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Versatile Linearly Polarized Photon Generation from a Quantum Emitter in Metasurface-Decorated Waveguides

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ABSTRACT

Linearly polarized quantum sources with high purity and well-defined polarization angles are the fundamental blocks in the photonic quantum technological evolution. However, due to the orientation of the dipole moment with the quantum emitters, the polarization state of the emitted photons is intrinsically limited. Therefore, it is impossible to generate arbitrary linear polarization states simultaneously. Here, we propose a new concept of versatilely generating linearly polarized emission based on a quantum metasurface platform that combines nano-diamonds containing color centers with metasurface-decorated waveguides. By tailoring the size and orientation of the slit meta-atom on the waveguide, linearly polarized emission with arbitrary polarization angles can be achieved with the degree of linear polarization larger than 0.999.

Keywords: linearly polarized emission, quantum emitter, metasurfaces, dielectric-loaded waveguide

1. INTRODUCTION

Linearly polarized quantum sources with high purity and well-defined polarization angles are the fundamental blocks in the photonic quantum technological evolution. However, due to the orientation of the dipole moment with the quantum emitters, the polarization state of the emitted photons is intrinsically limited. To generate linearly polarized quantum sources, separate single photons are typically combined with additional polarization optics that rely on birefringent materials, such as quartz or mica, where the phase retardation is gradually accumulated as light propagates over a distance much longer than its wavelength. As a result, the resulting quantum sources are inherently bulky, thereby severely limiting the possibilities of miniaturizing and densely-integrating quantum systems to the nanoscale. During the past few years, metasurfaces, subwavelength elements arranged in a strictly or quasi-periodic fashion, has attracted progressively increasing attention due to the ease of fabrication and smaller insertion losses, while enabling unprecedented control over the polarization state of optical fields with high efficiencies and thus revolutionizing traditional bulky polarization optics with ultrathin flat devices.

Despite certain achievements, the metasurface-enabled polarization optics so far are limited to the classical regime while linearly polarized quantum sources with high purity and well-defined polarization angles are still largely unexplored. It is highly desired to generate quantum sources with arbitrary linear polarization states in a controllable manner. Here, we propose a new concept of versatilely generating linearly polarized emission based on a quantum metasurface platform that combines nano-diamonds containing color centers with metasurface-decorated waveguides. By tailoring the size and orientation of the slit meta-atom on the waveguide, linearly polarized emission with arbitrary polarization angles can be achieved with the degree of linear polarization larger than 0.999. This presented platform gives a new perspective of compact integration and versatile polarization generation for quantum sources.

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2. DESIGN PRINCIPLE AND DISCUSSION

Fig. 1a depicts the schematic diagram of the designed configuration composed of radially oriented dielectric-loaded waveguides supporting user-defined propagated SPP modes coupled from a quantum emitter (QE). The waveguides are designed as hydrogen silsesquioxane (HSQ) on top of a silver substrate, which can be possibly patterned by the standard electron-beam lithography (EBL). Near to the end of waveguides, meta-atoms are assembled with etched rectangle slits. Upon excitation from a QE, the TM-polarized SPP modes are guiding over the waveguides and subsequently scattered into free-space photons with well-defined linear polarization states by the slit meta-atoms oriented normal to the direction of the waveguides. Additionally, linearly polarized photons with customized polarization angles can be realized via rotating the meta-atoms.

![Figure 1. Schematic of metasurface-decorated waveguides containing a QE for versatile linearly polarized photon generation.](image)

To investigate the performance of the proposed configuration, we performed full-wave simulations by using the finite-difference time-domain (FDTD) method (Lumerical Inc. software). Firstly, an electric dipole oriented normal to the surface in the z-direction and located 30 nm from the surface of silver (Ag) substrate is used to excite radially polarized SPPs at the vacuum wavelength of 670 nm. Without waveguides, in-plane diverging radially polarized SPPs are excited and propagating on the air-Ag interface, as shown in Fig. 2(a). Once a straight HSQ waveguide with an optimal width of 400 nm is introduced to cover the QE, the excited SPPs are coupled into waveguide modes, as shown in Fig. 2(b). Specifically, 48.3% of the SPP power is coupled to waveguide modes due to the confined enhanced electric field in Fig. 3(b). Besides mode guiding, the straight waveguide also constitutes a cavity around the dipole, thereby leading to a Purcell factor of 4.2, as shown in Fig. 3(b). However, there’s still half of the SPP power emitted by dipole leaking to the direction perpendicular to the straight waveguide. To improve the coupling efficiency, we arrange four waveguides along the radial directions and achieve the ultra-high coupling efficiency of 91.1%, as shown in Fig. 3(c). The corresponding Purcell factor is increased a little bit to 4.6. At the optimal width of 400 nm, the propagation length can reach 21.9 µm if we use the Jonson-Christy data to describe the optical constant of the Ag.
To generate linearly polarized photon emission, the width $L_x$, length $L_y$ and rotation angle $\theta$ of the slit meta-atom are finely optimized. As shown in Fig 4(a), the confined SPP mode propagates along the HSQ-Ag interface and resonates back and forth at the sidewalls of the meta-atoms, leading to field enhancement. Then the slit meta-atom functions as an in-plane electric dipole along the direction of the waveguides and result in linearly polarization emission. The $E_x$ component of SPP mode clearly demonstrates that most of SPPs are scattered to free-space photons while the remaining SPPs continue to propagate along the interface. The slit height etched in the Ag substrate can be determined by collecting the emitted power on top of the meta-atom. Due to the broadband spectrum of QEs, such as nitrogen-vacancy center in nano-diamonds\(^{11}\), we simulate 5 wavelengths near 670nm in Fig. 4(c), which demonstrates a broadband resonance except for a small shift in the peaks.

To show the capability of versatile linearly polarized photon generation, the meta-atom is rotated with a series of angles from 0 to 80° by a step of 10°. The angle of linear polarization (AoLP) of the scattered photons is calculated in the far-field by retrieving the Stokes Parameters. As expected, the AoLP of scattered photon closely matches the corresponding rotation angles of the meta-atom, as depicted in Fig. 4(d). When the slit meta-atom is rotated, the $E_x$ component of the waveguide mode can be decomposed into two orthogonal components along the long and short axis of the slit, respectively. The short-axis electric field can efficiently drive the dipole resonance and finally leads to linearly polarized emission with tailorable AoLP. Importantly, the purity of the linear polarization, which is described by the degree of linear polarization (DoLP), is approaching 1 even with large rotation angles, as shown in Fig. 4(e).
3. SUMMARY

We have numerically demonstrated a promising quantum metasurface platform for versatile linearly polarized photon generation, which combines nano-diamonds containing color centers with metasurface-decorated waveguides. By tailoring the size and orientation of the slit meta-atom on the waveguide, linearly polarized emission with arbitrary polarization angles can be achieved with a high DoLP. Our approach can be a promising solution for compact on-chip polarized quantum sources.
REFERENCES


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