Supporting Information

Multifunctional dielectric metasurfaces consisting of color holograms encoded into color printed images

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Supplementary Note 1 Instantaneous field distributions (enlarged view)

**Figure S1** Instantaneous electric and magnetic fields on xz and yz cross-sections through TiO2 cone. This is a larger version of Fig. 2b of the main text. The direction of the field is shown by arrows and the strength of the field is indicated by the color.
Supplementary Note 2 Simulated reflectance spectra of metasurfaces comprising cones with different top radii

Figure S2 This is a larger version of Fig.2(c) of the main text. In that figure, for display purposes, the different reflection spectra are vertically offset and the reflectance is provided in arbitrary units (a.u.). In this figure, the reflectance spectra are not offset and absolute values of reflectance are quoted.

Supplementary Note 3 Experimental setup for the reflectance measurements

The experimental set-up used for the reflectance measurements is schematically illustrated as Figure S3. White light is generated by a laser-driven light source (Energetiq LDLS™). This is coupled into a monochromator (Princeton Instruments Acton SP2150). As the monochromator employs a diffraction grating, the desired output wavelength $\lambda$ from the monochromator will be accompanied by the wavelengths $\lambda/m$ ($m=2, 3\ldots$). Since our light source is broadband, we use a filter after the monochromator to remove the undesired accompanying wavelengths. Such filters are often referred to as “order sorting filters”.

The light emerging from the filter then passes through a beam splitter and is focused by an objective lens (magnification = 10X, numerical aperture = 0.3) onto the sample. The light reflected from the sample is collected by the same objective lens, is (partly) reflected by the beam splitter, and then is collected by a power meter (Thorlabs PM 100D).
To calibrate our system, we place a piece of a polished silicon wafer where the metasurface sample would normally sit. We then vary the wavelength of the illuminating light using our monochromator and measure the power at each wavelength with our power meter. In this way, the intensity vs wavelength $I(\lambda)$ for the case of the silicon sample is found.

We next replace the silicon piece with the metasurface sample. In the system, the focal spot is smaller than the extent of each metasurface (200 $\mu$m*200 $\mu$m). To ensure that the focal spot is centered on the metasurface sample of interest, we remove the power meter, thereby allowing the light to continue to a CCD camera. This allows us to directly observe the metasurface and thus allows us to adjust its position appropriately. We next put the power meter back into the system (between the beam splitter and the CCD camera). We then measure the intensity vs wavelength curve $I'(\lambda)$ in the same way as before (but this time for the metasurface). The reflectance of the silicon $R(\lambda)$ can be readily found using the Fresnel reflection equations, with the refractive index of the silicon as reported in the literature [1]. This allows us to find the reflectance of our metasurface sample as follows:

$$I'(\lambda) R(\lambda)/ I(\lambda)$$

Note that this (standard) method makes use the fact that any wavelength-dependence of the transmittance or reflectance of the objective lens and beam splitter are cancelled out since $I(\lambda)$ and $I'(\lambda)$ are measured in the same way. To further verify our approach, we repeat our measurements, but this time replacing the polished silicon wafer with a sample comprising a thick (300 nm) aluminium film on a silicon substrate. Using the refractive index of aluminum as reported in the literature [1], we determine the expected reflectance of the aluminium sample, and we determine the reflectance of our metasurface sample. We find that the results obtained in this way (with the aluminium reference) are in good agreement with the results obtained with the silicon reference.

Figure S3 Schematic of the experimental setup for the reflectance measurement.
Supplementary Note 4 Measured reflection spectra displayed on CIE chromaticity diagram

To further illustrate the colors available with the fabricated TiO2 cones, we convert the ten measured reflection spectra (Fig. 4b of main manuscript) to color space. The results are plotted below.

Figure S4 CIE 1931 representation of reflection spectra measured from fabricated TiO2 cone arrays (provided as Figure 3b of main text). Points R, G, B represent the structures we use for the device that comprises a color printed image that encodes a color hologram.

Supplementary Note 5 Zeroth order reflected light and the off-axis design

Here we explain the appearance of our holographic image, in particular the presence of the zero-th order spots. A detour phase hologram contains numerous pixels that all contribute to the observed patterns. To facilitate physical interpretation, we take the simplest case, i.e., interference of the light from two neighbouring pixels to illustrate the origin of the zeroth order. Each pixel is assumed to contain a rectangular-shaped aperture of extent \((w_x \times w_y)\). Only the aperture transmits light and the other parts of the pixel are opaque. The distance between the two apertures is \(D\). The far field distribution of the light transmitted through the first aperture can be written as\(^2\)

\[
U_f(u, v) = \frac{w_x w_y}{\lambda f} \sin \left( \frac{w_x (u + \lambda f \alpha)}{\lambda f} \right) \sin \left( \frac{w_y v}{\lambda f} \right) \exp \left\{ j \frac{2\pi}{\lambda f} \left[ (u + \lambda f \alpha) x_0 + v y_0 \right] \right\} \tag{S1}
\]

Where \((u, v)\) represents the coordinates in the observation plane. \(\lambda\) is the wavelength, \(f\) is the focal length of the lens that is used to perform the Fourier transform. \(\alpha\) is equal to \(\sin(\theta)/\lambda\) where \(\theta\) is the polar angle of the light in standard spherical coordinate notation. Here, we consider the case where the azimuthal angle of the light (standard spherical coordinate notation)
is $\phi = 0^\circ$. In Ref [2], the angled incidence is illustrated. However, the results also apply to the case where the hologram is illuminated at normal incidence, and $(\theta, \phi)$ represent the angles of outgoing light. Here $(x_0, y_0)$ denotes the coordinates of the aperture in the hologram plane.

Similarly, the far field distribution for the second aperture is

$$U'_f(u, v) = U_f(u, v) \exp \left( j \frac{2\pi}{\lambda_f} uD \right)$$  \hspace{1cm} (S2)

The total field is given by

$$U_{total}(u, v) = U_f(u, v) + U'_f(u, v) = U_f(u, v) \left[ 1 + \exp \left( j \frac{2\pi}{\lambda_f} uD \right) \right]$$  \hspace{1cm} (S3)

From Eq. (S3), it can be seen that the field distribution of the observation plane can be modified by varying $D$. However, the field at the central point ($u=0, v=0$) of the observation plane remains does not depend on $D$. It is given as follows

$$U_{total}(0,0) = 2U_f(0,0) = \frac{2w_xw_y}{\lambda_f} \text{sinc}(w_x\alpha) \exp(j2\pi\alpha x_0)$$  \hspace{1cm} (S4)

The intensity is thus given by:

$$I_{total}(0,0) = |U_{total}(0,0)|^2 = \left[ \frac{2w_xw_y}{\lambda_f} \text{sinc}(w_x\alpha) \right]^2$$  \hspace{1cm} (S5)

Since $\text{sinc}(w_x\alpha) \neq 0$ for our detour phase holograms, the zeroth order cannot be eliminated.

To avoid the overlap between the zeroth order and the desired holographic image, we use an off-axis design. As shown in Fig. S5, the holographic image is moved downward from the image center, at which the zeroth order is located.

**Figure S5** Schematic of off-axis design. The intersection between the two white dashed lines depicts the image center where the zeroth order is located. Note that the dashed lines are not part of the holographic image and are included in this figure for illustration purposes.

The central spot (A in Fig. S6) corresponds to the zeroth order accompanying the desired holographic images (green ‘Physical’, blue ‘Mental’ and red ‘Spiritual’), and is a mixture of red, green and blue laser beams. In addition, a small blue spot (B) and a green spot (C) on the right side of the central spot can be seen. These are due to crosstalk between the holographic patterns. For example, while the reflection experienced by blue light from the green hologram is weak (as desired), it is not zero. This results in the feature that we denote as spot B. This can be thought of as the central spot of the crosstalk image (i.e. a much dimmer version of the word...
The reflectance of the blue light from the red hologram is so weak that the crosstalk image is not observed. Similarly, the spot C is the central spot of another crosstalk image that is produced when the green light shines on the red hologram. I.e. it is a much dimmer version of the word ‘spiritual’, but in green. Note that the low reflectance of the blue hologram (“mental”) for green light means that the crosstalk image that would result is not readily visible. Red crosstalk images are not visible. This is because the green (“physical”) and blue (“mental”) holograms have low reflectance at the wavelength of the red laser. While the central spots of the crosstalk images can be seen, the word patterns of the crosstalk images are too dim to be observed on the pattern produced on the laboratory wall (Fig. S6).

Figure S6 Locations of the zeroth orders and crosstalk patterns.

Supplementary Note 6 Diffraction angle of the holographic image

In the main text, we stated that the supercell size and the detour phase are given as follows:

\[
\Delta x = m \lambda / \sin(\theta) \quad (S6)
\]

\[
\varphi_{\text{detour}} = m \times 2\pi \times \delta x / \Delta x \quad (S7)
\]

Where \(\delta x\) is the displacement of the TiO\(_2\) cone array from the supercell center. The classic text [2] considers the case with \(m=1\), and proves that the diffraction angle is \(\theta\). For convenience, we hereafter use the subscript “1” to denote the case in the text, where \(\Delta x_1 = \lambda / \sin(\theta)\) and \(\varphi_{\text{detour1}} = 2\pi \times \delta x_1 / \Delta x_1\). The field distribution in the holographic image plane can be expressed as:

\[
U_f(u_1, v_1) = \sum_{p=0}^{N_x-1} \sum_{q=0}^{N_y-1} (w_x)_{pq} (w_y)_{pq} \exp \left[ -i \varphi_{\text{detour1}} \right] \exp \left[ i \frac{2\pi}{\lambda_f} (u_1 p \Delta x_1 + v_1 q \Delta y_1) \right]
\]

\[ (S8) \]

Where \((N_x, N_y)\) represent the total number of supercells in the \(x\) – and \(y\) – directions of the hologram. Explanations of other parameters can be found in Supplementary Note 5.

Here in this paper, we consider the case with \(m = 2\), and thus have:

\[
\varphi_{\text{detour2}} = 2 \times 2\pi \times \delta x_2 / \Delta x_2 \quad (S9)
\]

We use the subscript “2” to indicate that we consider the case with \(m = 2\). In our hologram design, we make \(\delta x_2 = \delta x_1\). Since \(\Delta x_2 = 2\Delta x_1\), Eq. (S9) becomes:
\[ \varphi_{\text{detour}2} = \frac{2 \times 2 \pi \times \delta x_1}{2 \Delta x_1} = \varphi_{\text{detour}1} \]  

(HS10)

Hence our design carries the same detour phase as the \( m = 1 \) design. However, the plane wave term of Eq. (S8) is different, depending on whether \( m = 1 \) or \( m = 2 \). For \( m = 1 \), it is given by:

\[ \exp \left[ i \frac{2 \pi}{\lambda_f} (u_1 p \Delta x_1 + v_1 q \Delta y_1) \right] \]  

(S11)

While in our design \( (m = 2) \), we have:

\[ \exp \left[ i \frac{2 \pi}{\lambda_f} (u_2 p \Delta x_2 + v_2 q \Delta y_2) \right] = \exp \left[ i \frac{2 \pi}{\lambda_f} (2u_2 p \Delta x_1 + v_2 q \Delta y_1) \right] \]  

(S12)

We also have \( \Delta y_1 = \Delta y_2 \) as the cones are displaced along the \( x \)-direction, and \( \Delta y \) value do not affect the analysis. For the \( m = 2 \) case, Eq. (S8) then becomes

\[ U_f(u_2, v_2) = \sum_{p=0}^{N_x-1} \sum_{q=0}^{N_y-1} (w_x)_{pq} (w_y)_{pq} \exp \left[ -i \varphi_{\text{detour}1} \right] \exp \left[ i \frac{2 \pi}{\lambda_f} (2u_2 p \Delta x_1 + v_2 q \Delta y_1) \right] \]  

(S13)

Eq. (S13) can also be written as

\[ U_f(u_2, v_2) = \sum_{p=0}^{N_x-1} \sum_{q=0}^{N_y-1} (w_x)_{pq} (w_y)_{pq} \exp \left[ -i \varphi_{\text{detour}1} \right] \exp \left[ i \frac{2 \pi}{\lambda_f} (u_2 p \Delta x_1 + v_2 q \Delta y_1) \right] \exp \left( i \frac{2 \pi}{\lambda_f} u_2 p \Delta x_1 \right) \]  

(S14)

Without the last term \( \exp \left( i \frac{2 \pi}{\lambda_f} u_2 p \Delta x_1 \right) \), Eq. (S14) will be the same as the \( m = 1 \) design in the text book [Eq. (S8)], where the reconstructed image is projected to \( \theta_1 \) direction (25° for the parameters chosen here). However, with this term it can be seen from Eqs. (S8) and (S14) that at an arbitrary point \( (u_2, v_2) \), where \( u_2 = u_1/2 \) and \( v_2 = v_1 \), we have \( U_f(u_2, v_2) = U_f(u_1, v_1) \).

Figure S7 Schematics of the projection angle of the hologram

The projection angle of the hologram can be schematically shown in Fig. S7. For the \( m = 1 \) case, the projected image is represented by point A, which has the coordinates \( (u_1, v_1) \) and it
forms an angle of $\theta_1$ with the metasurface normal. For the $m = 2$ case, the image is shifted to point $B (u_2, v_2)$ with $u_2 = u_1/2$ and $v_2 = v_1$. As a result, its projection angle satisfies

$$\tan(\theta_2) = \frac{\tan(\theta_1)}{2}$$

(S15)

And hence

$$\theta_2 = \arctan\left(\frac{\tan(\theta_1)}{2}\right)$$

(S16)

Hence the diffraction angle is $13.1^\circ$, which agrees well with our measured results.

**Supplementary Note 7 Pixel size discussion**

Here, we investigate the effect of the number of TiO2 cones within each pixel upon its optical properties. In the next section (Supplementary Note 8) we discuss the fact that the TiO2 cones are distributed in an almost continuous manner in the vertical direction. This is not the case for the horizontal direction. In investigating the effect of pixel size upon optical properties, therefore, we only consider the horizontal direction. In other words, we simulate arrays of TiO2 cones that are periodic in the vertical direction, but are of varied width in the horizontal direction. Specifically, we investigate TiO2 arrays containing two, three, four and five cones along the horizontal direction. We consider the pixel designed for green light, though we expect similar findings would occur for the red and blue pixels. As discussed in the main manuscript (e.g. Fig. 4), the green pixel we use in the fabricated device (color printed image & color hologram) contains four TiO2 cones in the horizontal direction.

Here we simulate the far field scattering property of the green pixel. The boundary condition in the vertical direction is periodic. In the horizontal direction, the boundary condition is set to be PML (perfectly matched layer). Illumination is a plane wave (vertically polarized) at normal incidence. The intensity of the scattered light from pixels of different widths in the horizontal direction (with different numbers of cones) is shown in Figure S8a. It can be seen that with the reduction of the number of cones in the horizontal direction, the scattering efficiency in all directions decreases.

We also investigate the effect of pixel width in the horizontal direction upon the printed color via simulations (Figure S8b). In the main text we use the microscope Nikon Eclipse LV150NA to observe the printed colors, and the objective lens used has NA=0.15. This means that the cone of light that can enter or exit the microscope has half angle up to $8.63^\circ$. To be consistent with that, we simulate the far field scattering intensities from $-8.63^\circ$ to $8.63^\circ$, and integrate the results to emulate the experimental measurement approach. A similar method is also used in Supplementary Note 9 to explain the x- y- polarization dependent colors and is found to yield results in agreement with the experimental results.
**Figure S8** (a) Far-field scattering intensity of TiO$_2$ cone arrays of varied width in the horizontal direction (number of cones). '2 cones' means that the array has two cones in the horizontal direction. Scattering intensity is normalized. We set the intensity to be 1 when there are five cones in the horizontal direction and the scattering direction is 0. (b) Simulated printed colors versus width of cone array in horizontal direction.

We next consider the effect of pixel width (in the horizontal direction) upon cross-talk. As the reflection spectrum changes with the pixel width, one would also expect modification to the cross-talk. Here we define the suppression ratio (SR) as the power at the operating wavelength (here taken as $\lambda=532$ nm) divided by the power at other wavelengths ($\lambda=635$nm and $\lambda=450$ nm). The crosstalk of the holographic images drops with increase of suppression ratio. As shown in Table S1, the average suppression ratio is higher for four and five cones than the other two cases.

<table>
<thead>
<tr>
<th>samples</th>
<th>SR at $\lambda=635$ nm</th>
<th>SR at $\lambda=450$ nm</th>
<th>Average SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cones</td>
<td>32.6</td>
<td>26.5</td>
<td>29.6</td>
</tr>
<tr>
<td>3 cones</td>
<td>19.58</td>
<td>52</td>
<td>35.8</td>
</tr>
<tr>
<td>4 cones</td>
<td>22.6</td>
<td>68.69</td>
<td>45.6</td>
</tr>
<tr>
<td>5 cones</td>
<td>69.24</td>
<td>19.4</td>
<td>44.3</td>
</tr>
</tbody>
</table>

When one considers efficiency, color and suppression ratio, one may conclude that designs with four or five cones in the horizontal direction are good candidates. However, one also needs to keep in mind that the TiO$_2$ cones of neighbouring pixels may overlap with one another if the pixel horizontal width is greater than half the supercell width. Since the width of each supercell is 2.52 $\mu$m, and the chance of overlapping is less if we choose to employ a design that is four cones wide (width 1.36 $\mu$m) than if it is five cones wide (1.7 $\mu$m). With these considerations in mind, we use pixels with horizontal widths of four cones.
**Supplementary Note 8 Phase distributions of the hologram**

The phase distribution of the hologram is far from being random\[^3\]. Table S2 shows the phase values of part of the hologram HG (area 1 in Fig. S9). It can be seen that relatively few pixels have abrupt phase changes from neighbouring pixels in the same line.

![Figure S9 Phase distribution of the hologram HG.](image)

### Table S2 Phase values of area 1 in Fig. S9. Rows and lines are along the $x$ and $y$ directions, respectively.

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.823213</td>
<td>1.618841</td>
</tr>
<tr>
<td>1.00016</td>
<td>1.758362</td>
</tr>
<tr>
<td>1.051952</td>
<td>1.765022</td>
</tr>
<tr>
<td>1.047847</td>
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<td>1.073947</td>
<td>1.701769</td>
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<td>2.419542</td>
<td>3.389539</td>
</tr>
<tr>
<td>1.465558</td>
<td>3.711016</td>
</tr>
</tbody>
</table>

As discussed in the main manuscript, the pixel size of the hologram in the $x$-direction is $\Delta x = m\lambda/\sin(\theta)$. We choose $m = 2$. This results in the detour phase (from cone array displacement) being equal to $4\pi\delta x/\Delta x$. This means that the $x$-position of the cone array (with respect to supercell center) only needs to be displaced from $-\Delta x/4$ to $\Delta x/4$ to cover a detour phase shift of $-\pi$ to $\pi$.

Due to the fact that in each row, the pixels only change phase gradually, the TiO$_2$ cones are almost continuously distributed in the vertical direction and discontinuous in the horizontal direction (Fig. 5b in the main text).
**Supplementary Note 9 The polarization dependent colors of the printed image**

Our metasurface devices, as viewed via optical microscopy, show different colors as the polarization state of the incident light is varied (Fig. S10a-b). Supplementary Note 8 discusses the spatial distribution of the TiO$_2$ cones, i.e. almost continuous in the $y$-direction and discrete in the $x$-direction. Hence, we simulate the far-field scattering to understand the polarization behaviour. We consider an array of TiO$_2$ cones that is infinitely long in the $y$-direction and finite in the $x$-direction (i.e. four cones wide, Fig. S10c).

![Figure S10 Polarization-dependent color of the metasurface. (a)-(b) Optical microscope images of metasurface when incident light is vertically ($y$) or horizontally ($x$) polarized. (c) Schematic of simulated TiO$_2$ cone array. Since the array is infinitely long in the $y$-direction, we only calculate the scattering intensity in the $xz$ plane. (d) Simulated far-field scattering intensity for $x$-polarized and $y$-polarized illumination at normal incidence, at different far-field angles. Simulations are performed for structure of panel c, with cone parameters matching that of region I (i.e. green outer ‘ring’ area of printed image). The solid (dash-dot) lines represent the case when the incident light is $y$($x$) polarized. Angles are between the scattering direction and the normal to the substrate (i.e. $z$ direction). Spectrum of the light source is taken as being the standard D65 type. (e) CIE 1931 representation \cite{3} of spectra predicted by simulations when the incident light is $y$-or $x$-polarized. Point A1(A2) corresponds to the simulated color when area I is illuminated by the $x$($y$) polarized light. Point B1(B2) corresponds to the case in area II. Point C1(C2) is the case in area III.](image)

From Figure S10d, it can be seen that $y$-polarized illumination is expected to produce a spectrum with a major peak in the green region, which is consistent with the green color
observed from the fabricated device (Fig. S10a). On the other hand, for \(x\)-polarized illumination, simulations predict two peaks. These are at wavelengths corresponding to the blue and red portions of the visible spectrum, and thus produce a purple color. This is consistent with the CIE 1931 color representation (produced from the spectrum simulated as Fig. S10d) and is also consistent with the color photograph of the fabricated device (Fig. S10b). We interpret the polarization-dependence of the observed color as arising from the polarization-dependence of the coupling between TiO\(_2\) cones. Our interpretation is as follows. The electric field distribution in the near-field of a TiO\(_2\) cone is such that the electric fields are mostly concentrated in regions aligned with the polarization of the electric field illuminating the cone. As discussed, in our device, the cones are arranged so that they form nearly continuous lines along the \(y\)-axis. When the illumination is \(y\)-polarized, coupling between the cones mainly occurs between neighbours along the \(y\)-axis. The arrangement of cones along the \(x\)-direction is less important. Therefore, despite the fact that the array is only four cones wide in the \(x\)-direction (i.e. not infinitely-wide), the scattering spectrum peaks in the green portion of the spectrum as intended. On the other hand, with \(x\)-polarized illumination, the fact that there are only a finite number of cones along the \(x\)-direction has a substantial impact upon inter-cone coupling, thereby resulting in the reflection spectrum being substantially different from the \(y\)-polarized case.

**Supplementary Note 10 Holographic image observed in bright lab environment**

![Image](image1.png)

**Figure S11** (a) Image on a paper screen (case 2 in Fig. 6 of the main text) observed in bright lab environment (i.e. room lights are on). The camera forms an angle of about 45° with the screen normal. (b) Since the focused image is small, a lens (\(f=20\) mm) is inserted between the camera and the paper screen for magnification. The angle of the camera is adjusted to minimize the image distortion caused by focusing. Scalebar: 1 cm.

**Supplementary Note 11 Two different holograms encoded into very similar printed images**

![Image](image2.png)

**Figure S12** (a) - (b) Two similar Yoga-posed printed images encoded with two completely different holographic images as shown in Fig. 6b and d in the main text.
Supplementary Note 12 Efficiency measurements

In this section, we discuss the efficiency of our device. As discussed, our device is multifunctional, in that it functions as both a color printed image and a color hologram. We consider the efficiencies of these two functions in turn below.

We begin by considering the efficiency of the device as a color printed image. We believe that the most appropriate metric is the reflectance at the target wavelength (i.e. red, blue or green). We furthermore believe that it is appropriate for these to be measured from samples that contain TiO2 cones in periodic arrays, rather than color printed images. This is because the average reflectance measured from the latter would be highly dependent on the image itself. E.g. an image with little green would have a low average reflectance at green wavelengths. It thus may appear to have a low efficiency (at green wavelengths), though in reality it functions as desired. We thus instead measure the reflectance from periodic arrays of TiO2 cones. As discussed in the main text, we use three designs for TiO2 cones. For green, the cone period and top radii are \((p, r) = (340 \text{ nm}, 92 \text{ nm})\). For red, we have \((p, r) = (400 \text{ nm}, 120 \text{ nm})\). For blue, we have \((p, r) = (265 \text{ nm}, 77 \text{ nm})\) for blue. The measured reflectance spectra of these designs are shown below.

![Figure S13](image)

**Figure S13** Measured reflectance spectra of TiO2 cone arrays. “B”, “G” and “R” denote the three different samples measured. These have reflectance peaks at blue, green and red wavelengths, respectively.

We next quantify the efficiency of our device as a hologram. Note that unlike the reflection spectra discussed above, this efficiency must be measured from a hologram. It should thus be kept in mind that the efficiency will be pattern-dependent. As discussed, the TiO2 cones are arranged to form the color printed image with encoded hologram. Since we use detour phase, some areas of the sample are not decorated with antennas. Hence efficiency of the hologram is lower than the curve in Figure S13. Here we use the sample that projects the words ‘Physical’, ‘Mental’ and ‘Spiritual’ for the efficiency measurement. The efficiency of the hologram is defined as \(P_{\text{holo}}/P_{\text{in}}\). Here \(P_{\text{holo}}\) represents the power of the holographic patterns in the \(\pm 2^{\text{nd}}\) orders (not include the central spots as in Figure S6). The measured efficiency is shown in Table S3.
### Table S3 Measured hologram efficiency

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{horo}}$ (μw)</th>
<th>$P_{\text{in}}$ (μw)</th>
<th>Hologram efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>635 nm</td>
<td>60.2</td>
<td>1250</td>
<td>4.82</td>
</tr>
<tr>
<td>532 nm</td>
<td>35.5</td>
<td>760</td>
<td>4.67</td>
</tr>
<tr>
<td>450 nm</td>
<td>23.9</td>
<td>932</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Author/s:
Wen, D; Cadusch, JJ; Meng, J; Crozier, KB

Title:
Multifunctional Dielectric Metasurfaces Consisting of Color Holograms Encoded into Color Printed Images

Date:
2020-01-17

Citation:

Persistent Link:
http://hdl.handle.net/11343/240514

File Description:
Supplementary files