Multi-band plasmonic color filtering through nanostructured metal thin film for RGB-NIR image sensor

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Abstract We propose a novel on-chip color filter consisting of periodic corrugated metallic nano-gratings concentrically surrounding a sub-wavelength single aperture for a multispectral imaging of visible to near-infrared (NIR). NIR image sensor provides a significant information such as range measurement imaging and biological tissue imaging. By integrating our proposed RGB-NIR plasmonic color filter on a single image sensor, improved image recognition such as range image and tissue image in color will be performed. Wavelength-selected incident light coupled with surface plasmons transmits through the sub-wavelength aperture as propagating beaming light, which has the advantage to suppress the spatial color cross-talk between the pixels. We demonstrated the multi-band color filtering from visible to NIR range using our proposed plasmonic color filter, leading to spectral narrow bandwidth and higher color purity than those reported previously.

Keywords: surface plasmon resonance, color filter, metal thin film, multispectral image sensor

1. Introduction

Modern nanofabrication techniques have given rise to new color filtering techniques using subwavelength-sized metal structures. In particular, since color selectivity through periodic hole arrays in metallic thin films was reported by Ebbesen et al. in 1998 [1], color filters based on surface plasmon resonance (SPR) by nanostructured metallic thin films have been actively studied for imaging applications [2,3]. In this study, we proposed a new multi-band plasmonic color filter with concentric periodical corrugation in the silver thin film which is applied to the image sensor [4]. Figure 1(a) shows a schematic of the proposed plasmonic color filters integrated on an image sensor. The proposed structure has a single subwavelength aperture surrounded by a concentric periodical corrugation on the silver film surface following the idea by Lezec et al. [5]. A selected wavelength of incident light excites SPR by the concentric periodical corrugation on the silver film and transmits the central aperture as a beaming light (Fig.1(b)). We considered that the beaming transmission property would be expected to suppress the spatial color cross-talk between pixels in the image sensor.

In conventional organic color filters, secondary transmission is generated in the NIR region. An external infrared cut filter is typically mounted on an organic color filter to eliminate this secondary transmission of NIR light. In such cases, image processing systems or multispectral filter arrays are required for the simultaneous imaging of RGB and NIR light because of the external infrared cut filter [6,7]. In contrast, each color can be selected using plasmonic color filters for simultaneous imaging without an external infrared cut filter. Plasmonic color filters with integrated image sensors can acquire visible information in addition to invisible information such as distances in time-of-flight range imaging using NIR light pulses; biological imaging of the absorption of biomolecules using deep tissue penetration within the NIR window is also possible. Plasmonic color filtering is expected to provide improved image recognition and reduced system size compared to conventional systems, which is particularly important in applications such as vehicle-mounted cameras, security, and biological tissue engineering. Here, we design and fabricate a silver film plasmonic filter with concentric periodical corrugations and demonstrate its multi-band color filtering in RGB-NIR range.

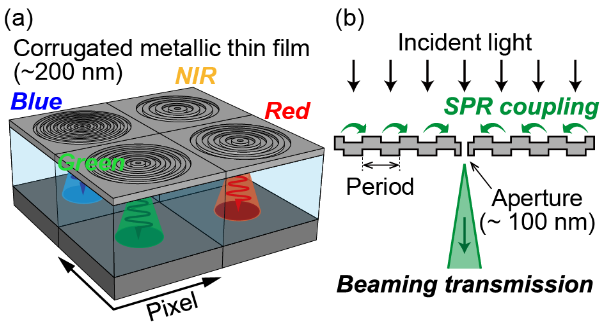

Fig. 1. Schematic of the proposed plasmonic color filters integrated image sensor. (b) Cross-sectional view of bull's eye plasmonic color filter.

2. Simulation and experimental results for plasmonic color filters

Transmission characteristics of a single aperture with concentric periodical grooves in silver thin film were simulated by using finite-difference-time-domain (FDTD) algorithm. The silver thin film with periodic corrugation was defined with structural parameters of the corrugation period, groove depth, film thickness, and aperture diameter. We designed the plasmonic color filter operating RGB and NIR by investigating the

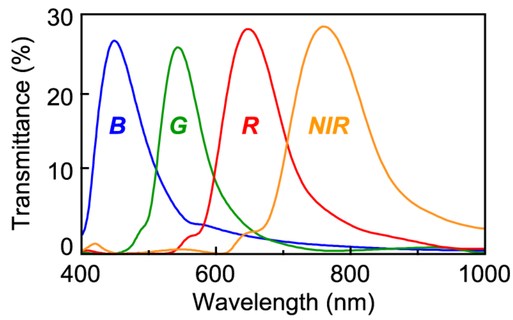

Fig. 2. Simulated transmission spectra of the proposed silver film plasmonic filter optimized for RGB-NIR wavelengths.

transmission spectrum dependence on each structural parameter. Figure 2 shows the summary of simulation results of the transmission spectra for B, G, R, and NIR. For example, the transmission efficiency of 28 % at the wavelength of 650 nm was obtained from the filter with the corrugation period of 500 nm, the film thickness of 180 nm, the groove depth of 80 nm, and the aperture diameter of 90 nm. The spectrum width of a full-width at half- maximum (FWHM) was 100 nm in each color. According to the simulation results, the plasmonic color filter with concentric periodical corrugation was fabricated on a glass substrate by using standard electron beam lithography, vacuum evaporation, and focused ion beam (FIB). Figure 3(a) shows SEM images of the fabricated silver thin film with corrugation period of 600 nm. The silver film with 180-nm-thick was evaporated by vacuum evaporation. The aperture with ~100 nm in diameter was drilled at the center by FIB. By patterning the metal surface with a concentric periodical corrugation, the light of a selected wavelength coupled with surface plasmons is transmitted as a beaming light through the sub-wavelength aperture at the center. The transmission intensity distribution was measured by illuminating the white light of Xenon lamp. Figure 3(b) shows an optical transmission image at the transmission side of fabricated plasmonic color filter with corrugation period of 600 nm. It is clearly observed a red color of transmission from the central aperture. The bright field image is shown as the inset in Fig. 3 (b).

Figure 4 (a) shows the transmission spectra for various periods of 350 -700 nm with 50 nm steps measured by spectrometer. In the spectral measurement, transmission spectral band with Gaussian distribution was obtained in each optical color filter. Each spectral bandwidth indicated the full-width at half-maximum of 100 nm. The peak wavelength for the fabricated plasmonic filters shifted to longer wavelength from visible to NIR with increasing the corrugation period. Measured transmission spectra are plotted as the color coordinates (x, y) in CIE 1931 color space shown in Fig. 4 (b). White solid line shows the color gamut of the standard RGB. The x-y color coordinates corresponding to the measured transmission spectra of the filter with the corrugation period for RGB indicated almost equivalent that of sRGB. The coordinates corresponding to the measured transmission spectra of the filter for NIR indicated nearby the neutral point exhibiting of saturated colors.

3. Conclusion

We successfully demonstrated the multi-band color filtering from visible to NIR range by plasmonic color filter fabricated as the silver thin film with concentric periodical corrugation surrounding a single sub-wavelength aperture. The transmission spectral band with FWHM of 100 nm was obtained in plasmonic color filter with the period of 350 -700 nm. The color values of the transmitted light almost agree with the sRGB color gamut are obtained, providing higher color reproducibility than previously studied plasmonic filters. This plasmonic color filter is expected the multispectral imaging from UV to IR spectral range. Further, we believe that our plasmonic color filters for simultaneous imaging will facilitate new discoveries in the fields of biophotonics, opto-electronics, and plasmonics research.

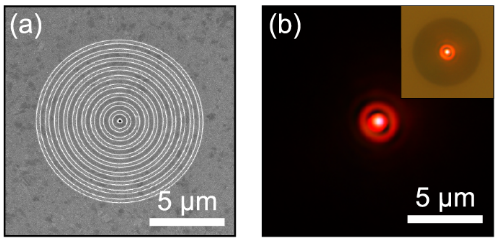

Fig.3. (a) SEM image of the fabricated silver film plasmonic color filter with corrugated period of 600 nm. (b) Optical transmission image at the transmission side of plasmonic color filter. Bright field image is shown as inset.

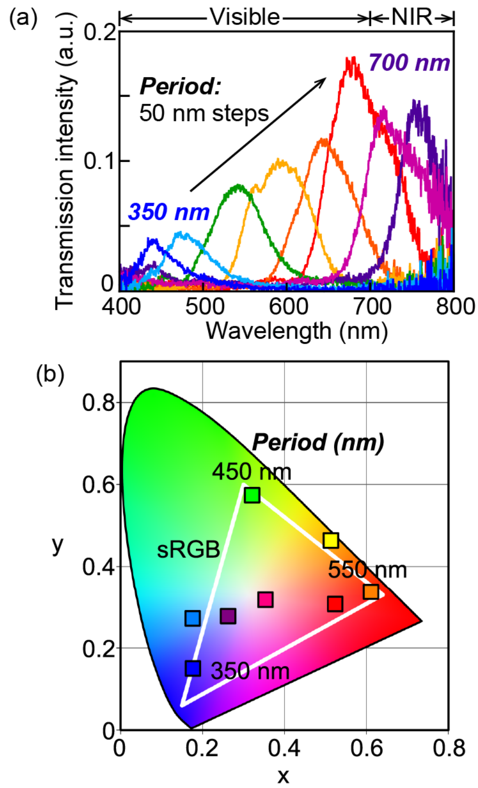

Fig. 4. (a) Measured transmission spectra for various periods with 50 nm steps. (b) Chromaticity of plasmonic color filter in CIE 1931 color space. White solid line shows a standard RGB color gamut.

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