Dielectric multi-momentum meta-transformer in the visible

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Metasurfaces as artificially nanostructured interfaces hold significant potential for multi-functionality, which may play a pivotal role in the next-generation compact nano-devices. The majority of multi-tasked metasurfaces encode or encrypt multi-information either into the carefully tailored metasurfaces or in pre-set complex incident beam arrays. Here, we propose and demonstrate a multi-momentum transformation metasurface (i.e., meta-transformer), by fully synergizing intrinsic properties of light, e.g., orbital angular momentum (OAM) and linear momentum (LM), with a fixed phase profile imparted by a metasurface. The OAM meta-transformer reconstructs different topologically charged beams into on-axis distinct patterns in the same plane. The LM meta-transformer converts red, green and blue illuminations to the on-axis images of “R”, “G” and “B” as well as vivid color holograms, respectively. Thanks to the infinite states of light-metasurface phase combinations, such ultra-compact meta-transformer has potential in information storage, nanophotonics, optical integration and optical encryption.

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Metasurfaces composed of tailored nanostructures arranged two-dimensionally hold great capabilities to locally control light’s phase, amplitude and polarization states at the subwavelength scale. Due to this control capability, metasurfaces can provide specific transmission (T) and reflection (R) functions to work as planar photonic components carrying customized information. Such information can be unlocked via a distinguished field distribution reconstructed at the observed region. When an incident light $U_{inc}(x_0, y_0)$ impinges upon a metasurface $U_{meta}(x_0, y_0)$, the field distribution can be expressed by the convolution of $U_{meta}(x_0, y_0)$ and an impulse response $h(x, y, z)$ that relates the fields at the metasurface. Therefore, the field distribution on the observation plane can be expressed as (more detail are shown in Supplementary Note 1):

$$U(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U_{meta}(x_0, y_0) U_{inc}(x_0, y_0) h(x - x_0, y - y_0, z) dx_0 dy_0$$

(1)

The diversity of metasurfaces’ function $U_{meta}(x_0, y_0)$ serves as the base for realizing lenses, color and polarization filters and holograms.

Multi-tasked metasurfaces are preferably desired for more compact nanophotonic devices, which could simultaneously carry multiple distinguished field distributions $U(n)$ at observed regions. Based on Eq. 1, previously reported multi-tasked metasurfaces can be divided into three categories (shown in Fig. 1a–c). The first approach takes advantage of spatial separation as shown in Fig. 1a. By separating the observed regions $(S^0)$ or interleaving subarrays $(S^{n})$ specifically designed for each functionality on the metasurface, the spatial multiplexed metasurface can reconstruct different field distributions $(U(n))$, but its efficiency is limited. The second approach resorts to adjusting functions $U_{meta}(x_0, y_0)$ of the metasurface by changing polarizations or incident angles or wavelengths of beams as shown in Fig. 1b. By tailoring meta-atoms, the structurally multiplexed metasurface carries polarization-, angle- or wavelength-dependent responses $U_{meta}(x_0, y_0)$ to reconstruct different field distributions $(U(n))$. This method can achieve higher efficiency than the previous one, but the efficiency is still limited by the coverage of the required phases that meta-atoms need to achieve. Another approach, as shown in Fig. 1c, is based on OAM multiplexing chip to read out the pre-set incident light $(A_{inc})$, which pre-generate various information-carrying multilocal beams arrays with corresponding OAM states. Each ring groove of the chip can out-couple a determined OAM order, which equivalently provides a “key” array to read out the distributions $U(n)$ locked in the preset beams by the spatial light modulator (SLM). However, the outcoupling efficiency of slits is much smaller than that in the previous two methods and it needs the beam array to illuminate each meta-atom. So far, a majority of reported multi-tasked metasurface are resorting to the spatial freedom, structure complexity or pre-modulation with decoupler, and there is a lack of a convenient way to realize multi-tasked functionality by intrinsic properties of light.

In this paper, we report a transmission-type multi-momentum meta-transformer, which transforms the intrinsic phases of OAM ($h$) and LM ($k_x h$) of the incidence light, into various distinct patterns in the same plane (Fig. 1d). The meta-transformer is made of the minimalist TiO$_2$ nano-fin array (Fig. 1g, h) and provides a phase profile $\psi_{meta}(x_0, y_0) = 2\pi(x_0, y_0)$ for the right circularly polarized beam with spin angular momentum (SAM). The phase is based on geometric phase and $\phi(x_0, y_0)$ is the orientation angle of nano-fins as a function of position. For a given fabricated metasurface, incident beams $U_{inc}(x_0, y_0)$ carrying OAM or LM are able to impart extra phase profiles $\psi_{OAM}(x_0, y_0)$ or affect impulse response $h(k_x)$ to the transmitted light to realize distinct patterns in the same plane right on axis. A multi-OAM phase retrieval algorithm is proposed to design the OAM meta-transformer, which can “read out” the order of the incident vortex beam. To be more specific, an image which tells the order of the incident vortex beam will be reconstructed at a given plane under illumination of vortex beam with certain orders as shown in Fig. 1e. In addition a multi-LM phase retrieval algorithm is proposed to design a LM meta-transformer, that can reconstruct patterns “R”, “G” and “B” in the same plane by illuminating it with red $(k_x^R)$, green $(k_x^G)$ and blue $(k_x^B)$ beams, respectively (Fig. 1f). This is due to the impulse response in Eq. 1 which is $k_x$-dependent. Moreover, such LM meta-transformer has demonstrated the capability to display vivid colorful images, thanks to the high-efficiency of the dielectric metasurface and the on-axis imaging feature for all wavelengths.

Results

Principle of multi-momentum meta-transformer. The metasurface consists of a set of amorphous TiO$_2$ nano-fins arranged in square pixels on a quartz substrate (Fig. 2a). The pixel size is $325 \times 325$ nm$^2$ and the TiO$_2$ nano-fin is 80-nm-wide, 250-nm-long and 600-nm-high, which rotates in plane with an orientation angle $\varphi$. When a circularly polarized beam is normally incident on the metasurface from the side of quartz, the transmitted light converts to the opposite circular polarization (CP) and acquires a phase delay of $\pm 2\varphi$ (Supplementary Note 2). Numerical FDTD solutions is employed to optimize the geometrical parameters of nano-fins, such that the conversion from one CP to the opposite CP is efficient for the operation in broadband visible range (as shown in Fig. 2b).

Figure 2c presents the schematic of OAM meta-transformer. A collimated vortex beam with native phase profile $\psi_{OAM}(x_0, y_0)$ illuminates the metasurface with its own as-fabricated phase $\psi_{meta}(x_0, y_0)$ from the quartz substrate, and the transmitted beam carries the total phase profile $\psi_T(x_0, y_0) = \psi_{OAM}(x_0, y_0) + \psi_{meta}(x_0, y_0)$ on illuminating area (Supplementary Note 3). The metasurface’s phase function $\psi_{meta}(x_0, y_0)$, which is fixed after the fabrication, is defined by the in-plane orientation of nano-fin array. The extra phase profile $\psi_{OAM}(x_0, y_0)$ from the incident vortex beam is dynamically changeable. As a degree of freedom of light, by feeding different spiral phases to the single-phase metasurface, one meta-transformer can, therefore, provide multiple different phase profiles, resulting in different patterns on the same plane.

The phase function $\psi_{meta}(x_0, y_0)$ of OAM meta-transformer is designed by the multi-OAM phase retrieval algorithm (Supplementary Note 4). The orientation angle of each nano-fin is determined by the retrieval phase $\psi_{meta}(x_0, y_0)$. The schematic diagram of the experimental setup is shown in Supplementary Fig. 3a and its specification can be found in Supplementary Note 6. As shown in Fig. 2d, at the given observation plane ($z = 60\mu m$), a judiciously designed metasurface reconstructs an “apple” pattern under illumination with a collimated Laguerre Gaussian beam with $l^{(1)} = -5$, while it shows a “spider” pattern instead when the OAM of the incident beam is changed to $l^{(2)} = 5$. The reconstructed images restore the features of the designed pattern and the crosstalk is suppressed.

Figure 2e presents the physical principle of LM meta-transformer. The phase function $\psi_{meta}(x_0, y_0)$ of a metasurface is defined by the in-plane orientation of nano-fin array, which means that the designed metasurface is able to provide the dispersionless phase profile. In the Fresnel region, the impulse
response $h$ of Eq. 1 is

$$h(x, y, z) = \frac{e^{ik_z z}}{i\lambda z} e^{ik_0(x^2+y^2)}$$

(2)

Therefore, when collimated monochromatic beams illuminate the metasurface, this dispersionless phase profile $\psi_{\text{meta}}(x_0, y_0)$ can control the monochromatic beams with different LMs to achieve different E-field distribution in a given plane (shown in Fig. 2e).

To realize the LM meta-transformer, the key idea is to reconstruct LM-dependent patterns in the same plane. In the visible region, the monochromatic beams with different LMs represent different colors. So three-primary colors (red 633 nm, green 532 nm, and blue 488 nm) are chosen in this work. Based on the $k_0$-dependent impulse response, the multi-LM phase retrieval algorithm (Supplementary Note 5) is deployed here to calculate the phase distribution $\psi_{\text{meta}}(x_0, y_0)$. Hence, the wavelength-dependent patterns are reconstructed in the same plane (at $Z_0$) and the unwanted patterns are moved out of the observed plane. In this design, based on the retrieval phase profile $\psi_{\text{meta}}(x_0, y_0)$, the nano-fins ($600 \times 600$) with rotation angles are fabricated on a total area of $192 \times 192 \mu m^2$. The schematic diagram of the experiment setup of color meta-hologram is shown in Supplementary Fig. 3b and the specificisation of the experiment setup can be found in Supplementary Note 6. The image is captured by a CCD camera. Figure 2f shows the holographic images of letter patterns “R”, “G”, “B” at a certain distance ($z=195 \mu m$), corresponding to the RGB color incident beams (633 nm, 532 nm, and 488 nm). The images corresponding
to the RGB color incident beams are independent from each other, and the cross-talk among different LMs is eliminated, due to \( k_0 \)-dependent impulse response.

**Discussion**

The OAM meta-transformer can now work as an OAM displayer, as demonstrated in Fig. 3a. This meta-transformer is formed by 300 \( \times \) 300 nano-fins on the total area of 97.5 \( \times \) 97.5 \( \mu \text{m}^2 \). As shown in Fig. 3b, the designed OAM meta-transformer reconstructs the patterns "0", "3" and "6" with the incident 0th-, 3rd- and 6th-order vortex beams, respectively. Compared with Fig. 2d, the OAM meta-transformer in Fig. 3b has lower phase difference among the incident vortex beams and encodes more OAM states, which may reduce the performance. Nevertheless, the reconstructions in Fig. 3b are clearly recognizable. The reconstructed patterns present the incident beam's topological charge values, which suggest a potential application of OAM topological charge displacer (OAM detection by direct reading) with such OAM meta-transformer.

Based on \( k_0 \)-dependent impulse response, the LM meta-transformer generates LM-dependent patterns on the identical position (Fig. 2e, f). Under illumination of red, green and blue beams simultaneously, these generated patterns overlapping each other enable the realization of colorful holographic images (Supplementary Note 7). The colorful holographic images contain not only three-primary colors (RGB) but also their secondary colors (cyan, magenta, yellow, as well as white). Moreover, the LM meta-transformer can also support complex patterns with gradient color (in Fig. 4a, b). Figure 4b reports the simulation and experimental results for each color and their superposition. These results indicate the accurate spatial control of the reconstructed images, and the cross-talk among different LMs is eliminated. The key feature for such gradient color image is that the color gamut spans the whole color triangle. Therefore, the LM meta-transformer has the capability to display vivid colorful image.

The capability is a critical issue for the multi-tasked metasurface. Based on the multi-momentum phase retrieval algorithm provided in this work, a single meta-transformer is able to support 5 OAM states ranging from −8 to 8 or 6 LM states in the visible region (Supplementary Note 8). With the help of the polarization-dependent response\(^{21,42,43} \) of TiO\(_2\) nano-fins, the number of patterns encoded in a meta-transformer can increase to 9 for OAM or 11 for LM. Furthermore, the capability of a meta-transformer can also be improved by increasing the number of units\(^ {25} \), and widening the multi-momentum state region. Besides, by considering the donut shapes of vortex beams, introducing random phase masks\(^ {44} \), and combining the LM and
OAM simultaneously in the phase retrieval algorithm, the multi-momentum meta-transformer has the potential to remarkably increase the carried information states.

In summary, we report a synergetic strategy of engaging OAM and LM of the incident beam with a single-phase metasurface, which significantly enriches the output of reconstructed patterns. OAM introduces the additional phase information from the incident beam, while the LM affects the phase information of impulse response. These two momentum degrees of freedom, in principle lead to infinite combined states, which enables metasurface with a large number of functions and may lead to new opportunities in 3D imaging, anti-counterfeiting, optical communication, and real-time detection.

**Methods**

**Numerical simulation.** The amorphous TiO2 nano-fins were optimized by Lumerical FDTD Solution (a commercial software). In this simulation, TiO2 nano-fins with measured refractive index were placed on quartz substrate. Two sources polarized along x- and y-axes with a 90° phase shift was used to form the right circularly polarized incident beam, and this beam illuminated TiO2 nano-fins from the substrate side. The periodic boundary condition was used along x- and y-directions, and the perfect matched layer (PML) was chosen along z-direction.

**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Code availability**

The codes that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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