Development of a highly sensitive compact sized optical fiber current sensor

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Abstract: We have experimentally developed a highly sensitive and a compact size current sensor by using the CdSe quantum dots-doped bend insensitive optical fiber, operating in the visible band of wavelength. The modified sensitivity of this sensor was about 675 μrad/(Turn.A.m) for the loop radius of just 10 mm, which is more than 16 times larger than that of the single mode optical fiber current sensor.

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OCIS codes: (060.2310) Optical fibers; (230.2240) Faraday Effect

References and links

1. Introduction

Optical fiber current sensors are attracting worldwide researchers because of their advantages such as lightweight, cost effectiveness and their use in developing all optical fiber devices (e.g. switches, modulators, circulators, and isolators, etc.). Although less sensitive, optical fiber current sensors certainly have advantages over their counterpart bulk glass current sensors as they don’t need bulk optical devices such as polarizers, birefringent plates, special launching lenses; instead they use all optical fiber devices that can be simply spliced, thereby avoiding precision alignment and careful handling [1–9]. Reported optical fiber current sensors include: (a) Fiber Bragg grating (FBG) based optical fiber arrays [9], which have disadvantages such as a high temperature sensitivity, handling difficulties, and a high cost of infrared pumping components needed to develop sensors, (b) Single mode optical fiber current sensors [10,11] that are very portable, light in weight, have small size, and are compatible with existing optical devices; however their low sensitivity to the magnetic field is a main concern, and (c) Specialty optical fiber current sensors e.g., Eu²⁺-ions doped optical fibers that show enhanced Faraday rotation [12] and CdSe quantum dots-doped optical fibers [13] with better current sensitivity than the single mode fiber current sensor. However, all these optical fiber current sensors need big windings of the size of 7.5 cm radius because sharp loops cause substantial radiation losses. In contrary, to make a handy, and a small size current sensor device, the optical fiber used has to be wound with a loop size as small as possible (e.g. 10 mm of radius). Therefore, existing silica glass optical fibers reported for current sensing are not clearly suitable to make small size devices. In this regards, flint glass fibers having smaller photo-elastic coefficient as compared to silica glass fibers have shown bend insensitivity (for birefringence) and enhanced current sensitivity, nearly twice than that of silica glass fibers [14,15]. A major drawback of such devices is their incompatibility with existing optical fibers and networks, which predominantly consist of silica glass fibers.
Recently, bending loss insensitivity in the optical fiber has been successfully addressed by various researchers including our group [16–22]. For the visible wavelength operating fibers, which are of interest to develop the current sensor, bending loss of just 0.23 dB/loop for the loop radius of 5 mm has been reported at 633 nm [20]. It is noted that for a visible wavelength optimized single mode optical fiber, the bending loss exceeds well beyond 100 dB for one loop of 5 mm radius and explains well why these single mode optical fibers cannot support compact devices that need very sharp loops. Therefore, to build a small and a compact device, natural choice will be to use bending-loss insensitive optical fiber (BIF) operating in the visible region (so that low cost visible wavelength sources can be used). A limitation of BIFs for current sensing application is their low sensitivity to the magnetic field, which is the same as the single mode optical fiber. Bend insensitivity along with high magneto-optic sensitivity can be achieved by unifying two technologies of BIF and CdSe quantum dots doped optical fiber to produce a highly sensitive magnetic field sensor. In a current communication, we address this issue by reporting the development of CdSe quantum dots (QDs) doped BIF, where quantum dots were incorporated in the core of the optical fiber. We measured the modified current sensitivity of the CdSe QDs-doped BIF to be more that 16 times than that of the single mode fiber at 633 nm. Describing these effects, we first describe the experimental part to discuss the fabrication of a specialty optical fiber doped with CdSe QDs and having a bend insensitivity function, then we determine the magnetic sensitivity of this fiber in terms of a Verdet constant and finally, we show current sensing results of the current sensor developed using this fiber. It is worth mentioning that the BIF that is discussed in this paper is bending-loss insensitive, and to make it bending-birefringence insensitive, one needs methods such as twisting, annealing, etc.

2. Experiments

To develop the bend insensitive optical fiber, an optical fiber preform with germano-silicate glass composition was fabricated by using the MCVD technique where low index trenches were formed by boron doping during the fabrication of preform. CdSe quantum dots were incorporated in the core of the preform by using the solution doping technique where the toluene solution containing CdSe quantum dots (Sigma Aldrich, peak absorption \( \leq 600 \text{ nm} \), 7.5 mg in 1.5 ml solution) was used. After the solution doping process, subsequent drying of the soaked preform was carried out and an additional glass layer was deposited to reduce possible evaporation of dopants. The optical fiber was drawn with an outer diameter of 125 \( \mu \text{m} \) at 2000 \( ^\circ \text{C} \) using a drawing tower. The optical fiber had the refractive index profile as shown in Fig. 1. A cutoff wavelength was measured to be about 600 nm by using the bend reference technique.

Bending loss characteristics of the CdSe QDs-doped optical fiber were measured by using 1 to 18 loops of various diameters. Input power was applied to the fiber by using a wideband white light source and the output power was detected by the optical spectrum analyzer. The bending loss characteristics of the fiber at 633 nm are shown in Fig. 2 for various numbers of loops at 5 mm of radius. The mean bending loss of the CdSe QDs-doped BIF was about 0.47 dB/loop at 633 nm for 5 mm of a loop radius. Variations of the bending loss of this fiber at various loops of different radii are show in Fig. 3 where a negligible bending loss can be observed for 20 mm bending radius while just 0.18 dB/loop bending loss can be observed for 10 mm of bending radius at 633 nm. These results prove that the bend insensitivity of the CdSe QDs-doped BIF was quite good.
Fig. 1. Refractive index profile of the CdSe QDs-doped bend insensitive optical fiber.

Fig. 2. Bending loss in the CdSe QDs-doped BIF at various bending loops of 5 mm radius. The mean bending loss was 0.47 dB/loop for the 5 mm of bending radius at 633 nm.

Fig. 3. Mean bending loss in the CdSe QDs-doped BIF at various loop sizes. The mean bending loss was 0.47 dB for a loop of 5 mm bending radius and 0.18 dB for the loop of 10 mm radius at 633 nm.
We measured the absorption spectrum of the fiber by using the cutback technique and this spectrum was used to determine the existence of quantum dots. As shown in Fig. 4, two distinct absorption peaks were observed at 608 nm and 585 nm that are related to the CdSe quantum dots in the optical fiber [23]. To further ascertain the presence of CdSe quantum dots, we carried out the transmission electron microscopy (TEM) measurement of the preform sample. As shown in Fig. 5, CdSe quantum dots with radius less than about 2 nm can be observed. The concentration of CdSe quantum dots can be determined by using the absorption coefficient data of Fig. 4. An approximate equation representing the relationship between the absorption cross section and the size of CdSe QDs is expressed as [23]:

$$\sigma = (550.1 \times 10^5)a^3 \quad (1)$$

where $\sigma$ is the absorption cross section in m$^2$, $a$ is the quantum dot radius in m. For CdSe QDs having peak absorption around 608 nm, $\sigma = 4 \times 10^{-19}$ m$^2$, giving the quantum dot size (radius) of about 2 nm, which matches well with the TEM measurement (Fig. 5). The concentration of CdSe QDs (per m$^3$) can also be approximately evaluated using the relationship [23]:

$$C = 8 \times 10^6 / \sigma \quad (2)$$

Equation (2) gives CdSe QDs concentration of about $2 \times 10^{25}$ quantum dots per m$^3$. With this high concentration of CdSe QDs, it is expected that the magneto-optic sensitivity of the CdSe QDs-doped BIF should be high [24].

Fig. 4. Absorption spectrum of the CdSe QDs-doped BIF. CdSe QDs related absorption peaks were absorbed at 608 nm and 585 nm.

Fig. 5. TEM photograph of the CdSe QDs-doped preform sample.
Next, to determine the magnetic sensitivity of the CdSe QDs-doped BIF in terms of the Faraday rotation, we launched the linearly polarized light from the HeNe gas laser (633 nm) into the CdSe QDs-doped BIF (71 cm) that was kept under the influence of magnetic field generated by the dc solenoid and the output power was detected and applied to the polarimeter, which determined the Faraday rotation angle by using a Poincare sphere. Care was taken to minimize the linear birefringence of the fiber and measurements were performed at room temperature (25 °C), which was maintained constant throughout the experiment. Various measurements of the Faraday rotation angle with the applied magnetic field at 633 nm are shown in Fig. 6. Considering the beat length of BIF to be about 10 m (as discussed in the next section), the fiber sample with 71 cm can be approximately considered to be free from random polarization effect, although a small increasing spread in the readings with increased magnetic field does indicate the linear polarization effect. It can be noticed that the mean Faraday rotation angle of the polarization plane was about 40.8 degrees for 0.14 T (as shown in Fig. 6), which is about 2.6 times greater than the Faraday rotation angle of the single mode optical fiber at 633 nm [13]. This enhanced magnetic field sensitivity can be contributed to the high CdSe quantum dots concentration. The Verdet constant of the CdSe QDs-doped BIF can be determined from measurements of Fig. 6 as follows. When the plane of polarization of the light beam passes through the medium that is under uniform magnetic field parallel to the light propagation direction, it rotates by an angle given by,

$$\theta = V B L$$

(3)

where $\theta$ is the rotation angle of polarization plane of light in radians, $B$ is the magnetic field in Tesla, and $V$ is the Verdet constant, which depends on the wavelength, and $L$ is the length of fiber under the influence of magnetic field. A mean value of the Verdet constant was calculated to be 7.2 rad/(T.m). This value is quite higher than that of the CdSe QDs-doped fiber reported earlier in [13].

![Fig. 6. Various measurement results for the Faraday rotation angle with respect to the applied magnetic field measured at 633 nm for the CdSe QDs-doped BIF (Fiber length = 71 cm).](image)

Finally, an experimental arrangement for sensing the current by using the CdSe QDs-doped BIF is shown in Fig. 7. The He-Ne gas laser emitting at 633 nm (10 mW) was used as
the input source. The linearly polarized light at 633 nm was launched into the optical fiber using a collimator. The optical fiber with just 4 m of length was twisted manually with 15 twists per meter to minimize the linear birefringence effect in the optical fiber and then it was wound on a plastic drum (10 mm radius) by using 64 loops. Its output was directly launched into a photo detector attached to the polarimeter connected to a personal computer (PC), which displayed the Faraday rotation angle by using the built-in software. A conductor carrying a high current of 40 A was inserted in the hollow portion of the drum. The magnetic field generated due to flow of the current was detected in terms of Faraday rotation angle by the Pioncare sphere on PC. All measurements were carried out at room temperature.

![Twisted CdSe QDs-doped BIF](image)

**Fig. 7.** A current sensor using the CdSe QDs-doped bend-insensitive optical fiber.

### 3. Results and discussion

As explained earlier, for CdSe quantum dots concentration of $2 \times 10^{25}$ QDs/m$^3$, we obtained the Verdet constant to be about 7.2 rad/(T.m). This high value of the Verdet constant is contributed to the existence of CdSe quantum dots and it is quite higher than the reported mean value of 4.6 rad/(T.m) in the other CdSe QDs-doped optical fiber [13] due to high concentration of quantum dots in our fiber. The current sensor shown in Fig. 7 was realized by using the CdSe QDs-doped BIF with 10 mm of loop radius, which is the smallest size optical fiber current sensor reported so far. Without twists, Pioncare measurements were random due to the presence of significant linear birefringence in the BIF. As per earlier studies, by twisting the fiber by 10 to 15 twists/m, the effect of linear birefringence can be minimized [11,25]. With the twisting rate of 15 twists/m for the CdSe QDs-doped BIF, the Pioncare measurements showed observable results.

Variations of the Faraday rotation angle at 633 nm with the current flowing in the conductor are shown in Fig. 8 for the CdSe QDs-doped BIF. Performance of the optical fiber current sensor is usually determined in terms of the current sensitivity defined as:

$$S = \frac{\theta}{IN}$$

where $S$ is the sensitivity, $N$ is the number of turns, and $I$ is the current in ampere. To consider effects of the loop size, we define the modified current sensitivity as
\[ S' = \frac{\theta}{IN(R)} \quad (5) \]

where \( S' \) is the modified current sensitivity in rad/(A.Turn.m) and \( R \) is the radius of a loop in meter. Comparison of performances of current sensors reported with our CdSe QDs-doped BIF current sensor is listed in Table 1. It can be observed that CdSe QDs-doped BIF current sensor showed the modified current sensitivity of 675 µrad/(A.Turn.m) that is over 8 times and 16 times larger than the modified current sensitivities of the CdSe QDs-doped optical fiber (non-BIF) current sensor and the single mode optical fiber current sensor, respectively.

![Graph](image)

**Fig. 8.** Variations of the Faraday rotation angle (at 633 nm) with respect to the current in the conductor measured for the CdSe QDs-doped BIF (Loop radius = 10 mm). Bars show standard deviation.

**Table 1.** Comparison of modified current sensitivities (µrad/(Turn.A.m)) of various reported optical fiber current sensors.

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<tr>
<td>675 *(6.75 @10 mm)</td>
<td>80 *(6 @75 mm)</td>
<td>41.34 *(3.1 @75 mm)</td>
<td>59.74 *(4.48 @75 mm)</td>
<td>74.4 *(5.58 @75 mm)</td>
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*Current sensitivity in µrad/(A.Turn) @ loop radius

With regards to the birefringence in the BIF, which is defined as \( \Delta n = n_{eff_x} - n_{eff_y} \), where \( n_{eff} \) is the effective index and suffixes \( x \) and \( y \) represent \( x \)-polarization and \( y \)-polarization direction, respectively. The birefringence in units of radian/m can be expressed by:

\[ \Delta \beta = (\beta_x - \beta_y) = \frac{2\pi}{\lambda} \Delta n \quad (6) \]

where \( \beta \) is the propagation constant, and \( \lambda \) is the operating wavelength. The beat length where the state of polarization repeats itself is given by

\[ L_b = \frac{\lambda}{\Delta n} \quad (7) \]

Assuming that the plane wave is travelling in \( z \)-direction and stress exists in only \( x-z \) or \( y-z \) plane, the stress related linear birefringence in the optical fiber is expressed as:
\[
\Delta n = \left(\frac{\sigma}{2}\right) (\rho_{11} - \rho_{12})
\]

where \(n\) is the cladding index, \(\rho_{11}\) and \(\rho_{12}\) are stress-optical coefficients (\(\rho_{11} = 0.12, \rho_{12} = 0.27\) for silica glass), and \(\sigma\) is the stress tensor.

In earlier studies regarding birefringence of optical fibers, the single mode optical fiber had shown the beat length of about 30 m to 100 m and the dispersion shifted fiber with boron doping had shown higher birefringence as compared to the single mode optical fiber with the beat length value of about 10 m and the polarization mode dispersion of about 0.061 ps/(km)^{1/2} [26,27]. Typical commercial bend insensitive optical fiber of [28] has the polarization mode dispersion of about 0.06 ps/(km)^{1/2}, and by considering the boron doping and similarity between our and reported fibers, for the qualitative discussion, the beat length of our BIF can be assumed to be about 10 m.

When the optical fiber is straight, by using Eq. (6) to Eq. (8), its linear birefringence can be calculated to be \(6.33 \times 10^{-8}\) or \(0.628\) radians/m at 633 nm with \(\sigma = 2.73 \times 10^{-7}\). However, when this optical fiber is bent with the bending radius of \(R_b\), the linear birefringence (rad/m) due to bending is expressed as [29]

\[
\Delta n_b = \left(\frac{\sigma}{2}\right) (\rho_{11} - \rho_{12}) \left[\frac{\pi}{\lambda} \left(1 + \nu_p\right) \frac{f^2}{R_b}\right]
\]

where \(\nu_p\) is the Poisson’s ratio (\(= 0.17\)), and \(f\) is the fiber radius (\(= 62.5 \mu m\)). For the case of optical fiber loops with 10 mm of radius, the linear birefringence of the optical fiber is about 52.6 rad/m with \(\sigma = 2.28 \times 10^{-5}\) at 633 nm, which is equivalent to the beat length of about 12 cm. When the optical fiber with large linear birefringence (as in the case of bent BIF) is subjected to the magnetic field parallel to the propagation direction, resulting circular birefringence will be dominated by the bend related linear birefringence, and this results in the significant reduction in the response of the current sensor to the magnetic field. As suggested in the earlier report, the effect of linear birefringence can be limited by twisting the optical fiber with the twist rate of 10-15 twists/m [30], which is quite less to make the circular birefringence a dominating factor. As we have already discussed, after twisting, the Faraday rotation was about 1° for 40 A of current, which was although enough to detect the current, was quite small and indicates the presence of stray linear birefringence in the bent optical fiber. To elaborate this point, let’s take a specific example. In the presence of the circular birefringence and the linear birefringence, the signal \(R\) (in arbitrary units) at the photo-detector is given by [31]:

\[
R = 2\theta \frac{\sin[4\theta^2 + (\Delta n_b L)^2]}{4\theta^2 + (\Delta n_b L)^2}
\]

where \(\theta\) (in radians) is the rotation of the plane of polarization due to circular birefringence. After twisting the BIF by 15 twists/m and passing of the current through the conductor (40 A), we measured \(\theta\) to be equal to 0.0075 rad at \(L = 4\) m. By using this data, and the linear birefringence due to bending of the BIF calculated from Eq. (9), i.e., to be \(\Delta n_b = 52.6\) rad/m, gives \(R = 4.3 \times 10^{-7}\). Now, consider a case where the linear birefringence is negligible in the bent BIF, i.e., \(\Delta n_b = 0\), and we get \(R = 0.035\), a huge improvement in the value of \(R\). Thus, in the presence of linear birefringence, one needs sensitive-photo detector at the receiving end so that even a low quality signal can be accepted. In the earlier work, the problem of linear birefringence was addressed by annealing the optical fiber at 850 °C followed by slow cooling [32]. In another approach to reduce the linear birefringence effect, elliptically birefringent fibers were produced by spinning preforms during the drawing process [33]. Although for our CdSe QDs-doped optical fiber current sensor we did not carry out annealing and spinning (rather we used twisting), it detected current from 1A to 40A reasonably well in the...
temperature controlled laboratory environment. It is noted that, to make it more stable during the harsh environment, one would need annealing the BIF before applying it for the temperature sensing application [32].

4. Summary

We have developed an optical fiber current sensor by using the CdSe QDs-doped bend insensitive optical fiber. The bending loss of the fiber was mere 0.47 dB for one loop of 5 mm radius, and 0.18 dB for one loop of 10 mm radius at 633 nm. This allowed us to build a very tiny size optical fiber current sensor (10 mm of radius), which showed the modified current sensitivity to be 16 times larger than that of the single mode optical fiber operating at 633 nm.

Acknowledgements

This work was supported by the GIST Top Brand Project (Photonics 2020), Ministry of Science and Technology, South Korea, by the National Core Research Center (NCRC) for Hybrid Materials Solution of Pusan National University, by the Brain Korea-21 Information Technology Project, Ministry of Education and Human Resources Development, South Korea, and by the GTI, Gwangju Institute of Science and Technology, Gwangju, South Korea.