Science AAAS

Planar Photonics with Metasurfaces

Alexander V. Kildishev *et al.*

Science **339**, (2013);
DOI: 10.1126/science.1232009

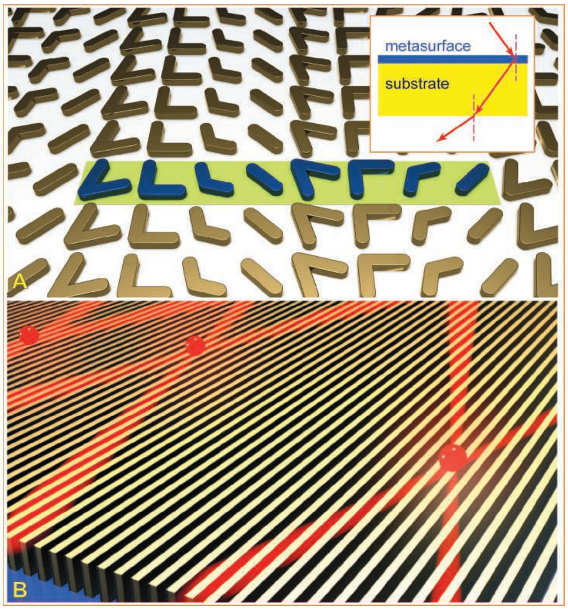
Planar Photonics with Metasurfaces

Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaev*

Background: Metamaterials (MMs) are smartly engineered structures with rationally designed, nanostructured building blocks that allow us to build devices with distinct responses to light, acoustic waves, and heat flows that are not attainable with naturally available materials.

Advances: The latest developments have shown that optical metasurfaces comprising a class of optical MMs with a reduced dimensionality can exhibit exceptional abilities for controlling the flow of light; achieve the anomalously large photonic density of states; and, similar to their bulk analog, provide superresolution imaging. Such a planar photonics technology is expected to facilitate new physics and enhanced functionality for devices that are distinctly different from those observed in their three-dimensional MM counterparts. As a result, this technology will enable new applications in imaging, sensing, data storage, quantum information processing, and light harvesting.

Outlook: The recent progress in optical metasurfaces can address the major issues hampering the full-scale development of MM technology, such as high loss, cost-ineffective fabrication, and challenging integration. The studies of new, low-loss, tunable plasmonic materials—such as transparent conducting oxides and intermetallics—that can be used as building blocks for metasurfaces will complement the exploration of smart designs and advanced switching capabilities. This progress in metasurface design and realization will lead to novel functionalities and improved performance and may result in the development of new types of ultrathin metasurface designs with unparalleled properties, including increased operational bandwidths and reduced losses. These new designs would also be compatible with planar, low-cost manufacturing. In turn, these advances will lead to ultrathin devices with unprecedented functionalities, ranging from dynamic spatial light modulation to pulse shaping and from subwavelength imaging or sensing to novel quantum optics devices.



Plasmonic metasurfaces at work. (A) A nanoantenna-array plasmonic metasurface used to experimentally demonstrate negative refraction (inset) and reflection angles. The unit cell of a representative metasurface (blue) consists of eight gold V-shaped antennas repeated periodically. **(B)** A hyperbolic metasurface enhancing the radiation rate of quantum emitters. The metasurface is arranged of a thin subwavelength metallic grating deposited on a dielectric substrate.

School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA.

*Corresponding author. E-mail: shalaev@purdue.edu

READ THE FULL ARTICLE ONLINE
http://dx.doi.org/10.1126/science.1232009

Cite this article as A. V. Kildishev *et al.*, *Science* **339**, 1232009 (2013). DOI: 10.1126/science.1232009

ARTICLE OUTLINE

RELATED ITEMS IN *SCIENCE*

J. B. Pendry, D. Schurig, D. R. Smith, *Science* **312**, 1780 (2006). DOI: 10.1126/science.1125907

Z. Liu, H. Lee, Y. Xiong, C. Sun, X. Zhang, *Science* **315**, 1686 (2007). DOI: 10.1126/science.1137368

N. I. Zheludev, *Science* **328**, 582 (2010). DOI: 10.1126/science.1186756

C. M. Soukoulis, M. Wegener, *Science* **330**, 1633 (2010). DOI: 10.1126/science.1198858

A. Boltasseva, H. A. Atwater, *Science* **331**, 290 (2011). DOI: 10.1126/science.1198258

N. Engheta, *Science* **334**, 317 (2011). DOI: 10.1126/science.1213278

N. Yu *et al.*, *Science* **334**, 333 (2011). DOI: 10.1126/science.1210713

X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, *Science* **335**, 427 (2012). DOI: 10.1126/science.1214686

O. Hess, K. L. Tsakmakidis, *Science* **339**, 654 (2013). DOI: 10.1126/science.1231254

BACKGROUND READING

New physics of optical MMs expands the functionality of modern photonic devices. Reduction in thickness of the bulk MMs, along with the use of alternative plasmonic materials, gives a new class of advanced, ultrathin optical elements: optical metasurfaces, which exhibit extended or completely new capabilities.

N. I. Zheludev, Y. S. Kivshar, *Nat. Mater*. **11**, 917 (2012). DOI: 10.1038/nmat3431

G. V. Naik, J. Liu, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 8834 (2012). DOI: 10.1073/pnas.1121517109

F. Aieta *et al*., *Nano Lett*. **12**, 1702 (2012). DOI: 10.1021/nl300204s

J. Kim *et al*., *Opt. Express* **20**, 8100 (2012). DOI: 10.1364/OE.20.008100

Planar Photonics with Metasurfaces

Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaev*

Metamaterials, or engineered materials with rationally designed, subwavelength-scale building blocks, allow us to control the behavior of physical fields in optical, microwave, radio, acoustic, heat transfer, and other applications with flexibility and performance that are unattainable with naturally available materials. In turn, metasurfaces—planar, ultrathin metamaterials—extend these capabilities even further. Optical metasurfaces offer the fascinating possibility of controlling light with surface-confined, flat components. In the planar photonics concept, it is the reduced dimensionality of the optical metasurfaces that enables new physics and, therefore, leads to functionalities and applications that are distinctly different from those achievable with bulk, multilayer metamaterials. Here, we review the progress in developing optical metasurfaces that has occurred over the past few years with an eye toward the promising future directions in the field.

With the recent advances in micro- and nanofabrication methods, one can now control the flow of light in a way that was not possible before. Metamaterials (MMs) are engineered structures with rationally designed, nanostructured building blocks ("meta-atoms"). MMs allow us to build devices with responses to light, acoustic waves, and heat flows that are unattainable with naturally available materials (*1*–*3*). In the artificial patterns of meta-atoms, the propagation of electromagnetic energy can be defined by the spatial and spectral dispersions of the effective dielectric and magnetic properties. These synthetic structures offer the distinct potential to guide and control the flow of electromagnetic energy in an engineered optical space (*2*) and open the door to a number of applications that were previously considered impossible (*4*). We are no longer constrained by the electromagnetic response of natural materials and their chemical compounds. Instead, we can tailor the shape and size of the structural units of a MM, tune the composition and morphology of the nanostructure, and achieve new, desired functionalities. The extraordinary properties of optical MMs and transformation optics (TO) devices (*2*), which were conceived by MMs, enable a negative refractive index, imaging with the nanometer-scale resolution, invisibility cloaks, efficient light concentrators, nano-optics and quantum information applications (*1*–*4*).

Optical metasurfaces comprise a class of optical MMs with a reduced dimensionality that demonstrate exceptional abilities for controlling the flow of light beyond that offered by conventional, planar interfaces between two natural materials (*5*). Such two-dimensional (2D) and quasi-2D MMs provide us with the distinct possibility to fully control light with planar (or nearly planar) MM elements and, thus, to realize "planar photonics." Metasurfaces enable new physics and phenomena that are distinctly different from those observed in their 3D counterparts. Moreover, they are compatible with on-chip nanophotonic devices, which is of critical importance for future applications in opto-electronics, ultrafast information technologies, microscopy, imaging, and sensing.

A metasurface structured on the subwavelength scale in the lateral directions can be deterministic (i.e., periodic and aperiodic) or random. In practice, such a metasurface is represented by a patterned metal-dielectric layer that is very thin compared with the wavelength of the incident light and is typically deposited on a supporting substrate. The functionality of a device based on such a metasurface depends directly on the effective, surface-confined, optical dispersion. Effective optical properties, along with nonconventional far-field responses of ultrathin metasurfaces, for example, have been found to deviate from classical reflection and refraction laws (*5*, *6*). Hence, the responses of metasurfaces cannot be inferred from the experimental responses for bulk materials. To design reliable flat photonic devices, a fundamental understanding of the extraordinary properties, as a function of the lateral dimensional features and the structural ordering, is required. There is a critical need to develop innovative theoretical, experimental, and fabrication approaches to unleash the power of functional optical metasurfaces.

In a long-wavelength regime (from radio to terahertz waves), surface-confined metallic antenna arrays, or "metafilms" (*7*–*9*), containing multiple antenna elements have already been successfully used for communication applications (*10*–*12*) or as highly confined cavity resonators (*13*, *14*). Similar to optical metasurfaces, the antenna elements in such "reflectarrays" (*10*) and "transmitarrays" (*12*) also act as phase-controlling resonators for manipulating the direction in which radio or microwave signals are received or broadcast. Nevertheless, the desired phase shifts in the reflect- and transmitarrays are obtained with the dimensions of resonant elements and array periods of a magnitude comparable in size to the incident or transmitted free-space wavelength (*15*).

The importance and power of planar photonics was demonstrated earlier for the specially designed case of planar chiral elements (*16*–*19*). The recently discovered generalized Snell's law suggests a way toward ultimate control of light propagation (*5*). As demonstrated by Yu *et al.* (*5*), special nanoantenna-array metasurfaces create phase discontinuities for light propagating through the interfaces and drastically change the flow of reflected and refracted light, as initially demonstrated for the mid-infrared (mid-IR) wavelength of 8 μm (*5*). This phenomenon has recently been extended to the near-IR wavelength region (*6*), where it was also shown that the effect is robust and broadband. With these new approaches, metasurfaces could be used to fully control all light parameters, including frequency, phase, polarization, momentum, and angular momentum (*20*–*23*). Metasurface-based optical vortex plates (*21*), aberration-free and ultrathin flat lenses, and axicons at telecommunication wavelengths (*24*) have recently been demonstrated. Ni *et al*. also reported that extremely thin (30 nm) and very small (2 μm in radius) metalenses based on Babinet complementary nanoantennas (V-shaped slots in a metal sheet) can be used for the extra-strong focusing of light (with a focal length as short as 2.5 μm) in the visible wavelength range (*25*). In addition, ultrathin terahertz planar lenses have also been proposed (*26*).

Another recent demonstration showed that 3D effects on light propagation can be obtained without the need for complex inclusions in bulk MMs. Instead, planarized, broadband, bianisotropic MMs consisting of stacked nanorod arrays can be used (*27*). These nanorod arrays contain a tailored rotational twist and were shown to constitute an ultrathin, broadband circular polarizer that can be directly integrated within nanophotonic systems (*27*). Plasmonic metasurfaces have also been proposed and realized as quarter-wave plates (*28*, *29*). Metasurfaces can be used to effectively couple propagating waves to surface waves (*30*), which could be of great importance for on-chip nanophotonic applications. Kang *et al*. have also shown that thin, U-shaped aperture antennas can be used to completely convert circularly polarized light into its cross-polarized counterpart (*31*). As shown by Shu *et al*. (*32*), transformation media can generate optical beams with desirable orbital angular momenta (OAM) [see also (*33*)]. Simon *et al*. have reported that specially engineered metasurface-based OAM states can be used also for high-efficiency quantum cryptography and a new quantum-key distribution protocol, exploiting, for example, the recursive properties of the Fibonacci sequence (*34*). Finally, it has been shown that so called fishnet and multilayer MM structures can be used for

School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA.

*To whom correspondence should be addressed. E-mail: shalaev@purdue.edu

computer-generated holograms (35, 36). Conventionally, phase holograms are made by changing either the thickness or the refractive index of a material. In contrast, metasurfaces can create ultrathin holograms that rely on subwavelength-sized antennas to modulate the phase appropriately and create the hologram image.

We note that the control of the phase with metasurfaces can be related, in some cases, to the fundamental physics associated with the Pancharatnam-Berry phase. This geometrical phase appears when the light polarization follows a geodesic triangle on the Poincaré sphere (37, 38). The phase difference between the initial and final states differs in this case by an amount representing half of the solid angle encompassing by the triangle. It has been demonstrated that continuous, space-variant, subwavelength gratings can result in this phase change, which is not due to optical path differences but rather stems from local changes in polarization, representing the geometrical space-domain Pancharatnam-Berry phase [see, for example, (39)]. The subwavelength, periodic structure in this case behaves as a uniaxial crystal. By controlling the local orientation of such a grating, one can form space-variant wave plates. Based on these computer-generated, space-variant, subwavelength dielectric gratings, a family of Pancharatnam-Berry phase optical elements has been demonstrated; this family includes blazed diffraction gratings and polarization-dependent focusing lenses (39), image-encrypting devices (40), vectorial vortices, and spiral phase elements producing helical beams with different topological charges (41, 42), as well as near- and mid-IR holograms employing circularly polarized illumination (43). For example, in the design of the experiments by Hasman *et al.* and Niv *et al.* (39, 42), for incident light with a wavelength of 10.6 μm, the typical depth and period of a designed GaAs dielectric grating structure were ~2 μm each. It was also shown that when plasmons are involved, one can develop an important quantum weak measurement tool (44) and observe various fundamental phenomena, such as the plasmonic Aharonov-Bohm effect and the optical spin Hall effect (45, 46).

To advance the emerging metasurface technology further and enable real-life applications for metasurfaces, there is a critical need to develop a new material platform that provides performance enhancements and new functionalities combined with manufacturing and integration capabilities. To enable the large-scale fabrication and chip integration of metasurfaces, customizable, cost-effective, and semiconductor-compatible materials are required (47). Metasurfaces that incorporate such materials can contribute to a new class of hybrid, chip-scale devices (48) that are expected to revolutionize nanophotonic and optoelectronic circuitry through smart integration of multiple functions in the metallic, dielectric, and semiconductor building blocks. Due to their 2D nature that is advantageous for wafer-scale processing and complex integration, metasurfaces hold great promise to win the race for the most technologically important research among artificially structured materials. We will focus on three areas that we believe are important for the current and future developments of the field: (i) nanoantenna-based metasurfaces, (ii) hyperbolic metasurfaces (HMSs), and (iii) the use of new material platforms for metasurfaces, enabling a generation of switchable devices that could be integrated with the existing semiconductor technology into complex, multifunctional systems.

Nanoantenna-Array Metasurfaces

By engineering a phase discontinuity along an interface, one can fully steer light and accomplish unparalleled control of anomalous reflection and refraction described by the generalized Snell's law (5)

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \lambda_0\nabla\Phi/2\pi \quad (1)$$

$$\sin(\theta_r) - \sin(\theta_i) = n_i^{-1}\lambda_0\nabla\Phi/2\pi \quad (2)$$

where θ_t, θ_i, and θ_r are the angles of refraction, incidence, and reflection, respectively; n_t and n_i are the refractive indices of the two media at the transmission and incident side, respectively, and λ_0 is the free-space wavelength. These expressions indicate that a gradient in a phase discontinuity, $\nabla\Phi$, along an interface can modify the direction of the rays refracted and reflected by the device, and this can be achieved in a very thin layer. Note that $\nabla\Phi$ is essentially an additional momentum contribution that is introduced by coupling to the nanoantennas (NAs) and breaking the symmetry at the interface; hence, the light wave bends accordingly to conserve the momentum.

The degree of light control is illustrated in Fig. 1. Metasurface functionalities are combined with low losses due to the fact that they are ultrathin. This could lead to a variety of devices enabling extraordinary light modulation and control.

Metasurfaces with symmetry-breaking V-shaped nanoantennas create abrupt phase shifts from 0 to 2π in cross-polarized light and, thus, can be used for a number of planar optical elements. For example, to achieve the lensing functionality, the NAs can be arranged in concentric rings (24, 25). Along with their different shapes, the NAs can be distributed in such a way that the abrupt phase shifts cause the wave propagating through the interface to experience a fully constructive interference at a distance *f*. Therefore, the outgoing cross-polarized light is focused at a focal length *f* (24, 25). Such ultrathin metalenses can be designed to generate, for example, nondiffracting Bessel beams (24), which are extremely important for laser machining, high-precision position alignment, and sensing. By using Babinet-complementary NAs, one can significantly increase the signal-to-noise ratio, which is the ratio of the cross-polarized light that experiences the anomalous refraction to the transmitted light with the original polarization (25).

One of most interesting applications for metasurfaces could be related to ultrathin, deeply subwavelength spatial light modulators (SLMs). It is important to note that such SLMs can also provide ultrafast, dynamically controlled responses.

Metasurfaces can also be used as broadband mid-IR chemical sensors. The mid-IR range is an important part of the spectrum, especially for

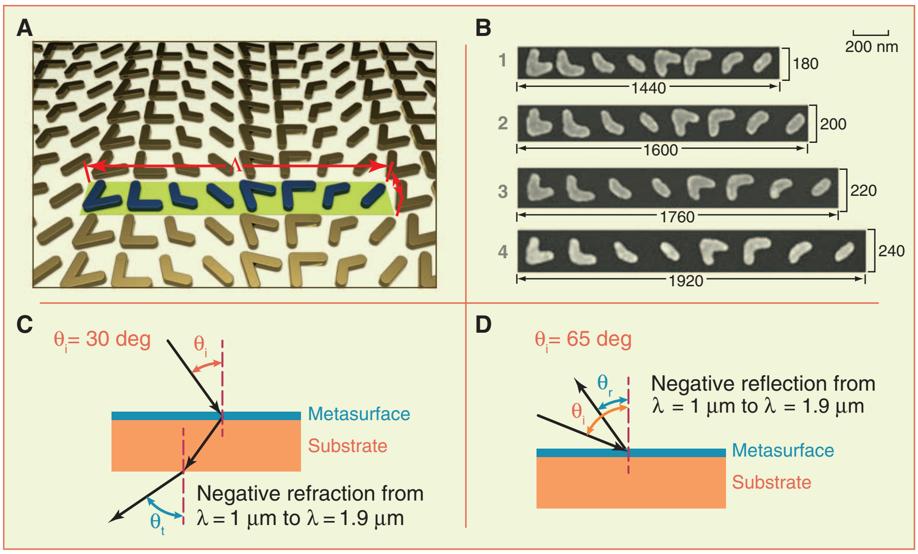


Fig. 1. Nanoantenna-array metasurfaces. (**A**) Schematic view of a representative nanoantenna array. The unit cell of the plasmonic interface (blue) consists of eight gold V-shaped antennas with 40-nm arm width and 30-nm thickness, repeated with a periodicity of Λ in the *x* direction and Λ/8 in the *y* direction. The phase delay for cross-polarized light increases along the *x* axis from right to left. (**B**) Scanning electron microscope images of the unit cells of four antenna arrays with different periods fabricated on a single silicon wafer. (**C** and **D**) Negative refraction (θ_t) (C) and reflection (θ_r) (D) angles are obtained experimentally for incident cross-polarized light with 30° and 65° incidence angles (θ_i), respectively, for the range of near-IR wavelengths (λ) from 1.0 to 1.9 μm (6).

chemical sensing, because many chemicals exhibit signature absorption spectra in the mid-IR. It is well known that plasmonic structures with their local-field enhancement can dramatically increase sensitivity and, thus, can be used for efficient sensing. With metasurfaces, one can further increase the sensitivity. Unlike conventional plasmonic structures, which translate the change in the local environment into the intensity of the detected light, metasurfaces can transform the local environmental changes into a shift in the angle of the anomalous reflection and refraction ($\Delta\theta_r$, and $\Delta\theta_t$, respectively) as depicted in Fig. 2A. The detection of angular shifts can be substantially more sensitive than the detection of small intensity changes. Thus, metasurfaces could be an efficient way to produce ultrasensitive chemical sensors in the mid-IR.

Because metasurfaces can precisely control the phase of the incident light at the nanoscale, they can also be used as building blocks for metastructures with extremely large values of refractive index in the optical range. Such materials with an extra-large refractive index could find very important applications in nanophotonics, super-resolution imaging, and sensing devices. Access to extreme refractive index values that are unattainable with natural materials can be achieved by using the large phase changes over the deeply subwavelength scale provided by a single layer of a NA-based metasurface. With two or more layers of such metasurfaces, one can slow down the light inside the layers by creating additional phase shifts in the propagation direction. Figure 2B illustrates how a multilayer of metasurfaces can operate as a MM with an extra-large refractive index. The right panel of Fig. 2B illustrates the phase change accumulated by a beam of light propagating through a normal homogenous material (the green line) and through a MM consisting of several metasurfaces (the red curve). The slope of each curve indicates the effective refractive index. Because of the abrupt phase changes due to metasurfaces, the beam in the MM can accumulate phase much faster than in normal materials; hence, the MM provides a much larger effective refractive index than in normal materials.

In addition to the control of incident light, metasurfaces can also control and manipulate surface electromagnetic waves. Applications can be realized by designing metasurfaces that support and transform surface waves. For example, cloaking of 3D objects using bulk MMs can be extended to surface structures that cloak surface discontinuities from detection via propagating surface waves (e.g., surface plasmon polaritons). As mentioned previously, metasurfaces allow one to very effectively couple propagating waves to surface waves (*30*). One can apply the transformation optics approach to control the propagation of surface-confined waves with metasurfaces. This extends the previously proposed TO approach for the surface plasmon waves (*49*) to the generalized TO concept for waves supported by metasurfaces.

To advance the proposed functionalities further, it is important to add switching and modulation capabilities to metasurface devices. Switchable metasurfaces could be extremely important for applications involving dynamic beam steering. One can employ phase-changing materials such as chalcogenide glass, transition-metal oxides (e.g., vanadium oxide), and liquid crystals as possible candidates for switching. By precisely controlling the phase change acquired by the beam passing through a metasurface, one can also develop an approach for advanced pulse shaping. Dynamically controlled pulse shaping can be enabled by combining ultrathin metasurfaces with phase-changing and nonlinear dielectrics.

Hyperbolic Metasurfaces

Highly anisotropic hyperbolic metamaterials (HMMs), which are usually made of alternating metal and dielectric layers or using metal wires embedded in a dielectric host, are metallic in one direction and dielectric in the other directions (Fig. 3) (*50–57*). In HMMs, light encounters extreme anisotropy, causing its dispersion to become hyperbolic. This leads to dramatic changes in the light's behavior. For example, HMMs enable many exotic applications for nanoscale imaging and efficient light concentration (*50–52*, *58*, *59*). Additionally, HMMs can enhance the density of states for photons within a broad spectral range (*53–55*, *60*, *61*). The radiative decay rate for light emitters is proportional to the photonic density of states (PDOS); thus, the radiative decay can be efficiently enhanced in HMMs. This recent discovery of a broad-band singularity in the PDOS for HMMs (*61*) could revolutionize PDOS engineering, enabling light sources with dramatically increased photon extraction and, ultimately, leading to nonresonant single-photon sources, which could be used, for example, for quantum communication protocols and other quantum information applications (*60*).

However, bulk HMMs usually exhibit high loss. Moreover, it is difficult to place emitters inside 3D HMMs to efficiently use the high PDOS. Thus, it is important to develop quasi-2D HMSs that could offer important advantages over their 3D counterparts because such HMSs would be chip-compatible and would typically have small losses that are relatively easy to compensate. Planar and ultrathin HMSs also offer straightforward device fabrication and integration. Complementing the distinct properties of the NA-based metasurfaces considered above, HMSs would also provide broadband control over the PDOS.

One of the interesting surface phenomena that holds promise for developing efficient HMSs with a number of applications in nano-optics and imaging is a Dyakonov surface wave. Dyakonov plasmon surface waves occur at the interface between two media, at least one of which is

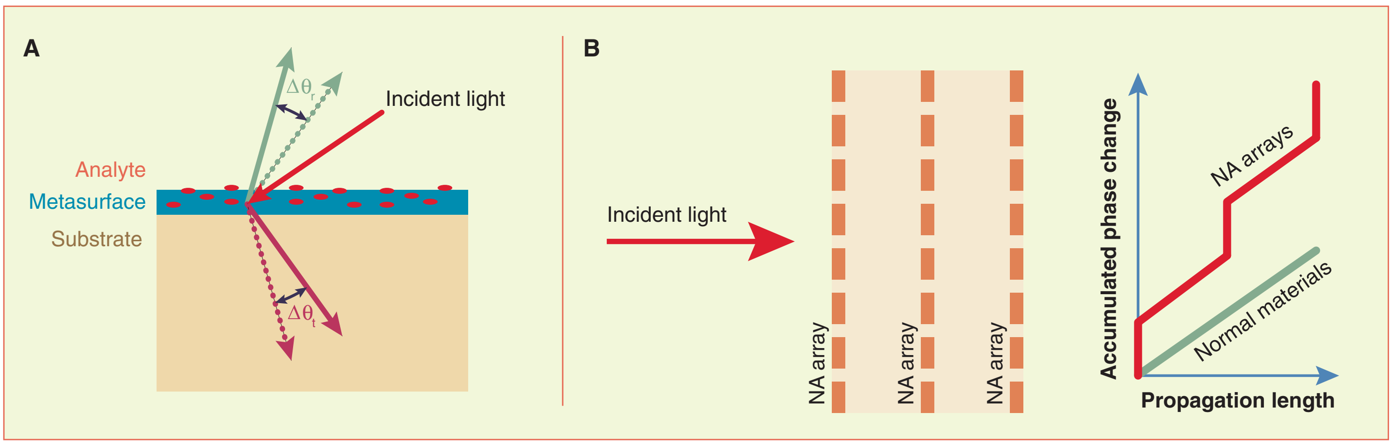


Fig. 2. Example applications of optical metasurfaces. (**A**) A metasurface acting as a chemical sensor: The analyte molecules adsorb onto the metasurface, causing a shift in the resonance of the constituent NAs. This results in shifts in the angle of the anomalously reflected and transmitted beams ($\Delta\theta_r$ and $\Delta\theta_t$, respectively). (**B**) Illustration of an extra-large refractive-index MM consisting of three metasurfaces (left panel). The right panel shows the accumulated phase change for light propagating through a normal homogenous material (green line) and through a MM consisting of three metasurfaces (red curve). The slope of each curve indicates the effective refractive index.

anisotropic, and where one component of the permittivity of either media has to be negative (56). These surface waves can be observed in two different geometries. The first is a layer of metal covered with a uniaxial dielectric material. The second possibility is to employ an HMM layer covered with an isotropic dielectric layer. Both of these configurations can support surfaces waves exhibiting hyperbolic dispersion, which causes highly directional propagation of the surface waves with unbounded wave vectors (limited in magnitude only by the inverse of the size of the structural unit) in a broad wavelength range. It is important to note that the PDOS in HMSs diverges similarly to PDOS in their 3D counterparts. Naturally, the unbounded isofrequency curves of HMSs immediately suggest a diverging, anomalously large PDOS. Importantly, though, the hyperbolic dispersion can be achieved within a wide spectral range; thus, the expected enhancement of the emission rate on HMSs has a broad bandwidth similar to that of their 3D counterparts.

We note that the anomalously large PDOS in HMSs could open up the exciting possibility of creating a new generation of active, on-chip light sources with dramatically increased photon extraction. Moreover, PDOS engineering achievable in HMS could lead to novel laser designs with extraordinary properties such as wide-band tunability and high directionality.

One of the interesting directions in this field is exploring how to use HMSs for quantum optical applications, such as the control of spontaneous emission and "single-photon guns," which could be very important for quantum information applications (60). As follows from the considerations above, one can expect emission enhancement from quantum emitters on HMSs. In contrast to bulk HMMs, quantum emitters can be placed directly on the interfaces of HMSs. In addition, the hyperbolic dispersion relation of the Dyakonov surface waves implies that the emitted light on the surface is highly directional, which will improve the collection efficiency. The surface nature of this approach makes it inherently compatible with on-chip integration. Figure 4A illustrates an example of a geometry involving quantum emitters on a HMS.

Another important application for HMSs is a surface hyperlens for superresolution imaging, which was previously proposed and realized for the 3D case (52, 58, 62). Figure 4, B and C, illustrates the hyperlensing effect for HMSs consisting of metallic gratings on top of a dielectric substrate. Figure 4B shows a surface hyperlens without the magnification effect. Two scatterers on top of the grating are separated by a subwavelength distance and behave as sources. The surface waves are confined in a preferred angular direction, along which the wave vector of the Dyakonov plasmons is perpendicular to the isofrequency curve. For the hyperlensing condition (when the hyperbolas of the isofrequency curves are flat), the waves emerging from the two sources are parallel to each other and will be resolvable at a distance far away from the sources. The design can be readily changed to produce a magnifying effect,

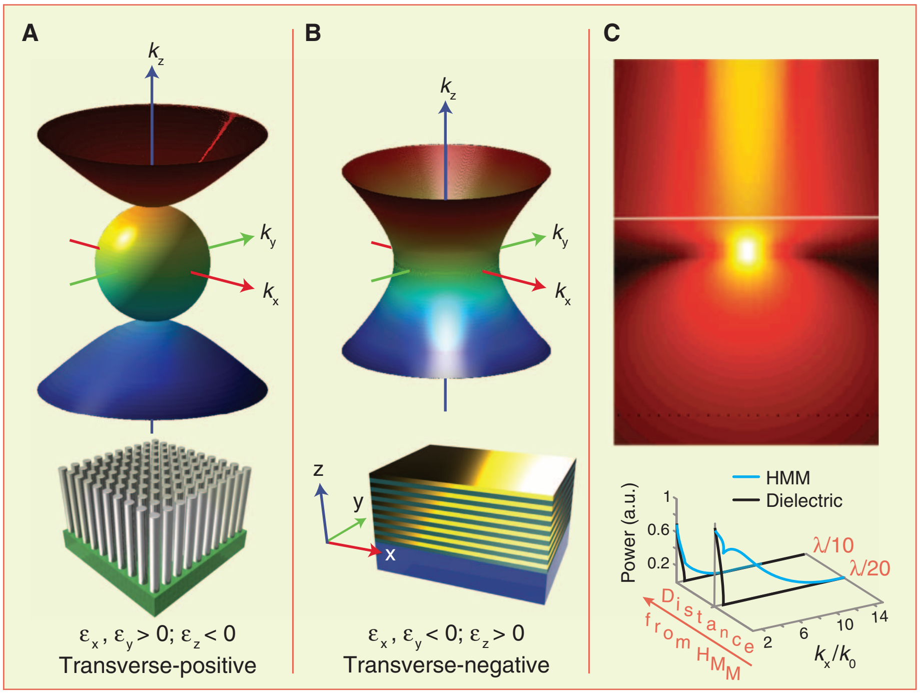


Fig. 3. Metamaterials with hyperbolic dispersion. (**A** and **B**) Examples of 3D HMMs with extreme anisotropy [transverse positive (TP) and transverse negative (TN)] made of plasmonic nanowires in a dielectric host (A) and alternating layers of metallic and dielectric materials (B). The sphere in the center of (A) represents the dispersion relation in a conventional, isotropic material, whereas the two hyperbolic surfaces describe the dispersion in a TP HMM. The dispersion for the TN HMM is shown in (B). The unbounded wave vectors in HMMs imply an extremely high effective refractive index and, thus, the possibility of superresolution imaging. This also leads to a singularity in the density of states that occurs over the entire bandwidth where hyperbolic dispersion is achieved. k_x and k_0, the tangential components of the normalized wave vector; ε_x, ε_y, and ε_z, the diagonal components of the permittivity tensor; λ, the free-space wavelength. (**C**) Simulated emission in an HMM (top) and power spectrum in a HMM as compared to conventional dielectric (bottom) (54). a.u., arbitrary units.

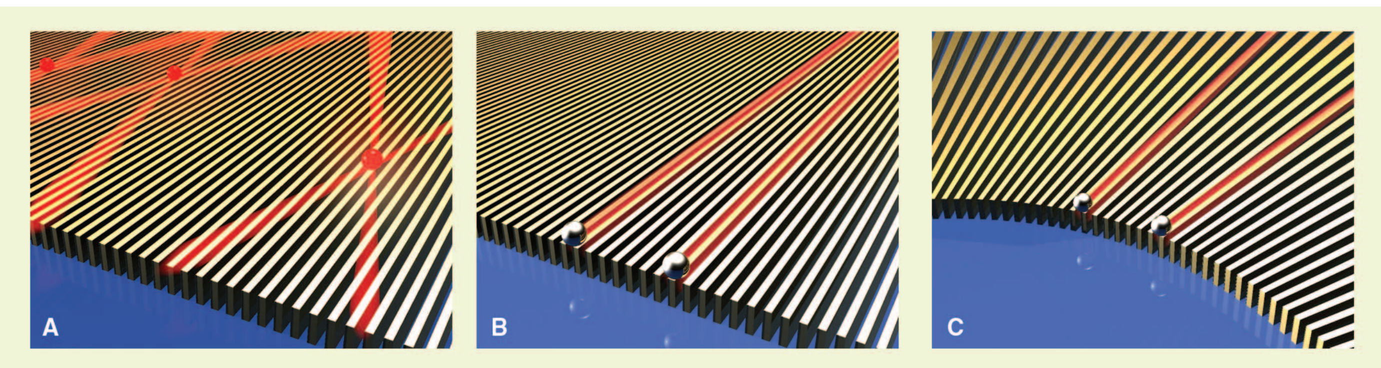


Fig. 4. Hyperbolic metasurfaces. (**A**) Illustration of a HMS enhancing the emission rate of quantum emitters on a metasurface consisting of a metallic grating on a dielectric substrate. (**B** and **C**) Illustration of a surface hyperlens without magnification (B) and with magnification (C). The two scatterers are on the top of the grating and have a subwavelength separation.

as shown in Fig. 4C. A grating made of strips that become wider with distance from the sources will magnify the image of the sources. When the light is directed in the opposite direction, the same HMS designs can be employed as light concentrators. Such HMSs could focus light to a subwavelength-sized spot and could be used for efficient, on-chip light harvesting.

The enhancement in the PDOS provided by HMSs also enables the engineering of thermal radiation and near-field heat transport. Engineering the thermal radiation of emitters over a broad band of mid-IR frequencies that is enabled by HMSs also allows the efficient control over the flow of heat, which is essential for many applications such as surveillance, sensing, detection, and imaging.

Improved Plasmonic Materials for Metasurfaces

The search for novel, low-loss, tunable materials that can be used as building blocks for metasurfaces will no doubt complement the exploration of smart designs and lead to new functionalities and improved performance. Similar to other plasmonic systems, one of the largest obstacles to overcome in metasurfaces is optical loss arising in the metallic unit cells (*47*, *57*). Metals such as silver and gold have traditionally been selected as the plasmonic materials of choice because they have large free-electron concentrations and high electrical conductivities. Although these metals work well in the infrared and microwave spectral regions, they suffer from high losses arising in part from interband transitions as the incident light approaches the technologically important telecommunication and visible wavelengths (*57*). One common approach to loss compensation is the addition of a gain medium in or around the plasmonic material. This approach can partially or fully compensate the loss in metals, but the incorporation of such active materials is very challenging (*63*). Often, the gain that can be provided by usual materials is barely enough to compensate the losses. Hence, an efficient alternative approach is needed to realize extremely low-loss or lossless devices. Another related fact limiting optical MM applications is the large plasma frequency of noble metals (~2000 THz) that cannot be adjusted (*57*). This is disadvantageous for a number of applications such as hyperlenses, transformation optics, and epsilon-near-zero materials (materials where the real part of the effective dielectric permittivity approaches zero) that enable subwavelength-resolution imaging, cloaking, and directional beaming, respectively. Ideally, for many applications, metals should not be too metallic (so that their permittivity would be comparable in magnitude to that of dielectrics but opposite in sign) and should have an adjustable or tunable plasma frequency to enable controllable or switchable devices. Moreover, noble metals are not compatible with the established semiconductor processing technologies, restricting MM and metasurface devices to the proof-of-concept stage only.

Those issues can be addressed by developing new material platforms that use low-loss, tunable materials for metasurface devices with improved performance, new functionalities, switchability, and compatibility with existing semiconductor technologies. The recent search for new plasmonic materials (*47*, *57*, *64–66*) defined new, intermediate carrier density materials as the best candidates that exhibit low loss, extraordinary tuning, and modulation capabilities and that are compatible with standard semiconductor fabrication and integration procedures.

Recently, the most promising classes of new plasmonic materials have been outlined and include materials such as inorganic ceramics [notably transparent conducting oxides (TCOs) (*57*, *64*, *65*) and transition metal nitrides (*65*, *66*)], and the merits of these materials for different applications have been explored (*57*, *64–66*). Heavily doped (10^{21} cm^{-3}) TCOs, such as indium tin oxide and zinc oxide doped with aluminum or gallium, have been shown to be promising plasmonic materials in the near-IR range (*57*, *64–66*). In the visible range, intermetallics such as silicides, germanides, borides, and nitrides could serve as plasmonic materials (*47*). Naik *et al*. have demonstrated that the optical performance of gold can be at least matched by that of TiN (*65*, *66*).

It is also important to study the possibility of incorporating tunability and switching and/or modulation capabilities into metasurface systems. Along with phase-change materials like liquid crystals, chalcogenide glasses, and transition-metal oxides (e.g., vanadium oxide), the usage of TCOs for electro-optical switching of metasurface devices can be explored. The addition of electro-optical capabilities to metasurface devices, particularly in the infrared domain, can be optimized by exploiting the shift of the electromagnetic response driven by an applied voltage. Feigenbaum and Atwater have shown that heavily doped semiconductor oxides and TCOs support extraordinary tuning and modulation of their complex refractive indices because their carrier concentrations can be changed by orders of magnitude through the application of an electric field (*67*). It is also important to look into the possibility of using the strong optical nonlinear responses that can be exhibited by the intermediate carrier density materials (*68*) proposed above to add new, useful functionalities to metasurface devices.

The recent progress in optical metasurfaces could address the major issues—such as high loss, cost-ineffective fabrication, and challenging integration—that are hampering the full-scale development of MM technology. This progress can result in the development of new types of ultrathin metasurfaces with unparalleled properties, including increased operational bandwidths and reduced losses; these metasurfaces would also be compatible with planar, low-cost manufacturing. In turn, this development could lead to novel, ultrathin devices that offer unprecedented functionalities ranging from dynamic spatial light modulation to pulse-shaping and beam-steering and from nanoscale-resolution imaging and sensing to novel quantum optics devices.

References and Notes

1. V. G. Veselago, The electrodynamics of substances with simultaneously negative values of ε AND μ. *Sov. Phys. Usp.* **10**, 509 (1968) and references therein. doi: 10.1070/PU1968v010n04ABEH003699
2. J. B. Pendry, D. Schurig, D. R. Smith, Controlling electromagnetic fields. *Science* **312**, 1780 (2006) and references therein. doi: 10.1126/science.1125907; pmid: 16728597
3. C. M. Soukoulis, M. Wegener, Optical metamaterials—more bulky and less lossy. *Science* **330**, 1633 (2010) and references therein. www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=21164003&dopt=Abstract doi: 10.1126/science.1198858; pmid: 21164003
4. N. I. Zheludev, Y. S. Kivshar, From metamaterials to metadevices. *Nat. Mater.* **11**, 917 (2012) and references therein. doi: 10.1038/nmat3431; pmid: 23089997
5. N. Yu *et al.*, Light propagation with phase discontinuities: Generalized laws of reflection and refraction. *Science* **334**, 333 (2011). doi: 10.1126/science.1210713 pmid: 21885733
6. X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, Broadband light bending with plasmonic nanoantennas. *Science* **335**, 427 (2012). doi: 10.1126/science.1214686; pmid: 22194414
7. E. F. Kuester, M. A. Mohamed, M. Piket-May, C. L. Holloway, Averaged transition conditions for electromagnetic fields at a metafilm. *IEEE Trans. Antenn. Propag.* **51**, 2641 (2003). doi: 10.1109/TAP.2003.817560
8. C. L. Holloway, M. A. Mohamed, E. F. Kuester, A. Dienstfrey, Reflection and transmission properties of a metafilm: With an application to a controllable surface composed of resonant particles. *IEEE Trans. Electromagn. Compat.* **47**, 853 (2005). doi: 10.1109/TEMC.2005.853719
9. Y. Zhao, N. Engheta, A. Alù, Homogenization of plasmonic metasurfaces modeled as transmission-line loads. *Metamaterials* **5**, 90 (2011). doi: 10.1016/j.metmat.2011.05.001
10. D. M. Pozar, S. D. Targonski, H. D. Syrigos, Design of millimeter wave microstrip reflectarrays. *IEEE Trans. Antenn. Propag.* **45**, 287 (1997). doi: 10.1109/8.560348
11. D. Sievenpiper, L. Zhang, R. F. J. Broas, N. G. Alexopolous, E. Yablonovitch, High-impedance electromagnetic surfaces with a forbidden frequency band. *IEEE Trans. Microwave Theory Tech.* **47**, 2059 (1999). doi: 10.1109/22.798001
12. C. G. M. Ryan *et al.*, A wideband transmitarray using dual-resonant double square rings. *IEEE Trans. Antenn. Propag.* **58**, 1486 (2010). doi: 10.1109/TAP.2010.2044356
13. M. Caiazzo, S. Maci, N. Engheta, A metamaterial surface for compact cavity resonators. *IEEE Antenn. Wireless Propag. Lett.* **3**, 261 (2004). doi: 10.1109/LAWP.2004.836576
14. C. L. Holloway, D. C. Love, E. F. Kuester, A. Salandrino, N. Engheta, Sub-wavelength resonators: On the use of metafilms to overcome the λ/2 size limit. *IET Microwave Antenn. Propag.* **2**, 120 (2008). doi: 10.1049/iet-map:20060309
15. N. Engheta, Antenna-guided light. *Science* **334**, 317 (2011). doi: 10.1126/science.1213278; pmid: 22021846
16. A. Papakostas *et al.*, Optical manifestations of planar chirality. *Phys. Rev. Lett.* **90**, 107404 (2003).
17. S. L. Prosvirnin, N. I. Zheludev, Polarization effects in the diffraction of light by a planar chiral structure. *Phys. Rev. E* **71**, 037603 (2005).
18. S. L. Prosvirnin, N. I. Zheludev, Analysis of polarization transformations by a planar chiral array of complex-shaped particles. *J. Opt. A* **11**, 074002 (2009).
19. Y. Svirko, N. Zheludev, M. Osipov, Layered chiral metallic microstructures with inductive coupling. *Appl. Phys. Lett.* **78**, 498 (2001). doi: 10.1063/1.1342210
20. F. Aieta *et al.*, Out-of-plane reflection and refraction of light by anisotropic optical antenna metasurfaces with phase discontinuities. *Nano Lett.* **12**, 1702 (2012). doi: 10.1021/nl300204s; pmid: 22335616

21. P. Genevet *et al.*, Ultra-thin plasmonic optical vortex plate based on phase discontinuities. *Appl. Phys. Lett.* **100**, 013101 (2012). doi: 10.1063/1.3673334
22. R. Blanchard *et al.*, Modeling nanoscale V-shaped antennas for the design of optical phased arrays. *Phys. Rev. B* **85**, 155457 (2012).
23. S. Larouche, D. R. Smith, Reconciliation of generalized refraction with diffraction theory. *Opt. Lett.* **37**, 2391 (2012). doi: 10.1364/OL.37.002391; pmid: 22739918
24. F. Aieta *et al.*, Aberration-free ultrathin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces. *Nano Lett.* **12**, 4932 (2012). doi: 10.1021/nl302516v; pmid: 22894542
25. X. Ni, S. Ishii, A. V. Kildishev, V. M. Shalaev, Ultra-thin, planar, Babinet-inverted plasmonic metalenses. *Light Sci. Appl.* 10.1038/lsa.2013.28 (2013).
26. D. Hu *et al.*, http://arxiv.org/abs/1206.7011v1 (2012).
27. Y. Zhao, M. A. Belkin, A. Alù, Twisted optical metamaterials for planarized ultrathin broadband circular polarizers. *Nat. Commun.* **3**, 870 (2012).
28. Y. Zhao, A. Alu, Manipulating light polarization with ultrathin plasmonic metasurfaces. *Phys. Rev. B* **84**, 205428 (2011).
29. N. Yu *et al.*, A broadband, background-free quarter-wave plate based on plasmonic metasurfaces. *Nano Lett.* **12**, 6328 (2012).
30. S. L. Sun *et al.*, Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves. *Nat. Mater.* **11**, 426 (2012). doi: 10.1038/nmat3292; pmid: 22466746
31. M. Kang, T. H. Feng, H. T. Wang, J. S. Li, Wave front engineering from an array of thin aperture antennas. *Opt. Express* **20**, 15882 (2012). doi: 10.1364/OE.20.015882; pmid: 22772278
32. W. X. Shu *et al.*, Generation of optical beams with desirable orbital angular momenta by transformation media. *Phys. Rev. A* **85**, 063840 (2012).
33. N. M. Litchinitser, Structured light meets structured matter. *Science* **337**, 1054 (2012) and references therein. doi: 10.1126/science.1226204; pmid: 22936768
34. D. S. Simon, N. Lawrence, J. Trevino, L. Dal Negro, A. V. Sergienko, http://arxiv.org/abs/1206.3548 (2012).
35. B. Walther, C. Helgert, C. Rockstuhl, T. Pertsch, Diffractive optical elements based on plasmonic metamaterials. *Appl. Phys. Lett.* **98**, 191101 (2011).
36. S. Larouche, Y. J. Tsai, T. Tyler, N. M. Jokerst, D. R. Smith, Infrared metamaterial phase holograms. *Nat. Mater.* **11**, 450 (2012). doi: 10.1038/nmat3278; pmid: 22426458
37. M. V. Berry, The adiabatic phase and Pancharatnam's phase for polarized light. *J. Mod. Opt.* **34**, 1401 (1987). doi: 10.1080/09500348714551321
38. S. Pancharatnam, Generalized theory of interference, and its applications. Part I. Coherent pencils. *Proc. Indiana Acad. Sci.* **44**, 247 (1956).
39. E. Hasman, V. Kleiner, G. Biener, A. Niv, Polarization dependent focusing lens by use of quantized Pancharatnam–Berry phase diffractive optics. *Appl. Phys. Lett.* **82**, 328 (2003). doi: 10.1063/1.1539300
40. G. Biener, A. Niv, V. Kleiner, E. Hasman, Geometrical phase image encryption obtained with space-variant subwavelength gratings. *Opt. Lett.* **30**, 1096 (2005). doi: 10.1364/OL.30.001096; pmid: 15943278
41. A. Niv, G. Biener, V. Kleiner, E. Hasman, Spiral phase elements obtained by use of discrete space-variant subwavelength gratings. *Opt. Commun.* **251**, 306 (2005). doi: 10.1016/j.optcom.2005.03.002
42. A. Niv, G. Biener, V. Kleiner, E. Hasman, Manipulation of the Pancharatnam phase in vectorial vortices. *Opt. Express* **14**, 4208 (2006). doi: 10.1364/OE.14.004208; pmid: 19516574
43. U. Levy, H.-C. Kim, C.-H. Tsai, Y. Fainman, Near-infrared demonstration of computer-generated holograms implemented by using subwavelength gratings with space-variant orientation. *Opt. Lett.* **30**, 2089 (2005). doi: 10.1364/OL.30.002089; pmid: 16127919
44. Y. Gorodetski *et al.*, Weak measurements of light chirality with a plasmonic slit. *Phys. Rev. Lett.* **109**, 013901 (2012).
45. Y. Gorodetski, S. Nechayev, V. Kleiner, E. Hasman, Plasmonic Aharonov-Bohm effect: Optical spin as the magnetic flux parameter. *Phys. Rev. B* **82**, 125433 (2010).
46. N. Shitrit, I. Bretner, Y. Gorodetski, V. Kleiner, E. Hasman, Optical spin Hall effects in plasmonic chains. *Nano Lett.* **11**, 2038 (2011). doi: 10.1021/nl2004835; pmid: 21513279
47. A. Boltasseva, H. A. Atwater, Low-loss plasmonic metamaterials. *Science* **331**, 290 (2011). doi: 10.1126/science.1198258; pmid: 21252335
48. P. Y. Fan *et al.*, An invisible metal–semiconductor photodetector. *Nat. Photonics* **6**, 380 (2012). doi: 10.1038/nphoton.2012.108
49. Y. M. Liu, T. Zentgraf, G. Bartal, X. Zhang, Transformational plasmon optics. *Nano Lett.* **10**, 1991 (2010). doi: 10.1021/nl1008019; pmid: 20465268
50. D. R. Smith, D. Schurig, Electromagnetic wave propagation in media with indefinite permittivity and permeability tensors. *Phys. Rev. Lett.* **90**, 077405 (2003).
51. X. D. Yang, J. Yao, J. Rho, X. B. Yin, X. Zhang, Experimental realization of three-dimensional indefinite cavities at the nanoscale with anomalous scaling laws. *Nat. Photonics* **6**, 450 (2012). doi: 10.1038/nphoton.2012.124
52. Z. Jacob, L. V. Alekseyev, E. Narimanov, Optical hyperlens: Far-field imaging beyond the diffraction limit. *Opt. Express* **14**, 8247 (2006). doi: 10.1364/OE.14.008247; pmid: 19529199
53. H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, V. M. Menon, Topological transitions in metamaterials. *Science* **336**, 205 (2012). doi: 10.1126/science.1219171; pmid: 22499943
54. Z. Jacob *et al.*, Engineering photonic density of states using metamaterials. *Appl. Phys. B* **100**, 215 (2010). doi: 10.1007/s00340-010-4096-5
55. M. A. Noginov *et al.*, Controlling spontaneous emission with metamaterials. *Opt. Lett.* **35**, 1863 (2010). doi: 10.1364/OL.35.001863; pmid: 20517443
56. Z. Jacob, E. E. Narimanov, Optical hyperspace for plasmons: Dyakonov states in metamaterials. *Appl. Phys. Lett.* **93**, 221109 (2008).
57. P. R. West *et al.*, Searching for better plasmonic materials. *Laser Photonics Rev.* **4**, 795 (2010) and references therein. doi: 10.1002/lpor.200900055
58. A. Salandrino, N. Engheta, Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations. *Phys. Rev. B* **74**, 075103 (2006).
59. A. J. Hoffman *et al.*, Negative refraction in semiconductor metamaterials. *Nat. Mater.* **6**, 946 (2007). doi: 10.1038/nmat2033; pmid: 17934463
60. Z. Jacob, V. M. Shalaev, Plasmonics goes quantum. *Science* **334**, 463 (2011). doi: 10.1126/science.1211736; pmid: 22034423
61. Z. Jacob, I. I. Smolyaninov, E. E. Narimanov, Broadband Purcell effect: Radiative decay engineering with metamaterials. *Appl. Phys. Lett.* **100**, 181105 (2012).
62. Z. W. Liu, H. Lee, Y. Xiong, C. Sun, X. Zhang, Far-field optical hyperlens magnifying sub-diffraction-limited objects. *Science* **315**, 1686 (2007). doi: 10.1126/science.1137368; pmid: 17379801
63. S. M. Xiao *et al.*, Loss-free and active optical negative-index metamaterials. *Nature* **466**, 735 (2010). doi: 10.1038/nature09278; pmid: 20686570
64. G. V. Naik, J. J. Liu, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, Demonstration of Al:ZnO as a plasmonic component for near-infrared metamaterials. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 8834 (2012) and references therein. doi: 10.1073/pnas.1121517109; pmid: 22611188
65. G. V. Naik, J. Kim, A. Boltasseva, Oxides and nitrides as alternative plasmonic materials in the optical range. *Opt. Mater. Express* **1**, 1090 (2011) and references therein. doi: 10.1364/OME.1.001090
66. G. V. Naik *et al.*, Titanium nitride as a plasmonic material for visible and near-infrared wavelengths. *Opt. Mater. Express* **2**, 478 (2012). doi: 10.1364/OME.2.000478
67. E. Feigenbaum, H. A. Atwater, Resonant guided wave networks. *Phys. Rev. Lett.* **104**, 129 (2010).
68. J. A. Schuller *et al.*, Plasmonics for extreme light concentration and manipulation. *Nat. Mater.* **9**, 193 (2010). doi: 10.1038/nmat2630; pmid: 20168343

Acknowledgments: We thank A. Sokolov, X. Ni, and G. Naik for useful discussions. This work was partially supported by Air Force Office of Scientific Research grant FA9550-12-1-0024, U.S. Army Research Office grant 57981-PH (W911NF-11-1-0359), NSF grant DMR-1120923, and NSF award Meta-PREM no. 1205457.

10.1126/science.1232009