OPTICS

Matte surfaces with broadband transparency enabled by highly asymmetric diffusion of white light

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The long-standing paradox between matte appearance and transparency has deprived traditional matte materials of optical transparency. Here, we present a solution to this centuries-old optical conundrum by harnessing the potential of disordered optical metasurfaces. Through the construction of a random array of meta-atoms tailored in asymmetric backgrounds, we have created transparent matte surfaces that maintain clear transparency regardless of the strength of disordered light scattering or their matte appearances. This remarkable property originates in the achievement of highly asymmetric light diffusion, exhibiting substantial diffusion in reflection and negligible diffusion in transmission across the entire visible spectrum. By fabricating macroscopic samples of such metasurfaces through industrial lithography, we have experimentally demonstrated transparent windows camouflaged as traditional matte materials, as well as transparent displays with high clarity, full color, and one-way visibility. Our work introduces an unprecedented frontier of transparent matte materials in optics, offering unprecedented opportunities and applications.

INTRODUCTION

Conventional wisdom to realize transparency demands minimizing disordered light scattering. Nevertheless, achieving a matte appearance necessitates disordered light scattering, as demonstrated in Fig. 1A. Therefore, for a long time, transparency and matte appearances have been considered two conflicting optical properties that cannot coexist in the same material. Even if the thickness of a matte material is reduced to a level that allows a portion of light to pass through, it can only achieve translucency instead of transparency, similar to frosted glass. Here, our work challenges this long-existing perception. Using disordered optical metasurfaces (1-10) composed of two-dimensional arrays of specially designed meta-atoms in asymmetric backgrounds, we have achieved highly asymmetric diffusion that dominates in reflection and diminishes in transmission across the full visible spectrum. Such a highly asymmetric diffusion of white light is absent in any previously known optical material. It opens the possibility of achieving a matte appearance in reflection without sacrificing clear transparency, even when the disordered light scattering is strong and the transmittance is low. While the concept of undistorted transmission has been discussed previously using a random-flip configuration (11), our work overcomes significant limitations, such as microscopic fabrication constraints imposed by electron beam lithography, limited bandwidth unable to cover the entire visible spectrum, and dispersive diffusion efficiency, thereby enabling the first practical implementation of this unique phenomenon.

RESULTS

Realization of highly asymmetric diffusion of white light via macroscopic disordered metasurfaces

An optical surface that is transparent in transmission and matte in reflection, denoted as a transparent matte surface (TMS), can be realized by imposing random phase shifts to reflection and uniform phase shifts to transmission, as shown in Fig. 1B. Nonetheless, this phenomenon holds significance only when it is realized on a macroscopic scale and encompasses the entire visible spectrum, which appears to be exceptionally challenging via the previous approach (11).

Here, we present a practical approach to accomplish this ambitious goal, i.e., realizing macroscopic TMSs with stable and optimal diffusion efficiency across the entire visible spectrum. The design principle is described as follows. We consider a metasurface consisting of a randomly arranged set of two meta-atoms: meta-atom I and meta-atom II. In this random binary optical system (11-13), the degree of diffusion could be characterized by $\xi = 1 - \frac{R_{\text{spe}}}{R_{\text{tot}}}$ in re-flection or $\xi = 1 - \frac{T_{\text{ball}}}{T_{\text{tot}}}$ in transmission, respectively. Here, R_{spe} and T_{tot} are the specific terms of the lifetime terms of terms o T_{bal} are the specular reflectance and ballistic transmittance, and R_{tot} and T_{tot} are the total reflectance and transmittance, i.e., the sums of the specular or ballistic part and the diffusive part in reflection or transmission, respectively. From the far-field radiation theory, we can calculate ξ as a function of the phase difference $\Delta \phi$ and amplitude ratio η of the scattering from the two meta-atoms (see section S1). The averaged results calculated from 10 sets of random 100 × 100 configurations are shown in Fig. 1C. ξ is almost unity when $\Delta \phi = \pi$ and is near zero when $\Delta \phi = 0$ under a broad range of η , i.e., $0.5 < \eta < 2$ (11–14). The reason that $\Delta \phi$ plays a more important role than η can be grasped intuitively by examining the interference between reflections from two distinct types of meta-atoms. As $\Delta \phi$ transitions from π to 2π (0), the interference undergoes a gradual shift from a destructive to a constructive nature. The schematic illustrating this evolution is depicted in fig. S3. Therefore, to realize TMSs, the phase difference in reflection $(\Delta \varphi_r)$ and transmission $(\Delta \varphi_t)$ should be $\Delta \varphi_r \approx \pi$ and $\Delta \varphi_t \approx 0$ in the whole visible spectrum. Broadband $\Delta \phi_t \approx 0$ can be achieved by using the reciprocity principle and local space inversion (11) or equivalent optical paths under certain circumstances. We note that there are many

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Fig. 1. Broadband TMSs enabled by highly asymmetric diffusion across the full visible spectrum. (**A**) Traditional methods of achieving a matte surface, such as rough surfaces (left) and random scatterers (right), result in diffused light in both transmission and reflection channels. (**B**) By introducing random phase shift in reflection and uniform phase shift in transmission, optical metasurfaces allow for highly asymmetric diffusion of light, effectively combining matte appearance and transparency. (**C**) The degree of diffusion as a function of the phase difference and amplitude ratio of the radiation from the two meta-atoms in 10 sets of random 100 × 100 configurations. (**D**) The two meta-atoms are composed of reflecting patches (yellow) with a thickness d_g located at depths d_1 and d_2 beneath the surface of the dielectric substrate (gray). (**E**) The mechanism of achieving broadband near- π phase difference in the reflection coefficients $r_1 = a + b_1$ and $r_2 = a + b_2$. (**F**) Calculated phase differences in reflection ($\Delta \phi_t$) and transmission ($\Delta \phi_t$) for meta-atoms with gold patches of $d_g = 28$ nm and $d_1 = 70$ nm and $d_2 = d_1 + 90$ nm. $\Delta \phi_t \approx \pi$ and $\Delta \phi_t \approx 0$ are realized in the whole visible spectrum (380 to 780 nm). For comparison, $\Delta \phi_r$ and $\Delta \phi_t$ for meta-atoms in (11) are shown as dashed curves, where the dispersion of $\Delta \phi_r$ is distinct. (**G**) Calculated far-field radiation power (*P*) pattern at the wavelength of 413 nm for a unit of TMS (gray figure) composed of 800 × 800 random sequences of the two meta-atoms. (**H**) Measured (symbols) and calculated (curves) specular reflectance and transmittance of the gold TMS-coated GW of $d_g = 28$ nm, $d_1 = 70$ nm, and $d_2 = 160$ nm, and the GW coated with a gold film of the same thickness (28 nm).

other designs of metasurface resulting in broadband phase differences in transmission, such as transmissive Pancharatnam-Berry phase metasurfaces with extremely high efficiency (15, 16). However, obtaining broadband $\Delta \varphi_r \approx \pi$ typically requires intricate structures with zero transmission(12, 13), which are not suitable for our scenario that necessitates a manageable transmission to preserve transparency.

It turns out that the asymmetric backgrounds of the meta-atoms can provide a previously unknown route for obtaining broadband $\Delta \varphi_r \approx \pi$. The issue of backgrounds was seldom discussed in most of the previous metasurface designs, except for some special cases (17–21). Here, we consider the asymmetric backgrounds induced by the substrate of the meta-atoms. As shown in Fig. 1D, the optical meta-atoms consist of reflecting metal or dielectric patches embedded at varying depths beneath the dielectric surface. The optical path in the transmission is exactly the same through the two meta-atoms. Therefore, we have $\Delta \varphi_t \approx 0$. On the other hand, the reflection coefficients of the two meta-atoms are approximately $r_1 = a + b_1$ and $r_2 = a + b_2$, respectively. Here *a*, b_1 , and b_2 denote the contributions from the dielectric surface and the embedded patches in the reflection are ignored here because they are much smaller. *a* is a real number determined by the refractive

index of the dielectric substrate. By varying d_1 and d_2 , it is possible to change the argument of b_1 and b_2 such that they are either in phase or out of phase to a, respectively, at a central frequency f_0 , as shown in the left panel of Fig. 1E. The remarkable finding is that, as the frequency changes from f_0 to $f_0 + \Delta f$, the reflection coefficients r_1 and r_2 can remain nearly opposite to each other over a broad spectrum, as demonstrated by the pink shadow region in the right panel of Fig. 1E. Such a broadband π phase difference is attributed to the phase corrections of γ_1 and γ_2 caused by a. The mathematical proof of this mechanism is shown in section S2. We note that if the dielectric layers above the reflective patches are absent, i.e., a = 0, then the phase difference of π can only be obtained at a single frequency because the phase shifts of b_1 and b_2 under frequency change Δf , i.e., α and β , are distinct.

As a typical example, we first consider meta-atoms consisting of gold patches of thickness $d_g = 28$ nm and choose the central wavelength to be $\lambda_0 = c/f_0 = 540$ nm, where *c* is the speed of light. From the opposite phase condition between b_1 and b_2 at f_0 , it is obtained that $d_2 = d_1 + 90$ nm. We then calculate phase differences between the two meta-atoms in reflection ($\Delta \varphi_r$) and transmission ($\Delta \varphi_t$) as functions of d_1 and wavelength λ . It is found that when $d_1 = 70$ nm, $\Delta \varphi_r \approx \pi$ and $\Delta \varphi_t \approx 0$ are achieved in the whole visible spectrum (380 to 780 nm), shown in

Fig. 1F as solid curves. For comparison, the phase difference in the reflection coefficients for the meta-atoms in (11), also shown in Fig. 1F as a dashed curve, suffers from severe frequency dispersion. $\Delta \varphi_r \approx \pi$ is only achieved around 680 nm, resulting in lower diffusion efficiency at other frequencies and vanishing diffusion for blue light. The design of the TMS unit involves arranging the two meta-atoms depicted in Fig. 1D in an 800 \times 800 random pattern, measuring 0.72 mm \times 0.72 mm in size. Optimization of this random pattern is detailed in section S1. The metal patches are set to a lateral scale of 900 nm, which is small enough to diffuse light in the visible band and large enough to be fabricated using standard industrial lithography. The far-field radiation power pattern at a wavelength of 413 nm, calculated and depicted in Fig. 1G, shows a highly asymmetric (backward) optical diffusion. This is evident from the diversification of reflected light in many backward directions and the absence of diffusion in transmitted light. It is worth noting that the principle to reduce specular reflection via interference between two particles was also utilized to achieve optical materials of ultra-wideband nonreflection (22). At other frequencies, the specular reflectance is approximately 1%, mainly due to differences in the reflectance of the meta-atoms. We note that it is still significantly lower than that of the glass substrate (~7%). In contrast, the case without a dielectric layer on the top and the metasurface from (11) only has a minimal specular reflection around 660 and 680 nm, respectively, indicating a narrowband diffuse reflection (as shown in fig. S4).

The TMS design presented here has a significant advantage: it can be easily mass-produced through industrial lithography, which is crucial for any practical applications of metasurfaces. We fabricate a macroscopic TMS by repeating the TMS unit from Fig. 1G on a 4-inch glass wafer (GW). In the fabrication, we have chamfered the right angles of the metal structures to avoid potential singularity effects (23) and adopted an aligned double-exposure process to fabricate the two complementary layers of random metal patches, which, in principle, applies to any complementary bilayer structures (24). More details of the TMS fabrication process are described in Materials and Methods. Experiments have been conducted to measure the transmittance and specular reflectance of a 28-nm-thick gold TMS (with $d_g = 28$ nm, $d_1 = 70$ nm, and $d_2 = 160$ nm) and a 28-nm-thick smooth gold-film-coated glass wafer (GF-coated GW). The results align well with theoretical calculations, as shown in Fig. 1H. The measured average transmittance of the TMS-coated GW is 0.28. The variant transmittance at different frequencies may lead to color changes in the transmitted images as shown in fig. S5. We note that the variation in the transmittance spectrum is attributed to the dispersive nature of the gold. By adopting other metal materials with a much weaker dispersion, an almost constant transmittance spectrum could be achieved. We also note that the proposed scheme of constructing TMS has almost no restriction on the transmittance. By reducing the thickness of metal patches or replacing metal patches with dielectric ones, the transmittance of the TMS can be increased significantly. The measured average specular reflectance of the TMS-coated GW is 1.3%, which is significantly lower compared to 34% for the GF-coated GW and 7% for the uncoated GW. When the incidence is from the other side of the GW, the condition of broadband π phase difference is violated, resulting in an increase in the specular reflectance at specific frequencies, e.g., over 10% at $\lambda > 677$ nm (as shown in fig. S6).

TMS-enabled camouflage of windows and cameras

The macroscopic TMSs can function as camouflaged windows due to their low-gloss appearance and clear transparency. We then experimentally evaluate the performance of this macroscopic TMS in a mini photographic studio, which mimics the window of a room. A circular hole in the studio is covered with a TMS-coated GW (28 nm, Au). A bottle of flowers is placed in front of the studio, as depicted in Fig. 2A. The



Fig. 2. Experimental demonstration of TMSs for camouflage of windows. (A) The experimental setup. The TMS-coated GW (28 nm, Au) is mounted on a hole of a mini photographic studio. Inset, SEM micrograph of part of the TMS. Scale bar, 5 µm. (**B**) (Left) A zoom-in photograph of the TMS in (A), where almost no mirror image is observed due to the matte appearance. (Right) A photograph taken inside the studio shows a clear image of the bottle of flowers viewed through the TMS-coated GW (28 nm, Au). (**C**) (Left) A photograph taken outside the studio of a commercial AF mounted on a hole, showcasing a severely blurred mirror image of the flowers. (Right) A photograph taken inside the studio of the flowers and bottle.

zoomed-in image of the TMS, shown in the left panel of Fig. 2B, confirms its matte appearance, as the mirror image of the flowers is barely visible. The TMS is found to have a similar appearance to unpolished gold and does not change with the angle of observation, as demonstrated in fig. S7. For comparison, a commercial anti-glare film (AF) is used, and the photograph taken with the same conditions is shown in the left panel of Fig. 2C. We emphasize that each set of comparison photographs throughout the entire article was taken under the same lighting conditions and camera settings, ensuring fairness. The mirror images of the flowers are severely blurred, confirming the diffuse reflection. The right panel of Fig. 2B shows a clear photograph of the flowers, which is taken inside the photographic studio through the TMS-coated GW, confirming the perfect clarity of the TMS-coated GW as if viewed through an open hole. The perfect clarity of the TMS is angle independent, as demonstrated in fig. S8. In contrast, a photograph taken through the AF under the same conditions is shown in the right panel of Fig. 2C, where the image of the flowers and bottle is significantly blurred as if viewed through frosted glass. This blurring effect would be apparent to the naked eye as long as the AF is not tightly attached to the observed objects, as demonstrated in fig. S9. The TMS-coated GW thus exhibits both matte appearance and clear transparency, demonstrating its functionality as a camouflaged transparent window. The transparency and matte appearance of this window can be dynamically adjusted by manipulating the brightness contrast between the ambient lights in the front and rear. In general, the matte appearance of TMSs takes precedence when the brightness ratio between ambient lights on the observer and object sides approaches infinity. Conversely, it gradually diminishes as this ratio decreases toward zero. This exceptional feature is also confirmed under outdoor conditions with natural light, as shown in movie S1. We have also made a direct comparison of the functionalities of the GF-coated and TMS-coated GWs, and the AF, considering both objects are placed in front of and behind them, as presented in fig. S10.

The matte appearance and transmittance of the TMS can be tailored by changing the material and thickness of the reflecting patches, respectively. In addition to the gold TMS ($d_g = 28 \text{ nm}$) shown in Fig. 2A, we fabricated a titanium TMS ($d_g = 28 \text{ nm}$) and gold TMSs with different thicknesses ($d_g = 17 \text{ nm}$, $d_g = 35 \text{ nm}$) on GWs using industrial lithography. The samples are placed over the hole, and photographs are taken both outside and inside the studio, with the same camera parameters and environment as in Fig. 2B (fig. S11). From the photographs, it is seen that the TMS samples appear as matte surfaces in reflection, while also being clearly transparent. The appearance and transmittance are both customizable using different materials or structures in the TMS. For instance, the titanium TMS has the gray appearance of unpolished titanium, while the transmittance of the gold TMS decreases as the thickness of the reflecting patches increases. The measured and calculated transmission and reflection spectra of these TMSs are shown in fig. S12.

Thanks to the highly asymmetric diffusion of white light, TMSs maintain clear transparency even with low transmittance. This makes TMSs appear as matte opaque materials, like white walls or unpolished metal, in bright outdoor conditions but remain transparent for indoor occupants. Figure 3A depicts the phase differences of two meta-atoms with aluminum reflecting patches, as schematically shown in the inset. Here, $d_a = 25$ nm, $d_1 = 70$ nm, and $d_2 = 160$ nm. Clearly, $\Delta \varphi_t \approx 0$ and $\Delta \varphi_r \approx \pi$ are achieved in the entire visible spectrum. The measured and calculated spectra of the specular reflectance and transmittance of the TMS-coated GW (25 nm, Al) are plotted in Fig. 3B. It is seen that the TMS-coated GW has a very low transmittance of ~3%, which is close to that of an aluminum film with the same thickness of 25 nm coated on a GW (Al-coated GW). Moreover, the specular reflectance of the TMScoated GW is ~1% in the visible spectrum due to diffuse reflection, which is 80 times lower than that of the Al-coated GW of the same thickness (25 nm). The experimental results coincide well with the theoretical calculation. The top panels in Fig. 3 (C and D) show a camera



Fig. 3. Experimental demonstration of TMSs for camouflage of cameras. (**A**) Calculated phase differences in reflection $(\Delta \varphi_r)$ and transmission $(\Delta \varphi_t)$ for two metaatoms constructed by aluminum patches of $d_a = 25$ nm, $d_1 = 70$ nm, and $d_2 = 160$ nm. (**B**) Measured (symbols) and calculated (curves) specular reflectance and transmittance of the aluminum TMS-coated GW, and the GW coated with an aluminum film of the same thickness (25 nm). (**C** and **D**) (Top) Photographs of the camera behind the TMS-coated GW and AF. (Bottom) Photographs of a bottle of flowers taken by the camera behind the TMS-coated GW and AF with the exposure time extended.

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closely attached to the TMS (25 nm, Al) and the AF. Clearly, the TMS has the appearance of a truly opaque unpolished aluminum plate (fig. S13), while the AF cannot hide the lens of the camera, losing the camouflage functionality. The bottom panels in Fig. 3 (C and D) show the photograph of a bottle of flowers taken by the attached camera. Amazingly, despite being blocked by a seemingly opaque aluminum plate, the camera can still take a very clear image of the bottle of flowers through the TMS, in sharp contrast to the blurred image through the AF.

TMS-enabled transparent displays

With both a matte appearance and clear transparency, TMSs offer an alternative approach to transparent displays using projection, as schematically demonstrated in Fig. 4A. The matte appearance of TMSs across the entire visible spectrum results in a wide-angle and full-color display (fig. S14). In Fig. 4B, a colorful butterfly is projected onto a TMS-coated GW (28 nm, Au) with a real sunflower placed behind it. The butterfly and sunflower are both clearly visible. In contrast, when the TMS-coated GW is replaced with an AF, as shown in Fig. 4C, the

image of the sunflower is blurred, and the brightness of the butterfly is much dimmer than on the TMS. An important application of transparent displays is augmented reality, as schematically shown in Fig. 4D. A webcam captures the image of an object behind the TMS, which is then analyzed by a pretrained deep neural network (GoogLeNet). If the object is successfully identified, its name is projected; otherwise, "unidentified" is displayed. As shown in Fig. 4E, a tennis ball is successfully recognized through the TMS-coated GW (28 nm, Au), and its name is displayed. In contrast, the blurring effect of the AF prevents such recognition, as shown in Fig. 4F (see additional examples in movies S2 and S3). In contrast to the prevailing transparent display configurations, such as the amalgamation of transparent and display units on a screen (25, 26), or the utilization of a beam splitter for a see-through projection screen, TMS-enabled transparent displays offer distinct advantages, including superior clarity, an expansive viewing angle, heightened spatial resolution, and polarization independence.

The highly asymmetric light diffusion of TMSs also enables a one-way display. For projector screens made of cloth or fabric, the



Fig. 4. Transparent displays and augmented reality by TMS. (A) Schematic diagram of the transparent displays based on TMS. The butterfly image was projected onto the TMS-coated GW or AF with a real sunflower behind it. (B and C) Photographs taken under the same camera parameters for the TMS-coated GW (B) and AF (C). (D) Schematic diagram of an augmented reality application. A webcam captures the image of a tennis ball placed behind the TMS-coated GW/AF, which is processed by machine vision technologies for recognition. (E and F) Photographs taken under the same camera parameters for the TMS-coated GW (E) and AF (C). (G) Schematic diagram for verifying full-color and one-way displays. Photographs are taken from both sides of the TMS-coated GW or AF under the same camera parameters, with the image of a row of colored pencils projected from the front side. (H and I) Combined photographs for the TMS-coated GW (H) and AF (I).

displayed content is usually observable from both sides of the projector screen due to the light diffusion in both reflection and transmission (27, 28). However, the asymmetric diffusion of TMSs significantly reduces the diffusion in transmission, leading to high contrast in the brightness of the displays on the two sides. This is verified in the experimental setup in Fig. 4G. An image of a row of colored pencils is projected onto the TMS-coated GW (28 nm, Au) or AF, and photographs are taken from both sides under the same camera parameters and combined in Fig. 4 (H and I), for the TMScoated GW and AF, respectively. Clearly, the displayed pencils on the TMS are much brighter on the side of the projection (front view), indicating that light diffusion is mainly confined to reflection. In contrast, the displayed pencils on the AF have comparable brightness on both sides and are markedly dimmer than those on the TMS. This unique one-way visibility not only safeguards the privacy of displayed contents but also enables double-sided displays without cross-talk (see fig. S15).

DISCUSSION

We note that the reflecting patches in the design of TMSs can be made of any material, such as metals (29, 30), e.g., gold or titanium, and dielectrics (31-34), e.g., silicon. The choice of dielectrics could result in a lower loss. Nevertheless, metal-based TMSs offer a remarkable advantage, i.e., good insulation for infrared thermal energy, which makes them useful for heat insulation in windows and vehicle glass (see fig. S16), similar to low-E glass (35). TMSs with matte appearances can avoid the notorious increase of glare in reflection due to reduced transmittance in traditional low-E glass coatings.

Diffusing light (12, 13) by metasurfaces may be regarded as the opposite functionality of cloaking a corrugated surface (36). Compared with random bulk media (37-41), the metasurface approach has avoided wave localization (37) and large absorption (38). Recently, diffusive metasurfaces have provided unprecedented dynamic visual effects through spectrally and angularly shaping the reflected light (42, 43). However, the transmission properties of these metasurfaces have not been studied. Here, both the transmission and reflection channels are considered and manipulated independently, making it possible to maintain the clarity of transparency while achieving a matte appearance. The concept of disorder engineering, which has had a significant impact on high-resolution imaging (44), optical spin-Hall effect (45), and high-capacity holograms (46), can be further applied to TMSs to refine and optimize the performance of diffusion. Compared with previous sophisticated techniques for broadband phase manipulation (47-50), e.g., artificial intelligence-assisted design (51), the design strategy of utilizing asymmetric backgrounds is more convenient and facilitates largescale fabrication (52) through industrial lithography.

Our work challenges the long-standing human intuition that matte materials cannot be transparent. Despite exhibiting matte appearances, TMSs have retained transparency with almost perfect clarity, far beyond that of commercial AFs. This counterintuitive property blurs the fundamental distinction between transparent materials like windows and matte materials like walls and enables the camouflage functionality for windows and cameras. The matte appearance, distinct from the standard glossy appearance of windows, opens new possibilities in the exterior design of automobile and house windows. It also eliminates the reflective glare caused by glossy surfaces, which is a common form of light pollution (fig. S17). TMSs could conveniently realize large-scale transparent displays with high clarity, full color, and one-way visibility, avoiding the decrease in transparency due to the light scattering from embedded components or impurities in traditional approaches. The potential applications of TMSs cover a broad range of transparent devices, including windows, lenses, and screens.

MATERIALS AND METHODS

The TMS sample has been fabricated by multilayer aligned stepper photolithography on a 4-inch GW with a thickness of 500 µm. First, lithography defined a randomly distributed patch pattern on the wafer with a photoresist. Then, a metallic film with designed thickness is deposited by electron beam evaporation on the patterned wafer, covering both the areas with the photoresist and where the photoresist has been removed. After that, the left photoresist was removed with solvent, leaving only the first layer of metallic patch pattern on the GW. Then, a 90-nm-thick silica layer is deposited by plasma-enhanced chemical vapor deposition as a spacer layer. The process continued with spin coating a photoresist layer, followed by a second lithography process. The second layer of metallic film was deposited, and a lift-off procedure was performed to remove the photoresist, leaving the second layer of the metallic patch pattern. Last, a 70-nm-thick silica layer is deposited to cover the entire sample area.

Supplementary Materials

This PDF file includes: Supplementary Text Figs. S1 to S17 Legends for movies S1 to S3

Other Supplementary Material for this manuscript includes the following: Movies S1 to S3

REFERENCES AND NOTES

- A. V. Kildishev, A. B. Oltasseva, V. M. Shalaev, Planar photonics with metasurfaces. *Science* 339, 1232009 (2013).
- 2. N. Yu, F. Capasso, Flat optics with designer metasurfaces. Nat. Mater. 13, 139–150 (2014).
- W. T. Chen, A. Y. Zhu, F. Capasso, Flat optics with dispersion-engineered metasurfaces. Nat. Rev. Mater. 5, 604–620 (2020).
- N. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, Z. Gaburro, Light propagation with phase discontinuities: Generalized laws of reflection and refraction. *Science* 334, 333–337 (2011).
- X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, Broadband light bending with plasmonic nanoantennas. *Science* 335, 427 (2012).
- S. Sun, Q. He, S. Xiao, Q. Xu, X. Li, L. Zhou, Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves. *Nat. Mater.* 11, 426–431 (2012).
- X. Chen, L. Huang, H. Mühlenbernd, G. Li, B. Bai, Q. Tan, G. Jin, C. Qiu, S. Zhang, T. Zentgraf, Dual-polarity plasmonic metalens for visible light. *Nat. Commun.* 3, 1198 (2012).
- C. Pfeiffer, A. Grbic, Metamaterial Huygens' surfaces: Tailoring wave fronts with reflectionless sheets. *Phys. Rev. Lett.* **110**, 197401 (2013).
- X. Ni, A. V. Kildishev, V. M. Shalaev, Metasurface holograms for visible light. *Nat. Commun.* 4, 3807 (2013).
- L. Huang, X. Chen, H. Mühlenbernd, H. Zhang, S. Chen, B. Bai, Q. Tan, G. Jin, K. Cheah, C. Qiu, J. Li, T. Zentgraf, S. Zhang, Three-dimensional optical holography using a plasmonic metasurface. *Nat. Commun.* 4, 3808 (2013).
- H. Chu, X. Xiong, Y. Gao, J. Luo, H. Jing, C. Li, R. Peng, M. Wang, Y. Lai, Diffuse reflection and reciprocity-protected transmission via a random-flip metasurface. Sci. Adv. 7, j935 (2021).
- T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, Q. Cheng, Coding metamaterials, digital metamaterials and programmable metamaterials. *Light Sci. Appl.* 3, e218 (2014).
- L. Gao, Q. Cheng, J. Yang, S. Ma, J. Zhao, S. Liu, H. Chen, Q. He, W. Jiang, H. Ma, Q. Wen, L. Liang, B. Jin, W. Liu, L. Zhou, J. Yao, P. Wu, T. Cui, Broadband diffusion of terahertz waves by multi-bit coding metasurfaces. *Light Sci. Appl.* 4, e324 (2015).

- C. B. Burckhardt, Use of a random phase mask for the recording of fourier transform holograms of data masks. *Appl. Optics* 9, 695–700 (1970).
- W. Luo, S. Sun, H. Xu, Q. He, L. Zhou, Transmissive ultrathin pancharatnam-berry metasurfaces with nearly 100% efficiency. *Phys. Rev. Appl.* 7, 44033 (2017).
- M. Jia, Z. Wang, H. Li, X. Wang, W. Luo, S. Sun, Y. Zhang, Q. He, L. Zhou, Efficient manipulations of circularly polarized terahertz waves with transmissive metasurfaces. *Phys. Rev. Appl.* 8, 16 (2019).
- H. T. Chen, J. Zhou, J. F. O'Hara, F. Chen, A. K. Azad, A. J. Taylor, Antireflection coating using metamaterials and identification of its mechanism. *Phys. Rev. Lett.* **105**, 73901 (2010).
- C. Pfeiffer, N. K. Emani, A. M. Shaltout, A. Boltasseva, V. M. Shalaev, A. Grbic, Efficient light bending with isotropic metamaterial Huygens' surfaces. *Nano Lett.* 14, 2491–2497 (2014).
- A. H. Dorrah, M. Chen, G. V. Eleftheriades, Bianisotropic Huygens' metasurface for wideband impedance matching between two dielectric media. *IEEE Trans. Antennas Propag.* 66, 4729–4742 (2018).
- K. Im, J. Kang, Q. Park, Universal impedance matching and the perfect transmission of white light. *Nat. Photonics* 12, 143–149 (2018).
- H. Chu, H. Zhang, Y. Zhang, R. Peng, M. Wang, Y. Hao, Y. Lai, Invisible surfaces enabled by the coalescence of anti-reflection and wavefront controllability in ultrathin metasurfaces. *Nat. Commun.* 12, 4523 (2021).
- X. Zheng, J. Lin, Z. Wang, H. Zhou, Q. He, L. Zhou, Manipulating light transmission and absorption via an achromatic reflectionless metasurface. *PhotoniX* 4, 3 (2023).
- J. B. Pendry, P. A. Huidobro, Y. Luo, E. Galiffi, Compacted dimensions and singular plasmonic surfaces. *Science* 358, 915–917 (2017).
- F. Qin, L. Ding, L. Zhang, F. Monticone, C. C. Chum, J. Deng, S. Mei, Y. Li, J. Teng, M. Hong, S. Zhang, A. Alu, C. W. Qiu, Hybrid bilayer plasmonic metasurface efficiently manipulates visible light. *Sci. Adv.* 2, e1501168 (2016).
- K. Lin, C. Wang, H. Tseng, L. Chang, C. Li, C. Wang, Polarization-selective ultra-broadband reflective diffuser as a smart projection screen. *Adv. Photonics* 3, 2200016 (2022).
- S. R. Soomro, H. Urey, Design, fabrication and characterization of transparent retro-reflective screen. *Opt. Express* 24, 24232–24241 (2016).
- C. W. Hsu, B. Zhen, W. Qiu, O. Shapira, B. G. Delacy, J. D. Joannopoulos, M. Soljačić, Transparent displays enabled by resonant nanoparticle scattering. *Nat. Commun.* 5, 3152 (2014).
- Z. Li, Q. Dai, M. Q. Mehmood, G. Hu, B. L. Yanchuk, J. Tao, C. Hao, I. Kim, H. Jeong, G. Zheng, S. Yu, A. Alù, J. Rho, C. Qiu, Full-space cloud of random points with a scrambling metasurface. *Light Sci. Appl.* 7, 63 (2018).
- F. Neubrech, X. Duan, N. Liu, Dynamic plasmonic color generation enabled by functional materials. Sci. Adv. 6, c2709 (2020).
- X. Duan, S. Kamin, N. Liu, Dynamic plasmonic colour display. Nat. Commun. 8, 14606 (2017).
- D. Lin, P. Fan, E. Hasman, M. L. Brongersma, Dielectric gradient metasurface optical elements. *Science* 345, 298–302 (2014).
- M. Decker, I. Staude, M. Falkner, J. Dominguez, D. N. Neshev, I. Brener, T. Pertsch, Y. S. Kivshar, High-efficiency dielectric Huygens' surfaces. *Adv. Opt. Mater.* 3, 813–820 (2015).
- A. Arbabi, Y. Horie, M. Bagheri, A. Faraon, Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission. *Nat. Nanotechnol.* **10**, 937–943 (2015).
- S. S. Kruk, L. Wang, B. Sain, Z. Dong, J. Yang, T. Zentgraf, Y. Kivshar, Asymmetric parametric generation of images with nonlinear dielectric metasurfaces. *Nat. Photonics* 16, 561–565 (2022).
- A. Grosjean, E. Le Baron, Longtime solar performance estimations of low-E glass depending on local atmospheric conditions. *Sol. Energy Mater. Sol. Cells* 240, 111730 (2022).
- X. Ni, Z. J. Wong, M. Mrejen, Y. Wang, X. Zhang, An ultrathin invisibility skin cloak for visible light. Science 349, 1310–1314 (2015).
- P. Sheng, B. van Tiggelen, Introduction to Wave Scattering, Localization and Mesoscopic Phenomena (Taylor & Francis, 2007).

- K. Pichler, M. Kühmayer, J. Böhm, A. Brandstötter, P. Ambichl, U. Kuhl, S. Rotter, Random anti-lasing through coherent perfect absorption in a disordered medium. *Nature* 567, 351–355 (2019).
- R. Schittny, M. Kadic, T. B. U. Ckmann, M. Wegener, Invisibility cloaking in a diffusive light scattering medium. *Science* 345, 427–429 (2014).
- M. Horodynski, M. Kühmayer, C. Ferise, S. Rotter, M. Davy, Anti-reflection structure for perfect transmission through complex media. *Nature* 607, 281–286 (2022).
- H. Cao, A. P. Mosk, S. Rotter, Shaping the propagation of light in complex media. *Nat. Phys.* 18, 994–1007 (2022).
- K. Vynck, R. Pacanowski, A. Agreda, A. Dufay, X. Granier, P. Lalanne, The visual appearances of disordered optical metasurfaces. *Nat. Mater.* 21, 1035–1041 (2022).
- F. Sterl, E. Herkert, S. Both, T. Weiss, H. Giessen, Shaping the color and angular appearance of plasmonic metasurfaces with tailored disorder. ACS Nano 15, 10318–10327 (2021).
- M. Jang, Y. Horie, A. Shibukawa, J. Brake, Y. Liu, S. M. Kamali, A. Arbabi, H. Ruan, A. Faraon, C. Yang, Wavefront shaping with disorder-engineered metasurfaces. *Nat. Photonics* 12, 84–90 (2018).
- E. Maguid, M. Yannai, A. Faerman, I. Yulevich, V. Kleiner, E. Hasman, Disorder-induced optical transition from spin Hall to random Rashba effect. *Science* 358, 1411–1415 (2017).
- B. Xiong, Y. Liu, Y. Xu, L. Deng, C. W. Chen, J. N. Wang, R. Peng, Y. Lai, Y. Liu, M. Wang, Breaking the limitation of polarization multiplexing in optical metasurfaces with engineered noise. *Science* **379**, 294–299 (2023).
- W. T. Chen, A. Y. Zhu, V. Sanjeev, M. Khorasaninejad, Z. Shi, E. Lee, F. Capasso, A broadband achromatic metalens for focusing and imaging in the visible. *Nat. Nanotechnol.* 13, 220–226 (2018).
- S. Wang, P. C. Wu, V. Su, Y. Lai, M. Chen, H. Y. Kuo, B. H. Chen, Y. H. Chen, T. Huang, J. Wang, R. Lin, C. Kuan, T. Li, Z. Wang, S. Zhu, D. P. Tsai, A broadband achromatic metalens in the visible. *Nat. Nanotechnol.* 13, 227–232 (2018).
- M. K. Chen, X. Liu, Y. Wu, J. Zhang, J. Yuan, Z. Zhang, D. P. Tsai, A meta-device for intelligent depth perception. *Adv. Mater.* 35, e2107465 (2023).
- X. Liu, M. K. Chen, C. H. Chu, J. Zhang, B. Leng, T. Yamaguchi, T. Tanaka, D. P. Tsai, Underwater binocular meta-lens. ACS Photonics 10, 2382–2389 (2023).
- M. K. Chen, X. Liu, Y. Sun, D. P. Tsai, Artificial intelligence in meta-optics. *Chem. Rev.* 122, 15356–15413 (2022).
- H. Kang, D. Lee, Y. Yang, D. Kyo Oh, J. Seong, J. Kim, N. Jeon, D. Kang, J. Rho, Emerging low-cost, large-scale photonic platforms with soft lithography and self-assembly. *Photonics Insights* 2, R04 (2023).

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