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Fiber Twist-based Wavelength Tunability in Tapered Optical Fiber Filters

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ABSTRACT

This work demonstrates the tunability of tapered single mode fiber (SMF) and tapered polarization maintaining fiber (PMF) filters based on fiber twisting method. One end of the tapered fiber was twisted from 0° until 100° using the Vytran Fiber Processing System. Observation on the spectral output shows that the fiber twisting technique is a viable option to impart tunability in tapered fibers with total shift of 15 and 10 nm, respectively for SMF and PMF. Better tunability is observed in the SMF filter due to its simple physical structure and more straightforward interferometry effect but a significantly higher extinction ratio is observed for the PMF filter. Both filters exhibited region of linear wavelength shift with corresponding R^2 values of 0.9924 and 0.9294 for SMF and PMF. The simplicity and reliability of the filter may pave the way for the development of a practical and compact tunable all-fiber filter for laser systems.

Keywords: Fiber twist, optical filter, tapered fiber, wavelength tunable

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INTRODUCTION

In the past few decades, fiber optics technology has been a major research and development area, especially in the communication field. The ultimate aim in

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optical fiber development is to produce all-fiber devices or components to achieve coupling simplicity, ease of use, and compactness. This effort has led to the production of fiber-based component not only for communication, but also in sensing applications (Alberto et al., 2018; Correia et al., 2018; Pospíšilová et al., 2015).

One of the focus is on the wavelength-selective comb filter, which features operating simplicity and multiple wavelengths selection. A spectral output consisting of periodic resonant frequencies is conceived post-filtering process, whereby the distance between the two neighbouring frequencies is known as the free spectral range (FSR) (Jung et al., 2010). The filter is typically integrated into a laser cavity to create multiple seed signals necessary for the generation of multiwavelength laser (Martinez-Rios et al., 2014; Srivastava et al., 2014). One desired parameter in optical filter is wavelength tunability, which allows variation to the filtered wavelengths based on the intended use. Several fiber-based filters have been proposed with varying success in terms of tunability. One of them is the PMF-based Lyot filter, which unfortunately has limited tunability feature due to its dependence on the physical length difference between the two PMF sections (Fok & Ge, 2017). Tunable double Sagnac loops in a ring erbium-doped fiber (EDF) laser (Wang et al., 2012) is also an alternative wavelength-selective filter but it shows irregular output spectrum attributed to inaccurate refractive index difference of PMFs, inaccurate length of PMFs, and splicing loss. Other than that, polarization independent tunable all-fiber comb filter based on a modified dual-pass MZI can only attain discrete tunability of the spectral spacing (Zhi-Chao et al., 2009).

A simpler alternative proposed in recent times is the tapered optical fibers. Tunability in tapered fibers is acquired through its high sensitivity towards environmental changes such as stress, strain, and temperature (Da Silveira et al., 2015; Ali et al., 2014; Musa et al., 2016). The stretching of the fiber down to tens of micrometres makes it more pliable which enables bending at a much larger angle without physical damage. In Ali et al. (2014), wavelength tunability was achieved simply by varying the bend radius of the tapered region. However, a practical mechatronic mechanism to induce such bend has yet to be developed and the overall size of the device must consider the largest radius of the bend. Additionally, increasing the amount of bending on the taper leads to a higher loss in the system. Application of axial strain to achieve wavelength tunability has been tested on single taper (Kieu & Mansuripur, 2006) as well as cascaded taper (Jaddoa et al., 2016). Both studies demonstrated tuning range that was dependent on the stretching distance accorded by the linear stage thus longer motorized stage will be required for wider tuning range. In Selvas-Aguilar et al. (2014), temperature-based wavelength variation was employed for tapered fiber immersed in glycerol. Careful consideration, however, must be given to the surrounding media as glycerol may degrade at high temperature and could also generate micro-bending in the tapered fiber section.

In general, strain-based tuning is the preferred method as it is more straightforward, and variation of wavelength can be achieved faster compared to temperature-based approach. Nevertheless, device utilizing such technique must consider the range of motion of the strain-inducing mechanism. In this work, tapered fiber-based filter with wavelength tunability based on fiber twist concept is investigated. Stationary rotation stages were employed to twist the fiber-under-test. Two types of fiber; SMF and PMF were tapered, tested, and compared to observe any performance differences. The findings determined that both filters can utilize the proposed method to induce tension-based tunability. This may lead to the development of a practical all-fiber taper filter with precise and compact wavelength tunability mechanism.

MATERIALS AND METHODS

In this work, the proposed fiber twist method was deployed on Corning SMF-28 fiber to elucidate its effect towards basic tapered fiber filter while 30 cm Fujikura Panda-type PMF with corresponding birefringence and attenuation of 4.5×10^{-4} and 0.5 dB/km was included to ascertain any improvement accorded by the more complex birefringence-influenced effect in the fiber. Prior to tapering, the protective coating was removed for both the SMF and PMF. A stripper was used for the SMF while the protective coating of the PMF was removed by dipping the fiber into hydrochloric acid for about 1.5 hours. This was necessary as the the double acrylate coating of the PMF is difficult to remove using a stripper. Then, the fiber was placed onto the fiber holder block (FHB) of Vytran GPX-3400 Optical Glass Processing Workstation for the tapering process. This machine can perform precise fusion splicing and tapering with its filament furnace assembly and precision stages. Its real-time control system allows manipulation of dimensions, uniformity, and reproducibility of the fabricated taper as the pulling speed and heat are kept at a constant value of 1 mm/s and 42 W, respectively. Figure 1 illustrates the geometry of the non-adiabatic tapered optical fiber used throughout the experiment, with parameters of waist diameter, waist length, up-taper length and down-taper length set at 10 μm, 12 mm, 5 mm and 5 mm following previously reported work (Musa et al., 2016).

The tapered fiber was kept on the FHB and both ends of the tapered fiber were spliced to single-mode fiber pigtail. One end was connected to a C+L-band light source while the other end to an optical spectrum analyzer (OSA), as shown in Figure 2(a). One end of the tapered fiber was then twisted by the Vytran FHB, which can rotate up to 120^{o}. In this experiment, Section 1, which was connected to the broadband light source was rotated anticlockwise from 10^{o} up to 100^{o} with a step angle of 10^{o} while Section 2 was fixed as shown in Figure 2(b). In order to observe the correlation between tension and wavelength shift, the spectral output for each step angle rotation was acquired via the OSA while the tension on the fiber was recorded manually based on the readings provided by the Vytran

Tension Monitoring System, which observes linear tension subjected on the FHB relative to its initial condition (Thorlabs, 2015).

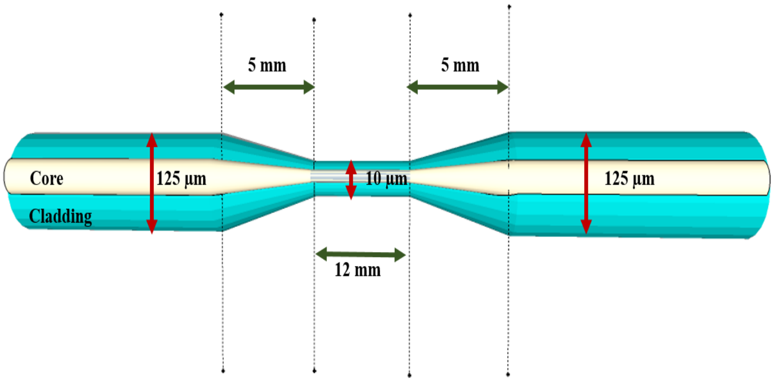


Figure 1. Structure and dimensions of fabricated tapered optical fiber

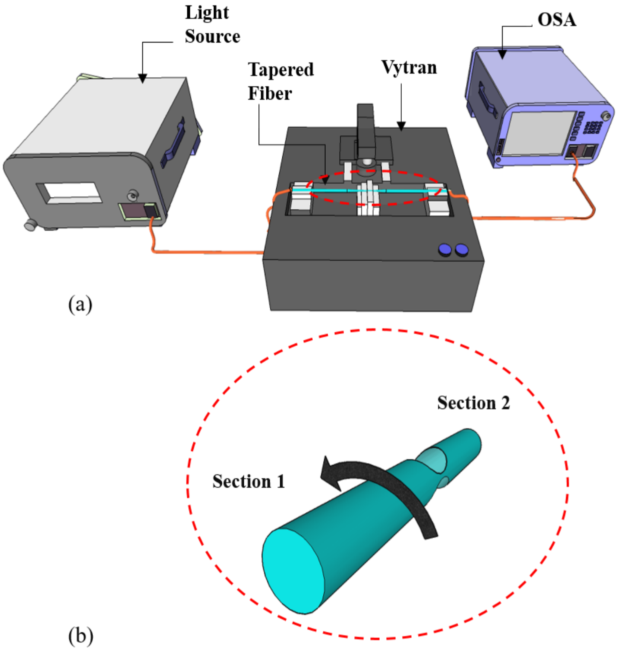


Figure 2. (a) Experimental setup and (b) illustration of fiber twist

RESULTS AND DISCUSSION

During tapering process, the fiber is heated at high temperature and stretched to form the tapered region. When stretched, the core and cladding fuse together, creating a new core and making the surrounding air as the new cladding. As light propagates from the single mode fiber to the down-taper region, the dramatic decrease in core diameter will excite higher order modes that propagate along the tapered region. At the end of the tapered region, the modes recombine, and the phases interfere. A comb-like spectrum is then produced due to the constructive and destructive interference of modes (Jung et al., 2010).

The interference yields periodic fringes as shown in Figure 3, which exhibits the insertion loss of the fabricated taper filters derived from the difference between spectral output with and without taper. The C-band insertion loss for SMF filter and PMF filter recorded average values of 6.2 dB and 7.8 dB, respectively while the free spectral range (FSR) for both filters was about 8 nm. Insertion loss of the PMF filter is higher due to the coupling mismatch between PMF fiber to the SMF pigtail (Jung et al., 2010). The 3-dB linewidths of the SMF and PMF filters are 3.3 nm and 3.9 nm, respectively with corresponding average extinction ratios of 6.5 dB and 18.0 dB, respectively. The significant difference between the extinction ratios can be attributed to the strong birefringence property of PMF and demonstrates the better capability of PMF filters to suppress unwanted signal (Piekarek et al., 2017).

Figure 4 shows the preliminary results of the spectral profile for SMF and PMF filters with twist angles of 40°, 50°, 60° and 70°. The spectra depict gradual shifting to the left or towards the shorter wavelength with larger twist angle. No significant loss of power was

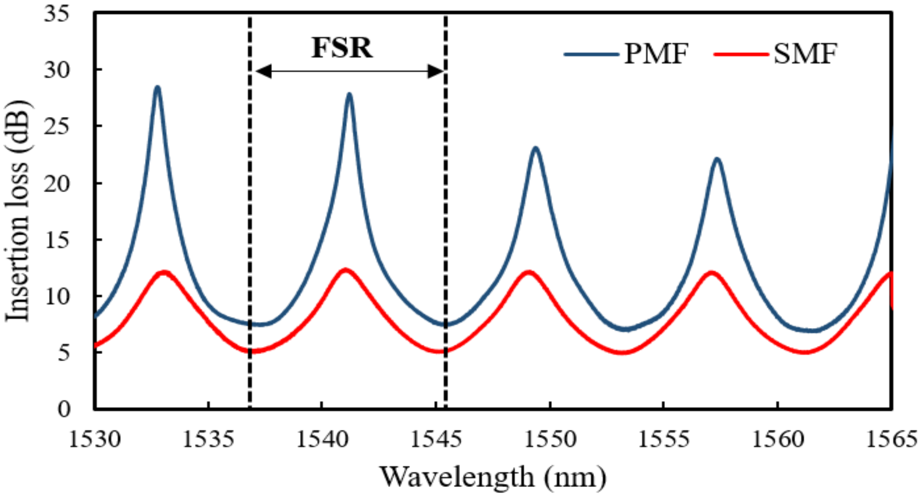
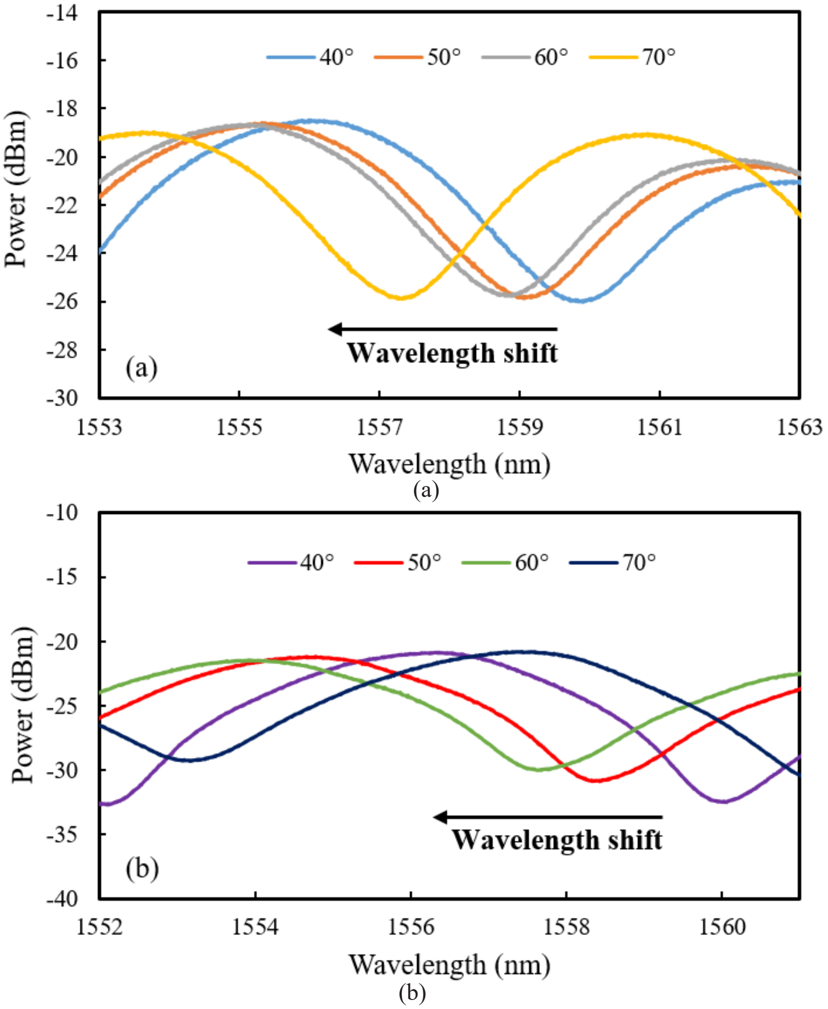


Figure 3. The insertion loss of SMF and PMF taper filters

observed during the shifts as no change was introduced to the critical angle involved in total internal reflection.

Figure 5(a) and 5(b) show the correlation between wavelength shift and tension to the angle of twist for both SMF and PMF filters. The wavelength shifts are measured by subtracting the peak or depth of the shifted spectrum against the same peak or depth of the reference spectrum. The measurement for tension was calculated by subtracting the tension reading against the reference tension when the fiber was twisted.

The wavelength shift curve in Figure 5(a) shows a minimal shift of SMF filter at 0^o to 20^o twist angle which then turns linear afterwards for 15 nm shift and eventually plateaud after reaching 80°. The reason for this trend can be observed from the tension

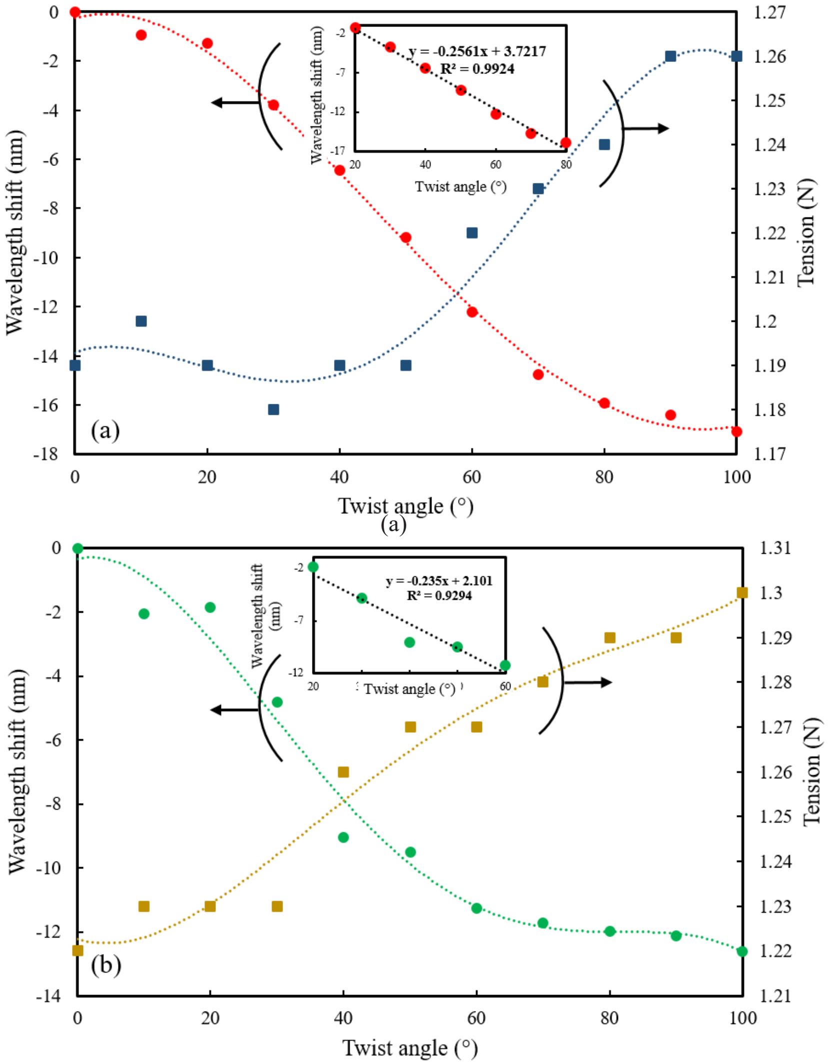


(a)

(b)

Figure 4. Spectral observation during fiber twist for (a) SMF and (b) PMF taper filters

curve, which depicts an inverted profile with similar behavior. Small twist angle produces minimal difference in tension thus explaining the lack of wavelength shift while at the larger twist angle, the wavelength shift lessens as the tension value saturates. A similar trend is observed for the PMF filter in Figure 5(b) albeit with smaller range of linear shift (20^o to 60^o twist angle), smaller total wavelength shift (10 nm), and higher tension, which could be attributed to the more complex PMF physical structure and light interference. The same reasons could also contribute to its lower linear region R^2 value of 0.9294 compared to the R^2 of SMF filter at 0.9924.



(a)

(b)

Figure 5. Wavelength shift and tension with respect to the angle of rotation for (a) SMF and (b) PMF taper filters. Insets show close-ups of linear shift region of the filters

CONCLUSIONS

In conclusion, the use of fiber twist method to achieve wavelength tunability in tapered SMF and PMF filters has been proven feasible. The shift of wavelength was correlated to the tension induced during the twisting process and region of linear shift was observed for both filters. Wider tunability range and better stability were observed for tapered SMF filter but stronger suppression capability can be obtained from the tapered PMF. The use of commercially available motorized rotation stage can be considered to develop a practical fiber filter with compact form factor and precise continuous wavelength control.

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