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Optimization Method for Plasmonic Color Filters of High Optical Efficiency

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Abstract

Various studies with regard to increasing the optical efficiency of plasmonic color filters have previously been conducted, such as mixing materials or applying diverse pattern shapes. Fundamentally, it is important to maximize the photonic crystal effect by finding the optimum periods of lattice as well as calculating the most efficient transmission area. In this study, we propose a technical method for optimizing the plasmonic color filters that have a high color gamut and luminance by analyzing the light spectrums based on the 1931 color coordinate system. Moreover, we suggest a calculation method in order to define the individual color purity of red and green and blue filters. Consequently, efficiency values are obtained independently from each color filter by evaluating the color purity and the luminance. The final result obtained from simulation are 27.6% of relative luminance and 25.3% of color gamut. The proposed optimization method is applicable to all plasmonic color filters having photonic crystal arrays.

Keywords: *Plasmonic Color Filters, Surface Plasmon Resonance, Photonic Crystal Arrays, Color Purity Index, Color Filter Efficiency*

1. INTRODUCTION

Plasmonic color filters (PCFs) are a device that combines the amplifying effect of surface plasmon resonance (SPR) and the filtering effect of photonic crystal (PC) arrays. By forming nano-sized arrays, a periodicity forms in the metal film in order to filter the visible light through the PC effects. Furthermore, by forming a dielectric film on the top and bottom of the metal layer, an effect, in which light is amplified by the SPR phenomenon, is obtained [1]. Due to the fact that the wavelength of light varies only by adjusting the size and period of the photonic crystal arrays, it is possible to create red and green and blue filters in a single manufacturing process on a single substrate. Such benefits can reduce both material costs and manufacturing time, and as a result, PCFs have been attracting attention as the next-generation color filter (CF) devices. Nevertheless, some problems exist, too. Firstly, large-area lithography techniques for fine processing of nanoscale patterns are still insufficient in the manufacturing of PCFs, and secondly, the optical

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efficiency of PCFs is lower than that of conventional color filters using an organic color resist [2]. Previously, our laboratory has introduced large-area PCFs using a laser interference lithography process, moreover many researchers have also announced the PCF fabrication method using such e-beam lithography and nanoimprint lithography processes [3-6]. Other prior researchers have also conducted various studies on materials and lattice structures, pattern shapes of PCFs in order to improve the optical efficiency [7-10]. The brightness and chromaticity of color filters natively have trade-off characteristics, because, the color filter uses only the filtered wavelength in order to obtain the desired color. Nevertheless, studies on finding find the optimum conditions to increase both the chromaticity and brightness of PCFs are being steadily conducted. In this study, we introduce a method to maximize the light efficiency of PCFs by analyzing the spectrum appearing at various periods and hole-sizes based on the 1931 color coordinate system.

2. SIMULATIOM AND ANALYSIS

We have applied a square lattice and circular holes to the PCF structures used in the simulation. A glass substrate and a dielectric layer (LiF 50nm; bottom, LiF 150nm; top) and a metal layer (Al 150nm) are used for the structure. A complete layer stack was modelled using a commercial software, Lumerical FDTD Solutions for the simulation. FDTD solutions can obtain transmission spectrums corresponding to each design by utilizing three-dimensional nanostructures that have a wide range of shapes and sizes. The resulting transmission spectrums can be determined by tristimulus values via integrating the spectrums with the light source spectrum (standard light source, D65) and the color matching functions in the wavelength range of visible light, 380nm~780nm. The color coordinates and the relative luminance are calculated by the following equations [11]:

$$X = \int_{380}^{780} I(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = \int_{380}^{780} I(\lambda)\bar{y}(\lambda)d\lambda$$
$$Z = \int_{380}^{780} I(\lambda)\bar{z}(\lambda)d\lambda \quad (1)$$

Where $I(\lambda)$ is the intensity of transmitted spectrums, and $\bar{x}(\lambda)$ and $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are color matching functions, and X and Y and Z are tristimulus values.

$$Y_{RL} = \frac{Y_{TL}}{Y_{LS}} \quad (2)$$

Where Y_{RL} is the relative luminance, and Y_{TL} is the tristimulus value Y of transmitted light, and Y_{LS} is the tristimulus value Y of light source.

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z}$$
$$x + y + z = 1 \quad (3)$$

Where x and y and z are color coordinates. Furthermore, color coordinates can be expressed by two values "x, y", which can be indicated on a two-dimensional plane of the 1931 color coordinate system. The area of the triangle created by the three xy coordinates (red, green, blue) is proportional to the color gamut of the color filter [2].

3. RESULTS AND DISCUSSION

An increase of aperture ratio (t*he area of hole / the area of lattice*, AR) means that the size of holes increases in the lattice unit. In Figure 1(a) and 1(b), when the aperture ratio gradually increases at the fixed period of lattice, it can be observed that the Y value of the spectrum is increasing. The above spectrum displays a green color because the central wavelength (λ_{max}) of the main transmittance peak is 500~550nm.

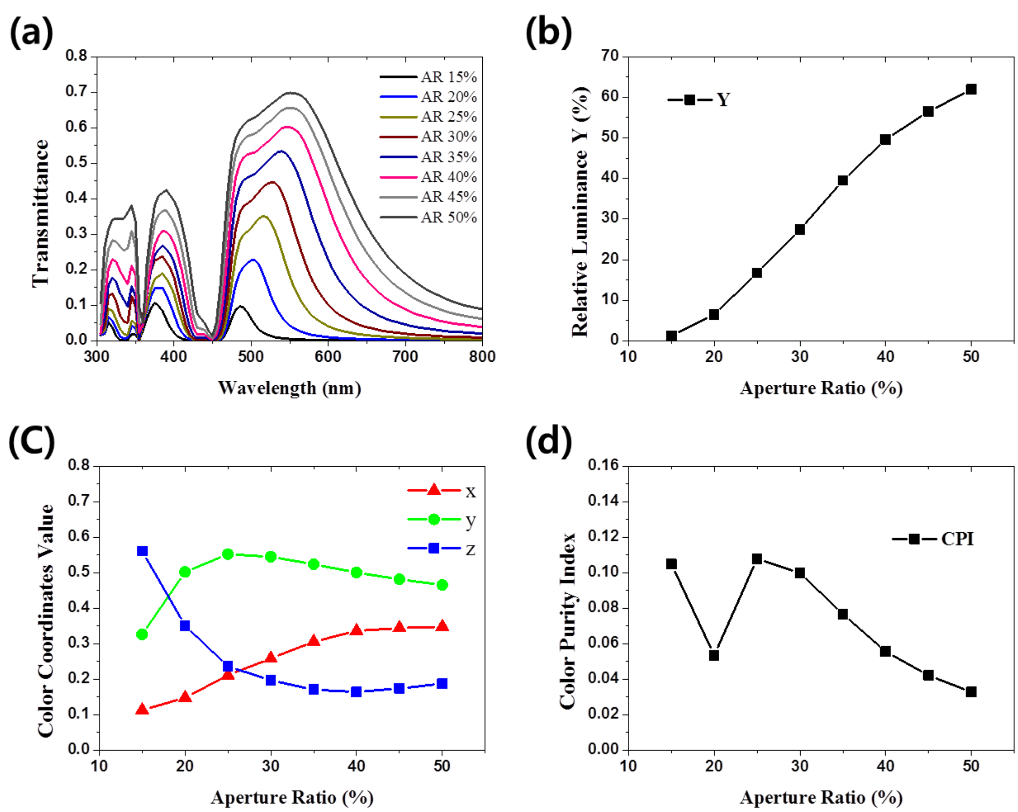

Figure 1. (a) Continuous spectrums by increasing aperture ratio, and with the fixed period of holes. (b) Relative luminance curve of the spectrums. (c) Color coordinates curves of the spectrums. (d) CPI curve of the spectrums.

Figure 1(c) shows the color coordinates of the spectrums. Because x, y and z move apart in different directions, it is difficult to estimate either and increase or decrease in chromaticity. Therefore, a single index is required in order to represent the chromaticity. Hence, we would like to suggest the color purity index (CPI). A tristimulus value Y, which corresponds with the value y in color coordinates, represents a degree of green color purity [11]. As the y value increases (x and z value decreases), an increase in the green color purity can be expected. Therefore, the larger the difference between y and x, and y and z, the larger the green color purity, i.e., (y-x)*(y-z). Because "y" is the highest value in the green region, it can thus be expressed by the following formula again:

$$CPI = [Maximum(x,y,z) - Median(x,y,z)] \times [Maximum(x,y,z) - Minimum(x,y,z)] \quad (4)$$

Similarly, the same equation can be applied in the regions of red and blue. Higher CPI implies that the color purity of red, green or blue is high; low CPI value means that the color purity is low because x and y and z values are similar to each other. That is, The CPI is an indicator representing the color purity of red and green and blue (RGB), regardless of the specific color. Figure 1(d) shows the CPI values of the spectrums. Therefore, both the higher CPI values and the luminance values of color filters lead to the expectation that the total efficiency of the color filter (CF efficiency) is high.

$$CF\ efficiency = Y_{RL} \times CPI \quad (5)$$

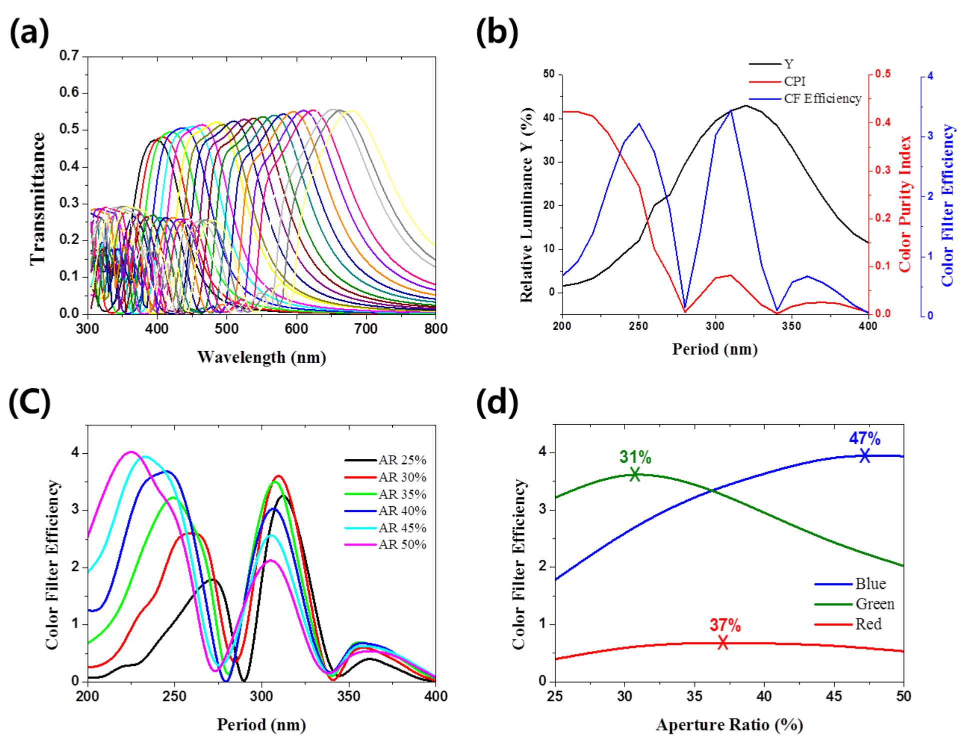

Figure 2. (a) Continuous spectrums by increasing the period of holes, and with the fixed aperture ratio. (b) Relative luminance, CPI, and CF efficiency curves of the spectrums. (c) CF efficiency curves at the various aperture ratio conditions. (d) Curves of connecting the maximum points of each of the CF efficiency

Figure 2(a) shows the spectrums that are generated by gradually increasing the period of holes via intervals of 10nm as well as by fixing the aperture ratio in order to obtain the continuous spectrums of having a relatively constant transmittance. As the periods increase, the central wavelength λ_{max} also appears to increase. The equation shown below represents a relationship between the central wavelength and the period [12]:

$$\lambda_{\max(i,j)} = \frac{P}{\sqrt{i^2+j^2}}\sqrt{\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m+\varepsilon_d}} \quad (6)$$

Where P is the period of the array, and ε_m and ε_d are the permittivity of the metal and the dielectric layer respectively; the (i,j) number originated from the reciprocal vectors in the 2D array determines the resonance modes. Figure 2(b) shows the curves of Y_{RL} and CPI and CF efficiency. Although the transmittances of spectrums are relatively constant, the luminance increases as the period increases, and then decreases after passing the maximum point at period 320nm (λ_{max} = 550nm). This is due to the fact that humans perceive the brightest light in the 550nm wavelength region [11]. The curve of CPI values is observed as a peak in each of the blue, green, and red color zone. CF efficiency is also observed in the form of a peak at the blue, green, and red color region. The maximum point of each peak indicates the periods having the highest efficiency at the given aperture ratio. By the same method, it is possible to obtain such CF efficiency curves at various conditions of the aperture ratio, in Figure 2(c). Figure 2(d) shows the graphs devised by connecting the maximum points of CF efficiency curves. Consequently, it is possible to find the optimum aperture ratios and the periods of red, green, blue. Both the optimum periods and the diameter of holes are shown in Table 1. The spectrums and color gamut space (illustrated by *Color Gamut Calculator*) of the final results are also shown in Figure 3(a) and 3(b), relative luminance; 27.6%, color gamut; 25.3% .

Table 1. The optimized condition of plasmonic color filter

	Period (nm)	Diameter of Holes (nm)
Red	360	247
Green	316	198
Blue	236	182

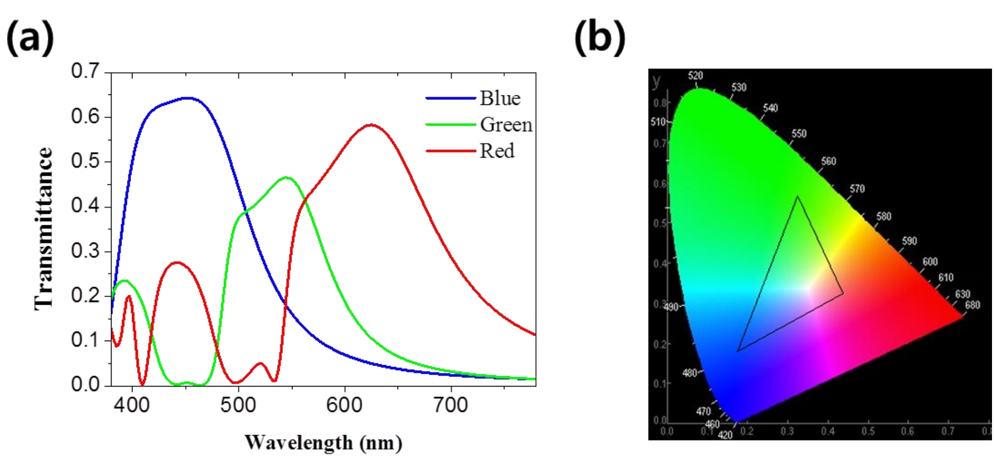

Figure 3. (a) Red and green and blue spectrum of the optimized PCF.
(b) Color gamut space of the optimized PCF.

4. CONCLUSION

In this research, we calculate the luminance values and color coordinates based on the 1931 color coordinate system. In addition, we were able to calculate the optimized spectrums of the high optical efficiency by adapting both the CPI and the CF efficiency. Compared to the results previously announced in our laboratory, the resulting color gamut has decreased by 29%, whereas the relative luminance increased by 188% (on the simulation). This optimization method may also be applied to other PCFs having different materials or different layer thicknesses.

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