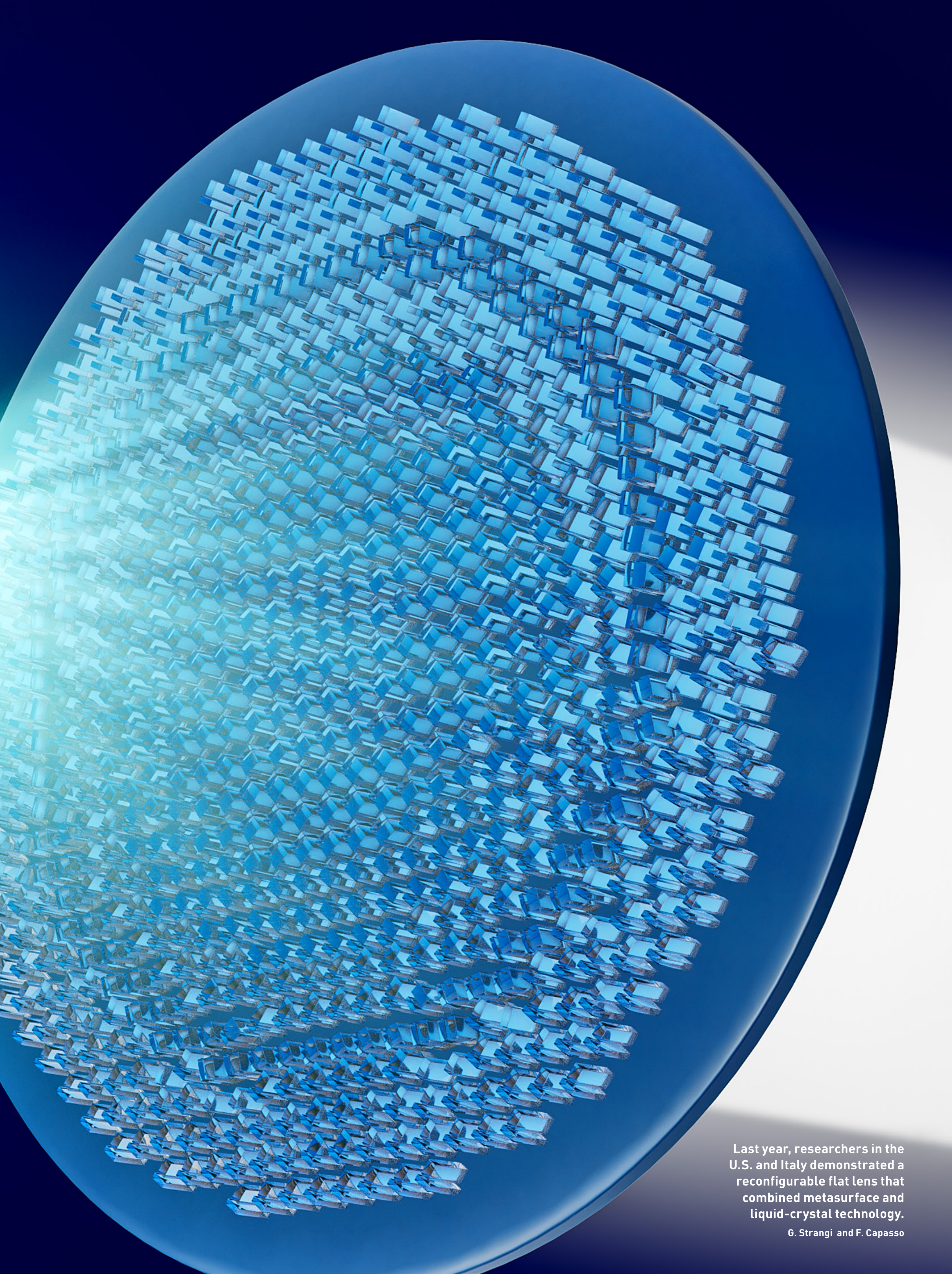
Active control of optical properties could take metasurface applications to the next level.

Tunable Metasurfaces

Controlling Light in Space and Time

Soham Saha, Deesha Shah, Vladimir M. Shalaev and Alexandra Boltasseva



Last year, researchers in the U.S. and Italy demonstrated a reconfigurable flat lens that combined metasurface and liquid-crystal technology.

G. Strangi and F. Capasso

Over the last two decades, metasurfaces—engineered surfaces that manipulate light through spatially arranged nanoscale features, or "meta-atoms"—have emerged as a powerful concept for tailoring and controlling light's fundamental properties. Conventional optical elements such as lenses, phase shifters, polarizers and filters are bulky, requiring a length scale of many wavelengths to change the flow of light passing through them. Optical metasurfaces, in contrast, can manipulate phase, amplitude and polarization with a single layer of optical nanoantennas with deeply subwavelength dimensions. The prospect of replacing conventional bulky optical components with such ultrathin, flat structures makes metasurfaces a crucial part of the design toolkit for miniaturizing future optical components—and for enabling entirely new functionalities.

Metasurfaces allow the tailoring of light–matter interaction almost at will, through proper selection of shape, size and orientation of nanometer-scale elements. Until recently, however, many demonstrated metasurfaces have been essentially static, with the specific light–matter interaction "baked into" the metasurface. Making the optical properties of metasurfaces dynamically controllable, in real-time, could take their functionalities to the next level and expand the boundaries of fundamental optical science. Gigahertz- to terahertz-speed optical transistors for telecom (spanning the visible to mid-infrared wavelengths), beam-steering devices for smart-cars and lidar, and active cloaking for defense applications are but a few examples of devices that need dynamically configurable optical properties.

For metasurfaces, such dynamic control can be achieved by tuning the surface's dielectric permittivity or changing its topology (geometry). Doing so opens up many possible applications. Amplitude modulation—where the intensity of light is changed by controlling the metasurface's reflectance, transmittance and absorbance—finds use in optical computation and data transfer. Wavefront manipulation through phase control could allow beam-steering for lidar and autonomous vehicles, flat tunable lenses for 3D imaging and endoscopy, and holograms for augmented and virtual reality (AR/VR). Polarization control is important to applications such as beam formation, polarimetry and optical trapping.

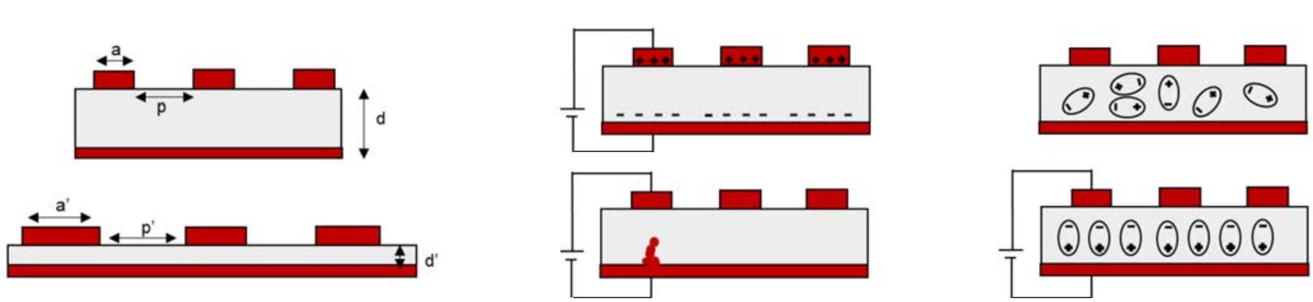
This feature looks at recently demonstrated approaches to creating such dynamically tunable metasurfaces, and at the applications and new physics that such dynamic control enables. (A complete list of references and resources for this article can be found online at www.osa-opn.org/link/tunable-metasurfaces.)

Tunable lenses with MEMS

Lenses are crucial to a vast array of optical systems, ranging from imaging and optical characterization to biosensing. Thus it's not surprising that metasurface-based designs for compact lenses have been a key research focus. Dynamically tunable, metasurface-based lenses could prove a particularly good fit for applications such as imaging and AR/VR. These applications strongly favor varifocal lenses with a large range of focal lengths—and have been held back by bulky components, slow switching speeds (few to tens of Hertz) or limited tuning ranges.

One way to tune a metasurface's properties in real time is through mechanical actuation—reconfiguring the physical shape and spatial arrangement of its

Techniques for active control of metasurfaces



Mechanically reconfiguring the subwavelength dimensions (a) or periods (p) of a metasurface's meta-atoms, or its interlayer spacing (d), can change its optical response.

An applied bias causes electron to accumulate under the gate (top) or electromigration of ions into the modulating material (bottom), locally changing the permittivity.

In liquid crystals, an applied bias or heat causes the domains to align in a crystalline formation.

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Making the optical properties of metasurfaces dynamically controllable, in real-time, could expand both their functionalities and the boundaries of fundamental optical science.

nanoantennas. Such reconfiguring is possible through micro- or nano-electro-mechanical systems (MEMS/NEMS), which involve nanostructures that can be mechanically controlled, or through metasurfaces fabricated on an electrically actuated substrate. With MEMS, the focal length of metasurfaces can be dynamically tuned by reconfiguring either the geometry of or the spacing between the nanostructures.

MEMS and NEMS systems based on current technologies have a switching speed on the order of kHz to MHz. In one flat metalens design, from the lab of Andrei Faraon, a stationary lens sits on a glass substrate and a moving lens on a silicon nitride membrane, with the membrane electrostatically actuated to change the distance between the two metasurfaces and, thus, the focal length. The resulting varifocal lens has an operating frequency of 4 kHz and a tuning range greater than 180 diopters. (See pp. 38–39 for images of this and other systems discussed below.)

Other mechanical-tuning methods involve placing meta-atoms on flexible and stretchable substrates and varying their periodicity by stretching or compressing the substrates. For example, a group led by Ritesh Agarwal has used gold antennae placed on polydimethylsiloxane (PDMS) for dynamic holography, with the location of the image plane changed by stretching the substrate, allowing the structure to switch between distinct images. Another interesting example, explored by the team of Nicholas Kotov, includes Kirigami composites, which incorporate the traditional Japanese art of cutting paper into stretchable polymers, generating complex shapes that reversibly deform and allow the tuning of optical properties.

Tunable metasurfaces: The material platforms

MECHANICAL (Hz to MHz)

Materials: Silicon, aluminum, gold, copper, silicon nitride, polyimide, Galinstan, silicon dioxide, PDMS

Applications: Beam-steering, lens, filters, absorbers, emitters, polarizers, switches

PHASE-CHANGE (kHz)

Materials: VO_2, liquid crystals, dichalcogenides

Applications: Sensing, memory, beam-steering, nanofocusing

ELECTRICAL (kHz-GHz)

Materials: Silicon, TCOs, 2D materials

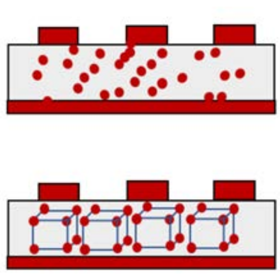
Applications: Beam-steering, nanofocusing, phase-shifting, polarization shifting, optical switching, polarimetry

OPTICAL (MHz-THz)

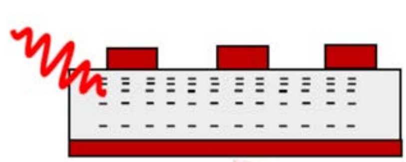
Materials: GST, TCOs, direct bandgap semiconductors, nonlinear crystals

Applications: Optical transistors, beam-steering, dynamic nanofocusing, optical cloaking, optical isolator

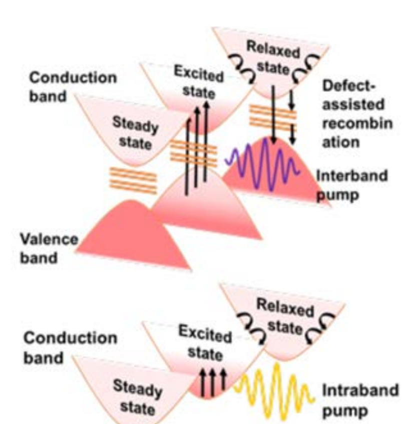
View references for this table: www.osa-opn.org/link/tunable-metasurfaces.



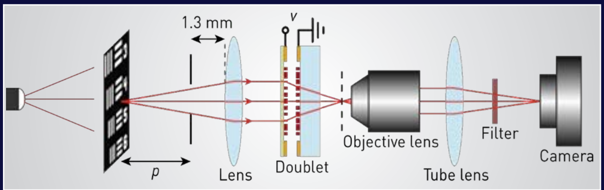
In phase-change media, optical pumping, heat or current changes the atoms from a disordered to an ordered state, changing permittivity and band structure.



An optical pump can either generate or excite electrons, changing the permittivity of the material along the skin-depth of the pump.



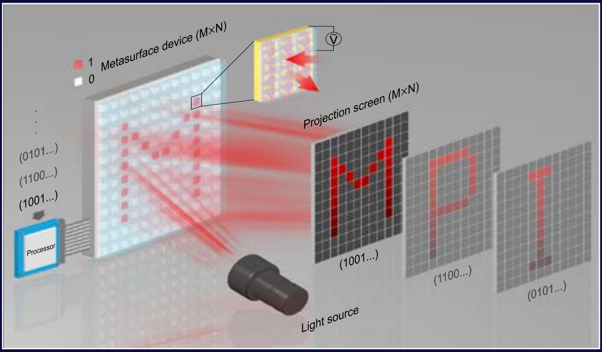
A tunable-metasurface gallery



MEMS-tunable flat lens

An applied bias changes the gap between two metalenses, and thus the focal length.

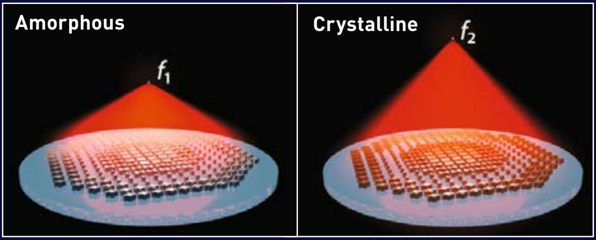
E. Arbabi et al., Nat. Commun. **9**, 812 (2018); CC-BY 4.0



Dynamically controllable display

A liquid-crystal-encapsulated metasurface is phase-modulated by voltage-driven changes in the liquid crystals.

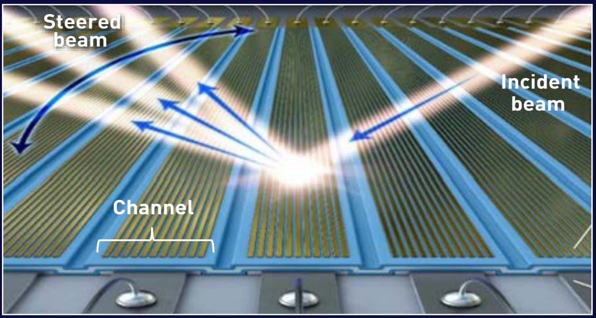
J. Li et al., Nat. Commun. **11**, 1 (2020); CC-BY 4.0



GSST metasurface

A reconfigurable, all-dielectric metalens achieved diffraction-limited performance.

M.Y. Shalaginov et al., Nat. Commun. **12**, 1225 (2021); CC-BY 4.0



Dynamic beam-steering

Phase and amplitude control, by varying top and bottom gates sandwiching an ITO layer, allows steering of reflected beam.

J. Park et al., Nat. Nanotechnol. **16**, 69 (2021); reprinted by permission of Springer Nature

Displays and dynamic focusing with liquid crystals

Liquid crystals (LCs) comprise elongated molecules with orientations that can be controlled thermally or by an external electrical field. By integrating metasurfaces with LCs—employing techniques that are well established from the display industry—a device's reflection amplitude and polarization can be strongly modulated by applying an electrical bias or heating, which changes the crystalline phase of the LC.

The LC–metasurface combination can enable active control of nanophotonic devices. For example, as shown by a team led by Na Liu, individual pixels can be controlled in LC-encapsulated metasurfaces, manipulating the phase relations between adjacent cells and allowing dynamic generation of programmable images. Ultracompact metasurfaces have already been explored in endoscopes to replace bulkier lenses. Dynamic control over focusing length, using metasurfaces immersed in liquid crystals, can enable real-time scanning and 3D imaging, pushing this technology to the next step.

Tunable optics with phase-change materials

Phase-change materials (PCMs) undergo dramatic changes in optical properties under a thermal or electrical impulse. Thermal excitation can be generated electrically from resistive heating, or through optical pumping. The large changes in the material's refractive index shift the metasurface resonances, allowing amplitude and phase modulation.

Realizing nanophotonic devices for beam steering, reconfigurable metalenses and filters requires dynamic control of amplitude and phase. One way to achieve large phase and amplitude modulation is by using metasurfaces fabricated on top of vanadium dioxide (VO_2), a PCM with a low transition temperature of around 340 K and a reversible insulator-to-metal transition.

Dichalcogenides like GeSbTe (GST) experience large, reversible refractive-index changes upon heating. This makes them suitable for implementing reconfigurable waveguides and lenses for nanophotonic applications such as subwavelength polariton focusing, recently shown by the Capasso group. The Giessen group utilized this ability to change between the crystalline and the amorphous states to make plasmonic beam-switching metasurfaces and bifocal metalenses, in which the beam-steering direction and the focal lengths were changed by the simultaneous application of heat and an optical pulse.

Another optical phase-change material (OPCM), $Ge_2Sb_2Se_4Te$ (GSST), has broadband transparency in the infrared wavelengths and lower loss than GST. The Juejun

Realizing nanophotonic devices for beam steering, reconfigurable metalenses and filters requires dynamic control of amplitude and phase.

Hu group at MIT has employed GSST to make reconfigurable lenses for aberration and crosstalk-free lensing in the MIR wavelength regime, and electrically configurable metasurfaces for beam-deflection in the NIR.

Electrical control of beams and wavefronts

Electrical control is perhaps the most widely used technique to tune a material's optical properties. Electrical biasing has been comprehensively explored in semiconductor technology, and field-effect modulation is possible at very low voltages, offering the prospect of power-efficient devices. In field-effect modulation, the active material is subjected to a voltage bias, which results in either an injection or depletion of free carriers. An increase in carrier density locally enhances losses and decreases permittivity; a carrier-density decrease has the opposite effect.

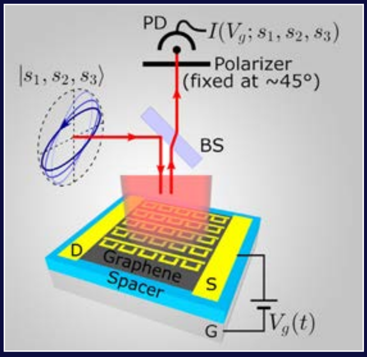
Bulk metals, which have large carrier densities, don't allow appreciable field-effect tuning of optical properties. Materials such as transparent conducting oxides (TCOs), however, have lower carrier concentrations, leading to larger relative changes under an applied bias and enabling strong modulation of their optical properties. In TCOs, electrical gating creates an accumulation or depletion layer with a thickness of a few angstroms to a few nanometers, within which a substantial change in the complex permittivity occurs. Combining TCOs with plasmonic nanostructures—which concentrate the local field within a narrow gap—circumvents the small modulation region, allowing for compact, efficient devices.

When the phase-manipulation by individual pixels or meta-atoms can be individually controlled, this effect can be extended to dynamic beam-steering and focusing. In one example, researchers led by Junhyun Park and Byoung Lyong Choi achieved wide-angle beam steering through wavefront control with gate-tunable TCO metasurfaces, with independent control of phase and amplitude. Such multifunctional metasurfaces can initiate integrated on-chip electro-optical devices such as scanning systems for self-driving cars, lidar systems and nanofocusing systems in endoscopes.

An interesting aspect of field-effect modulation in TCOs—electromigration—can afford another route to changing optical properties. When an electric field is applied, ions from the contact can migrate into the conducting oxide through a dielectric, leading to growth and nucleation of the metal. Such filamentation alters the medium's effective thickness, changing its optical response at millivolt-scale biasing. This transport mechanism could open new directions in the development of metasurfaces for memristors.

Ultrafast polarimetry with a graphene metasurface

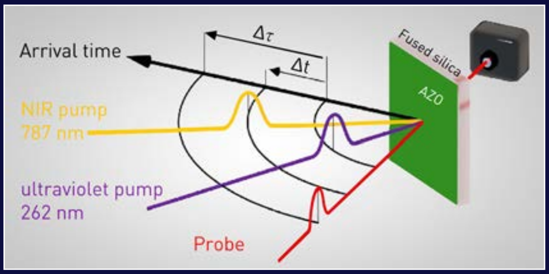
Permittivity shifts in ultrathin, monatomic films of the 2D material graphene have been used in mid-infrared polarimetry. Conventional polarization measurements require readings of light intensities by placing a polarizer and a quarter-wave plate at different angles and then



Graphene-enabled polarimetry

A graphene metasurface enables polarimetry in the mid-IR.

Reprinted with permission from M. Jung et al., ACS Photon. 5, 4283 (2018);



All-optical transistor

An infrared (intraband) pump increases transmission, and a UV pump decreases transmission; when both overlap with the probe, they cancel each other out.

M. Clerici et al., Nat. Commun. 8, 15829 (2017);

extracting the Stokes parameters. The group of Gennady Shvets experimentally demonstrated an electrically tunable anisotropic metasurface that performs polarimetry. The gate-tunable metasurface's Stokes parameters are measured *a priori* at multiple values of the gate voltage. Afterwards, by fitting to a simple model, all normalized Stokes parameters of the incident light incumbent on the graphene metasurface can be determined. Here, the speed of polarimetry is determined by the gating speed of graphene and can reach tens of MHz, orders of magnitude faster than conventional methods.

All-optical transistors

All-optical control is perhaps the fastest way to dynamically tune a material's optical properties. In all-optical switches, a pump light pulse changes the optical properties of the controlled metasurface, which in turn modifies the response of another, probe light pulse. This is the optical equivalent of a transistor—one in which photons control photons. In all-optical modulation, the switching speed is not limited by the resistive–capacitative delays of an electrical circuit, enabling potential computation speeds beyond those possible with electronics.

When a material is excited with an optical pulse, the incoming photons interact with electrons. If the energy of the photons is above the material's band gap, electrons are excited to the conduction band, making the material more metallic. If the energy is lower than the band gap, the electrons are energized, decreasing the absorption. This changes the reflectance, transmittance and absorbance of the metasurface. In contrast to electrical gating, where the accumulation or depletion region is typically a few angstroms thick, in all-optical switching the refractive-index change occurs over the material's entire skin depth, spanning tens to hundreds of nanometers.

Utilizing the epsilon-near-zero enhancements of nonlinearities, our lab, along with researchers at Herriot-Watt University, U.K., demonstrated all-optical addition of signals in TCO films at femtosecond timescales. Other groups have demonstrated all-optical switching in direct-band-gap semiconductor-based metasurfaces and epsilon-near-zero metasurfaces, with switching speeds spanning picoseconds to femtoseconds.

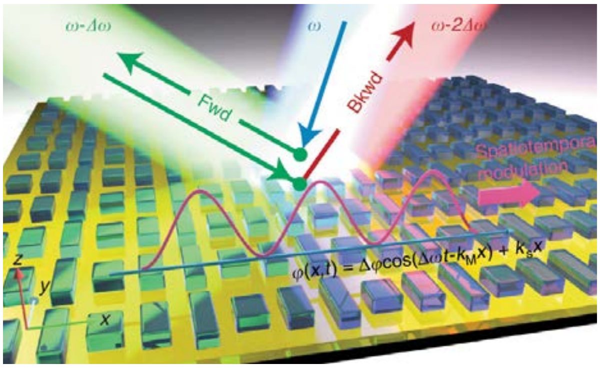
Enabling new physics

The large power requirements of all-optical switches still represent an obstacle to their commercial availability. But in the experimental lab, when the optical properties of metasurfaces are modulated at an ultrafast temporal scale—particularly the sub-picosecond timescale enabled by all-optical control—the door can open to new physics and to exotic physical phenomena.

Bending light in space and time. In classical refraction, a refractive-index change from n_1 to n_2 across a spatial boundary alters the wave vector of light passing through the boundary, as described by the basic equation $n_1\lambda_1 = n_2\lambda_2$. The velocity and wavelength change, but frequency is conserved. The relationship is used to describe the bending of light in space—but can light also "bend" in time?

In such time-refraction, an optical pump pulse that excites electrons suddenly and briefly changes the material's optical properties, creating a refractive-index boundary defined in time. This time-dependent index change causes the frequency of probe light passing through the boundary to change, while conserving the wave vector ($n_1f_1 = n_2f_2$). The frequency of the probe redshifts if the pump beam lags the probe, and blueshifts if the pump leads the probe. Time-varying metasurfaces can be used to accelerate photons, generating higher-harmonic signals through optical pumping. The time refraction in such materials can also be used to design nonreciprocal devices and to study topological effects in the time domain.

Optical velocity cloaking. The frequency shift obtained in time-varying metasurfaces is analogous to the conventional Doppler shift observed when light reflects from a moving object—but is achieved by a stationary metasurface whose optical properties vary with time. This can have applications in the design of Doppler cloaks, by which



A nonreciprocal device

In one active-metasurface nonreciprocal device, a parametric process arising from dynamic phase modulation converts light with frequency ω impinging on the metasurface to a reflecting beam with frequency ω – Δω, while the back-propagating beam with frequency ω – Δω is converted to ω – 2Δω instead of ω. The result is nonreciprocal light reflection at a specific wavelength.

X. Guo et al., Light Sci. Appl. **8**, 2047 (2019);

When the optical properties of metasurfaces are modulated at an ultrafast temporal scale, the door can open to new physics and to exotic physical phenomena.

dynamic metasurfaces at the surface of moving targets can be used to modify or compensate for the actual Doppler shift, cloaking its velocity from an observer or a detector.

Optical isolation. The ultrafast permittivity tuning afforded by optically tunable metasurfaces unlocks new possibilities for optical isolators—a crucial ingredient for avoiding back-scattering from defects or boundaries in laser and communication systems. Metasurfaces could have an advantage here over conventional optical diodes, which rely on bulky magnetic components.

When the index or the phase profile of a metasurface is modulated in time, a forward-propagating optical wave "sees" a different optical response than a backward propagating wave; as a result, light only propagates forward, but not backward. For example, a nanometer-thick temporally modulated metasurface can demonstrate nonreciprocal light reflection at wavelengths around 860 nm, making such devices a viable option to replace lossier or bulkier magneto-optic isolators.

Toward a meta-future

As this broad survey suggests, metasurfaces tunable by any of a combination of methods can allow dynamic amplitude, phase and polarization modulation—intriguing for a variety of applications. But while great progress has been made in realizing dynamic metasurfaces in the lab, their incorporation into actual devices and applications will depend on a variety of practical considerations, such as power consumption, chip area, fabrication compatibility, robustness and price.

These issues of practical implementation are ultimately rooted in materials science. For example, CMOS-compatible compounds capable of large, reversible changes in permittivity, with ultrafast relaxation times and acceptable energy consumption, would greatly accelerate the large-scale implementation of tunable metasurfaces. Forming a proper material foundation for tunable metasurfaces will require a comprehensive investigation on the permittivity modulation limits of new and existing tunable materials, under different stimuli such as voltage, light and heat.

The large power-requirements of all-optical modulators involving nonlinear optical elements can be reduced by designing perfect absorbers and high-quality-factor metasurfaces and resonators that can offer large on–off ratios at low powers. Power consumption can also be reduced by operating at longer wavelengths, where a small change in the free-carrier concentration results in a large change in the refractive index. Even newer methods of active control, like chemical modification, electromigration and magneto-optic switching, are increasingly showing routes toward more control over the optical properties of materials. And incorporating global-optimization and machine-learning techniques into metasurface design promises to greatly accelerate progress.

All this calls for multidisciplinary research approaches that combine materials science, theory and engineering to expand the horizons of material platforms for tunable metasurfaces. With the ever-accelerating progress in design techniques, and ever-broadening databases of tunable optical materials, the future of metasurfaces seems bright indeed. OPN

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Optical control

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