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PERSPECTIVE

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Metasurfaces for quantum photonics

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Rapid progress in the development of metamaterials and metaphotonics allowed bulky optical assemblies to be replaced with thin nanostructured films, often called metasurfaces, opening a broad range of novel and superior applications of flat optics to the generation, manipulation and detection of classical light. Recently, these developments started making headway in quantum photonics, where novel opportunities arose for the control of non-classical nature of light, including photon statistics, quantum state superposition, quantum entanglement and single-photon detection. In this Perspective, we review recent progress in the emerging field of quantum-photonics applications of metasurfaces, focusing on innovative and promising approaches to create, manipulate and detect non-classical light.

Recent years have seen a resurgence of diffractive optics, enabled by advances in the nanofabrication of large-area arrays of metallic and dielectric nanoresonators with high precision, reasonable throughput and relative ease of production. These developments opened up a new era of so-called flat optics, with key components called metasurfaces (two-dimensional structures composed of optically thin arrays of scatterers, such as subwavelength-sized antennas), which are increasingly used to replace whole sets of traditional optical elements[1–9]. These devices enable efficient beam steering, local control of optical polarization and enhancement of the emission and detection of light[10–14].

Metasurfaces possess unique capabilities to fully control light within a subwavelength layer[15]. That includes wavelength- and polarization-selective control of complex diffraction. Moreover, metasurfaces enable new physics and a range of phenomena that are distinctly different from what can be achieved in bulk optics or 3D metamaterials. One such example is the generalized law of reflection and refraction, where metasurfaces can be utilized for the redirection of an incident beam by employing antenna arrays with prescribed phase gradients, while ensuring unprecedented design flexibility with complete control of both amplitude and phase. Metasurfaces can also tailor near-field responses, which is crucial when dealing with optical sources and detectors, enabling perfect absorption, emission enhancement and detailed design of light–matter interaction properties.

Metasurfaces have now become a staple in classical optics, and there is increasing interest in bringing novel functionalities enabled by flat photonics to the realm of quantum optics[16]. Quantum optical technologies require sources of single photons, entangled photons and other types of non-classical light, as well as newer methods of detection. The quantum states could be based on different degrees of freedom of light polarization, direction and orbital angular momentum. Metasurfaces have great potential for the realization of each of these states, as we discuss here. We first draw attention to the demonstration of the quantum interference[17,18] of two independent photons at a classical optical device (a beam splitter), which allows entanglement manipulation—a milestone in the field of quantum optics. However, a beam splitter is a simple device that can only change its reflectivity, and thus does not have much functionality. Metasurfaces have much broader functionality and have great potential to manipulate single photons and produce a wide variety of multiphoton entangled states. For example, a metasurface can entangle the orbital and spin degrees of freedom, whereas a beam splitter cannot. Some of these applications have started to appear in the past few years or even months, and they will be discussed below. We also note that the detection of non-classical light carrying useful information, such as small phase changes introduced by an object, requires special methods as the measurement of intensity does not give complete information on non-classicality. The most prominent non-classical detection methods are measurements of the intensity correlations and statistics[19] and homodyne detection analysis[20]. Ideally, one would like to have full photon statistics, and with the availability of single-photon edge sensors, it is becoming possible to distinguish between signals with one photon and two photons[21], for example. Other types of quantum measurement, such as the weak values associated with the state[22], are being successfully implemented using metasurfaces.

Non-classical optics has a wide range of applications in quantum communications[23,24], computation[25], random number generation[26,27] and sensing[28–30]. Utilizing quantum-mechanical effects such as photon indivisibility, quantum superposition and entanglement offer the prospect of a quantum revolution, with qualitative improvements in a wide range of technologies. Quantum optical internet could provide security ensured by the laws of physics, with small-scale implementations already showing notable progress[31,32]. Distributed quantum computation facilitated by quantum optical links is poised to enable ultrafast simulations of complex quantum systems with subsequent advances in medicine, chemistry and material science[33]. Quantum-enhanced optical sensing is already revolutionizing cutting-edge measurements[34,35]. All of the above could benefit substantially from the physics of metasurfaces, providing compact, fast and precise control of quantum photonic states.

In this Perspective, we review major directions in this recently emerged research field by looking at how metasurfaces can be employed to generate, manipulate and detect non-classical light. We discuss three major directions, illustrated schematically in Fig. 1. Generation includes the integration of metasurfaces with single-photon emitters based on quantum dots[36] and solid-state colour centres[37,38], 2D arrangements of subwavelength nonlinear sources of non-classical light based on spontaneous parametric down-conversion (SPDC)[39] and implementations of metasurface concepts in atomic quantum optics[40]. The manipulation of

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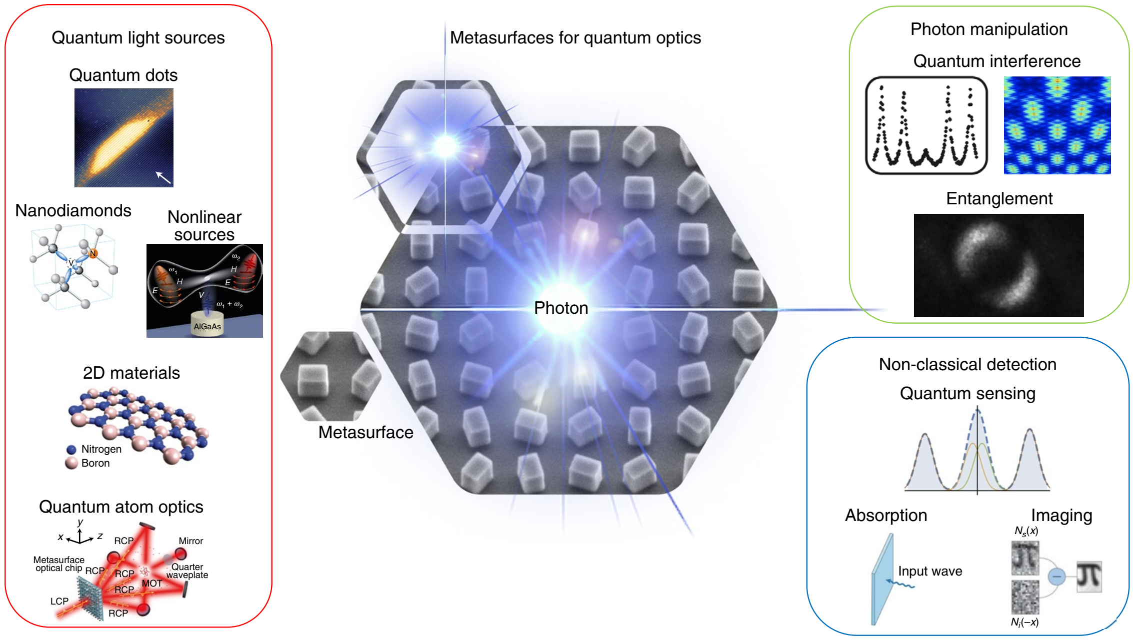

Fig. 1 | Quantum optics with metasurfaces. Illustration of different cases of interaction between optical metasurfaces and photons, with three major directions discussed in this Perspective: quantum light sources (left), photon manipulation (top right) and the non-classical detection of light (bottom right). Quantum light sources include quantum dots[36], nanodiamonds[37], nonlinear optical methods able to entangle *H* and *V* polarizations of electric field *E* (ref. [39]), 2D materials[38], and atomic optics, where a metasurface can for example be used to focus left and right circular polarizations of light (LCP and RCP, respectively) into a magneto-optical trap (MOT)[40]. Photon manipulation involves the control of key effects in quantum optics—interference[41,42] and entanglement[7]. Non-classical detection includes quantum sensing[44], perfect absorption[48], and quantum imaging, where $N_{s/i}(x)$ stands for the number of signal/idler photons detected in the position *x*, illustrating the subtraction of the quantum correlated noise pattern[49]. Insets adapted with permission from: refs. [7,40], AAAS; ref. [36], MDPI; refs. [37,38,41,44,48,49], Springer Nature Limited; refs. [39,42], OSA. Distributed under Creative Commons license CC BY 4.0.

photonic states focuses on the utilization of metasurfaces for the control of quantum interference[41,42] and quantum entanglement[7,43], enabling a range of application such as quantum information processing and complete quantum state tomography. Metasurfaces can be used for quantum-enhanced sensing[44], weak measurements that do not destroy quantum states[45–47], perfect absorption[48] of single photons and quantum imaging[49].

Quantum light sources

Nanophotonics is attractive for enhancing the generation of single photons and photon pairs for further processing and coupling to optical circuitry, and is considered to be one of the critical enabling technologies for quantum communication and computation systems[50]. In this context, the coupling of non-classical light sources to metasurfaces enables enhanced emission control beyond that provided by single nanoparticles. The use of metasurfaces in nonlinear and atomic quantum light systems considerably increases their non-classical functionalities.

Single-photon emitters. The conventional approach to the realization of a single-photon source is to make use of spontaneous emission from a single two-level system emitting one photon at a time—the so-called quantum emitter—that can be selected from various structures, including dye molecules, quantum dots and colour centres in crystals. The advantage of such emitters is that one has a source of single photons with a well-defined wavelength, and these are deterministic sources of single photons. Besides, a number of fundamental aspects can be investigated, such as cooperative and many-body effects, which can lead to both emitter–photon and emitter–emitter entanglement. However, the radiative lifetimes of quantum emitters, often on the order of 10 ns, are too long to meet the speed requirements of optical communication and information-processing systems. The rate of spontaneous emission can, however, be increased by placing a quantum emitter in a suitable photonic environment with an increased electromagnetic local density of states, as discussed in the literature[51,52]. This concept has been reviewed by Vaskin et al. in the context of light-emitting metasurfaces[53]. In this approach, shown schematically in Fig. 2a, a metasurface can be employed as a special photonic environment that provides novel ways to manipulate and control quantum light with flat optics.

Iwanaga et al.[54] demonstrated that the photoluminescence response of sparsely distributed quantum dots embedded in semiconductors coupled to plasmonic metasurfaces (Fig. 2b) can undergo a significant increase in activity, and become superlinear with respect to the excitation laser intensity under weak excitation. The photoluminescence response was examined at room and cryogenic (9 K) temperatures, showing that hot electrons mostly contribute to superlinear photoluminescence responses at room temperature, whereas induced transitions between the excitonic levels in the quantum dots are significant at 9 K. This demonstration may have important implications for the realization of efficient single-photon-emitting devices.

Wu et al.[55] achieved lasing by using an extremely high-quality bound state in the continuum. They used an array of dielectric cylinders, which produced a bound state in the continuum that was then coupled to semiconductor colloidal nanoplates. Even more importantly, they were able to tune the lasing wavelength by changing the diameter of the cylinders. Similar approaches may be extended to non-classical emission regimes.

Paniagua-Domínguez et al.[56] fabricated a metalens with near unity numerical aperture and subwavelength thickness. These

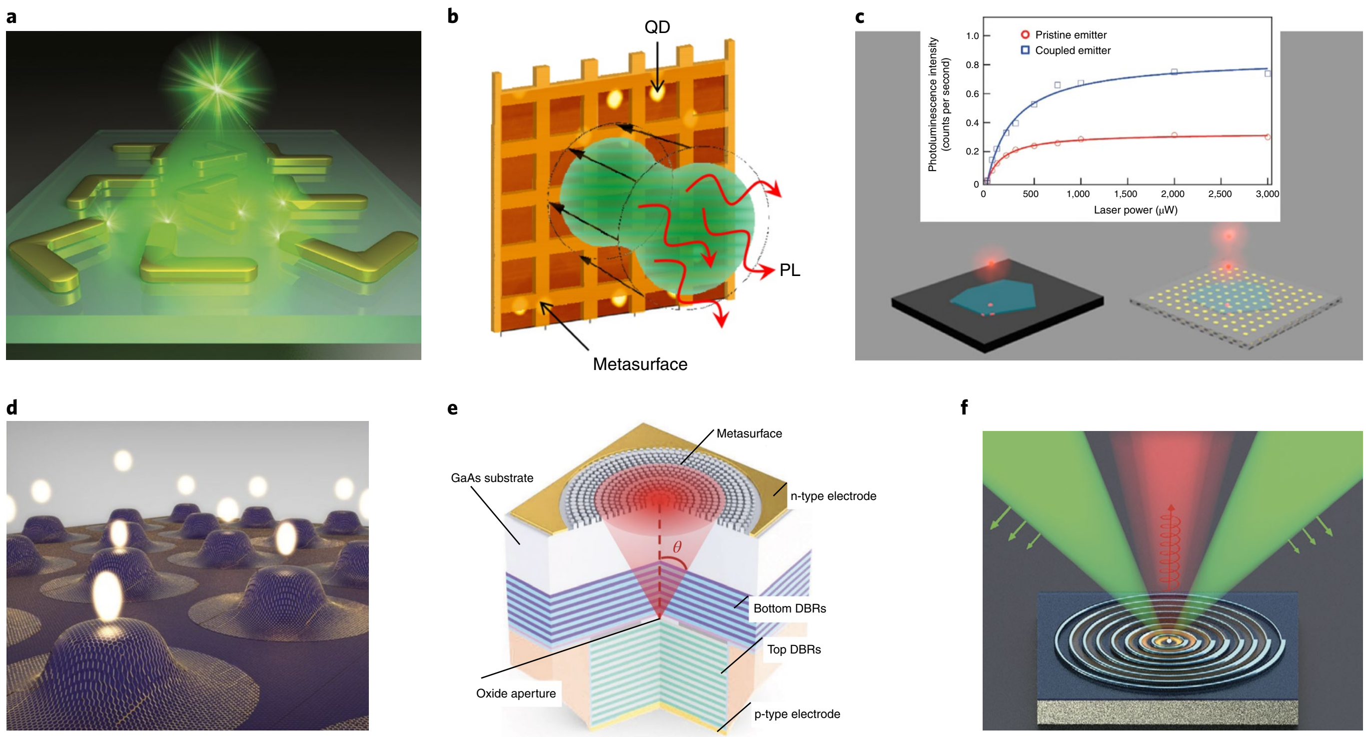

Fig. 2 | Integration of single-photon emitters with metasurfaces. **a**, Illustration of a single quantum emitter interacting with metasurface scatterers featuring Purcell enhancement. **b**, Plasmon metasurface coupled to quantum dots (QDs) for superlinear photoluminescence (PL). Black arrows show pump direction, red arrows show quantum dot emission. **c**, Deterministic coupling of single quantum emitters in 2D hBN with a plasmonic nanocavity array, showing the enhancement of the emission rate (see the inset for increased photoluminescence from a coupled emitter compared to a pristine emitter). **d**, Single-photon emitters in 2D hBN activated by a metasurface comprised of silica pillars. The activation is induced by strain. **e**, Metasurface for programmable directional emission integrated with a vertical cavity surface-emitting laser. DBR stands for a distributed Bragg reflector, θ is the collection angle. **f**, Metasurface-enabled generation of circularly polarized single photons. Green arrows represent pump polarization, red arrows show single photon polarization. Figure adapted with permission from: ref. [53], De Gruyter (**a**); ref. [54], ACS (**b**); ref. [57], ACS (**c**); ref. [59], OSA (**d**); ref. [60], Springer Nature Limited (**e**); and ref. [61], Wiley (**f**). Distributed under Creative Commons license CC BY 4.0.

authors showed how such a lens can be used to collect light from colour centres in nanodiamonds. This metalens substantially extends the range of collection angles, and is able to efficiently bend light at angles as large as 82°. This significantly increases the collection efficiency of photons from quantum emitters compared with the conversional approach.

Two-dimensional materials such as graphene, hexagonal boron nitride (hBN) and transition metal dichalcogenides can also serve as single-photon sources. Compared with semiconductor quantum dots, these materials can be integrated more easily with photonic metasurfaces. One of the most straightforward ways to utilize such integration is for Purcell enhancement. Tran et al.[57] showed that quantum emitters in 2D hBN can be deterministically coupled to a plasmonic nanocavity array. As shown in Fig. 2c, Purcell enhancement in the weak coupling regime when coupled to a plasmonic metasurface leads to enhanced emission rates and reduced fluorescence lifetimes. Importantly, the single-photon statistics in this case is largely preserved, as demonstrated by the value of the normalized second-order intensity correlation for zero delay time.

Following the demonstration of large-scale quantum-emitter arrays in atomically thin WS_2 at a cryogenic temperature by Palacios-Berraquero et al.[58], Proscia et al.[59] showed that single-photon emission from defects in hBN at room temperature cannot only be amplified via integration with a metasurface, but the single-photon-emitting defects themselves can also be induced via strain when hBN is placed on top of a specially designed metasurface. Figure 2d shows an illustration of emitters in hBN activated when strain is introduced by an array of silicon rods. This finding is important because it allows near-deterministic activation of sites for single-photon emission. Through the combined control of strain and external electrostatic potentials, Proscia et al.[59] demonstrated the realization of arrays of room-temperature single-photon sources with well-defined positions.

Another important contribution to metasurface optics has recently been revealed by Xie et al.[60]. As shown in Fig. 2e, a metasurface integrated with the back side of the substrate can be combined with a light source for the purpose of beam shaping. In this design, centrosymmetric GaAs nanopillars of different diameters are used as polarization-insensitive meta-atoms. The light source in question is a vertical cavity surface-emitting laser, but the same approach is also expected to work to obtain directional emission of non-classical single-photon sources. This work shows that such metasurface integration enables highly efficient arbitrary control of the emission beam profiles, including self-collimation, and the formation of Bessel and Vortex beams.

Extending this approach to non-classical light, Kan et al.[61] showed that dielectric metasurfaces can be used for the generation of highly directional circularly polarized single photons. As shown in Fig. 2f, in this work a nanodiamond containing a single nitrogen vacancy centre that can emit single photons was placed in the centre of an optical metasurface composed of concentric periodic width-varying dielectric nanoridges atop a thin dielectric film on a metallic substrate. The arrow with a helix in the red beam illustrates a collimated stream of circularly polarized single photons, whereas

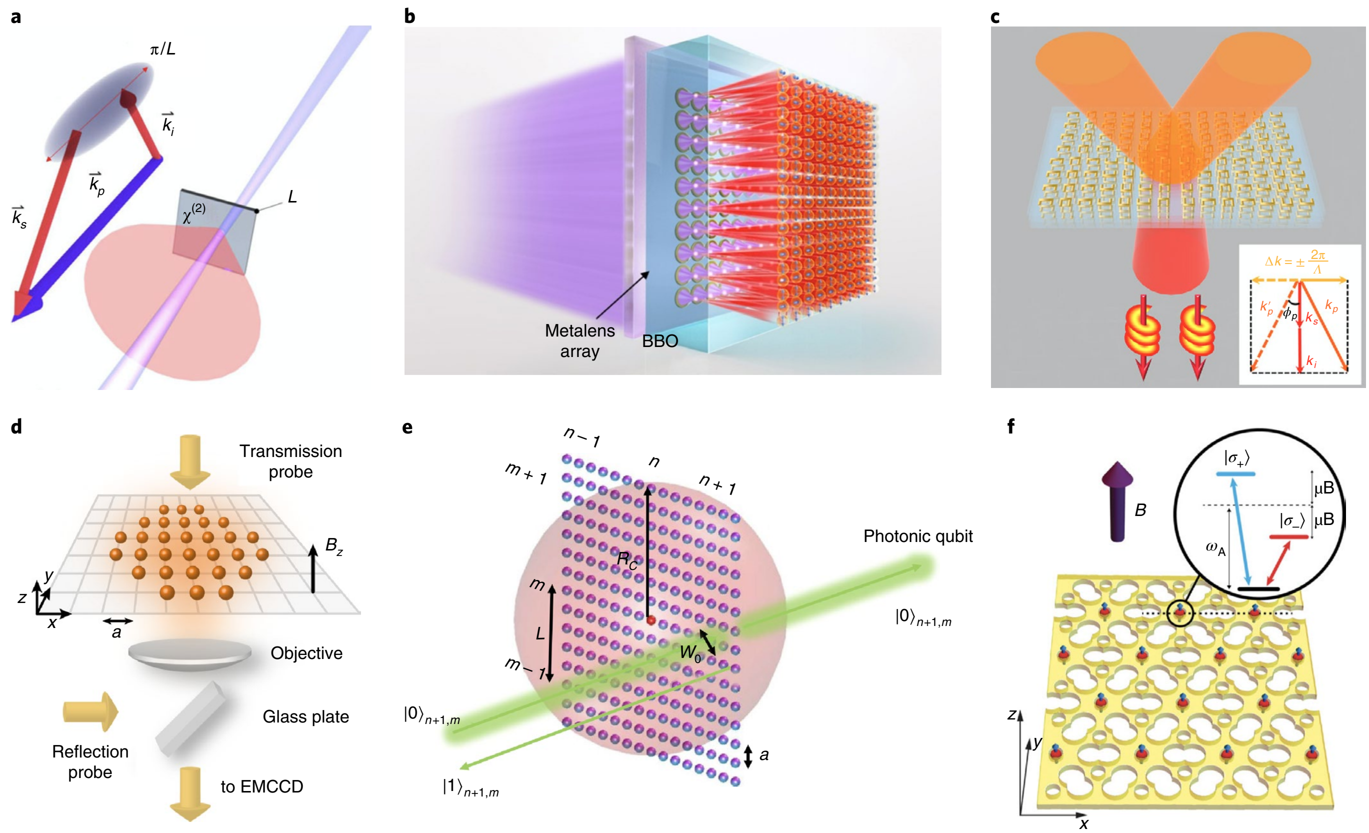

Fig. 3 | Nonlinear and quantum metasurfaces. a, Generation of entangled photons without momentum conservation. $\mathbf{k}_p$, $\mathbf{k}_s$ and $\mathbf{k}_i$ are wave vectors for pump, signal and idler, respectively, L is the interaction length. **b**, Metalens multiphoton quantum source based on barium borate (BBO). **c**, Illustration of the parametric down-conversion process in the nonlinear metamaterial. The inset shows the geometry of photon interactions, where Λ is the modulation period and Φ_p is the angle between pump and signal/idler wave vectors. **d**, Set-up to study the cooperative response of the atomic lattice with period a, acting as a mirror for circularly polarized light after applying magnetic field **B** polarized in z direction. **e**, Quantum metasurface based on a 2D lattice of atoms. The considered parameters are the interaction strength $R_c/a = 57$ and mode width $W_0 = 1.56\lambda$, where λ is the wavelength. **f**, Photonic membrane dielectric metasurface with an embedded triangular lattice of quantum emitters. Figure adapted with permission from: ref. [66], APS (**a**); ref. [70], AAAS (**b**); ref. [71], Wiley (**c**); ref. [77], Springer Nature Limited (**d**); ref. [78], Springer Nature Limited (**e**); and ref. [79], APS (**f**).

the green cones represent a tightly focused radially polarized pump beam. In this configuration, a single-photon chirality of 0.8 and high directionality leading to a collection efficiency of 92% can be achieved.

Nonlinear metasurfaces. With metasurfaces composed of planar lattices of optical subwavelength resonators, one can miniaturize substantially nonlinear photon sources[62,63] that utilize spontaneous four-wave mixing or SPDC. It should be noted that SPDC is at the present the most versatile source of heralded single photons and entangled photon pairs over a large region of spectrum; it continues to be the workhorse of the community. Thus, it is desirable to enhance the efficiency of conversion. The use of ultrathin metasurfaces may allow quantum entanglement between photons at ultrashort timescales across the visible and infrared regions, leading to new opportunities for quantum spectroscopy, sensing and imaging. This has not yet been realized experimentally, although the first modelling steps have been taken recently[64].

Phase-matching-free spontaneous four-wave mixing was reported earlier, but only in the degenerate regime[65]. Figure 3a illustrates a more recent observation of SPDC free of phase matching with a frequency spectrum an order of magnitude broader than that of phase-matched SPDC[66]. Replacing a thin nonlinear membrane with a structured nonlinear metasurface incorporating AlGaAs nanodisks, for example, would enable enhanced photon-pair generation via SPDC[39]. This will provide the potential for generating photons with tailored quantum entanglement for nonlinear quantum spectroscopy, quantum sensing and ghost imaging[67–69].

The generation of photon pairs in nonlinear materials enables the creation of non-classical entangled photon states. By integrating a metasurface lens with a nonlinear BBO crystal, as shown in Fig. 3b, one can realize a multipath SPDC photon-pair source. This is promising for high-dimensional entanglement and multiphoton state generation. Such a structure was realized by Li et al.[70] for a 10×10 metalens array. They demonstrated four-photon and six-photon generation with high indistinguishability of photons generated from different metalenses. This metasurface-based quantum photon source is compact, stable and allows easy switching between various high-dimensional entangled quantum states, representing a promising new platform for integrated quantum photonic devices.

The generation and modulation of photonic entanglement based on parametric down-conversion processes in a nonlinear plasmonic metasurface was studied by Ming et al.[71]. Through flexible nanostructure design, it is possible to tailor the nonlinear photonic interaction in the metamaterial system; the spatial properties of the generated photonic state can be steered as desired (Fig. 3c). It is possible to give a vortex structure to the second-order nonlinearity, which facilitates the generation of a range of entangled states of orbital angular momentum. This theoretical framework is based on the nonlinear Huygens–Fresnel principle and a differential approach utilized to mitigate the intrinsic loss of the system. This platform could be valuable for applications in quantum information processing.

Quantum metasurfaces and atomic arrays. The metasurface platform for on-chip quantum state engineering offers a promising route for scaling from two-qubit to many-body entanglement by introducing a multifunctional metasurface. The metasurface approach is especially promising when applied to atomic arrays and emitters[72–76]. As these metasurfaces enable photonic multitasking, optical trapping of the qubits can be assigned as additional independent functionality to the primary task of manipulating the flow of photons. These functionalities can be combined with topological properties.

Rui et al.[77] reported the direct observation of the cooperative and directional subradiant response of a 2D square array of atoms in an optical lattice: a quantum metasurface. They observed a spectral narrowing of the collective atomic response well below the quantum-limited decay of individual atoms into free space. Through spatially resolved spectroscopic measurements, they demonstrated that the array acts as an efficient mirror formed by only a single monolayer of a few hundred atoms. Figure 3d illustrates the atomic lattice probed by circularly polarized light. For transmission, both the probing and the residual transmitted fields at the plane of the atoms were collected and imaged. The metasurface contained around 200 atoms in this experiment.

Substantial efforts have now been focused on structuring the properties of light with metasurfaces. The next step is to explore the possibility of generating atom–photon entanglement between atomic metasurfaces and non-classical light to control the many-body entangled photonic states. Such quantum metasurfaces can be realized by preparing and manipulating entangled states of atomic reflectors and scattering light from them, constituting a new platform for manipulating both classical and quantum properties of light. Figure 3e illustrates a quantum metasurface realized by entangling the macroscopic response of atomically thin arrays to light[78]. Such a system allows for parallel quantum operations between atoms and photons, as well as for the generation of highly entangled photonic states and 3D cluster states suitable for quantum information processing.

Perczel et al.[79] suggested an experimentally feasible nanophotonic platform for exploring many-body physics in topological quantum optics. Their system is composed of a 2D lattice of nonlinear quantum emitters with optical transitions embedded in a membrane metasurface, as shown in Fig. 3f. The emitters interact through the guided modes of the metasurface, and a uniform magnetic field gives rise to wide topological bandgaps, robust edge states and a nearly flat band with a nonzero Chern number. In the schematic of Fig. 3f, the out-of-plane magnetic field B splits the $|\sigma_+\rangle$ and $|\sigma_-\rangle$ atomic transitions.

Metasurfaces can also be used to redirect light to create cold atom ensembles. Zhu et al.[40] demonstrated an experimental implementation of an optical scheme in which a metasurface replaced multiple bulky optical elements, allowing the generation of a cold atom ensemble by using a single laser beam. In this miniaturized scheme, the authors were able to achieve atom numbers in the range of 10^7, and a temperature of 35 μK. These characteristics mean that this approach is suitable for quantum sensing, making metasurfaces highly attractive for the generation of cold atom ensembles.

These results demonstrate efficient optical metasurface engineering based on structured ensembles of atoms and pave the way towards controlled many-body physics with light, as well as novel light–matter interfaces at the single quantum level.

Photon manipulation with metasurfaces

Some of the earliest demonstrations of the interaction between metasurfaces and non-classical light were in the field of plasmonics. Altewischer et al.[80] investigated the effects of nanostructured metallic films on the properties of entangled photons. As shown in Fig. 4a, an optically thick metal film perforated by a periodic array of subwavelength holes was placed in the confocal telescope (TEL) in the paths (A1 and A2) of the two entangled photons generated by a BBO crystal and controlled by a half-wave plate (HWP). The metasurface converted photons into surface plasmon waves, and the question was whether photon entanglement, which is critical for many quantum optical applications, would survive the conversion into plasmons. The entanglement after going through the plasmonic metasurface was well maintained, despite substantial losses. This work has opened the field of metasurfaces for quantum optical manipulation, enabling the use of plasmonic, and later dielectric, metasurfaces in quantum photonics.

Quantum interference. The principal manifestations of quantum light are associated with non-classical interference, which is an enabling phenomenon for the manipulation of quantum states in a variety of applications. It is known that the fluctuation properties of the quantum vacuum are determined by the propagators or the Green's tensors $G_{ij}(r, r', \omega)$, where r is the point of observation, r' is the point of origin, and ω is the frequency (ref.[81]). The free-space propagators are isotropic leading to $G_{ij}(r, r', \omega) = \delta_{ij}$, where δ_{ij} is Dirac's delta function. However, in the presence of a finite-sized medium or metasurface, the isotropy is broken, and the quantum vacuum becomes anisotropic with significant consequences. For example, G_{xx} not equal to G_{zz}, which in turn results in new quantum interferences. Following the prediction of quantum interference in anisotropic environment[82], Jha et al.[83] demonstrated theoretically that metasurfaces can be used for remote quantum interference engineering. In this model (Fig. 4b), a specially designed metasurface created strongly anisotropic quantum vacuum in the vicinity of a quantum emitter at a distance d much larger than wavelength λ. In this case, the metasurface can induce quantum interference among radiative decay channels, thus opening a path to the engineering of long-range interactions in solid-state systems and quantum atom optics.

Quantum emitters can also be integrated with anisotropic metasurfaces, which can couple the levels of a quantum emitter through the quantum interference effect, leading to remarkable chiral effects. Kornovan et al.[84] recently predicted that a combination of the metasurface anisotropy and tilt of the emitter quantization axis with respect to the anisotropic metasurface normal results in non-symmetric dynamics between the transitions from the left-circular state to the right-circular state. It was shown that for four-level atoms with an s to p transition placed near an anisotropic metasurface, an effective optical activity can emerge due to the anisotropy of the system through the quantum interference of the multiple decay channels of the emitter. This effect offers new avenues to the engineering of nanoscale quantum optical systems.

Quantum-emitter long-lifetime coherence can also be controlled by metasurfaces, as predicted recently. Lassalle et al.[85] designed a metasurface to act as a spherical mirror while inverting the absolute rotation direction of the electric field with respect to that of the incident circularly polarized one. This inversion of the electric field rotation can be achieved by using nanoantennas, which act as half-wave plates, as the result of the π phase shift between the long and short axes of the nanoantennas. The result is the creation of a long-lifetime coherence between the two ground states of a quantum emitter, which can be viewed as a first step towards controlling the interactions between several quantum emitters with metasurfaces and generating quantum entanglement.

It has been known for decades that any discrete unitary operator could be realized using conventional optics[86]; however, this approach remained difficult to scale before the arrival of nanophotonics. Recent advances in nanotechnology enabled the integration of beam splitters and couplers in tailored plasmonic structures, yet

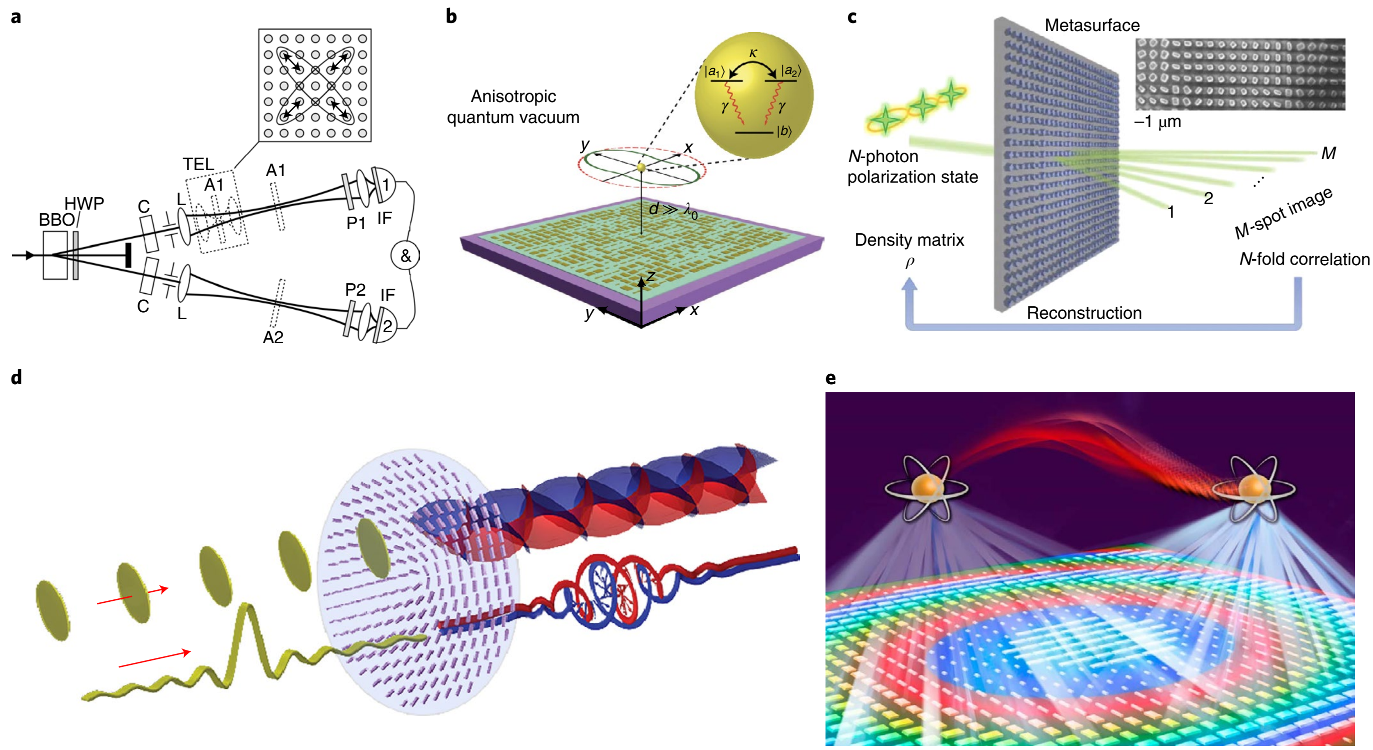

Fig. 4 | Photon manipulation by metasurfaces. **a**, Photon entanglement transmitted thorough a plasmonic metasurface. After the generation, photon pairs pass through compensators C and are focused by lenses L into the arrays with holes A, after which they pass through polarizers P and interference filters IF into the coincidence scheme. **b**, Metasurface-enabled long-distance quantum interference. The inset shows a three-level atom with levels a_1, a_2 and b, and a dipole moment γ, where the coupling strength of the orthogonal transitions κ depends on the anisotropy of the quantum vacuum. **c**, Quantum optical state reconstruction based on a metasurface. The top-right inset shows a scanning electron microscope image of the fabricated all-dielectric metasurface with a scale bar of 1 μm. **d**, Quantum entanglement of photon orbital angular momentum and spin using metasurfaces. A single vertically polarized photon is arriving from the left, as illustrated by the yellow wave packet, with no orbital angular momentum, as illustrated by the yellow flat phase fronts. After passing through a metasurface (purple), it exits as an entangled state, depicted as a superposition of the red and blue electric field amplitudes, with the corresponding vortex phase fronts. **e**, Quantum entanglement between atomic qubits mediated by a metasurface. Figure adapted with permission from: ref. [80], Springer Nature Limited (**a**); ref. [83], APS (**b**); ref. [88], AAAS (**c**); ref. [91], AAAS (**d**); ref. [93], ACS (**e**).

such miniaturization came at the cost of material losses and complex photon–plasmon coupling interfaces that restrict the platform scalability[87]. Wang et al.[88] revealed an opportunity to break away from the conventions of lengthy sequential implementations or lossy plasmonic designs, and realized several multiphoton interferences in a single flat all-dielectric metasurface. This scalable approach is based on parallel quantum state transformations encoded in multiple metagratings across the photon beams, taking advantage of the transverse spatial coherence of the photon wavefunctions extending across the beam cross-section. This principle required considerable development for successful application to multiphoton states due to the high dimensionality of the Hilbert space spanned by the photon number and non-classical multiphoton interference features. This same approach could also be extended to arbitrary polarization state manipulation[89].

Metasurfaces should allow the reconstruction of the total multiphoton quantum state, including the phase, coherence and multiparticle entanglement. Wang et al.[88] realized an all-dielectric metasurface that spatially splits a tomographically complete set of components of a multiphoton polarization state, such that a simple averaging measurement of correlations with polarization-insensitive on/off detectors enables the accurate reconstruction of a multiphoton density matrix. Figure 4c shows a metasurface imaging multiphoton quantum-polarization states, where an input N-photon state is encoded in polarization. The correlation measurements between M output spots enable full reconstruction of the input N-photon quantum density matrix.

Quantum entanglement. Several recent realizations of metasurfaces have enabled intricate control of quantum entanglement. This is because specially designed metasurfaces allow the manipulation of the spin–orbit interaction, which was previously achieved using q plates[90]. Figure 4d shows recent experiments on the generation of entanglement between the spin and orbital angular momenta of photons by Stav et al.[91]. In this work, the photons from a pair were split, directing one through a unique metasurface and the other directly to a detector to signal the arrival of the other photon. The photon that passed through the metasurface was then measured, showing that it acquired orbital angular momentum and that it became entangled with its spin. In the second experiment, the photon pairs passed through the metasurface and were measured using two detectors to show that they had become entangled: the spin of one photon became correlated with the orbital angular momentum of the other photon, and vice versa.

It has been established[92,93] that a metasurface can be employed to mediate quantum entanglement between two qubits trapped on a metasurface and separated by macroscopic distances by engineering their coherent and dissipative interactions. As an example, Jha et al.[93] modelled two distant trapped atomic qubits positioned at a macroscopic distance from the metasurface. The metasurface shown in Fig. 4e was designed such that the spontaneous emission from the source qubit was efficiently directed towards the target qubit at the single-photon level. As a result of this interaction, quantum entanglement between the two qubits emerges instantly and lasts much longer than the lifetime of individual qubits. As such,

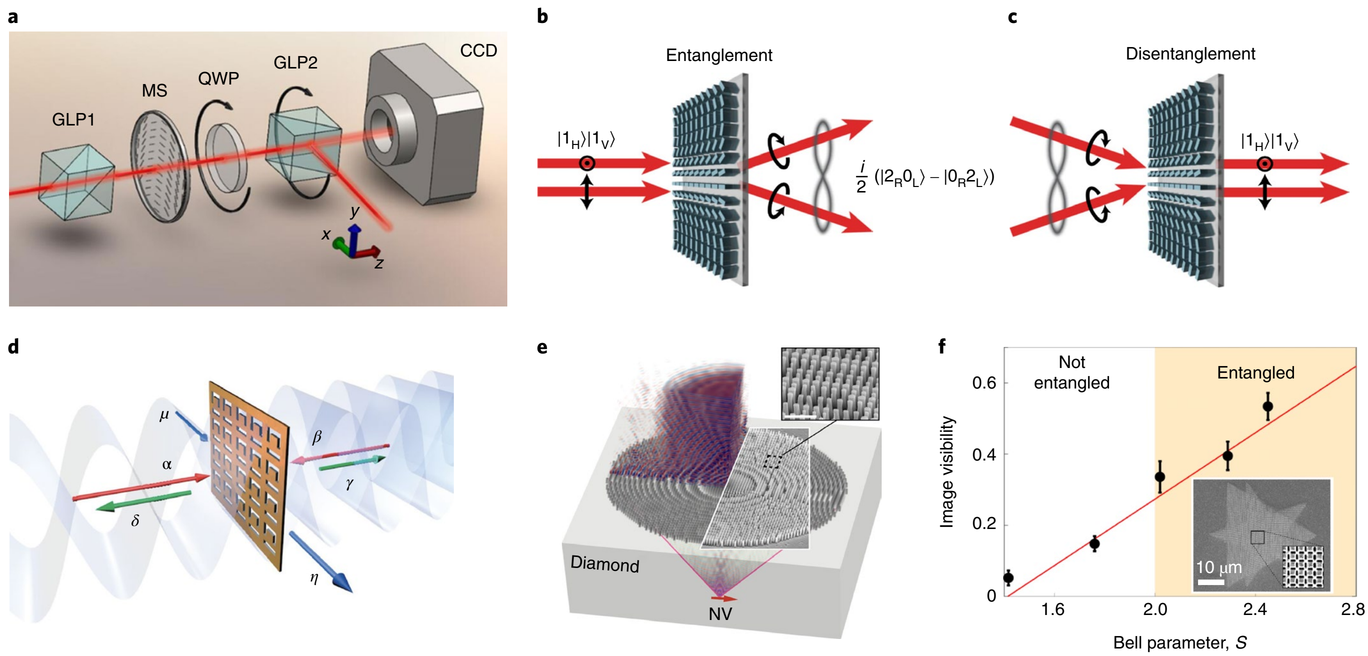

Fig. 5 | Detection of non-classical light with dielectric metasurfaces. a, The photonic metasurface (MS) version of the experiment on weak measurements. GLP is a Glan laser polarizer, CCD is a charge-coupled device, QWP is a quarter-wave plate. **b**,**c**, Spatial entanglement (**b**) and disentanglement (**c**) of a two-photon state at a metasurface. **d**, Schematic of metamaterial input and output ports. The interaction of two coherent beams in a thin absorber is shown, here represented as a plasmonic metasurface: the film is described as a lossy beam splitter with two input photon channels α and β, two photon output channels γ and δ and plasmon input and output channels μ and η. **e**, Diamond metalens used to collect and collimate the emission of an individual nitrogen–vacancy (NV) centre. The inset shows a scanning electron microscope image of the metasurface. **f**, Imaging with entangled photons. Image visibility for the triangle image is plotted versus the herald photon polarizer angle for increasing degrees of entanglement as measured by the Bell parameter *S*. Error bars are given by Poissonian statistics. The inset shows the metasurface used in the experiments. Figure adapted with permission from: ref. [94], AIP (**a**); ref. [95], Springer Nature Limited (**b**,**c**); ref. [100], Springer Nature Limited (**d**); ref. [102], Springer Nature Limited (**e**); and ref. [106], APS (**f**). Distributed under Creative Commons license CC BY 4.0.

spatially scalable interaction channels offered by the metasurface enable the robust generation of entanglement.

These examples demonstrate that metasurfaces can offer notable advantages for the non-classical manipulation of light, including intricate control of quantum correlations and entanglement.

Non-classical photon state detection and excitation with quantum light

In classical optics, metasurfaces show extraordinary abilities to manipulate the phase and polarization of light, and their applications can be extended to the quantum optics, including non-classical detection. In this context, metasurfaces improve the performance of a range of techniques, including weak measurements, interferometry-based sensing, quantum absorption and quantum imaging.

Quantum sensing. One of the important concepts in quantum optical detection that can be enhanced by metasurfaces is weak measurements. Chen et al.[94] employed a dielectric metasurface with a tiny phase gradient that keeps the measured system almost undisturbed, and thus may simplify existing schemes in quantum weak measurements. Three stages are generally involved in quantum weak measurements: a measured system is prepared in the initial state, then a weak coupling of an observable is introduced by a detector, then the final state of the system is post-selected. It is critical to introduce a weak coupling and to keep the measured system almost undisturbed. Here, the desired coupling strength can be obtained by tailoring the shape and size of the structural units of the dielectric metasurface. Note that in weak measurements, one works with initial and final states, which are nearly orthogonal, and one needs to have the capability to change the state. This is where Glan polarizers are useful, as one can change the pre- and post-selected states by arbitrary amounts.

Figure 5a shows the metasurface version[94] of the weak measurement experiment[22,45–47]. The initial state of the photon is preselected by a Glan laser polarizer (GLP1). The dielectric metasurface (MS) generates a small space-variant phase and plays the role of the weak magnetic field. The final state is post-selected by a second Glan laser polarizer (GLP2). Here, the dielectric metasurface introduces tiny momentum shifts to the photons. By designing the structure of the metasurface, any desired weak coupling strength between the device and the system can be obtained. In general, the tiny momentum shifts are introduced by different interferometer systems in quantum weak measurements. The weak measurements are particularly useful for resolving two nearby quantum states on the Poincaré sphere.

Next, we describe the recent demonstration of a hybrid integrated quantum photonic system with potential applications in quantum sensing. This metasurface is capable of entangling and disentangling two-photon spin states at a dielectric metasurface, as shown in Fig. 5b,c. A path-entangled two-photon *N*00*N* state with circular polarization that exhibits a quantum Hong–Ou–Mandel interference visibility of 86 ± 4% was generated via the interference of single-photon pairs at a nanostructured dielectric metasurface. Georgi et al.[95] demonstrated non-classicality and phase sensitivity in a metasurface-based interferometer with a fringe visibility of 86.8 ± 1.1% in the coincidence counts. Such a high visibility proves the metasurface-induced path entanglement inside the interferometer.

This approach offers exciting applications in sensing and quantum measurements based on interferometry. For example, a phase-changing object on the metasurface would introduce a relative phase between the two components of the output state in Fig. 5a resulting in a sensitive phase sensor. Another interesting possibility would be an interferometer with two metasurfaces with the phase object between them. Monitoring of changes in the output state would enable highly sensitive phase measurements up to the Heisenberg limit[96]. The generated entangled states could also be exploited in entangled microscopy to improve resolution[97].

Photon absorption. Many concepts in the physics of metasurfaces depend on the ability to absorb light very efficiently, and metasurfaces provide novel approaches such as coherent absorption. Extending the control of absorption down to very low light levels and eventually to the single-photon regime is of great interest. The absorption can be made very efficient by using interference of coherent beams so that the two absorption channels add, coherently leading to coherent perfect absorption, as first proposed by Wan et al.[98].

Coherent photon absorption with quantum light was first suggested by Huang et al.[99]. Later, Roger et al.[100] demonstrated the coherent absorption of single photons in a deeply subwavelength 50% absorber and revealed that while the absorption of photons from a travelling wave is probabilistic, standing wave absorption can be observed deterministically, with nearly unit probability of coupling a photon into a mode of the material (Fig. 5d). These results bring a better understanding of the coherent absorption process, which is of central importance for light harvesting, detection, sensing and photonic data processing applications.

A more recent work by Lyons et al.[101] extended this concept to photon pairs. Here, a metasurface was utilized to coherently absorb two-photon states with 40% efficiency. This concept is very promising, as multiphoton absorption processes have a nonlinear dependence on the number of photons, and engineering devices capable of absorbing pairs of photons efficiently is very challenging. In this paper, the demonstration of coherent absorption of $N=2$ $N00N$ states makes it possible to enhance the number of two-photon states that are absorbed by up to a factor of two with respect to a linear absorption process. This result is appealing for applications where multiphoton absorption is important but limited by damage induced by the high peak powers traditionally used in multiphoton experiments. These experiments lead to the possibility of manipulating quantum states such as squeezed states by using coherent perfect absorption and metasurfaces.

Quantum imaging. The process of making a visual representation plays an important role in optics, and metasurfaces have recently been shown to be a very promising platform in the field of non-classical imaging. This includes both the use of metasurfaces for classical imaging of single-photon emitters and imaging with non-classical light.

Huang et al.[102] developed a metalens for imaging of quantum emitters. They used a quantum platform based on diamond with nitrogen vacancy centres, which are known to harbour electron spins that can be manipulated at room temperature (Fig. 5e). Each nitrogen vacancy centre emits light that provides information about the spin's quantum state. A metasurface was fabricated on the surface of a diamond, acting like a metalens to collect photons from a single qubit in the diamond and direct them into an optical fibre. This is the first key step in efforts to realize compact quantum devices operating at room temperature.

Quantum entanglement is a key resource that can be exploited for a range of applications such as quantum teleportation, quantum computation and quantum cryptography. Efforts to exploit entanglement in imaging systems have so far led to solutions such as quantum imaging with undetected photons[103] and ghost imaging[67,104]. The latter, however, has found useful classical implementations—although with quantum light, one would expect better signal-to-noise ratio. In a recent work, Petrova et al.[105] showed how ghost imaging techniques can be used to characterize the infrared properties of metasurfaces using visible photons, which is important due to the varying availability of sensitive detection techniques depending on the wavelength range. Altuzarra et al.[106] demonstrated an optical imaging protocol that relies uniquely on entanglement. As shown in Fig. 5f, two polarizing patterns imprinted and superimposed on a metasurface are separately imaged only when using entangled photons. Unentangled light is not able to distinguish between the two patterns. Entangled photon imaging of functional metasurfaces promises advances towards the use of nanostructured subwavelength devices in quantum information protocols and a route to efficient quantum state tomography.

Conclusion and outlook

Recent intense efforts in developing the field of electromagnetic metasurfaces have focused on exploring the new physics that can lead to breakthrough applications in quantum photonics. Now active metasurfaces with external control of their characteristics, and the use of the flat optics to control quantum light and quantum properties such as single-photon emission and non-classical detection, will become crucially important.

Metasurfaces integrated with quantum emitters could be used as a special metadevices platform for quantum photon sources. In the regime of weak coupling, Purcell enhancement of quantum emitters or their enhancement of spontaneous emission rates, along with spatial multiplexing and directionality control, could enable the development of efficient single-photon sources for quantum optics. Besides the Purcell enhancement, this approach could also enable sensing of single atoms or molecules. Metasurfaces can be employed to manipulate many-body cooperative interactions among the emitters. In particular, metasurfaces could boost the efficiency of many processes such as Förster resonance energy transfer[107,108]. The strong coupling and ultrastrong coupling of emitters to metasurfaces need to be investigated in more detail. We also note the fundamental and practical advances in the realization of multiphoton quantum interference that take place at the subwavelength scale. These approaches may pave the road to novel types of ultrathin metadevices[109] for the manipulation and measurement of multiphoton quantum-entangled photon states. In addition, coherent perfect absorption could become an important technique for monitoring very weak absorption, as this would disturb the conditions for perfect absorption and any leaking light would be a measure of such absorption.

The unique properties of metasurfaces that allow the manipulation of photons (for example, the arrival of two photons together at a port or the arrival of one) and the production of states of non-classical light could find use in a variety of areas, including free-space communications and quantum imaging. A key strength of this system is that it enables complete quantum state measurements using simple polarization-insensitive single-photon click detectors. Combining the metasurface with single-photon-sensitive charge-coupled device cameras could allow multiple-timeframe images of quantum states. This type of metasurface is thus analogous to a quantum camera lens that allows fast imaging-based measurements of quantum states.

Metasurfaces themselves might become a novel type of enabling device for routing and manipulating non-classical light in quantum communications, quantum information processing and quantum computing, thereby providing a route to numerous practical applications including, among others, the development of unbreakable encryption, as well as opening the door to new possibilities for quantum information systems on a chip.

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