Demonstration of All-Optical Fiber Isolator Based on a CdSe Quantum Dots Doped Optical Fiber Operating at 660 nm

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***Abstract*—A novel all-optical fiber isolator with 14 dB isolation at 660 nm was demonstrated using the CdSe quantum dots doped optical fiber, which was fabricated by using the modified chemical vapor deposition and high temperature drawing processes. The Faraday rotation angle of 45 degrees was obtained at the fiber length of 183 cm under the magnetic field of 0.119 T.**

***Index Terms*—Faraday effect, fiber isolator, optical fiber, quantum dots.**

I. Introduction

OPTICAL isolator, which is a non-reciprocal device to allow propagation in only one direction, has gained much attention for its applications in high power optical fiber lasers, optical amplifiers, and high-speed fiber optic communication systems to block unwanted back reflections and unwanted propagation of light [1]–[17]. When the linearly polarized light propagating through the medium undergoes 45° rotation of plane of polarization due to applied magnetic field and if this light is reflected back to the medium again, the plane of polarization the light is again rotated by 45°. Thus, the back-reflected light with 90° rotation of the plane of polarization is blocked resulting in isolation of the reflected light. This phenomenon can be used to avoid self-oscillations of the fiber amplifier and to decrease the noise in the light signal, and to prevent the damages of the signal source or laser source caused by back-reflections from optical devices such as fiber optic connectors and receivers [1]–[4].

Most popular optical isolators using paramagnetic glasses, magneto-optic garnet crystals, films, and ridge waveguides are based on the well-known magneto-optic Faraday effect. But they need bulk optical parts such as birefringence plates and special launching lenses and thus precision alignment and careful handling are needed [1], [5]–[10]. In this scenario, isolators made by using optical fibers with large Faraday effect are of great interest for all-optical device applications, fiber laser system and fiber optic amplifiers because they offer advantages like low insertion loss, high return loss, and high isolation together with no need of bulky optical parts and precise alignment [11]–[15].

Recently, a diode laser or a second-harmonic signal source operating at 660 nm is known to be used as a laser source in fiber laser systems for industrial and bio-medical applications [16]–[18]. However, in our best knowledge, an all-optical fiber isolator operating at 660 nm wavelength has been not yet reported; mainly due to the low sensitivity of silica glass fiber, which is attributed to its low magneto-optic sensitivity at visible wavelength (Verdet constant $\sim -0.64\ \mathrm{rad/T{\cdot}m}$ at 1550 nm and $-0.22\ \mathrm{rad/T\cdot m}$ at 1310 nm [19]–[21]). Even though specialty optical fibers such as annealed fiber, twisted fiber, spun fiber and flint glass fiber were suggested to improve the magneto-optic sensitivity by reducing linear birefringence of fibers [22], [23], drawbacks such as complicated fabrication process, high splicing loss, and high cost are still bottlenecks in their mass production. To overcome these problems, phosphate or borosilicate glass optical fibers incorporated with Tb-ions having high Verdet constant were reported where a rod-in-tube technique was used [11]; the propagation loss of fiber was found to be significantly higher than that of silica glass fiber. In the current communication, we report the development and demonstration of the all-optical fiber isolator based on the specialty optical fiber doped with CdSe quantum dots (QDs) for enhanced magneto-optic sensitivity, which is the first reported isolator allowing optical isolation at 660 nm [24].

II. Theory

Faraday effect arises as a result of the different indices of refraction for right and left circularly polarized lights (n_+ versus n_-). The equation of motion of a valence electron in magnetic field is defined by the complex refractive index relationship [19], [25], [26],

$$(n_\pm - ik_\pm)^2 = \varepsilon_\infty \left\{ 1 - \frac{\left(4\pi N e^2\right)^2}{(m^*\varepsilon_c)^2 \omega \left[\omega \pm \left(\frac{He}{m^* c}\right) - i\nu\right]} \right\} \tag{1}$$

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where $n_\pm$ and $k_\pm$ are refractive and absorptive indices, respectively, $N, e, m^*, \varepsilon_\infty$, and ε_c are total valence electrons, an electronic charge, the effective mass of electron, the background dielectric constant, and dielectric constant of the medium, respectively, ω is an operating angular frequency, H is the magnetic field, c is the velocity of light and ν is the scattering frequency. Equation (1) shows that the alteration of the indices of refraction for left and right-circularly polarized lights are affected by the magnetic field.

Refractive indices, $\mathrm{n}_\pm$, are influenced by the change between polarization states and their differing energy levels in terms of quantum mechanics [19], [25], [26]. The interaction of a photon with the right-circular polarization can cause electrons in spin-down states to make transition to spin-up states. Similarly, the left-circular polarization can cause electrons states to make transitions from 1/2 states to $+1/2$ states. Superposition of these effects of electronic transitions gives the Faraday effect [19], [27]. In QDs, infinite potential wells cause excitons and electrons to experience confinement energies as the quantum dot size reduces. A strong confinement influences the exchange interaction of electrons and holes causing modifications in Verdet constant [19]. Therefore, the CdSe QDs doped optical fiber is a good candidate to develop all-optical fiber isolator.

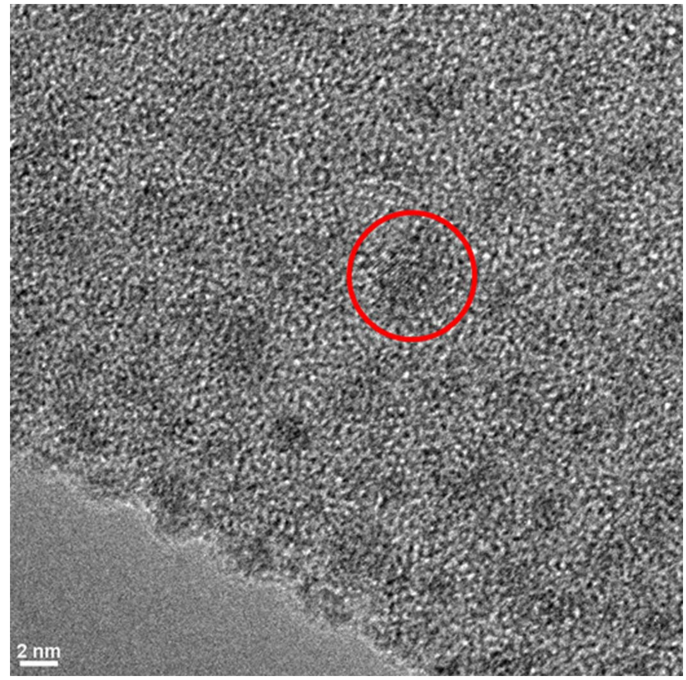

Fig. 1. TEM image of the CdSe QDs doped optical fiber preform.

III. Experiments

A fiber preform doped with CdSe QDS was fabricated by using the modified chemical vapor deposition (MCVD) process. Core layers of alumino-germano-silica glass deposited onto inner surface of a silica glass tube was doped by the solution doping process using a toluene solution containing CdSe QDs (Sigma-Aldrich: Lumidot CdSe QDs in toluene, peak absorption ~ 650 nm, 7.5 mg in 1.5 ml solution) at room temperature [19]–[21]. It was observed during the experiments that incorporation of CdSe QDs in the core of the optical fiber preform was quite challenging. Although not fully stabilized, we used a simple technique to deal with the problem. Initially the core layers were deposited inside the silica glass tube in the form of soot at 1400°C and the soot was cooled to room temperature. Then the doping solution was infiltrated into the soot of core part for 1 hour to incorporate CdSe QDs. The wet soot was then dried by flowing Cl_2 and He gases in the tube. To reduce possible evaporation of the dopants during sintering of the soaked layers of the core part at about 2100°C, an additional silica glass layer was deposited onto them. Then the tube was collapsed and sealed into a rod preform. Finally, the preform was drawn into fibers with outer diameter of 125 μm at 2150°C by using the draw tower. The core diameter and the cut-off wavelength of the fabricated fiber were 5.4 μm and 560 nm, respectively. The mode field diameters (MFDs) of the optical fiber were 13.1 μm and 13.6 μm at 1310 nm and 1550 nm, respectively, which were measured by using the optical fiber analysis system (Model: 2500, PK Technology).

The GeO_2 concentration was about 1.5 mole% in the optical fiber core and the estimated concentration of CdSe QDs was about 2.2 $\times 10^{24}$ m^{-3}. The average CdSe QDs size in the core of the fiber preform was about 4 nm in diameter (size distribution: 2.0 nm to 4.8 nm) obtained from the transmission electron microscopy (TEM, FEI Tecnai G2 F30 S-TWIN) as shown in Fig. 1, [19]. The TEM photograph clearly shows the morphology of CdSe QDs in the optical fiber preform core retained even after the high temperature MCVD process, which is crystalline, to be roughly spherical without agglomeration. To verify the existence of CdSe QDs in the CdSe doped optical fiber core which was drawn from the preform at high temperature again, the optical absorption spectrum of the CdSe QDs doped fiber was measured. The absorption peaks due to CdSe QDs in the fiber core was found to appear at 622 nm, 633 nm, and 662 nm as shown in Fig. 2. Note that the absorption spectrum with multi-peaks was due to the size difference of the embedded QDs as shown in Fig. 1 [21], which is also the evidence of the existence of CdSe QDs in the fiber core after drawing the preform into the fiber at high temperature of about 2150°C. Absorption coefficient of the fiber was about 0.0008 cm^{-1} at 660 nm.

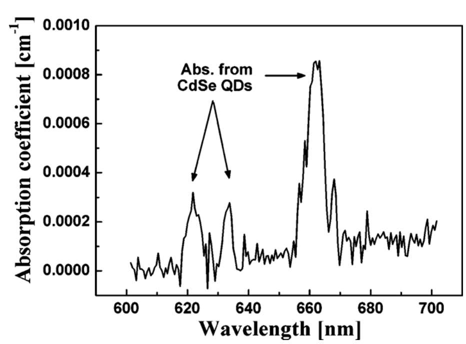

Fig. 2. Absorption spectrum of the CdSe QDs doped optical fiber.

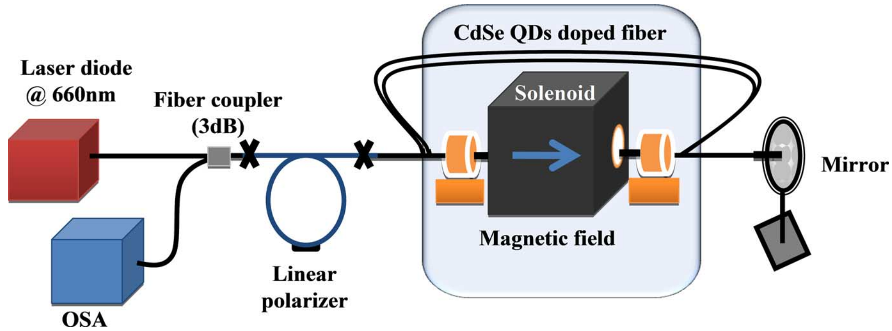

Fig. 3. Experimental set-up to measure the magneto-optic properties of the CdSe QDs doped optical fiber for a fiber isolator application.

To measure a Faraday rotation angle of the CdSe QDs doped optical fiber, a linearly polarized light from a 660 nm laser diode was launched through a linear polarizer into the fiber of the effective length of 183 cm under magnetic field generated by a DC solenoid. Note that the CdSe QDs doped optical fiber was wound around the solenoid to increase the length of the fiber, which is the total length of the fiber under the same direction of magnetic field. The output power was applied to the polarimeter (PA510: Thorlabs, USA) and the Faraday rotation angle was determined by using a Poincare sphere. Experimental set-up with the fiber isolator configuration is shown in Fig. 3, where the LD output power was ~ 1.1 mW. The reflected output optical spectrum by the reflection mirror (Silver coated mirror) was monitored by the optical spectrum analyzer (OSA, resolution: 1 nm). The CdSe QDs doped optical fiber was single mode at the wavelength of 660 nm and a fiber type linear polarizer (operating at 660 nm, OZ Optics Ltd.) was directly spliced with the fiber. Optical loss of the present fiber isolator was less than 1.7 dB, including < 1 dB of insertion loss of the linear polarizer, 0.6 dB of propagation loss in the CdSe QDs doped fiber of 183 cm length, and < 0.1 dB of splicing loss between the linear polarizer and the CdSe QDs doped fiber. The propagation loss of the fiber can be decreased by shortening the length of the fiber by using a strong magnet tube instead of the lengthy DC solenoid and that would make all-optical fiber isolator with less than 1 dB of insertion loss.

IV. Results and Discussion

Figs. 4 and 5 show the measurement results of the Faraday rotation angle and the change in polarization states on a Poincare sphere of the CdSe QDs doped optical fiber at 660 nm as a function of magnetic field, respectively. With the increment of applied magnetic field by varying DC current of the solenoid, the Faraday rotation angle of the CdSe QDs doped fiber was found to increase linearly as shown Fig. 4. When the magnetic field of 0.119 T was applied to the effective length 183 cm of the fiber, the Faraday rotation angle reached to 45°. Since the polarization angle of 90° rotation of back-reflected light is expected due to the non-reciprocal nature of the Faraday effect, this result clearly demonstrates a possibility of developing all-optical fiber isolator that can block the reflected light at 660 nm. In the earlier work, the Verdet constant of the CdSe QDs doped fiber was measured to be 3.8 $\mathrm{rad/T \cdot m}$ and 0.358 $\mathrm{rad/T \cdot m}$ at 633 nm and 1310 nm, respectively [19]–[21]. The Verdet constant at 1310 nm decreased about 0.1 times as compared to its value at 660 nm, due to the absence of CdSe QDs related absorption peak at 1310 nm. This also justifies the use of 660 nm in this work as an operating wavelength for the Faraday isolator.

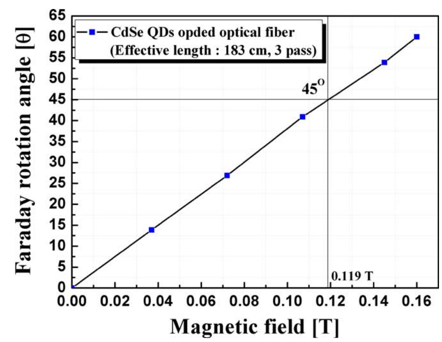

Fig. 4. Variation of the Faraday rotation angle of the CdSe QDs doped optical fiber with magnetic field.

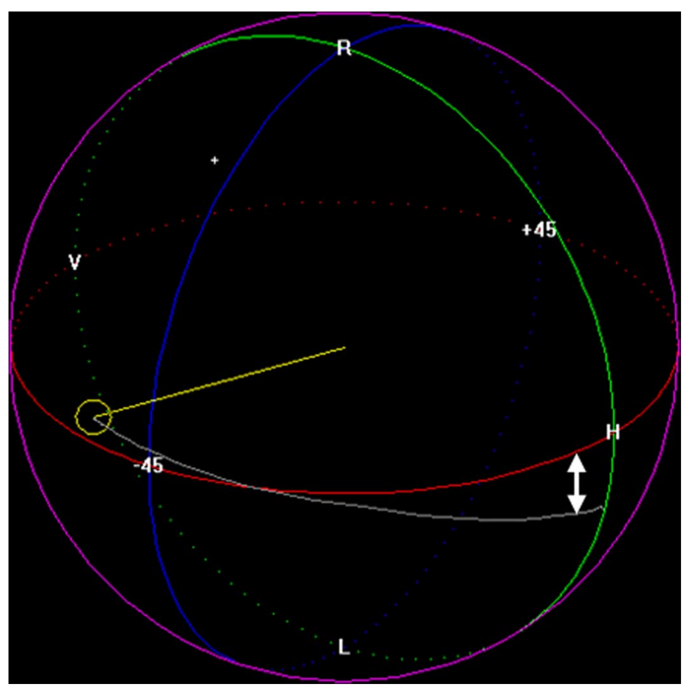

Fig. 5. Faraday rotation of the CdSe QDs doped optical fiber on a Poincare sphere.

Fig. 5 shows the Faraday rotation, i.e., the change in polarization states, of the CdSe QDs doped optical fiber on a Poincare

TABLE I
EXPERIMENTAL RESULTS OF THE ALL-OPTICAL FIBER ISOLATOR USING THE CDSE QDS DOPED OPTICAL FIBER UPON MAGNETIC FIELD APPLICATION

Solenoid current [A]	Magnetic field [T]	Faraday rotation angle [θ]	Output power [dBm/nW]	Normalized output power	Isolation [dB]
0	0	0	-50.67/8.56	1.000	0
10	0.037	27.8	-51.99/6.31	0.737	1.32
20	0.072	53.8	-54.44/3.59	0.420	3.77
30	0.107	81.8	-60.22//0.95	0.111	9.55
35	0.124	95.0	-64.64/0.04	0.034	13.97
40	0.145	107.8	-59.54/1.11	0.130	8.87
45	0.160	120.0	-57.02/1.98	0.232	6.34

sphere. It is noted that the light signal from the LD at 660 nm passed through the fiber type linear polarizer, and its polarization state was nearly maintained at the output of solenoid. As shown in Fig. 5, a small gap (indicated by the arrow) between polarization state of output signal (gray line) and linearly polarized state (red line) was found on the sphere, which indicates a change of polarization state of the light signal from linear to elliptical or circular. This can be mainly attributed to induced linear birefringence of the optical fiber by bending from the winding of the optical fiber around the solenoid to increase an effective length.

Regarding the Faraday rotation, as the light is reflected directly backward, rotation is additive due to non-reciprocal nature of the Faraday effect. The measurement of actually reflected power at the input side with change in the magnetic field strength would only give the idea of isolation offered by the fiber optic device. For this, an experiment (see Fig. 3) was carried out by using the reflection mirror, which reflected the 660 nm excitation from the CdSe QDs doped optical fiber and the back reflection power was measured by using the 3 dB coupler (at 660 nm). Fig. 6 shows the variation of the normalized output power (reflected power) of the fiber with the measured Faraday rotation angle upon varying magnetic field from 0 to 0.160 T. The normalization was made with respect to the output power without magnetic field. The normalized output power was found to decrease with the increase of the Faraday rotation angle and no output power was detected at the angle of 90°, indicating an excellent isolation property. When the Faraday rotation angle was over 90°, the output power increased again because the polarization state started to return back to the original state. The reflected optical power can be simply described from the Malus' law as [28]

$$I = I_0 \cos^2 \theta \quad (2)$$

where I and I_0 are the power of the reflected optical signal (backward proportion) and the incident light source (forward propagation) by the OSA, respectively, and θ is Faraday rotation angle. Note that the attenuation factors such as bending, coupling, splicing, and reflecting loss of optical power were ignored in the equation. As shown in Fig. 6, the obtained output power data were fitted to a cosinusoidal curve and matched well with a small deviation error. The optical isolation of the present CdSe QDs doped optical fiber isolator with respect to the applied magnetic field is shown in Fig. 7. The maximum isolation

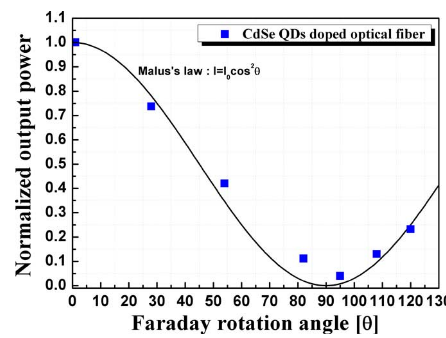

Fig. 6. Variation of the normalized output power of the CdSe QDs doped optical fiber with Faraday rotation angle.

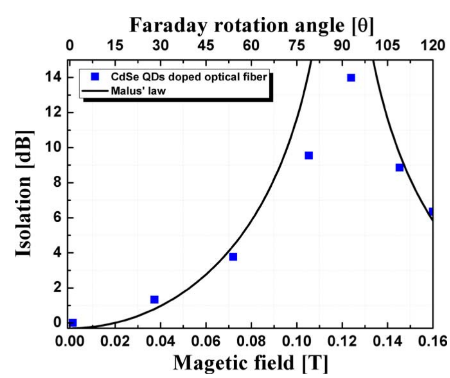

Fig. 7. Variation of the optical isolation of the CdSe QDs doped optical fiber with magnetic field.

was about 14 dB at 0.124 T and it increased as the magnetic field increased from 0 to 0.124 T. When the magnetic field was larger than 0.124 T, the isolation decreased due to the fact of polarization state started returning to the earlier state. The small deviation of the magnetic field (0.124 T) for the maximum isolation of 14 dB from that (0.119 T) for the Faraday rotation angle of 45° is due to the linear birefringence variations induced by environmental noise by using the reflection mirror. This error can be decreased further by using a total reflection mirror such as fiber Bragg grating at 660 nm [11], [29].

The mismatch between experimental results and lines obtained from the theory (the Malus' law) in Figs. 6 and 7 is due to the linear birefringence of the optical fiber induced by windings of the optical fiber around the solenoid to increase the effective length. To enhance accuracy and performance of the all-optical fiber isolator, the linear birefringence should be minimized along the fiber. This could be done by using specialty optical fiber of high Verdet constant so that a short length of the fiber can be used, thereby eliminating bending of the optical fiber to induce very high circular birefringence [6]. The experimental results of the all-optical fiber isolator using the CdSe QDs doped optical fiber upon applying the magnetic field are summarized in Table I. This all-optical fiber isolator can find applications in various optical fiber devices such as optical switches, optical modulators, non-reciprocal elements in laser gyroscopes, optical circulators, and optical sensors.

V. Conclusion

A novel all-optical fiber isolator operating at 660 nm was developed and demonstrated by using the CdSe QDs doped optical fiber. Faraday rotation angle of 45° and the optical isolation of 14 dB were obtained at 0.119 T and 0.124 T of magnetic field, respectively, by using the fiber with the effective length of 183 cm.

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