Faraday Effect in an Optical Fiber Doped with CdSe Quantum Dots

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An optical fiber doped with CdSe quantum dots was developed by using the modified chemical vapor deposition process, and its magneto-optic property was investigated. The Verdet constant of the CdSe quantum-dot-doped optical fiber was found to be improved by more than two times as compared to the undoped single-mode optical fiber. The measured value of the Verdet constant was about 4.25 rad T$^{-1}$m$^{-1}$ at 632 nm for the CdSe quantum-dot-doped optical fiber.

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I. INTRODUCTION

Recently, semiconductor quantum-dot (QD)-doped glasses and fibers have attracted attention due to their applications, such as Faraday rotators, current sensors, etc., in the area of magneto-optic effects [1–3]. Information that can be used to explain the electronic states and the effective masses and to understand the theory of matter can be extracted by studying the Faraday effect in semiconductors. The bulk semiconductor response upon applying a magnetic field has already been explored [4, 5], and semi-magnetic semiconductors (II-Mn-VI) follow bulk semiconductors, where a giant Faraday rotation has been measured [6,7]. Transformation from bulk materials to nanocrystals enhances the Faraday rotation [7], and the effect of size quantization on the exciton energy has been studied [8]. In one such study, silica glass doped with Cd$_{1-x}$Mn$_x$Te nanocrystals showed large enhancements in the Faraday effect as compared to the bulk Cd$_{1-x}$Mn$_x$Te crystal [9]. Research work in the area of SiO$_2$ glasses doped with CdS, CdTe, and CdSe semiconductor nanocrystals has shown enhancements in the Faraday effect by at least a factor of two [10]. The nanocrystal size and the interatomic lattice spacing have been found to have a significant effect on the magnitude of the Faraday rotation.

The advantage of quantum dots in a glass is from the controllability of the quantum dot size, and thereby the magneto-optic responses. Thus, semiconductor nanocrystal, such as CdSe QDs, have already been well studied in bulk glasses and have shown a strong magnetic dependence of its optical properties [11]; however, such studies have not been carried out in the case of optical fibers doped with semiconductor quantum dots. Considering a single-mode optical fiber, its main advantage is its portability because no bulk optics (containing lenses, glass polarizer, etc.) are needed to couple light in or out of the fiber. If used as a Faraday rotator, single-mode optical fiber’s light weight, small size, and compatibility with existing light devices such as laser diodes and detectors, make the Faraday rotator a very compact device. However, a disadvantage of an optical fiber is that it is not very sensitive to magnetic effects. Earlier, our group made some efforts to address this issue by doping an optical fiber core with europium ions [1]. In the present communication, we report the fabrication of an optical fiber doped with CdSe quantum dots by using the modified chemical vapor deposition (MCVD) process. Its Faraday rotation was shown to be enhanced by more than a factor of 14 as compared to that of a single-mode optical fiber.

II. EXPERIMENTS

An alumino-germano-silicate optical fiber preform was fabricated at about 2200 °C by using the modified chemical vapor deposition technique, and its core was doubly-doped at room temperature with a solution containing CdSe quantum dots (Sigma-Aldrich, peak absorption =

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Fig. 1. Experimental setup to measure the Faraday rotation angle.

Fig. 2. Spectral absorption characteristics of the CdSe QD-doped optical fiber.

650 nm, 5 mg/ml in tuleone, solution: 1.5 mL, approximate concentration: $1.1 \times 10^{26}$ QDs/m$^3$) by using a modified solution doping technique. An additional glass layer was deposited after the solution doping, and the soaked preform was subsequently dried to reduce possible evaporation of dopants. The optical fiber was drawn with an outer diameter of 125 µm at 2000 °C by using a drawing tower. The optical fiber had a core diameter of 5.36 µm, a GeO$_2$ concentration of 1.5 mole% in the optical fiber core, and a cutoff wavelength of 559 nm. A single-mode optical fiber without CdSe quantum dots was also fabricated, which had a cutoff at 600 nm.

The absorption spectrum was measured using a cut-back method, where emission from a broadband light source was coupled into the optical fiber, and output powers were noted for a short and a long length of the same optical fiber; the power ratio was used to calculate the absorption coefficient.

To measure the Faraday effect in the CdSe quantum-dot-doped optical fiber, we used the experimental setup shown in Fig. 1. A He-Ne laser (632 nm, 10 mW), a linear polarizer, a 71-cm-long DC solenoid, an optical fiber collimator, and a polarimeter for a wavelength band of 450 ~ 700 nm (PA510: Thorlabs, USA) were used. The Faraday rotation angle of the CdSe QD-doped optical fiber was measured under the magnetic field by placing it inside a solenoid. The polarimeter was interfaced with a personal computer (PC), and the polarization data were obtained. Careful alignment was carried out to eliminate the alterations in the polarization due to external factors. For this purpose, a linearly-polarized laser beam (632 nm) was directly focused onto the optical fiber, and the output of the fiber was directly focused on to the detector head of the polarimeter.

III. RESULTS AND DISCUSSION

The absorption spectrum of the CdSe QD-doped optical fiber is shown in Fig. 2, where the absorption peak at 662 nm can be attributed to the existence of CdSe QDs in the optical fiber core. The small amplitude of the absorption coefficient indicates that the CdSe quantum-dot concentration was low because the MCVD process was carried out at a high temperature of 2200 °C and survival of quantum dots at this temperature is difficult. However, it is worth noting that our double-doping technique, followed by deposition of an additional glass layer, was partially successful to retain some of the CdSe quantum dots. Even with a low concentration of CdSe quantum dots, we noticed a very good magneto-optic effect in the present optical fiber, as will be discussed below. To measure the Faraday rotation angle of the fiber at different magnetic fields, we continuously varied the solenoid current as shown in the set-up of Fig. 1. A typical measurement result for the changing polarization states on a Poincare sphere during the Faraday rotation measurement is shown in Fig. 3. We measured the deflection of the Faraday rotation angle upto 22 degrees, which can be further increased by increasing the magnetic field. Measured variations of the Faraday rotation angle with respect to the applied solenoid current are illustrated in Fig. 4. The Faraday rotation angle was found to vary almost linearly with the solenoid current, and this linear dependence could be calculated as $\theta/I = 0.546$ degree/A, with a standard deviation of 0.186 degrees, where $\theta$ is the Faraday rotation angle in degrees.
Table 1. Comparison of the values of the Verdet constant for different optical fibers.

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<td>4.25 rad T⁻¹m⁻¹ (at 632 nm)</td>
<td>−0.93 T⁻¹m⁻¹ (1310 nm)</td>
<td>−2.1 T⁻¹m⁻¹ (632 nm)</td>
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*aMeasured

Fig. 3. Faraday rotation of the CdSe QD-doped optical fiber on a Poincare sphere.

and \( I \) is the solenoid current.

The Faraday rotation angle data was further used to determine the Verdet constant, which is defined as

\[
V = \frac{\theta}{BL} = \frac{\theta/I}{(B/L)L},
\]

where \( V \) is the Verdet constant, \( B \) is the applied magnetic field, and \( L \) is the optical fiber's length under a magnetic field (= 71 cm). The value of \( V \) for the optical fiber doped with CdSe quantum dots (using Fig. 4) was calculated to be 4.25 rad T⁻¹m⁻¹. A similar process was adopted to measure the Verdet constant of the undoped single-mode optical fiber. A comparison of the values of the Verdet constant for different optical fibers is listed in Table 1, where the measurement wavelength depended on the cutoff wavelength of each optical fiber; our CdSe quantum-dot-doped optical fiber and undoped single-mode optical fiber were single-mode at 632 nm while the other fiber under consideration (Eu-doped) was multimode at that wavelength (which produced a random rotation at 632 nm). The Verdet constant of the CdSe quantum-dot-doped optical fiber can be observed to be more than twice that of the undoped single-mode optical fiber, proving the advantage of CdSe quantum-dot in the core of an optical fiber. From a device point of view, for example, for a current sensor, this will result in a sensor with CdSe quantum dots doped in the optical fiber being more than twice as sensitive as an undoped optical fiber sensor. The Faraday rotation in the optical fibers doped with CdSe quantum dots, from the quantum-mechanical standpoint, can be attributed to a linear superposition of effects of various electron transitions involving the right and the left circular components of the index of refraction. These effects contribute to the susceptibility tensor and, thereby, to the differential magnitude of the interactions of waves (having different circular polarizations) with the component electrons in the quantum dots [11]. One can state that the Verdet constant can be further improved by increasing the concentration of CdSe QDs and by optimizing the QD size.

IV. CONCLUSION

In conclusion, the CdSe QD-doped optical fiber showed an enhanced magneto-optic effect. The Verdet constant was measured to be 4.25 rad T⁻¹m⁻¹ at 632 nm for the CdSe quantum-dot-doped optical fiber while it was about −2.1 rad T⁻¹m⁻¹ for the undoped single-mode optical fiber at 632 nm.
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