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ABSTRACT

Metasurfaces – artificial 2D sheet structures with sub-wavelength periodicity and dimensions of elements – are paving the way to improve traditional optical components by integrating multiple functionalities into one optically flat device. With the progress in nano-fabrication methods, different applications of metasurfaces were demonstrated experimentally, ranging from artificial plasmonic colouring to flat optical components. In this work, we demonstrate implementation of a bifunctional gap-surface-plasmon-based metasurface which, in reflection mode, splits orthogonal linear light polarizations and focuses into different focal spots. The fabricated configuration consists of 50 nm thick gold nanobricks with different lateral dimensions, organized in an array of 240 nm x 240 nm unit cells on the top of a 50 nm thick silicon dioxide layer, which is deposited on an optically thick reflecting gold substrate. Structure is fabricated using standard electron beam lithography and lift-off techniques. Characterization is performed using scanning electron microscopy and optical measurements, including investigation of wavelength dependence of efficiency, focal length and polarization extinction ratio. Our device features high efficiency (up to \(\sim 65\%\)) and polarization extinction ratio (up to \(\sim 30\,\text{dB}\)), exhibiting broadband response in the near-infrared band (750 – 950 nm wavelength) with the focal length and numerical aperture dependent on the wavelength of incident light. The proposed optical component can be straightforwardly integrated into photonic circuits or fiber optic devices which employ polarization multiplexing.

Keywords: gradient metasurfaces, flat optics, plasmonics, gap surface plasmons

1. INTRODUCTION

Quasi-two-dimensional artificial metallic and dielectric structures of sub-wavelength dimensions, known as optical metasurfaces,\(^1\)\(^-\)\(^4\) have developed tremendously in recent years.\(^5\)\(^-\)\(^11\) Applications of metasurfaces range from artificial plasmonic coloring\(^12\),\(^13\) to flat optical components.\(^14\),\(^16\) It is important to note, that many of the demonstrated functionalities cannot be realized with conventional (bulk) optical components. For more information, we refer to recent reviews.\(^17\),\(^18\)

Possibility to integrate various functionalities into one optical component of a sub-wavelength thickness is one of the important advantages of metasurfaces.\(^19\),\(^21\) For example, single-chip multi-functionality is highly advantageous for optical systems which exploit polarization properties of light, e.g. polarization multiplexed fiber-optic communications\(^22\) or polarization-assisted sensing.\(^23\) Here, we demonstrate an implementation of a bifunctional metasurface, which can be directly employed in such systems. It functions as a polarization-sensitive parabolic reflector (and thus it is also referred as metamirror), simultaneously focusing and splitting orthogonal light polarizations into different focal spots at the design wavelength \(\lambda = 800\,\text{nm}\). Illustration of the working principle of metamirror is shown in Figure 1. Constitutive elements of the device are so-called gap surface plasmon (GSP) resonators,\(^24\),\(^27\) which are widely used within the metasurface research community for efficient light steering applications.\(^17\)

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GSP resonators support highly localized plasmonic resonances that form flexible meta-atom building blocks with the possibility to engineer the local phase and reflection/transmission amplitude in phase gradient metasurfaces.\textsuperscript{17,28} GSP-based metasurfaces typically operate in the reflection mode, which enables high efficiency (up to $\sim 80\%$ for various applications).\textsuperscript{16}

The metamirror is comprised of a grid of GSP resonators with periodicity of $\Lambda = 240$ nm, which are assumed to be not coupled between each other. The unit cell of that grid is comprised of lithographically patterned gold nanobricks of height $t = 50$ nm and lateral dimensions $L_x$ and $L_y$. The nanobricks lie on a silicon dioxide layer ($t = 50$ nm) deposited on optically thick gold substrate, as shown in the inset of Figure 2. Such a metal-insulator-metal (MIM) configuration supports GSP resonances, whose intrinsic property is strong field confinement in the dielectric layer under the metal nanobrick. Due to this property, a negligible coupling between neighboring unit cells is permissibly assumed,\textsuperscript{16} which facilitates the construction of phase gradient metasurfaces.

Optical response of the considered MIM configuration is modelled using a commercially available finite-element software (Comsol Multiphysics). Model assumes normally incident light (of wavelength $\lambda = 800$ nm) polarized along the $x$-axis. Complex reflection coefficient $r = |r| \exp(i\phi)$ is calculated in a parametric sweep through all possible combinations of nanobrick lateral dimensions $L_x$ and $L_y$, while other geometric parameters are kept constant.

These two degrees of freedom in the design geometry give control over reflection phase, $\phi$, in almost full $2\pi$ phase space, as shown in colour-map in Figure 2. Moreover, it is possible to control phase response of the unit cell independently for two orthogonal linear light polarizations – transverse magnetic (TM) or $x$-polarization, and transverse electric (TE) or $y$-polarization. Figure 2 shows phase response (or phase map) for TM polarization, whereas phase response for TE is the transpose of the map shown in Figure 2 (i.e. $L_x$ and $L_y$ variables are interchanged for orthogonal polarizations). Considered GSP resonator has a high reflection amplitude $|r|$ (with exception of small region of dimension space close to the resonance), as shown in contour map in Figure 2, which is an important property for the effective metamirror performance.
2. DESIGN AND FABRICATION

The main design principles for light-steering metasurfaces are derived from the generalized laws of reflection and refraction. For focusing in reflection, a hyperboloidal phase gradient (also referred to as phase profile) needs to be imposed, which can be shown by investigating the optical path difference of rays reflected from the metasurface. If the incident light is assumed to be a plane wave with a harmonic time dependence, $E(x,t) = E_0 \exp[i(k \cdot x - \omega t)]$, the incident light is assumed to be a plane wave with a harmonic time dependence, $E(x,t) = E_0 \exp[i(k \cdot x - \omega t)]$,
then the reflected light wave differs only by a factor \(\exp[i\phi(\alpha)]\), which is the reflection phase (\(\alpha\) indicates the polarization, i.e. either TM or TE). In order to focus reflected plane wave, phase accumulated in the redundant optical path has to be compensated, which is made by imposing a hyperboloidal gradient of reflection phase (i.e. local reflection phase becomes a function of spatial coordinates).

For considered case of simultaneous polarization splitting and focusing, two phase profiles are imposed independently for each of two orthogonal polarizations. Centres of hyperboloid profiles are shifted one from another in order to separate focal points. The two conditions for reflection phase \(\phi = \arg(r)\) can be described by the following equations:

\[
\phi_{(TM)}(x, y) = \frac{2\pi}{\lambda} \left( d_z^{(TM)} - \sqrt{(x - d_x^{(TM)})^2 + (y - d_y^{(TM)})^2 + (d_z^{(TM)})^2} \right) \\
\phi_{(TE)}(x, y) = \frac{2\pi}{\lambda} \left( d_z^{(TE)} - \sqrt{(x - d_x^{(TE)})^2 + (y - d_y^{(TE)})^2 + (d_z^{(TE)})^2} \right)
\]

where \(d_z^{(TM)}\) and \(d_z^{(TE)}\), \(d_x^{(TM)}\) and \(d_x^{(TE)}\), \(d_y^{(TM)}\) and \(d_y^{(TE)}\) are coordinates of the focal spots for TM and TE polarizations along \(z\), \(x\) and \(y\)-axis respectively.

It is important to note that, in comparison to previous works,\(^{14,16,29}\) we practically do not limit the choice of the metasurface constitutive elements. Instead of choosing relatively small amount of possible unit cells, in this design, the appropriate \(L_x\) and \(L_y\) parameters for each unit cell are chosen from the entire space of simulated values (Figure 2). Even though the optimization of lithographic fabrication becomes more challenging (due to so-called proximity effect), the reflection phase profile obtained with this approach can be constructed in a more accurate way.\(^{30}\) Although with this approach the individual elements are fabricated with worse tolerances, deviations from the desired phase profile are smaller compared to the case when the deviations arise from a more abrupt phase steps (which is direct consequence of limited choice of constitutive elements).

The geometry of the design which was selected for experimental investigation is shown in Figure 3a. With parameters set to \(d_z^{(TM)} = d_z^{(TE)} = 15\ \mu m\), \(d_x^{(TM)} = d_x^{(TE)} = 5\ \mu m\), and \(d_y^{(TM)} = d_y^{(TE)} = 0\), metamirror is designed to diverge orthogonal polarizations by an angle of \(\sim 37^\circ\) and focuses them at a distance of 15\ \mu m. The diameter of the metamirror defines the focusing ability of the metamirror, expressed in the value of numerical aperture \(\text{NA} \approx \sin \left[\tan^{-1}(D/2d_z^{(\alpha)})\right]\) (where \(D = 40\ \mu m\) is diameter of the metamirror). For this particular design NA value is evaluated to be 0.8.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Design of the polarization splitting and focusing metamirror: (a) geometry of the metamirror design; (b)-(c) SEM images of the fabricated sample at different magnifications.

The bifunctional metamirror sample was fabricated using EBL and lift-off techniques. First, the substrate is prepared: a 150\ nm-thick layer of Au and 50\ nm of SiO\(_2\), with 3\ nm-thin titanium layers in between for adhesion.
purpose, are deposited on a Si wafer. Thermal evaporation (Cryofox TORNADO 405 evaporation system by Polyteknik) is used for gold and titanium layers, while RF-sputtering (same equipment) is employed for SiO2. Further, a 200 nm layer of PMMA 950 A2 resist (MicroChem) is spin-coated. This layer is used as a stencil material for creating nanobrick structures. The designed pattern is then created using EBL (JEOL-640LV SEM with an ELPHY Quantum lithography attachment). Gold nanobricks are formed by thermal evaporation of 3 nm of Ti and 50 nm of Au followed by the lift-off process (etching away stencil material and development). As can be seen from scanning electron microscope (SEM) images in Figure 3b-c, apart from the smallest features, fabrication quality of the resulting sample is in overall accordance with our initial design geometry, also at the level of the meta-atom building blocks of the metasurface.

3. EXPERIMENTAL DETAILS

Optical characterization of the sample is performed using a tunable Ti-Sapphire laser (3900S CW by Spectra-Physics). Schematic diagram of the experimental setup is depicted in Figure 4. Laser beam is to focused onto the sample by an ×60 objective, preceded by passing through a neutral density (ND) filter, a combination of a Glan–Thompson and a half-wave plate, and two beam splitters. The reflected light is collected using the same objective and directed via a beam splitter to an imaging lens that focuses light onto a CCD camera. Additional white-light illumination is used for convenience of visually locating the metamirror on the surface of the sample.

![Schematic diagram of the experimental setup for optical characterization of the fabricated sample. Planes A and B are planes at which flat gold and metamirror samples produce focused spots on the CCD camera screen (images shown in Figure 5c).](image)

In this setup the focusing effect can be verified by comparing reflection from the flat unstructured gold surface and the fabricated metamirror. From geometrical optics, it can be shown that the plane in which the flat gold surface produces a focused spot on the CCD camera screen (referred to as plane A in Figure 4) is at a distance \(d = 2d_z^{(\alpha)}\) away from the plane B, in which metamirror results in a deflected and focused spots on the screen. Optical images of the focused spots created by the flat gold surface and bifunctional metamirror, when illuminating the sample with \(\lambda = 800\) nm light at different polarization states are shown in Figure 5c. As can be
seen, metamirror deflects TM polarization to the right hand-side and TE polarization to the left hand-side from the origin.

4. RESULTS AND DISCUSSION

Characterization of the optical properties of the fabricated bifunctional metamirror showed relatively good focusing characteristics in 750–950 nm wavelength range, despite the minor imperfections in the fabrication (Figure 3b–c). The measured focal length $f$ is slightly smaller than its initially designed value ($\sim 13 \mu m$ instead of $15 \mu m$ at $\lambda = 800 \text{ nm}$). However, this deviation can be explained by the spherical aberrations of the objective and imaging lens in the setup, which was not taken into account.

![Graphs showing performance of the fabricated metamirror sample evaluated at five wavelengths in the 750–950 nm range: (a) efficiencies measured for orthogonal polarizations; (b) polarization extinction ratio, defined as ratio of intensities of observed spots; (c) images of spots (brightness adjusted for better visibility) produced by flat gold surface and metamirror correspondingly in the planes A and B, when illuminated by laser beam at $\lambda = 800 \text{ nm}$ wavelength with different polarizations.](image-url)

The figure of merit for the fabricated device is its focusing efficiency. Due to practical reasons, it is defined as the ratio of intensities of the light reflected by the metamirror located in plane B and by a flat unstructured gold surface in plane A. In other words, it shows which portion of the reflected light goes into focal spot, compared to the plane mirror-like reflection. As can be seen from Figure 5a, it reaches $\sim 65\%$ in the best case, which is significantly larger than in the demonstrations of similar devices.\textsuperscript{14,29} Though maximal efficiency for both polarizations was anticipated to be found at the design wavelength (800 nm), that was not observed in our experiments: peak efficiency for TM polarization is blue-shifted, whereas for TE it is red-shifted. We attribute this mismatch with design expectations to various fabrication-related issues and unaccounted experimental errors. Nevertheless, fabricated device shows comparatively high efficiency ($> 45\%$) over the entire measurement range (750–950 nm).

Furthermore, the polarization-extinction ratio (PER) was studied, reported in Figure 5b. PER is defined as the ratio of intensities in correct and incorrect focal spots. Correct focal spot corresponds to the point where the light of one of two orthogonal polarizations is expected to be focused, whereas incorrect spot is the one in which light of the same polarization is not expected to be focused. As can be seen, measured PER is very high, reaching $30 \text{ dB}$ value. It implies that only $\sim 1/1000$ of the incident power is deflected into the incorrect
focal spot (conservative estimate). The error bars in Figure 5 indicate the measurement uncertainty due to inaccuracy in the axial positioning of the metamirror during the focal length measurement (±1 µm) and the unknown sensitivity of the CCD camera at different wavelengths (taken to be ±10% as a conservative estimate).

In summary, in this work we have demonstrated a broadband and efficient bifunctional metasurface which performs simultaneous focusing and splitting of orthogonal light polarizations. The main physical mechanism which establishes operation of the device is excitation of the localized GSP modes in a MIM configuration. Existence of these modes allows to construct two nearly independent reflection phase gradients for two orthogonal polarizations of incident light. Devices similar to the demonstrated prototype can be directly integrated into various systems which employ polarization multiplexing. While we have demonstrated operation in the near-infrared band, this design can be optimized to operate equally efficiently also in the telecommunication window. As a last note, demonstrated prototype has potential for extension to a large-scale fabrication, for example using modern roll-to-roll methods, which are getting developed for the mass-production of metasurfaces.31,32

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