Liquid crystal-powered Mie resonators for electrically tunable photorealistic color gradients and dark blacks

Trevon Badloe1, Joohoon Kim1, Inki Kim1,2,3, Won-Sik Kim4, Wook Sung Kim5, Young-Ki Kim6,7,8 and Junsuk Rho1,4,6,7,8

Abstract
Taking inspiration from beautiful colors in nature, structural colors produced from nanostructured metasurfaces have shown great promise as a platform for bright, highly saturated, and high-resolution colors. Both plasmonic and dielectric materials have been employed to produce static colors that fulfill the required criteria for high-performance color printing, however, for practical applications in dynamic situations, a form of tunability is desirable. Combinations of the additive color palette of red, green, and blue enable the expression of further colors beyond the three primary colors, while the simultaneous intensity modulation allows access to the full color gamut. Here, we demonstrate an electrically tunable metasurface that can represent saturated red, green, and blue pixels that can be dynamically and continuously controlled between on and off states using liquid crystals. We use this to experimentally realize ultrahigh-resolution color printing, active multicolor cryptographic applications, and tunable pixels toward high-performance full-color reflective displays.

Introduction
Metasurfaces consisting of meticulously designed subwavelength structures, known as meta-atoms, have been actively researched as optical components to modulate electromagnetic (EM) waves1. Various practical applications of metasurfaces have already been demonstrated such as in holography2–4, lensing5–8, and all-solid-state lidar9,10. By utilizing nanoscale structures, the operating wavelengths of metasurfaces are moved to the visible regime, thus providing a platform for high-resolution and -performance nano-optics with an extremely small form factor. Upon continuous advances in nanofabrication techniques11, commercially viable metasurfaces are becoming a reality. Along with controlling the wavefront of light for focusing and imaging with metalenses, display technology using metaholography or advanced color filters is another promising application of metasurfaces that could have profound impacts in many fields such as direct view displays, image projection systems, and even micro-displays for augmented reality (AR) headsets.

Taking inspiration from nature, structural coloration is a method of reflecting or transmitting certain wavelengths of light. Compared to traditional methods of producing aesthetically pleasing colors through pigments and dyes, structural colors based on metasurfaces have the additional benefits of being resistant to fading over time and providing ultrahigh-resolution, all while also potentially being environmentally friendly12 with applications in optical security13,14 and biosensing15. Notably, metasurfaces have been exploited as a method of increasing the color performance and resolution of organic light emitting diode-based displays to over 10,000 pixels per inch.
Although structural colors using various plasmonic and dielectric materials have been proven, with the gamuts that extend beyond conventional display technologies, their static nature is a fundamentally limiting factor. In the current Internet of things (IoT) era, dynamically tunable metasurfaces and colors would be a giant step forward in the incorporation of such planar optical components into consumer devices.

Recently, research into actively tunable structural colors using metasurfaces has been plentiful, with a number of different approaches. Materials with tunable optical properties, such as phase change materials, or through chemical reactions, have been demonstrated. However, these approaches generally rely on the use of plasmonics, which comes with the drawback of substantial Ohmic losses in the visible region, which detrimentally affects the brightness and color performance. Other noteworthy strategies include employing electrochromic semi-conductors or polymers with optical properties that can be controlled electrically, and also the physical manipulation of the spatial locations of the meta-atoms through the use of stretchable substrates.

In conventional displays, liquid crystals (LCs) have been a key component in color rendition for a number of years. Their versatility has also led to numerous applications in combination with metasurfaces for electrically tunable active nanophotonic devices, including examples of structural color. Despite these efforts, for active metasurface-based structural color, several functionalities still need to be realized simultaneously. Namely, bright, saturated colors are required, along with a dark black state. Furthermore, the management of intermittent states between bright and dark is paramount to allow the production of gradients of color to produce photorealistic results through access to the entire color gamut. Up to now, these functionalities have yet to be realized in a single tunable metasurface. Moreover, examples of tunable structural color using LCs have relied on plasmonic metasurfaces, which suffer from unavoidable Ohmic losses at blue wavelengths, limiting their applicability at those wavelengths, and black states have only been achieved through the use of a secondary polarizer to block the polarized light after interaction with the metasurface.

More details of comparisons with our work and previously reported tunable structural color metasurfaces with LCs can be found in Supplementary Note 1.

Here, we numerically design and experimentally demonstrate electrically tunable all-dielectric metasurfaces and investigate their use in cryptographic applications, as well as for full-color reflective displays. The ellipsoidal meta-atoms provide a polarization dependent optical response that is modulated through the implementation of an electrically tunable LC cell, providing an almost linear transition between bright saturated states and dark black ‘off’ states (Fig. 1). We prove the ability of the metasurfaces to not only produce high-quality photorealistic color prints, and as a technology to hide and display multicolored information, but also as...
fully controllable color pixels without the need for any additional optical elements, such as analyzers. Furthermore, the underlying principles of the working mechanisms are revealed and discussed in terms of Mie scattering and the hybridization with quasi-guided mode resonances (qGMR) that originate from the lattice. This work has the potential to be extended to fully tunable reflective displays that cover the whole range of different hues with controllable brightness, low power film displays that are only activated under appropriate security conditions, and micro-displays for AR headsets, having impact not only on the display industry but also with promise for application in security systems.

Results and discussion

One of the simplest strategies to create tunable reflective metasurfaces is to integrate polarization dependent anisotropic meta-atoms with a LC modulator to electrically control the linear polarization (LP) of the incident light. We employ low-loss hydrogenated amorphous silicon (a-Si:H)\(^\text{48}\) for the meta-atoms, designed to have a high refractive index (\(n\)) and low extinction coefficient (\(k\)) across the visible spectrum (Supplementary Note 2). This allows us to exploit the strong Mie scattering properties of the meta-atoms to produce bright spectral colors in reflection. We determine that ellipsoidal shaped meta-atoms provide the best reflectance and LP-dependency (Supplementary Note 3). By carefully designing the Mie scattering response of the dielectric meta-atoms and arranging them on a lattice with specific periodicities\(^\text{20}\), the hybridization of Mie scattering of the meta-atoms with the qGMR from the periodic array greatly amplifies the response, resulting in the desired spectral modulation (Supplementary Note 4). This can be understood by considering the meta-atoms playing three distinct roles. Namely: (1) Mie resonators that allow light to be outcoupled to free space through their resonant modes such as the electric and magnetic dipoles (ED and MD), (2) A subwavelength grating through the arrangement of the meta-atoms on a 2D periodic lattice, and (3) A thick waveguiding layer that supports the in-plane propagation modes. The refractive index of the background medium (\(n_{\text{back}}\)) and substrate (\(n_{\text{sub}}\)), as well as the periodicity (\(P\)) of the nanostructures are important factors that contribute to the momentum matching conditions to excite the qGMR\(^\text{49}\). The lower bound of these parameters determines the location of the Rayleigh-Wood anomaly, where the normally incident light is diffracted and propagates at 90°, i.e., in the plane of the meta-atoms, and the diffuse anomalies described by Fano are located. Here, we use a glass substrate in the background of air (i.e., \(n_{\text{sub}} = 1.46\) and \(n_{\text{back}} = 1\)). This helps to bring the lattice enhanced scattering into the visible regime for use for bright structural color production, as well as being relevant for real-world applications as no extra index matching background layers are required. The upper bound of the qGMR is determined by the effective refractive index of the meta-atom unit-cell, i.e., the geometry of the meta-atom. Therefore, the design of the meta-atom requires a fine balance between all of the different parameters. We note that extra protective layers could be added if \(n\) of the medium and the dimensions of the meta-atoms are designed accordingly to produce the desired scattering and momentum matching conditions. The height of the meta-atoms is another key parameter for determining how strongly the EM fields can be confined inside the structure through the formation of displace currents along the propagation direction. Therefore, a height of 110 nm is chosen for the meta-atoms. This results in a slight loss of performance in terms of the color gamut that can be produced (Supplementary Note 5). In compensation, however, we can achieve outstanding black states and grayscales of color through the modulation of LP axis (\(\hat{L}\)) from 0 to 90°, i.e., from along the long axis (\(\hat{a}\)) to the short axis (\(\hat{b}\)) of the meta-atoms (Fig. 2a). Furthermore, despite this sacrifice, the achieved gamut is still comparable with sRGB (Supplementary Note 6), proving the validity for this decision. The optimal designs are chosen with regards to both the color and black states using the definition of color difference (\(\Delta E\)) from the International Commission of Illumination (CIE), which aims to take into account the non-uniformities of the human eye being more sensitive to certain colors compared to others (Supplementary Note 7). The designs that give the lowest total \(\Delta E\) with consideration of the black state (i.e., \(\Delta E_{\text{RGB}} + \Delta E_{\text{black}}\)) are therefore determined to be: \(P = 420\) nm, \(\hat{a} = 336\) nm, and \(\hat{b} = 118\) nm for red; \(P = 360\) nm, \(\hat{a} = 266\) nm, \(\hat{b} = 112\) nm for green; and \(P = 300\) nm, \(\hat{a} = 204\) nm, and \(\hat{b} = 73\) nm for blue, respectively. The calculated \(\Delta E\) for the red, green, and blue colors are 15.8, 20.4, and 13.8, respectively, with \(\Delta E\) for the black, off states, of 4.6, 3.5, and 6.9.

We perform multipole analysis to uncover the physical origin of the scattering moments in the anisotropic ellipsoid meta-atoms to produce red, green, and blue colors (Fig. 2b) (Supplementary Note 8). It is clear to see that when \(\hat{L} || \hat{a}\), strong MD and ED responses are excited. When \(\hat{L} \perp \hat{a}\), however, the scattering is extremely suppressed as the momentum matching conditions are no longer met, and the dominant scattering modes lie on the blue side of the Rayleigh-Wood anomaly, prohibiting them from being enhanced through the lattice resonances. Interestingly, for the red pixel, the dominant mode is the ED rather than the MD. This can be understood through consideration of the physical dimensions of the meta-atoms that require larger periodicities to enhance the scattering through the qGMR at longer wavelengths.
Since the height of all meta-atoms must be consistent due to fabrication limitations, the meta-atoms designed to produce red are therefore rather short and fat with a very low aspect ratio, which hinders the excitation of the MD. To experimentally demonstrate the LP dependency of the designed colors, we fabricate color swatches for the optimized red, green, and blue designs. Measured reflectance spectra and corresponding optical micrographs of the fabricated 100 × 100 µm samples are shown in Fig. 2c, d. When \( \hat{L} \) is manipulated from 0 to 90°, we observe the red, green, and blue reflectance to be linearly controllable with remarkably dark black states. We measure the contrast ratio of reflectance to be 42, 37, and 47 for the red, green, and blue meta-surfaces, respectively. Although the measured reflectance spectra are in good agreement with the simulations, the peaks of the green and red spectra in particular are broader. These discrepancies are attributed to fabrication errors such as slight inclines in the sidewall and the deviations from the designed elliptical shapes of the meta-atoms which have been shown to hinder such high quality factor resonances. \(^{50,51} \)

As a practical presentation of high-resolution color printing based on the designed meta-atoms, we fabricate several metasurfaces to produce photorealistic images (Fig. 3a). Grayscale images are discretized into 91 steps depending on the brightness of the pixel to represent 91 levels of LP (from 0 to 90° in 1° steps), and the relevant meta-atoms are rotated by the necessary angle to achieve the required reflectance. When the ~500 × 300 µm samples are illuminated with LP 0°, the high contrast photorealistic image is clearly displayed. For these single-color micro-prints, we assume that each pixel is represented by a single meta-atom as the rotation of local meta-atoms determines the scattering properties and therefore color, and \( P \) is constant over the whole metasurface, akin to the local phase modulation often utilized in geometric phase meta-holograms. Since the color depends on \( P \), the PPI for the red (Fig. 3a-i), green (Fig. 3a-ii), and blue images (Fig. 3a-iii) are ~60,000, ~70,000, and ~85,000, respectively.

Since the Mie scattering response of the meta-atoms is dependent on their geometry, it is possible to create anisotropic meta-atoms that display different shades and hues of colors for one polarization of light, while still maintaining the dark black states for the orthogonal polarization by designing meta-atoms with different dimensions along \( \hat{a} \) and \( \hat{b} \) of the ellipsoid within the same \( P \) (Supplementary Note 9). The simulated reflection spectra of the red meta-atoms with \( P = 420 \) nm producing 5 distinct shades of red are shown in Fig. 3b, while Fig. 3c shows the decrease in the reflectance at the peak wavelength of 614 nm. This is achieved by varying \( \hat{a} \) to control the color, while simultaneously modulating \( \hat{b} \) to achieve...
the consistent black states (Fig. 3d). We exploit this to demonstrate multicolored cryptographic images that can be switched between on and off states by modulating \( \mathcal{L} \) from 0 to 90° (Fig. 3e). Each image is made up of 1000 × 1000 meta-atoms, so the samples are 420 × 420 \( \mu m \), 360 × 360 \( \mu m \), and 300 × 300 \( \mu m \) in size for the red, green, and blue images, respectively. This technique could be used to hide colorful aesthetic information that can be uncovered when illuminated by the correct LP and completely hidden under the orthogonal LP.

In order to provide electrical tunability to the reflective color metasurfaces, we integrate them with a LC cell. The cell is designed to modulate the incident LP light that illuminates the metasurface. A planar alignment layer is spin-coated onto the top glass substrate (with no electrode) and the bottom substrate with
interdigitated ITO electrodes (Fig. 4a). The two substrates are rubbed to provide a tangential orientation to the LCs (i.e., the long axis of the LC molecules is perpendicular to the substrate normal) and then assembled in an anti-parallel fashion with a gap of 5.4 μm. Finally, the cells were filled with a nematic LC, 5CB(4-Cyano-4′-pentylbiphenyl), and attached onto the metasurface (Supplementary Note 10). The incident light first passes through a linear polarizer with its optic axis parallel to the y-axis. As the LP 90° then passes through the LC cell, we can precisely control the LP state by controlling the in-plane electric field that rotates the optic axis of the LCs, thus changing the rotation axis in the Poincare sphere (Fig. 4b).

Using the LC integrated metasurfaces, we demonstrate electrically tunable full-color active cryptographic prints. By aligning $\hat{L}$ along $\hat{a}$, the images can be fully displayed and hidden with continuous intermediate states of reflectance by controlling the applied electric field (Supplementary video 1). The fabricated 350 × 400 μm color prints show vivid color rendition and dark states as designed (Fig. 4c). Since the size of the meta-atoms for different colors require different $P$, the size of the image i.e., number of pixels, to cover the same physical space was calculated for each color and combined to form the final image. Slight mismatches between the boundaries of each color led to visible lines where the reflection of the background can be seen through the image, which could be improved by designing the image to have a more precise alignment between colors to alleviate the obvious gaps.

Finally, we investigate the electrical tuning of the ellipsoidal meta-atoms as active pixels in full-color reflective display applications. Mixing the reflectance spectra of the primary additive colors (red, green, and blue) allows the production of the secondary colors of yellow, magenta, and cyan, as well as white when all three are combined (Fig. 5a). Since the anisotropic meta-atoms can produce both bright colors and dark blacks, they can be combined to create pixels to display any shade and brightness of desired color. To prove this concept, we fabricate four separate samples. In each of the samples, the meta-atoms for one color are rotated by 90° compared to the other two, while for the final sample, all meta-atoms are aligned in the same direction. We observe all the designed colors, as well as dark black and bright white (Fig. 5b).
calculated locations of the mixed colors are plotted on the CIE 1931 Chromaticity Diagram, showing that even when mixed, the produced color gamut is comparable to the sRGB gamut. When the individual colors are combined into a single large pixel, the meta-atoms that are not required to contribute to the color production are necessarily black, therefore lowering the overall brightness of the colors compared to the individual subpixels. The brightness of the color is also affected by the size of the subpixels, with bigger subpixels providing brighter colors at the expense of larger pixels and lower PPI (Supplementary Note 11). Here, as a simple proof-of-concept, we combine the pixels in a 1:1:1 manner that produces a white tone of the desired temperature (Supplementary Note 12). Horizontal lines of meta-atoms are chosen for the design of the subpixels, which maximizes the number of meta-atoms for the subpixels in the direction of the required momentum matching to induce the qGMR. As a compromise between resolution and brightness, we choose subpixels to have four horizontal lines of meta-atoms per color, resulting in a PPI of ~6000. By integrating the sample in Fig. 5b ii with the LC cell, electrical tuning of the color from green to magenta is achieved using the external bias (Fig. 5d). With the LP of the incident light on the LC cell set to LP 0°, as the LCs modulate $\hat{L}$, the reflected color is tuned from green at $E = 0.0 \ \mu\text{m}^{-1}$ (where $\hat{L}\parallel\hat{a}$ for green and $\hat{L}\perp\hat{a}$ for red and blue), through to gray at $E = \sim 0.4 \ \mu\text{m}^{-1}$ (where $\hat{L}$ is at $\sim 45^\circ$ to $\hat{a}$ for all meta-atoms), finally to magenta at $E = 1.0 \ \mu\text{m}^{-1}$ (where $\hat{L}\parallel\hat{a}$ for red and blue and $\hat{L}\perp\hat{a}$ for green). It should be noted that the discrepancy between
the magenta color produced using static polarizers and
the LC cell is due to the LCs not providing the exact phase
retardance required for complete conversion between
orthogonal LP states at the applied biases, which is a
technical issue rather than a fundamental flaw with the
device design and fabrication.

Conclusion
In conclusion, we have designed, characterized, and
experimentally realized a platform for electrically tunable
structural color using all-dielectric metasurfaces in com-
bination with LCs. We first presented high resolution and
contrast static color printing, furthermore, by employing
LCs as a method of electrically controlling the LP of the
incident light, we proved the use of the anisotropic meta-
atoms for use in electrically tunable metasurfaces as
cryptographic and reflective display applications. To the
best of our knowledge, this is the first demonstration of
fully controllable metasurface-based structural color that
can produce not only bright saturated colors, but also
black and white pixels, as well as all combinations of
states in between. Furthermore, no extra polarizers are
required to block the reflected light and produce the black
states, as they are achieved purely by suppressing the back
scattering through the meta-atom design. The switching
time of the color depends solely on the LC cell, and is
generally on the scale of milliseconds. Since the spectral
modulation is achieved with a large contribution from
qGMR, the reflected colors depend on the incident angle
of the light and the correct colors are retained up to
angles of around 10° (Supplementary Note 13). Several
interconnected factors should be considered for the final
choice for the number of meta-atoms that make up a
subpixel, which dictate the brightness and color tem-
perature, and in turn the PPI of the device. This choice
could be tailored for the desired purpose, such as high
resolution, or a specific color temperature. Reflective
displays could also have an important role to play in the
IoT future, where masses of information are being con-
sumed daily and energy efficiency is paramount, especially
for locations of limited power supply. This proposed
scheme can easily be applied in transmission mode albeit
with the use of a subtractive color palette (Supplementary
Note 14)\textsuperscript{52}. Transflective displays could also be an
interesting option for energy efficient display technologies\textsuperscript{53},
but have yet to be achieved using metasurfaces. Due to the
dependence on the refractive index of the surrounding
media on the momentum matching conditions required
for the hybridization and enhancement of the Mie scatter-
ing and qGMR, the proposed metasurfaces display
asymmetric transmission (Supplementary Note 15),
making it difficult to achieve such transflective displays.
However, this could be overcome with the utilization of
an index matching layer and the proper design of meta-
atoms. Furthermore, the unique property of blocking
certain amount of light at specific wavelengths has
potential to be applied in smart windows or mirrors that
modify the transmitted or reflected colors and their
relative brightness. Moreover, the all-dielectric nature of
the devices presented here lead to the simple integration
with CMOS processes for scalable fabrication. The
achievable color gamut using the design concept estab-
lished here could possibly be further improved by
employing materials with no optical losses throughout the
visible regime, or by optimizing the meta-atom design
using machine learning or computational techniques\textsuperscript{54–56}.

It should be noted that the polarization of the incident
light could also be controlled using electrically tunable
waveplates with rotatable polarizers, and this element is
one of the main limiting factors on resolution and mini-
aturization. The use of an additional polarizer in previous
systems result in a significant loss of the intensity of the
incident light, as only the light with polarization parallel
to the optic axis of the polarizer can pass, which quickly
becomes significant if the light passes the polarizer mul-
tiple times. The light intensity loss in the LC system,
however, is negligible, leading to a much more energy
efficient device with brighter and more vivid colors. The
LC acts solely as a phase retarder to the LP state of light,
therefore any subsequent interactions with the LC, such
as after reflection from the metasurface, act only to retard
the phase back to the original state. Therefore, LCs have
the potential for further miniaturization, allowing for
extremely high-resolution displays using metasurfaces.

From a technical point of view, the PPI of state-of
the-art displays varies based on the size of the device.
As the size of the screen increases, the PPI naturally
decreases, which requires the user to utilize the display
from a farther distance in order to see a clear image. If
we consider a few practical examples of the latest high-
end 4 K displays in consumer devices, 6.5 inch mobile
displays have reached \( ~650 \) PPI, whereas 24 inch
monitors generally achieve \( \sim 200 \) PPI, and large tele-
visions over \( \sim 40 \) inches provide \( \sim 100 \) PPI. For the
metasurfaces proposed here to achieve a comparable
PPI to these state-of-the-art displays, we could afford
to utilize subpixels made up of \( \sim 35, \sim 120, \) and \( \sim 250 \)
rows of meta-atoms for mobile displays, monitors, and
large televisions, respectively. This could be easily
achieved using the metasurfaces proposed here as
demonstrated in Supplementary Note 11. However, a
key hurdle to overcome before realizing such
metasurface-based displays comes from limitations in
large-scale nanofabrication. Recently, advances in
nanoimprinting techniques have suggested a potential
answer\textsuperscript{11}, in particular, roll-to-roll printing could
achieve the continuous printing of metasurfaces. Resin
embedded with high-\( n \) dielectric nanoparticles has
been proven as an exciting material for such nanoimprinting methods, and has also been used in direct 3D printing using two-photon lithography.

**Materials and methods**

**Reflection spectrum simulation**

An in-house developed RCWA solver was used to calculate the reflection spectra of the meta-atoms, under normal and oblique incidence. All color calculations were performed using the open-source package, ‘Color’, in Python. The D50 illuminant and CIE 1931 2° standard observer were used throughout. The electric and magnetic field profiles were calculated using the finite-difference time-domain (FDTD) solver, Lumerical, Ansys, with periodic boundary conditions in the x- and y-directions, and perfectly matched layers in the z-direction. In minimum pixel size simulations, perfectly matched layers are used for all boundaries and the simulation size along the x- and y-directions are set to

\[(x, y) = (1 + (N_x, N_y)) \times P\]

**Multipole expansion**

The multipole scattering cross-sections were calculated using the commercially available FEM software, COMSOL Multiphysics. The multipole moments are given as

\[
D^a = \frac{1}{\omega} \int d^3 r \left\{ j_0(kr)f_0(r) + \frac{k^2}{2} \left[ 3(r \cdot J)r_a - r^2 f_2(kr) \right] \right\},
\]

\[
D^m = \frac{3}{2} \int d^3 r (r \times J) f_1(kr),
\]

\[
Q^a_{aß} = -\frac{1}{\omega} \int d^3 r \left[ r_a rß - \frac{3}{2}(r \cdot J) rß \frac{f_0(kr)}{kr} \right] + \frac{\omega^2}{4} \left[ 5(r \cdot J) r_aß - r^2 (r_aß + rß a) - r^2 (r \cdot J) rß \right] \frac{f_2(kr)}{kr}.
\]

\[
Q^m_{aß} = \frac{5}{2} \int d^3 r \left[ r_a (r \times J) rß + rß (r \times J) rß \right] \frac{f_2(kr)}{kr},
\]

where \(D^a, D^m, Q^a_{aß}, Q^m_{aß}\) are electric dipole, magnetic dipole, electric quadrupole, magnetic quadrupole, respectively, \(a, ß = x, y, z\); \(J = -i\omega (\varepsilon - \varepsilon_h) E\) is the induced current density, \(\varepsilon (x, \omega)\) and \(\varepsilon_h\) are the permittivity of the scatterer and the host medium (air), and \(j_n(z)\) is the spherical Bessel function.

The radiation power is given as

\[
P = \frac{1}{c_1^2} \frac{k^4}{12 \pi \eta} \sum_{\alpha ß} |D^\alpha| \frac{k^2}{12 \pi \eta} \sum_{\alpha ß} |Q^a_{aß}|^2 + \frac{1}{c_2^2} \frac{k^4}{12 \pi \eta} \sum_{\alpha ß} |Q^m_{aß}|^2 + \frac{\eta^2}{c_1^2} \frac{k^4}{12 \pi \eta} \sum_{\alpha ß} |D^m| \frac{\eta^2}{c_2^2} \frac{k^4}{12 \pi \eta} \sum_{\alpha ß} |Q^m_{aß}|^2,
\]

where \(\eta\) is the wave impedance of the host medium. The scattering cross-sections are given as the radiation power divided by the power flux of the incident plane wave, \(E_0^2/(2\eta)\).

**Metasurface fabrication**

Metasurfaces were fabricated on a 500 μm-thick glass substrate. A 110 nm-thick layer of a-Si:H was deposited using plasma enhanced chemical vapor deposition (PECVD, BMR Technology HiDep-SC) with a flow rate of 10 sccm for SiH4 and 75 sccm for H2. Chamber pressure and temperature were 25 mTorr and 200 °C, respectively. The standard EBL process (ELONIX, ELS-7800) was used to transfer meta-atoms onto a single layer of positive tone photoresists (495 PMMA A2, Micro-Chem). Acceleration voltage and beam current is 80 kV and 100 pA, respectively. The exposed patterns were developed by MIBK/IPA 1:3 developer mixed solution. A 30 nm-thick chromium (Cr) layer was deposited using electron beam evaporation (KVT, KVE-ENS4004). The lift-off Cr meta-atoms were used as an etching mask for the a-Si:H film. Cr patterns were transferred onto the glass substrate using a dry etching process (DMS, silicon/metal hybrid etcher). The remaining Cr etching mask was removed by Cr etchant (CR-7).

**Patterned ITO glass plate preparation**

A photoresist (AZ GXR-601, MERCK) was spin-coated at 1000 rpm for 10 s followed by at 2500 rpm for 30 s. Subsequently, the photoresist covered substrates were baked at 90 °C for 90 s. After UV exposure with a photomask for 20 s, the substrates were baked at 110 °C for 90 s. The exposed photoresist was removed using a developer (AZ 300 MF Developer, MERCK) for 1 min and etched in an acid solution (pure water:hydrochloric acid, 32–38% (Avantor Performance Materials, LLC):Nitric acid = 2:2:1) for 2.5 min.

**LC cell preparation**

The LC cells were assembled using a patterned ITO glass plate coated with a polyimide (Nissan Chemical Korea) and a bare glass plate. Both plates were rubbed using velvet texture to achieve a unidirectional orientation of the LC molecules. The glass plates were assembled in the anti-parallel direction of the rubbing. The gap between the glass plates was set by glass spacers mixed with UV glue (NOA 65, Norland Products, Inc.). 5CB (Jiangsu Hecheng Display Technology Co., Ltd.) was filled into the cell in the isotropic state to avoid the memory effect of alignment by flow. The wires for applying the electric field were soldered onto the ITO patterns using lead after removing off the polyimide on the substrate.

**Optical measurement**

A homebuilt optical measurement setup was used to image the realized colors and the reflection spectra. The source was a xenon arc lamp (Newport, 66907-150XF-R1). The light was collimated with two biconvex lenses (Thorlabs, LB1630) and passed through a linear polarizer.
(Thorlabs, LPVISC050), beam splitter (SIGMAKOKI, TFA-30C05-10), objective lens (Olympus, LMLFNL 20X) and reflected from the sample. The reflected light passed the objective lens and reflected from the beam splitter. Finally, the light was captured by a CCD camera (Lumenera, INFINITY 2-1 RC), and was analyzed by a spectrometer (HORIBA, iHR 320).

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Author details
1 Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea. 2 Department of Biophysics, Institute of Quantum Biophysics, Sungkyunkwan University, Suwon 16419, Republic of Korea. 3 Department of Intelligent Precision Healthcare Convergence, Sungkyunkwan University, Suwon 16419, Republic of Korea. 4 Department of Chemical Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea. 5 Department of Electrical Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea. 6 POSCO-POSTECH-RIST Convergence Research Center for Flat Optics and Metaphotonics, Pohang 37673, Republic of Korea. 7 National Institute of Nanomaterials Technology (NINT), Pohang 37673, Republic of Korea.

Author contributions
T.B., J.K., I.K., and W-S.K. contributed equally. J.R., Y-K.K., T.B., and I.K. conceived the concept and initiated the project. T.B performed the numerical calculations, developed the codes, and analyzed the data. J.K. and I.K. fabricated the metasurfaces, and conducted the experimental characterization and measurements. W-S.K. and I.K. designed LC modulator and conducted the optical measurements. T.B. mainly wrote the paper. All authors contributed to the discussion and analysis and have given approval of the final version of the paper. J.R. and Y-K.K. guided the entire project.

Conflict of interest
The authors declare no competing interests.

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