Realization of amplitude-type hologram based on nanostructured metasurfaces

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Abstract. Conventional Amplitude-type holograms are generated by recording the interference fringes on a photosensitive material. In this paper, taking advantage of the characteristics of metasurfaces that can continuously control the amplitude of electromagnetic waves, a silver-nanopolarizer-based metasurface is proposed to realize amplitude-type holograph. An off-axis meta-hologram is designed and fabricated with e-beam lithography. And experimental results show that it can project a holographic image in the far field with high-fidelity, indicating that this amplitude hologram has the ability of continuous amplitude modulation and is safe and stable, so it has application spaces in holography, optical holography, holographic encryption, anti-counterfeiting, etc.

1. Introduction
Today, phase-only holograms [1-3] have been highly developed and widely used in many fields of diffractive optics, such as holography, computer generated holography and optical sensing. In principle, phase-only hologram does not attenuate the energy of light and it has high diffraction efficiency, but its manufacturing process is extremely complicated and the holographic effect is unstable, which is greatly affected by manufacturing errors and wavelength fluctuations.

Metasurface refers to an artificial material composed of a two-dimensional periodic sub-wavelength structure array, which has a highly flexible light response capability. Recent reports show that by designing a suitable sub-wavelength structure [4], the phase, amplitude, and polarization of incident light can be arbitrarily controlled. Therefore, metasurfaces have great application potential in the fields of flat lenses, holography, beam generation, and polarization devices. Therefore, we can conceive of the effective control of the incident light amplitude based on the metasurface. Malus’ law can determine the emergence amplitude of the linearly polarized light. After research, we have found that the metasurface is based on metal [5] or dielectric [6] nanobricks. The surface has a unique feature. The polarized light incident along the short axis of the nanobrick can be mostly transmitted while reflecting the polarized light along the long axis. More importantly, the transmitted light is only related to the steering angle of the nanobricks, which can further reduce the influence of manufacturing errors and wavelength fluctuations. In order to further verify our ideas, we designed and manufactured an amplitude-based hologram based on the proposed metasurface. Experimental results show that this concept can achieve satisfactory holographic effects and can effectively control the amplitude.

2. WORKING PRINCIPLE OF METASURFACE HOLOGRAMS WITH SILVER NANOBRECKS
The disordered hologram to be designed is composed of an array of silver nanobricks placed on a silicon dioxide flat substrate. The same geometric parameters of all nanobricks are: cell size C, height H, width W and length L. Only the angle between the short axis of the nanobrick and the x-axis, that is, the direction angle $\theta$ is different. The schematic diagram of the anisotropic nanostructure to be designed is shown in figure 1(a). Due to the different parameters of the long axis and the short axis of the nanobrick, the electromagnetic response of the nanobrick along the short axis and the long axis will be different. In general, the basic principle is to control the performance of anisotropy by adjusting the geometric parameters of nanobricks. During the simulation process, we use CST Microwave Studio software to simulate and optimize the unit structure of nanobrick. In the simulation, an LP plane wave is incident along the normal direction of the polarization of the short or long axis of the nanobrick to illuminate the nanobrick unit cell with periodic boundary conditions. After many simulation designs, the optimal size structure of a group of nanobricks is finally determined: C is 300 nm, H is 85 nm, W is 80 nm, and L is 165 nm.

![Figure 1](image)

**Figure 1.** The positive and negative amplitude modulation diagrams of the metasurface based on Ag nanobricks. (a) Schematic diagram of the silver nanobrick unit cell. (b) The reflectance and transmittance vs wavelength (495-700 nm) curve, where x and y refer to the polarization direction of silver nanobrick. Orientation angle $\theta$ in (b) is 0°. (c) A simplified version of the orthogonal-polarization optical path, consisting of a polarizer, a nano-polarizer, and an analyzer. (d) The relationship between the output light amplitude and the turning angle of the nanobrick. 

On the basis of this size structure, when the direction angle $\theta$ is fixed at 0°, the transmittance $T_x$, $T_y$ and reflectivity $R_x$ of the nano-brick unit structure are obtained, and the relationship between $R_s$ and wavelength is shown in figure 1(b). Under the condition of working wavelength of 632.8 nm, $R_x$ and $T_y$ reach 91%, while $T_x$ and $R_y$ are lower than 5%. From figure 1(b), it can be concluded that the incident light along the $y$-axis (short axis) direction is almost completely transmitted, while the incident light along the $x$-axis (long axis) direction is almost completely reflected. Accordingly, silver nanobrick design can act as a linear polarizer. Next, put the metasurface between the polarizer and the analyzer to test the role of the metasurface as a polarizer, set orthogonal-polarization optical path, put the metasurface between the polarizer and the analyzer to test the role of the metasurface as a polarizer,
as shown in figure 1 (c). The green and blue double-headed arrows indicate the polarizer and analyzer, respectively, and the direction of the arrow indicates the transmission axis. In accordance with the law of Malus, the following equation can be drawn between the transmitted light incident on amplitude relation:

\[ A_{\text{out}} = (Y - X)\sin(2\theta)A_{\text{in}}/2 \]  

(1)

Wherein X and Y are nanobrick complex amplitude transmission coefficient along a major axis and a minor axis, \( \theta \) represents the nano metasurface steering angle, \( A_{\text{in}} \) is the amplitude of the transmitted light polarizer (green arrow). We can regard the nanobrick as an ideal polarizer (\( Y=1 \) and \( X=0 \)), then (1) can be simplified to \( A_{\text{out}} / A_{\text{in}} = \sin(2\theta)/2 \). As shown in figure 1(d), the ratio of the amplitude of the transmitted light to the amplitude of the incident light is proportional to the sine relationship of the turning angle of the nanobricks, and the amplitude modulation of the incident light can be achieved by changing the turning angle of the nanobricks.

3. G-S ITERATIVE ALGORITHM UTILIZING AMPLITUDE HOLOGRAM

We can obtain the phase of the hologram through the GS iterative algorithm and convert the amplitude matrix distribution of the hologram, as shown in figure 2. Firstly, we preprocess the target image to obtain the discretized pixels. That is to say, the brightness of all pixels is the largest, so as to achieve the purpose of "brightness". In order to obtain the optimal distribution, iterative calculation is performed. After a finite number of steps, the convergence condition is satisfied, and the iteration is terminated to obtain the optimal amplitude distribution \( f(x,y) \) as shown in figure 2.

We convert the amplitude distribution matrix of the hologram into the orientation angle of the nano-brick unit structure one-to-one. In the simulation process, we treat each nanobrick unit structure as an ideal polarizer (\( Y=1 \) and \( X=0 \)). Therefore, we have obtained the orientation angle matrix of all nanobrick unit structures of the hologram:

\[ \theta(x,y) = \frac{1}{2}\arcsin[2f(x,y)] \]  

(2)
4. DEMONSTRATION AND INSPECTION OF AMPLITUDE HOLOGRAPHY BY METASURFACE

In order to verify our design, the experimental device shown in figure 3(a) was designed, and an off-axis Fourier hologram was designed with LP light incidence as an example. The target image is a grayscale image, which contains two flowers, and the number of pixels is 220×220. Then, based on the optimized amplitude distribution obtained, standard electron beam lithography (EBL) was used to create a hologram sample. In the next step, EBL is used to make a holographic sample, and a partial view of the image obtained by scanning under a scanning electron microscope (SEM) is shown in figure 3(d). Then we use a polarizer and analyzer to form an orthogonal-polarization path, and insert a filter (with a center wavelength of 633 nm) into an microscopic system. As shown in figure 3(c), we place the sample in the orthogonal-polarization light path, irradiate the sample with He-Ne laser and use a commercial camera to capture the holographic image with high fidelity and clarity at normal incidence (632.8 nm), as shown in figure 3(b). Therefore, the ideas we put forward can be well realized.

![Figure 3](image)

Figure 3 Experimental example diagram of amplitude-type holography (a) Simplified version of experimental device layout diagram (b) Far-field decoding holographic effect diagram (c) Holographic image obtained under the working wavelength of 632.8nm (d) SEM photo of the fabricated sample.

5. Discussion

In our design, first of all, the difference lies in the continuous amplitude modulation of the hologram, which is different from the traditional DOE or phase-only hologram. We need to place the hologram in the orthogonal-polarization light path for decoding and illumination. In order to obtain the final holographic image, it does not need to be reproduced under the irradiation of a polarization-controlled laser light source like the traditional way, which also ensures that the amplitude-type hologram we designed has a certain degree of confidentiality.

Secondly, the amplitude-type hologram based on silver material that we designed has a wide tolerance for factors such as manufacturing errors and wavelength fluctuations that occur in the manufacturing process of the metasurface technology, and has a large tolerance range.

6. Conclusion

In this article, we propose a method to realize amplitude-type hologram based on silver material-based metasurfaces. The hologram of the experimental results can project a holographic image in the far field, indicating that this amplitude hologram can work well under coherence light illuminance. The proposed meta-hologram has the ability of continuous amplitude modulation, safety, and stable error
tolerance, and has application spaces in optical holography, holographic encryption and optical anti-counterfeiting.

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