Nanostructured metallic color filter for wide-range and multi-band image sensor

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Introduction

Simultaneous imaging in visible and near-infrared is requested to provide improved image recognition in vehicle mounted camera and security camera. Furthermore, it is expected that such an image sensor would be applied for biological tissue engineering. However, conventional image sensor is used only for visible or infrared due to the absorption optical property of color filters and the proper sensitivity range of sensor devices. According to the increasing attention for multiplex camera of optical communications, night view, and biomedical applications, multispectral imaging technique are developed by time sequential scanning of spatial or spectral dimensions [1, 2]. Although these techniques provide detailed spectral information, the systems are complex. For more practical one-shot multispectral image acquisition, various types of multispectral filter arrays using single CMOS image sensor are proposed and developed to acquire the visible and near-infrared images [3-6].

In recent years, new approach for simultaneous image acquisition for visible and near-infrared are proposed by using plasmonic color filters. Plasmonic color filters made by metallic thin film can be used for band-pass filters. In 1998, T. W. Ebbessen *et al.* discovered that metal films with sub-wavelength sized periodic hole arrays act as optical color filters due to the surface plasmon coupling and the selected color transmission [7]. The transmission spectral band is tuned ranged from ultraviolet to near-infrared by changing the hole diameter and the period of the array. A plasmonic hole array color filter was integrated with CMOS image sensors and photodiodes for the demonstration of optical color filtering functionality in the visible [8-11]. Here, we proposed a new optical color filter of nanostructured metallic thin film based on surface plasmon resonance. Figure 1 shows the schematic image of proposed optical color filter made by metal. The proposed structure has a single aperture surrounded by a concentric periodical corrugation on the metal surface following the idea by Lezec *et al.* [12]. A selected wavelength of incident light excites surface plasmon resonance by the periodic corrugation on the metal surface and transmits through the central aperture as a beaming light. We considered that this beaming light transmission property would be expected to reduce the spatial color cross-talk between pixels in image sensor. The visible and near-infrared light is filtered by various corrugation periods on metal surface.

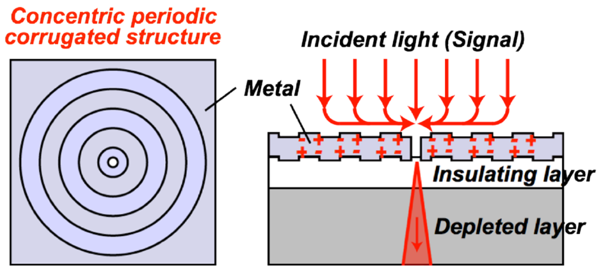

Fig. 1 Schematic image of metallic color filter with concentric periodical corrugation.

Simulation and experimental results for plasmonic color filters

The transmission characteristics of a single aperture with concentric periodic grooves in silver thin film were simulated by finite-difference-time-domain (FDTD) algorithm. In simulation, the transmission spectrum dependence on the corrugation period, the film thickness, the groove depth, and the aperture diameter was investigated. Figure 2(a) shows the summary of simulation results of optimized transmission spectra for blue, green, red, and near-infrared. The spectral width of a full-width at half-maximum (FWHM) was 100 nm in each color. For example, in the red color filtering, the transmission efficiency of 28 % was obtained at the wavelength of 650 nm 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. Figure 2(b) shows the cross-sectional view of the intensity field distribution at the incident wavelength of 650 nm. Plane wave of the incident light is irradiated from the top. The incident light excites surface plasmon resonance and the enhanced electric field is observed on the metal surface. Surface plasmon coupled light transmits from the central sub-wavelength aperture with beaming light.

According to the structural parameters optimized by FDTD simulation, we fabricated the silver thin film of optical color filter on glass substrate by using electron beam lithography, vacuum evaporation, and focused ion beam. Figure 3 shows SEM images of fabricated plasmonic color filters. The periodic concentric corrugation is patterned by electron beam lithography. The periods are varied from 300 -600 nm with 100 nm steps. Silver with the thickness of 200 nm is deposited by vacuum evaporation. The sub-wavelength aperture with 100 nm in diameter is drilled at the center by focused ion beam.

By patterning the metal surface with a concentric periodic corrugation, the light of wavelength coupled with surface plasmons is transmitted as a beaming light through the sub-wavelength aperture at the center. The transmission intensity distribution and the spectrum were measured by illuminating the white light of Xenon lamp at normal incidence. As shown in Fig. 4 of optical transmission image, the selected color of blue, green, yellow, and red is observed in the corresponding periodic concentric corrugation with the periods of 300, 400, 500, and 600 nm, respectively. The inset shows the blight field image observed from transmission side. It is clearly observed that light of the selected wavelength transmitted from the central aperture.

In the spectral measurement, transmission spectral band with Gaussian distribution is obtained in each optical color filter as shown in Fig. 5. The peak wavelength for each color filter of blue, green, yellow, and red colors is observed at the wavelength of 410, 530, 600, and 680 nm, respectively. The spectral

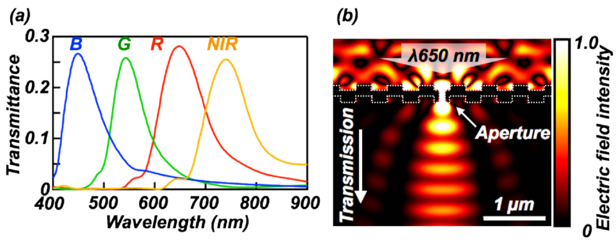

Fig. 2 (a) Simulation results of optimized transmission spectra for blue, green, red, and near-infrared (b) Electric field intensity distribution at the incident wavelength of 650 nm.

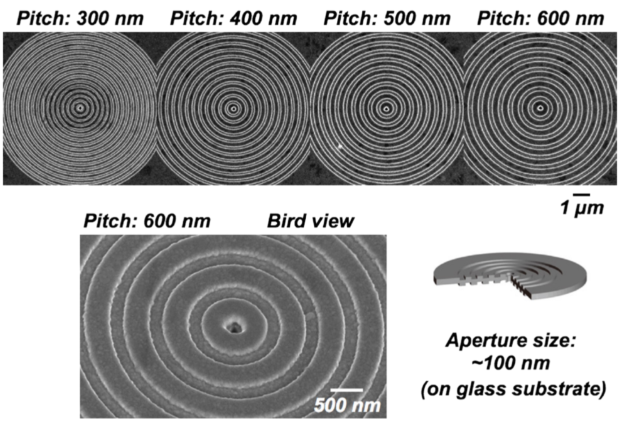

Fig. 3 SEM images of silver thin film with a concentric periodic corrugation for various periods of 300 -600 nm. Aperture about 100 nm in diameter is drilled at the center.

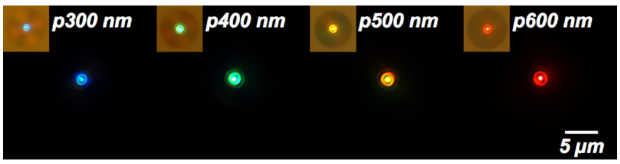

Fig. 4 Optical transmission images through the fabricated silver optical color filter. Multi-band of transmission blue, green, yellow, and red is observed.

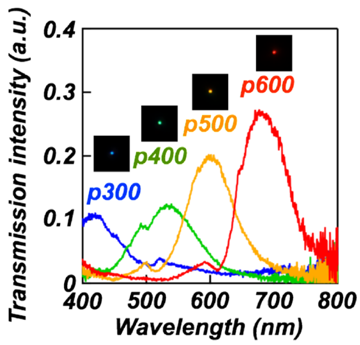

Fig. 5 Transmission spectra for each color filter. The peak wavelength of each filter is appeared at the wavelength of 410 nm (blue), 530 nm (green), 600 nm (yellow), and 680 nm (red).

width of FWHM for each band is about 100 nm. This spectral bandwidth is much narrower than previously demonstrated plasmonic color filters of metallic hole arrays.

Conclusion

Numerical modeling performed during this study has allowed to obtain optimized parameters of the surface plasmon resonance color filter leading to peak transmittance of 28 %. The central wavelength of the filter is tunable by changing its structural parameters.

We successfully demonstrated the optical color filtering in visible range by our proposed corrugated metallic thin film. As one of the next steps, we would demonstrate color filtering for spectral range to near-infrared.

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