Plasmonic polarization color filtering using 1D corrugated metallic thin films

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Abstract
We proposed a plasmonic polarization color filter composed of a 1D periodic corrugated metal thin film aimed for the simultaneous imaging of color and polarization. A selected color of polarized light oscillating in the periodic direction of the corrugation transmitted through the metal thin film due to the surface plasmon resonance coupling. We fabricated 1D periodic corrugated aluminum thin films by a lithography process and demonstrated their transmission characteristics.

Keywords: Plasmonics, Polarization, Color filter, CMOS image sensor

1. Introduction

Polarization imaging requires at least three polarization directions of photographs to calculate the angle and degree of polarization. The simplest imaging method is the rotation of a linear polarizer attached to the camera lens. In 2016, Y. Zhao *et al*. proposed multiband polarization imaging system consisting of multiple color cameras and four monochrome polarization cameras with different polarization direction of the mounted polarizers [1]. Multiband polarization imaging allows simultaneous acquisition of spectral and polarization information. The measured spectrum reveals the material composition of the target, and polarization provides information such as specular reflections and surface normal. In 2018, Y. Maruyama *et al*. developed an image sensor with stacked wire-grid polarizer arrays and color filters [2]. Integration of stacked filters in a single image sensor achieved parallax-free operation. One-shot simultaneous acquisition of spectral and polarization information improves time resolution.

In this research, we focused on plasmonic color filters to develop a polarization color image sensor using a single filter. The film thickness of plasmonic color filters is about 100 to 200 nm, which is thinner than that of organic color filters. By thinning the filter layer, it is expected to suppress optical crosstalk to neighboring pixels and improve color reproducibility. Since Ebbesen *et al*. reported color selectivity of the periodic hole arrays in metal thin films in 1998 [3], color filters based on surface plasmon resonance by metal thin films with sub-wavelength holes have been actively investigated for imaging applications [4-6]. Here, we proposed a plasmonic polarization color filter based on a 1D periodic corrugated metal thin film for the development of a filter with wavelength and polarization selectivity.

2. Plasmonic polarization color filter based on 1D corrugated metal thin film

Figure 1 shows a schematic image of the plasmonic polarization color filter. A selected color of polarized light oscillating in the periodic direction of the corrugation transmitted through the metal thin film due to the surface plasmon resonance coupling. A single-layer nanostructured metal thin film allows significant simplification of fabrication process and integration into image sensors. The continuous metal thin film with corrugation at both interfaces was fabricated via a straightforward process of metal evaporation on the corrugated substrate.

TM polarization irradiation to a 1D periodic corrugated metal thin film excites surface plasmon resonance on the metal surface. We discovered that surface plasmon excited on the incident side induces surface plasmon in the corrugation on the transmission side by thinning the continuous metal film to about 20 nm (Fig. 2). The surface plasmon induced on the transmission side decouples as propagating light, and wavelength-selected light is passed through. Plasmonic color filters transmit light of any wavelength by appropriately designing the period, because the resonance wavelength of surface plasmons depends on the period of the corrugation. On the other hand, TE polarization is reflected because it does not excite surface plasmon resonance. Therefore, the proposed 1D periodic corrugated metal thin film exhibits color and polarization selectivity. We designed and fabricated an aluminum thin film plasmonic polarization color filter with 1D periodic corrugations and demonstrated its wavelength and polarization selectivity in the visible range.

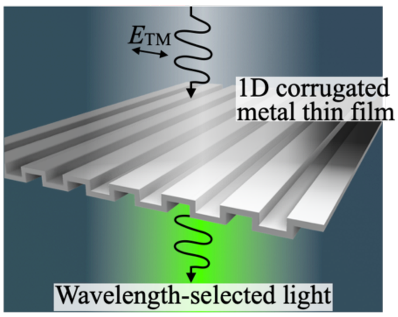

Fig. 1. Schematic image of the plasmonic polarization color filter.

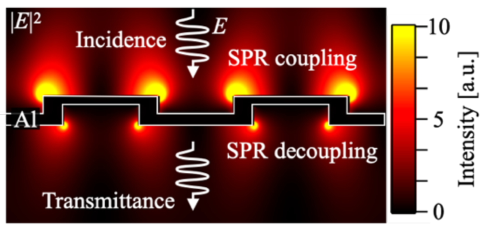

Fig. 2. Electric field intensity distribution at peak transmission wavelength λ = 570 nm.

3. Simulation results

The transmittance and the peak wavelength also depend on parameters such as metal layer thickness, groove depth, and groove width. We optimized the plasmonic polarization color filter based on the simulation of the transmission spectra dependence on the structural parameters. The simulation was performed on a 1D periodic corrugated thin film made of aluminum, which excites surface plasmon resonance in the visible range and has high affinity to CMOS processes.

The optimized corrugated thin film with a period of 200-500 nm exhibited multispectral transmittance characteristics with a maximum transmittance of 43% (Fig. 3 (a)), despite being a non-aperture metal film. The peak transmission wavelength shifted to longer wavelengths as increasing the period. We investigated the polarization transmission characteristics of 1D corrugated aluminum thin film. A single bandpass transmission peak due to surface plasmon resonance was obtained in TM polarized light irradiation (Fig. 3 (b)). The polarization extinction ratio was 13 dB.

4. Experimental results

According to the structural parameters optimized by the simulation, we fabricated the 1D periodic aluminum thin film using an electron beam lithography, reactive ion etching, and vacuum deposition. A dimethylpolysiloxane (PDMS) layer was spin-coated on the aluminum thin film to match the surface plasmon resonance wavelengths at both interfaces. By depositing the aluminum film on the patterned SiO_2 substrate, the various period corrugated metal thin film was fabricated in a single process. We fabricated plasmonic color filters with various periods from 200 to 500 nm and measured the transmission spectra.

Figure 4 shows the transmitted light images of the plasmonic polarization color filters with various corrugation periods in the range between 200 and 500 nm. As shown in Fig. 4, multiple transmitted light includes the three primary colors of red, green, and blue, in addition, intermediate colors such as yellow are observed according to the corrugation periods. In the spectral measurement, a single transmission band and a maximum transmittance of 40% were obtained by the resonance coupling and decoupling. A single transmission peak due to surface plasmon resonance was obtained only when irradiated with TM polarized light. The polarization extinction ratio was 10 dB. We demonstrated the wavelength and polarization selectivity of the proposed plasmonic polarization color filter.

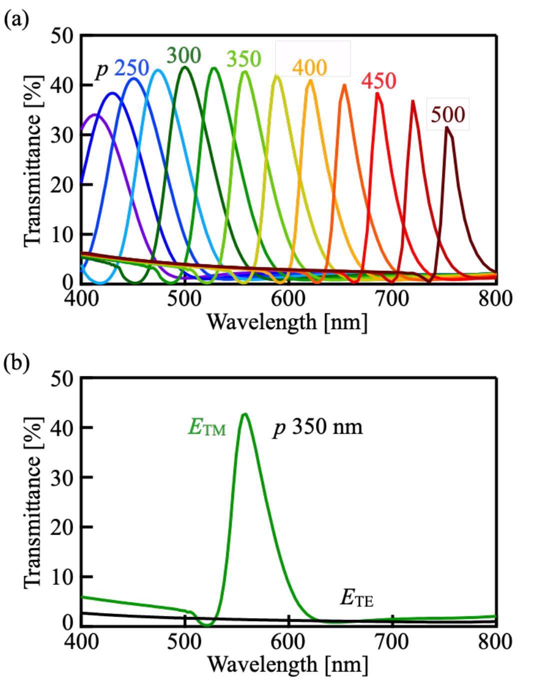

Fig. 3. Transmission spectra of plasmonic polarization color filter (a) with corrugation period ranging from 200 to 500 nm, (b) for TM and TE polarized light irradiation.

5. Conclusion

In this study, we proposed a plasmonic polarization color filter based on 1D periodic corrugated metal thin films. We demonstrated that the plasmonic color filter exhibits multispectral transmission characteristics that depend on the corrugation period. The fabricated 1D corrugated aluminum thin film exhibited an extinction ratio of 10 dB as a polarizer. Polarized color filtering using a non-aperture single-layer of metal film has never been reported before that was performed by a concept of plasmon coupling and decoupling in the continuous metal thin film. Aluminum thin film filter is highly compatible with CMOS processes and is applicable to high temperature and long-term sunlight exposure conditions. In summary, image sensors with plasmonic polarized color filters are expected to be applied in automobiles, product inspection, and surveillance cameras.

References

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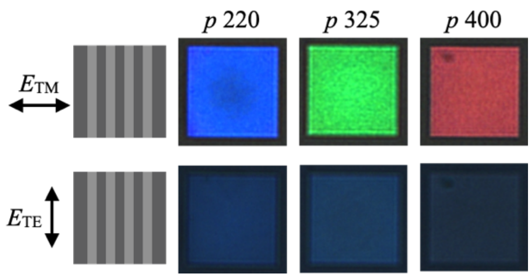

Fig. 4. Transmitted light image of the fabricated 1D corrugated metal thin film with a corrugation period of 220, 325, and 400 nm for TM and TE polarized light irradiation.