MEMS cantilever–controlled plasmonic colors for sustainable optical displays

Zhengli Han††, Christian Frydendahl†, Noa Mazurski, Uriel Levy*

Conventional optical displays using indium tin oxide and liquid crystal materials present challenges for long-term sustainability. We show here a cost-effective and complementary metal-oxide semiconductor (CMOS)–compatible fast and full-range electrically controlled RGB color display. This is achieved by combining transmission-based plasmonic metasurfaces with MEMS (microelectromechanical systems) technology, using only two common materials: aluminum and silicon oxide. White light is filtered into RGB components by plasmonic metasurfaces made of aluminum nanohole arrays. The transmission through each color filter is modulated by MEMS miniaturized cantilevers fabricated with aluminum and silicon oxide on top of the color filters. We show that the relative transmission of a color subpixel can be freely modulated from 35 to 100%. The pixels can also operate well above 800 Hz for future ultrafast displays. Our work provides a road to future circular economic goals by exploiting advances in structural colors and MEMS technologies to innovate optical displays.

INTRODUCTION

Optical displays have become a ubiquitous technology in daily life, being an essential component of smart phones, computers, televisions, etc. These same devices make up roughly half of the 50 million metric tons of e-waste produced every year globally (1). In estimate, less than 20% of the mass of the world’s annual e-waste is recorded as being recycled (1). For example, typically, only metals are extracted from plastic circuit boards. The remaining 40 million metric tons of waste is mainly unaccounted for, generally ending up in burn pits or landfills in developing countries, where many of the toxic elements contained within (such as indium, lead, and mercury) pose serious threats to human and environmental health. Annual e-waste production is predicted to grow to more than 120 million metric tons by 2050, with the majority of this increase being from devices reliant on displays (1–3). One of the main reasons for the low rate of recycling of displays is the cost associated with the process due to the large variety of materials included in a device (3), making “virgin” materials favorable over recycled materials in terms of cost—despite the fact that it is up to 10 times as energy efficient to recycle, e.g., metals, over extracting new metals from ore (1). There is thus an urgent need for alternative display technologies that are easier to recycle and are financially feasible to be incorporated into a circular consumer electronics economy (4–7)—not only to preserve finite resources but also to lower total energy usage of the manufacturing industry and lower total global carbon emissions (1). In particular, some of the most critical materials to find replacements for are the liquid crystals (LCs) and indium tin oxide (ITO), which are used for the pixel brightness control in all common digital displays such as LCDs (liquid crystal displays), LEDs (light-emitting diode displays), and OLEDs (organic light-emitting diodes displays) (2, 3, 8). We show here a new type of optical display technology, based on structural colors and flexible micromechanical shutters, that could be an ideal candidate to enable the future transition toward a circular electronics economy. We have summarized the different components of a common LCD and our proposed device in Fig. 1; here, we have also listed some of the main issues with LCDs and how our proposed device can replace many of the components causing the issues with more sustainable alternatives (which, in some cases, also promises inherently better device performance).

Structural colors generate colors from nanostructures by plasmonic or dielectric optical resonators or gratings (9–13). While abundant in nature (14), engineered passive structural colors have also been demonstrated to great effect in the past decade (9–11, 13, 15–17). Both metallic (18–22) and dielectric structures (12, 23–25) have been shown, and generic “structural color papers” that can be “painted” using a high-power laser has also been demonstrated (23, 26–30). Apart from passive structural colors, tunable or “dynamic” structural colors for display applications are also seeing increasing interest (11). Recent demonstrations include chemical processes to change the local refractive index to shift the resonant color (31, 32) or using LCs as in a conventional LCD monitor to modulate color pixel transmission (11, 33). The use of electrostatic forces to align plasmonic resonant metal nanorods to generate colors has also been shown (34). Very recently, thin films with reversible gate-tunable color switching were also demonstrated (35). The disadvantages of these techniques are that either their color switching speed is slow, or it is difficult to individually control pixels, or they do not greatly simplify the composite materials required to manufacture the display—while the number of materials in the display unit is closely related to the end-of-life-cycle management (2, 3, 8).

MEMS (microelectromechanical systems) technology has been used in the past to generate alternative displays and color filters (36, 37). MEMS display technologies can generally be categorized into several groups, such as digital micromirror devices (38), laser scanning displays (39), interferometric modulator displays (40), digital microshutters (41), and grating light valves (42). MEMS generally offers substantial power reduction when compared with most other display technologies, but each actuation technique has its own unique advantages and disadvantages (36, 37). For example, laser scanning displays offer almost-perfect color gamut displays, as the image is generated by scanning three different monochromatic red, green, and blue (RGB) lasers, but generally suffer from speckle, causing imaging artifacts (36).
MEMS combined with structural colors was very recently demonstrated (43). The work used silicon-on-insulator wafers to build a silicon grating above a silicon substrate. By controlling the gap in between the grating and substrate, the reflection color was changed among green, yellow, and red. This combined approach shows several advantages, such as low power consumption and complementary metal-oxide semiconductor (CMOS)–compatible fabrication. However, from the mechanism of the color control, it is difficult to cover the full range of RGB colors, and it is difficult to show black color. Grating-based structural colors are also well known to have issues with viewing angle because of their diffractive nature, and as the device works in reflection mode, it is hard to incorporate a dedicated light source that would allow viewing in low ambient light conditions.

Here, we bring together plasmonic metasurfaces and MEMS technology to generate transmission-type dynamic color control using only two common and easily recyclable materials: aluminum and silicon oxide (glass). We demonstrate the generation of a full range of RGB color subpixels. The colors are generated by optical transmission–based plasmonic metasurfaces consisting of aluminum nanohole arrays, and the relative transmission/brightness of each color subpixel is modulated by a MEMS cantilever made of aluminum and silicon oxide fabricated on top of the metasurface. By using the nanohole array itself as the actuation electrode for the cantilever, application of a bias between the two then causes electrostatic forces to pull the cantilever down and close off light transmission through the plasmonic array, effectively “shutting it off.” By modulating the actuation voltage, we show how it is directly possible to modulate the overall brightness of each pixel by changing its average transmission in time via fast modulation.

Our method allows for fast pixel switching speeds well in the excess of 800 Hz (which is noticeably faster than the currently available displays), and by using the metasurfaces themselves as the actuation electrodes, it is possible to individually address and modulate specific color subpixels—an essential feature for making an RGB display, and eliminates the need for transparent electrodes made of, e.g., ITO. Furthermore, as the entire fabrication process is based on lithography and the materials used are generally considered cost-effective and CMOS compatible, it is also expected that our approach could enable substantial fabrication cost reductions for mass-scale manufacturing of optical displays.

Our work shows that it is possible to make a fast, full color range display, using just two component materials. This is an important
step toward simplifying implementations of digital displays and a crucial step toward display technologies with simplified end-of-life-cycle reprocessing procedures—essential for achieving future circular economic and e-waste management goals (4–7).

RESULTS
Device design and operating principle
The general working principle of the device is shown in Fig. 2A. A plasmonic nanohole array filters white continuum illumination into a single color when it is transmitted through the array. Then, the transmission through the array is modulated by a flexible MEMS cantilever, which is actuated by an electrostatic potential applied between the nanohole array and the cantilever. The cantilever motion resembles more the unrolling of a rolled up sheet rather than a stiff vibrating beam. This allows the metasurfaces to be completely unobstructed by the cantilevers when in their rolled-up default position, allowing for high optical transmission. An example of a fabricated device can be seen in the scanning electron microscopy (SEM) images in Fig. 2B, and a video of the cantilever motion with low-frequency actuation voltage can be seen in movie S1.

To demonstrate the usefulness of our approach toward display applications, we have fabricated three different types of nanohole arrays, each one respectively filtering for RGB-visible light (44). By varying the diameter and period of the nanoholes, we are able to change the plasmonic resonance response and thus control the transmission spectrum at will. The diameters of the nanoholes for red, green, and blue are 208, 154, and 124 nm and have corresponding periods between the nanohole centers of 380, 312, and 252 nm. A set of SEM images and transmission microscope images of the generated arrays can be seen in Fig. 2C, with finite-difference time-domain (FDTD)-simulated and experimentally measured transmission

---

**Fig. 2. Device design and working principle.** (A) Schematic of the device. A plasmonic nanohole array filters white continuum light into one color upon transmission. The array's transmission can then be modulated via a mechanical cantilever, which blocks off the array when a voltage is applied between the cantilever and the nanohole array. (B) SEM image of the fabricated cantilevers and the nanohole array. Scale bars, 50 μm. (C) Top: SEM images of the generated nanohole arrays for the red (R), green (G), and blue (B) color pixel elements. Bottom: White light transmission microscope images for each of the color pixel elements. Scale bars, 250 nm (SEM images) and 30 μm (microscope images). (D) Experimental (solid lines) and FDTD-simulated (dashed lines) transmission spectra of the nanohole arrays.
spectra available in Fig. 2D. From the spectral measurements, we see that the peak transmission efficiencies are ∼45% for the red color filter and ∼35% for the green and blue color filters. The measured results show noticeable broader spectra at longer wavelength for each curve as compared to the simulation. This is likely from fabrication imperfections and inhomogeneous broadening and the small aperture used in the measurement being slightly misaligned to the small nanohole array. The details of the spectral measurements and simulations are available in Materials and Methods.

The overall fabrication of the device is done in two steps: First, the nanohole arrays and a solid electrode are defined and fabricated using electron beam (EB) lithography with evaporation of a 100-nm aluminum layer and liftoff. Then, a spacer oxide (to block electrical breakdown when the cantilever is touching the array) of 210-nm silicon oxide is sputtered on top of the nanoholes. Besides insulating the array from the cantilever, the spacer layer also encapsulates and protects the aluminum nanoholes. In the next step, a sacrificial layer of photoresist is added on top of the array (to later release the cantilevers). Then, using ultraviolet (UV) photolithography, the cantilevers and their electrodes are defined. The cantilevers are fabricated by sequential sputtering of 100 nm of silicon oxide, followed by 100 nm of aluminum, and wet patterning. Reactive-ion etching (RIE) is then used to etch away the sacrificial layer of photoresist to lastly release the cantilevers from the nanohole array and the device substrate. The total lateral size of a nanohole array is $30 \times 36 \, \mu m^2$, and its accompanying cantilever is $\sim 30 \times 60 \, \mu m^2$. For more details on the fabrication, see Materials and Methods, the Supplementary Materials, and fig. S1.

**Modulation of color pixel brightness**

After fabricating the nanohole arrays and cantilevers, we characterize the modulation of light transmission through them using the setup shown in Fig. 3A. By matching the laser spot size to that of one nanohole array/cantilever, we can measure the performance of a single cantilever. The transmission is measured as the photovoltage of a silicon photodiode connected to an oscilloscope. For full details of the transmission modulation measurements, see Materials and Methods. It is important to note that the frequency of the light modulation by the cantilevers is doubled relative to the drive voltage frequency (see Fig. 3B). This is because despite the fact that the voltage is applied in alternating patterns of positive and negative voltage, both polarities cause the cantilevers to be attracted toward the nanohole array. Only when the gate voltage, $V_G$, goes toward 0 V do the cantilevers return back to their natural upward position. This is due to that the cantilevers are operated by capacitive charging, so when either polarity is applied, there is a corresponding accumulation of positive and negative charges on the nanohole array and the cantilever. This charge accumulation causes the cantilever to actuate down toward the nanohole array, due to electrostatic attraction, regardless of the polarity. The gate voltage is applied in alternating patterns of positive and negative bias to avoid permanent charge accumulation, which would pin the cantilever down permanently if
not discharged (45, 46). We generally apply a sine-wave pattern for $V_G$, as the gradual change in polarity allows the cantilevers more time to release and recover. If we apply a square-wave instead, we find that the cantilevers get stuck in the downward position without modulating the light. This is because there is effectively no time at which no bias is applied, and there is no time for the cantilevers to recover to their upward position.

We can write the total force on a cantilever as the sum of a restoring spring force and an attractive electrostatic force. Assuming a parallel plate actuator for simplicity (see fig. S2 for more details), we get (45)

$$F_{tot}(x, t) = F_{spring}(x) - F_{electrostatic}(x, t)$$

(1)

$$= kx - \frac{1}{2}A_0^2 \epsilon_0 \frac{S}{(g - x)^2} V_G^2(t)$$

(2)

Here, $k$ is the spring constant of the cantilever, which is determined by its materials and geometry, $x$ is its displacement, $\epsilon_0$ is the dielectric constant of vacuum, $S$ is the area of the cantilever, $g$ is the initial gap between the cantilever and the nanohole electrode, and $V_G$ is the time-dependent drive voltage.

We see from Fig. 3C how the light transmission can be changed by adjusting the amplitude of the drive voltage signal. When the device is run at high frequencies, it is not able to fully close because of its limited time response, but by increasing the drive voltage, the cantilever gets closer to a fully closed state (from the larger electrostatic force on the cantilever), i.e., less light goes through the blue curve than the red curve in Fig. 3C. If we consider the “well-behaved” cantilever motion at lower frequencies (Fig. 3B), we find that the rise time of the modulation is $\sim 0.23$ ms, while the fall time is $\sim 1.2$ ms. This tells us that the restoring force is generally quite a lot stronger than the electrostatic attractive force when outside the electrostatic pull-in range of the motion (45). Figure 3D (top) shows the peak-to-peak modulation of light in decibels through the nanohole array for different drive voltages. We see from this that the $\sim$3 dB point for the device is at $\sim 400$ Hz input, i.e., $\sim 800$ Hz actual light modulation. For higher frequencies, the peak-to-peak modulation of the light is reduced substantially, as the cantilever does not have time to properly close because of the limited fall time of the motion.

To measure strictly the brightness modulation of the cantilever, we have introduced the relative transmission, $T_{rel} = T/T_0$, where $T_0$ is the transmission of the laser through the metasurface when the cantilever is completely open. We can characterize the average transmission of light through the array over time for different frequencies and voltages. For a given measurement of the normalized relative transmission through the sample over time, $T_{rel}(t)$, we can calculate the average relative transmission as

$$\langle T_{rel} \rangle = \frac{\sum_{t=1}^{N} T_{rel}(t)}{N}$$

(3)

where $N$ is the total amount of equidistant points in time sampled. We can then see that the average transmission through the sample goes up with the drive frequency (Fig. 3D, bottom). Because the speed of the modulation depends on the electrostatic force, we can also modulate the average transmission by changing the peak-to-peak drive voltage, as seen in Fig. 3E. From measuring several cantilevers, we generally see good uniformity in their response, finding, on average, only a $\sim 5\%$ variation in their modulation characteristics.

If the motion of the cantilevers is generally faster than the flicker fusion threshold (47) of an observer, i.e., the point at which periodic motion/loss modulation can no longer be discretely observed, then the modulated response will instead look like the averaged transmission signal. For optical displays, the flicker fusion threshold is generally regarded as being $\sim 60$ to $100$ Hz (different viewing conditions can affect the threshold, and it is different for each individual) (47). Motivated by this concept, we decide to test whether indeed our device is able to modulate the overall brightness of the transmitted color, as would be necessary for optical display applications, by applying a periodic bias with different gate voltage.

The results can be seen in Fig. 4. Using the transmission imaging setup as outlined in Fig. 4A, we can observe the different brightness of the color arrays simply by varying the amplitude of drive voltage while maintaining a 100-Hz input sine wave, as seen in Fig. 4 (B and C). Because the frame rate of our camera (32 Hz) is slower than the modulation speed of the cantilevers, we record a series of images (100) and average them together to approximate how a human eye would see the blurred motion of the cantilever. The achieved colors in Fig. 4B are thus only a rough approximation of how a human observer would see the dimming of the pixels.

**Color mixing**

To fully analyze the color space supported by such aluminum metasurfaces, we have fabricated a set of larger metasurfaces without cantilevers on top, using an aluminum RIE dry etching process (see Materials and Methods below). By using larger metasurface areas, we can more accurately measure the transmission spectra as we do not need to focus the illuminating light. The recorded transmission spectra were converted into the International Commission on Illumination (CIE) 1931 color space xyY coordinates (see Materials and Methods below) and can be seen in Fig. 5. For comparison, we have also shown the chromaticity points of the sRGB scale, which is the standard color space for most commercial optical displays. The color space corresponding to the spectra in Fig. 2 can be seen in fig. S4.

If the colors that make up two points in the CIE xyY chromaticity diagram can be freely mixed, then any colors on a straight line between those two points can also be achieved. Thus, inside a triangle of points, if all three colors corresponding to the points can be mixed freely, then all the colors inside the triangle can be achieved. Figure 5 shows this with roughly 50:50 mixed colors, although any other mixing ratio could also be achieved.

**DISCUSSION**

The capabilities of our “proof-of-concept” device shown here could be further improved in several ways. First, the cantilevers are being actuated in air, and drag from air resistance is thus limiting the speed of their motion. Encapsulating the device and operating it in a standard low vacuum of $\sim 10^{-3}$ torr could greatly increase the modulation frequencies that could be achieved.

Second, the mechanical properties of the cantilevers could be further optimized. It is possible that by changing the dimensions or the thicknesses of the SiO$_2$ and Al layers, even higher frequencies of modulation could be achieved and the average transmission could be better controlled as well. In the same fashion, adding a high-frequency modulation to the drive voltage could further stabilize the
The magnitudes of the driving voltages used here (roughly ±70 V) are also something that could be greatly reduced through optimization of the cantilever design, especially by reducing the cantilever size both in width and length, such that after device fabrication, the gap between the cantilever and the bottom electrode will be reduced, which will markedly lower the pull-in voltage. Another method to reduce the driving voltage is to reduce the spring constant by increasing the cantilever aspect ratio so less total electrostatic force is needed to pull down the cantilever. Note that the spring constant should be kept above a certain level to avoid cantilever stiction, which is a common issue in low–spring constant MEMS devices (45, 46, 48). Further optimization of the cantilever design could also greatly expand the voltage range used for brightness modulation (and increase the achievable modulation depth along with it). We have only been able to study this aspect in a narrow

![](image.png)

Fig. 4. Color brightness modulation. (A) Experimental setup used for the brightness measurements. The home-built microscope is reconfigured to a transmission-type scheme. (B) The resulting brightness observed when the cantilevers are modulated at different peak-to-peak voltages with a 100-Hz driving sine wave. A total of 100 images were recorded with a frame rate of 32 Hz and averaged together. An average RGB color is also displayed from within the color pixel area. (C) Relative luminance value from the averaged RGB values when converted to xyY, normalized to the unmodulated pixel.

![](image.png)

Fig. 5. Chromaticity and color mixing. (A) CIE xyY chromaticity map extracted from the measured transmission spectra of white light transmitted through RGB metasurfaces and mixed colors from illuminating combined metasurfaces. The range of sRGB colors is shown for comparison. Insets show transmission microscope images of the nanohole metasurfaces used in the measurements, and each image is roughly 100 × 100 µm². (B) Top: Transmission spectra of the RGB metasurfaces used to calculate the chromaticity. Bottom: Transmission spectra of the mixed color metasurfaces.
range of voltages (Fig. 3E) for this cantilever design, as voltages below the values studied do not allow actuation, and values much above this can cause permanent dielectric breakdown.

With the current set of parameters and dimensions of the color pixel, we did not notice any color nonuniformity (besides that of the irregularity of the metasurface in general). If our pixel aspect ratios were different (i.e., notably longer than wide), then some amount of color irregularity may appear, where the areas of the pixel most close to the cantilever base are dimmed more than the ones furthest away. This is because the cantilever must “unfold” from its base, so the areas near the base are covered by the cantilever for a longer amount of time than the ones furthest away. Even then, for high enough frequency operation, this irregular dimming would likely be reduced to a human observer. As the brightness dimming is entirely controlled by the cantilever (where cantilevers can be potentially controlled individually in future work), we would expect similar dimming for the other colors.

Our design also remains competitive with existing technology in terms of power consumption. MEMS devices are well known to have low power consumption, and we find that a ~18.5 cm display unit using such cantilevers would consume in the magnitude of 1 W of power during operation (see fig. S3 and surrounding discussion).

In terms of lifetime, our devices have been operated for several hours at hundreds of Hertz modulation, without any observable degradation in quality (when operated within reasonable parameters). An extended time series of the modulation is shown in fig. S5. The measurements were carried out over a few weeks, with devices left under ambient conditions without signs of degradation. However, before large-scale display implementations, further long-term stability and lifetime studies will be required.

As for the plasmonic nanohole arrays, further optical design with the aim to narrow the spectral transmission would greatly expand the achievable color space. For example, our red nanohole array contains a great deal of “blue” light in its transmission spectrum (see Fig. 2D), and in general, the arrays allow for a low amount of “white light” transmission. The color filtering mechanism shown here relies purely on plasmonic resonances. Alternatively, making a combination of diffractive and plasmonic resonances could potentially achieve ultranarrow color filters, as has been shown recently in the short-wave infrared regime (49). While the metasurfaces demonstrated here do not achieve much more than ~50% peak efficiency, it is likely possible to make more efficient structural color filters, such as by using a different design or exploiting a dielectric resonance. The on/off extinction ratio of our method is also expected to be very high, as the aluminum cantilever can essentially shut off optical transmission completely, allowing for high-contrast ratios in display applications.

In terms of scalability, our approach is also expected to enable cost-effective large-scale fabrication of color displays. For one, the entire device only relies on three lithography steps for its fabrication, and two, all of the used materials are CMOS compatible and considered to be at a low cost. While we have used e-beam lithography for our particular device, it is possible in industrial-quality extreme UV lithography to generate structures in the range of 5 nm (50), which is well below any feature size in our device.

As our device only consists of aluminum and glass, we believe that it would be relatively easy to recycle via a combination of mechanical and heating processes, and/or chemical processes. Essentially the color/display element of a display could be crushed to a fine powder in a mechanical press. Then, as the melting temperatures of glass and aluminum are noticeably different \( T_{\text{mel,Al}} = 660^\circ \text{C} \) versus \( T_{\text{mel,\text{SiO}_2}} = 1723^\circ \text{C} \), the aluminum and glass components could be melted out of the powder at different temperatures in a furnace. Alternatively, the powder could be suspended in an acid, which would selectively dissolve the aluminum to form an aluminum salt dissolved in the liquid. The resulting liquid could then be strained from the remaining glass particles, and the aluminum could be extracted by either electrochemical processes or chemical reduction (3).

To conclude, we have shown that it is possible to generate a full range of RGB color pixels using plasmonic metasurfaces in the form of nanohole arrays and demonstrate the modulation of the average transmission of such an array by a micromechanical cantilever, which is actuated by applying an electrostatic potential between the nanohole array and the cantilever. We find the ~3 dB point for the transmission modulation to be ~800 Hz, which is well above the speeds of conventional display technology (60 to 124 Hz) and well above the human flicker fusion threshold (60 to 100 Hz). Taking advantage of this property, we have shown that the average transmission through an array can be controlled by changing the magnitude of the applied voltage or by changing the drive voltage frequency.

Making a pixel that consists of three subpixels each of an RGB nanohole array can thus allow for color mixing between the RGB subpixels, by individually controlling their average transmission, making their brightness dim to a human observer. From the transmission spectra of each of our nanohole arrays, we have extracted the chromaticity and shown the color space that could be achieved in such a plasmonic color display.

Future studies into the potential impact of such sustainable display technologies are also needed. This will require accounting for the current models of projected increase in demand of digital displays (tied to global economic development and transitions to more service-based economies) while comparing the full life cycle costs of such displays as compared with conventional technologies, especially display types such as OLEDs, quantum dot displays, and micro-LED displays.

Our results highlight how plasmonic structural colors and MEMS technology can be combined to generate a color display, based on only two materials that can be fully recyclable. Given the immense prevalence and importance of displays in modern society, such reduction of component materials is predicted to become critically important in the future if circular economic goals of easily and economically viable recyclable consumer goods are to be achieved.

MATERIALS AND METHODS

**FDTD simulation**

FDTD simulations were carried out using the commercial software Lumerical FDTD (Ansys). The nanohole arrays were simulated using periodic boundary conditions for the \( x \) and \( y \) directions, and perfectly matched layers were used in the \( z \) direction. The smallest mesh element size was 2 nm. The dielectric functions of the aluminum used the values from Palik (51), and the glass was kept as a lossless dielectric with refractive index of 1.45.

**Sample fabrication**

The device fabrication includes two lithography techniques: EB lithography and photolithography. We use EB lithography to make
the nanohole arrays for the color filters, and photolithography for the MEMS cantilevers. First, polymethyl methacrylate (PMMA) was coated on a glass substrate, followed by EB lithography with an ELS-G1000 (Elionix) system. An acceleration voltage of 100 kV and a beam current of 1 nA were used. Then, 100-nm-thick aluminum (Al) was deposited with EB evaporation on the wafer. We used lift-off to pattern the nanohole arrays and the bottom electrodes for the cantilevers. A thin layer oxide of 210 nm was deposited with sputtering on the wafer to tune the color of the nanohole arrays to the desired color. The oxide layer also works as an insulating layer for the electrodes when actuating the cantilevers. Next, a photoresist sacrificial layer was patterned on the wafer with photolithography using an MA6 mask aligner (SÜSS MicroTec). A 100-nm oxide and sacrificial layer was patterned on the wafer with photolithography the electrodes when actuating the cantilevers. Next, a photoresist sacrificial layer was patterned on the wafer with photolithography, followed by Al wet etching and oxide wet etching. The cantilevers are released by O₂ plasma with an RIE machine (Oxford).

For the metasurfaces used in the color space and color mixing experiment, we opted to use an RIE dry etching process to pattern the nanohole structure into the aluminum layer, rather than lift-off, as this leads to substantially less roughness of the nanoholes and correspondingly less inhomogeneous broadening of the transmission spectrum. The diameters of these nanoholes for red, green, and blue are 212, 160, and 120 nm and have corresponding periods between the nanohole centers of 430, 330, and 250 nm.

**Transmission spectroscopy**

We characterize the optical transmission of the plasmonic metasurfaces by illuminating them with a white light source (tungsten halogen lamp) through a microscope condenser lens. The transmitted light is collected with a microscope objective (Nikon, 50×, numerical aperture of 0.45) and directed into an Ocean Optics Flame spectrometer. An aperture is placed in the image plane to spatially select only the metasurface region (around a diameter of 25-μm circular area) to enter the spectrometer.

**Light modulation measurements**

The cantilevers’ modulation of light was measured using a red laser pointer. Following the setup in Fig. 3A, the laser light was coupled from above in a home-built reflection microscope, where it was aligned to a single cantilever at a time. Tungsten probes were mechanically pressed against the aluminum electrodes on top of the device using XYZ 500MIM 3D (three-dimensional) stages (Quater Research & Development), and a bias voltage was applied between them using an SDG 2082X (SIGLENT) function generator. The voltage output of the signal generator was amplified using a model 2350 high-voltage amplifier (TEGAM). The transmitted laser light through the nanohole array was then measured using a silicon photodiode (DET100A/M, Thorlabs). The voltage output of the photodiode and the applied bias were both monitored on an InfiniiVision DSOX2004A (Keysight) oscilloscope. The measured transmission signals were converted to $T_{rel}$ signals of values between 0 and 1, by first subtracting the off-state voltage from the lowest frequency measurement and then normalizing the signals to the highest value of the lowest frequency measurement.

**Color mixing and color gamut**

CIE 1931 xyY chromaticity coordinates were calculated from the recorded transmission spectra. Using the CIE 1931 color matching functions, $x$, $y$, and $z$ (52), the tristimulus values, $X$, $Y$, and $Z$ were then calculated as (53)

$$X = \frac{1}{N} \int_0^\infty I(\lambda) \left[ T(\lambda) x(\lambda) \right] d\lambda,$n

$$Y = \frac{1}{N} \int_0^\infty I(\lambda) \left[ T(\lambda) y(\lambda) \right] d\lambda,$n

$$Z = \frac{1}{N} \int_0^\infty I(\lambda) \left[ T(\lambda) z(\lambda) \right] d\lambda,$n

where $I$ is the spectral power distribution of the illuminating light source, $T$ is the normalized transmission spectrum of a nanohole array color filter, $\lambda$ is the wavelength, and $N$ is given as

$$N = \int_0^\infty I(\lambda) \, d\lambda.$n

The “brightness” (luminance) and “color” (chromaticity) of the light transmitted through the nanohole array can then be described by the CIE xyY coordinates. The tristimulus value $Y$ from above is the luminance per definition, and the $x$ and $y$ chromaticity coordinates are given by normalization as

$$x = \frac{X}{X + Y + Z},$$n

$$y = \frac{Y}{X + Y + Z}.$n

The final coordinate $z = Z/(X + Y + Z) = 1 − x − y$ is not independent and is generally disregarded.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abn0889

**REFERENCES AND NOTES**

1. A new circular vision for electronics, time for a global reboot. Technical Report, World Economic Forum. https://www.weforum.org/reports/a-new-circular-vision-for-electronics-time-for-a-global-reboot (2019).
2. V. Bhakar, A. Agur, A. K. Digalwar, K. S. Sangwan, Life cycle assessment of CRT, LCD and LED monitors. Procedia CIRP 29, 432–437 (2015).
3. V. Lahtela, S. Virolainen, A. Uwaoma, M. Kallioinen, T. Kärki, T. Sainio, Novel mechanical pre-treatment methods for effective indium recovery from end-of-life liquid-crystal display panels. J. Clean. Prod. 230, 580–591 (2019).
4. A. V. Kneese, The economics of natural resources. Popul. Dev. Rev. 14, 281–309 (1988).
5. W. R. Stahel, The circular economy. Nat. News 531, 435–438 (2016).
6. J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232 (2017).
7. M. Geissdoerfer, P. Savaget, N. M. P. Bocken, E. J. Hultink, The circular economy–a new sustainability paradigm? J. Clean. Prod. 143, 757–768 (2017).
8. S.-J. Lee, J. Cooper, Estimating regional material flows for LCDs, in Proceedings of the IEEE International Symposium on Electronics and the Environment (2008), vol. 19, p. 21.
9. Y. Gu, L. Zhang, J. K. W. Yang, S. P. Yeo, C. W. Qiu, Color generation via subwavelength plasmonic nanostructures. Nanoscale 7, 6409–6419 (2015).
10. A. Kristensen, J. K. W. Yang, S. I. Bozhevolnyi, S. Link, P. Nordlander, N. J. Halas, N. A. Mortensen, Plasmonic colour generation. Nat. Rev. Mater. 2, 16088 (2016).
11. L. Shao, X. Zhuo, J. Wang, Advanced plasmonic materials for dynamic color display. Adv. Mater. 30, 1704338 (2018).
12. T. Lee, J. Jang, H. Jeong, J. Rho, Plasmonic-and dielectric-based structural coloring: From fundamentals to practical applications. Nano Converg. 5, 1–21 (2018).
13. S. D. Rezaei, Z. Dong, J. Y. E. Chan, J. Trisno, R. J. H. Ng, Q. Ruan, C.-W. Qiu, N. A. Mortensen, J. K. W. Yang, Nanophotonic structural colors. ACS Photonics 8, 18–33 (2021).
14. S. Kinoshita, S. Yoshioka, Structural colors in nature: The role of regularity and irregularity in the structure. ChemPhysChem 6, 1442–1459 (2005).
15. M. Song, D. Wang, S. Peana, S. Choudhury, P. Nyga, Z. A. Kudyshev, H. Yu, A. Balsevaz, V. M. Shalaev, A. V. Kildishe, Colors with plasmonic nanostructures: A full-spectrum review. Appl. Phys. Rev. 6, 041308 (2019).
16. Y. Wu, Y. Chen, Q. Song, S. Xiao, Dynamic structural colors based on all-dielectric mie resonators, Adv. Opt. Mater. 9, 2002126 (2021).
17. X. Zuan, J. Li, Q. Liu, F. Yi, S. Wang, W. Lu, Artificial structural colors and applications. Innovation 2, 100081 (2021).
18. K. Kumar, H. Duan, R. S. Hegde, S. C. W. Koh, J. N. Wei, J. K. W. Yang, Printing colour at the optical diffraction limit. Nat. Nanotechnol. 7, 557–561 (2012).
23. X. Zhu, W. Yan, U. Levy, N. A. Mortensen, A. Kristensen, Resonant laser printing of nano color palette. ACS Nano 10, 492–498 (2016).

24. W. Yang, S. Xiao, Q. Song, Y. Liu, Y. Wu, S. Wang, J. Yu, J. Han, D.-P. Tsai, All-dielectric nano color palette. ACS Nano 10, 71–77 (2016).

25. N. Roostaei, N. S. Shnan, S. M. Hamidi, Red and blue color production by flexible all-dielectric color chips. ACS Nano 10, 166345 (2021).

26. P. Zijlstra, J. W. M. Chan, M. Gu, Five-dimensional optical recording mediated by surface plasmons in gold nanorods. Nature 459, 410–413 (2009).

27. X. Chen, Y. Chen, J. Dai, M. Yan, D. Zhao, Q. Li, M. Qiu, Ordered Au nanocrystals on a substrate formed by light-induced rapid annealing. Nano Scale 6, 1756–1762 (2014).

28. X. Zhu, C. Vannmehre, E. Hajlund-Nielsen, N. A. Mortensen, A. Kristensen, Resonant laser printing of structural colors on high-index dielectric metasurfaces. Sci. Adv. 3, e1602487 (2017).

29. W. Yang, S. Xiao, Q. Song, Y. Liu, Y. Wu, S. Wang, J. Yu, J. Han, D.-P. Tsai, All-dielectric metasurface for high-performance structural color. Nat. Commun. 11, 1864 (2020).

30. N. Roostaei, N. S. Shnan, S. M. Hamidi, Red and blue color production by flexible all-dielectric color chips. Optik 230, 166345 (2021).

31. X. Duan, S. Kamin, N. Liu, Dynamic plasmonic colour display. Nat. Commun. 8, 14606 (2017).

32. X. Duan, N. Liu, Scanning plasmonic color display. ACS Nano 12, 8817–8823 (2018).

33. D. Franklin, R. Frank, S.-T. Wu, D. Chanda, Actively addressed single pixel full-colour plasmonic display. Nat. Commun. 8, 15209 (2017).

34. N. J. Greubusch, K. Charipar, J. A. Geldmeier, S. J. Bauman, P. Johns, J. Naciri, N. Charipar, K. Park, R. A. Vaia, J. Fontana, Dynamic plasmonic pixels. ACS Nano 13, 3875–3883 (2019).

35. Z. Yan, Z. Zhang, W. Wu, X. Ji, S. Sun, Y. Jiang, C. C. Tan, L. Yang, C. T. Chong, C.-W. Qiu, R. Zhao, Floating solid-state thin films with dynamic structural colour. Nat. Nanotechnol. 16, 795–801 (2021).

36. S. T. S. Holmström, U. Baran, H. Urey, MEMS laser scanners: A review. J. Micromech. Microeng. 23, 259–275 (2014).

37. J. Ma, Advanced MEMS-based technologies and displays. Displays 37, 2–10 (2015).

38. L. J. Hornbeck, Digital light processing for high-brightness high-resolution applications, in Projection Displays III (International Society for Optics and Photonics, 1997), vol. 3013, pp. 27–40.

39. J. Tauscher, W. O. Davis, D. Brown, M. Ellis, Y. Ma, M. E. Sherwood, D. Bowman, M. P. Helsel, S. Lee, J. W. Coy, Evolution of MEMS scanning mirrors for laser projection in compact consumer electronics, in MOEMS and Miniaturized Systems IX (International Society for Optics and Photonics, 2010), vol. 7594, p. 7594A0.

40. J. B. Sampell, MEMS-based display technology drives next-generation FPDs for mobile applications. Inform. Display 22, 24 (2006).

41. N. Hagood, R. Barton, T. Brosnihan, J. Fijol, J. Gandhi, M. Halfman, R. Payne, J. Lodewyk Steyn, 35.5: Late-news paper: A direct-view MEMS display for mobile applications, in 3D Symposium Digest of Technical Papers (Wiley Online Library, 2007), vol. 38, pp. 1278–1281.

42. D. M. Bloom, Grating light valve: Revolutionizing display technology, in Projection Displays III (International Society for Optics and Photonics, 1997), vol. 3013, pp. 165–171.

43. A. L. Holstein, A. F. Cihan, M. L. Brongersma, Temporal color mixing and dynamic beam shaping with silicon metasurfaces. Science 365, 257–260 (2019).

44. Q. Chen, D. R. S. Cumming, High transmission and low color cross-talk plasmonic color filters using triangular-lattice hole arrays in aluminum films. Opt. Express 18, 14056–14062 (2010).

45. H. Toshiyoshi, Electrostatic actuation. Compr. Microsyst. 2, 1–38 (2008).

46. Z. Han, K. Kohno, H. Fujita, K. Hirakawa, H. Toshiyoshi, MEMS reconfigurable metamaterial for terahertz switchable filter and modulator. Opt. Express 22, 21326–21339 (2014).

47. C. Landis, Determinants of the critical flicker-fusion threshold. Physiol. Rev. 34, 259–286 (1954).

48. Z. Han, K. Kohno, H. Fujita, K. Hirakawa, H. Toshiyoshi, Tunable terahertz filter and modulator based on electrostatic mems reconfigurable srr array. IEEE J. Sel. Top. Quantum Electron. 21, 114–122 (2014).

49. M. S. Bin-Alam, O. Reshef, Y. Mamchur, M. Z. Alamm, G. Carlow, B. T. Sullivan, J.-M. Ménard, M. J. Huttunen, R. W. Boyd, K. Dolgaleva, Ultra-high-Q resonances in plasmonic metasurfaces. Nat. Commun. 12, 974 (2021).

50. G. Yeap, S. S. Lin, Y. M. Chen, H. L. Shang, P. W. Wang, H. C. Lin, Y. C. Peng, J. Y. Sheu, M. Wang, X. Chen, B. R. Yang, C. P. Lin, F. C. Yang, Y. K. Leung, D. W. Lin, C. P. Chen, K. F. Yu, D. H. Chen, C. Y. Chang, H. K. Chen, P. Hung, C. S. Hou, Y. K. Cheng, J. Chang, L. Yuan, C. K. Lin, C. C. Chen, Y. C. Yeo, M. H. Tsai, H. T. Lin, C. O. Chiu, K. B. Huang, W. Chang, H. J. Lin, K. W. Chen, R. Chen, S. H. Sun, Q. Fu, H. T. Yang, H. T. Chiang, C. C. Yeh, T. L. Lee, C. H. Wang, S. L. Shue, C. W. Wu, R. Lu, W. R. Lin, J. Wu, F. Lai, Y. H. Hu, B. Z. Tien, Y. C. Huang, L. C. Lu, J. He, Y. Ku, J. Lin, M. Cao, T. S. Chang, S. M. Jang, 5nm CMOS production technology platform featuring full-fledged EUV, and high mobility channel FinFETs with densest 0.021 μm 2 SDRAM cells for mobile SoC and high performance computing applications, in Proceedings of the 2019 IEEE International Electron Devices Meeting (IEDM) (IEEE, 2019), pp. 36–37.

51. E. D. Palik, Handbook of Optical Constants of Solids (Academic Press, 1998), vol. 3.

52. J. Guild, The colorimetric properties of the spectrum. Philos. Trans. R. Soc. A 230, 149–187 (1931).

53. D. Malacara, Color vision and Colorimetry: Theory and Applications (2003).

Acknowledgments: We wish to thank M. Saidian and S. Elav of The Hebrew University Center for Nanoscience and Nanotechnology for assistance with the device fabrication. Funding: We acknowledge funding from the Israeli Ministry of Science and Technology. Z.H. is supported by the PBC Fellowship Program. Author contributions: The idea for the project was devised by Z.H., C.F., and U.L. Optical design and FDTD simulations were done by Z.H. Sample fabrication was done by Z.H. and N.M. SEM images were recorded by N.M. Optical characterization was done by C.F. and Z.H. Data analysis was done by C.F. The work was supervised by U.L. All authors contributed to the writing of the manuscript and interpretation of the results. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Submitted 2 November 2021
Accepted 8 March 2022
Published 20 April 2022
10.1126/sciadv.abc0889

Han et al., Sci. Adv. 8, eabc0889 (2022) 20 April 2022 9 of 9