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Short Communication

Enhanced light extraction by heterostructure photonic crystals toward white-light-emission

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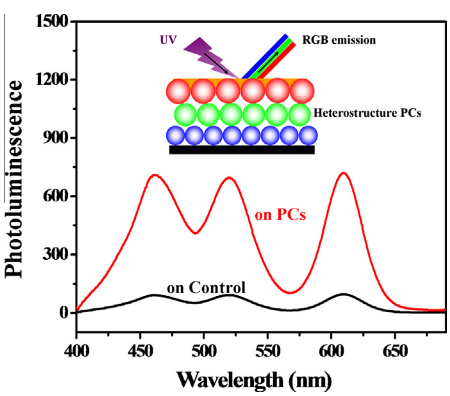
GRAPHICAL ABSTRACT

The simultaneous enhancement of red, green, and blue emission intensity by heterostructure photonic crystals with tri-stopbands is presented, which have potential for developing optical devices of high performance.



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ABSTRACT

In this work, we present a novel approach on the simultaneous enhancement of intensity of red, green, and blue (RGB) emission by heterostructure colloidal photonic crystals (PCs) with tri-stopbands. The intensity of RGB emission on heterostructure PCs with tri-stopbands overlapping emission wavelengths of RGB QDs can be up to about 8-fold enhancement in comparison to that on the control sample. Furthermore, CIE diagrams show the chromaticity parameters approaching that of white light. The method will be favorable for developing optical devices of high performance.

1. Introduction

White-light-emission systems based on phosphors with flexibly selected emission color and high efficiency have drawn a greatly increased interest in the fields of optoelectronics [1,2]. Basically, white-light-emission systems can be achieved using the complementary color wheel rule composed of two-color system (blue and yellow) or, more commonly, a three-color system (blue, green, and red, that is RGB) [3]. In this regard, three-color system through the mixing of independently emitting quantum dots (QDs) could

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be proposed to be the most promising materials in the optoelectronic fabrication due to high luminescence quantum yield, good photo-stability, size-tunable emission and cheap solution processability [4,5]. Combined with UV light, highly efficient RGB QDs have been utilized as light conversion phosphors for white light emission [6–9]. However, most of these optical films based on the QDs have small Stokes shift owing to a strong aggregation phenomena and low light-extraction efficiency resulted from the scattering problem [10,11]. Therefore, it is still challenging to develop the white light film for incorporating QDs that can keep their high luminescent performance.

As we know, photonic crystals (PCs) as unique optical materials have received great attention due to its special light manipulation property [12–14]. Especially, optical gain in PC science is regarded optical amplification mediated by stimulated emission of photons [15–19]. Additionally, the PCs surface possesses large surface-to-volume ratios for the effective dispersion of phosphors, which can avoid self-quenching effect. For example, Cunningham et al. demonstrated 108-fold enhancement of photoluminescence on the PC slabs by a combination of high-intensity near fields with strong coherent scattering effects of guided resonance [18,19]. In our previous work, a 162-fold enhancement of luminescent signal based on heterostructure PCs with dual stopbands was also demonstrated [20]. Thus, PCs as the excellent optical substrate are a promising tool to manipulate and improve luminescent signal. Unfortunately, at that time our work did not involve the application of heterostructure PCs. Herein, a strategy of combining heterostructure PCs as the substrate and RGB QDs applied as the optical film is developed for white-light-emission. We show that an obvious enhancement of white-light intensity based on heterostructure PCs with tri-stopbands comparison to that on the control sample. This is achieved by engineering the structure of PCs to make tri-stopbands overlapping the emission wavelength of RGB QDs, respectively. Furthermore, RGB emission can be improved simultaneously at a single excitation wavelength, and CIE diagrams show the chromaticity parameters approaching that of white light. The means of white-light enhancement on heterostructure PCs with tri-stopbands can lead to strong light harvestings and provide an opportunity for developing the optical device with high performance.

2. Experimental

2.1. Materials

Styrenes (St), methyl methacrylate (MMA), acrylic acid (AA) were purified by distillation under reduced pressure. The initiator of $(NH_4)_2S_2O_4$ (APS) was recrystallized three times. All reagents and materials were purchased from Aldrich unless otherwise noted.

2.2. Fabrication of heterostructure PC films

Monodisperse latex spheres of Poly(St-MMA-AA) were synthesized via our previous method [21]. The resulting latex spheres were used directly without purification. The polydispersity of the latex spheres was about 0.5%, which was detected by ZetaPALS BI-90plus (Brookhaven Instrument). The heterostructure PCs with tri-stopbands are fabricated by the successive vertical depositions of three latex spheres with different diameters onto glass substrates at the constant temperature of 60 °C and humidity of 60%. The glass slides were first treated with a chromic–sulfuric acid solution to ensure clean surfaces. After the samples were dry, they were sintered at 85 °C for 30 min to increase the stability of the samples.

2.3. Fabrication of crosslinked heterostructure PC films

Photo-crosslinkaged heterostructure PC films were fabricated by immersing acrylamide solution for illumination of ultraviolet light via the Ref. [22]. As a result, a crosslinked polymer network would form among latex spheres and solvent resistance of the PCs got improved.

2.4. Preparation of luminescent PC films

The blue, green, and red QDs solution (10 mg/mL chloroform) (mass radio of R:G:B is = 7:6:3), were added into a 1 ml transparent PMMA/chloroform solution (1 g of PMMA mixed with 10 ml of chloroform solution). The RGB QDs-loaded PCs films were prepared by spin-coating the chloroform solution of RGB QDs and PMMA mixtures onto photo-crosslinkaged heterostructure PC films and glass substrates (as the control sample) at 1200 rpm for 20 s, respectively.

2.5. Characterization

The SEM image was obtained with a field-emission SEM (JEOL JSM-4800, Japan), after sputtering the samples with a thin layer of gold. The UV–Vis absorbance spectrum was obtained by an ultraviolet–visible spectrophotometer (UV-2600, Japan). The photoluminescence spectrum was measured by a Hitachi F-4500 fluorescence spectrophotometer. The micro-reflectance spectrum observation of the PC films was carried out by combining a reflected microscope (Olympus MX40, Japan) and a fiber optic UV–Vis spectrometer (Ocean Optic HR 4000, USA). The illuminating light was focused onto the PC films through an objective lens and the reflected light was collected by the same lens and then transported to the spectrometer through the optic fiber.

3. Results and discussion

Commercially available RGB QDs which can be adjusted to generate white light emitting are chose. UV–Visible absorption spectra of the trichromatic QDs in chloroform solutions used are presented in Fig. 1a. The trend of the absorption toward longer wavelength is observed. The photoluminescence (PL) spectra of the three samples exhibit band-to-band emission bands centered at 467 nm, 520 nm and 610 nm, respectively. Their respective PL spectra show large Stokes shifts, indicating that the emission can be dominated by defect-related mechanisms [23]. Moreover, it can be seen that their full width at half maximums are about 30 nm, indicating their narrow size distribution. Here, we selected PC films from latex spheres with diameter 197 nm, 210 nm and 265 nm, whose stopbands are at 473, 510 and 613 nm, spectrally corresponding to the emission wavelength of the trichromatic QDs, respectively. As shown in Fig. 1b, the three stopbands of PC films match clearly the emission peak of the individual QDs. The triple period structure of the PCs can offer tri-dielectric stopbands, which leads to a dramatic modification of light propagation and emission properties of the luminescent medium.

Heterostructure PCs are fabricated by the successive depositions of three particles with different diameters onto a substrate [24–28]. Fig. 2a–c presents scan electron microscope (SEM) side views of heterostructure PC films composed different self-assembly concentrations of P(St-MMA-AA) spheres with 197_{down}–210_{middle}–265_{up}. This clearly shows the growth of one PC over another with good ordering. In general, the film thickness depends on such parameters as solution concentration, temperature, air humidity, and sphere size. Keeping all parameters constant except the solution concentration, we explored the effect upon the film