Metasurface-Enabled Generation of Circularly Polarized Single Photons

Yinhui Kan, Sebastian K. H. Andersen, Fei Ding,* Shailesh Kumar, Changying Zhao, and Sergey I. Bozhevolnyi*

Single photons carrying spin angular momentum (SAM), i.e., circularly polarized single photons generated typically by subjecting a quantum emitter (QE) to a strong magnetic field at low temperatures, are at the core of chiral quantum optics enabling nonreciprocal single-photon configurations and deterministic spin-photon interfaces. Here, a conceptually new approach to the room-temperature generation of SAM-coded single photons (SSPs) is described, which entails QE nonradiative coupling to surface plasmons being transformed, by interacting with an optical metasurface, into a collimated stream of SSPs with the designed handedness. Design, fabrication, and characterization of SSP sources, consisting of dielectric circular nanoridges with azimuthally varying widths deterministically fabricated on a dielectric-protected silver film around a nanodiamond containing a nitrogen-vacancy center, are reported. With properly engineered phases of QE-originated fields scattered by nanoridges, the outcoupled photons are characterized by a well-defined SAM (with the chirality >0.8) and high directionality (collection efficiency up to 92%).

Single-photon sources constitute one of the crucial enabling technologies for quantum communications,[1–4] quantum computation,[4–6] and quantum-enhanced metrology.[7–9] Typical stand-alone quantum emitters (QEs) used for realizing single-photon sources feature low emission rates, nondirectional emission, and poorly defined polarization properties,[10–13] characteristics that prevent QEs from being directly used in quantum technologies.[14,15] By using properly nanostructured environment, i.e., by coupling QEs with nanocavities or nanoantennas, the QE emission rates can be enhanced drastically due to the Purcell effect.[16–19] Many efforts have also been dedicated to obtaining high collection efficiency by directing the QE emission with surrounded nanostructures, including Yagi-Uda antennas[20–23] and bullseye gratings,[24–28] demonstrating that highly directional beams can straightforwardly be realized by utilizing different kinds of bullseye structures in forms of concentric ridges. Regarding the single-photon purity and photon indistinguishability, recent reports have proved that these two parameters can simultaneously reach high levels with properly chosen QEs incorporated at cryogenic temperatures in semiconductor cavities.[29–31] At the same time, generation of single photons with well-defined polarization properties has rarely been addressed, while the use of (especially) spin angular momentum (SAM)-coded single photons (SSPs) became very quickly the forefront of research investigations within chiral quantum optics[32] concerned with chiral light-matter interactions in photonic nanostructures that offer fundamentally new functionalities, such as spin-photon interfaces and spin-controlled photon switching.[33] With SSPs at hand it is thus straightforward to realize a chiral waveguide coupler in which the handedness of the incident light determines the propagation direction in the waveguide.[32,34] The direct SSP generation is however a rather complicated and challenging issue: in order to create two nondegenerate circularly polarized QE states one should realize the sufficiently pronounced Zeeman splitting by subjecting QEs, e.g., quantum dots[35] or color centers in diamond,[36] to strong magnetic fields at low temperatures.[35,36] It should be noted that the circular polarization degree of low-temperature emission from vacancies in diamond did not exceed 10% even at very high (10 T) magnetic fields.[36]

In this work, we demonstrate a viable strategy for the room-temperature generation of highly directional SSPs based on dipolar QEs nonradiatively coupled to surface plasmon-polariton (SPP) modes, which upon interaction with an optical metasurface radiate into free space in the form of a collimated single-photon stream carrying the designed spin angular momentum (SAM). The proposed configuration represents a hybrid system consisting of a pre-selected nanodiamond (ND) containing a
Figure 1. Generation of spinning single photons. a) Schematic of SSP source consisting of a QE with a normal to the surface dipole transition located at the center of an optical metasurface composed of concentric periodic width-varying dielectric nanoridges atop a thin dielectric spacer, serving for metal protection and reduction of QE quenching, and a metal substrate supporting SPP modes at the QE radiation wavelength. The green cones represent a tightly focused radially polarized pump beam that produces a strong longitudinal electric field component at the focal plane. The arrow with a helix in the red beam illustrates an outgoing collimated stream of photons carrying the SAM. b) Radial cross section of our configuration showing schematically SPPs, which are excited by an NV center, propagating along the surface and outcoupled by scattering off HSQ nanoridges. The metasurface is composed of 150 nm thick HSQ width-varying nanoridges with the period $P = 550$ nm, a 20 nm thin SiO$_2$ spacer and a 200 nm thick Ag substrate. c) The simulated phase shift $\theta$ and azimuthal angle $\phi$ as a function of the nanoridge width $w$, demonstrating that, when the width $w$ varies from 110 to 407 nm around the center, the scattered electric field phase changes continuously within the full $2\pi$ phase range.

nitrogen vacancy (NV) center with desired single QE characteristics, which is located in the center of an optical metasurface composed of hydrogen silsesquioxane (HSQ) circular nanoridges with azimuthally varying widths deterministically fabricated atop a silicon dioxide (SiO$_2$) spacer and silver (Ag) substrate (Figure 1a). It should be emphasized that, unlike recently introduced quantum metasurfaces interacting with free propagating streams of photons,$^{[37,38]}$ the system of nanoridges constituting the metasurface interacts in our case with (nonradiative) SPP modes transforming their fields into unidirectional circularly polarized single photons. Our arrangement (Figure 1a) can be viewed as a meta-atom that, upon illumination with a pump optical wave, would spontaneously emit well-collimated and unidirectional SSS at room temperature and without magnetic fields applied, a unique property that opens fascinating perspectives in chiral quantum optics, such as, for example, straightforward realization of a single-photon chiral waveguide coupler.

QEs used in our experiments are selected by monitoring their emission when illuminated with a tightly focused radially polarized pump laser beam at the wavelength of 532 nm that produces a strong longitudinal electric field component at the focal plane, which is perpendicular to the surface plane. This procedure ensures that the QEs, which are selected for the realization of SSP generation, have sufficiently large projections of their radiative dipole transitions on the direction perpendicular to the surface. The selected NV centers, when excited with the pump light, couple efficiently and nonradiatively into cylindrically diverging SPP modes supported by the air–SiO$_2$–Ag interface,$^{[33,34]}$ which are subsequently scattered by the circular nanoridges with properly engineered phases and thus converted into outgoing photons (Figure 1b). High directionality of emitted photons is secured by matching the nanoridge spacing $P$ to the SPP wavelength calculated for a vacuum wavelength of 665 nm, coinciding with the maximum emission of the negatively charged NV state.$^{[39]}$ The polarization state of emitted photons is controlled with the HSQ metasurface consisting of width-gradient nanoridges that modify the phase of the scattered fields locally by introducing the phase shift $\phi$ varying with the azimuthal angle $\theta$ (Figure 1c). By linearly changing the nanoridge width $w$ from 110 to 407 nm with the azimuth $\theta$, the relative phase shift $\phi$ of the scattered electric field is continuously changed within the full $2\pi$ phase range (Figure 1c). Therefore, the electric fields scattered at two arbitrary points separated by the azimuthal angle $\theta = \pi/2$ (e.g., A and B) are not only orthogonal to each other but also phase-shifted by $\pi/2$, generating thereby (in the far-field domain) circularly polarized outgoing photons (Section S1, Supporting Information). It should be noted that trapezoid shaped (straight) metallic nanorods used for beam steering$^{[40,41]}$ bear some resemblance to our dielectric circular nanoridges with azimuthally varying widths, although the physics of tailoring the phase of scattered light is rather different.

The performance of the proposed device is first studied using the three-dimensional (3D) finite-difference time-domain (FDTD) simulation of QE-excited SPP waves scattered by a width-varying system of HSQ circular nanoridges (Figure 2a), in which the refractive index of HSQ is set as 1.43$^{[42]}$ and the QE is treated as an electric dipole oriented normal to the surface in the $z$ direction and located at the distance of 50 nm from the SiO$_2$ surface. The QE radiation wavelength of 665 nm is chosen to coincide with the maximum emission of the negatively charged NV state,$^{[39]}$ resulting in the nanoridge period $P = 550$ nm matching to the SPP wavelength. The radius of the inner ring is then optimized to be 585 nm to ensure the highest quantum efficiency at the design wavelength of 665 nm along with the reasonably high Purcell factor of $\sim$4.0 (Section S1, Supporting Information). For the considered configuration, the quantum efficiency, $\eta_{QE}$, defined as the ratio between the radiative and total decay rates$^{[43]}$ is found to be $\eta_{QE} \approx 0.46$, a somewhat low
value due to a relatively low refractive index of HSQ nanoridges that can however be improved by using high-index dielectrics, e.g., titanium dioxide (TiO₂), up to 0.8 (Section S1, Supporting Information). The intensity of the resulting outcoupled QE radiation is found concentrated near the perpendicular to the surface plane direction (Figure 2b) with the divergence angle of only ±4°, as determined at the full width at half-maximum (FWHM) of intensity distribution. The fraction of radiative light collected by the first objective with a numerical aperture (NA) of 0.9 is calculated to be ±0.92 (i.e., the collection efficiency ηce of 92%).

We evaluate the degree of circular polarization in the far field by the normalized Stokes parameter defined as \( P_c = (I_R - I_L)/(I_R + I_L) \), where \( I_R \) and \( I_L \) denotes the intensity for the right-hand (left-hand) circular polarization. \( P_c = 1, 0, -1 \) represents the ideal right-hand circular, linear polarization, and left-hand circular polarizations, respectively. It is seen that, for the considered design (Figure 2a), the right-hand circular polarization is observed at the central area of the angular distribution, i.e., of the Fourier plane (Figure 2c), i.e., precisely where the maximum intensity is located (cf. Figure 2b). This matching becomes even more transparent when both the far-field intensity and polarization angular distributions are 3D displayed with the height being proportional to the far-field intensity and the color to the field polarization state (Figure 2d). It is also seen that some radiation would come out with the left-hand circular polarization, indicating that the design can further be perfected. It is clear that, while the azimuthally varying width of nanoridges serves the purpose of controlling the phase of outcoupled radiation, this gradient introduces azimuthal variations in the radiation amplitude, which is an undesirable (though not strong) effect causing asymmetry in the outcoupled radiation pattern and imbalance in the resulted polarization. In the case of uniform scattering amplitude, the dominant central peak in the far-field intensity distribution would exhibit the designed circular polarization, being surrounded by a rather weak ring with the opposite circular polarization (Figure S1, Supporting Information). The finite numbers of outcoupling nanoridges and simplified design, in which we use for simplicity the linear width-gradient (Figure 1c), might also contribute to deviations from the ideal performance. Nevertheless, the full 3D simulations of the considered configuration demonstrate that the circularly polarized QE emission can be realized with an integrated metal-dielectric hybrid system composed of a width-gradient nanoridge metasurface interacting with SPP waves excited by a well-aligned QE. Finally, it should be emphasized that the considered metasurface configuration is sufficiently robust with respect to fabrication induced imperfections at the 10 nm scale (Figure S5, Supporting Information), which is a typical level of accuracy that can be ensured with the fabrication based on standard electron-beam lithography.

The experimental demonstration of SSP generation involves several technological steps requiring proper adjustment of nanofabrication parameters. To facilitate the fine-tuning, we first conducted the essential experimental steps using ~100 nm diameter NDs containing on average ~400 NV centers per ND (Adamas Nanotechnologies). These NDs can easily be located with the dark-field microscopy producing very bright spots (Section S2, Supporting Information). After spin-coating NDs on the 20 nm thin SiO₂ spacer atop Ag substrate, the relative position of a selected ND with respect to prefabricated gold aligning markers is determined using the corresponding dark-field microscopy image. The HSQ width-gradient circular nanoridges (Figure 3a,e) are subsequently fabricated around the selected NDs with standard electron-beam lithography using the aligning markers (Section S2, Supporting Information). The fabricated meta-atom arrangements with the selected ND surrounded by nanoridges are then excited with a tightly focused radially polarized 10 μW pump cw-laser beam at the

Figure 2. 3D simulation of SSP generation. a) Schematic top view of the width-gradient nanoridge metasurface with a QE. b) Far-field angular intensity distribution (in the Fourier plane) of the outcoupled QE radiation, featuring a very bright spot at the center, i.e., near the perpendicular to the surface plane direction, with the divergence angle of only 4.01°. c) Far-field polarization state distribution (in the Fourier plane) of the outcoupled QE radiation with the red color corresponding to the right-hand circular polarization and the blue to left-hand one. d) 3D representation of the superimposed beam intensity and polarization far-field distributions, with the height reflecting the light intensity and the color indicating the polarization. The dominant peak is red-colored, demonstrating that the majority of photons carry the designed SAM, i.e., possess the right-hand circular polarization.
wavelength of 532 nm that produces a strong longitudinal electric field component at the focal plane, which is perpendicular to the surface plane (Section S3.1, Supporting Information). This optical pump configuration ensures that thus excited NV centers (in the selected NDs) have sufficiently large projections of their radiative dipole transitions on the direction perpendicular to the surface, making thereby the experimental conditions to be similar to those used in our simulations (Figure 2).

The far-field distributions of intensity and polarization state of the emitted radiation can be determined by a set of intensity measurements, giving the four Stokes parameters with $S_0$ as the total intensity of the emission, $S_1$ is the intensity difference between linear horizontal and vertical polarization, $S_2$ is the intensity difference between linear +45° or −45° polarization, and $S_3$ is the intensity of right- or left-hand circular polarization. These Stokes parameters are determined by the intensities measured with a properly oriented quarter-wave plate and linear polarizer mounted on rotation stages (Section S3.2, Supporting Information). The far-field intensity distributions for the both realized configurations (Figure 3b,f) demonstrate well-collimated outcoupled beams with the FWHM divergence of $\approx 6.1°$, which is understandably larger than the simulated value of $\approx 4°$ because of spatial spread in NV centers inside NDs.

We evaluate the chirality of emitted photons using a modified $S_3$-parameter that is corrected for unpolarized light and defined as $R = S_3' / \sqrt{S_1'^2 + (S_3')^2 + (S_3')^2}$, in which $S_1'$, $S_3'$, and $S_3'$ are the Stokes parameters normalized to the corresponding total intensity ($S_0$) obtained in each measurement. The far-field chirality distributions indicate that the majority of photons (deduced from the corresponding intensity distributions) carry the designed SAM, i.e., possess the right-hand circular polarization. The intended intensity–chirality matching becomes even more transparent when both the far-field intensity and polarization angular distributions are 3D displayed with the height being proportional to the far-field intensity and the color to the field polarization state (Figure 3d,h). Overall, these experiments with multi-photon emitters demonstrate the feasibility of our approach for generation of photons carrying the designed SAM.

The demonstration of SSP generation requires the usage of NDs containing single color centers. For this purpose, we selected $\approx 30$ nm diameter NDs with a small faction containing single NV centers (MicroDiamant). Due to the small size these NDs have very low scattering cross sections (roughly three order of magnitudes smaller than that previously used with many NV centers) and are very problematic to localize on the dark-field microscopy images. In these experiments, the single-vacancy ND positions are determined using fluorescence images that are obtained using considerably higher laser powers ($\approx 200$ µW) under otherwise the same conditions than in the experiments with many NV centers (Figure 4a). The relatively weak single-photon emission from the selected ND leads to a relatively poor signal-to-noise ratio, especially in the final configuration with the fluorescence from the fabricated HSQ metasurface being...
Figure 4. Experimental demonstration of SSP generation. a) The fluorescence image featuring the selected ND—a bright spot in the center of a white-dashed circle indicating the area to be occupied by metasurface nanoridges. Aligning markers (crosses) are also seen due to the gold fluorescence. b,f) The measured (in the microscope objective back-focal plane) far-field emission intensity distributions of uncoupled (b) and coupled (f) NV center. The white circle indicates the extent of objective NA (NA = 0.9). c,g) Far-field polarization state distributions (in the Fourier plane) of the emission of uncoupled (c) and coupled (g) NV center, with the red color corresponding to the right-hand circular polarization and the blue to left-hand one. d,h) The second-order correlation function $g^{(2)}(t)$ measured before (d) and after (h) the metasurface fabrication. e) The fluorescence image featuring the selected ND as a bright spot in the center of a weakly fluorescing circular area representing the HSQ metasurface fabricated with the same parameters as that shown in Figure 3a. The fact that the ND-related bright spot is located exactly at the center of the metasurface-related circle confirms the accuracy of the positioning of HSQ nanoridges with respect to the ND. i) Emission spectra of the selected ND before (blue) and after (red) the metasurface fabrication. j) 3D representation of the superimposed beam intensity and polarization far-field distributions, with the height reflecting the light intensity and the color indicating the polarization. The dominant peak is red-colored, demonstrating that the majority of photons carry the designed SAM, i.e., possess the right-hand circular polarization. k) Emission saturation dependencies on the pump laser power before (blue) and after (red) the metasurface fabrication.

clearly visible (Figure 4e), a detrimental circumstance that serves however the purpose of enabling to assess the accuracy of the positioning of HSQ nanoridges with respect to the ND.

The single-vacancy ND used for demonstrating the SSP generation is systematically characterized before and after the fabrication the metasurface width-gradient circular nanoridges, i.e., in the uncoupled and coupled (to the metasurface) configurations. A band-pass filter with the spectral range of 650 ± 20 nm that includes the strongest emission of the single NV center (Figure 4i) is used to characterize the far-field intensity and polarization state distributions (Sections 3.2 and 3.3, Supporting Information). As anticipated, before the metasurface fabrication, the measured far-field fluorescence intensity is homogenously distributed (Figure 4b), and no circular polarization is observable (Figure 4c). After the fabrication, the intensity distribution demonstrates a well-collimated beam concentrated in the center with the angular FWHM of ≈4.7° (Figure 4f), which is slightly larger than the simulated value of ≈4° (Figure 2b) but smaller than that observed (≈6.1°) with many NV centers (Figure 3b). These differences might be considered as indications that the NV center is located slightly off the metasurface center but not as much as some NV centers contained in the large (~100 nm diameter) NDs used in the experiments with many NV centers. The corresponding polarization state distribution (Figure 4g) reveals that the main emission detected is characterized by the right-hand circular polarization ($P_c > 0.8$ in the centre). The intended intensity–chirality matching becomes even more transparent when both the far-field intensity and polarization angular distributions are 3D displayed (Figure 4j), although the noise background blurs the resulting image (cf. Figures 3d and 4i).
Fitting a three-level model to the second-order correlation data confirms that the selected NV center remains a single-photon source throughout the experiment, although the second-order correlation minimum deteriorates from $g^{(2)}(0) \approx 0.17$ (Figure 4d) to $g^{(2)}(0) \approx 0.27$ (Figure 4h) measured, corresponding to before and after the metasurface fabrication. As mentioned above the decrease in the signal-to-noise ratio is associated with the occurrence of the fluorescence from the fabricated HSQ metasurface. In general, the NV emission becomes significantly larger after the metasurface fabrication, primarily due to the redirecting of SPP waves (excited by the pumped NV center) toward the detection by scattering off the nanoridges. Thus, the saturated photon rate, $R_s = \eta QE/\tau$, measured without the band-pass filter, increases by a factor $R_s/R_{s0} = 2.74$, from $R_{s0} = 104$ kcps to $R_s = 284$ kcps after introducing the width-gradient nanoridges, while the saturation power remained nearly unchanged $P_{s0} = 320 \mu$W before and $P_s = 391 \mu$W after the metasurface fabrication (Figure 4k). A slight increase in the latter might simply be related to the additional contribution from HSQ fluorescence. The increase in the saturated photon rate is in good agreement with the numerical simulations predicting the ratio $R_s/R_{s0} = 3.29$. Considering the fact that only a minor lifetime enhancement of $\tau_s/\tau = 1.4$ is expected from our simulations matching the experimentally observed enhancement $\frac{\tau_s}{\tau} = 1.2 – 1.5$ (Section S3.4, Supporting Information), we infer that the increased photon rate is primarily due to an improvement in the quantum efficiency that results from the SPP waves being scattered to free space. Indeed, our modelling predicts a nearly double increase in the quantum efficiency, from $\eta_{QE0} \approx 0.24$ to $\eta_{QE} \approx 0.46$, after the introduction of metasurface, while the collection efficiency increases only slightly, from $\eta_0 = 0.75$ to $\eta = 0.92$ (when considering a relatively large NA of 0.9).

The proposed and demonstrated general approach to the implementation of complete control over scattering wavefronts emerging from a single distributed (in the surface plane) SPP quantum generated by an excited QE opens the doorway to engineering integrated photon sources capable of generating SAM-coded single photons with controllable far-field distributions at room-temperature. This approach can straightforwardly be extended to generation of single photons carrying also orbital angular momenta and composing, in general, vector beams by appropriately adjusting the width gradient in circular nanoridges along with judiciously choosing the smallest radius. Further improvements of the experimental realizations include the use of high-refractive index nanoridges, e.g., made of titanium dioxide ($\text{TiO}_2$), and gap-plasmon resonators in order to boost up the quantum efficiency (up to 0.8) and the Purcell enhancement of the emission rates (by $10^4$ times) respectively. Moreover, the purity, indistinguishability can be improved in the future by using other QE configurations (e.g., quantum dots) and semiconductor materials (e.g., AlGaAs and InGaAs). While the current grating design is optimized for a $2\pi$ phase variation with the azimuthal angle, it is further desirable to maintain a constant scattering amplitude. We envision the control and management of the scattering amplitude by varying the height of nanoridges, e.g., by making use of grayscale electron beam lithography. The access to engineering SAM-coded single-photon states may find numerous applications in quantum key distribution, interaction with chiral QE transitions and polarization filtering of laser light in resonant fluorescence experiments. We would like to emphasize that the proposed and demonstrated on-chip configuration for well-collimated and unidirectional SSP generation cannot simply be reduced to a combination of a single-photon source and quarter-wave plate, because the latter would require the availability of efficient unidirectional generation of well-collimated and linearly polarized single photons, whose realization is a challenging and yet to be solved task.

In summary, we have proposed a conceptually new approach to the room-temperature on-chip SSP generation, in which the QE excitation is first spread over a phase-gradient metasurface by nonradiative coupling to SSP modes and then outcoupled, by interacting with the metasurface, into a collimated stream of SSPs with the designed handedness. We reported the design, fabrication and characterization of SSP sources, consisting of dielectric circular nanoridges with azimuthally varying widths deterministically fabricated on a dielectric-protected silver film around a nanodiamond containing a nitrogen-vacancy center. We have also demonstrated using numerical simulations that the developed approach is sufficiently robust with respect to fabrication induced imperfections at the 10 nm scale, which are well within the accuracy that can be ensured with the fabrication based on standard electron-beam lithography. We believe that the developed room-temperature SSP generation approach opens new fascinating perspectives within integrated optical quantum technologies, in general, and chiral quantum optics, in particular.

**Experimental Section**

The substrate is fabricated by ohmic evaporation of 3 nm Ti, 200 nm Ag, 3 nm Ti topped by RF-sputtering of 20 nm SiO$_2$ on a Si wafer, followed by the alignment markers for determining the relative position of NDs. With multiple NV centers, 100 nm NDs containing ~400 NV centers (Adamas technology) are first spin-coated on the samples. The relative positions of the NDs in the coordinate frame of the alignment marks are determined by a dark-field microscopy image. An HSQ layer was subsequently spin-coated at 1000 rpm (60 s) and prebaked at 160 °C for 2 min. The gradient-width bullseye gratings are patterned around the ND by electron beam lithography by aligning to the markers, followed by development using 25% TMAH (tetramethylammonium hydroxide) for 4 min. Single-photon experiments were conducted using natural ND 0–0.05 μm GAF (Microdiamant). As so small ND’s were not visible in dark-field images and few ND’s contain NV centers, the NV position was determined based on fluorescence maps instead using the same image treatment as for ND with multiple NV centers.

The NDs are driven by radially polarized beam, which is focused onto the sample using a 100 0.9x NA objective. Fluorescence collected by same objective is filtered from the laser light. Recording the fluorescence photon rate with an avalanche photodiode (APD1) while scanning the sample, using a piezo stage, allowed for locating NV centers by the recording of fluorescence maps. For determining the Stokes parameters, a broadband quarter-wave plate mounted on a motorized rotation stage is flipped into the optical path together with a polarizer. A flip mirror projects the Fourier plane onto a CCD camera. Second-order correlation measurements were recorded by histogramming the timing delay between photon detection events between APD1 and APD2 in a start–stop configuration. Fourier plane images of $S_2$ were obtained by setting the fast axis of the quarter-wave plate to respectively $\pm 45^\circ$ with respect to the polarization axis. For measuring the $S_3$ and $S_2$ Stokes
parameters, the quarter-wave plate is removed and the polarizer is mounted on the motor stage. The detailed information about the setup and measurement can be found in the Supporting Information.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
Y.H.K. and S.K.H.A. contributed equally to this work. The authors gratefully acknowledge financial support from the European Research Council under Grant No. 341054 (PLAQNAP). S.I.B. acknowledges the support from the Villum Kann Rasmussen Foundation (Award in Technical and Natural Sciences 2019). F.D.Z. acknowledges the support of Villum Experiment (Grant No. 00022988) from Villum Fonden. C.Y.Z. and Y.H.K. acknowledge the support from the National Natural Science Foundation of China (Grant No. 51636004) and the China Scholarship Council (Grant No. 201806230179).

Conflict of Interest
The authors declare no conflict of interest.

Keywords
circular polarization, metasurfaces, quantum emitters, single photons, surface plasmon polaritons

Received: November 28, 2019
Revised: January 28, 2020
Published online: March 1, 2020

[1] L. Duan, M. D. Lukin, J. I. Cirac, P. Zoller, Nature 2001, 414, 413.
[2] J. W. Pan, Z. B. Chen, C. Y. Lu, H. Weinfurter, A. Zeilinger, M. Zukowski, Rev. Mod. Phys. 2012, 84, 777.
[3] Y. H. Yu, B. Yu, M. Y. Jing, L. T. Xiao, S. T. Jia, G. Q. Qin, G. L. Long, Light: Sci. Appl. 2016, 5, e16144.
[4] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, G. J. Milburn, Rev. Mod. Phys. 2007, 79, 135.
[5] J. L. O'Brien, Science 2007, 318, 1567.
[6] T. Chanelière, D. N. Matsukevich, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, A. Kuzmich, Nature 2005, 438, 833.
[7] V. Giovannetti, S. Lloyd, L. Maccone, Nat. Photonics 2011, 5, 222.
[8] X. L. Chu, S. Gotzinger, V. Sandoghdar, Nat. Photonics 2017, 11, 58.
[9] J. T. Hugall, A. Singh, N. F. van Hulst, Science 2018, 361, 391.
[10] S. K. H. Andersen, S. I. Bozhevolnyi, Nano Lett. 2017, 17, 700.
[11] J. Kim, O. Benson, H. Kan, Y. Yamamoto, Nature 1999, 397, 500.
[12] M. Segev, Science 2018, 361, 1101.
[13] K. Wang, J. G. Titchener, S. S. Kruk, L. Xu, H. P. Chng, M. Parry, I. I. Kravchenko, Y. H. Chen, A. S. Solntsev, Y. S. Kivshar, D. N. Neshev, A. A. Sukhorukov, Science 2018, 361, 1104.
[14] S. K. H. Andersen, S. Kramar, S. I. Bozhevolnyi, Nano Lett. 2017, 17, 3889.
[15] Z. Li, E. Palacios, S. Butun, K. Aydin, Nano Lett. 2015, 15, 1615.
[16] S. Gao, W. Yue, C.-S. Park, S.-K. Lee, E.-S. Kim, D.-Y. Choi, ACS Photonics 2017, 4, 322.
[17] H. Siampour, S. Kumar, V. A. Davydov, L. F. Kulikova, V. N. Agafonov, S. I. Bozhevolnyi, Light: Sci. Appl. 2018, 7, 61.
[18] G. M. Akselrod, C. Argypoulos, T. B. Hoang, C. Ciraci, C. Fang, J. Huang, D. R. Smith, M. H. Mikkelsen, Nat. Photonics 2014, 8, 835.
[19] A. Pors, S. I. Bozhevolnyi, ACS Photonics 2015, 2, 228.
[20] M. Geissler, Y. N. Xia, Adv. Mater. 2004, 16, 1249.