Fabrication of helical long-period fiber gratings by use of a CO$_2$ laser

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We present a method of helical long-period fiber grating (H-LPFG) fabrication by use of a CO$_2$ laser for use as an optical torque sensor. A conventional optical fiber grating has periodic vertical index changes along its fiber axis, but a H-LPFG has a screw-type index modulation. The helical index modulation is obtained with the asymmetric index change caused by a single-side laser beam exposure. The H-LPFG shows peak shifts with codirectional or contradirectional torsion to the helix. Also, the polarization-dependent loss is measured to be relatively small compared with that of a conventional long-period fiber grating. © 2004 Optical Society of America

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Compared with conventional optical fiber gratings, helical optical fiber gratings are distinguished in the refractive-index modulation of a helical structure such as a screw (Fig. 1). Poole et al.$^1$ were the first to demonstrate the helical structure of a long-period fiber grating (LPFG) fabricated with wiring for a two-mode fiber spatial-mode coupler. However, in the method with wiring it is hard to control the period of the gratings since the period of the LPFG is determined by the thickness of the wire in that experiment. Here we demonstrate a helical LPFG (H-LPFG) fabricated with the surface deformation method by use of a CO$_2$ laser and single-mode fiber. We also theoretically investigate it with the coupled-mode theory between the core and the cladding modes.

Compared with the studies on a grating tuned by application of lateral stress or temperature, relatively little work on grating-type torque sensors has been reported. Recently, all-fiber torque-sensing systems were demonstrated with elasto-optic effects induced by shear stress,$^2$ length changes in a fiber grating bonded to a torsion beam,$^3$ and polarization analysis of the light transmitted through a twisted birefringent fiber.$^4$ However, a H-LPFG has a different mechanism for monitoring applied torsion. When torque is applied to this H-LPFG, the helical pitch ($\Lambda$) of Fig. 1 can be directly changed. Finally, the changes in the pitch affect the phase-matching condition of the helical grating, and the resonance wavelength can be changed.

The helical structure shown in Fig. 1 can be fabricated by rotation of the asymmetric index change along the fiber axis. We have already confirmed that asymmetric index changes can be induced by the conventional single-side beam exposure method with a CO$_2$ laser.$^5$ The fabrication setup (Fig. 2) was designed to rotate the asymmetric index change induced by a single-side beam exposure.

In the characteristic study the H-LPFG shows a similar transmission graph (Fig. 4 below) to that of a conventional LPFG. However, it shows peak shifts when it is twisted. Thus this property can be applied to the optical fiber torque sensors.

The H-LPFG can also be described by the conventional coupled-mode theory between the core and the cladding modes. Derivations of a conventional LPFG can be found in numerous articles; see, for example, Ref. 6. However, a small modification is needed considering the helical structure of the grating. The susceptibility (Fig. 1) of the helical grating can be expressed in the form of rotating asymmetric susceptibility:

$$\epsilon = \begin{pmatrix} \cos Kz & -\sin Kz & \epsilon_a & 0 \\ \sin Kz & \cos Kz & 0 & \epsilon_b \end{pmatrix} \times \begin{pmatrix} \cos Kz & \sin Kz \\ -\sin Kz & \cos Kz \end{pmatrix} = \begin{pmatrix} \epsilon_+ + \epsilon_- \cos 2Kz & \epsilon_- \sin 2Kz \\ \epsilon_- \sin Kz & \epsilon_+ - \epsilon_- \cos 2Kz \end{pmatrix},$$

where $\epsilon_- = (\epsilon_a - \epsilon_b)/2$, $\epsilon_+ = (\epsilon_a + \epsilon_b)/2$. $\epsilon_a$ and $\epsilon_b$ are the maximum and minimum of the susceptibility ellipsoid of the grating, respectively, and $K(= \text{sign } 2\pi/\Lambda)$ is the helical parameter presenting the screw direction and period. The sign
function of $K$ can be $+1$ or $-1$ for a right- or left-handed helix, respectively. Then the coupled-mode equation with the helical susceptibility can be derived as

$$
\left( \frac{\partial A_k^H}{\partial z} \right) = iC \text{ sign}(\beta_k) \sum_l \left[ \varepsilon_- \cos(2Kz) \langle E_k^H | E_l^H \rangle - \varepsilon_- \sin(2Kz) \langle E_k^H | E_l^V \rangle \right]
$$

$$
\times \left[ \frac{A_l^H}{A_k^V} \right] \exp[i(\beta_l - \beta_k)]z,
$$

(2)

where $A_k^H$ and $A_k^V$ are the horizontal and vertical polarization amplitudes, respectively. Constant $C = \omega / (4\epsilon_0 \mu)$, and $\langle E_i^A | E_j^B \rangle = \int E_i^A E_j^B dx dy$ is the field overlap integral. The coupling coefficient can be expressed by

$$
\kappa = \varepsilon_- \langle E_k^H | E_l^H \rangle = \varepsilon_- \langle E_k^H | E_l^V \rangle = \varepsilon_- \langle E_k^V | E_l^H \rangle = \varepsilon_- \langle E_k^V | E_l^V \rangle.
$$

Considering the copropagating coupling between core mode $k$ and one of the cladding modes $l$ with positive helical parameter $K$, the coupled-mode equation can be summarized as

$$
\frac{\partial A_{co}^H}{\partial z} = iC \frac{\kappa}{2} (A_{co}^H - iA_{co}^V) \exp[i(\beta_{co} - \beta_{cl} - 2K)z],
$$

(3)

$$
\frac{\partial A_{cl}^H}{\partial z} = iC \frac{\kappa}{2} (A_{co}^H + iA_{co}^V) \exp[i(\beta_{co} - \beta_{cl} - 2K)z],
$$

(4)

$$
\frac{\partial A_{co}^V}{\partial z} = -i \frac{\partial A_{co}^H}{\partial z},
$$

(5)

$$
\frac{\partial A_{cl}^V}{\partial z} = i \frac{\partial A_{cl}^H}{\partial z}.
$$

(6)

Finally, Eqs. (3)–(6) can be merged into

$$
\begin{bmatrix}
A_{co}^H(z) \\
A_{co}^V(z)
\end{bmatrix} = \begin{bmatrix}
\cos(sz) + i(\Delta \beta/2\sin(sz)) & i(\kappa/s)\sin(sz) \\
\kappa/s\sin(sz) & \cos(sz) - i(\Delta \beta/2\sin(sz))
\end{bmatrix}
\begin{bmatrix}
A_{co}^H(0) \exp(-i\Delta \beta z/2) \\
A_{co}^V(0) \exp(i\Delta \beta z/2)
\end{bmatrix},
$$

(7)

where $\Delta \beta = \beta_{co} - \beta_{cl} - 2K$ and $s = [\kappa^2 + (\Delta \beta/2)^2]^{1/2}$. Similar expressions can be obtained for the vertical part of the wave. The final Eq. (7) is similar to that of a conventional LPFG, whereas the phase-matching condition ($\beta_{co} - \beta_{cl} - 2K = 0$) is a little different since the phase-matching condition for a conventional LPFG is $\beta_{co} - \beta_{cl} - K = 0$.

In Fig. 3 the transmission spectrum of the H-LPFG was obtained analytically by use of the following parameters: coupling coefficient $\kappa = 2.15 \times 10^{-5}$, $L = 6$ cm, and $\Lambda = 811 \mu$m. The transmission curve was similar to that of a conventional LPFG, as expected in Eq. (7).

The schematic apparatus for the fabrication is shown in Fig. 2. The helical index modulation is induced by laser beam irradiation onto a fiber while it rotates and moves continuously along the optical fiber axis. We adopted the deformation method for the fabrication. The CO$_2$ laser was used to inscribe the clear asymmetric index change and to minimize the laser beam polarization perturbations on the index modulation since the polarization of the writing UV beam was shown to have an effect on the photoinduced birefringence. The method using a CO$_2$ laser does not need a photosensitivity fiber. This is also an advantage in fabrication.

The fabrication setup (Fig. 2) is composed of two rotating fiber holders, a rotation motor, a translation stage, a focal lens, and a guider. Two rotating fiber holders are linked to the rotation motor, so the
the fiber was supported by a guider on the bottom. For fabrication time was 120 s, and the fabricated grating length was 410 μm and 5 cm, respectively. The resonant wavelength and the peak depth were measured to be 1545.8 nm and −11.4 dB, respectively. PDL is defined as the maximum change in the transmitted power for polarizations, and it is sensitive to the depth of the transmission spectrum. Thus we tried to match the peak depth only. Moreover, it is difficult to reproduce exactly the same transmission spectrum with different fabrication methods. The PDL meter for the PDL measurements was equipped with a tunable laser diode, a motorized polarization controller, and a powermeter. The measurement results of the transmission spectra and the PDL values were plotted in Fig. 5. The H-LPFG showed a dramatically low PDL value (0.42 dB) with −10.1 dB of peak depth compared with the 7.36 dB of PDL value for a conventional LPFG with −11.4 dB of peak depth. The azimuthally uniform index modulation of an overall H-LPFG might be the main cause of the significantly low PDL.

motor simultaneously rotates the holders at a speed of 37 rpm. While the fiber rotates, the actuator translates the fiber along its axis. The actuator speed is 500 μm/s, and the helical pitch is 811 μm. Helical pitch Λ was set to be of the order of 1000 μm, considering that the grating period of a conventional LPFG is approximately 500 μm, and the resonance wavelength of a H-LPFG is proportional to half of the helical pitch: \( \lambda_R = \Delta n (\Lambda/2) \). The laser exposure time was 120 s, and the fabricated grating length was 6 cm. The fiber used in the experiments was normal single-mode fiber made by Samsung. For fabrication the fiber was supported by a guider on the bottom to prevent sagging. The CO₂ laser power was 5 W, and the laser beam diameter of 4.8 mm was focused to 394 μm with a 38-mm focal-length lens. The transmission graphs of the fabricated H-LPFG were measured with a broadband source and an optical spectrum analyzer. As expected in Eq. (7), the measured transmission graphs of Fig. 4 were similar to that of a conventional LPFG. However, they showed that the resonance peaks were shifted when torsion was applied. The codirectional or contradirectional torsion to the helix of the LPFG effectively reduced or enlarged helical pitch Λ. Thus 90° (4.17 turns/m) of codirectional twist made the spectra of HE₁₁, HE₁₂, and HE₁₃ shift to a shorter wavelength part by 3.4, 3.90, and 5.1 nm, respectively. They also shifted to a longer wavelength part by 3.38, 3.89, and 5.08 nm, respectively, with 90° (4.17 turns/m) of contradirectional twist. The small difference might be caused by experimental error in applying torsion. These wavelength shifts are barely measurable in a conventional LPFG, and these characteristics showed the feasibility of a torque sensor.

For the analysis of polarization characteristics we measured the polarization-dependent loss (PDL) of the fabricated H-LPFG. We measured the PDL in the range of the main peak (HE₁₃) without torsion. For comparison of the PDL level, we also fabricated a conventional LPFG with the single-side surface deformation method. The grating period and the grating length were 410 μm and 5 cm, respectively. The resonant wavelength and the peak depth were measured to be 1545.8 nm and −11.4 dB, respectively. PDL is defined as the maximum change in the transmitted power for polarizations, and it is sensitive to the depth of the transmission spectrum. Thus we tried to match the peak depth only. Moreover, it is difficult to reproduce exactly the same transmission spectrum with different fabrication methods. The PDL meter for the PDL measurements was equipped with a tunable laser diode, a motorized polarization controller, and a powermeter. The measurement results of the transmission spectra and the PDL values were plotted in Fig. 5. The H-LPFG showed a dramatically low PDL value (0.42 dB) with −10.1 dB of peak depth compared with the 7.36 dB of PDL value for a conventional LPFG with −11.4 dB of peak depth. The azimuthally uniform index modulation of an overall H-LPFG might be the main cause of the significantly low PDL.

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