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Supporting Information

ABSTRACT: Metamaterial Huygens’ surfaces manipulate electromagnetic wavefronts without reflection. A broadband Huygens’ surface that efficiently refracts normally incident light at the telecommunication wavelength of 1.5 μm is reported. The electric and magnetic responses of the surface are independently controlled by cascading three patterned, metallic sheets with a subwavelength overall thickness of 430 nm. The peak efficiency of the device is significantly enhanced by reducing the polarization and reflection losses that are inherent to earlier single-layer designs.

KEYWORDS: Metamaterial, metasurface, Huygens, lens, plasmonics

Metamaterials have received much attention due to their ability to provide extreme control of electromagnetic fields. However, at near-infrared and visible wavelengths, metamaterials have been hampered by fabrication challenges and high loss, significantly limiting their impact.1 This has led to the development of metasurfaces: the two-dimensional equivalent of metamaterials.2,3 Metasurfaces can impart discontinuities on electromagnetic wavefronts, giving them the ability to generate novel lenses for a myriad of nanophotonic applications including optical tweezing, image sensors, and displays.4,5 In contrast, more conventional optics such as dielectric lenses and spatial light modulators are bulky, which limits their integration into nanophotonic systems.6–9 Optical metasurfaces reported to date only manipulate electric polarization currents, which fundamentally limits their maximum efficiency due to polarization and reflection loss.10–12 Efficiencies on the order of 5% are typical in these previous designs. In addition, many of these metasurfaces suffer from low phase coverage or only work for a single polarization.4,13 This limits their ability to tailor an incident wavefront. In fact, the surface equivalence principle dictates that a magnetic response must be present for complete control of an electromagnetic wavefront by a surface.14 This has led to the development of metamaterial Huygens’ surfaces, which use collocated electric and magnetic polarizabilities to realize reflectionless low profile lenses.15

At microwave frequencies, generating a magnetic response is straightforward using split-ring-resonators.16 However, this approach has its challenges at optical frequencies.17 Alternatively, cascading metallic layers upon one another can also generate a magnetic response due to circulating electric currents.18–20 This has led to the well-known fishnet structure, which provides both an electric and magnetic response to realize a negative index of refraction.20 However, bulk metamaterials such as the fishnet structure generally exhibit relatively low phase shifts per unit cell as light propagates through them. In contrast, the inhomogeneous metasurfaces developed here exhibit large phase shifts across a subwavelength thickness. To date, optical metasurfaces designs that incorporate a magnetic response have been proposed, but no experiments have been performed.21–23

In this paper, the first experimental metamaterial Huygens’ surface at optical frequencies is demonstrated. An isotropic unit cell consisting of cascaded sheet admittances (patterned metallic sheets) is proposed, and a straightforward design procedure is detailed. The magnetic response is generated by circulating, longitudinal electric currents supported by the cascaded metallic sheets. Simulations demonstrate that the proposed structure achieves large phase coverage while maintaining high transmission. A proof-of-concept metamaterial Huygens’ surface is designed to refract normally incident light to an angle of 35° from normal at the design wavelength of 1.5 μm (see Figure 1). Simulations show that the surface exhibits a high efficiency of 30%, and an order of magnitude improvement in the extinction ratio over previously reported metasurfaces. The metamaterial Huygens’ surface is then fabricated by sequentially patterning three gold (Au) sheets.

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using standard electron beam lithography and liftoff processes, while employing SU-8 dielectric spacers between them. Measurements are performed using a spectroscopic ellipsometer, and the performance significantly exceeds previously reported metasurfaces. In addition, this work presents the first experimental demonstration of an isotropic metasurface that is capable of providing wavefront control for arbitrarily polarized light.

To begin, a unit cell is developed that exhibits high transmittance and large phase coverage. Consider a single, patterned metallic sheet. Provided its periodicity is subwavelength, any pattern can be represented as a well-defined, sheet admittance boundary condition with \( Y_s \rightarrow \vec{E}_t = \vec{J}_s \), where \( \vec{J}_s \) is the surface current on the metallic sheet, and \( \vec{E}_t \) is the electric field tangential to the sheet. The sheet admittance \( Y_s \) is a scalar quantity since the patterns considered here are isotropic. The imaginary part of the sheet admittance can be controlled by changing the pattern on the metallic sheet. The real part of the sheet admittance represents metallic losses. Previous metasurfaces that only used a single sheet admittance to tailor light suffered from significant reflection loss, since electric currents are bidirectional radiators.\(^{22}\) However, cascading multiple sheet admittances upon one another generates an additional magnetic response because the cascaded sheets can support longitudinal circulating electric currents.\(^{24}\) With collocated electric and magnetic currents, each unit cell of the metasurface generates a unidirectional radiated field to realize a reflectionless Huygens’ source.\(^{25}\) Metasurfaces composed of reflectionless unit cells have come to be known as metamaterial Huygens’ surfaces since they manipulate electromagnetic wavefronts in the same manner Christiaan Huygens analyzed wavefront propagation.\(^{26}\)

It has been shown that at least three sheet admittances (see Figure 2a) are required to obtain complete phase control while maintaining high transmittance.\(^{22,24}\) To realize the sheet admittances, the geometry shown in Figure 2b is chosen.\(^{23}\) The unit cell is isotropic and consists of three 30 nm thick Au sheets patterned on a SiO\(_2\) substrate. The Au sheets are separated by 200 nm thick SU-8 dielectric spacers to realize an overall thickness of 430 nm (\( \lambda_0/3.5 \)). It should be emphasized that it is more appropriate to model this structure as a two-dimensional metasurface rather than a bulk metamaterial because it exhibits large phase shifts across a subwavelength
overall thickness.\textsuperscript{27} However, this is somewhat of an approximation due to the notable thickness. The SiO\textsubscript{2} substrate is modeled as a lossless, infinite half space with an index of refraction of \(n_{\text{SiO}_2} = 1.45\). The index of refraction of the SU-8 is \(n_{\text{SU-8}} = 1.57\). The relative permittivity of Au is described by the Drude model \(\varepsilon_{\text{Au}} = \varepsilon_\infty - \omega_p^2/\omega^2\) (see Supporting Information Figure S5). Each of the three sheet admittances can be modeled as a parallel LC circuit (see Supporting Information). In Figure 2d, the transmittance, transmittance and transmitted phase, and reluctance are plotted as a function of the outer sheet admittances (\(Y_{s1} = Y_{s3}\)). From the analytic model that includes losses (see Supporting Information Figure S4), it was found that enforcing the condition \(Y_{s1} = Y_{s3} = Y_{s2}/1.5\), provides a good trade-off between maximizing transmission and phase coverage, while minimizing loss and reflection. It should be noted that transmittance and phase coverage increase with reduced metallic loss.

A beam-refracting metamaterial Huygens’ surface is then realized by stipulating a linear phase progression across the surface.\textsuperscript{21} This example was chosen because its performance is straightforward to characterize in experiment.\textsuperscript{10} In future work, elaborate phase profiles can be stipulated to achieve more exotic wavefronts. Figure 3a shows a section of the designed Huygens’ surface that refracts normally incident light to an angle of 35.2° at a wavelength of 1.5 \(\mu\)m. Further design details and exact dimensions are supplied in Table S1 of the Supporting Information. Each supercell contains five unit cells whose simulated performance is shown in Figure 2d. Simulations were performed using the full-wave solver, CST Microwave Studio. It can be seen that there is a good agreement between the simulated data points and the analytic model. Figure 3b,c shows the wavelength dependence of the transmittance and transmitted phase shift of the five unit cells. It should be noted that the achievable phase coverage was reduced due to Au loss. If the minimum transmittance of each unit cell is stipulated to be 0.15, the achievable phase coverage is limited to 260° rather than the ideal 360°. In addition, the transmittances of each unit cell are not identical. Both the reduced phase coverage and nonidentical transmittance creates aberration in the transmitted field. For periodic structures such as beam-refracting surfaces, these aberrations can be easily quantified using well-known Floquet theory.\textsuperscript{31} In short, the transmitted field can be decomposed into propagating Floquet harmonics. For example, transmission into the \(n = 0\) harmonic corresponds to light that is transmitted in the normal direction (\(\phi_t = 0°\)), whereas the \(n = 1\) harmonic corresponds to the refracted direction (\(\phi_t = 35.2°\)). The goal here is to maximize the power in the \(n = 1\) harmonic, while minimizing the power in other harmonics.

The simulated performance of the designed metamaterial Huygens’ surface is shown in Figure 4. Figure 4a shows a time snapshot of the steady-state electric field when a plane wave is normally incident from the SiO\textsubscript{2} substrate at a wavelength of 1.5 \(\mu\)m. It can be seen that the Huygens’ surface efficiently refracts the incident light to \(\phi_t = 35.2°\). The ripple in the field is from power that is scattered into undesired Floquet harmonics. In Figure 4b, the transmittance is plotted as a function of the refracted angle and wavelength. This shows the angular dependence of the various Floquet harmonics. It can be seen that the majority of the transmitted power is in the \(n = 1\) harmonic. As the operating wavelength varies from 1.2 to 2 \(\mu\)m, the refracted angle of this harmonic scans from \(\phi_t = 27.5°\) to \(\phi_t = 50.3°\). The power that is refracted is better quantified in Figure 4c, which plots the transmittance and reflectance versus wavelength. In this plot, the s- and p-refracted curves correspond to the transmittance of the two polarizations into the \(n = 1\) Floquet harmonic. Also shown are two of the loss mechanisms of the Huygens’ surface, which include reflection...
Reflected denotes the total transmittance that is not in the polarized light. At the design wavelength of 1.5 \( \mu \text{m} \), the transmittance of the \( n = 1 \) Floquet harmonic (\( \phi = 35.2^\circ \)) is much larger than the \( n = -1 \) (\( \phi = -35.2^\circ \)) and \( n = 0 \) (\( \phi = 0^\circ \)) harmonics. (c) Transmittance and reflectance versus wavelength for both polarizations. s- and p-refracted denotes the transmittance of light that is refracted into the \( n = 1 \) harmonic for the s- and p-polarizations, respectively. s- and p-reflected denotes the total reflectance. s- and p-undesired transmittance denotes the total transmittance that is not in the \( n = 1 \) harmonic. Virtually no power (\(-60 \text{ dB}\)) is scattered into cross-polarized light.

Figure 4. Simulated beam-refracting metamaterial Huygens’ surface. (a) Time snapshot of the steady-state, \( y \)-polarized electric field when a plane wave is normally incident from the bottom at a wavelength of 1.5 \( \mu \text{m} \). The incident electric field has an amplitude of 1 V/m. (b) Transmittance as a function of wavelength and refracted angle for \( s \)-polarized light. At the design wavelength of 1.5 \( \mu \text{m} \), the transmittance of the \( n = 1 \) Floquet harmonic (\( \phi = 35.2^\circ \)) is much larger than the \( n = -1 \) (\( \phi = -35.2^\circ \)) and \( n = 0 \) (\( \phi = 0^\circ \)) harmonics. (c) Transmittance and reflectance versus wavelength for both polarizations. s- and p-refracted denotes the transmittance of light that is refracted into the \( n = 1 \) harmonic for the s- and p-polarizations, respectively. s- and p-reflected denotes the total reflectance. s- and p-undesired transmittance denotes the total transmittance that is not in the \( n = 1 \) harmonic. Virtually no power (\(-60 \text{ dB}\)) is scattered into cross-polarized light.

and transmission into undesired Floquet harmonics (for example, \( n = -2, n = -1, n = 0, n = 2 \) harmonics). Virtually no power (\(-60 \text{ dB}\)) is scattered into cross-polarized light. The power that is lost due to Au absorption is \( 1 - (\text{refracted}) - (\text{transmitted undesired}) \), which is approximately 60% at the wavelength of 1.5 \( \mu \text{m} \). The metamaterial Huygens’ surface is isotropic since the s- and p-polarized curves coincide over much of the operating wavelengths. The difference between the two polarizations is most likely due to the coupling between spatially varying unit cells since this is not accounted for in the analytic model. It should also be noted that the response is broadband. The refracted field maintains a transmittance that is greater than half its peak value over a bandwidth of 1.33 to 1.95 \( \mu \text{m} \) (38%) for both polarizations. Two important performance metrics are the peak efficiency (transmittance in the refracted direction) and extinction ratio (ratio of the refracted transmittance to normal transmittance). Simulations demonstrate a peak efficiency and extinction ratio of 32.6% and 11.6 dB, respectively, for \( s \)-polarized light and 30.4% and 10.3 dB, respectively, for \( p \)-polarized light.

The fabrication process is shown in Figure 5a. The design is fabricated on a 500 \( \mu \text{m} \) thick SiO\(_2\) substrate. First, the bottom sheet admittance (\( Y_{33} \)) is fabricated by patterning a 2 nm Ti adhesion layer and 28 nm Au layer using standard electron beam lithography and liftoff. Next, a 200 nm thick, SU-8 dielectric layer is spin coated onto the wafer, which naturally planarizes the surface for the following layer (measured roughness <5 nm). This process is repeated until three Au layers are patterned to achieve the unit cell shown in Figure 2b. The patterned area is 500 \( \mu \text{m} \times 500 \mu \text{m} \). Scanning electron microscope (SEM) pictures of the fabricated metamaterial Huygens’ surface are shown in Figure 5 b,c.

The fabricated sample is measured using the transmission module of an ellipsometer (V-VASE, J. A. Woollam Co.). A monochromator scans the wavelength of a normally incident light source, and the transmitted power is measured at each refracted angle. Unlike in the simulations of Figure 4, the incident light in measurements propagates in the +\( z \) direction, which simplifies the alignment procedure. This has minimal effect on the transmittance but does increase the reflectance. Simulations suggest that when the incident light propagates in the +\( z \) direction, the refracted transmittance is at most 3% different from when the incident light propagates in the \(-z \) direction. The measured transmittance in the refracted direction and normal direction are shown in Figure 6a,b for s-polarized and p-polarized light, respectively. From SEM pictures, the dimensions of the fabricated surface are off by \( \sim 30 \) nm, which causes the discrepancy between the measured performance and the simulations presented in Figure 4. To demonstrate that the difference between the fabricated and designed dimensions is the cause of error between measurement and simulation, the fabricated dimensions are also simulated, which is shown in Figure 6. It can be seen that the resimulated and measured performance agree for the refracted power. However, the power that is transmitted into the normal direction is still \( \sim 5\% \) larger in measurement than simulation, but the trends are the same. The difference between simulation and measurement can be attributed to additional fabrication and measurement errors. If the fabricated sample is not centered on the incident beam for the ellipsometry measurements, a small percentage of the power is not captured by the metamaterial Huygens’ surface. In addition, there is some uncertainty when modeling the surface roughness and loss of the Au, which introduces error into the simulations. Despite the various sources of error, these measurements achieve a peak efficiency and extinction ratio of 19.9% and 2.93 dB.
dB, respectively, for s-polarized light and 18.0% and 3.05 dB, respectively, for p-polarized light. This is an improvement of a factor of 3 in efficiency and a factor of 4 in extinction ratio over the state of the art. In addition, the response is isotropic, which enables control of an arbitrary incident polarization.

However, it should be noted that this increased performance does come at the expense of an increased thickness and a multilayer fabrication process.

A low profile metamaterial Huygens’ surface is experimentally demonstrated for the first time at optical wavelengths. The efficiency is improved over previous metasurfaces by adding a magnetic response, which reduces reflection and polarization loss. In addition, the surface exhibits an isotropic response and large extinction ratio. In future work, the fabrication process can be further optimized so that the fabricated dimensions are closer to the design. In addition, large area soft lithography processes, such as nanoimprint lithography, can be used to dramatically reduce the cost of metasurfaces. This work can find numerous applications such as low profile lenses, computer-generated-holography, nondestructive evaluation, and stealth technologies. In addition, novel types of beams such as Airy beams, Bessel beams, and vortex beams can be generated with high efficiency. By using anisotropic sheet admittances, polarization control such as linear-to-circular polarization conversion could also be achieved.
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■ ASSOCIATED CONTENT

1 Supporting Information
Additional information and figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interest.

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■ REFERENCES

(26) Huygens, C. Traité de la Lumière; Pieter van der Aa: Leyden, 1690.
