micro-tapering method. The micro-tapering method consists of two simultaneous processes. One is a heating process and the other is an elongation process by using a pulling device, all of which are automatically controlled by a computer. For heating process, LPG and $O_2$ gas were used. For elongation process, motorized stage with fiber holder was adopted to pull and elongate the PMF. By controlling gas flow and motorized stage speed, diameter of the PMF can be adjustable. While the PMF was adiabatically tapered, the optical spectrum was monitored by using a white light source, and an optical spectrum analyzer (OSA). The microscopic images of the tapered PMFs with the diameters of 57 μm, 44 μm, and 36 μm are shown in Fig. 2. The total length ($L$) of the PMFs used in the experiment was 185 mm and the tapered lengths ($l$) of the PMFs were kept constant as 20 mm. The tapered length ($l$) is determined by only the elongation length using the motorized stages while the diameter of the tapered PMF is dependent on the distance (Z) of the torch moving left and right along with the PMF. For example, if the moving distance (Z) of the torch is shorter, the

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shorter length of the PMF will be tapered resulting in the thinner tapered diameter of the PMF, and vice versa.

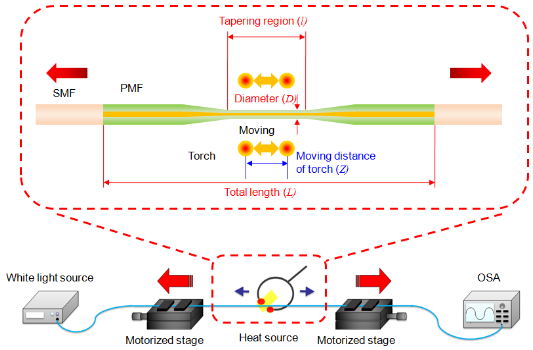


Figure 1. Scheme for the fabrication of a tapered PMF.

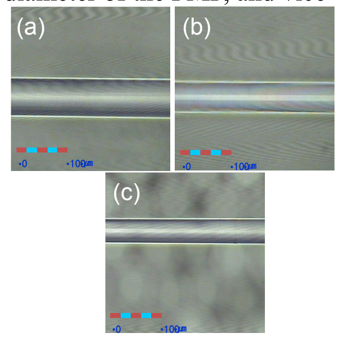


Figure 2. Microscope images of the tapered PMFs with different diameters: (a) 57 μm, (b) 44 μm, and (c) 36 μm.

The experimental setup for the Sagnac loop interferometer based on the tapered PMF is shown in Fig. 3. The Sagnac interferometer consists of a white light source, a 3-dB coupler, a polarization controller (PC), an OSA. After inserting the tapered PMF in the Sagnac interferometer, we measured the transmission spectra corresponding to different waist diameters by using an OSA.

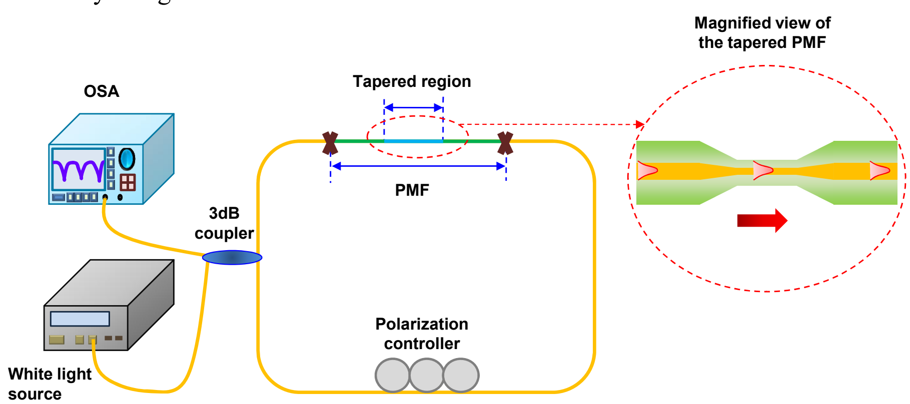


Figure 3. Experimental setup for the Sagnac loop interferometer based on the tapered PMF

When external perturbations, such as temperature, strain, and pressure, are changed, the peak wavelength can be shifted because of the variation of the phase difference. The phase difference ($\Delta\varphi$) between two counter-propagating beams depending on the fiber birefringence can be written as [4]

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n L\,, \tag{1}$$

where $\lambda$, $L$, $\Delta n$ are the phase difference, the wavelength of the input source, the total length of the PMF, and the birefringence of the PMF, respectively. From Eq. (1), the external perturbation-induced wavelength shift can be derived as

$$\frac{\partial\lambda}{\partial\zeta_{ext}} = \frac{\Delta\lambda}{\lambda}L\left[\kappa\frac{\partial(\Delta n)}{\partial\zeta_{ext}}\right], \tag{2}$$

where $\kappa$ is a ratio of the sensitivity of the untapered PMF to that of the tapered PMF and $\zeta_{ext}$ is the external perturbation, such as ambient index. The birefringence ($\Delta n$) of the PMF strongly depends on the tapered diameter, which can be expressed by [11]

$$\Delta n = B_{glass}\left(\frac{r_2 - r_1}{r_2 + r_1}\right)\left(\frac{24}{b^4}\left(r_2 - r_1\right)^4 - 1\right)n_{eff}\,, \tag{3}$$

where $B_{glass}$ is a characteristic constant of a glass. $r_1$, $r_2$, are the inner and the outer radii of the stress applying parts in the PMF. $b$ is the tapered diameter of the PMF. $n_{eff}$ is the effective index of the core of the PMF. The birefringence ($\Delta n$) strongly depends on the diameter of the optical fiber because of the variation of the effective index of the core ($n_{eff}$) [12]. By substituting Eq. (3) into Eq. (2), we obtain

$$\frac{\partial\lambda}{\partial\zeta_{ext}} = \frac{\Delta\lambda}{\lambda}L\cdot\kappa\cdot B_{glass}\left(\frac{r_2 - r_1}{r_2 + r_1}\right)\left(\frac{24}{b^4}\left(r_2 - r_1\right)^4 - 1\right)\frac{\partial n_{eff}}{\partial\zeta_{ext}}\,. \tag{4}$$

In Eq. (4), it is evident that the ambient index sensitivity of the tapered-PMF-based Sagnac interferometer is changed by the diameter of the tapered PMF. Since the large value of the propagation constant □ improves the sensitivity of the tapered fiber to external perturbation change, the tapered fiber with the small diameter is more sensitive to the ambient index change [13].

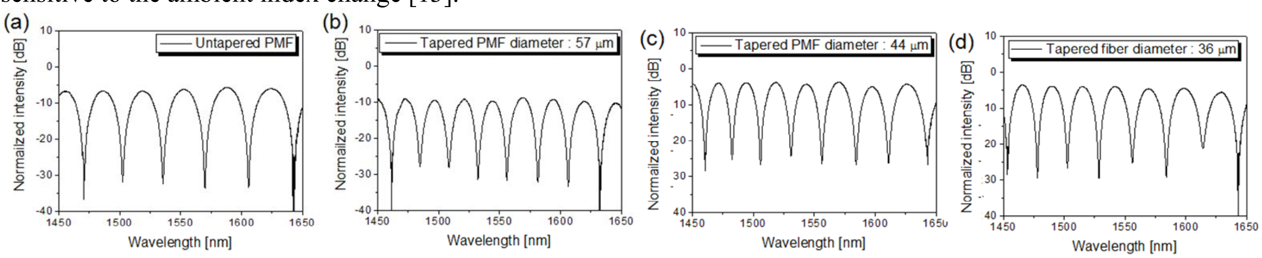


Figure 4. Transmission spectra of the tapered PMF-based Sagnac interferometers with different waist diameters of 125 (a), 57 (b), 44 (c), and 36 μm (d), respectively.

Figure 4 shows transmission spectra of the Sagnac loop interferometer composed of (a) an untapered PMF and the tapered PMFs with different diameter of (b) 57 μm, (c) 44 μm, and (d) 36 μm, respectively. In the Sagnac interferometer, a 3-dB coupler splits the input light equally into the two counter-propagating lights resulting in the interference patterns because of the relative phase difference introduced to the two orthogonal guided modes by the PMF. For the case of the untapered PMF, the wavelength spacing was measured to be 33 nm. For the case of the tapered PMF-based Sagnac interferometer, the wavelength spacing was changed by reducing the waist diameter of the PMF. Since the core mode expansion in the tapered PMF changes its birefringence, the wavelength spacing of the tapered PMF-based Sagnac interferometer can be changed [10]. The wavelength spacings corresponding to different waist diameters of 57-μm, 44 μm, and 36 μm were measured to be 23.8 nm, 25 nm and 25.9 nm respectively.

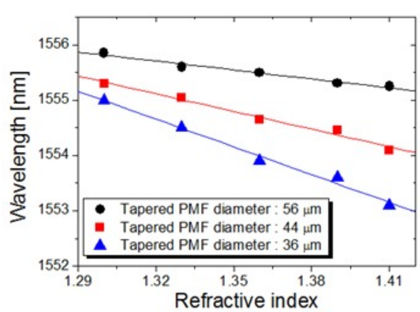


Figure 5. Peak wavelength shifts of the tapered PMF-based Sagnac interferometers with different waist diameters of 57, 44, and 36 μm as a function of ambient RI.

Figure 5(a) depicts the peak wavelength shifts as a function of RI in a RI range from 1.3 to 1.41. Since the field distribution of the core mode in the tapered PMF is expanded to the cladding region, the Sagnac interferometer based on the tapered PMF becomes sensitive to ambient index change. The interference patterns were shifted to shorter wavelengths as the ambient RI was increased. The RI sensitivities of the Sagnac loop interferometer configured by using the tapered PMFs with different waist diameters of 36, 47, and 57 μm were measured to be - 5.59, - 10.65, and - 16.72 nm/RIU, respectively. Experimental results indicate that the RI sensitivity of the proposed Sagnac interferometer can be improved by reducing the waist diameter.

## 3. CONCLUSION

We experimentally investigated a novel RI sensor using Sagnac interferometers based on tapered PMFs with various waist diameters. To make the PMF-based Sagnac interferometer sensitive to RI change, PMFs were tapered by using a micro-tapering method. After fabricating various tapered PMFs with different waist diameters of 36, 44, and 57μm, we measured transmission characteristics of the tapered PMF-based Sagnac interferometers with variations in ambient indices. The reduction of the waist diameter of the PMF made the Sagnac interferometer sensitive to ambient index change. The sensitivities of Sagnac loop interferometers using the tapered PMFs with different waist diameters of 36, 47, and 57μm were measured to be - 5.59, - 10.65, and - 16.72 nm/RIU in the range of RI from 1.3 to 1.41. The proposed Sagnac loop interferometer based on the tapered PMF must be a useful for RI sensing applications with the improved sensitivity.

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