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Quantum metaphotonics: Recent advances and perspective

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Jihua Zhang ; Yuri Kivshar

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Jihua Zhang[1,2,a)] and Yuri Kivshar[2,b)]

AFFILIATIONS

[1] Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, People's Republic of China
[2] Research School of Physics, The Australian National University, Canberra ACT 2601, Australia

[a)] **Author to whom correspondence should be addressed:** zhangjihua@sslab.org.cn
[b)] **Electronic mail:** yuri.kivshar@anu.edu.au

ABSTRACT

Quantum metaphotonics has emerged as a cutting-edge subfield of meta-optics employing subwavelength resonators and their planar structures, such as metasurfaces, to generate, manipulate, and detect quantum states of light. It holds a great potential for the miniaturization of current bulky quantum optical elements by developing a design of on-chip quantum systems for various applications of quantum technologies. Over the past few years, this field has witnessed a surge of intriguing theoretical ideas, groundbreaking experiments, and novel application proposals. This Perspective aims to summarize the most recent advancements and also provides a perspective on the further progress in this rapidly developing field of research.

I. INTRODUCTION

Recent development of advanced photonic technologies underpins the rapid progress in efficient generation, manipulation, and detection of quantum states. One of the breakthroughs of modern photonics is the development of compact subwavelength-thick optical structures, such as *optical metasurfaces*. Metasurface physics can be viewed as the realization of a broader field of *metaphotonics* that enrich traditional optics with new concepts and functionalities provided by metamaterials. Being seemingly close to the two-dimensional realization of metamaterials, metasurface physics brings many novel physical concepts[1,2] and provides a planar platform to the design of compact, multifunctional, broadband, and fast optical components with tiny thickness, giving birth to a new generation of achromatic metalenses, diffractive elements, filters, polarization converters, and many others. Some years ago, it became clear that these achievements can be useful for the functionality and scalability required by large-scale quantum information processing. The use of subwavelength nanostructures can dramatically speed up quantum photonic processes, such as the spontaneous emission rate to enable high-speed single photon sources and overcome the rate of decoherence processes.[3]

Advanced concepts of metamaterials applied to quantum technologies hold great promise for the development of quantum metaphotonics. They offer the dramatic enhancement of single-photon emission from solid-state quantum emitters. The dramatic speed-up of the spontaneous emission may also allow quantum decoherence to be overcome and for the generation of indistinguishable photons even outside of cryostats. The use of resonant dielectric structures with low losses would allow us to open full potential of meta-optics for applications in the quantum domain.

This progress has been recognized in many recent publications being summarized in several review papers on this topic.[3–10] However, the potential of quantum metaphotonics and quantum metasurfaces is still being explored, and ongoing research continues to unlock new functionalities and applications. Over the past few years, we observe rapid developments of intriguing theoretical ideas, realizations of groundbreaking experiments, and proposals for novel applications.

The use of metaphotonic structures is expected to move the generation of quantum states of light to a new level. For quantum communication, metasurfaces can provide the states with enormous information capacity and fast switching capabilities. For quantum imaging, unprecedentedly tight photon–photon correlations will lead to the realization of super-resolution effects. Both quantum spectroscopy and quantum sensing may benefit from the availability of states with practically unlimited spectral bandwidth. On the other hand, resonant metasurfaces may produce very narrowband quantum states for coupling to other quantum systems. Finally, the research on quantum metaphotonics is expected to stimulate other fields, such as material science and quantum information.

This Perspective aims to summarize the most recent advancements and provide our personal view on the further development of this rapidly developing field of research. We shape our presentation of the most recent results around three major areas driven by selective functionalities of quantum metasurfaces and quantum metaphotonics elements, as depicted in Fig. 1. First, we discuss the use of flat optics for quantum light sources, including single-photon sources created by integrating metasurfaces with quantum emitters,[11] two-photon sources by employing nonlinear metasurfaces,[12] and multiphoton sources by integrating a metalens array with a nonlinear crystal.[13] Next, we discuss the use of metasurfaces for quantum light manipulation, including but not limited to quantum interference,[14] quantum state modulation,[15] and quantum logic gates.[16] Next, we overview several ideas for the use of metasurfaces for quantum light detection, including quantum sensing,[17] quantum state characterization,[18] and quantum imaging.[19] Accordingly, Secs. II–IV are devoted to the discussions of results in these three major directions. Finally, in Sec. V, we provide our perspective on the anticipated future developments in this rapidly growing field.

II. METAPHOTONICS FOR QUANTUM LIGHT SOURCES

In quantum photonics, non-classical light sources are needed for the implementation of quantum protocols and algorithms. These sources include the most commonly used single-photon and two-photon states, as well as more complicated multiphoton, squeezing,

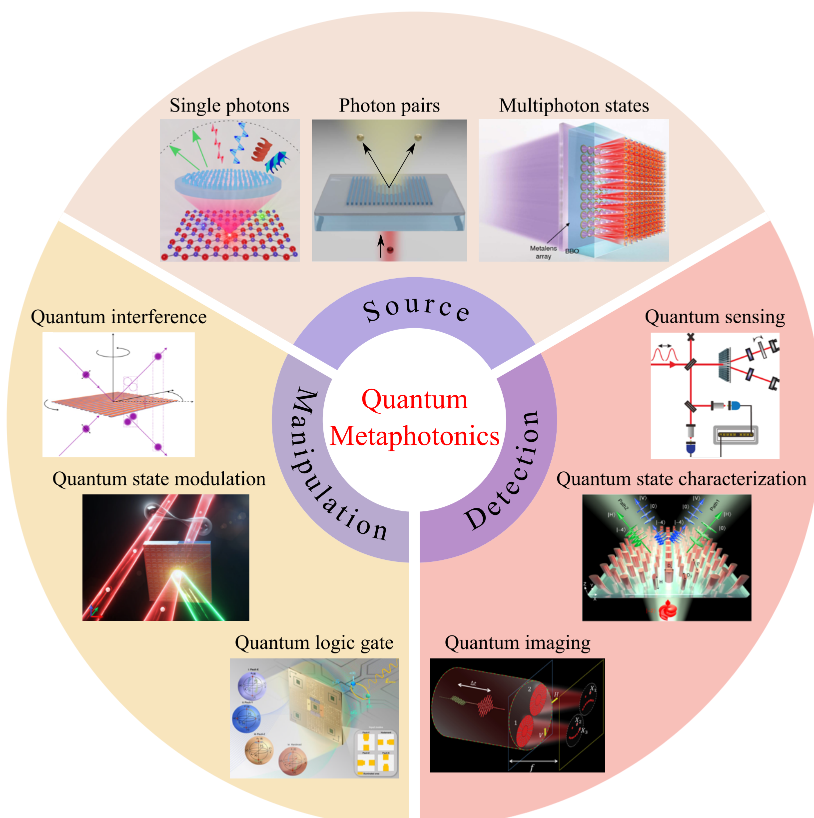

FIG. 1. Functionalities of quantum metaphotonics. Top: Quantum light sources: examples of single-photon source,[11] two-photon source,[12] and multiphoton source,[13] respectively. Left: Quantum light manipulation: interference,[14] state modulation,[15] and logic gates.[16] Right: Quantum light detection: sensing,[17] state characterization,[18] and imaging.[19] Li *et al.*, eLight **3**, 19 (2023). Copyright 2023 Author(s), licensed under a Creative Commons Attribution (CC BY) license. Zhang *et al.*, Sci. Adv. **8**, eabq4240 (2022). Copyright 2022 Author(s), licensed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). Reproduced with permission from Li *et al.*, Science **368**, 1487 (2020). Copyright 2020 AAAS. Reproduced with permission from Li *et al.*, Nat. Photonics **15**, 267 (2021). Copyright 2021 Springer Nature. Zhang *et al.*, Light Sci. Appl. **11**, 58 (2022). Copyright 2022 Author(s), licensed under a Creative Commons Attribution (CC BY) license. Ding *et al.*, Adv. Mater. **36**, 2308993 (2023). Copyright 2023 John Wiley and Sons. Georgi *et al.*, Light Sci Appl. 8, 70 (2019). Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license. Reproduced with permission from Wang *et al.*, Nano Lett. **23**, 3921 (2023). Copyright 2023 American Chemical Society. Yung *et al.*, iScience **25**, 104155 (2022). Copyright 2022 Author(s), licensed under a Creative Commons Attribution (CC BY) license.

and cluster states. Most of these source states have been generated through quantum spontaneous transitions, such as single photons by spontaneous emission (SE) from a single quantum emitter (QE) and photon pairs by spontaneous parametric down-conversion (SPDC) or spontaneous four-wave mixing from nonlinear materials. It is well understood that the rate of spontaneous transition can be effectively controlled by the photonic environment through the Purcell effect.[20–22] However, the accelerated photon emission may go to unwanted channels, such as non-radiative absorption, surface and guided modes, or radiation of photons with unusable properties in polarization, direction, and orbital angular momentum. Fortunately, it is possible to use the same photonic structure to route the emitted photons into the desired channels. Based on this fundamental principle, metaphotonics have been widely utilized to develop miniaturized and integrated quantum light sources with an enhanced emission rate to well-defined modes in different degrees of freedoms, such as wavelength, polarization, and wavefront.

In a general figure, for a spontaneous transition process (e.g., SE from a QE and SPDC from a nonlinear material) in a photonic environment, both its transition rate/probability in the near field and emission profiles in the far field are determined by the Green function supported by the photonic structure. The Green function $\mathbf{G}(\boldsymbol{r}, \boldsymbol{r}_0)$ quantifies the electric field at a position $\boldsymbol{r}$ emitted by a dipole at another position $\boldsymbol{r}_0$. According to Fermi's golden rule, the SE rate is proportional to the local density of states (LDOS), which is determined by the imaginary part of the trace of the Green tensor at the same location of the QE.[23] On the other hand, a QE can be considered as a dipole with a strength proportional to the pump field at the position of the QE. Obviously, the far field emitted by a QE in a photonic structure is directly governed by the Green function supported by the structure. Interestingly, based on the quantum classical correspondence theory,[24] SPDC can be treated as an extended dipole array in the nonlinear region at two daughter (signal and idler) photon frequencies, and their joint dipole strength or SPDC generation matrix is proportional to the product of the pump field and nonlinear coefficient. Following this, the far-field two-photon transition amplitude of SPDC can be explicitly expressed by the integration in the nonlinear region over the product of two Green functions at the signal and idler frequencies with their joint dipole strength.[24] Finally, the pump field distribution in the photonic structures, which determines the dipole strength at the emission frequencies, depends on the external source profile and the Green function at the pump frequency due to the reciprocity of the Green function. Therefore, the key problem in a photonic structure engineered QE and SPDC quantum light sources is to design the Green function. Metaphotonics, which employs a single nanoparticle, a finite-size cluster of properly designed nanoparticles, and an infinite-size periodic planar array of nanoparticles and clusters, have the full degree of freedom to design the photonic structures in the 2D space with subwavelength resolution and thus engineer the Green function with unprecedented capability. With other advantages such as ultracompact size and ease of fabrication and integration, metaphotonics empowered the QE single-photon source and SPDC photon-pair sources have recently attracted intensive research (Fig. 1).[6,7,25]

It is worth noting that except some regular shaped structures, such as multilayer thin films and sphere, most photonic structures and almost all metaphotonic structures have no analytical form of Green function. In these structures, the Green function can only be calculated by numerical simulations. An efficient and powerful way to accomplish this is based on the quasi-normal modes (QNMs) supported by the photonic structures. In the QNM theory, the Green function is simply related to the tensor product of the near and far fields of each QNM and the frequency detuning of the eigenfrequency of the QNM with respect to the frequency of interest.[26] With this theory and tool, one can transfer the design goal from the complex Green function to the simple QNMs through the complex eigenfrequency of the QNMs and their electric field distributions in both the near and far fields. Both quantities can be easily obtained through an eigenfrequency study of the structure. It has been employed to model the SPDC from single nanoparticles.[27,28] Note that the QNM method can not only predict the behavior of the metaphotonics quantum light source but also tell you the contribution from each QNM and thus provide a clear physical insight of the enhanced quantum light source. By designing the dominant QNMs and their weighted sum (i.e., interferences), metaphotonics is able to enhance the emission rate of QEs or SPDC in the near field and in the same time control the far-field emission profiles in different degrees of freedom.

A. Single-photon sources

Solid-state QEs, such as quantum dots, molecules, color centers in diamond, and defects in 2D materials, are natural sources of single photons.[29,30] Under excitation by a pump laser whose photon energy is larger than the transition energy of the QE, the electron transits from the ground state to the excited state. Within a certain amount of time, the electron goes back to the ground state and the QE has a chance to emit a photon through the SE, which is caused by the interaction with the quantum vacuum state (i.e., zero photon Fock state $|0\rangle$). In the time window between the excitation of the electron and its going back to the ground state, the QE cannot absorb pump photons and thus cannot emit photons. Therefore, the radiative lifetime of SE intrinsically determines the maximum photon emission rate of a QE. As mentioned above, photonic structures, e.g., metasurfaces (MSs), are able to reduce this lifetime by increasing the LDOS at the position of the QE and improve the SE rate. On top of the rate enhancement, MSs can simultaneously increase the radiative emission to the far field through a specific radiation mode with pre-defined direction, polarization, or orbital angular momentum.

One efficient way to increase the SE rate is to put the QE close to a metal surface by exciting the high-k surface plasmon polariton (SPP) mode propagating along the metal surface. However, such a SPP mode is non-radiative. MSs realized by fabrication of nanoholes in the metal or dielectric nanostructures on top of the metal can couple the SPP into far-field radiation. Importantly, with the capability of MSs, one can choose to couple into specific polarization, direction, and orbital angular momentum by judicious design and arrangement of meta-structures. Another advantage of such MSs lies in that the unidirectional emission above the metal surface is guaranteed, which increases the collection efficiency. In this direction, the group of Bozhevolnyi and their collaborators have reported a series of experimental work by integrating nanodiamonds with color centers with dielectric nanostructures forming MS atop metal (e.g., gold and silver) films supporting the SPP propagation, leading to the directional generation of single photons with desired properties, such as circular polarization,[31] radial polarization,[32] circular polarization with orbital angular momentum,[33,34] and linear polarization with orbital angular momentum.[35] In their latest work, a multi-channel signal-photon emission with control on both direction and polarization is demonstrated by embedding a nanodiamond with single Germanium vacancy center into a holographic MS, which sits on a silver substrate with a thin SiO_2 spacer layer.[36] Efficient generation of two well-collimated (divergences <6.5°) single-photon beams at 602 nm propagating along different 15° off-normal directions and featuring orthogonal linear polarizations is realized [Fig. 2(a)]. The two-beam single photons show a second-order correlation function $g^{(2)} \sim 0.1$ and an external quantum efficiency over 80%. In another interesting experiment, Jia *et al.* demonstrated multichannel single-photon emissions from CdSe colloidal QDs with independent control on spin angular momentum and linear momentum (i.e., direction) by an anisotropic MS made by specially arranged nano-grooves etched into a metal film.[37]

In most cases, precise positioning of the QE with respect to the metaphotonic structures is needed in the QE-meta-optics system in order to obtain the optimized performance. This is typically done by first locating the position of the QE before the nanofabrication of the meta-structures. Recently, Xue *et al.* have proposed a scalar-superposition MS supporting high-robust placement of the QE in tailoring the polarization of a QE.[38] The metasurface is formed by nano-scatters, which are nano-holes etched on a metal substrate, as shown in Fig. 2(b). The emitted single photons by the QE are first coupled to the SPP mode on the metal surface. The SPPs are then scattered to the far field by the scattering units, which are properly designed to support far-field scattering with the same polarization state. The total far-field scattered light will be the interference of all scattered fields and have the common polarization state of all scattering units. The most interesting part lies in that this polarized single photon emission is robust to the position of the QE on the metal surface. The requirement on the placement accuracy of the QE is released to three times of the wavelength in this work. Note that before this work, a similar idea of increasing the placement robustness of QE with an in-plane dipole was proposed and demonstrated by the simple thin-film meta-structures.[43]

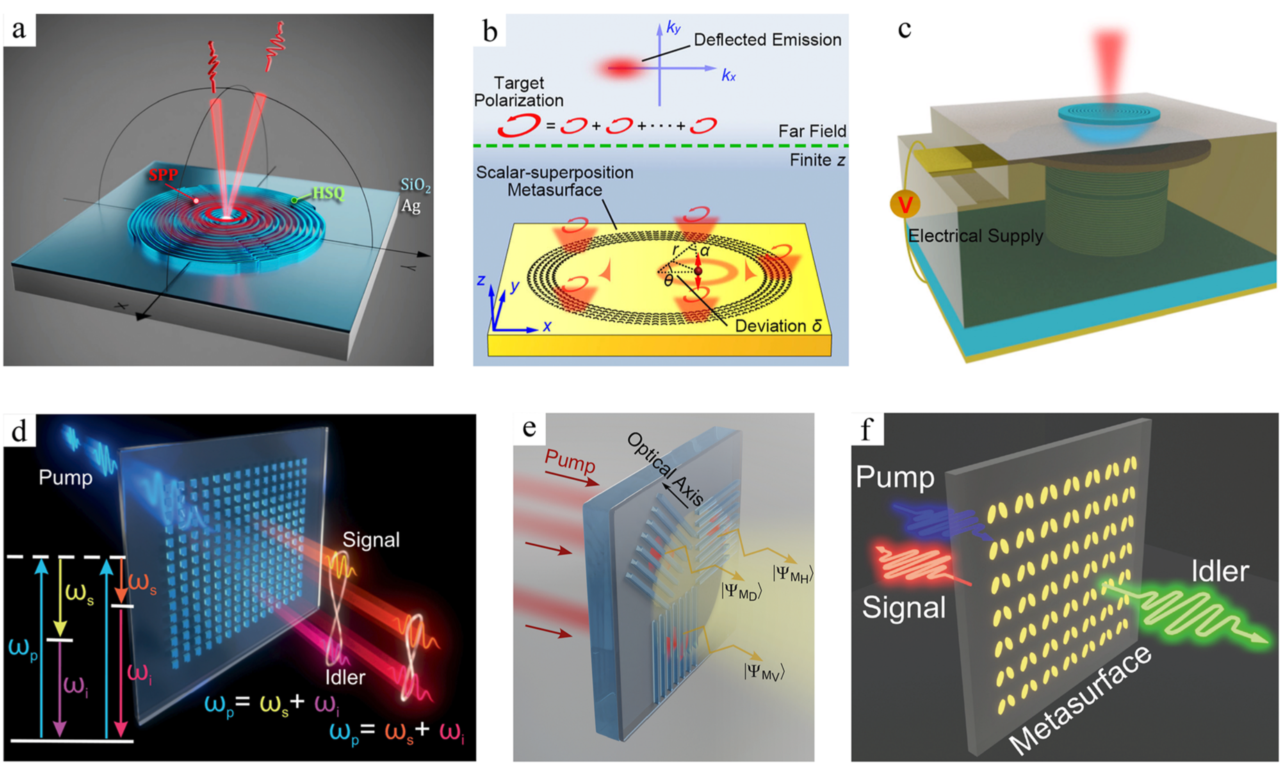

FIG. 2. Meta-optics quantum-light sources based on quantum emitters and nonlinear metasurfaces. (a) Collimated single-photon emission into two off-normal directions with orthogonal linear polarizations by integrating a QE with a MS atop a metal film.[36] Komisar *et al.*, Nat. Commun. **14**, 6253 (2023). Copyright 2023 Author(s), licensed under a Creative Commons Attribution (CC BY) license. (b) Single-photon emission into a desired polarization by integrating a QE with a MS with robust placement of the QE on the MS.[38] Reproduced with permission from Xue *et al.*, Laser Photonics Rev. **16**, 220179 (2022). Copyright 2022 John Wiley and Sons. (c) Directional single-photon emission by integrating a QE with a MS and an on-chip electrically injected microlaser.[39] Li *et al.*, Light Sci. Appl. **12**, 65 (2023). Copyright 2023 Author(s),licensed under a Creative Commons Attribution (CC BY) license. (d) Entangled photon pairs from a MS with multiple symmetry-protected quasi-BIC resonances.[40] From Santiago-Cruz *et al.*, Science **377**, 991 (2022). Copyright 2022 AAAS. (e) Photon pairs from a multiplexed MS with polarization control beyond the fixed nonlinear susceptibility of the nonlinear material.[41] Reproduced with permission from Ma *et al.*, Nano Lett. **23**, 8091 (2023). Copyright 2023 American Chemical Society. (f) Bidirectional photon pairs from a resonant MS.[42] Son *et al.*, Nanoscale **15**, 2567 (2023). Copyright 2023 Author(s), licensed under a Creative Commons Attribution 3.0 Unported Licence.

We would like to mention that current QEs can already support the photon emission rate on the order of megahertz without Purcell acceleration, which is sufficient enough for many quantum applications. In this case, routing the emitted photon into desired channels is more critical. Metalens is an ideal meta-optics to collimate the single photons from a single QE by placing the QE in its focal plane. For example, Huang *et al.* fabricated nanopillars directly on the surface of diamond to function as a metalens and collimate the photons emitted from a vacancy center inside the diamond.[44] Direct fabrication on the high-index diamond eliminates the reflection loss at the diamond-air interface. The collection efficiency can be further improved by adding a back metal mirror, which also forms a mirror image of the QE.[45] By accurately integrating the QE and its mirror image on the two foci of a spin-splitting bifocal silicon metalens on the top, on-demand spin-state generation and splitting of single photons with direction control can be achieved. More recently, simultaneous multi-dimensional tailoring of direction, polarization, and orbital angular momentum of single photons from a defect in hexagonal boron nitride has been demonstrated with a multifunctional metalens (Fig. 1).[11] This could unleash the full potential of single-photon QEs for their use as high-dimensional quantum sources for advanced quantum photonic applications.

Although with great advancements on the rate enhancement and routing control of single photons from QEs, most of these works still rely on an external pump laser. Ultimate miniaturization of QE single photon sources would benefit from an integration with the pump laser. Toward this goal, Li *et al.* have recently made a major step by deterministically fabricating a planar circular Bragg grating as a bright single photon source and an electrically injected micropillar as a highly directional pump microlaser on a single chip [Fig. 2(c)].[39] The circular Bragg grating and micropillar are individually optimized and heterogeneously integrated together by using a potentially scalable transfer printing process capable of fabricating a multitude of devices in a single run. The single QE was pumped by an on-chip micropillar laser under electrical injections, exhibiting high-performances in terms of the source brightness and single-photon purity thanks to the coupling of the QD to the cavity mode of the CBG. This work paves a way for realizing fully integrated metaphotonics engineered single photon sources.

B. Two-photon sources

Until now, the most common way to generate two-photon source is based on the nonlinear SPDC process, where one pump photon goes through a second-order nonlinear material and spontaneously splits into two daughter photons called signal and idler. Conventionally, SPDC photon-pair sources rely on nonlinear crystals, such as lithium niobate, BBO, and KTP, which have a typical thickness on the scale of millimeters to centimeters. The stringent phase-matching condition limits the emission wavelengths and directions of the photon pairs to a certain range. A pioneering work from M. Chekhova's group reveals that when the thickness of the nonlinear material is reduced to wavelength or subwavelength scale, the photon wavelength and angle are one order of magnitude broader than the that of thick crystals due to the relaxed phase matching condition.[46,47] This means strongly enhanced entanglement in the energy and momentum degrees of freedom and promises to improve the time and spatial resolutions of many quantum photonic techniques beyond the current state of the art. Although the overall SPDC rate is much lower than that from thick nonlinear crystals, this work shows that the SPDC from subwavelength-thick nonlinear materials is measurable and potentially useful. The same group has recently proposed an efficient way to remove the thermal background through time distillation, which increased the purity of the two-photon state from 0.002 to 0.99.[48] This method further increases the practicability of nanoscale and ultrathin SPDC sources. Slightly before, Sukhorukov *et al.* developed the quantum classical correspondence theory of SPDC, which stated that the quantum SPDC process can be explicitly described by the classical Green function[24] or equivalently by its classical reverse process called sum frequency generation (SFG).[49] This theory not only provides a design and analysis tool for the metaphotonic SPDC source but also proves that an efficient classical SFG source will serve as an efficient quantum SPDC source. In the meantime, it is well developed that patterning thin films into nanostructures, i.e., forming nanoantennas and MSs, can boost the classical nonlinear process at nanoscale by leveraging the optical resonances.[50–53] Therefore, the aforementioned theory and experiment have laid the foundation to explore the ultrathin metaphotonic SPDC source.

As a start, single nanoantennas were studied. Enhanced SPDC from an AlGaAs nanocylinder by Mie-type resonances at all three interacting wavelengths (i.e., pump, signal, and idler) was proposed and experimentally demonstrated by Marino *et al.*, generating photon pairs with a rate of 35 Hz.[54] The SPDC rate is significantly higher than conventional SPDC photon sources when normalized to the pump energy stored by the nanoantenna. This report of measurable SPDC from a single nanoantenna proves the feasibility of nanoscale SPDC source and opens the way for generating more complex photon states, such as polarization correlation and entangled Bell states from a single nanoantenna[28,55] and multiphoton quantum states by multiplexing several antennas. Later, Grange *et al.* reported SPDC experiments from single lithium niobate microcubes[56] and single GaAs nanowires,[57] further improving the SPDC rate by 40 times and showing the potential of realizing nanoscale SPDC sources at different material platforms.

To further increase the SPDC rate and directionality of the photon pairs, arranging the nanoantennas into a periodic array, i.e., forming a MS, is a natural idea. The first nonlinear-MS SPDC experiment was reported by a collaborating team in Germany using a $LiNbO_3$ MS, which consists of nanoresonators in the shape of truncated pyramids.[58] By leveraging the electric and magnetic Mie-like resonances at various wavelengths, the SPDC rate is enhanced up to two orders of magnitude within a narrow bandwidth, when compared with an unpatterned film of the same thickness and material. It also demonstrated the spectral control of the photon pairs by engineering the resonances and pump wavelength. This work opens the path toward the use of nonlinear MSs as versatile sources of photon pairs. Later, more research studies showed that the SPDC enhancement can be further boosted by leveraging other types of resonances with a higher quality factor. For example, strong enhancement of SPDC through the high-quality-factor nonlocal resonances, such as bound state in the continuum (BIC), was theoretically predicted in both AlGaAs and $LiNbO_3$ MSs,[59–61] which predicted a SPDC enhancement over five orders of magnitude over the unpatterned film. In experiment, we demonstrated a $LiNbO_3$ MS with nonlocal guided mode resonances (GMRs), which supported high and tunable quality factor and led to an 450-times enhancement of the SPDC over the thin film of $LiNbO_3$ of the same thickness (Fig. 1).[12] The proposed MS avoids nanofabrication on the nonlinear material and thus maximizes the nonlinear material volume and reduces noise from the fabrication induced material damage. The coincidence to accidental ratio (CAR) is up to 5000, which is larger than most of conventional crystal and waveguide SPDC sources. Furthermore, the non-classical spatial correlation of the generated photon pairs was experimentally verified in this work via the Cauchy–Schwarz inequality violation experiment and later numerically quantified via Schmidt decomposition of the two-photon wavefunction,[62] which is promising for many free-space quantum applications, such as quantum imaging, as will be shown later.

With further development, MSs have recently shown a great potential to directly generate complex quantum states, which are incapable for conventional SPDC sources, opening new opportunities for compact quantum information processing. One unique feature of MS over crystal lies in the fact that it is possible to fabricate several different MSs on a single substrate. Utilizing this feature, Santiago-Cruz *et al.* proposed a GaAs MS for direct generation of frequency cluster states by coherently pumping several MSs at multiple different wavelengths [Fig. 2(d)].[40] At the same time, the SPDC rate was strongly enhanced through the BIC resonances with quality factors up to 1000. In another work, we investigated the engineering of the polarization state of the photon pairs from $LiNbO_3$ MS beyond the limit of the intrinsic nonlinear susceptibility tensor and formulated an efficient approach to generate arbitrary polarization-entangled qutrit states by simultaneous pumping of three closely patterned MSs with different orientations [Fig. 2(e)].[41] The polarization qutrit state is optically tunable by the pump distributions on three MSs, which can be readily achieved by a spatial light modulator. Another exotic state comes from the freedom to choose the emission directions of the photons due to the relaxed phase matching condition. For example, the first MS SPDC experiment was performed in a configuration where both daughter photons were collected in the reflection direction,[58] which is impossible in thick nonlinear crystals. As a matter of fact, it is experimentally verified that a single MS can simultaneously generate transmission–transmission, reflection–reflection, and transmission–reflection photon pairs [Fig. 2(f)].[42,63] The use of both directions of emission will fuel the development of more complicated architectures of nanoscale sources of quantum light.

A summary on the performance of those experimentally demonstrated nonlinear-MS SPDC sources is shown in Table I.

Finally, it is worth mentioning that quantum dots can also generate entangled photon pairs through the biexciton–exciton cascaded radiative process and its integration with broadband meta-optics, such as circular Bragg grating, can lead to two-photon sources with improved performance in terms of rate, efficiency, degree of entanglement, and indistinguishability.[64–66] Further development of the QE-meta-optics integration platform is promising for deterministic generation of two-photon sources.

C. Multiphoton sources

Multiphoton states with a photon number over two are critical and desired in many quantum technologies to increase the scalability, capacity, sensitivity, and resolution.[67] The common way to create multiphoton states is through time-multiplexing of single photons from a QE or assembly of multiple photon-pair sources from nonlinear spontaneous photon-pair generation. The meta-optics enabled multiphoton source from QE has not been reported yet. While the idea of generating multiphoton states through multiplexing several nanoantennas or MSs is straightforward, the practical challenge lies in that the rate of the meta-optics enabled SPDC source is still too low to observe a multiphoton coincidence counting event. Nevertheless, a groundbreaking experiment was performed by Li *et al.* to generate multiphoton states by integrating a 10×10 metalens array on the front surface of a nonlinear crystal (Fig. 1).[13] Up to six photons generated from different metalenses with high indistinguishability were experimentally verified. This work provides a compact and practical platform for the development of advanced on-chip quantum photonic information processing.

III. METAPHOTONICS FOR QUANTUM LIGHT MANIPULATION

Light manipulation, transforming an initial state of light into a target state, is the most widely studied function of meta-optics since its birth. On the other hand, almost all optical-manipulation elements for classical optics can find their use in quantum optics, such as beam splitters, waveplates, filters, and so on. Therefore, meta-optics enabled quantum light manipulation shares the same advantages of meta-optics in classical light manipulation, including ultra-compact size, stability, controllability, multi-dimensionality, and

TABLE I. Summary of experimentally demonstrated SPDC sources from resonant metasurfaces.

References	Material	Thickness (nm)	Resonance type	Measured rate[a] at pump power	Enhancement[a]	CAR
58	$LiNbO_3$	680	Mie	5.4 Hz at 70 mW	20	361
12	$LiNbO_3$	304	GMR	1.8 Hz at 85 mW	450	5000
40	GaAs	500	BIC	0.08 Hz at 9 mW	>1000	~ 9.5[b]
41	$LiNbO_3$	300	GMR	0.83 Hz at 85 mW	210	~ 1700[b]
42	GaP	150	BIC	0.24 Hz at 70 mW	67	~ 4.8[c]
63	$LiNbO_3$	308	GMR	2.92 Hz at 91 mW	NA	7500

[a]Note that the measured rate and enhancement depend on the filtering bandwidth, collection angle and efficiency, detection efficiency of single-photon detectors, and the properties of optics in the setup. Therefore, the measured rate does not represent the real internal generation rate from the metasurface.
[b]Estimated from the second-order cross-correlation function by CAR = $g^{(2)}(0) - 1$.
[c]Estimated from the coincidence histogram in Fig. 2(b) of Ref. 42.

multi-functionality. These have stimulated many meta-optics quantum optical devices, which have the potential to replace the convectional bulky counterparts with better performance or enable new light-manipulation functionalities beyond those can be achieved by conventional optical elements. In the following, we will summarize the most recent advancements in meta-optics for quantum light manipulation, including quantum interferences, entanglement manipulation, atom cooling and trapping, metasurface by atom array, metasurface for quantum computing, and some other emerging directions.

A. Quantum interferences

Photon interferences play critical roles in many quantum photonic technologies ranging from quantum computing, communication, to quantum metrology and state characterization. Implementation of quantum interferences with MSs was pioneered by Wang *et al.*, who reported interference of multiphoton polarization-encoded states with photons coming from the same spatial modes on a one-input-six-output silicon MS [Fig. 3(a)].[68] The two-photon correlations between two distinct output ports at different time delays resemble those obtained in the conventional Hong–Ou–Mandel (HOM) experiment on a cube beam splitter[69] and expand their generalizations to lossy beam splitters. Comparing with the cube beam splitter, this MS enabled interferometer has much smaller size, flexibility of realizing different optical responses by MS design, and six output ports with the possibility of extending more. The later can enable 15 distinct two-photon correlations at the output. Furthermore, MS can have a non-unitary transmission matrix, being a new degree of freedom to engineer the photon interference behavior. Li *et al.* explored a non-unitary two-input-two-output MS for quantum interference (Fig. 1).[14] They demonstrated dynamical and continuous control over the effective interaction of two single photons such that they show bosonic bunching, fermionic antibunching, or arbitrarily intermediate behavior, beyond their intrinsic bosonic nature. In the above work, the tuning was realized by mechanical rotation of the metasurface. One promising direction is to use reconfigurable MSs for tunable quantum interference.[70] It is possible to use MS to perform arbitrary U(2) transformations or even two-qubit U(4) operations by combining the spatial and polarization degrees of freedom.[71] In order to implement quantum interference for more photons, a multiport MS interferometer would be necessary. Recently, a promising method by employing the multiple diffraction orders of a MS grating has been proposed for such a task.[72] The demonstrated multiport interferometer by a single MS supports an ultra-stable and tailored multiport transformation, which remained a challenge in the free-space configuration due to the requirement of deep subwavelength stability, and its implementation has typically relied on active phase locking[73] or integrated photonics circuits.[74] These experiments prove that MSs not only can achieve an interference performance similar to the ones of traditional optical elements but also reach new regions of interference patterns by tuning the transmission matrix. Therefore, MSs are promising candidates for integrated quantum interferometry and its related applications, such

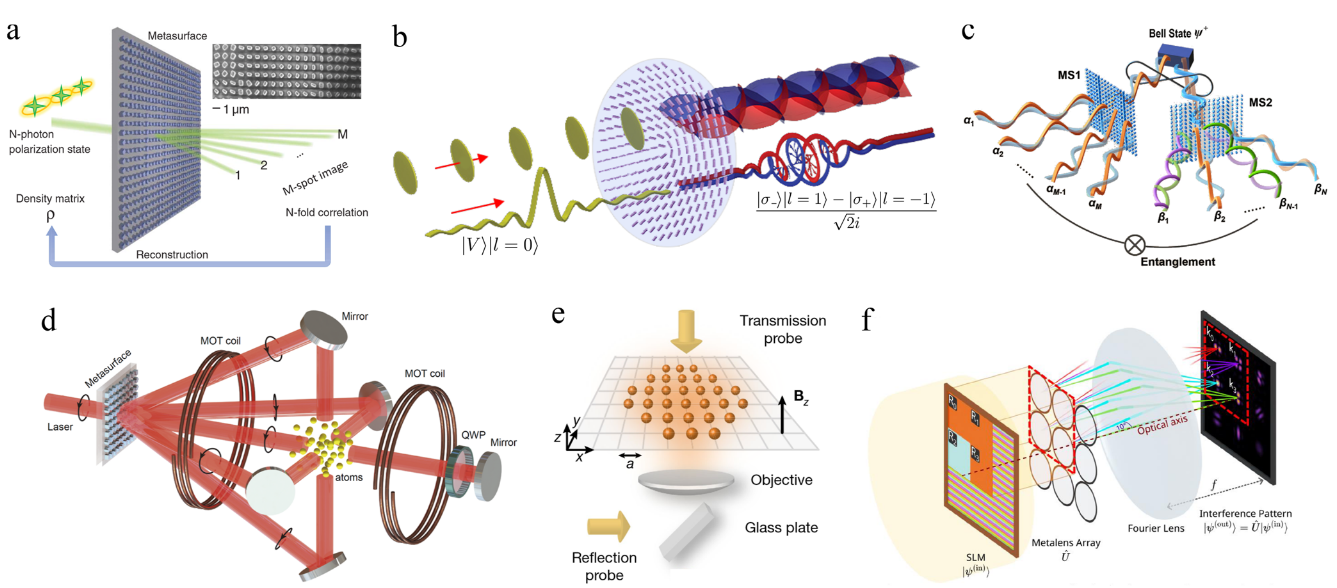

FIG. 3. Metasurface-based light manipulation for quantum photonics. (a) Multiphoton interference and state reconstruction using a MS.[68] Reproduced with permission from Wang *et al.*, Science **361**, 1104 (2018). Copyright 2018 AAAS. (b) Quantum entanglement of the spin and orbital angular momentum of photons using a MS.[77] Reproduced with permission from Stav *et al.*, Science **361**, 1101 (2018). Copyright 2018 AAAS. (c) Multichannel distribution and transformation of polarization entangled photons using a MS.[78] Reproduced with permission from Gao *et al.*, Phys. Rev. Lett. **129**, 023601 (2022). Copyright 2022 American Physical Society. (d) A centimeter-scale dielectric MS for the generation of cold atoms.[79] Reproduced with permission from Jin *et al.*, Nano Lett. **23**, 4008 (2023). Copyright 2023 American Chemical Society. (e) A subradiant optical mirror formed by a single structured atomic layer.[80] Reproduced with permission from Rui *et al.*, Nature **583**, 369 (2020). Copyright 2020 Springer Nature. (f) MS for programmable quantum algorithms with quantum and classical light.[81] Tanuwijaya *et al.*, Nanophotonics **13**, 927 (2024). Copyright 2024 Author(s), licensed under a Creative Commons Attribution 4.0 International License.

as quantum state characterization[68,72] and quantum sensors[17] (see more details later in Secs. IV A and IV B). Finally, MS has also been reported for remote quantum interferences.[75,76]

B. Entanglement manipulation

Entanglement is a pure quantum feature underpinning many quantum enhanced technologies. As entanglement typically involve at least two modes in two degrees of freedom of the photons, MSs are very suitable to control entanglement due to their ability for multi-dimensional manipulation. A pioneering work from Stav *et al.* proposed a novel MS to create entanglement between spin and orbital angular momentum of a single photon by using the geometric phase that arises from the photonic spin–orbit interaction [Fig. 3(b)].[77] Nonlocal correlations and entanglement between the spin and orbital angular momentum of two different photons are also created by the MS. In the previously mentioned metalens array based multi-photon source, the same platform is also able to generate high-dimensional two-photon path entanglement with different phases and high fidelities.[82] MSs can not only generate entanglement between photons but also realize disentanglement of two photons,[17] modification of the degree of entanglement,[83] entanglement between two qubits separated by macroscopic distances,[84] and entanglement distillation.[15,85] A plasmonic MS with all-optically tunable polarization dependent transmissions was demonstrated to continuously control the degree of entanglement between two photons from a non-maximally entangled one to that with fidelities higher than 98%, enabling the function of entanglement distillation (Fig. 1).[15] By placing two one-input-multi-output MSs at the paths of two polarization entangled photons, Gao *et al.* reported the multichannel distribution and transformation of entangled photons [Fig. 3(e)].[78] In their experiments, 2×2 and 4×4 distributed entanglement states, including Bell states and superposition of Bell states, are demonstrated with high fidelity and strong polarization correlation.

C. Atom cooling and trapping

A new application of MS enabled light manipulation is to construct the complex optical fields needed for cooling and trapping atoms in a very compact form. In an atom trapping experiment, overlap of multiple circularly polarized beams coming from different directions is needed. This often requires multiple bulky beam splitters, waveplates, and mirrors in conventional optics. Zhu *et al.* reported the use of a MS to replace the conventional bulky optical elements for creating cold atoms with a single incident laser beam [Fig. 3(d)].[86] In their experiment, a single MS was applied for realizing both functions of beam splitting and polarization control. Atom numbers of 10^7 and temperatures of 35 μK of relevance to quantum sensing were achieved in a compact and robust fashion. This temperature is comparable to what one would get in standard magneto optical trapping (MOT) systems. Recently, the same group has fabricated a centimeter scale MS for MOT, which further increases the diffraction efficiency to 47% and successfully traps atoms with numbers up to 1.4×10^8 and temperature down to 7 μK.[79] In parallel, Hsu *et al.* reported the use of MS lens to trap single atoms.[87] MS MOT paves a way toward fully integrated cold atom sources and quantum devices. Together with other intriguing proposals and experiments,[88,89] MS is becoming a powerful platform for optical twizzlers.[90] One of the promising applications of MS MOT would be constructing a thin layer of cold atom array, which can function as a MS to manipulate both classical and quantum lights, as discussed below.

D. Metasurfaces by atom arrays

A new approach to construct optical MS is through a two-dimensional array of atoms or atom-like QEs, which play similar roles to the dielectric and plasmonic nanoantennas in conventional MSs.[80,91–100] For example, a planar atomic array with subwavelength spacing of atoms was proposed as MSs for collectively manipulating light,[101] and in particular, they can act as a mirror to reflect light. Rui *et al.* performed the first experimental demonstration of this phenomena by using only a few hundred atoms [Fig. 3(e)].[80] Importantly, the cooperative optical response of the atom array can be readily tuned by the atom density and ordering or an external pump light. They also observed the narrowing of the resonance transmission/reflection linewidth below the fundamental quantum limit of the single-atom Wigner–Weisskopf linewidth. It is also possible to create entanglement between the atom MS and the scattered photons, constituting a new platform for simultaneous control of the quantum and spatiotemporal properties of light in free space, cavity-free parallel quantum operations on multiple photonic degrees of freedom, and the preparation of highly entangled photonic states suitable for quantum information.[94] A recent study from Levin *et al.* analyzed the implementation of cluster states generation protocols by employing quantum MSs made out of sub-wavelength atomic arrays, including fundamental quantum logic gates useful for general quantum computation and communication purposes.[100]

E. Metasurfaces for quantum computing

Quantum computing promises to outperform the classical computing in certain tasks and has attracted much attention. The basic building blocks of quantum computing include a physical platform to implement a quantum bit, logic gates, and algorithms. Recently, MSs have been proposed and demonstrated for all these essential parts of quantum computing in a compact and multifunctional manner. Chen *et al.* proposed a concept of analog quantum bit to emulate a qubit and used a Pancharatnam–Berry (PB) phase MS as a physical platform to implement such a concept.[102] A PB phase MS was experimentally fabricated to validate that the proposed analog qubit can be used to emulate the quantum bit in terms of both mathematical and geometrical representations. Ding *et al.* reported a novel MS-based all-optical diffractive neural network to implement quantum logic gate operations (Fig. 1).[16] In comparison to previous works of quantum computing systems based on bulky optical elements, the proposed optical quantum logic gate is only composed of a single-layer MS with a compact size, which provides significant superiority in integration. Furthermore, it could be extended to more complex quantum architectures, such as CNOT gates, rotating operators, multi-quantum bit operation, and others via increasing the layers with optimized channels and multiplexing. In another work, Tanuwijaya *et al.* proposed and experimentally demonstrated a programmable MS capable of performing quantum algorithms at the single photon level [Fig. 3(f)].[81] By selectively exciting subsets of metalenses and interpreting the interference patterns at specific output directions, two programmable quantum algorithms, i.e., Grover's algorithm and the quantum Fourier transform, were demonstrated onto the same metalens array on a MS. These works open the door for applications of MSs in integrated and large-scale quantum computing and algorithms.

IV. METAPHOTONICS FOR QUANTUM LIGHT DETECTION

Metaphotonics has also been widely studied for the detection and characterization of quantum photonic states. It should be noted that the light-detection metaphotonics is strongly associated with the light-manipulation metaphotonics in Sec. III. Most meta-optics, e.g., MSs, are still playing the role of light manipulation, while the detection of photons is based on single photon detectors (SPDs) positioned after the meta-optics. It is the quantum state manipulations or transformations implemented by the meta-optics that enable or enhance the desired detection applications, such as sensing and imaging. Therefore, the optical functions of the MSs in this section are similar to those in Sec. III, or in some cases, the same MS enables both manipulation and detection.

A. Quantum sensing

Quantum sensors can support a sensitivity beyond the classical shot noise limit. Metaphotonic quantum sensing has a rich history from plasmonic quantum sensors[103] to MS quantum sensors.[9] Dowran *et al.* demonstrated a quantum enhanced plasmonic sensor to enhance the sensitivity in measuring the local changes of the refractive index in air.[104] By using a plasmonic MS consisting of a triangle nanohole array drilled in a 100 nm-thick silver film and bright entangled twin beams as the source, they measured a sensitivity on the order of $10^{-10} RIU/\sqrt{\text{Hz}}$, which is nearly five orders of magnitude better than previous proof-of-principle implementations of quantum-enhanced plasmonic sensors. Kim *et al.* used a plasmonic quantum MS to confine the incident infrared probe light in a micrometer-thick nitrogen vacancy layer beneath the diamond surface through the plasmonic lattice resonance and thus enhanced the infrared absorption for the readout of the nitrogen vacancy singlet transition for a magnetometer [Fig. 4(a)].[105] By optimizing the spin readout, this plasmonic quantum sensing metasurface can enable a near-spin-projection-noise-limited sensitivity below $1\text{nT}/\sqrt{\text{Hz}}$ per μm^2 of sensing area. As mentioned before, Georgi *et al.* developed a dielectric MS to generate a two-photon path-entangled NOON state.[17] Based on the same MS, they then built an interferometer to probe the phase changes of one path and obtained an enhanced sensing visibility for the entangled state at zero time delay over the disentangled one at a large time delay (Fig. 1).

B. Quantum state characterization

Quantum state characterization is typically accomplished by performing a sequence of identical measurements in a series of different bases, a process called quantum state tomography.[109] The change of projection into different bases is realized by tuning of several bulky optical elements. For example, the measurement of the two-photon polarization state requires 16 projection measurements by rotating the angles of four waveplates positioned before two polarizers.[110] MSs, due to their ability to manipulate multiple degrees of freedom and multiple bases in the same time, can significantly simplify the setup and process needed for the quantum state characterization. For example, the silicon MS proposed by Wang *et al.* for quantum interference, as shown in Fig. 3(a), was utilized for a robust reconstruction of amplitude, phase, coherence, and entanglement of multiphoton polarization-encoded states by simultaneously imaging multiple projections of quantum states.[68] In their experiments, two-photon states are reconstructed through nonlocal photon correlation measurements with polarization insensitive click detectors positioned after the MS, and the scalability to higher photon numbers is established theoretically. Later, Wang *et al.* proposed and demonstrated a two-MS scheme for the measurement of two-photon polarization state, where each MS has four districts functioning as a polarizer for four different polarization states [Fig. 4(b)].[106] The needed 16 projection measurements were done by spatially translating the MS into different districts. As a result, reconstruction of the four Bell states was achieved with fidelity over 93.45%. A similar two-MS approach was proposed to characterize the polarization Bell state without the need of spatial translation of the MSs.[111] Other than the polarization state, Wang *et al.* have recently reported the characterization of an OAM state of single photons by a dielectric MS (Fig. 1).[18] By replacing the conventional bulky optical components in OAM measurements, such as spiral phase plate, q-plate and spatial light modulator by a single MS, they reconstructed the density matrix of an arbitrary OAM state with high fidelity and measured the Schmidt number of the OAM entanglement. Recently, we have proposed and demonstrated a two-input-three-output dielectric MS to realize the single-shot characterization of indistinguishability between two photons in several different degrees of freedom [Fig. 4(c)].[72] Topology optimization is employed to design a silicon MS with multiple targets, i.e., polarization independence, high transmission, and high tolerance to measurement noise. Based on the fabricated MS, we experimentally quantified the indistinguishability of two photons from a nonlinear crystal with fidelity over 98.4%, without any reconfigurable and phase-locking elements. MS has also been used for quantum weak measurements,[112] randomized measurement of photonic qubits with mitigated estimation error,[113] and efficient characterization of multiphoton entanglement with fewer measurements, higher accuracy, and robustness against optical loss.[114]

C. Quantum imaging and image processing

MSs and metalens have been extensively studied for imaging and image processing using a classical light source.[115,116] The combination of MS and quantum light source is leading to new opportunities in the field of quantum imaging.[19,107,108,117–120] Zhou *et al.* proposed and experimentally demonstrated a switchable optical edge detection by a high-efficiency dielectric MS and a polarization-entangled photon source [Fig. 4(d)].[107] By selecting a proper polarization state in the heralding arm of the entangled photon source, either normal image or edge image is obtained. Importantly, compared to the case by using classical light sources, the quantum edge detection scheme shows a high signal-to-noise ratio at the same photon flux level. Recently, a similar concept has been demonstrated for the nonlocal weak-measurement microscopy.[121]

Yung *et al.* combined the polarization-sensitive capability of MSs with HOM-type interference to generate images with tailor-made two-photon interference and coincidence signatures (Fig. 1).[19]

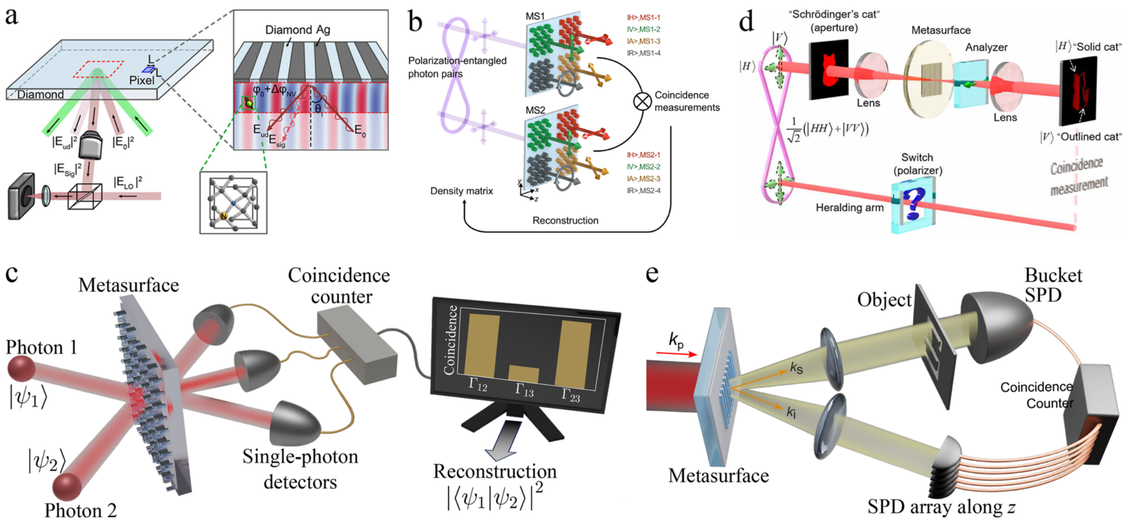

FIG. 4. Metasurface-enabled quantum light detection. (a) Absorption-based diamond spin microscopy on a MS.[105] Reproduced with permission from Kim *et al.*, ACS Photonics **8**, 3218 (2021). Copyright 2021 American Chemical Society. (b) Quantum tomography of polarization-entangled states with a MS.[106] Reproduced with permission from Wang *et al.*, Appl. Phys. Lett. **121**, 081703 (2022). Copyright 2022 AIP Publishing LLC. (c) Single-shot characterization of photon distinguishability with a MS.[72] Reproduced with permission from Zhang *et al.*, arXiv:2401.01485 (2024). (d) Quantum edge detection with a MS.[107] Zhou *et al.*, Sci. Adv. **6**, eabc4385 (2020). Copyright 2020 Author(s), licensed under a Creative Commons Attribution (CC BY) license. (e) Quantum imaging using entangled photon pairs from a nonlinear MS.[108] Reproduced with permission from Zhang *et al.*, Asia Communications and Photonics Conference/2023 International Photonics and Optoelectronics Meetings (2023). Copyright IEEE.

As mentioned before, MS based SPDC source can support large angle photon emission with strong spatial entanglement, which can facilitate the field of view and resolution in quantum imaging. Recently, we have performed the first quantum imaging experiment using a MS based quantum light source with spatial entanglement [Fig. 4(e)].[108] By combining quantum ghost and scanning imaging protocol, we realized two-dimensional quantum imaging using only a one-dimensional detector array.

V. CONCLUSION AND OUTLOOK

Metaphotonics provides novel opportunities to design and fabricate optical devices for manipulating and routing non-classical light. It is underpinned by a smart design and the physics of metamaterials originating from the study of optically induced electric and magnetic resonances. Quantum metasystems can find many applications, including, among others, the development of unbreakable encryption, as well as they can open the door to new possibilities for quantum information systems on a chip for integrated quantum photonics,[122,123] employing powerful tools of inverse design and machine learning developed for quantum metasurfaces.[124] We note that current experiments all rely on the integration of conventional bulky optical elements with metasurfaces, which play one of the roles in the generation, manipulation, and detection of quantum lights. In the future, we expect the development of metaphotonic quantum optical systems by integrating multiple metasurfaces for quantum light generation, manipulation, and detection.

Nonlinear metasurfaces are used as special metadevices for conversion of light frequency and wave mixing.[125] For quantum applications, nonlinear metasurfaces are employed for the efficient generation of photon pairs, and novel materials are being explored for SPDC, including multilayer stacked two-dimensional materials.[126–128] In addition, metasurface-based SPDC sources can be developed for exotic wavelength ranges, such as UV, mid-IR and THz, with applications in quantum imaging with undetected photons.[129] Furthermore, nonlinear metasurfaces can be employed for multiphoton parametric down-conversion and high-harmonic generation (HHG).[130,131] HHG can be used as a source of coherent broadband radiation in the form of pulses with duration reaching attosecond timescales, and the emitted high harmonics can be squeezed or entangled. Quantum effects can modify the spectrum and photon correlations showing when individual frequency components become squeezed. An attractive direction is integration of such metasurfaces with electrically injected quantum emitters or integration of nonlinear metasurfaces with electrically injected pump light.

Structuring light in multiple degrees of freedom, from spatial to temporal, holds great promise for advancing modern photonics.[132,133] Structuring light as single photons and entangled states allows for accessing high-dimensional Hilbert spaces for fundamental tests of quantum mechanics and advanced quantum information processing.[134] Metasurfaces have been developed for the generation, manipulation, and detection of structured classical light, but they can offer a versatile platform for structuring the quantum states of light toward high-dimensional photonic quantum processing.

More recent developments in quantum metasurfaces aim exploring the new physics that can lead to breakthrough applications in quantum technologies. This includes, for example, the use of metasurfaces for levitation[135,136] and a novel direction of spatiotemporal quantum metasurfaces.[137] In addition, active and tunable metasurfaces with externally driven change of their properties to control quantum light and quantum properties, such as single-photon emission, manipulation, and non-classical detection, will become crucially important.[15,138] Coherent photon absorption by metasurfaces is also worth further exploring.[139–141]

The further steps will include the development of new approaches and tools to bring quantum metasurfaces to atomic and solid-state based systems involving atom–atom, atom–photon, and photon–photon entanglements, for example, by employing atomic planar arrays where coherent scattering of incident light beams can be highly collimated in the forward and backward direction.[142] The atomic planar arrays share features with fabricated metasurfaces, but a specific feature of atomic arrays is the possibility for the state manipulation via internal levels for photon storage, switching, gates, etc. Solid-based quantum metasurfaces can also be realized by deterministically preparing arrays of silicon-vacancy centers, which has been proven recently as promising quantum emitters for photon generation.[143]

In summary, quantum metaphotonics has emerged as a cutting-edge development of metamaterial driven concepts to generate, manipulate, and detect quantum states of light. It can be employed for the miniaturization of current bulky quantum optical elements as well as design of on-chip quantum systems for quantum technologies. Over the past few years, this field has witnessed a surge of intriguing theoretical ideas, groundbreaking experiments, and novel applications, which we summarized in this paper to encourage the further development of this exciting research field.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Jihua Zhang: Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yuri Kivshar**: Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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