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METASURFACES for quantum technologies

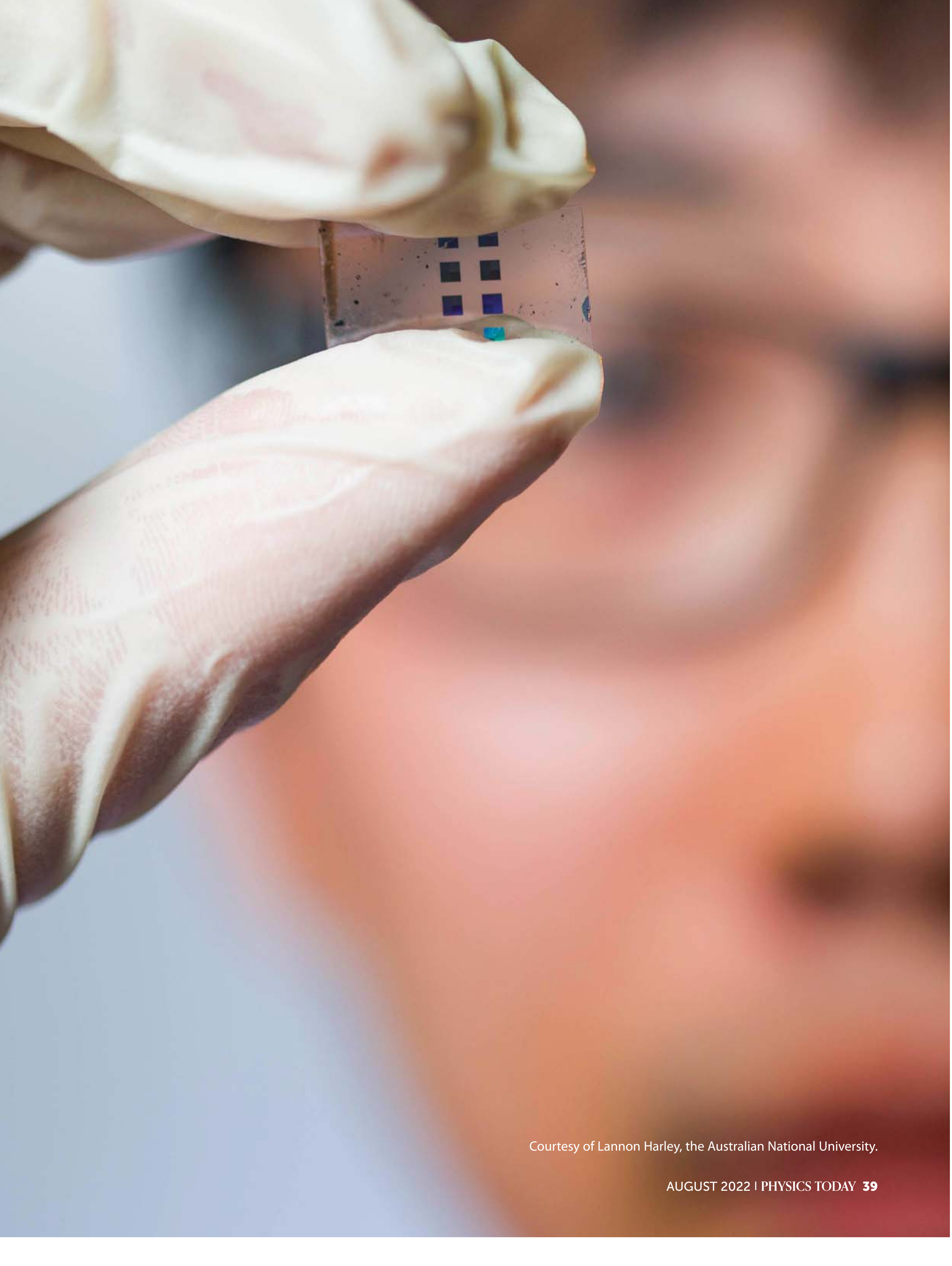
Kai Wang, Maria Chekhova, and Yuri Kivshar

Subwavelength planar structures can generate, reshape, and entangle photons in a compact and stable device.

In the past decade, optical metasurfaces have become increasingly popular tools for bending, focusing, and otherwise transforming light. They precisely control light–matter interactions with subwavelength structures. The planar surfaces comprise metallic or dielectric optical resonators that manipulate electromagnetic waves in specialized and novel ways.[1,2] The idea of pairing light scattering with planar optical structures isn't new: For more than 50 years, researchers have designed diffractive optical elements that serve as beam shapers, beamsplitters, and diffusers.[3] But metasurfaces are more efficient and adaptable than diffractive components and can provide flexible control of light–matter interactions.

Conventional optical components guide electromagnetic wavefronts as light propagates in a bulk medium along optical paths of different lengths. Metasurfaces, on the other hand, control the phase, amplitude, and polarization of light waves within a distance much less than the wavelength.[2,4] The resulting optical elements and devices are effectively two-dimensional, offer new functionalities, and outperform their traditional bulk counterparts.[4–6]

Metasurfaces consist of carefully arranged subwavelength unit cells, often called meta-atoms. The optical response of a meta-atom depends on its height, width, material, and other properties. To achieve the desired functionality in an optical component, researchers fabricate an array of meta-atoms whose parameters vary across the device based on their specific contribution. Meta-atoms can operate as subwavelength resonators[5,7] (see box 1), or they can contribute to effective averaged parameters.[4]


Courtesy of Lannon Harley, the Australian National University.

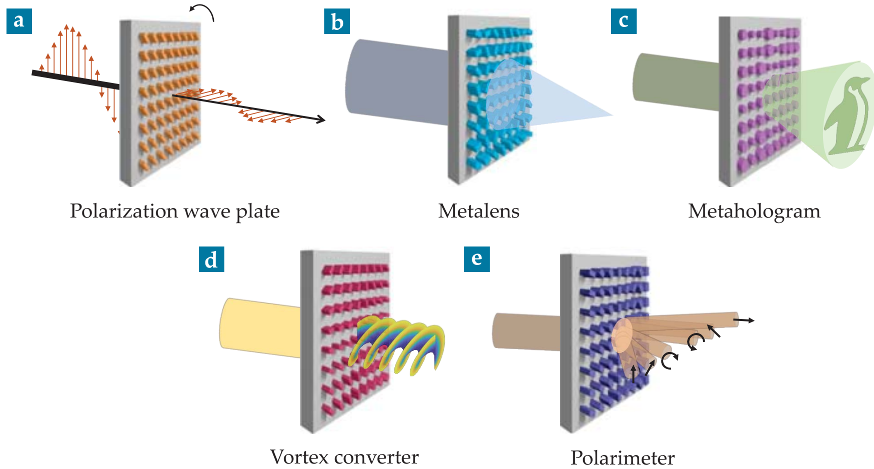


FIGURE 1. METASURFACES use subwavelength structures to manipulate light's wavefront. They can **(a)** rotate light's polarization, **(b)** focus light, **(c)** generate three-dimensional images, **(d)** change light's orbital angular momentum, **(e)** separate light based on polarization, and more. The ultrathin devices can replace bulky traditional classical-optics components.

Optical metasurfaces have demonstrated many functionalities, such as those depicted in figure 1, and sometimes even several at once. Many of those applications constitute promising alternatives to conventional bulky optical elements and devices. The metasurfaces are ultrathin, lightweight, and ultracompact and may overcome some limitations of their traditional counterparts. Metasurfaces may soon replace bulky traditional wave plates, vortex converters, lenses, and holograms operating at many frequencies. After successfully using them in classical-optics applications in the past decade, scientists have recently expanded the use of metasurfaces to the quantum realm.[8]

From classical to quantum

In quantum information science and technology, photons are ideal information carriers. But encoding and transforming information in them requires new types of optical devices beyond classical ones. The flexibility, compactness, and high efficiency of metasurfaces are factors that make them promising quantum optics candidates.

The quantum states of light needed for quantum technologies include single photons and entangled photon pairs, among others. All those states have properties that cannot be described by classical theories of light. Free-space quantum optics components are essential tools to control those states, because they can readily access multiple intrinsic degrees of freedom, such as polarization, orbital angular momentum (OAM), and frequency. So far, most free-space applications rely on bulk optical elements, including beamsplitters, wave plates, and mirrors, many of which are designed to be dynamically reconfigurable to tune device behavior. Although those platforms have enabled the demonstration of quantum computation with linear optics,[9] they are challenging to align, bulky, prone to losing photons, and mechanically unstable, which introduces errors.

Metasurfaces can replace many of those bulky optical elements in quantum light applications in free space and at the interface between free space and photonic devices. As a conceptual illustration, figure 2 depicts how a metasurface could simultaneously transform photons from M input ports and send them to M transmission outputs. One could encode quantum information in multiple degrees of freedom: two degrees of freedom from the polarization, M_ω degrees of freedom from the frequency, M_O from the OAM, and M from the different spatial paths. For an input N-photon quantum state,

BOX 1. RESONANCES IN METASURFACES

Resonances substantially enhance the electric and magnetic fields, which is an important requirement for many functionalities. Several physical mechanisms are responsible for the field enhancement and mode engineering in metasurfaces, including local resonances, such as surface plasmon resonances; Mie resonances of individual nanoparticles; and collective resonances, such as guided-mode resonances and bound states in the continuum (BICs). For quantum applications, Mie resonances and BICs are particularly important.

Mie resonances are associated traditionally with the exact solutions to Maxwell's equations for the scattering of electromagnetic plane waves by spherical particles. In a broader context, they explain how high-index dielectric nanoparticles control light below the free-space diffraction limit, and recently, they have attracted attention because they can support optically induced electric and magnetic resonances of comparable strengths, which underpin the emerging field of Mie-tronics.[7]

BICs are light states that remain localized despite their energy residing in the continuous radiation spectrum of the surrounding propagating modes. They have attracted considerable interest because they provide a mechanism for long-term trapping of electromagnetic energy in open resonators. A true BIC is a mathematical object with an infinite quality factor Q, which is defined as the ratio of the resonance frequency to its spectral width. In practice, a BIC can be realized as a quasi-BIC—produced by what's known as a supercavity mode—where both the Q factor and the resonance width are finite. High-Q quasi-BIC modes enable light localization in conventional photonic structures, such as nanoantennas, coupled optical waveguides, and metasurfaces.

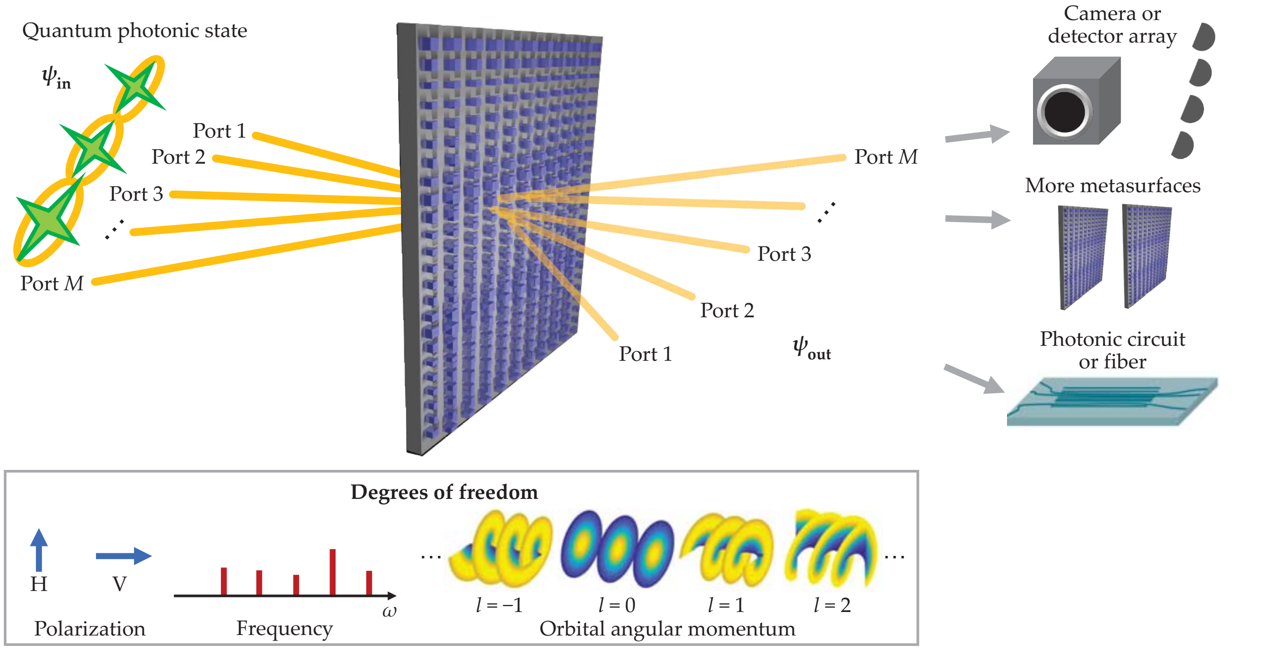


FIGURE 2. IN QUANTUM OPTICS, information can be encoded in light's polarization (horizontal H or vertical V), frequency ω, orbital angular momentum (given by quantum number l), and other properties. A metasurface can transform that information as it transmits photons from M input ports in state ψ_{in} to M output ports in state ψ_{out}. Those outputs can then lead to other optical elements, such as single-photon sensitive cameras, additional metasurfaces, and integrated photonic circuits or fiber interfaces, depending on the application.

the total number of degrees of freedom scales exponentially with N as $(2 \times M_\omega \times M_O \times M)^N$. The metasurface transforms an input state into a wide range of output states. Although the simplest metasurface designs offer static transformations, applying electric fields and many other emerging methods can dynamically tune the metasurface to make the transformations reconfigurable.

The metasurface's outputs can be used for quantum imaging, for example, which aims to improve imaging resolution, signal-to-noise ratio, and spectral range through clever applications of quantum entanglement. Cameras with single-photon sensitivity, such as single-photon avalanche photodiode image sensors, or arrays of single-photon detectors, such as superconducting nanowires, would then precisely measure the photons. Alternatively, the output could lead to other optical elements, such as additional metasurfaces or photonic circuits or fibers.

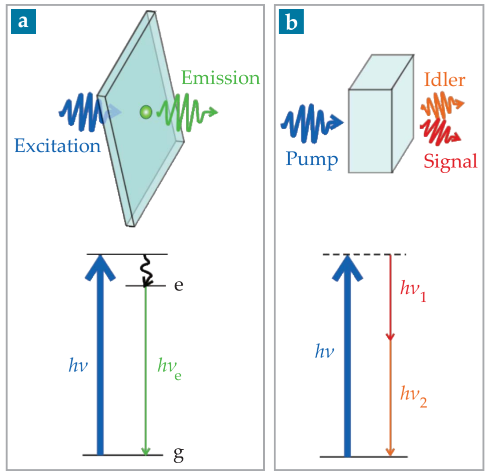
Many experimental efforts have demonstrated the use of metasurfaces for quantum state manipulation. One of the early explorations generated entanglement using the polarization and OAM of single photons.[10] In that 2018 work, Mordechai Segev and Erez Hasman of the Technion–Israel Institute of Technology and their colleagues directed a beam of linearly polarized single photons toward a metasurface that converted them to a superposition of states with OAM quantum number $l = 1$ and left-handed circular polarization and with $l = -1$ and right-handed circular polarization.

In another work, two of us (Wang and Kivshar) and our colleagues designed a metasurface that reconstructs the polarization states of N photons.[11] The design used one of M potential spatial input ports and sent the N photons that entered the port to the M possible output ports. Each output port projected the photon's polarization state to a judiciously designed polarization basis, and a detector was placed at each port. The detectors collectively measured the probability of N photons arriving at N ports simultaneously, known as N-photon nonlocal correlations. By repeatedly measuring the correlations between the measurements at the output ports, we reconstructed the density matrix of the N-photon polarization state—in our case, up to $N = 2$—which contains information about amplitude, phase, quantum entanglement, and coherence. The metasurface-based approach is scalable because the required number of output ports scales linearly with the photon number. What's more, fabrication imperfections can be accounted for with a one-time calibration measurement.

Metasurfaces are also particularly suitable for achieving nonunitary transformations—that is, state evolution that doesn't conserve energy. Such transformations can provide novel regimes for photon-state manipulation. For example, Xiang Zhang of the University of California, Berkeley, and his colleagues demonstrated that a nonunitary metasurface can tune the interference behavior between two photons.[12] The metasurface served as a beamsplitter with two spatial input ports and two spatial output ports, but it had an anisotropic phase response, a phenomenon that is responsible for the nontrivial losses behind the nonunitary response. By rotating the metasurface, Zhang and his team continuously tuned the photon interference between bosonic behavior, where the photons coalesced, and fermionic behavior, where they remained separate.

Andrey Sukhorukov's group at the Australian National University designed and realized a metasurface that performed nonunitary transformations to change the polarization states and degree of entanglement of two photons.[13] The nonunitary metasurface was made of silicon patterned with alternating

BOX 2. OBTAINING SINGLE PHOTONS AND PHOTON PAIRS



Single photons and photon pairs are the simplest quantum light states available in the lab. Single photons (see panel a) are emitted by atoms or their solid-state analogues—quantum dots, organic molecules embedded in crystals, or color centers in diamond—as they spontaneously transition from an excited state (e) to a ground state (g). They typically get into that excited state through a stimulated transition: a pump photon of energy $h\nu$ (blue arrow) followed by a relaxation to level e (black arrow). Then they spontaneously transition down (green arrow). Classical optics cannot explain such spontaneous transitions; their description requires a quantized field. A simple explanation is that the transitions are stimulated by the vacuum field. Although normally the vacuum field populates all radiation modes uniformly, it can be enhanced for certain modes—here, at the frequency ν_e—because of an optical cavity or a resonance. That enhanced vacuum field, in turn, enhances the spontaneous emission.

Photon pairs are most easily obtained through nonlinear optical processes, the simplest one being spontaneous parametric down-conversion, shown in panel b. In SPDC, a pump photon splits into two daughter photons, called a signal and an idler. The process is similar to the spontaneous emission of single photons: A pump photon (blue arrow) excites the nonlinear material to a temporary virtual state, and then the spontaneous transition returns the system to the ground state. That transition, which is mediated by the material's second-order susceptibility, produces a pair of photons (red and orange arrows). Similar to a single-photon transition, an enhanced vacuum field caused by a resonance—in this case, at one or both of the frequencies ν_1 or ν_2—increases the probability of a two-photon transition.

rectangular cuboids such that the diffractive loss depended on the input polarization state. Such a nonunitary metasurface can transform the polarization of a pair of photons in the same path from any arbitrary initial states to any desired final states.

Generating quantum light

Replacing bulk linear optical elements with metasurfaces is not enough to implement quantum technologies on ultrathin platforms. Those platforms must also generate quantum states of light. The resonances in metasurfaces, explained in box 1, are essential for that task.

Resonances act not only on incident light; they can also enhance the efficiency of spontaneous light emission. The enhancement is best understood in terms of vacuum fluctuations—the tiny and transient electromagnetic fields that inevitably fill space even at zero temperature. In a meta-atom, resonances increase the vacuum fluctuations at certain frequencies and decrease them in the rest of the spectrum, similar to the Purcell effect in optical cavities. The resonances boost the spontaneous emission of single photons and photon pairs, as explained in box 2. Moreover, they shape the spectrum and direction of the emitted light.

That enhanced spontaneous emission is, for a few reasons, particularly useful in conjunction with quantum dots and other sources of single photons. First, most single-photon sources have insufficient photon-emission rates for many practical applications. Second, they typically emit photons in a broad range of directions, which makes the radiation hard to collect. Finally, in most cases, the sources emit a broad spectrum of light, in which individual photons remain distinguishable and thus not suitable for quantum technologies. All those problems can be solved by embedding single-photon emitters into resonant metasurfaces.

Figure 3a shows the effect of a gallium arsenide metasurface on embedded indium arsenide epitaxial quantum dots.[14] The metasurface consists of nanoresonators with broken symmetry: Instead of perfect cubes, each resonator has a corner removed. That broken symmetry leads to a quasi-bound state in the continuum (BIC) resonance, which is a trapped light state with a sharp frequency (see box 1). The BIC is at a wavelength close to 1200 nm with a quality factor Q of about 100—as a result, within a bandwidth of about 12 nm, the spectral density of vacuum fluctuations is amplified 100-fold. Accordingly, the emission of a quantum dot, otherwise broad and not too bright (the black curve in figure 3a), is enhanced about two orders of magnitude within a narrow spectral range (blue curve). The resonance also makes the quantum dot emit preferentially in the direction normal to the metasurface.

Today, only four years after that original study, more advanced designs yield quasi-BIC resonances with Q factors as high as 10^4. Those resonances promise further enhancement of spontaneous emission and further shaping of the emission's spectrum and directivity. Metasurfaces can also shape the polarization by, for example, making a quantum dot emit differently polarized photons in different directions—an example of multifunctional operation.

Photon pairs

Last year one of us (Chekhova), Frank Setzpfandt at the University of Jena, and our research groups used metasurfaces as sources of entangled photons through a mechanism called

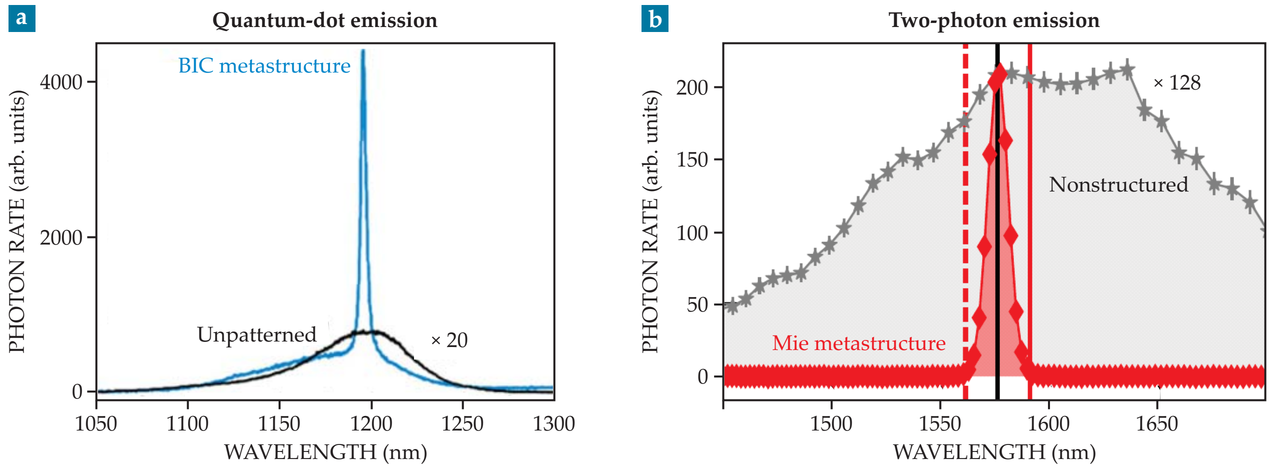


FIGURE 3. RESONANCES in metasurfaces enhance and shape the emission of quantum light. **(a)** In a gallium arsenide metasurface, resonances known as quasi-bound states in the continuum (BICs) sharpen and enhance the emission from an embedded indium arsenide quantum dot (blue) compared with the quantum-dot emission in a nonstructured GaAs layer (black). (Adapted from ref. 14.) **(b)** In a lithium niobate metasurface, the emission of photon pairs by a process known as spontaneous parametric down-conversion is also dramatically enhanced within a narrow spectral range (red) compared with the emission from a nonstructured lithium niobate layer (gray). (Adapted from ref. 15.)

spontaneous parametric down-conversion (SPDC), in which a material is excited by one photon and then emits two photons to return to the ground state[15] (see box 2). In that experiment, we fabricated a lithium niobate crystal with trapezoid-shaped single meta-atoms that each had what's known as a Mie-type resonance (see box 1). As shown in figure 3b, that resonance at 1591 nm led to an increase in the pair generation rate (solid red line) by two orders of magnitude within a 15 nm band, compared with the emission from the unstructured layer of the same material.

As in any nonlinear effect, SPDC in bulk crystals requires phase matching. In terms of photons, phase matching is equivalent to momentum conservation: The momentum of the pump photon is fully passed to the two daughter photons, called the signal and the idler. Similarly, energy conservation dictates that the frequency of the pump photon is equal to the sum of the daughter-photon frequencies. In thin materials, such as metasurfaces, energy conservation is still valid, but momentum conservation in the direction normal to the surface is relaxed. That relaxation follows from the uncertainty relation; restricting the source of photon pairs in space allows any value of their total momentum.[16]

The result is that thin sources of SPDC can emit photons in any direction and at any wavelength. The gray profile in figure 3b, for a nonstructured ultrathin layer of lithium niobate, illustrates just how broad the SPDC spectrum can be. Structuring the lithium niobate such that it has a Mie resonance concentrates the vacuum fluctuations in a narrow band, so photon pairs are efficiently emitted only when the signal or idler photon is resonant. The strongest enhancement occurs when both signal and idler photons are at resonance: The red curve shows an enhancement of two orders of magnitude in the two-photon emission rate in a narrow band near the resonance.

The relaxed momentum conservation for SPDC in metasurfaces also introduces flexibility in the choice of pump photon frequency. If the pump photon frequency is not double that of the resonance, the total energy is split unequally between the two daughter photons. The signal photon takes the resonance wavelength, and the idler takes the wavelength needed to conserve energy. Chekhova, Igal Brener of Sandia National

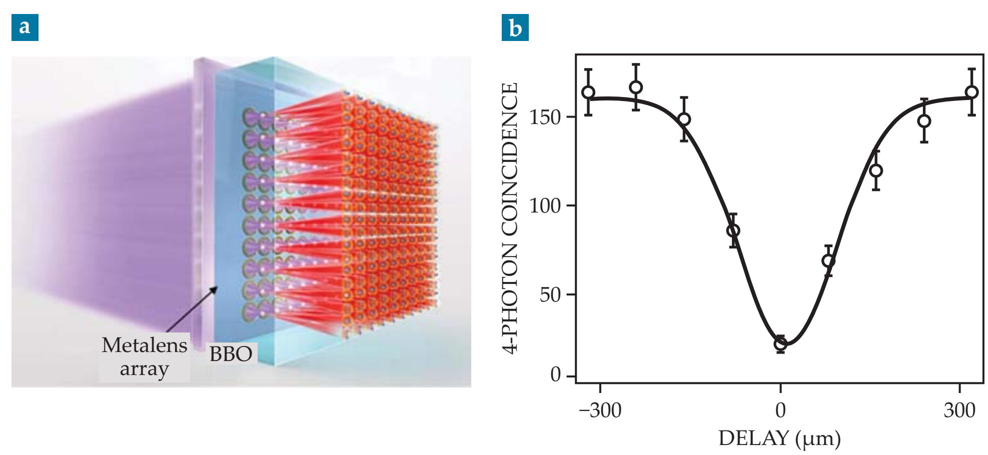


FIGURE 4. A METALENS ARRAY creates a multipath quantum source. **(a)** The nonlinear crystal device produces photon pairs (red) from each circular lens embedded in the beta-barium borate (BBO) crystal. **(b)** A pair of neighboring lenses produces four indistinguishable photons, which interfere and therefore cause a dip in the number of detected photon quadrupoles. (Adapted from ref. 18.)

Laboratories, and their research groups recently implemented such two-color SPDC in a BIC metasurface consisting of broken-symmetry GaAs resonators, similar to the metasurface that enhanced quantum-dot emission (shown in figure 3a). In that work,[17] the signal and idler wavelengths differed by about 50 nm. They can be separated even more by choosing other pump photon wavelengths.

A metasurface can offer multiple channels for SPDC photon-pair generation and higher-dimensional entanglement. For example, Din Ping Tsai of National Taiwan University and his colleagues implemented a multipath photon-pair source in a metasurface lens array integrated in a beta-barium borate crystal[18] (see figure 4a). The 10-by-10 metalens array forms a multichannel pump that, in turn, generates photon pairs in 100 channels. The researchers demonstrated four-photon and six-photon generation in which the photons from different lenses were highly indistinguishable. The dip in the measured four-photon coincidences at zero delay in photon arrival times (figure 4b), and similarly for six-photon coincidences, indicates that the photons have coalesced because of their indistinguishability. That metasurface-based quantum photon source can easily switch between various high-dimensional entangled quantum states.

Metasurfaces produce, route, and manipulate quantum states of light, which will be useful for free-space quantum communication, quantum information, quantum computation, and quantum imaging. Their key strength is the simultaneous control over many parameters of the quantum states. One promising application is integrating metasurfaces with single-photon-sensitive cameras as a sort of quantum camera lens. The metasurface could then transform the light as needed for fast imaging-based measurements of quantum states. On their own, metasurfaces may provide a path to numerous applications, including unbreakable encryption and quantum information on a chip.

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REFERENCES

1. A.V. Kildishev, A. Boltasseva, V. M. Shalaev, *Science* **339**, 1232009 (2013).
2. N. Yu, F. Capasso, *Nat. Mater.* **13**, 139 (2014).
3. P. Lalanne, P. Chavel, *Laser Photonics Rev.* **11,** 1600295 (2017).
4. H.-H. Hsiao, C. H. Chu, D. P. Tsai, *Small Methods* **1**, 1600064 (2017).
5. K. Koshelev, Y. Kivshar, *ACS Photonics* **8**, 102 (2021).
6. C.-W. Qiu et al., *Nano Lett.* **21**, 5461 (2021).
7. Y. Kivshar, *Nano Lett.* **22**, 3513 (2022).
8. A. Solntsev, G. Agarwal, Y. Kivshar, *Nat. Photonics* **15**, 327 (2021).
9. H.-S. Zhong et al., *Science* **370**, 1460 (2020).
10. T. Stav et al., *Science* **361**, 1101 (2018).
11. K. Wang et al., *Science* **361**, 1104 (2018).
12. Q. Li et al., *Nat. Photonics* **15**, 267 (2021).
13. S. Lung et al., *ACS Photonics* **7**, 3015 (2020).
14. S. Liu et al., *Nano Lett.* **18**, 6906 (2018).
15. T. Santiago-Cruz et al., *Nano Lett.* **21**, 4423 (2021).
16. C. Okoth et al., *Phys. Rev. Lett.* **123**, 263602 (2019).
17. T. Santiago-Cruz et al., http://arxiv.org/abs/2204.10371.
18. L. Li et al., *Science* **368**, 1487 (2020).

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