Transmission-type photonic crystal structures for color filters

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Abstract: A transmission-type structure based on woodpile photonic crystal layers is proposed for use in color filters. Selective bandpass filters for red, green, and blue wavelength bands are constructed using optimally designed multilayered woodpile photonic crystals. The R/G/B color filtering for a wide range of incidence angles of light is demonstrated numerically, and the operation principle and design method are described.

OCIS codes: (050.5298) Photonic crystals; (230.7408) Wavelength filtering devices.

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1. Introduction

The color filter is one of the most important components of display devices such as liquid crystal displays (LCDs), light emitting diodes (LEDs), image sensors, and digital holography

[1]. It provides spectral filtering of the intensity-modulated backlight to produce a color image. Characteristics of an effective color filter include low power absorption, high color purity,, omnidirectional filtering, and operational stability in the face of variations in heat, light, and chemicals. One feature in particular required by transmission-type display systems such as LCDs is high transmission efficiency. A conventional LCD color filter is fabricated using pigments or dyes containing red (R), green (G), and blue (B). In this fabrication process, the pigment-dispersion method has been widely employed due to low cost, sufficient uniformity, and high reliability. However, pigment-based color filters can cause depolarization due to scattering and birefringence [2] and, as a result, the transmission efficiency is degraded.

There have been a variety of approaches for high efficient color filters besides the pigment-dispersion method. Color filters with large scalability and practical transmission based on guided-mode resonance (GMR) of subwavelength surface binary gratings have been reported [3,4]. Recent research on surface plasmons (SPs) and their application has lead to improved color-filtering devices, with small sizes and active electro-optic control [5–7]. Intrinsic dissipative loss in metal, however, also decreases transmission efficiency and hinders practicality. A non-absorbing structural color, magnetically tunable and lithographically fixable, by means of superparamagnetic colloidal nanocrystal clusters [has been reported [8]. However, the resulting reflective color filters, with their one-dimensional structure, produce iridescence. Omnidirectional photonic crystal color filters for practical use in display devices have been proposed by a number of studies [9–11]. However, these offer reflective color filtering. Although defect modes in photonic crystals can be used to construct transmission-type filter [12], the transmission bandwidth of the defect mode is narrow since the defect mode is sort of resonant transmission and thus would be not appropriate for omni-directional wide-bandwidth bandpass color filter in visible wavelength region.

In this paper, a novel multilayered, wide-bandwidth transmission-type photonic crystal structure is proposed for color filtering using a wide range of incidence angles of light, and its optical characteristics are numerically investigated. Although this paper presents only numerical simulation, the proposed scheme – a lossless transmission-type omnidirectional color filter using a periodic photonic crystal structure – can be realized thanks to recent gains made in direct laser writing (DLW) technology.

2. Woodpile structure photonic crystals

The purpose of a transmission-type color filter is to transmit light within a certain range of wavelengths to provide separated luminance of the R (center wavelength, 633nm), G (center wavelength, 532nm), and B (center wavelength, 473nm) pixels and thus produce a specific color. To accomplish this, it is important for the filter to have good wavelength selectivity, and existing absorptive color filters are sufficient in this regard. However, if light efficiency is also considered, the ability to reuse light containing the deselected wavelengths becomes more valuable. As such, a structure which transmits the light of a selected wavelength (corresponding to color) and recycles the other wavelengths for later use is required. Figure 1 demonstrates band-rejecting filter layers in action. In Fig. 1(a), the R filter reflects the G-band and B-band, thus transmitting only the R-band, and the reflected G-band and B-band can then be recycled through other filters. As a result, it is possible to construct a lossless transmission-type color filter.

Figure 2 shows a multilayered structure of three-dimensional (3D) woodpile photonic crystals, designed to achieve the goal of a lossless transmission-type color filter. Woodpile photonic crystals have a diamond lattice structure and thus an omnidirectional photonic bandgap. T_x, T_y, and T_z represent the *x*-, *y*-, and *z*-directional periods respectively of the woodpile photonic crystals. They satisfy the relationship $T_y = T_x = T$ and $T_z = (2)^{1/2}T_x$ [13]. The band-rejecting properties of the proposed structure with various refractive indices are shown in Figs. 3(a) and 3(b) for transverse electric (TE) and transverse magnetic (TM) polarization of light respectively. If the number of staking rods with a refractive index greater than 1.75 is larger than about five or six, the woodpile photonic crystal structure has both a

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complete reflection photonic bandgap and partial transmissive passband. In Fig. 3, the number of staking rods of single woodpile layer is set to 6.

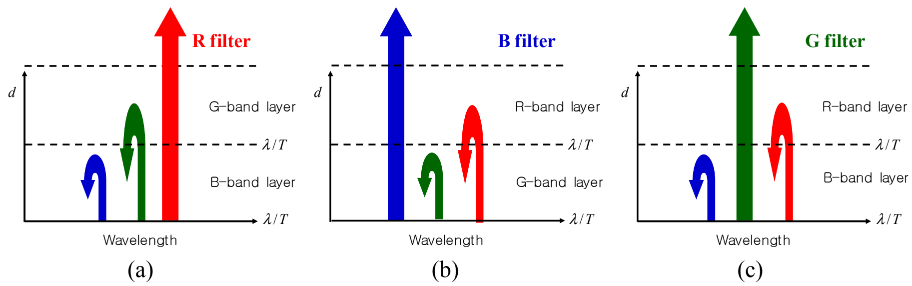

Fig. 1. Mechanism of transmission-type color filters: (a) red, (b) green, and (c) blue filters.

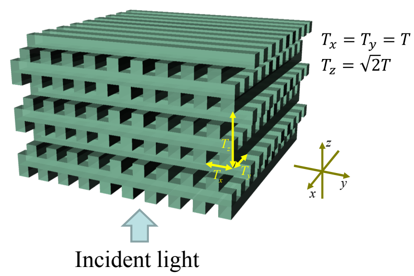

Fig. 2. Single woodpile photonic crystal slab.

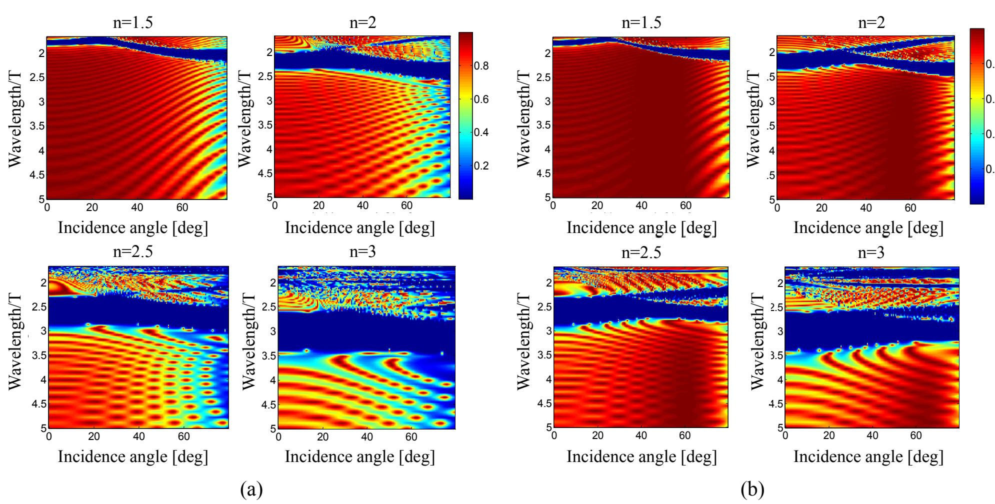

Fig. 3. The band-rejecting properties (transmission efficiency) of the proposed woodpile structure with various refractive indices for (a) TE polarization of light, and (b) TM polarization of light. The number of stacking rods is set to 6.

In both Figs, there is an omnidirectional bandgap to reject specific wavelength, indicated in blue. Hence, it is possible to control the rejected wavelengths or colors by changing the refractive index of the material within the woodpile structure, or by changing the periodic parameter T. In the next chapter, the practicality of a bandpass filter using these two methods will be reviewed.

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3. Transmission color filter structures

Because a single woodpile structure can work as a reflective-type band-rejecting filter, it is possible to produce a stacked structure that sequentially rejects two of the R/G/B bands and transmits the other. A woodpile photonic crystal multilayer (WPCML) structure is a stack of several woodpile photonic crystal layers with a specified internal structure (i.e., refractive index distribution or lattice matching) to realize the mechanism above.

The first method available to produce a functional WPCML structure is to fix *T* and vary the refractive index of each layer to provide band selectivity. This type of WPCML structure can be understood as a single woodpile photonic crystal stack with z-directional refractive index variation. Figure 4(a) illustrates a WPCML structure with three layers and three different z-directional refractive indices n_1, n_2, and n_3. The second possible structural configuration for a WPCML structure is one with different periodic parameters T_1, T_2, and T_3 but the same refractive index for all layers [Fig. 4(b)]. Depending on the design scheme, any number of layers can be used; it does not have to be restricted to three. Light with an arbitrary incidence angle and polarization is incident on the bottom of the structure (*x*-*y* plane) as shown by the grey arrow in Fig. 4. Each photonic crystal layer is designed to provide band-reject filtering for a specific range of wavelengths within the incident light to meet the principles outlined in Fig. 1. The overlap of these band-rejecting regions within each photonic crystal layer can then produce specific optical passband.

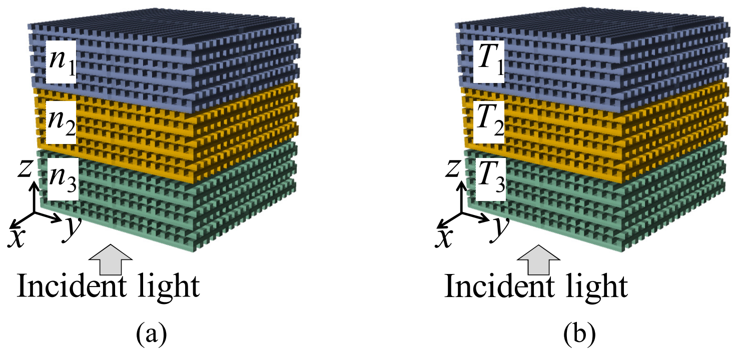

Fig. 4. Transmission-type color filters of woodpile structure: (a) index modulation type with the same period, and (b) period modulation type with same permittivity.

In order to obtain efficient bandpass filters, an optimization approach is used. The optimization parameters are the number of woodpile photonic crystal layers *N*, the period parameters T_1, T_2, ⋯, T_N and the refractive indices of the respective woodpile layers, n_1, n_2, ⋯, n_N. To obtain a functional WPCML RGB color filter structure, various design parameter combinations are explored with full three-dimensional vectorial electromagnetic analysis based on the Fourier modal method [14]. The transmission and reflection characteristics of the WPCML is efficiently modeled with the scattering matrix (S-matrix) method. The single layer of the WPCML is characterized by the Bloch eigenmodes represented by the pseudo-Fourier series and the S-matrix method establishes the electromagnetic relationships between layers connected by infinitely multiple reflections and transmissions of electromagnetic waves. In particular, the Fourier modal method is advantageous for modeling periodic photonic structures such as WPCML since the mathematical form of the Bloch eigenmodes is based on the Fourier series.

The optimal combination of structural parameters is one that maximizes the transmitted light intensity peak in the R, G, and B color-bands. In the choice of structure, tuned is the damping of the transmittance of unwanted color bands under the small transmission threshold of 0.0001. Through this optimization procedure, we have found combinations of structural parameters for the R, G, and B color filters. Each woodpile photonic crystal layer has a finite thickness large enough to show a complete photonic bandgap. For a woodpile photonic crystal layer with period T_x and refractive index n, the optical transmittance function, $TR_r(\theta,\lambda)$ is analyzed by varying both the incidence angle from 0 (deg) to 85 (deg) and the ratio of wavelength to period T_x from 1.75 to 5. For a WPCML structure with N layers, the total transmittance function of the WPCML structure is taken from the simple multiplication of the layer transmittance functions, $TR_{total}(\theta,\lambda) = TR_{r1}(\theta,\lambda) \cdot TR_{r2}(\theta,\lambda) \cdots TR_{rN}(\theta,\lambda)$. Although this paper deals with the results under the TE polarization of light, selected for convenience, similar results are likely to be obtained for the TM polarization of light because woodpile photonic crystals have a polarization-immune omnidirectional photonic bandgap structure.

The results of index-modulation-type WPCML color filter are listed in Table 1.

Table 1. Structural parameters of index modulation type

Color filter	Period	Refractive index (n)			
	T_x (nm)	*Layer 1*	*Layer 2*	*Layer 3*	*Layer 4*
Red	155.0	2.75	3.50	-	-
Green	195.5	2	2.25	3.5	-
Blue	171.0	1.5	1.75	3.25	3.5

The R, G, and B filters we designed are composed of two-, three-, and four-layers, respectively. The periods of the three WPCML structures are between 150 nm and 200 nm. Optimization shows that at least one layer should be an ultra-high refractive index material (UHRIM) with a refractive index greater than 3. In Fig. 5(a), we present the transmission properties of the index-modulation-type WPCML R-color filter based on the design parameters in Table 1. The first layer of the R filter is a woodpile photonic crystal with period T_x = 155 nm and refractive index n_1 = 2.75. The optical transmission function of the first woodpile photonic crystal layer, $TR_{r1}(\theta,\lambda)$ is analyzed with the incidence angle varying from 0 (deg) to 85 (deg), and the wavelength varying from 275 nm to 775 nm. In the same way, the optical transmission function $TR_{r2}(\theta,\lambda)$ of the second woodpile photonic crystal layer with n_2 = 3.50 is analyzed. The transmission functions, $TR_{r1}(\theta,\lambda)$ and $TR_{r2}(\theta,\lambda)$, are presented in the left and right panels of Fig. 5(a), respectively. It is noteworthy that red light passes the two-layer structure successfully for a wide range of incidence angles, while green and blue light are blocked by the photonic bandgap of the composite photonic crystal multilayered structure, as illustrated by the green and blue arrows in Fig. 5(a). The transmission function of the composite multi-layer, $TR_{Red}(\theta,\lambda)$, is obtained by $TR_{Red}(\theta,\lambda) = TR_{r1}(\theta,\lambda) \cdot TR_{r2}(\theta,\lambda)$ and is also shown in Fig. 5(a). It can be seen that only red light can pass through this WPCML structure, indicating its possible use as a transmission-type color filter. G and B color filters can be implemented in a similar manner. Figure 5(b) shows the optical transmission function of an optimized WPCML G-color filter. Red light passes through the first layer but is blocked by the second layer, whereas the blue light is rejected by the first layer. In Fig. 5(c), the structure and operational principle of the B-color filter is presented. Red and green light are rejected by the second and first layers. In terms of its application in display devices, the first and second layers of this structure can be considered optional because displays usually work with wavelengths between 380nm and 780nm; however, these layers can be considered a means of enhancing blue color purity.

Recently a great deal of interdisciplinary research has been devoted to UHRIM in the fields of meta-materials and composite polymers, which promises low-loss UHRIM in the visible light range [15–17]. Nevertheless, the index-modulation-type WPCML structure may not be practical due to the requirement of a UHRIM with a refractive index greater than 3.

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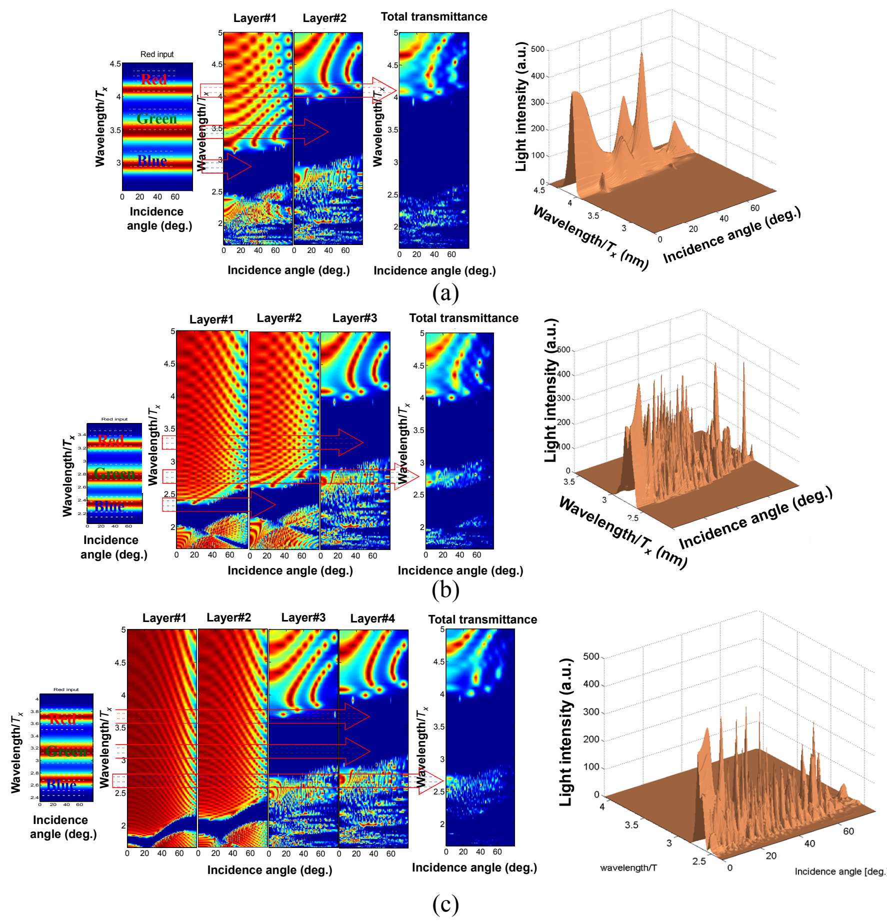

Fig. 5. Transmission structural color of an index-modulation-type woodpile layer structure and the characteristics of light transmission under RGB LED light through the WPCML structure: (a) red color filter, (b) green color filter, and (c) blue color filter.

The aforementioned WPCML structure with a different period for each layer and manufactured from a single material can also be an effective color filter after optimization. As it does not require the use of a UHRIM, in practice it can be fabricated with current DLW technology. In this case, the maximum photonic bandgap necessary is smaller than that required for the index-modulation-type WPCML structure (see the final layers in Fig. 5 as an illustration of this). In the case of period-modulation-type photonic crystal color filters, the photonic hetero-junction structure has been realized. The optimized solution for period T in each layer of the R/G/B color filter is shown in Table 2, and the transmission properties and transmission function of the WPCML structures as determined by numerical simulation are shown in Fig. 6. It is found that the proposed WPCML structures for use in R/G/B color filters show a reliable color selectivity of desired colors within a practical range of refractive indices n = 2.25-2.50.

However, in the case of both index modulation and period modulation, there are complex fluctuations in the transmission spectra of the R/G/B color filters, which can be ascribed simultaneously to both the inherent structural transmission properties of woodpile photonic crystal structures and the coherent Fabry-Perot interference effect. This problem is expected to be resolved with the use of diffusive structures or layers in the output plane of the WPCML structure that randomize the direction of radiating light. Also, the reuse of partially reflected light through recycling mechanisms in practical displays would reduce the fluctuation in the

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transmission spectra. The deselected light can be reflected back and recycled to increase the light efficiency. Consequently, the color filter spectrum would be further flattened in a display system.

Table 2. Structural parameters of period modulation type

Color filter	Refractive index	Periodic parameter *T* (nm)			
	n	*Layer 1*	*Layer 2*	*Layer 3*	*Layer 4*
Red	2.25	187nm	210nm	233nm	-
Green	2.5	140nm	175nm	245nm	-
Blue	2.5	210nm	233nm	245nm	-

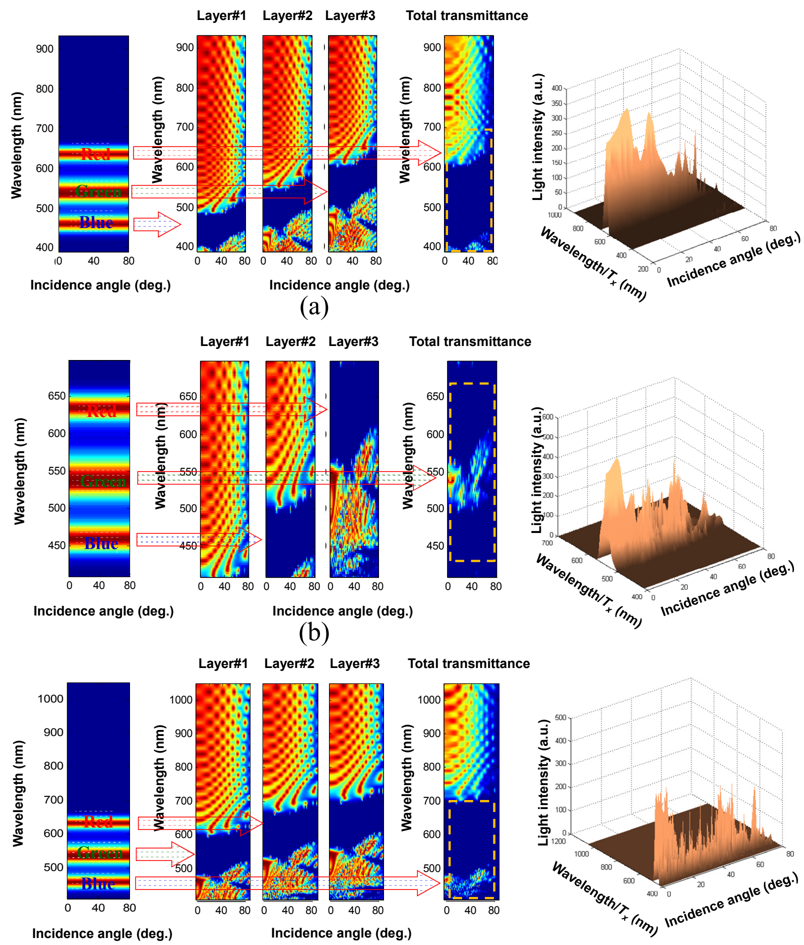

Fig. 6. Transmission structural color of a period-modulation-type woodpile layer structure and the characteristics of light transmission under RGB LED light through the WPCML structure: (a) red color filter, (b) green color filter, and (c) blue color filter.

4. Conclusion

We have proposed a transmission-type lossless color filter structure based on woodpile photonic crystals and analyzed the optical transmission spectra for a wide range of incidence angles. Both index-modulation-type and period-modulation-type woodpile layers can produce effective omnidirectional transmission color filters. R/G/B color filter designs based on this structure were also evaluated. From a practical standpoint, the period modulation type is the more promising of the two.

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