Plasmonic Metasurface for Color Hologram

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***Abstract*—We design an aluminum-based phase-modulated multi-color meta-hologram (MCMH) that is polarization-dependent and capable of producing images in three primary colors (red, green and blue). It has the structure of patterned aluminum nanorods which have surface plasmon resonances in these three colors controlled by different lengths of rods.**

***Index Terms*—Metasurfaces, aluminum plasmonics, meta-hologram, holography, nanoantennas, multi-color, polarization, switching.**

I. Introduction

Holograms, the optical devices to reconstruct pre-designed images, show many applications in our daily life. The multi-color rainbow holograms are sought after for artists and commercials but have the disadvantages of varying colors from different viewing angles. Traditional full-color holograms, Denisyuk hologram for example, use transparent films fabricated with three primary color photoresists [1]. Spatial light modulators (SLM) dynamically modulating the phase and amplitude of the light have been applied in liquid crystal displays (LCD) [2].

However, the scalar diffractive pattern employed in these techniques renders polarization unswitchable, and the photoresists are always rather thick compared to the wavelength of light. To save information with polarizations, we can use electromagnetic optics. Recently, Osaki et al. demonstrated the multiplexed thin hologram based on scattered plasmonic wave from different gratings [3]. Montelongo et al. demonstrated a two-color (blue and red) amplitude-modulated hologram based on plasmonic silver nanoparticle scattering [4]. The spatial phase modulation is more desirable than that of amplitude because of the brighter image by preserving amplitude. Therefore, a modulation of phase for holograms is preferred [5, 6]. Metasurfaces show the additional abilities to manipulate the phase and polarization of incident light [7], such advances have led to the demonstration of the high-efficiency and broadband meta-hologram with polarization-controlled dual images [5]. Unfortunately, multi-color holograms demonstrated so far employed mostly in near-infrared because efficient phase modulation covering the entire visible spectrum is difficult to be realized for gold and silver [5], while that of silver does not have access to the blue region [6]. Interestingly, aluminum with higher plasma frequency than that of gold and silver has recently been studied to achieve surface plasmon resonances into visible and UV region [8], which becomes the potential material for metasurface-based holograms.

Here we present a phase-modulated multi-color meta-hologram (MCMH) based on aluminum plasmonics, as shown in Fig. 1, that enables formation of polarization-dependent images in three primary colors [6].

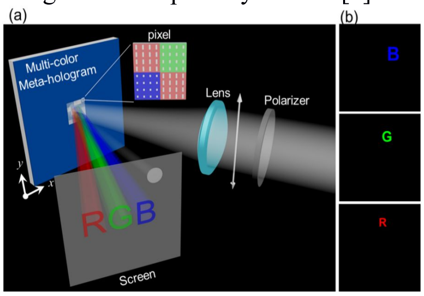

Fig. 1. (a) Designed MCMH under linearly polarized illumination. (b) The sizes and locations of the three images R, G, and B relative to the zeroth-order spot located at the upper right corner of the image screen.

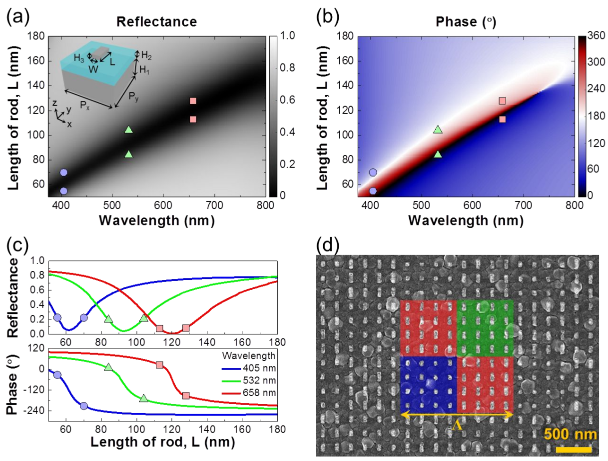

Fig. 2. Simulations of (a) reflectance and (b) phase of varying lengths of rods and wavelengths. (c) Simulated results of varying lengths of rods under illuminations of wavelengths of 405, 532, 658 nm. (d) SEM image of the MCMH sample. The colored area forms a pixel with four sub-pixels.

II. Design and Fabrication of MCMH

To design the nanorods for our hologram, we simulated the reflectance and phase with different lengths of nanorods under the normal illumination of linear polarized light (Fig. 2(a-c)). The continuous plasmonic resonance is across the visible spectrum. Narrow resonance and two-phase modulation scheme are used for the lower crosstalk and color multiplexing. Therefore, the two different rod lengths were chosen for each operating wavelength (405, 532, and 658 nm) in such a way that they yield a phase difference of π while maintaining approximately the same reflectance.

To determine the whole structure, we used the computer-generated hologram (CGH) [9] to calculate the 180 × 180 pixels of phase distribution and sampled the nanorods on each sub-pixel. The structure was fabricated with standard e-beam lithography. Figure 2(d) shows the scanning electron microscope (SEM) image of a small region of the fabricated sample. Each sub-pixel occupies 800 × 800 nm^2 consisting of 4 by 4 nanorods. One pixel consists of four sub-pixels. There are 2 red sub-pixels to compensate for the lower reflectance in red light.

III. Results and Discussion

We employed the white light illumination consisting of three laser diodes emitting at 405, 532, and 658 nm. The laser beam of any linear polarization can be selected by rotating the polarizer. The meta-hologram was placed onto the focal plane of lens where the reconstructed images are recorded directly by a CCD camera. Fig. 3(a) shows the reconstructed images with different operation wavelengths, which shows the color-multiplexing of MCMH in three primary colors. Taking into account of the wavelength dependence of the diffraction angle, we can project letter images to specific locations with predetermined size and order. There is an unintended letter G in red because of resonance crosstalk and overlap between the sub-pixels for letters R and G.

When we mixed three lasers together as a white light source, Figure 3(c, left) shows chromatic-blur-free image and matches well with the calculated result in Fig. 3(b). The polarization-dependent reconstructed images shown in Fig. 3(c) demonstrate the sensitivity to the light polarization. By integrating the areas of projected letter images under y- and x-polarized incident light, the extinction ratios are 16.7 for the red R and 8.5 for both the green G and blue B. The experimental values of extinction ratio are sufficient for polarization-multiplexing displays.

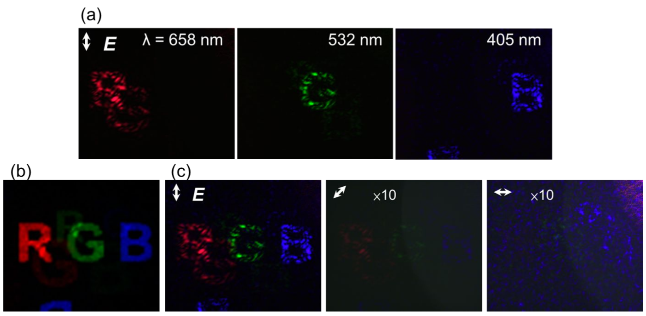

Fig. 3. (a) The recorded images under red (658 nm), green (532 nm), and blue (405 nm) illuminations with y-polarized laser beam. (b) The calculated reconstructed image. (c) Polarization-dependent reconstructed images show the sensitivity to the light polarization.

IV. Conclusion

We have demonstrated for the first time a phase-modulated full-color meta-hologram which is polarization-dependent using aluminum nanorods with resonances in red, green, and blue of the visible range. By using metasurface to demonstrate holograms, the common issue of multiple diffraction orders accompanying 3D holographic image is avoided because of its ultra-thin and subwavelength size. With proper choose of nanorod structures, a binary phase hologram capable of letter images of specified size at a predetermined location is demonstrated. The low-cost materials of aluminum and silica make MCMH mass-producible. The presented MCMH here can further be expanded to yield dual images with the design of cross nanorods which is actually a combination of two sets of perpendicular aluminum rods, each used to produce one image of a particular polarization. Subwavelength scale thicknesses of metasurfaces or meta-holograms provide promising flat optics and devices such as 3D imaging, nano-projector, security printing, data storage, etc.

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