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Refractive index of aqueous solution of CdTe quantum dots

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Abstract

The refractive index of aqueous solution of CdTe quantum dots is measured by the retroreflection method on the fiber-optic end face. The dependence of the refractive index on the temperature and the concentration of the quantum dots aqueous solution are investigated. The data of refractive index we measured in this paper may be useful in photonics applications of aqueous solution of CdTe quantum dots.

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1. Introduction

The magnitude of refractive index (RI) variation as a function of temperature, or the thermal coefficient of the refractive index, dn/dT, is a very important property for photonic materials and devices. It plays vital role in many areas of material science with special regarding to thin film technology, integrated optics, waveguide optics and fiber-optics [1,2]. Furthermore, thermal coefficient of the RI can also be used to calculate thermal expansion coefficient [3]. As we know, the refractive index of a medium depends on the density of the medium as well as temperature. With the decrease in solution concentration, the density of the solution decreases, resulting in a decrease in refractive index [4]. Recently, there are many literatures on investigating dn/dT and dn/dc of different materials [5–10].

In the last two decades, quantum dots (QDs), especially, CdS, CdSe, CdTe, PbS, GaN, GaAs, have been emphasized increasingly by many scientists due to peculiar optical properties. With research progress on QDs, it shows some potential applications. Photonics, telecommunication, biochemistry and biophysics applications based on QDs have been studied by many authors [11–22]. As we know, RI is a fundamental parameter for a material used for a photonics device. However, there is little report on measurement of refractive index of liquid doped QDs. In this paper, we investigate the RI of deionized water doped CdTe quantum dots. The retroreflection method on the fiber-optic end face in literature [23] is employed because its simplicity in principle and convenience to operate.

2. Experimental results and discussion

In our experiment, we chose pure deionized water as the solvent and water-soluble CdTe quantum dots as the solute. Four different concentrated samples with uniform sized CdTe QDs were used with concentration of $c1 = 1.917 \times 10^{-4}$ mol/l, $c2 = 1.597 \times 10^{-4}$ mol/l, $c3 = 1.198 \times 10^{-4}$ mol/l, and $c4 = 0.959 \times 10^{-4}$ mol/l, respectively. A light with a wavelength of 1550 nm was used in our experiment. As we measured that the absorption resonance of

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the CdTe QDs aqueous solution is located around 580 nm and it is transparent in the 1550 nm region.

The total reflectivity of light intensity on the interface of CdTe QDs aqueous solution and fiber is

$$R = \left(\frac{n_{fc} - n_s}{n_{fc} + n_s}\right)^2, \tag{1}$$

where n_s is the refractive index of CdTe QDs aqueous solution, and $n_{fc} = 1.4682$ is the effective mode index of fiber core. Here we ignore the extinction coefficient k, because the transparency of the solution at 1550 nm. In order to satisfy the condition of normal incidence, the fiber end face must be flat cleaved (with an error lease than 0.002 rad). We chose air and pure deionized water as the samples for our calibration to avoid the intrinsic reflection. The intrinsic reflection power P_0 can be achieved by the following relationship:

$$\frac{(P_{dw} - P_0)}{(P_{air} - P_0)} = \frac{(n_{fc} - n_{dw})^2/(n_{fc} + n_{dw})^2}{(n_{fc} - n_{air})^2/(n_{fc} + n_{air})^2}, \tag{2}$$

where $n_{dw} = 1.3325$, is the refractive index of pure deionized water, $n_{air} = 1$ [24] is the refractive index of air, P_{dw} and P_{air} are the measured reflection powers when the detected fiber tip is immersed in pure deionized water and air, respectively. Then we obtain:

$$n_s = \left[\frac{1+k}{1-k} \pm \sqrt{\left(\frac{1+k}{1-k}\right)^2 - 1}\right] n_{fc} \tag{3}$$

$$k = \frac{P_s - P_0}{P_{air} - P_0} \cdot \frac{n_{fc} - n_{air}}{n_{fc} + n_{air}}, \tag{4}$$

where P_s is the measured reflection power when the detected fiber tip is immersed in CdTe QDs aqueous solution and k is an intervening variable.

Fig. 1 displays the results of the measured refractive index at different temperatures ranged from 18 to 90 °C (testing points at: 18 °C, 30 °C, 40 °C, 50 °C, 60 °C, 70 °C, 80 °C, 90 °C) for different sample concentrations at 1550 nm. A polynomial of second order is employed to fit the experimental data:

$$n_s = n_0 + a_1 T + a_2 T^2 \tag{5}$$

with the following coefficients (T in Celsiur scale):

$$n_0 = 1.34915, \quad a_1 = -3.19786 \times 10^{-4}, \quad a_2 = 1.00893 \times 10^{-5}$$

The errors of n_0, a_1 and a_2 are 4.93×10^{-3}, 2.01675×10^{-4} and 1.82599×10^{-6}, respectively. The reason we choose second order polynomial is that the errors are the smallest among the polynomials from first order to sixth order. We rewrite the temperature dependence of the absolute RI of CdTe QDs aqueous solution as follows:

$$n_s = 1.34915 - 3.19786 \times 10^{-4} T + 1.00893 \times 10^{-5} T^2 \tag{6}$$

In addition, we can find in Eq. (6) that the thermo-coefficient of the CdTe QDs aqueous solution dn/dT is not a constant, and satisfies $dn/dT = -3.19786 \times 10^{-4} + 2.01786 \times 10^{-5} T$. The value of d^2n/dT^2 is about 2.01786×10^{-5}. The RI increases with temperature when $T > 16$ K, and it is agreeable with the experiment results.

Fig. 2 shows that the RI of CdTe QDs aqueous solution varied linearly with the molarity of the four samples at a given temperature. The regularity of the RI versus concentration of solution is interpreted in Ref. [25]. The slopes of the linear fitting curves dn/dc is about 1.04×10^{-2}. It is shown that the RI of CdTe QDs aqueous solution can be tuned by changing its concentration.

As we know, the refractive index of a solution is a function of its temperature T, concentration c, and the wavelength of the incident light and can be described as $n = n(T, c, \lambda)$. For small change in temperature, concentration and wavelength, the change of the refractive index is

$$\Delta n \approx \frac{\partial n}{\partial T}\Delta T + \frac{\partial n}{\partial c}\Delta c + \frac{\partial n}{\partial \lambda}\Delta\lambda \tag{7}$$

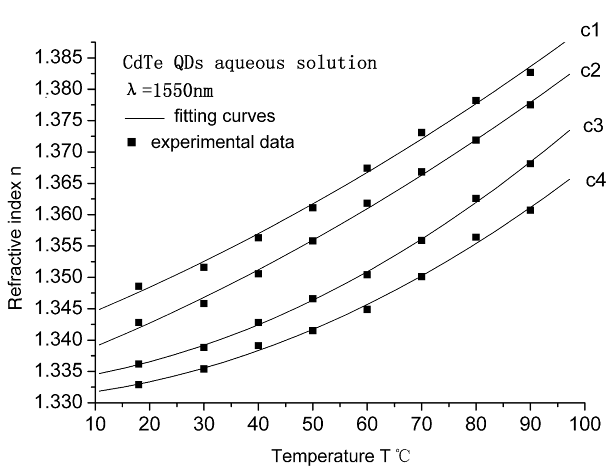

Fig. 1. RI of CdTe QDs aqueous solution (@1550 nm) versus temperature measured of each sample from 18 °C to 90 °C. The curve is a fit with a second order polynomial.

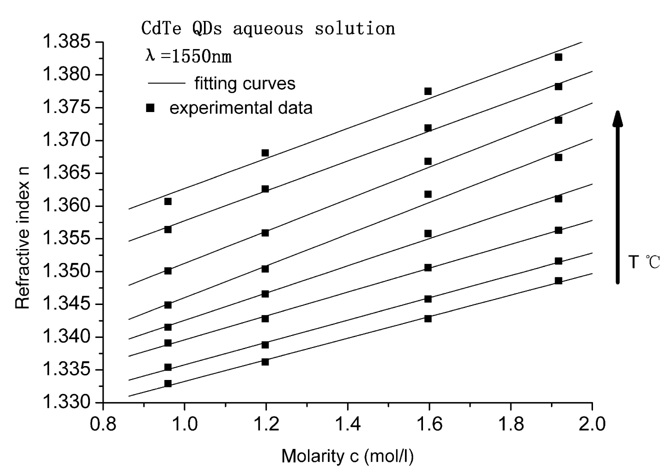

Fig. 2. RI of CdTe QDs aqueous solution (@1550 nm) versus concentration measured at varied temperature. The curves are fitted with a linear relation and dn/dc is about 1.04×10^{-2}.

In our experiment, since laser source is monochromatic wavelength is stable, $\Delta\lambda \approx 0$, wavelength effect can be neglected. So the change of refractive index of CdTe QDs aqueous solution Δn_s is

$$\Delta n_s \approx (-3.19786 \times 10^{-4} + 1.01786 \times 10^{-5} T)\Delta T + 1.04 \times 10^{-2} \Delta C \tag{8}$$

However, as there is an uncertainty of the effective mode index, the error will be propagated to the results of the refractive index of QDs solution. The uncertainty of the effective mode index is about 10^{-5}, and its effect on the results is at the order of magnitude of 10^{-5}. At a given propagation wavelength, one can tune the refractive index by changing the temperature and concentration of the solution. This information will be useful while QDs aqueous solution is applied in photonics devices.

It should be noted that the above formula for CdTe QDs aqueous solution is an empirical one. Because QDs effect should play a role in CdTe QDs aqueous solution, the behavior of its refractive index with regarding to concentration and temperature is different from that of liquid solution. Further theoretical study will be done to clarify the experimental phenomena.

3. Conclusions

We investigated the refractive index of CdTe quantum dots aqueous solution as a function of the temperature as well as concentration. Experimental results indicate that at a certain temperature, the variation of refractive index n with mole concentration c, dn/dc, is a constant about 1.04×10^{-2}, and the temperature coefficient of refractive index, dn/dT, obeys a relation of $dn/dT = -3.19786 \times 10^{-4} + 2.01786 \times 10^{-5} T$. An empirically tunable RI of CdTe QDs aqueous solution with temperature and concentration at the wavelength of 1550 nm is then achieved. The results provide fundamental database for QDs aqueous in photonics applications.

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