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Synthetic Multi-Spectral Material Filter based on Terahertz Metamaterial Combined with Thin-Film Etalon Structure

Heyoung Kang, Hyunseung Jung, and Hojin Lee*

MEMS Display and Sensor Laboratory
School of Electronic Engineering, Soongsil University, Seoul, 156-743, Korea
Phone: +82-2-820-0634 E-mail: hojinl@ssu.ac.kr

Abstract

In this paper, we demonstrate a numerical and experimental study of novel synthetic multi-spectral material (SMM) filters for visible and terahertz ranges. The proposed filter is based on double-layered complementary split ring resonators (CSRRs) combine with a thin-film etalon structure. The fabricated SMM filter can be fully the fabricated by conventional photolithography process to be confirmed to work as the transmissive color filter as well as the polarization dependent terahertz filter.

1. Introduction

In recent years, multi spectra imaging systems to gather distinct individual information distributed over terahertz, infrared, and visible spectral ranges simultaneously have attracted considerable attention from the diverse applications especially in space and security technologies [1]. Most recently, Iain et al. has proposed synthetic multi-spectral materials (SMMs) [2, 3] by integrating the plasmonic color filter and terahertz metamaterial filter into a single structure and revealed that the SMMs can maximize the spectral information density of multi-spectral imaging system. However, since these structures are fabricated from the nano-structure process using e-beam lithography [2], resulting in problems of high fabrication cost, low processing speed, and limited patterning area. In this paper, we proposed a novel flexible SMM filter combined with thin-film etalon that can be fully fabricated by conventional photolithography process. The proposed filter is composed of double-layered complementary split ring resonators (CSRRs) constituting the thin-film etalon structure, and show high transmission efficiencies in both visible and terahertz ranges.

2. Fabrication

The schematic of proposed SMM filter is shown in Fig. 1(a). The SMM filter is fabricated on a flexible polyethylene terephthalate (PET) film (188 μm). The bottom metal (Ag, 20 nm) was deposited by DC sputtering and patterned by wet etch. In order to make the constructive resonance for each color, SiO_2 was deposited by RF sputtering. Finally, the top metal (Ag, 20 nm) was deposited by DC sputtering and patterned by lift off. The dimensions of the periodic CSRRs are designed to have a peek frequency ranging from 0.3 THz to 2.1 THz, considering the transmission

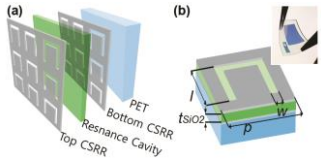

Fig. 1 (a) The exploded schematic view of the proposed synthetic multi-spectral material (SMM) filter**.** (b) Schematic diagram of the proposed SMM structure with geometrical parameters: w = 10 μm, l = 60 μm, and p = 90 μm. The value of t_{SiO2} varies with the corresponding color. Inset shows the photography of the fabricated SMM filter on flexible PET substrate.

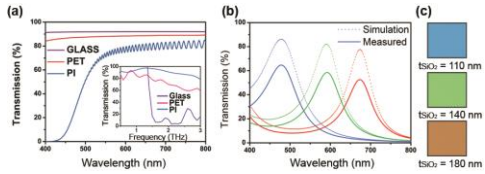

Fig. 2 (a) Measured transmission spectra of Glass, PET and PI substrates in the visible wavelength range and in the terahertz range (Inset). (b) Simulation (dotted lines) and measured (solid lines) spectra of thin-film etalon color filter fabricated on PET. (c) Optical microscopic images of blue, green and red color filters on PET substrates.

characteristics of the PET film which has a high transparency at a range of 0.3 Thz to 3THz. The details of geometrical parameters are shown in Fig. 1(b). The fabricated SMM filters are measured by UV/VIS/NIR spectrophotometer and by terahertz time-domain spectroscopy (THz-TDS), respectively.

3. Design and Results

Recently, Yoon et al. demonstrated the color filter based on thin film etalon structures on the glass substrate [4], where bottom and top metals act as reflecting mirrors and SiO_2 acts as a resonance cavity. In order to fine the suitable substrate for the proposed SM filter, we measured the transmission spectra of various films and compared their efficiencies. As show in Fig. 2(a), glass substrate show high transparency at visible range but, very low transmission efficiency at terahertz band. On the contrary, polyimide (PI) film shows a high transparency in terahertz ranges but very poor transmission in blue color range. Therefore, since the PET shows high transmission efficiency in both visible and terahertz range, we selected PET film as the substrate for our SMM filter. At first time, fabricated thin-film etalon color filters on PET film, and measure their transmission spectra by UV/VIS/NIR spec-

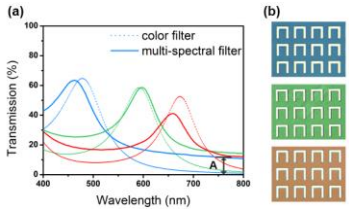

Fig. 3 (a) Measured transmission spectra of thin-film etalon color filters (dotted lines) and proposed synthetic multi-spectral filters (solid lines). A is baseline in the transmittance. (b) Optical microscopic images of corresponding blue, green and red synthetic multi-spectral filters.

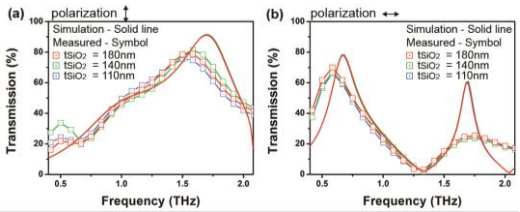

Fig. 4 Simulated (solid line) and measured (symbol) transmission spectra of the proposed synthetic multi-spectral optical filter (a) for the perpendicular polarization and (b) for the parallel polarization in the terahertz range.

trophotometer as shown in Fig. 2(b), where the center wavelengths is 480 nm, 590 nm, and 670 nm, and the corresponding transmission efficiencies are 64 %, 58 %, and 52 % respectively. Fig. 2(c) shows optical microscopic images fabricated of blue, green and red color filters. It should be noted that the measured values lower than the simulated ones in Fig. 2(b). We assume that this discrepancy in transmission efficiency is attributed to the slight difference in the surface roughness as well as the metal layer thickness.

In order to characterize our proposed SMM filter in both visible and terahertz ranges, double layered CSRRs are generated by being patterned on both top and bottom the metal sheets of thin film etalon structure. However, due to the opening on the metal pattern of CSRRs, the baseline of the transmittance in visible range is expected to increase by the window size of CSRRs to enable the light directly passing through the total window area of SMM s filters. Fig 3(a) shows the measured transmission spectra of the thin-film etalon color filters and our proposed SMM filters where we can confirm that both of them have identical center wavelengths and transmission efficiencies with a negligible difference. It should be noted that the discrepancy in the red filter between the measured and simulated spectra is attributed to deviations of the thickness of Ag as well as of the measurement set-up. Fig. 3(b) shows the optical microscopic images of fabricated blue, green and red SMM filters, respectively.

Since the color of the thin-film etalon filter is defined by adjusting the thickness of resonance cavity, we investigate the terahertz resonance properties of our proposed filter with various thicknesses of resonance cavity. Since the resonance properties of double-layered CSRRs are defined by the effective slits areas without coupling effect between top and bottom layers [5], we can expect that our proposed the SMM filters can have identical terahertz resonance frequency for various thicknesses of resonance cavity corresponding to each blue (110 nm), green (145 nm), and red (185 nm) colors as long as the window of CSRRs are kept same. In order to verify our expectation in terahertz spectral range, we measured the transmission spectra of the fabricated SMM filters with varying thickness of resonance cavity, and compare with the simulated data as shown in Fig.4. For the perpendicular polarization, the proposed SMM filter shows a good band-stop property with the center frequency fixed at 1.5THz while it shows two sharp resonance characteristics fixed at 0.6 and 1.7 THz for the parallel polarization, regardless of varying thickness of resonance cavity. The discrepancies between the experimental (symbols) and the simulated data (solid line) are assumed to be originated from deviations of the surface roughness of the structures.

4. Conclusions

We propose novel flexible SMM filters on PET films that work simultaneously in visible and terahertz range by integrating of terahertz metamaterials and thin-film etalon structures. We observed that the proposed SMM filters have high transmission efficiency in both visible and terahertz ranges. We also confirm that the variation in the thickness of resonance cavity has no effect on transmission in terahertz range. However, the window patterns of the double-layered CSRRs results in the increment the of baseline transmission, which can be removed by additional capping layer. We expect that the proposed SMM filter can be fabricated over the large are substrate by using conventional photolithography, which can bring the tremendous reduction in the manufacturing cost and time.

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