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Metasurface-Enabled Broadband Beam Splitters Integrated with Quarter-Wave Plate Functionality

Fei Ding,* Rucha Deshpande, Chao Meng and Sergey I. Bozhevolnyi

Conventional beam splitters and wave plates, while being essential components in diverse optical systems, require considerable space, especially when used in combination. Here, we design and experimentally demonstrate metasurface-enabled efficient broadband beam splitters integrated with quarter-wave plate (QWP) functionality for simultaneous power splitting and circular-to-linear polarization conversion in the near-infrared range. By utilizing two different gap-plasmon meta-atoms, which function as QWPs performing efficient circular-to-linear polarization conversion as well as provide the phase difference of $\pi$ between reflected linearly polarized beams, we design a metasurface that completely suppress the specular reflection (zero-order diffraction) and second-order diffraction, while ensuring efficient and equal beam splitting of a circularly polarized wave into two reflected beams with predesigned directions and well-defined linear-polarization states in the wavelength range of 750 – 950 nm. The fabricated metasurface exhibits excellent performance of circular-to-linear conversion and power splitting, with efficient suppression of specular reflection (< 1%) and splitting efficiencies above 50% for both right and left circularly polarized excitations at the design wavelength of $\lambda = 850$ nm. By enabling the combined functionalities of a conventional beam splitter and a QWP, our approach opens up new prospects for advanced research and applications targeting photonics integration and miniaturization.

Introduction

Beam splitters that can split a beam of light in two are the essential components of many optical and photonic systems, such as interferometers, thereby finding widespread applications in optical communications and quantum optics. Conventional state-of-the-art beam splitters are made of bulky prisms, flat glasses or plastic sheets. Therefore the resulting devices are suffering from inherently bulky and voluminous configurations, which goes against the current trend of integration and miniaturization in photonics. A promising solution is to use optical metasurfaces, surface-confined nanostructures that are capable of directly tailoring the wavefronts of impinging optical waves and realizing specific wavefront transformations. Owing to their remarkable capabilities in light manipulation, planar profiles as well as ease of on-chip fabrication and integration, metasurfaces have gained increasing attention and shown great potential in replacing bulk optics with ultra-compact flat optical components, including beam steerers, focusing lenses, optical holograms, waveplates, and spectrometers. At the same time, metasurfaces offer a new way for beam splitters to overcome the aforementioned limitations. Many exotic metasurface-based beam splitters, such as polarization-beam splitters and polarization-insensitive beam splitters, have been demonstrated previously.

Despite great achievements, most of up-to-date metasurface-based beam splitters are designed for a sole functionality of beam splitting. To fulfill the requirements of dense integration and miniimization in model photonics, it is highly desired to integrate as many functionalities into a single beam splitter as possible. Here, we design and experimentally demonstrate metasurface-enabled efficient broadband beam splitters integrated with quarter-wave plate (QWP) functionality for simultaneous power splitting and circular-to-linear polarization conversion in the near-infrared range by utilizing differently shaped gap-plasmon meta-atoms. Capitalizing on two different meta-atoms, which function as efficient QWPs performing circular-to-linear polarization conversion as well as provide the phase difference of $\pi$ between reflected linearly polarized (LP) beams, we design a metasurface beam splitter that efficiently splits a normally incident circularly polarized (CP) wave into two reflected beams with predesigned directions and well-defined linear-polarization states in the wavelength range of 750 – 950 nm, while suppressing the specular reflection and second-order diffraction. The fabricated metasurface exhibits excellent performance of circular-to-linear conversion and power splitting, with efficient suppression of specular reflection (< 1%) and splitting efficiencies above 50% for both right circularly polarized (RCP) and left circularly polarized (LCP) excitations at the design wavelength of $\lambda = 850$ nm.
Results and Discussion

Fig. 1(a) schematically illustrates the working principle of the proposed beam splitter with QWP functionality that enables simultaneous power splitting and circular-to-linear polarization conversion in the near-infrared range by utilizing gap-plasmon meta-atoms. On excitation with a CP plane wave, the polarization and phase shift of the reflected waves are, simultaneously and independently, tailored by each meta-atom that functions as an efficient nanoscale QWP (nano-QWP). Consequently, the reflected LP waves constructively interfere in the far-field to generate two identical beams with opposite directions, thereby combining the functionalities of a conventional beam splitter and a QWP within a compact device.

To design gap-plasmon nano-QWPs, we implement three-dimensional (3D) full-wave simulations to optimize the commonly used metal-insulator-metal (MIM) configuration (see Experimental section for details), which consists of gold (Au) nanoantennas tilted by 45° with respect to the x-axis, a silicon dioxide (SiO₂) dielectric layer, and a continuous Au film [Fig. 1(b,c)]. By properly optimizing the dimensions of the tilted Au nanoantenna, we can independently control the amplitudes and phases of detuned plasmonic resonances along the long- and short-axis when a CP light is impinging normally on the MIM structure from the top. When the relative phase difference Δφ between two detuned resonances along the long- and short-axis reaches ~90° and the reflection amplitudes possess nearly identical values, efficient circular-to-linear polarization conversion can be consequently achieved. Fig. 2(a) shows the simulated degree of linear polarization (DoLP) of the reflected beam when an RCP beam is normally incident, which can fully describe the figure of merit of a QWP. At the design wavelength of λ = 850 nm, the calculated DoLP is 95.28% and 99.95% for the ellipse-shaped and cross-shaped meta-atoms, respectively, validating the excellent QWP functionality. Additionally, the calculated angle of linear polarization (AoLP) is around 0° at λ = 850 nm [Fig. 2(b)]. As such, these two meta-atoms function as excellent nano-QWPs enabling polarization conversion between CP light and LP light. Besides the excellent capability of circular-to-linear polarization conversion, such two differently shaped meta-atoms could tailor the phase shifts of the reflected LP light. As shown in Fig. 2(c), the phase difference between these two meta-atoms is approximately equal to π radian for the reflected LP light. Meanwhile, their reflectivities are both above 70%, ensuring a high efficiency for the proposed metasurface-based beam splitter [Fig. 2(d)].

Capitalizing on predesigned unit cells, we take the so-called one-dimensional coding metasurface as an example and design a basic dual-beam splitter in reflection while maintaining the functionality of circular-to-linear polarization conversion. Fig. 3(a) illustrates the schematic of the metasurface supercell by periodically arranging cross-shaped and ellipse-shaped unit cells in alternative columns, which generates identical phase gradients along the x-axis and -x-axis at the same time, thereby directing the reflected light to two symmetric angles with respect to the x-axis. The split angle is equal to the anomalous reflection angle determined by the generalized Snell’s law for normal incident light: \( \theta = \sin^{-1} \left( \frac{\lambda}{n \cdot p} \right) \), where \( \lambda \) is the wavelength in free space and \( n \) = 6 is the number of elements compose a supercell. Thus, the theoretically calculated diffraction angles are ±28.2° at λ = 850 nm. As a final comment, it should be mentioned that \( n \) can take an arbitrary even integer larger than 2 (ESI Section S1).

We first performed 3D full-wave simulations with the supercell in Fig. 3(a) [See the Methods section for details]. Fig. 3(b,d) shows the electric field distributions of different components at the design wavelength of 850 nm for the normally incident RCP and LCP light, respectively. One can clearly see that the electric fields are no longer uniform due to...
the interference among multiple reflected beams in different directions. Additionally, the split multiple reflected beams become linearly polarized instead of circularly polarized. For instance, the RCP incident light is converted into \( p \)-polarized beams containing \( E_x \) and \( E_y \) components, whereas the \( E_z \) component is negligible. In order to retrieve the magnitudes and polarization states of the reflected waves in different directions, 3D far-field simulations were conducted (See the Methods section for details). Fig. 3(c) and 3(e) plot the corresponding far-field distributions of different decomposed components at \( \lambda = 850 \, \text{nm} \) under RCP and LCP excitations, where two dominating diffraction peaks appear at the angle \( \theta \) of \( \pm 28.08^\circ \), in good agreement with the theoretical values of \( \pm 28.2^\circ \). From Fig. 3(c), it can be seen that the \( p \)-polarized (\( x \)- and \( z \)-polarized components) reflected power (black dashed curve) coincides well with the total reflected power (red curve), and the \( s \)-polarized (\( y \)-polarized component) reflected power (blue dashed curve with circles) is almost zero at the \( \pm 1 \) diffraction orders under RCP excitation, confirming the required capabilities. The ratio between the reflected power of the desired \( p \)-polarization and \( s \)-polarization reaches as high as 180. When the incident light is switched to LCP, the \( s \)-polarized (\( y \)-polarized component, blue dashed curve with circles) reflected power becomes dominating while the \( p \)-polarized (\( x \)- and \( z \)-polarized components, black dashed curve) reflected power is nearly zero, as shown in Fig. 3(e). More simulated results at other wavelengths are presented in the ESI Figs. S3 and S4, validating the broadband performance. However, when the working wavelength deviates further from the design value of \( \lambda = 850 \, \text{nm} \), the unwanted zero-order diffraction would increase and become noticeable.

To experimentally demonstrate our proposed metasurface beam splitter with the QWP functionality, we fabricated the sample using the thin-film deposition, electron beam lithography (EBL), and lift-off process (see more details of fabrication in the Methods section). The optical and scanning electron microscope (SEM) images of a metasurface beam splitter with an overall lateral size of 30.6 \( \mu \text{m} \times 30.6 \, \mu \text{m} \) indicate high-quality fabrication despite the surface roughness as well as rounding at the edges and corners [Fig. 4(a,b)]. Following fabrication, we characterized the beam splitter using a homemade setup that can measure the light reflected at different diffraction orders directly (ESI Fig. S5). A super-continuous laser (NKT, SuperK EXTREME) was combined with an acousto-optic tunable filter (SuperK SELECT) to produce a monochromatic light source. The incident light was converted into a CP beam by using a Glan-Taylor polarizer (Thorlabs, GT15-B) and a super-achromatic QWP (Thorlabs, SAQWP05M-1700). Then the CP light was weakly focused on the sample with a beam diameter of \( \sim 20 \, \mu \text{m} \) using a lens with a focal length of 50 mm (Thorlabs, LA1131-ML), ensuring that the incident beam could cover most of the metasurface but didn’t exceed the metasurface boundaries. A beam splitter (Thorlabs, CCM1-BS014/M) was placed right after the lens to separate the incident light from zero-order diffracted light. The polarization states of the different diffraction orders upon reflection from metasurface were checked by adding a linear polarizer (Thorlabs, LPVIS100-MP2) in front of the power meter.

In Fig. 4(c,e), we plotted the measured total diffraction efficiencies and amount of light reflected into different diffraction orders and polarization bases. As expected, most of the light is split into \( \pm 1 \) order and the specular reflection in the zero-order is greatly suppressed when the operating wavelength is close to the designed value for both circular polarizations. Specifically, over 99% of the reflected light is confined within \( \pm 1 \) diffraction orders for both RCP and LCP excitations at the design wavelength of \( \lambda = 850 \, \text{nm} \). In addition, the experimentally measured splitting efficiencies are found to be above 50% for two circular polarizations at \( \lambda = 850 \, \text{nm} \). Importantly, it is impressive that the split dual-beams show expected polarization distributions. If the incident light is RCP, we mainly have the \( p \)-polarized components (i.e., \( x \)- and \( z \)-components) within the \( \pm 1 \) orders. Once the input is switched from RCP to LCP, the split beams become \( y \)-polarized. Besides the design wavelength, the beam splitter can efficiently split a normally incident CP wave into two reflected beams with predesigned directions and well-defined linear-polarization states in the wavelength range of 750 – 950 nm. The measurements are then compared with numerical calculations for which a supercell is modeled (see the Methods section for details), as shown in Fig. 4(d,f). In general, we observe a good...
agreement between the measured and calculated diffraction efficiencies under different polarization bases, verifying the broadband power splitting and circular-to-linear polarization conversion. The discrepancy in the reduced efficiency may be ascribed to the imperfections and surface roughness of the sample, as well as the increased material loss due to titanium (Ti) adhesion layers between dielectric-metal interfaces.

Fig. 4 Experimental implementation of the metasurface-enabled broadband optical beam splitter with quarter-wave plate functionality. (a) Optical image of the fabricated sample. (b) SEM images of the fabricated sample with different magnifications. (c) Measured and (d) simulated amount of light reflected into the lowest diffraction orders \( m \) and polarization bases as a function of wavelength for normally incident RCP light. (e) Measured and (f) simulated amount of light reflected into the lowest diffraction orders \( m \) and polarization bases as a function of wavelength for normally incident LCP light.

We subsequently verified the polarization states of the split dual-beams by recording intensity distributions as a function of the orientation of a linear polarization analyzer in front of the power meter. Fig. 5 displays the measured polarization states of the reflected beams in the planes perpendicular to the wave vectors of \( \pm 1 \) orders at the wavelengths of \( \lambda = 800, 850, \) and 900 nm for both LCP and RCP light, respectively. By rotating the linear polarization analyzer with a step of 10°, the measured intensity profiles assemble the cosine-squared patterns and can be described by Malus’ law, indicating high degrees of linear polarization for all the split beams. Specifically, the measured degrees of linear polarization are found to be 0.885 (0.875) and 0.863 (0.976) with the \( \pm 1 \) \( \mp 1 \) diffraction order for the RCP and LCP incident light at the wavelength of \( \lambda = 850 \) nm, respectively. Under RCP illumination, \( p \)-polarized dual-beams containing \( x \)- and \( z \)-components are created. When the incident light is switched to LCP, two \( s \)-polarized beams containing only \( y \)-components are directed to the \( \pm 1 \) orders.

Fig. 5 Experimentally measured polarization state in the planes perpendicular to the wave vector in the \( \pm 1 \) diffraction orders for the (a,b) RCP and (c,d) LCP excitation at wavelengths of 800 nm, 850 nm, and 900 nm.

Conclusions

In conclusion, we have proposed and demonstrated metasurface-enabled broadband efficient beam splitters integrated with the QWP functionality for simultaneous power splitting and circular-to-linear polarization conversion in the near-infrared range by utilizing gap-plasmon meta-atoms that function as highly efficient nano-QWPs and provide a phase difference of \( \pi \) between the reflected LP beams. The proof-of-concept beam splitter can efficiently split a normally incident CP wave into two reflected beams with predesigned directions and well-defined linear-polarization states in the wavelength range of 750 – 950 nm. More importantly, the fabricated beam splitter shows excellent performance of circular-to-linear polarization conversion and power splitting, with the specular reflection less than 1% and splitting efficiencies above 50% for both RCP and LCP excitations at the design wavelength of \( \lambda = 850 \) nm. Our proposed metasurface-based beam splitter can be scaled to operate at other relevant frequencies easily, such as the technologically difficult terahertz frequency. Owing to the versatility, compactness, integration compatibility and multifunctionalities, our approach opens up new prospects for dense integration and minimization in advanced photonic devices and systems.

Methods

Numerical simulation

All 3D full-wave simulations were performed using the commercially available software Comsol Multiphysics (ver. 5.3) based on the finite element method. In all cases, the corners of
the Au nanoantennas were round with a radius of 5 nm to consider the deviations in fabrication and eliminate singularities. In our MIM configurations, the permittivity of gold is described by the Drude model fitted with the experimental values\(^9\) where the damping rate is increased by a factor of three to consider the grain boundary effects and surface roughness in thin films. The SiO\(_2\) was assumed to be a lossless dielectric with a constant relative permittivity of \(\varepsilon = 2.1\). To optimize the QWPs, we only modeled a single unit cell by applying periodic boundary conditions on the vertical sides of the cell. The air domain above the nanoantennas was truncated using a perfectly matching layer (PML). An RCP place wave was set to impinge normally on the structure from the top. After simulation, both \(x\)- and \(y\)-polarized reflected waves were monitored to retrieve the DoLP, AoLP, reflection amplitudes as well as reflection phases. Regarding the supercell in Figure 3a, periodic boundary conditions were set on the vertical sides of the supercell and PML was also used. The diffraction efficiencies were then obtained by calculating the reflection into the different diffraction orders and normalizing with the incident light. To retrieve the magnitudes and polarization states of the waves in different directions, 3D far-field simulations were conducted, where a beam splitter consisting of four supercells in the \(x\)-direction and infinitely extended in the \(y\)-direction was modeled. A circularly polarized Gaussian input beam with a beam waist of 2 \(\mu\)m was considered invariant along the \(x\)-direction, and PMLs were used in the \(x\)- and \(z\)-directions. The far-field distributions were obtained by integrating the scattering fields.

**Sample Fabrication**

First, the successive layers of 3-nm-thick Ti, 130-nm-thick Au and 3-nm-thick Ti were deposited onto a silicon substrate using thermal evaporation with the deposition rates of 0.02 nm/s, 0.1 nm/s and 0.02 nm/s, respectively. Then a 50-nm-thick SiO\(_2\) spacer layer was prepared with radiofrequency sputtering with the deposition rate of 0.05 nm/s. After that, a 100-nm-thick e-beam resist PMMA (2\% in anisole, Micro Chem) layer was spin-coated, baked at 180°C for 2 min, and subsequently exposed at an acceleration voltage of 30 keV. After exposure, the sample was developed in a solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) of MIBK: IPA=1:3 for 40 seconds. During developing, a 2-nm-thick Ti adhesion layer and a 50-nm-thick Au layer were deposited using thermal evaporation. Finally, the top Au patterns were formed after a lift-off process using acetone.

**Conflicts of interest**

There are no conflicts to declare.

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**References**

33 M. Khorasaninejad and K. B. Crozier, *Nat. Commun.*, 2014, **5**, 5386
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Metasurface-enabled broadband beam splitters integrated with quarter-wave plate functionality for simultaneous power splitting and circular-to-linear polarization conversion have been demonstrated.