Full-color hologram using spatial multiplexing of dielectric metasurface

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In this Letter, we demonstrate theoretically a full-color hologram using spatial multiplexing of dielectric metasurface for three primary colors, capable of reconstructing arbitrary RGB images. The discrete phase maps for the red, green, and blue components of the target image are extracted through a classical Gerchberg–Saxton algorithm and reside in the corresponding subcells of each pixel. Silicon nanobars supporting narrow spectral response at the wavelengths of the three primary colors are employed as the basic meta-atoms to imprint the Pancharatnam–Berry phase while maintaining minimum crosstalk between different colors. The reconstructed holographic images agree well with the target images making it promising for colorful display. © 2015 Optical Society of America

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Phase-only computer-generated holography (CGH) possessing the merits of flexibility, simplicity, and low cost is a preferred technique that can reconstruct both real and virtual objects in display applications [1,2]. Taking advantage of recently developed metasurfaces to imprint abrupt interfacial phase changes at subwavelength scale [3–6], great achievements such as wide-angle projection, elimination of high-order diffraction, and broadband spectral response have been made toward promising applications for optical trapping [7], quantum optics [8], and integrated photonics [9]. However, most existing metasurface holograms can only reconstruct monochromatic images [10–16], which strongly limits their practical applications. To date, only a few research efforts have been conducted to construct metasurfaces having multicolor responses [17,18], and some issues such as the nontrivial spatial alignment, color crosstalk, low fidelity, and color mismatch between the hologram and computer display colorimetric systems have not been stressed yet. A colorful hologram is especially challenging for existing metasurfaces relying on metal antennas for phase modulation due to the operating wavelength is usually limited in near-infrared range, which is beyond the percept of human naked eyes, and the scaling down to visible range is hindered by the strong intrinsic loss and saturation effects in metal toward a short wavelength [19,20]. Therefore, a colorful metasurface hologram remains a major challenge, and more research efforts are highly desirable.

In this Letter, we demonstrate theoretically a full-color phase-only hologram using spatial multiplexing of dielectric metasurface subcells that can respond to three primary colors to reconstruct arbitrary RGB images. The target image with color quantity in computer display colorimetric system is converted to a hologram colorimetric system determined by the three primary colors according to color matching and transfer theory. The phase maps for the red, green, and blue components of the target image are then extracted through a classical Gerchberg–Saxton algorithm based on 16-level discreteness. Silicon nanobars are chosen as the basic meta-atoms to imprint the Pancharatnam–Berry phase due to its relatively low loss in visible range and narrow spectral response for low color crosstalk. The reconstructed images agree well with the target images, making such a scheme promising for colorful display.

The proposed scheme aims at illuminating the metasurface hologram with RGB lights simultaneously to get the reconstructions of the three RGB components of the target image at the same locations with the same sizes. Figure 1 shows the working principle of the metasurface hologram; incident red, green, and blue lights impinge on the metasurface and imprint the phases for each color component separately through corresponding subcells. The reflected lights of the three primary colors then propagate onto the image plane where three components of the reconstructed images compose to reproduce the colorful holographic image. Usually, the target colorful image for the CGH is obtained from the computer system where it is digitalized and stored under the RGB colorimetric system. The digitalized data uses \([R, G, B]\) to denote the quantities of the three color components, and each number ranges from 0 to 255 to represent different color levels [21]. The exact quantities of \([R, G, B]\) needed to mix a certain color vary dramatically according to the choice of the three primary colors. Therefore, the color conversion between the RGB colorimetric system and the hologram colorimetric system \([Rh, Gh, Bh]\) is the starting point.
unrelated, while the amplitude is forced to be the amplitude of the corresponding target color component. One iteration contains the successive processes from (2)–(4), and 20 iterations are enough to get a convergent phase map.

To imprint the calculated phase maps of the \([Rh, Gh, Bh]\) components onto the metasurface, silicon nanobar is chosen as the basic element to realize phase modulation due to its relatively low loss in a short wavelength compared with metal antennas and narrow spectral response for low crosstalk between different colors. The phase modulation mechanism relies on the Pancharatnam–Berry phase acquiring from the inversion of the absolute rotation direction of the electric field of radiation (in transmission or reflection) with respect to that of the incident one [24, 25]. By tiling the silicon nanobars with angle denoted as \(\theta(x, y)\), part of the incident circularly polarized light beam will be transformed to a beam of opposite helicity and imprinted with a geometric phase equal to \(\varphi(x, y) = 2\theta(x, y)\). This is equivalent to flipping the circular polarization in transmission or maintaining the same circular polarization in reflection. The orientation-controlled phase covers 0 to \(2\pi\) range while maintaining nearly equal reflection for all rotation angles, thus providing the full control over the wavefront.

To interpret the phase modulation of the silicon nanobar more clearly, a gradient metasurface supporting anomalous reflection light is demonstrated. Figure 2(a) shows the unit cell of the metasurface; silicon nanobars with rotation angles respect to Z axis from 0 to \(\pi\) with an increment of \(\Delta \theta = \pi/8\) are positioned on a glass substrate. The simulations are conducted using commercial finite-difference-time-domain method software, FDTD Solutions from Lumerical, Inc. In the simulations, the incident left-handed circularly polarized light is normal to the array plane, and periodic condition is used in each boundary of the

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**Figure 1.** Artistic impression of the full-color metasurface hologram.

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The holographic image is treated as the superposition of the three reconstructed components at the same locations with the same sizes. As the diffraction angle of the hologram is strongly dependent on the operating wavelength, the three components should be adjusted to counteract the size mismatch. The diffraction angle of the hologram, \(\alpha\), can be calculated according to \(\Delta P = \lambda/(2 \tan(\alpha/2))\), where \(\lambda\) is the operating wavelength, and \(\Delta P\) is the pixel size of the hologram [10]. Thus, the sizes of the three color components should be pre-scaled according to \(1/\lambda_{Rh}:1/\lambda_{Gh}:1/\lambda_{Bh}\) to make sure the first-order diffraction of the three images is spatially overlapped and aligned on the image plane.

The discrete phase map for each color component of the target image, \([Rh, Gh, Bh]\), can then be extracted separately using a classical Gerchberg–Saxton algorithm [23]. The algorithm involves iterative loops of propagations between the hologram plane and image plane. (1) The iteration starts on the image plane with a random initial phase and an amplitude of the target color component. (2) The wavefront is then propagated back to the hologram plane using inverse Fresnel diffraction. In the hologram plane, the phase map is extracted and discretized according to the phase discreteness level. Here, to ensure the fidelity of the holographic image, we adopt a high discreteness level of 16 with phase modulations from 0 to \(2\pi\) by an increment of \(\pi/8\), which is also feasible for state-of-the-art nanofabrication. (3) The new wavefront in the hologram plane calculated with the discrete phases and unit amplitude is then propagated to the image plane through Fresnel diffraction. (4) The phase of the new wavefront on the image plane is kept unchanged, while the amplitude is forced to be the amplitude of the corresponding target color component. One iteration contains the successive processes from (2)–(4), and 20 iterations are enough to get a convergent phase map.

To imprint the calculated phase maps of the \([Rh, Gh, Bh]\) components onto the metasurface, silicon nanobar is chosen as the basic element to realize phase modulation due to its relatively low loss in a short wavelength compared with metal antennas and narrow spectral response for low crosstalk between different colors. The phase modulation mechanism relies on the Pancharatnam–Berry phase acquiring from the inversion of the absolute rotation direction of the electric field of radiation (in transmission or reflection) with respect to that of the incident one [24, 25]. By tiling the silicon nanobars with angle denoted as \(\theta(x, y)\), part of the incident circularly polarized light beam will be transformed to a beam of opposite helicity and imprinted with a geometric phase equal to \(\varphi(x, y) = 2\theta(x, y)\). This is equivalent to flipping the circular polarization in transmission or maintaining the same circular polarization in reflection. The orientation-controlled phase covers 0 to \(2\pi\) range while maintaining nearly equal reflection for all rotation angles, thus providing the full control over the wavefront.

To interpret the phase modulation of the silicon nanobar more clearly, a gradient metasurface supporting anomalous reflection light is demonstrated. Figure 2(a) shows the unit cell of the metasurface; silicon nanobars with rotation angles respect to Z axis from 0 to \(\pi\) with an increment of \(\Delta \theta = \pi/8\) are positioned on a glass substrate. The simulations are conducted using commercial finite-difference-time-domain method software, FDTD Solutions from Lumerical, Inc. In the simulations, the incident left-handed circularly polarized light is normal to the array plane, and periodic condition is used in each boundary of the
unit cell to reduce the amount of computation. The permittivity of glass and silicon are extracted from the experimental data [26].

Figure 2(b) shows the phase distribution of the reflected left-handed circularly polarized light at 465 nm, which indicates that the normally incident plane wave is tilted as it is reflected from the nanobar array. The anomalous angle extracted from simulation is 23.4° and agrees well with that calculated from the theoretical expression $\arcsin(2\Delta\theta/k_0) = 22.8°$, where $k_0$ is the wave number in free space [4]. Even though the Pancharatnam–Berry phase does not rely on the wavelength for making its performance non-dispersive and highly robust against fabrication variations, the exact spectral response strongly depends on the antenna design. For a metasurface composed of metal antennas, the spectral response is usually wide because of the low $Q$-factor of the resonances, which is favorable for monochromatic holograms allowing broadband operation. However, this is no longer true for the colorful hologram because the broadband response leads to dramatic crosstalk between different primary colors. An ideal metasurface for high color fidelity is single frequency or at least narrowband, and this is satisfied by using silicon nanobar as a basic meta-atom. Figure 2(c) shows the reflections of the left-handed circularly polarized light of the silicon nanobars with different geometric parameters under the incident left-handed circularly polarized light. The reflection for circularly polarized light is calculated by $R_{LL} = [(r_{xx} + r_{yy} - (r_{yx} - r_{xy})i)/2]^2$, where $r_{xx}$, $r_{yy}$, $r_{yx}$, and $r_{xy}$ are the reflection coefficients for the linear polarized light [10]. The nanobar can be tuned to support a response from the three primary colors while still maintaining relatively narrow spectral response which is essential to alleviate the color crosstalk. One can notice that the reflection of the nanobar for blue light is relatively lower than that for green and red; this is due to the increasing loss of silicon toward the short wavelength.

Figure 3(a) shows one pixel of the proposed hologram composed of four metasurface subcells, one for red consisting of $10 \times 10$ units of silicon nanobars capable of responding to 633 nm incident light, one for green ($12 \times 12$ units for 532 nm light), and two for blue ($30 \times 30$ units for 465 nm light) to compensate for the low reflection. The minimum interval between the subcells is 750 nm, which is much larger than $\lambda_R/2$ to ensure that the coupling between the subcells can be safely ignored and different subcells can operate independently. Figure 3(b) shows the calculated phase map of the hologram array. The subcells for corresponding primary color operate independently; the color crosstalk mainly comes from the non-zero reflection at other primary colors. The efficiency of our hologram is mainly affected by the co-polarized conversion efficiency of the silicon nanobars. As demonstrated in the previous text, the co-polarized light is capable of manipulating the phase in reflection mode only. The maximum co-polarized conversion efficiency of nanobars can reach 100% when no loss is introduced but, for the real case, the conversion efficiency is degraded by the intrinsic loss in silicon which gradually increases toward a short wavelength. The total efficiencies which also take the spatial multiplexing into consideration are 13.2% for red, 11.1% for green, and 8.9% for blue. A further boost of efficiency can be realized by seeking low loss dielectric or introducing gain materials in the nanostructures.

To verify our design, the red, green, and blue components of the target image are reconstructed using Fresnel diffraction and composed to reproduce the holographic image [27]. The phase maps are multiplied with the amplitudes calculated from corresponding reflection coefficients, and then numerically propagated to the image plane 1 m away from the hologram. The wavefront amplitude of the blue component on the image plane consists of the responses from the Bh-subcells ($A_{Rh\rightarrow Bh}$), Gh-subcells ($A_{Gb\rightarrow Bh}$), and Rh-subcells ($A_{Rb\rightarrow Bb}$). The rule also holds for the other components:

$$A_{Rh} = A_{Rh\rightarrow Rh} + A_{Gb\rightarrow Rh} + A_{Bh\rightarrow Bb}$$
$$A_{Gb} = A_{Gb\rightarrow Gb} + A_{Gb\rightarrow Gb} + A_{Bh\rightarrow Gb}$$
$$A_{Bh} = A_{Bh\rightarrow Bb} + A_{Gb\rightarrow Bb} + A_{Bh\rightarrow Bb}$$

The three color components are then scaled and reconverted to a RGB colorimetric system to display on the computer system. The obtained intensity images are colored red, green, blue, and combined using photo editor software. The numerical operation is equivalent to observing a screen placed at a distance of 1 m away if the hologram is illuminated with corresponding lights. Except for experimental realization, the final color component on the image plane depends not only on the intensities of the reconstructed components, but also on the power distribution of the illumination and the visual function of the primary colors on human eyes. To maintain the color of the holographic image and the target image are equivalent, the intensities of the three incident lights should conform to $P(\lambda_{Rh}) : P(\lambda_{Gb}) : P(\lambda_{Bb}) = 8.2 : 6.9 : 8.6$ [22]. The results are shown in Fig. 4; the central patches in the images belong to the direct reflection light (zero-order diffraction) of the hologram array. The subcells for corresponding primary colors reside in corresponding subcells. The blue components reside in two subcells due to the low reflection of the metasurface at a short wavelength. (b) Calculated reflections of the subcells and the hologram pixel.
gram. Speckle noise is observed in the reconstruction images due to the color crosstalk and phase discreteness, which can be further improved by increasing the phase level. Figures 5(a) and 5(b) show an arbitrary RGB image and its holographic image; the target image can be well reconstructed using our metasurface hologram. The colors reproduced from the hologram are less saturated due to the degraded contrast ratio in the reconstruction caused by color crosstalk.

In summary, we demonstrate theoretically a full-color metasurface hologram capable of reconstructing arbitrary RGB images by spatial multiplexing of subcells for three primary colors. A silicon nanobar having a narrow spectral response, and a relatively low loss in short wavelength is chosen as the basic metaatom to imprint the phase maps which are extracted through a classical Gerchberg–Saxton algorithm for the red, green, and blue components of the target image. The crosstalk between different colors, spatial overlap and alignment of the three image components, incident intensities for primary colors, and color match between computer display and hologram colorimetric system are demonstrated. The reconstructed image agrees well with the target image making such a metasurface hologram suitable for future colorful display.

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