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Recommended Citation
L. Yuan et al., "Stress-Induced Birefringence and Fabrication of In-Fiber Polarization Devices by Controlled Femtosecond Laser Irradiations," Optics Express, vol. 24, no. 2, pp. 1062-1071, Optical Society of America, Jan 2016.
The definitive version is available at https://doi.org/10.1364/OE.24.001062

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Stress-induced birefringence and fabrication of in-fiber polarization devices by controlled femtosecond laser irradiations

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Abstract: Optical birefringence was created in a single-mode fiber by introducing a series of symmetric cuboid stress rods on both sides of the fiber core along the fiber axis using a femtosecond laser. The stress-induced birefringence was estimated to be $2.4 \times 10^{-4}$ at the wavelength of 1550 nm. By adding the desired numbers of stressed rods, an in-fiber quarter waveplate was fabricated with an insertion loss of 0.19 dB. The stress-induced birefringence was further explored to fabricate in-fiber polarizers based on the polarization-dependent long-period fiber grating (LPFG) structure. A polarization extinction ratio of more than 20 dB was observed at the resonant wavelength of 1523.9 nm. The in-fiber polarization devices may be useful in optical communications and fiber optic sensing applications.

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OCIS codes: (230.3990) Micro-optical devices; (220.4000) Microstructure fabrication; (060.2420) Fibers, polarization-maintaining; (260.1440) Birefringence.

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asymmetric stress [4]. This mechanism has been utilized to develop polarization controllers.

SMF is random and unknown. One polarization mode to the other. In general, the SOP of a light wave propagating through a conventional SMF. The intrinsic birefringence varies with time and location. In addition, the random intrinsic birefringence of the SMF is suppressed. For example, bending a SMF into coils can create additional birefringence as a result of asymmetric stress [4]. This mechanism has been utilized to develop polarization controllers.

1. Introduction

Control of the state of polarization (SOP) of light, especially in optical fibers, is essential to many applications, such as optical communications [1], spectroscopy, microscopy [2], and sensing [3]. However, most polarization controlling devices (e.g., waveplates and polarizers) used in existing fiber optic systems are still based on bulk-optic components. These bulk-optic devices have to be interfaced with optical fibers through collimators and pigtails. This not only increases the cost of implementation but also compromises the robustness of the system. It is highly desired that the waveplates and polarizers can be implemented in an all-fiber form with minimum insertion loss and desirable performance.

A single-mode fiber (SMF) supports two orthogonally polarized modes. In an ideal circular-core SMF, these two modes propagate with the same phase velocity. However, practical SMFs are not perfectly circularly symmetric. The two polarized modes propagate with slightly different phase and group velocities, resulting in an intrinsic birefringence in a conventional SMF. The intrinsic birefringence varies with time and location. In addition, random environmental effects such as twisting, bending and temperature variations could also introduce unknown birefringence. These environmental factors could also couple energy from one polarization mode to the other. In general, the SOP of a light wave propagating through a SMF is random and unknown.

A number of methods have been reported to create an additional birefringence of a large amount in SMFs. The created additional birefringence is much larger than the intrinsic birefringence. As a result, the random intrinsic birefringence of the SMF is suppressed. For example, bending a SMF into coils can create additional birefringence as a result of asymmetric stress [4]. This mechanism has been utilized to develop polarization controllers.
However, although the amount of birefringence can be flexibly controlled by manipulating the
coil, the large size and instability of the mechanical apparatus makes it impractical in field
applications. It has also been shown that a large amount of birefringence can be generated by
tapering a rectangular-shaped single-mode fiber [5]. Subsequently, miniaturized polarization
mode interferometers have been made possible based on the tapered rectangular-shaped
fibers.

High birefringence (Hi-Bi) or polarization maintaining (PM) optical fibers (e.g., panda,
bow-tie or elliptical core) have a large built-in birefringence and can be used to fabricate all-
fiber waveplates. The amount of phase retardation depends on the fiber birefringence and the
length of the fiber. For example, PM fiber based inline waveplates have been fabricated by
precise cleaving and controlled splicing [6]. However, it is hard to control the exact length of
the PM fiber during cleaving and fusion splicing. It has also been reported that an anisotropic
photonic crystal fiber (PCF) can be highly birefringent [7]. A large amount of birefringence
can be generated by deforming an air-holed photonic crystal fiber from its side, introducing an
ellipticity in both the core and the air holes [8]. The amount of birefringence can be controlled
by the degree of compression. However, in addition to the difficulty in the practical
implementation of such a large deformation, PCFs are expensive, difficult to splice, and could
be lossy when heavily deformed [9].

All-fiber polarizers have also been reported by various researchers over the years. Examples include the in-fiber polarizer based on the side-polished or D-shape fibers coated
with optical absorbing materials on the flat side [10, 11], the in-fiber polarizer based on
mechanically bending a Hi-Bi fiber [12], and the PCF in-line polarizer based on a long period
fiber grating (LPFG) fabricated using CO₂ laser irradiations [13], and the in-fiber polarizer
based on tilted fiber Bragg gratings (FBG) [14]. These reported devices have shown good
extinction ratios but most of them used specialty fibers except for the tilted FBG with simple
structure and low cost benefit.

The latest advancements in high power femtosecond (fs) laser technology have opened a
new opportunity to fabricate various optical devices and sensors in solid transparent materials
including optical fibers [15–20]. It has been reported that fs laser irradiations can generate
birefringence in transparent materials [21, 22]. Recently, a FBG written by a fs laser has been
reported to have a high birefringence [23] and a strong birefringence tuning around fiber core
using fs laser was also demonstrated [24].

In this paper, we report a new technique to generate birefringence in a SMF (SMF-28e,
Corning Inc.) by creating two parallel stress rods in the fiber cladding using a fs laser. The
position and size of the fs laser induced stress rods were optimized to minimize the insertion
loss. By controlling the total length of the stress rods, the amount of birefringence could be
precisely controlled to fabricate waveplates of desired retardations. Polarization dependent
LPFGs were fabricated by introducing periodic stress rods along the fiber, showing the
promise of being used as an in-fiber polarizer.

2. Device principle and theoretical analysis

It is well known that mechanical stresses produce additional refractive index change in optical
materials because of the photoelastic effect. As a fact, commercially available Panda and
Bow-tie PM fibers are fabricated by intentionally implanting axial stress rods along the fiber.
The stress rods introduce asymmetric index profile in the cross section of the fiber, resulting
in a systematic birefringence along the fiber.

Based on the same principle, we can use fs laser micromachining to create distributed
cuboid stress patterns in the cladding region of a single-mode optical fiber and produce
controlled birefringence along the fiber. As shown in Fig. 1, each pair of fs laser ablated
patterns are in parallel and very close (within several microns) to the fiber core. The two
ablated patterns create certain amount of normal stresses to the fiber core. Because the ablated
patterns are asymmetric radially in the cross section, it is expected that an asymmetric index
profile is created within the fiber, which shall result in a birefringence to the light propagating along the fiber.

The length, width, and height of each cuboid stress rod are denoted as $L_1$, $W$ and $H$, respectively. The distance between each two adjacent rods and the offset between the rod and the fiber core are $L_2$ and $D$, respectively. The amount of birefringence will depend on the amount of stress or the distance ($D$) between the ablated region and the fiber core. A smaller $D$ usually results in a large stress but may also cause larger loss.

The laser ablation induced birefringence allows us to fabricate in-fiber waveplates of desired polarization rotations. As shown in Fig. 1(b), each pair of laser-ablated rods produces a small amount of rotation in polarization. As the number of pairs increases, the total amount of polarization rotation will increase correspondingly. The amount of polarization rotation can thus be controlled to fabricate waveplates of desired polarization rotations.

![Fig. 1. Schematic illustration of stress rods created by fs laser micromachining inside an optical fiber: (a) Cross-section view; (b) top view.](image)

In addition to in-fiber waveplates, the ability to precisely control the birefringence of a single-mode fiber at specific locations also allows us to fabricate an in-fiber polarizer. As shown in Fig. 1(b), with an appropriate period and spacing, the periodic cuboid stress patterns can form a LPFG. Because of the birefringence, the two orthogonally guided polarization modes ($0^\circ$ and $90^\circ$) have different propagation constants and effective refractive indices [25]. As a result, the two polarization modes will be coupled to their corresponding cladding modes at different wavelengths, creating polarization dependent losses (PDL) at different wavelengths.

Figure 2 plots the simulated spectra of LPFGs inscribed in SMFs with the birefringence ($B$) of $5.0 \times 10^{-5}$ and $1.0 \times 10^{-4}$, respectively, according to the procedures detailed in [26]. The parameters used in the simulations included a core diameter of 8.2 μm, cladding diameter of 125 μm, core refractive index of 1.4682, cladding refractive index of 1.4630, grating period of 475 μm and grating length of 50 mm. For one polarization mode, we use the core refractive index listed above. For the other polarization mode, we modify the core refractive index according to the assumed birefringence value. As shown in Fig. 2, the birefringence produces two different resonant wavelengths for the two polarization modes. The difference between the resonant wavelengths ($\Delta \lambda$) is 25 nm for a birefringence of $5.0 \times 10^{-5}$, and 50 nm for a birefringence of $1.0 \times 10^{-4}$. The two polarization modes have different transmission losses at different wavelengths. The device can thus be used as a polarizer at the resonant wavelength of the LPFG, where one polarization has a large loss but the other polarization transmits through with a negligible loss.
Fig. 2. Simulated spectra of two LPFGs inscribed on the SMFs with birefringence (B) of $5.0 \times 10^{-5}$ and $1.0 \times 10^{-4}$, respectively.

3. Device fabrication

Figure 3 shows the experimental setup for fabrication of in-fiber polarization devices. The fs laser beam used for fabrication was similar to the one mentioned in our previous paper [16]. A standard single-mode optical fiber was buffer-stripped in fabricating regions, carefully cleaned using acetone and then clamped by two bare fiber holders (Newport 561-FH). During fabrication, the fiber was immersed in distilled water. The optical fiber, fiber holders and water tank were all mounted on a high-precision, computer-controlled three-axial translation stage (Newport, Inc.) with a resolution of 0.1 μm. The fs laser beam was focused inside the optical fiber through a water immersion objective lens (Olympus UMPlanFL 20x) with a numerical aperture (NA) of 0.4. The spot size of the focused beam was about 1 μm. The scanning velocity of the stage was set at 100 μm/s. The energy used for fabrication was 0.4 ~0.5 μJ per pulse.

Two types of in situ monitoring systems were used to monitor the performance of the polarization devices during the micromachining process as shown in Fig. 3. During waveplate fabrication, a tunable laser (Agilent 8168A), a polarization controller and a lightwave polarization analyzer (Agilent, 8509B) were used for in situ monitoring the polarization states while the stress rods were being added. During fabrication of the LPFG-based polarizer, a broadband source (1300-1700 nm), a fiber inline polarizer (Thorlabs ILP1550SM-FC), a polarization controller and an optical spectral analyzer (AQ6319) were used to measure the polarization dependent spectra of the LPFG.
4. Results and discussions

Figures 4(a) and 4(b) show the microscopic images of the stress rods fabricated inside a single-mode fiber. Pairs of stress rods were symmetrically fabricated inside cladding of the fiber. The dimension of stress rod was about $100 \times 10 \times 20 \ \mu\text{m}$. The rods were fabricated by fs laser irradiations layer-by-layer starting from the bottom to the top to avoid focusing through previously modified regions. The distance between two adjacent stress rods ($L_2$) was $10 \ \mu\text{m}$. The offset between the stress rod to the core ($D$) was $10 \ \mu\text{m}$.

The offset $D$ is a critical parameter that could affect the performance of the device. In general, a small $D$ would result in a large amount of stress to the fiber core, thus a large index modulation and birefringence. However, if $D$ is too small, the stress patterns may induce a large optical loss to the light propagating inside the fiber core.

![Microscopic images of two stress rod pairs fabricated inside a single-mode fiber using fs laser irradiations: (a) Top view and (b) side view.](image)

Experiments were conducted to investigate the influences of $D$ on the optical loss. Table 1 shows experimental results for three different offsets of 2, 5 and $10 \ \mu\text{m}$. To improve the measurement accuracy, the transmission loss per pair was calculated based on the total transmission loss of multiple pairs of stress rods in each experiment. When the stress rods were very close to the fiber core ($D = 2 \ \mu\text{m}$), the loss was 4.93 dB/pair which was unacceptably high. Increasing the offset to $10 \ \mu\text{m}$, the loss was reduced to an acceptable value of 0.08 dB/pair. Based on the results, the offset $D$ was set to $10 \ \mu\text{m}$ during the fabrications of the waveplate and the polarizer.

| Offset $D$ ($\mu\text{m}$) | Number of stress pairs ($n$) | Total transmission loss (dB) | Transmission loss per pair (dB) |
|---------------------------|----------------------------|------------------------------|-------------------------------|
| 2                         | 9                          | 11.36                        | 4.93                          |
| 5                         | 13                         | 4.35                         | 1.89                          |
| 10                        | 16                         | 0.19                         | 0.08                          |

4.1 Fiber inline quarter waveplate

To fabricate a fiber inline waveplate, pairs of stress rods were fabricated inside the fiber cladding. The dimension of each stress rod was $100 \times 10 \times 20 \ \mu\text{m}$. The distance between the two adjacent pairs of stress rods was $10 \ \mu\text{m}$. The offset $D$ was $10 \ \mu\text{m}$. Each pair of stress rods would add a little bit birefringence to the fiber. By controlling the amount of accumulated birefringence, waveplates of different phase shifts (e.g., quarter-wave and half-wave) could be fabricated.

We first set the wavelength and the output power of the tunable laser to 1550 nm and 0 dBm, respectively. By adjusting the polarization controller, the initial polarization state seen at the polarization analyzer was set at the $+45^\circ$ linear polarization in the equator with the Stokes vector of \{0.00, 1.00, 0.00\} on the Poincaré sphere (Fig. 5). Figure 5 also shows the...
five measured polarization states of the transmitted light on the Poincaré sphere, seen at
the polarization analyzer, after adding 4, 8, 14, and 16 pairs of stress rods into the cladding. The
measured Stokes vectors were {0.00, 0.97, −0.21}, {0.01, 0.79, −0.60}, {0.01, 0.30, −0.94}
and {0.00, 0.00, −0.99}, respectively.

After implanting 16 pairs of stress rods, the polarization state changed from the original +
45° linear polarization to the left-handed circular polarization, indicating of a 90° rotation in
polarization. In other words, the 16 pairs of stress rods created a quarter waveplate inside the
single-mode fiber. The insertion loss after adding 16 pairs of stress rods was measured to be
0.19 dB. The polarization dependent loss (PDL) of this in-fiber quarter waveplate was 0.21
dB measured using the lightwave polarization analyzer. It is interesting to note that the
marked positions along the longitude of the Poincaré sphere indicate that the polarization
states can be precisely controlled and gradually changed during the fs irradiation process.

Fig. 5. Stress rods induced polarization changes in a single-mode optical fiber shown on a
Poincaré sphere.

The 16 pairs of stress rods induced a total phase retardation of π/2 to the two orthogonal
polarization modes. That is,

\[ \frac{2\pi}{\lambda} B_f L = \frac{\pi}{2} \tag{1} \]

where \( \lambda \) is the optical wavelength in vacuum, and \( B_f \) is the birefringence of the fiber created
by the stress rods, defined as [27],

\[ B_f = |n_x - n_y| \tag{2} \]

where \( n_x \) and \( n_y \) are the effective refractive indices of the two orthogonal polarization modes,
respectively.

In our experiments, the optical wavelength \( \lambda \) was set at 1550 nm, and the length of the
stress rod was \( L = 100 \mu m \). Based on the Eqs. (1), the stress-induced birefringence \( B_f \) was
about \( 2.4 \times 10^{-4} \). The birefringence created by fs laser fabricated stress-rods is close to that of
typical polarization maintaining fibers (PMFs) [28, 29], such as the panda fiber (3.1 \times 10^{-4})
and the bow-tie fiber (3.8 \times 10^{-4}).

It should be noted that the fabrication efficiency for practical applications can be
significantly improved by increasing the scanning speed of the stages, reducing the dimension
of each stress rod or combining with the Galvo scanning system.

Three quarter waveplates were fabricated using exactly the same parameters. The
measured Stokes parameters were {0.03, 0.00, 1.00}, {0.00, 0.00, −0.99}, {0.00, 0.02, 1.00},
respectively. The small variations in Stokes parameters indicated that the fabrication process was repeatable.

4.2 Fiber inline polarizer based on LPFG

To fabricate the in-fiber polarizer based on a birefringent LPFG, the following parameters were used. The grating period \((L_1 + L_2)\) of the LPFG was set at 460 \(\mu\)m, where the length \(L_1\) remained to be 100 \(\mu\)m but the spacing between the adjacent pairs was increased to 360 \(\mu\)m. The height \(H\) was decreased to \(\sim 3\) \(\mu\)m and the width \(W\) was set at 4 \(\mu\)m to reduce the fabrication time. The offset \(D\) was also reduced to 8 \(\mu\)m. The pulse energy of the fs laser was adjusted to 0.5 \(\mu\)J.

The transmission spectrum of the LPFG was in situ monitored using the combination of a broadband source, polarization controller and OSA as shown in Fig. 3 (Type 2). The incident light was maintained the same polarization during the entire device fabrication. Figure 6 shows the transmission spectra of the fabricated LPFG with the increasing number of stress rods pairs. As more stress rods being added to the fiber, more light energy was coupled out from the core mode to the cladding modes. After adding 100 pairs of stress rods, the cladding mode with the highest transmission loss had the resonant peak wavelength of 1523.7 nm, the peak transmission loss of about 9 dB, and the insertion loss less than 2 dB.

![Fig. 6. Transmission spectra of the LPFG with increasing number of stress rod pairs at a preset input polarization.](image)

After device fabrication, we scanned the input polarization state to study the polarization dependence of the fabricated LPFG. As shown in Fig. 7(a), by slightly changing the input polarization, the strongest coupling (black line) of about 22 dB at the wavelength of 1523.9 nm was obtained. Continual change of the input polarization resulted in a weakest coupling (red line) at the same wavelength of 1523.9 nm but the strongest coupling at the wavelength of 1486.8 nm. Figure 7(b) shows the zoomed in spectra of two polarization states in the wavelength range of 1500-1540 nm, clearing indicating the wavelength dependent PDL. Such phenomena agree well with the simulation results shown in Fig. 2, which proves the principle of the in-fiber polarizer.

It should be noted that unexpected ripples appeared on the transmission spectra of the fabricated LPFG. This may be caused primarily by imperfections of the stress rod pairs during fabrication of such a long device (i.e., a LPFG of 4.6 cm in length). The stress-induced refractive index change and its distribution in the fiber core are sensitive to the strength of fs laser irradiations the offset \(D\). Although care attention has been paid to maintaining the
uniformity of irradiation and keeping the same offset \( D \) for all pairs, slight variations may still exist. In addition, the critical coupling polarization was slightly different from the preset polarization. We believed that this small difference might be caused by the initial misalignment of the stress rod pairs. The insertion loss of the LPFG seemed to be higher than that of the waveplate. This is caused by the smaller offset \( D \) and the larger number of stress rods. Nevertheless, the principle of the proposed device has been proven and the performance of the in-fiber polarizer may be improved by further optimizing the dimension of stress rod pairs, and the laser irradiation parameters such as the pulse width and energy.

![Fig. 7. Transmission spectra of in-fiber polarizer based on the stress-rod LPFG at two orthogonal polarizations. (a) Spectrum in the entire range; (b) zoom in spectrum of the cladding mode in the range of 1500-1540 nm.](image)

The device shown in Fig. 7(b) exhibits a high polarization extinction ratio of more than 20 dB at the resonant wavelength of 1523.9 nm. However, the spectral range (or bandwidth) of the fabricated device is much smaller than that of most bulk polarizers (~100 nm in bandwidth), tilted FBG based in-fiber polarizer [14] and insufficient for many applications. Future work will focus on the simulation of the polarization dependent spectral characteristics of the LPFG in correlation with the fabrication parameters, such as the \( D, H, W, L_1 \) and \( L_2 \). Another possible solution to increase the bandwidth and polarization extinction ratio is to design and fabricate broadband LPFGs, such as the turn-around-point LPFG [26] or other high order mode LPFGs.

5. Conclusion

Using a fs laser, parallel stress rods were fabricated inside the cladding of a single-mode fiber. These stress rods produced asymmetric refractive index distribution to the fiber core and created birefringence in the fiber. The amount of birefringence can be controlled by the dimension and relative alignment of the cuboid stress rods. At an offset of 10 µm, the stress-induced birefringence was estimated to be \( 2.4 \times 10^{-4} \) at the wavelength of 1550 nm, which is close to the birefringence of a typical PM fiber. The stress-induced birefringence of the controlled amount and at a flexible location entailed the capability to fabricate in-fiber polarization devices such as the in-fiber waveplate and polarizer studied in this paper. By controlling the length of the stressed rods, an in-fiber quarter waveplate was fabricated with an insertion loss of 0.19 dB and a PDL of 0.21 dB. A polarization dependent LPFG was fabricated by implanting periodic stress rods into the fiber. The periodic stress-induced birefringence resulted in wavelength and polarization dependent light coupling between the core mode and the cladding modes. As a result, the two orthogonal polarizations have different transmission losses at different wavelengths. The device can thus be used as a polarizer at the resonant wavelengths of the LPFG, where one polarization has a large loss but the other polarization transmits through with a negligible loss. The example device showed a peak polarization extinction ratio over 20 dB at the resonant wavelength of 1523.9 nm, but a
smaller bandwidth compared to the polarizers based on other principles. It is believed that the performance of the in-fiber polarizer may be improved by further optimizing the dimension of stress rod pairs and the laser irradiation parameters, as well as by designing a special LPFG to expand the bandwidth.

Acknowledgment

The research work was supported by the National Science Foundation under the grant CMMI-1360664.