

In-fiber linear polarizer based on UV-inscribed 45° tilted grating in polarization maintaining fiber

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Received July 3, 2012; revised July 25, 2012; accepted July 31, 2012;
posted August 7, 2012 (Doc. ID 171922); published September 11, 2012

We report an in-fiber linear polarizer structured by UV-inscribing a 45° tilted fiber grating (TFG) into polarization maintaining (PM) fiber along its principal axis. The polarization extinction ratio (PER) achieved by a 48 mm long 45° TFG has reached 46 dB at 1550 nm and the overall PER is >40 dB over a 50 nm wavelength range. Such 45° TFG based polarizers have many advantages over conventional products, including low loss, low cost, simple fabrication process, and no physical modification to the fiber, thus offering high stability and capable of handling high power. © 2012 Optical Society of America

OCIS codes: 060.2340, 230.5440, 060.2420, 050.2770.

Pure polarization state lights could avoid signal fading and provide in phase and high signal-to-noise ratio transmission and detection in photonics systems and applications. Recently, there has been more development in all-fiber sensors and laser systems, which require in-fiber polarizers with low loss and a high polarization extinction ratio (PER). So far, two major types of in-fiber polarizer have been reported: (1) the anisotropic absorption layer based, which has a small length cladding of fiber removed and replaced by a material that preferentially attenuates the transverse electric (TE) or transverse magnetic (TM) polarization mode in the fiber [1–3]; and (2) the chiral fiber grating based circular polarizer [4,5], which is formed by twisting a non-centric fiber to achieve the operation to circular polarized light. However, due to the bonding (deposition) structure, the former is limited to low power operation and suffers from thermal and mechanic stability problems. The chiral fiber gratings need specific fiber with an asymmetric structure, which may also limit the application in all-fiber systems. The UV-inscribed fiber grating technology has been greatly developed over the last two decades. It is now a mature technique to achieve in-fiber optical components (reflection mirror, dispersion compensator, mode coupler, sensors, etc.) with a simple fabrication process, free operating wavelength, and low loss in all SiO₂ based commercial and special fibers. The fiber gratings are formed by UV-induced refractive index modulation in the core, which does not physically modify the fiber, thus maintaining high mechanical strength and sustainable to high operation power [6,7]. The fiber gratings with blazed structure have excellent polarization managing properties, which have been attracting more interests in sensing, communication, and laser systems [8,9].

According to the total internal reflection (TIR) effect, the tilted fiber gratings can be sorted by three different mode coupling regimes according to the tilt angle: (1) $\theta < 23.1^\circ$ —backward cladding mode coupling; (2) $23.1^\circ < \theta < 66.9^\circ$ —radiation mode coupling; and (3) $\theta > 66.9^\circ$ —forward cladding mode coupling. When the tilt angle is equal to 45°, the grating will couple the TE polarization component out from the fiber core and leave the TM polarization propagating in the fiber. This polarization discrimination function composes a 45°

TFG in an ideal in-fiber polarizer. We have previously reported the UV-inscription of 45° TFGs into a standard telecom single mode fiber [10,11]. However, the linearly polarized light after the 45° TFG is not preserved in the non-polarization maintaining (PM) fiber. In this Letter, we report TM polarization mode pass in-fiber linear polarizers by UV-inscribing 45° TFG structure in PM fibers along the fast/slow axis of high PER.

The light incident at Brewster's angle on an optical interface will cease its TE component. For fiber gratings, the UV induced refractive index modulation is very small ($\Delta n \sim 10^{-4}$), far less than the index of fiber. So, the Brewster angle for a UV-inscribed grating is $\theta_{\text{Brewster}} = \text{atan}(n_{\text{core}} / (n_{\text{core}} + \Delta n)) \cong 45^\circ$. Thus, when the grating structure is inscribed into a fiber core at 45° with respect to the normal of fiber axis, the grating will radiate TE light out from the fiber core, acting as an in-fiber polarizer. Figure 1 shows the schematic of a UV-inscription of 45° TFG structure into a PM fiber. According to the tilted grating structure, we may define the equivalent slow-axis in the x direction, which is in parallel with the grating plate and the fast-axis in the y direction, which is vertical to the fiber axis, as shown in Fig. 1. So, a 45° TFG will polarize the light in the y direction.

When the 45° TFG is UV-inscribed in non-PM fiber, the inscription can be arbitrary with respect to the fiber axis. However, in a PM fiber, the UV-inscription must be along its principal axis (the slow- or fast-axis) in order

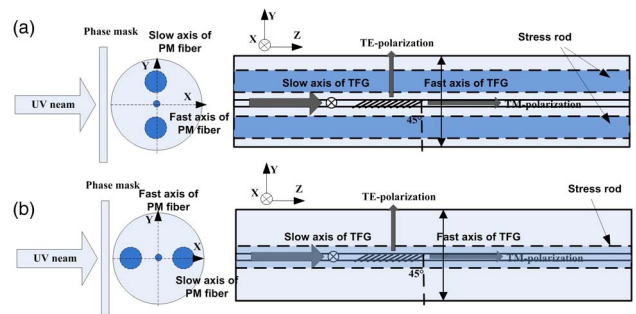


Fig. 1. (Color online) Schematic of a 45° TFG with defined slow- and fast-axis operation principle as an in-fiber polarizer for UV-inscription along (a) the fast-axis and (b) the slow-axis of a PM fiber.

to maintain linear polarization state of the propagating signal in the fiber. In order to inscribe a 45° TFG in the principal axis of the PM fiber, the slow- or fast-axis of the PM fiber samples were marked under a microscope prior to the UV-inscription. The PM fiber used for 45° TFG fabrications was a non-photosensitive fiber (PM1550, Corning). To inscribe strong 45° TFGs, the PM fiber was hydrogen loaded at 80°C for 48 h to increase its photosensitivity. The 45° tilted grating structure was inscribed into the fiber using a custom-design tilted phase mask (Ibsen) and a 244 nm UV source from a CW frequency doubled Ar+ laser (Coherent Sabre Fred). The pattern on the phase mask has a period of 1830 nm and tilted at 33.7° with an effective area of $50\text{ mm} \times 10\text{ mm}$ on a $70\text{ mm} \times 70\text{ mm}$ crystal substrate. The 1830 nm grating period and 33.7° were designed to ensure the modulated index fringes are at 45° in the fiber core and the central wavelength response is around 1550 nm [11,12].

Figure 2 shows the diffraction pattern and effective interference area (EIA) of the UV beam for a normal and a tilted phase mask. For the non-tilted phase mask, its diffraction pattern is parallel to the fiber axis and the EIA formed by the ± 1 order diffraction of the UV beam is only in the x - y plane, while for a tilted phase mask, the diffraction pattern is tilted and the EIA is not only in x - y but also spread in y - z plane, thus the fiber positioning is more critical for a tilted phase mask inscription.

After the UV-inscription, the 45° TFG structures were examined under a $100\times$ microscope objective (Axioscope-2 MOT plus, Zeiss). From the images shown in Figs. 3(a) and 3(b), it is clear that the tilted grating structures are exactly 45° for the inscription along both the slow- and fast-axis. We also investigated the light radiation direction by launching a 633 nm red light into the 45° TFGs. Figures 3(c) and 3(d) show the images of the 45° TFG inscribed along the fast-axis of the PM fiber with two observing directions. Clearly, when the observation is made in the fast-axis, there is no light irradiated from the surface as all light propagated in the fiber, whereas for the observing direction along the slow axis, we see the grating area illuminated as the light was strongly coupled out from the grating side.

The UV-inscribed 45° TFGs were evaluated for the central PER value and overall PER profile using a single wavelength laser at 1550 nm and a broadband source with a wavelength range from 1525 to 1608 nm, respectively.

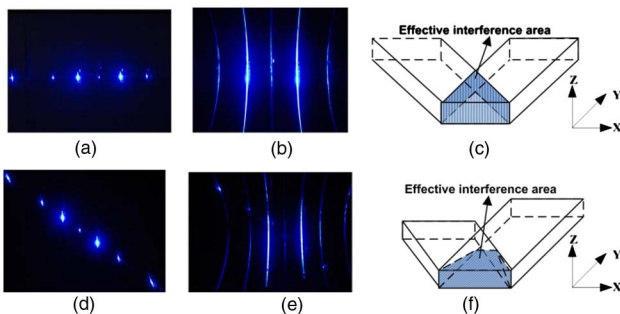


Fig. 2. (Color online) UV beam diffraction images by (a) and (b) a normal phase mask and fiber and (d) and (e) a tilted phase mask and fiber. Schematic of effective ± 1 order UV beam interference area after (c) a normal and (f) a tilted phase mask.

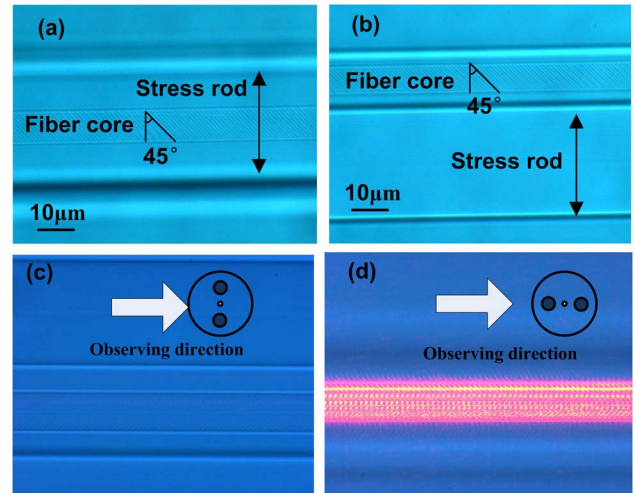


Fig. 3. (Color online) Micro-images of 45° TFGs in PM fibers inscribed along (a) slow- and (b) fast-axis. When launched with 633 nm red light to the 45° TFG inscribed along the fiber fast-axis, (c) no side radiation when observing from the fast-axis and (d) strong radiation from surface when observing along the slow-axis.

The central PER was measured by the difference of max and min transmission loss at 1550 nm with respect to all polarization states and the overall PER profile was calculated by using the Müller matrix method employing the commercial optical vector analyzer (LUNA 2000).

A number of 45° TFGs of different lengths were inscribed in the PM fiber and evaluated for PER. Figure 4(a) shows the PER of the 48 mm-long grating

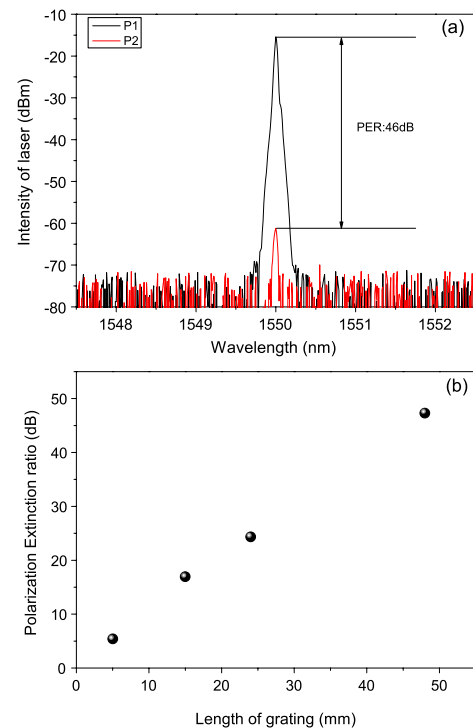


Fig. 4. (Color online) (a) Transmission spectra of a 48 mm-long 45° TFG measured using a single wavelength at 1550 nm at two orthogonal polarization states (P1 and P2). (b) PER as a function of grating length (5, 15, 25, and 48 mm).

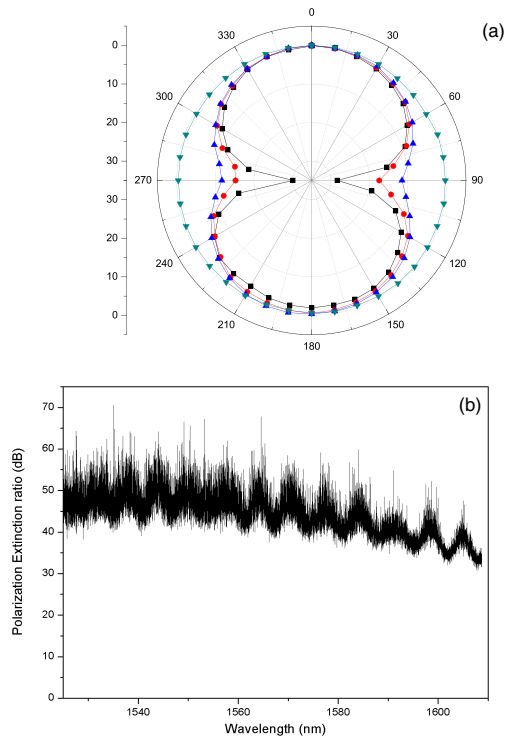


Fig. 5. (Color online) (a) Polarization distribution for three 45° TFGs with PERs of 10 dB (▲), 20 dB (●), and 40 dB (■) and a bare fiber (▼). (b) PER profile from 1525 to 1605 nm measured by LUNA optical vector analyzer 2000.

measured using a single wavelength at 1550 nm. The peak-to-peak difference in the figure clearly indicates the PER is ~ 46 dB, which is remarkable high. In the fabrication, we observed that under the same UV-inscription condition, the PER value is grating length dependent. Figure 4(b) plots the measured PERs for four 45° TFGs with different lengths—5, 15, 25, and 48 mm. It can be clearly seen from the figure that the PER is near-linearly proportional to the grating length, which provides a simple method to realize a polarizer with a designed polarization discrimination function.

The inscribed 45° TFGs were also evaluated for the degree of linear polarization by polarization distribution measurements using the method described in [11]. Figure 5(a) shows the polarization distribution plotted in polar coordinates for three gratings with low, medium, and high PER and a bare PM fiber for comparison. As shown in the figure, the higher the PER, the lower the output power at the azimuth angle of 90° and 270°, and a strong 45° TFG will show a near-perfect figure "8" shape indicating an ultra-high polarization discrimination degree, while the bare fiber gives a circle shape unlike any polarization property.

The UV-inscribed 45° TFGs in a PM fiber can achieve a high PER value not just for a single wavelength but also for a broad wavelength range. Figure 5(b) exhibits the overall PER profile for the 48 mm long grating from 1525 to 1608 nm using the optical vector analyzer. The result indicates the overall PER is >40 dB over a 50 nm wavelength range. Since the PER profile is Gaussian shape, which will be symmetric around its central resonance, the actual PER response of this grating could be broader extending to the shorter wavelength side. In comparison, the polarization function of this high quality 45° TFG has already exceeded many commercial fiber polarizer products.

We have demonstrated in-fiber linear polarizers by UV-inscribing 45° TFG structure in a PM fiber along its principal axis. A 48 mm long grating has achieved a PER around 46 dB at the central wavelength of 1550 nm and >40 dB over 50 nm wavelength range. The results show the a PER of 45° TFG is linearly proportional to the length of grating, which provides a simple method to produce in-fiber polarizers with a desired polarization discrimination function. Ultraviolet-inscribed 45° TFG offer an alternative technique to produce in-fiber polarizers with many advantages over the conventional products, including an easy fabrication process and non physical modification of the fiber, thus maintaining high mechanical and thermal stability and capable of handling high power operation.

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