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Polarization controlled colorful images reconstructed by reflective meta-hologram

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ABSTRACT

Holograms, the optical devices to reconstruct pre-designed images, have been evolved dramatically since the advances in today's nanotechnology [1-4]. Metamaterials, the sub-wavelength artificial structures with tailored refraction index, enable us to design the meta-hologram working in arbitrary frequency region. Here we demonstrated the first reflective type, dual image and high efficient meta-hologram with the incident angle as well as the coherence of incident wave insensitivity in visible region at least from $\lambda = 632.8$ nm to $\lambda = 850$ nm. The meta-hologram is composed of 50-nm-thick gold cross nano-antenna coupled with 130-nm-thick gold mirror with a 50-nm-thick MgF₂ as spacer. It shows different images "RCAS" and "NTU" with high image contrast under *x*- and *y*-polarized illumination, respectively. Making use of the characteristic of meta-materials, these optical properties of proposed meta-hologram can be transferred to arbitrary electromagnetic region by scale-up the size of the unit cell of meta-hologram, leading to more compact, efficient and promising electromagnetic components.

Keywords: Plasmonic metamaterials, metasurfaces, meta-hologram, reflection phase, cross nanoantennas, polarization-controlled dual images

1. INTRODUCTION

Meta-hologram takes the advantages of metamaterial showing the possibility to fabricate holograms working in arbitrary frequency. Metamaterials, the artificial materials with sub-wavelength structure, are invented showing their optical properties not from their chemical composition, but from their designed sub-wavelength structures [5-6]. In other words, metamaterials enable us to tailor our own materials with refraction index tunability which is determined by the resonance of sub-wavelength structure. Metamaterials have been demonstrated with board applications in sensing [7-8], energy harvest [9-12], super-imaging [13-14], cloaking [15-16] and novel electromagnetic devices [17-21].

Nowadays, thanks to advanced fabrication techniques, we have many optical devices for light manipulation, such as diffractive and gradient index (GRIN) optical devices [22-23] and spatial light modulator (SLM). In those devices, they make use of spatial variation in the refractive index to control the wavefront of light. Human eye, a typical GRIN for example, has the refractive index $n \sim 1.406$ in the central part down $n \sim 1.386$ in around. Since the refraction index variation is small $\Delta n \sim 0.02$, it needs enough thickness for phase accumulation to image with good resolution and focusing. Diffractive optical devices such as grating and Fresnel lens are usually thin and easy to be manufactured, but the drawback is that their optical properties are hardly to be changed once they are manufactured. SLM has large tunability of refraction index, but it is limited in particular electromagnetic frequency due to its optical material composition. In recent years, the 2D version of metamaterials so-called metasurface with its thickness much smaller than the wavelength of incident wave, have abilities to manipulate the phase of light from Microwave, THz, Far-IR, Mid-IR, NIR to visible region [24-30]. Once the phase of incident electromagnetic wave can be controlled, the meta-hologram designed by computer generated hologram (CGH) technique [31] can be fabricated in the above-mentioned frequencies.

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2. DESIGN AND FABRICATION OF META-HOLOGRAM

Here we presented the first reflective type, polarization-controlled dual image 4-level meta-hologram with high efficiency ($>18\%$ at $\lambda = 780$ nm) and broad working region in visible frequency at least from $\lambda = 632.8$ nm to $\lambda = 850$ nm. Figure 1 shows the functionality of our designed meta-hologram under 45° linearly-polarized illumination. The meta-hologram in this work consisted of 130-nm-thick gold mirror coupled with 50-nm-thick gold cross antenna with a 50-nm-thick MgF_2 as spacer. The phase of the reflected electromagnetic field is engineered independently by varying the length of cross along x- or y-direction. Therefore, the meta-hologram can generate the designed patterns in the far-field space by utilizing the metamaterials with varying geometry to satisfy the required phase distributions calculated by CGH. By carefully design the dimension of cross, the meta-hologram shows two different images “RCAS” and “NTU” in the case of x- and y-polarized illumination in a given wavelength of incident light. The most distinguished difference between meta-hologram and conventional hologram is that the images of meta-hologram are reconstructed by the coherent scattering wave of localized surface plasmon, and therefore the coherence of incident wave is not critical.

Figure 1. The functionality of our designed meta-hologram under 45° linearly-polarized illumination. The phase distribution of image “RCAS” and “NTU” were recorded on the meta-hologram by 50-nm-thick Au cross metamaterials with 50-nm-thick MgF_2 spacer and gold mirror. The images “RCAS” and “NTU” can be reconstructed by a linearly polarized incoherent wave with broadband and broad incident angle.

To define the geometric parameters of each cross-shaped nanoantenna distributed of the Au cross antenna, we first employed FDTD simulations to calculate the reflection phase and amplitude of a system that have the same Au mirror and MgF_2 spacer (as mentioned before) but with periodic array of Au nanorods. We calculate the reflection phase and amplitude as a function of the length L of Au rods under normally incident plane wave with wavelength $\lambda = 780$ nm and polarized along the long axis of rod. The thickness and width of each Au rods are fixed as 50 nm and 60 nm, respectively. In addition, the reflection amplitude is quite stable against L after carefully analysis the loss issue in the system (ex. scattering cross sections of nanorods). We selected 4 length parameters ($L = 60$ nm, 105 nm, 125 nm and 209 nm, respectively) corresponding to the reflection phase separated by $\pi/2$ to design a 4-levels phase meta-hologram. Finally, we implant the cross-shaped nanoantennas with specific geometric parameters in the proper surface location to meet the phase requirements for both polarizations, and the non-overlapping words “RCAS” and “NTU” can be projected to the

far field with x and y-polarized incident light, respectively. The meta-hologram sample is fabricated with standard e-beam lithography. The meta-hologram consists of 100×100 pixels each filling with 6×6 cross-shaped nanoantennas. Figure 2 present the SEM micrograph of a small region of the fabricated meta-hologram, the cross-shaped nanoantennas with various geometries within different pixels are corresponding to different phase delay.

Figure 2. The scanning electron microscope (SEM) image of meta-hologram.

3. CONCLUSIONS

We proposed and demonstrated a metamaterial-based and polarization-controlled dual images meta-hologram which has many advantages such as simple design principles, high efficiency, broadband working frequencies, and incident angle insensitivity. In particular, the dual images of meta-hologram can be reconstructed by incoherent light showing the most distinguished differences to conventional hologram. The fabrication and design of our proposed meta-hologram is very simple and we believed the efficiency of our proposed meta-hologram can be further improved by increasing the phase levels of meta-hologram. The polarization-controlled dual images of meta-hologram have potential application to perform 3D images. Finally, by combining the techniques of tunable metamaterials with the design of our proposed meta-hologram, it will be possible to fabricate the active meta-hologram working in arbitrary frequencies.

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