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Enhanced light extraction efficiency of plastic scintillator by photonic crystal prepared with a self-assembly method

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ABSTRACT

Plastic scintillators are extensively used in various radiation measurement systems. However the total internal reflection decreases the scintillation light output, leading to a low detection efficiency especially in these weak signal detection situations. In the present investigation, we have designed a light extraction scheme based on the photonic crystal formed with a monolayer periodic array of polystyrene nanospheres by a self-assembly method. The photonic crystal coated on the surface of plastic scintillator can significantly enhance the light extraction by 120% compared with the plain reference sample under X-ray excitation, which is achieved by the principle of the coupling of evanescent field near the scintillator-air interface with the photonic crystal.

1. Introduction

Plastic scintillators are extensively used in nuclear and particles physics experiments, industry and national security [1]. Plastic scintillators are easily fabricated and can be shaped into shapes as desired. Compared with single crystal scintillators, plastic scintillators can be easily made into thin sheets and fibers, which extend their applications. Plastic scintillators are particularly suitable for the measurement of a mixed neutron/gamma pulsed radiation based on the different sensitivity to neutron and gamma ray [2,3] or pulse shape discrimination technology [4–6].

Since the refractive index of plastic scintillators is about 1.58, a large portion of scintillation light is trapped into the internal of plastic, which cannot enter into photodetectors but leak at the edge of samples or be self-absorbed by the plastic matrix. According to Snell's law, the light with incident angle larger than the critical angle $\theta_C = \sin^{-1}(n_{air}/n_{plastic})$will be totally reflected. The extraction efficiency from one side of the scintillator-air interface can be calculated by formula (1).

$$\eta_{eff} = \frac{1}{2}\left(1 - \sqrt{1 - \frac{1}{n^2}}\right) \qquad (1)$$

where n is the refractive index. The extraction efficiency of a plain plastic scintillator is 11.1%.

For the application in pulsed neutron/gamma mixed radiation field, thin sheet of plastic scintillator is required for the sake of achieving a better neutron-to-gamma sensitivity ratio. For other application such as particle identification based on the time-of-flight [7], decay time measurement [8] excited by a single charged particle, a thin scintillator film to provide the start timing signal is preferred [9]. However thin sheet will lead to a rather low detection efficiency due to the weak luminescence. Therefore, the enhanced light extraction efficiency is critical in such applications.

In order to improve the extraction efficiency of scintillators, photonic structures covered on the surface of scintillator are designed and fabricated. Although a variety of photonic structures have been proposed in the application of light emitting diodes (LEDs) for the purpose of improved light extraction [10–12], their applications in scintillators must meet some special requirements. For example, a scintillator usually has a thickness ranging from millimeter to centimeter for effective absorption of radiation. So the photonic structures should be valid for the scintillators with macroscopic scale. A large area of several square centimeters is also required in a practical detection system. In recent years, several demonstrations of light extraction of scintillators based on the photonic structures are reported. For example, biologically inspired moth-eye-like structures have been used to improve light output of Lu_2SiO_5:Ce thin film scintillator [13]. Photonic crystal slabs fabricated with electron beam lithography have been utilized

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to improve the light extraction for heavy inorganic scintillator [14]. Photonic structures of an array of periodic nanospheres prepared with the self-assembly method have been proposed to extract scintillator light [15–17]. These structures are characteristic of whispering gallery modes due to Mie resonance of individual spheres and Bragg diffraction arising from the periodic arrangement [18]. Another advantage is that they can be easily and economically prepared with a large area which is important to the practical application in radiation detection [19]. In this paper, we demonstrate the enhanced light extraction of plastic scintillator using the photonic crystal of the monolayer of self-assembled hexagonal-close-packed (HCP) dielectric nanospheres.

2. Simulation and experimental methods

The numerical simulations for the transmission spectra were performed based on a rigorous coupled wave analysis (RCWA) method. The periodic boundary conditions were used. Considering a light source in the internal of scintillator, the incident angle indicates the propagation direction with respective to the normal direction of the scintillator-air interface.

EJ-212 plastic scintillator samples were commercially available from EljEn Technology, USA. The size of the samples used in the present experiment is $\Phi 30$ mm × 0.2 mm. The monolayers of polystyrene (PS) nanospheres with diameter of 500 nm were coated onto the plastic scintillator substrates using a modified self-assembly method [20]. The surface topography of structured scintillator was obtained by a Hitachi S-4800 field-emission scanning electron microscope (SEM). The emission spectra were measured with a fiber speedometer with a FFT-CCD under the excitation wavelength of 360 nm from an UV LED. Angle distribution of X-ray excited luminescence were recorded with an ETL 9215B photomultiplier tube. The sample and the X-ray tube were both fixed on a rotating platform which can rotate and display the emerging angle. The values recorded were the wavelength-integrated intensity.

3. Results and discussion

Fig. 1(a) illustrates the scheme of light extraction by the monolayer of an array of PS nanospheres. The top view SEM image in Fig. 1(b) shows that the prepared sample has a HCP structure with the diameter of 500 nm for the individual nanospheres.

Fig. 2 shows the simulated transmission spectra at 422 nm (peak of plastic scintillator) as a function of incident angle considering a light source in the internal of scintillator. For the plain reference sample, the transmission totally disappears beyond the critical angle for both s-polarization and p-polarization. However, for the sample covered with the photonic crystal, it is observed that beyond the critical angle, two transmission bands peaked at 47.8° and 64.2° appear for p-polarization, and three transmission bands peaked at 43.4°, 51.0° and 64.2° appear for s-polarization. These significant transmission bands beyond the critical angle imply that the photonic crystal indeed enables to outcouple the light trapped in the scintillator; thus significantly contributing to the light extraction. It should be noted that below the critical angle there are some transmission dips appear for both p-polarization and s-polarization, suggesting that photonic crystal will also lead to some extra increased reflection. However, it does not evidently harm to the light extraction since these reflected light can be re-reflected by the bottom interface and has chance to be re-extracted by the photonic crystal. Such multi-extraction process will significantly enhance the final extraction efficiency [15].

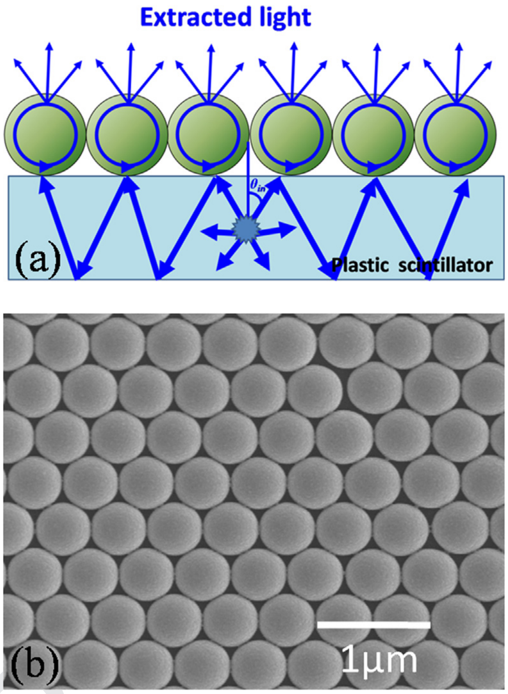

Fig. 1. Scheme of light extraction by photonic crystal formed with the monolayer of an array of PS nanospheres (a). The top view SEM image (b).

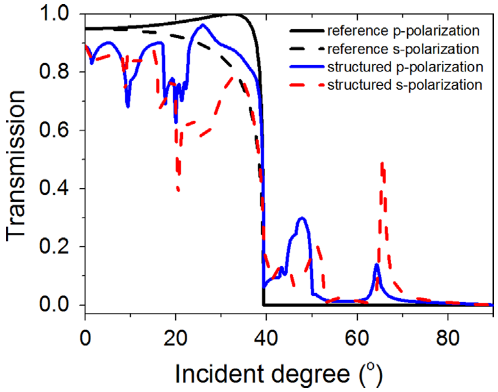

Fig. 2. Simulated transmission spectra at 422 nm as a function of incident angle considering a light source in the internal of scintillator for the photonic crystal covered sample and the reference sample.

The UV-excited luminescence spectra of the reference sample and photonic crystal covered sample at normal direction are shown in Fig. 3. Both samples exhibit two evident bands peaked at 422 and 444 nm and two shoulders at 400 and 477 nm. The enhancement can be observed in the whole range of emission spectrum. The enhancement ratio exhibits wavelength-dependence with the maximum value at 459 nm, shown in the inset of Fig. 3. For the photonic crystal covered sample, the extraction efficiency of wavelength-integrated spectrum increases by up to 135%. The reason of the enhanced light extraction with a photonic crystal is the coupling of evanescent field near the interface by the diffraction process which can be described by the diffraction equation [16]. Additionally, the array of nanospheres can form the whispering gallery modes which can propagate in the plane of the layer of array as a dielectric waveguide due to the coupling with the adjacent spheres [18]. Such guided modes with the characteristics of leaky nature can be diffraction into far field by the periodic structure, which can significantly contribute to the light extraction.

The angle profile of X-ray excited luminescence is measured according to the layout scheme shown in Fig. 4. The wavelength-

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