Broadband Focusing Flat Mirrors Based on Plasmonic Gradient Metasurfaces

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ABSTRACT: We demonstrate that metal–insulator–metal configurations, with the top metal layer consisting of a periodic arrangement of differently sized nanobricks, can be designed to function as broadband focusing flat mirrors. Using 50-nm-high gold nanobricks arranged in a 240-nm-period lattice on the top of a 50-nm-thick layer of silicon dioxide deposited on a continuous 100-nm-thick gold film, we realize a 17.3 × 17.3 μm² flat mirror that efficiently reflects (experiment: 14–27%; theory: 50–78%) and focuses a linearly polarized (along the direction of nanobrick size variation) incident beam in the plane of its polarization with the focal length, which changes from ~15 to 11 μm when tuning the light wavelength from 750 to 950 nm, respectively. Our approach can easily be extended to realize the radiation focusing in two dimensions as well as other optical functionalities by suitably controlling the phase distribution of reflected light.

KEYWORDS: Metasurfaces, plasmonics, metamaterials, Fresnel mirror, gap surface plasmons

Molding the flow of light is at the mainstream of current research efforts in modern nanophotonics. Tailoring the light propagation requires full control of the phase of optical fields, which is a condition difficult to reach at the micro- and nanoscale owing to rather limited variations in the permittivity and permeability of conventional materials. The material parameter space can, however, be extended by the use of artificial materials, the so-called metamaterials, whose optical properties arise from a subwavelength structuring of the metamaterial unit cell.1 Two important examples are the steering of the light utilizing transformation optics together with metamaterials,2,3 and anomalous refraction in negative index metamaterials.4,5

An alternative approach for enhanced light control is the usage of optically thin metal gratings with subwavelength periodicity, also known as metasurfaces. Despite having negligible thickness, metasurfaces show a strong influence on the impinging light at (plasmonic) resonances, leading to reflected and transmitted optical fields, whose amplitudes and phases are determined by the metasurface design.6 This property has been exploited in the design of compact optical components, such as wave plates,7−14 lenses,15−17 as well as components interfac ing propagating and surface waves.18,19 In general, metasurfaces rely on either the propagation of surface plasmon polaritons (SPPs) in slits in metal films7−9,15,16 or excitation of localized plasmon resonances (LSPs) in metallic nanostructures.10−14,17,18 Note that only the latter approach can create a true metasurface with vanishing thickness compared to the incident wavelength, although the phase control of the light, as evident from the paper of Lin et al.,17 is limited by π for isolated metasurfaces, which is a direct consequence of the fact that scattered light from dipolar scatterers is in-phase (out-phase) with the incident radiation at the low-frequency (high-frequency) side of the resonance.20 The full 2π phase space of LSP metasurfaces can, on the other hand, be reached by working with cross-polarized light (i.e., polarized in the direction perpendicular to the polarization of incident light) as has been successfully demonstrated with V-antenna metasurfaces in the near- and far-infrared regime.21−25 The drawback of this approach is its low efficiency in light manipulation and phase-front shaping (upper limit is estimated to ~10%24), which is related to the circumstance that only a small part of the scattered light can be cross-polarized.

In this Letter, we demonstrate, both numerically and experimentally, that a metal–insulator–metal (MIM) configuration in which the top metal layer consists of a subwavelength periodic arrangement of differently sized nanobricks, thus functioning as a metasurface in close vicinity of a metal film, can be designed to work as a parabolic reflector by spatially varying the phase of reflected light in accordance with a hyperboloidal phase profile. Thus, we design a one-dimensional focusing mirror with the focal length of 8 μm at the wavelength of 800 nm that shows a broadband (700−1000 nm) response and theoretical efficiency of up to ∼78%. The designed structure has been fabricated and characterized, verifying its broadband focusing properties and exhibiting, at a wavelength of 800 nm, the focal length of ~12 μm, and efficiency of up to ∼30%.

It should be noted that our configuration has conceptual similarities to the MIM configuration considered for interfacing propagating and surface waves in the microwave regime.18 In a very recent follow-up paper,26 this design was modified to

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produce gradient metasurfaces acting as blazed gratings for the incident (near-infrared) light polarized perpendicular to the direction of the phase gradient. Our approach, however, is different in several aspects. First, we consider gradient metasurfaces producing the phase variation along the polarization axis of the incident light; second, in our design, we vary both lateral dimensions of nanobricks, which allows us for a better discretization of the $2\pi$ phase space, using eight different elements rather than only four; finally, our final design and experiments target focusing mirrors, although the same design principle can equally well be utilized to construct mirrors mimicking blazed gratings.

The starting point of our design is a fundamental unit cell consisting of an optically thick gold substrate overlaid by a thin ($t_1 = 50$ nm) layer of silicon dioxide (the refractive index of 1.45) and a gold nanobrick with lateral dimensions $L_{x1}$, $L_{y}$, and height $t = 50$ nm centered within the cell (Figure 1a). The unit cell period $\Lambda$ is fixed at 240 nm throughout this Letter, and the incident light at the wavelength $\lambda = 800$ nm is propagating normal to the surface with the polarization along the $x$-axis.

The configuration is modeled in the commercial finite element software Comsol Multiphysics, where the permittivity of gold is described by interpolated experimental values. Interestingly, the considered unit cell is also known as a gap-plasmon resonator, whose resonances are related to constructive interference of counter-propagating gap surface plasmons (GSPs) and associated with a strong field confinement and enhancement in the dielectric spacer and, consequently, increased absorption. For this reason, similar structures are typically used in the design of efficient absorbers and thermal emitters. It should, however, be noted that these structures can be made reflective at the GSP resonance by choosing a subwavelength period and ensuring a weak coupling between nanobricks and a gold substrate, a circumstance that we exploit in the design of efficient focusing mirrors.

The considered periodic MIM configuration has a remarkable property that the phase of the reflected light can be adjusted to an arbitrary value (within $2\pi$ range), while maintaining a relatively high reflectivity of the structure, simply by varying the size and aspect ratio of the nanobricks. This property is demonstrated in Figure 1c for eight different nanobrick dimensions (see Figure 1b), where it is clearly seen that the phase of the reflection coefficient covers the whole $360^\circ$ in equal steps of $45^\circ$. At the same time, we observe only a weak variation in the reflection amplitude with an average value of $\sim 0.93$ (implying the reflectivity of $\sim 86\%$), thus exemplifying the reflection and phase-tuning capabilities of the considered metasurface configuration. Using the design of eight different MIM configurations covering the whole phase space, one can construct gradient metasurfaces with controlled phase profiles by spatially varying the dimensions of the nanobricks (to be arranged in the same 240-nm-period lattice) in accordance with the results shown in Figure 1b,c. The success of this approach, of course, encompasses the approximation that the phase of the reflected light from each element is only weakly influenced by a change in the dimensions of the neighboring elements, an assumption that was found acceptable for gradient metamaterials. A flat metasurface-based mirror that should be focusing in the $x$-$z$-plane can be designed by letting the reflection phase follow the hyperboloidal profile

$$\phi_{\text{fl}}(x) = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + f^2} - f \right)$$

which can easily be derived by simple geometrical arguments. Here, $f$ is the focal length of the focusing mirror. The phase profile $\phi_{\text{fl}}(x)$ is plotted as a solid line in Figure 2a for a focal length of 8 $\mu$m and wavelength of 800 nm, with the square markers representing the best fit to the phase profile at $x = p\Lambda$, where $p$ is an integer, using the eight elements shown in Figure 1. The focusing abilities of the metasurface depends on the numerical aperture $NA = \sin[\tan^{-1}(D/2f)]$, where $D$ is the width of the mirror. Consequently, increasing the numerical aperture by including more $2\pi$ periods (Figure 2a) results in better focusing properties, i.e., in smaller focal spot sizes (Figure 2b) and stronger fields at the focus (Figure 2c), as also illustrated with a few cross-sectional intensity distributions shown in Figure 2d. It should be noted that the focal spot sizes were found by fitting the cross-sectional intensity distributions to a Gaussian distribution and extracting the $e^{-1}$ full-widths ($w_x$ and $w_z$) as well as the center position $z_0$ along the $z$-axis (Figure 2b). Apart from expected improvements in focusing characteristics for larger numerical apertures, one notices a slight decrease in the efficiency (Figure 2c) that can be explained by...
stronger (diffuse) scattering due to the fact that the representation of the desired phase distribution becomes progressively difficult for larger distances from the center (Figure 2a). Still, the performance of the flat focusing mirror with N.A. = 0.80 is very good, resulting in a diffraction-limited spot in its focus (Figure 2d).

The designed focusing mirror exhibits the broadband response featuring good focusing characteristics and high efficiencies in the wavelength range of 700–1000 nm (Figure 3). As expected from eq 1, the focal length decreases rapidly for longer wavelengths so that the product \( f \lambda \) changes only slightly (Figure 3d). In fact, for conventional (macroscopic) Fresnel lenses and mirrors, this product determines the dimensions of the desired radiation focus.
Fresnel zones and is constant in the absence of dispersion of the materials used. At the same time, when considering focusing at distances comparable to the light wavelength, the product $\beta \lambda$ is expected (eq 1) to nonlinearly decrease for larger wavelengths (as indeed is seen in Figure 3d), with the focus deteriorated for wavelengths deviating from the designed one. Additionally, the dispersion of considered focusing metamirrors is influenced by wavelength dispersion in the phase response of individual elements of the designed metasurface as compared to that calculated for $\lambda = 800$ nm (Figure 1c). Still, the focusing quality remains high in the considered wavelength range of 700–1000 nm (Figure 3a). A rapid decrease in the focal length for longer wavelengths implies the corresponding increase in the numerical aperture that partially compensates an increase in the focal spot size along the $x$-axis due to diffraction (which increases for longer wavelengths) and even results in a decrease in the focal spot size along the $z$-axis (Figure 3b). Finally, it should be noted that the strong effect of wavelength-dependent changes in the focal length (from 12 to 4.5 $\mu$m when tuning the wavelength from 600 to 1100 nm, see Figure 3b) can be advantageously used for spatially separating light at different wavelengths (Figure 3a) or, when for example using these structures for Raman and nonlinear spectroscopies, for probing material response at different distances from the sample surface (as in confocal microscopies).

For experimental verification of the possibility of broadband radiation focusing with reflective GSP-based metasurfaces we have chosen the designed structure with NA = 0.73 (Figure 2a). Using electron-beam lithography and lift-off technique, a 240-nm-period 17.3 $\times$ 17.3 $\mu$m$^2$ array of 50-nm-high gold nanobricks of different sizes (designed in accordance with the procedure described above) has been fabricated on the top of a 50-nm-thick silica layer deposited on a continuous 100-nm-thick gold film (Figure 4). It is seen upon comparison of the scanning electron microscope (SEM) image of a segment of the fabricated structure (Figure 4b) and the designed geometry (Figure 4c) that the fabrication quality is quite satisfactory.

Optical characterization was conducted using a super-continuum light source (SuperK Extreme, NKT Photonics) with a fiber output, whose radiation at the selected wavelength is directed through a Glan-Thompson polarizer and focused onto the fabricated array by a $\times 60$-objective (NA = 0.85). The reflected light is collected by the same objective and directed via a beam splitter toward a CCD camera used for imaging the sample surface (with additional white light illumination) or the reflected radiation (spatial) intensity distributions. Since the fabricated focusing meta-mirror was expected to exhibit, due to its design, very short focal distances, we could not introduce a beam splitter between the sample surface and the imaging objective, so as to employ low-divergent illumination and investigate the focusing characteristics in a conventional manner. However, we could verify the focusing effect and measure the focal length by moving the sample surface from the plane, which resulted in a tightly focused spot in the image plane when illuminating a flat unstructured gold surface (plane A in Figure 4d), away from the microscope objective into the plane, at which the light reflected by the fabricated meta-mirror is tightly focused along the direction of structure-induced phase

Figure 4. Experimental demonstration of a focusing meta-mirror. (a) SEM image (bar length is 1 $\mu$m) of a part of fabricated 17.3 $\times$ 17.3 $\mu$m$^2$ and 240-nm-period array of gold nanobricks designed for the wavelength of 800 nm, along with (b) a high magnification SEM image of the structure to be compared with (c) designed geometry. (d) Schematic of ray propagation in the $x$–$z$-plane (red) and $y$–$z$-plane (green) corresponding to the axes shown in part a, when the sample is shifted to plane B away from the focal plane A (dashed blue line) of an objective by twice the focal length of the mirror, whose focusing in the $x$–$z$-plane is expected to result in a diffraction-limited (along the $x$-axis) spot. Optical images obtained for the sample placed in plane A and B when the light at 800 nm is incident on (e) flat gold surface and (f) fabricated array of gold nanobricks shown in part a. Note that the tight focus of the light beam on the sample surface, when the sample is in plane A, does illuminate a few nanobricks that cause its divergence in the $x$–$z$-plane.
adhesion layers between gold as well as the increased damping associated with 3-nm-thin Ti
stances, such as surface scattering and grain boundary e
one (Figure 3c) due to various fabrication related circum-
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measured at the wavelength of 800 nm (Figure 5a). Even
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to be slightly increasing for larger wavelengths (as expected due
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rapidly decrease for larger wavelengths as expected, with the
illumination conditions. Finally, the focal length was found to
that the spot size measured in this manner cannot be directly
indicating the high focusing quality of the meta-mirror. Note
for V-antenna metasurfaces.24 The spot size measured along the
substantially larger than the upper limit of 
μ
m-sized areas.
In summary, we demonstrated that metal–insulator–metal
configurations, with the top metal layer consisting of a periodic
arrangement of differently sized nanobricks, can be designed
to function as broadband focusing flat mirrors. Using 50-nm-high
gold nanobricks arranged in a 240-nm-period lattice on the top
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Notes
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