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Controlling electromagnetic waves with meta-surfaces

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A novel design, which involves an H-shaped sandwich structure, can efficiently convert propagating waves to surface waves.

Manipulation of electromagnetic (EM) waves (e.g., for anti-reflection, light absorption, and imaging applications) has long been restricted by the limited range of EM parameters exhibited by natural materials. Metamaterials (MTMs)—artificial materials composed of subwavelength functional EM microstructures arranged in specific macroscopic 'orders'—can be designed so that they exhibit specific values of permittivity and permeability. They therefore offer significantly more opportunities to control EM waves than with traditional materials. Artificial microstructures—or 'meta-atoms'—had an important role in the early development of MTMs, but with the advent of transformation optics (TO) theory, new ways to manipulate EM waves have emerged. The importance of MTM macroscopic orders has also now become recognized and has expanded wave manipulation abilities.[1] Despite the progress that has been made using TO theory to manipulate EM waves, the designs require that MTMs exhibit anisotropic and extreme parameters, which can limit their practical realizations.

Recently, a class of ultra-thin MTMs (meta-surfaces), with planar meta-atoms that possess distinct EM responses arranged in specific orders, has attracted substantial attention.[2–10] It has been found that a v-shaped antenna array can support anomalous reflection/refraction of impinging light, which cannot be described by the classical Snell's law (relationship between angles of incidence and reflection/refraction at a planar interface). Instead a new generalized formulation of Snell's law is required, which provides a better understanding of the reflection/refraction physics involved and increases the ability to control EM waves.[2,3] Surface waves (SWs)—also known as surface plasmon polaritons—have very short wavelengths and strong local fields. They can therefore be useful in subwavelength imaging and light harvesting, and have many optical applications. Conventional methods of exciting SWs with propagating waves (PWs) use prism or grating couplers, but these are inefficient.

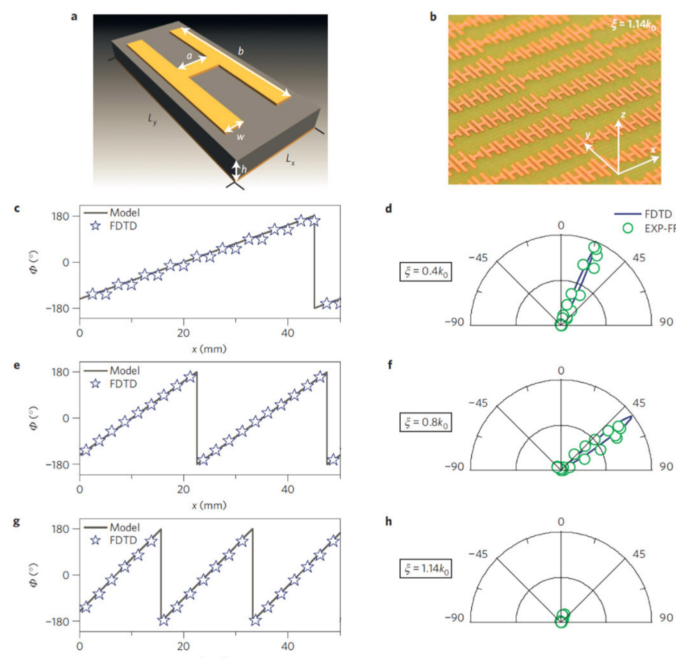

Figure 1. (a) Geometry of a gradient meta-surface unit cell. (b) Part of a fabricated (1.14-gradient) meta-surface sample. Modeled and finite-difference-time-domain (FDTD) simulated reflection phase (Φ) distributions for three different meta-surfaces are shown in (c), (e), and (g). Measured (EXP-FF) and simulated (FDTD) scattering patterns are shown in (d), (f), and (h). ξ: Reflection phase profile gradient. k_0: Wave vector in vacuum. (Reprinted with permission.[4])

We have introduced a new type of meta-surface and have demonstrated experimentally that it can function as a bridge to efficiently link PWs and SWs.[4] The building block of our meta-surface is a sandwich structure that consists of a metallic 'H' and a continuous metal sheet, which are separated by a dielectric (electrically insulating) spacer—see Figure 1(a). Near-field EM coupling between the 'H' and the metal sheet generates a magnetic response and leads to nontrivial changes in the reflection phase of the incident EM waves.[11] By carefully designing each

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'H' structure, our meta-surface can produce a linearly varying reflection phase profile. The metal sheet on the back of the structures ensures that there is a total reflection response at every local point. The gradient of the phase profile can be used to make a generalization of Snell's law, which shows that in some cases our meta-surface can be used to convert a PW to an SW.

To verify our design, we have fabricated three meta-surfaces—e.g., see Figure 1(b)—each with a different gradient value (0.4, 0.8, and 1.14 at an operating frequency of 15GHz). The reflection phase distributions of these samples, which we calculated via finite-difference-time-domain (FDTD) simulations, are shown in Figure 1(c), (e), and (g). We also measured the far-field (FF) scattering patterns of these samples under normal incident excitations (i.e., where the incident light is polarized parallel to the x-axis). The results—see Figure 1(d), (f), and (h)—show that the impinging EM waves are reflected at angles of 23° and 53° by the 0.4- and 0.8-gradient meta-surfaces, respectively. However, we do not detect any FF signal for the 1.14-gradient sample. We mapped the z-component of local electric field distribution on the 1.14-gradient meta-surface using results from near-field (NF) scanning measurements (see Figure 2). The NF experiments and the FDTD simulations demonstrate that the local electric field is indeed an SW that exhibits a well-defined parallel wave vector, and we therefore verify our theoretical conjecture of perfect PW-to-SW conversion.

To understand the inherent physics of these unusual phenomena, we developed a mode-expansion theory to study the scattering properties of our meta-surfaces.[6] The system can be modeled as a thin inhomogeneous MTM slab on top of a perfect electric conductor.[11] We expand the EM fields in each region to linear combinations of the corresponding eigenmodes, and then determine the expansion coefficients by matching appropriate boundary conditions. Using this method, we studied the reflection spectra of a 0.8-gradient meta-surface illuminated by EM waves with different incident angles. In all the cases that we studied, our calculations show that the incident PW is perfectly converted to another PW after the reflection, and that such reflections satisfy our generalized Snell's law.

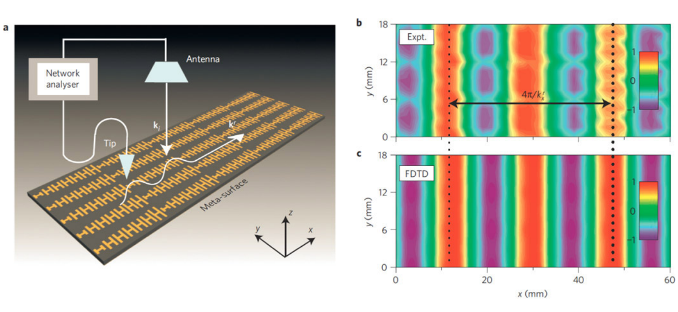

Figure 2. Near-field studies of the 1.14-gradient meta-surface. (a) Schematic diagram of the near-field scanning technique. (b) Near-field scanning measurements and (c) FDTD simulations of the local electric field distribution (z-component), with phase information, on part of the sample. The sample was illuminated with normally incident x-polarized EM waves. k_i: Incident wave vector. k^r: Reflected wave vector. Expt.: Experiment. (Reprinted with permission.[4])

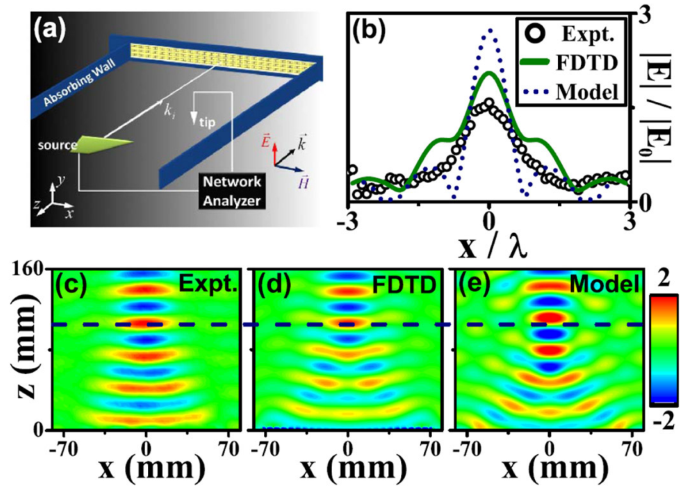

Figure 3. A flat microwave meta-surface with a parabolic reflection phase distribution. (a) Sketch of the experimental setup used to test the meta-surface. (b) Electric (E) field distributions along the focal line, obtained by experiment and by FDTD simulations on a realistic sample and on a model system. Also shown are instantaneous field measurements on the x-z plane, obtained by (c) experiment, and from FDTD simulations on (d) a realistic sample and (e) the model system. The dashed line denotes the designed focal line (100mm focal length). All fields are normalized against the input field strength (E_0), and the meta-surface is placed at the $z = 0$ plane. H: Magnetic field. λ: Wavelength. (Reprinted with permission.[7])

Based on our meta-surfaces, even more complex wave-front manipulations can be performed. For example, we have designed and fabricated a microwave meta-surface with a parabolic reflection phase distribution as a flat reflective mirror. This can be used to focus an impinging plane wave to a point (see Figure 3).[7] Our system is much thinner than the working wavelength, unlike conventional optical devices. The flat design of this meta-surface greatly improves device fabrication and decreases the amount of signal loss, since the EM waves do not enter the interior of the device. These factors all contribute to the high working efficiency and miniaturization of our system.

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We have designed, and experimentally verified, a new type of inhomogeneous meta-surface that can be used to control EM waves and efficiently convert PWs to SWs. So far our designs have been used with microwave frequencies, but it is possible to alter the surfaces so they can be used at optical wavelengths.[5,10] We now plan to use our meta-surface designs in various applications, including meta-holograms and unidirectional surface plasmon polariton couplers.[8,9] We also continue to investigate meta-surface related effects in other systems and other frequency domains so that we can develop further wave manipulation effects.

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