

# High extinction ratio in-fiber polarizers based on 45° tilted fiber Bragg gratings

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We report a near-ideal in-fiber polarizer implemented by use of 45° tilted fiber Bragg grating structures that are UV inscribed in hydrogenated Ge-doped fiber. We demonstrate a polarization-extinction ratio of 33 dB over a 100-nm operation range near 1550 nm. We further show an achievement of 99.5% degree of polarization for unpolarized light with these gratings. We also theoretically investigate tilted grating structures based on the Green's function calculation, therein revealing the unique polarization characteristics, which are in excellent agreement with experimental data. © 2005 Optical Society of America  
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Polarizers and other polarization-related devices are important for applications in optical fiber communication and sensing. Compared with bulk optic polarizers, in-fiber polarizers are more desirable in fiber systems owing to their light weight, low insertion loss, and high coupling efficiency. Several types of in-fiber polarizer have been demonstrated either by use of the surface plasmon resonance of polished conventional and etched D-shaped fibers coated with thin metallic films<sup>1,2</sup> or by embedding such fibers in birefringent crystals.<sup>3</sup> However, the polished fiber is fragile and must be housed in a bulk substrate, thus somewhat neutralizing the advantages of a fiber-based system. In recent years, fiber Bragg grating devices have been extensively exploited as wavelength-division multiplexing filters and polarization compensators for telecommunications applications and as strain or temperature sensors for smart-structure applications. With advances in UV-inscription technology and demands for its application, a variety of grating structures have been developed. One of these structures is the tilted fiber Bragg grating (TFBG), which exhibits strong polarization-dependent loss (PDL) effects<sup>4</sup> when the tilted angle is large and has been implemented as a PDL equalizer<sup>5</sup> and an in-line polarimeter.<sup>6</sup> We report, for the first time to our knowledge, in-fiber polarizers based on 45° TFBGs, achieving a polarization-extinction ratio higher than 33 dB covering a 100-nm operation range. We also present a theoretical investigation of the characteristics of TFBGs, which provides effective design guidance for achievement of high-performance in-fiber polarizers and polarization splitters.

As an alternative to coupled-mode theory, the spectrum of a TFBG may be simulated by the Green's function method (also known as the volume current method).<sup>7</sup> The loss of a core mode by a small section,  $\delta l$ , of a TFBG in a single-mode fiber can thus be expressed as  $-\alpha \delta l$ , where  $\alpha$  is the loss coefficient, and

can be calculated from

$$\alpha = -\frac{k_0^3 \delta n^2}{4n} \frac{1}{1 + (u^2/w^2)} \frac{K_1^2(aw)}{K_0^2(aw)} F, \quad (1)$$

where  $k_0 = 2\pi/\lambda_0$  is the wave vector of light in vacuum;  $\delta n$  and  $n$  are the perturbation and the original refractive indices of the core, respectively;  $a$  is the radius of the core; and  $u$  and  $w$  are, as is well known, the fiber waveguide parameters. Integration parameter  $F$  in Eq. (1) is defined as

$$F = \int_0^{2\pi} [1 - \sin^2 \theta_0 \cos^2(\delta - \phi)] \times \left[ \frac{KsJ_0(au)J_1(aKs) - uJ_0(aKs)J_1(au)}{Ks^2 - u^2} \right]^2 d\phi, \quad (2)$$

where  $Ks = (Kt^2 + k_0^2 n_{cl}^2 \sin^2 \theta_0 + 2Ktk_0 n_{cl} \sin \theta_0 \cos \phi)^{1/2}$  and  $\theta_0$  is the angle between the radiation beam and the fiber axis, which satisfies  $Kg - n_{eff} k_0 + k_0 n_{cl} \cos \theta_0 = 0$ ,  $\phi$  denotes the polarization of the core mode, and  $\delta$  is the tilting angle of the grating.  $Kt$  and  $Kg$  are wave vectors of the grating along the fiber axis and across the fiber cross section and are defined as  $Kt = 2\pi/\Lambda \sin \delta$  and  $Kg = 2\pi/\Lambda \cos \delta$ . In Eqs. (1) and (2),  $K$  and  $J$  are Bessel functions.

From Eqs. (1) and (2) we can calculate the transmission of the light bound within the core after it passes a TFBG. Figure 1(a) shows the simulated transmission spectra of TFBG structures of the same period (542 nm) and seven tilt angles for  $s$ -polarized light ( $s$  light, solid curve) and  $p$ -polarized light ( $p$  light, dashed curve). In the simulation the core size of the fiber is set to 4.5  $\mu\text{m}$ . It is clear from Fig. 1(a) that, although the evolving trends are similar for the transmission loss profiles of both polarization states, the change in amplitude for  $p$  light is more no-

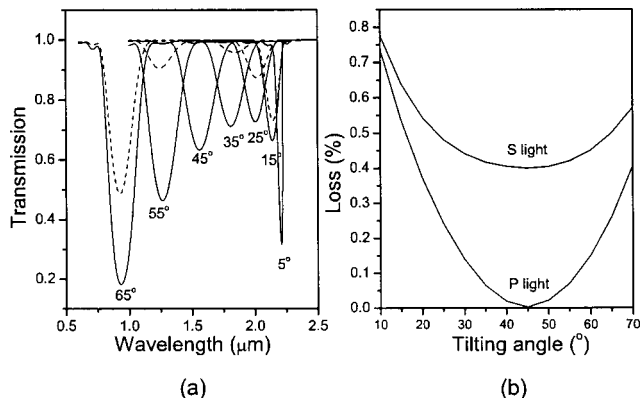


Fig. 1. (a) Transmission spectra of TFBGs with various tilting angles. Dashed curves, *p* light; solid curves, *s* light. (b) Transmission losses of TFBGs versus tilting angles for *s* light and *p* light. The peak wavelength is set to  $1.55 \mu\text{m}$  and the period is varied accordingly.

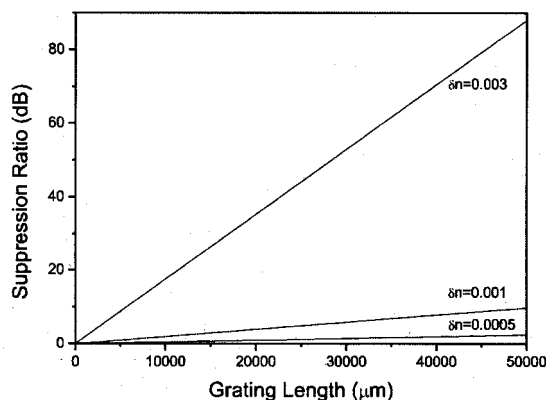


Fig. 2. Polarization-extinction ratio of *s* light to *p* light with respect to grating length for three grating strengths.

ticeable. The most interesting observation is that, when the tilted angle is  $45^\circ$ , the transmission loss of *p* light is almost zero, whereas the *s*-light loss remains significant. It is this unique characteristic that provides a mechanism through which one may implement an ideal in-fiber polarizer. To eliminate the influence of dispersion on the TFBG structures, we performed the simulation while the center wavelength was fixed at  $1.55 \mu\text{m}$  and the grating period was varied. Figure 1(b) shows the maximum transmission losses at several tilt angles for *s* and *p* light. Characteristics similar to those of Fig. 1(a) may be seen in Fig. 1(b). The transmission loss reaches a minimum when the tilting angle is  $45^\circ$ . At this critical angle the loss of *p* light is eliminated completely, although the loss of *s* light remains high. The null transmission loss of *p* light in  $45^\circ$  TFBGs may be explained by Brewster's law. One can imagine that the grating itself comprises a periodic structure of two-layer materials with slightly different refractive indices,  $n_1$  and  $n_2$ . The Brewster's angle for the interface is determined by  $\tan \theta_c = n_1/n_2$ . As  $n_1$  and  $n_2$  are almost identical ( $\Delta n < 0.01$ ),  $\theta_c$  is thus close to  $45^\circ$ . Therefore, when the index fringes of the grating are oriented at  $45^\circ$ , the *p*-light component in the core mode will

propagate through the TFBG structure, whereas the *s* light will be reflected by the  $45^\circ$  fringes and coupled into cladding and radiation modes. In the simulation we also examined the dependence of the polarization of the TFBG structure on grating length and grating strength. Figure 2 shows the variation of the polarization-extinction ratio as a function of grating length for three modulation levels of refractive index,  $\Delta n = 0.0005, 0.001, 0.003$ . It is evident that the extinction ratio increases linearly with grating length but varies significantly more with grating strength.

We fabricated  $45^\circ$  TFBGs in Ge-doped photosensitive fiber using the scanning phase mask technique and a 244-nm cw laser source. To ensure that the spectral response of the TFBGs with large tilt angles fell into the region near  $1.55 \mu\text{m}$  we specially purchased a phase mask with a large period (1800 nm) for this experiment. The phase mask was rotated by  $33.3^\circ$  to induce slanted fringes at  $45^\circ$  within the fiber core. The  $45^\circ$  slanted fringes were verified by examination with an oil-immersion, high-magnification microscope [Fig. 3(a)]. As the pattern field of the phase mask was only  $3 \text{ mm} \times 10 \text{ mm}$ , when the mask was rotated by  $33.3^\circ$  the maximum grating length was reduced to 4.6 mm, which resulted in low efficiency of cladding and radiation mode coupling. To produce strong TFBGs we adopted a concatenating technique in the UV-inscription process. We were able to fabricate a 40-mm-long  $45^\circ$  TFBG by concatenating 9 sections of grating and a 50-mm-long TFBG by concatenating 11 sections.

For an initial PDL investigation we used a system, as illustrated in Fig. 3(b), consisting of a broadband source (BBS), a fiber polarizer, a polarization controller (PC), and an optical spectrum analyzer (OSA). Figure 4(a) shows the PDLs for 4.6- and 40-mm gratings measured with this system. The maximum PDL of a 4.6-mm grating is only 6 dB at  $\sim 1.55 \mu\text{m}$ , whereas the 40-mm TFBG achieved a maximum value of 28 dB. The fact that the entire PDL profile

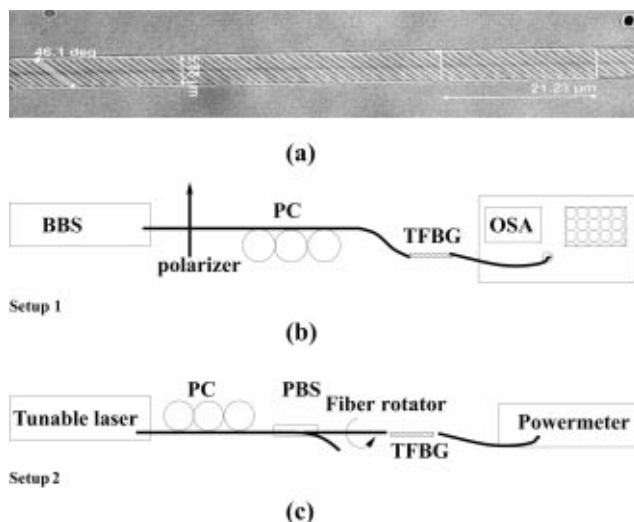


Fig. 3. (a) Image of slanted fringes of a  $45^\circ$  TFBG observed under a microscope. (b), (c) Experimental setups for characterizing the  $45^\circ$  TFBGs. PBS, polarizing beam splitter; other abbreviations defined in text.

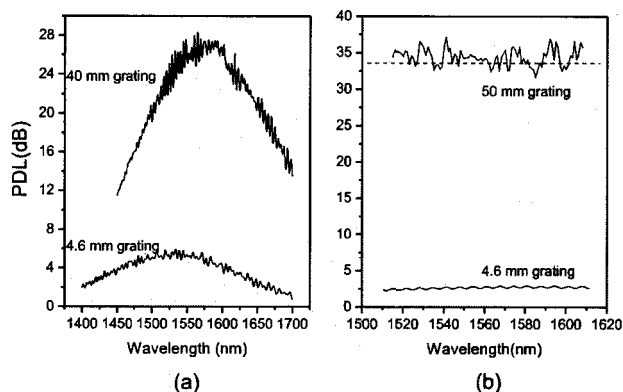


Fig. 4. PDLs of 4.6-mm and 40-cm TFBGs measured with the system shown in Fig. 3(b). (b) PDLs of 4.6-mm and 50-cm TFBGs measured with the EXFO PDL characterization kit.

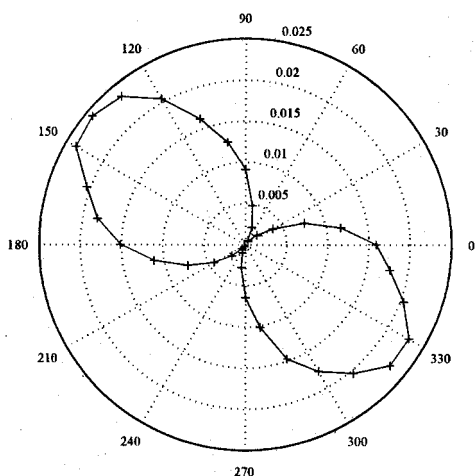


Fig. 5. Full PDL response of a 50-mm TFBG probed by linearly polarized light from  $0^\circ$  to  $360^\circ$ .

over 80 nm is near-Gaussian-like is due to the use of the broadband source. To measure the true maximum PDL profile, we further investigated the gratings, employing a commercial EXFO PDL characterization kit that incorporated a tunable laser to permit optimization of the maximum PDL over a 100-nm tuning range. Figure 4(b) plots comparatively the maximum PDL profiles of 4.6- and 50-mm  $45^\circ$  TFBGs. It can be seen clearly that the PDL extinction ratio of the 50-mm grating achieved an  $\sim 33$ -dB ratio across the entire 100-nm range. This performance exceeds that of typical commercial devices, for which a 30-dB polarization-extinction ratio is often quoted. Optimizing the UV inscription and increasing the grating length further should make even higher ( $\sim 40$ -dB) PDL extinction ratios possible. Note that the resonance on the PDL of the concatenating TFBGs could be caused by a stitch error that should be eliminated by use of a large phase mask or by precise control of the phase stitches during fabrication.

The full PDL response of the 5-cm TFBG was characterized by use of linearly polarized light from  $0^\circ$  to

$360^\circ$  in the setup illustrated in Fig. 3(c). We obtained linear polarization by rotating the powermeter pigtail on the output port of the polarization beam splitter. The transmission of the TFBG was measured as a function of the polarization direction of the light. The results for the 50-mm grating are plotted in Fig. 5. It is as expected that the PDL will go through two cycles because two maximum and two minimum PDL positions exist. The transmission reaches peaks at angles near  $140^\circ$  and  $320^\circ$ , while it becomes almost zero at the orthogonal directions to these two positions. The polarizing capability of the  $45^\circ$  TFBGs as in-fiber polarizers was also evaluated. First, radiation at  $1.55 \mu\text{m}$  from a tunable laser was depolarized with a polarization scrambler. The degree of polarization was then measured with a polarization analyzer, yielding a value of 1.2%, i.e., the radiation was almost unpolarized. Then the  $45^\circ$  TFBG was inserted between the scrambler and the polarization analyzer. The test result shows that a very high degree of polarization value of 99.51% was achieved by both 40- and 50-mm TFBGs.

In conclusion, we have both theoretically and experimentally investigated the polarization properties of  $45^\circ$  TFBGs. The results revealed that such TFBGs have a unique polarization characteristic, which may be exploited to implement ideal in-fiber polarizers. A polarization-extinction ratio of 33 dB over 100 nm was achieved by a 50-mm-long  $45^\circ$  TFBG. When the  $45^\circ$  TFBGs were used as polarizers, a 99.51% degree of polarization was achieved for completely unpolarized light. We anticipate that by optimizing the UV inscription and increasing the grating length further, an extinction ratio of as much as 40 dB will be achievable with such a structure. This type of TFBG could be an excellent candidate for implementation of low-cost-high-spec polarization devices for a wide range of applications.

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