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Dual-Band Metasurfaces Using Multiple Gap-Surface Plasmon Resonances

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Abstract: Metasurfaces operating at multiple spectral ranges with integrated diversified functionalities while retaining the flexible design strategy are highly-desired within the area of modern flat optics. Here we propose and demonstrate the use of multiple gap-surface plasmon (GSP) resonances for the realization of dual-band multifunctional metasurfaces by designing GSP meta-atoms that would resonate at two different wavelengths. By tailoring nanobrick dimensions of a simple GSP meta-atom so as to enable both the first-order resonance at 1450 nm and the third-order one at 633 nm, we design phase-gradient GSP metasurfaces for polarization-independent beam steering and polarization-splitting simultaneously at telecom (1350 – 1550 nm) and visible (575 – 675 nm) wavelengths. The fabricated metasurfaces show good performance with > 65% diffraction efficiency at the first-order resonant wavelength of 1450 nm and over 50% efficiency within the telecom range of 1350 – 1550 nm, while at the third-order resonant wavelength of 633 nm the diffraction efficiency is 20% and >10% within the visible range of 575 – 675 nm. Our findings demonstrate thereby a flexible and robust approach for the realization of efficient dual-band GSP metasurfaces that can readily be combined with complex integrated designs to implement multiple functionalities highly sought after for diverse applications.

Keywords: Dual-band, gap-surface plasmon, metasurface, multiple resonances, beam steering, polarization splitting
**Introduction**

With the freedom to arbitrarily control the phase, amplitude and polarization of reflected light at the subwavelength scale, gap-surface plasmon (GSP) metasurfaces allow to engineer selective properties of meta-atoms and integrate multiple functionalities in a single device with excellent performance.\textsuperscript{1-7} This property has shown immense potential for versatile applications that cannot be implemented using bulk optical devices relying on the phase accumulation when propagating through a high-refractive index medium between polished surfaces. However, the applicability of metasurfaces for multiwavelength operations is typically restricted due to the dispersion-limited response of meta-atoms. The phase gradient (produced by meta-atoms varying in size) changes for wavelengths away from the resonance, resulting in a deteriorated performance and making broadband operation difficult to achieve. In conventional GSP metasurfaces, the functionalities demonstrated so far have been limited to a fraction of the operating wavelength.\textsuperscript{8-17}

Multiwavelength metasurfaces have been demonstrated previously using complex meta-atoms with additional geometrical parameters to achieve well-defined phases and amplitudes for different wavelengths.\textsuperscript{18-25} For example, two independently designed metasurfaces were combined within an indium-tin-oxide layer to realize multifunctional meta-devices at both the visible and infrared wavelengths.\textsuperscript{22} Another popular way is to design meta-atoms with polarization-selective wavelength response enabling the independent control at different wavelengths with different input polarizations.\textsuperscript{23-25} However, due to the complex and selective nature of these approaches, flexible integration of both multiple functionalities and multiwavelength performance is difficult to achieve. Additionally, all types of meta-atoms require increased fabrication accuracy for shorter wavelengths, which is more difficult to implement for complicated metasurfaces.

In our work, we present a new approach to tackle these major challenges by using multiple GSP resonant modes, whose usage opens a way to the dual-band performance without significant modifications of the conventional GSP configuration. This is achieved by judiciously choosing the GSP meta-atom dimensions for the simultaneous realization of different order resonances at two different design wavelengths. At the same time, an inevitable increase in the meta-atom dimensions (while remaining subwavelength) to realize a higher-order resonance at a shorter wavelength helps to relax the fabrication constraints. The main design challenge in this approach is to ensure similar phase and amplitude responses for both wavelengths simultaneously (through the excitation of different order GSP modes). By propitiously selecting the GSP meta-atom dimensions to support both first-order mode at 1450 nm and third-order mode at 633 nm, we demonstrate, both theoretically and experimentally,
phase-gradient GSP metasurfaces based on isotropic and anisotropic meta-atoms for respectively polarization-independent beam steering and polarization-splitting realized simultaneously at telecom and visible wavelengths. The concept of multiple-order GSP modes can readily be employed as an added feature for all functionalities since it requires minimal modifications to the already developed design approaches. The findings of our study provide thereby a simple, flexible and robust approach for the realization of diverse dual-band GSP metasurfaces exploiting the existing (single-band) design approaches that have already been extensively explored for the multitude of versatile applications.

Results and discussions
We begin our design by considering the conventional GSP configuration with an emphasis on the physical mechanism of multiple GSP resonances, which can be implemented for dual-band metasurfaces. The meta-atom shown in Figure 1a represents a commonly used metal-insulator-metal (MIM) GSP resonator, being composed of a thin silicon dioxide (SiO$_2$) gap layer sandwiched between top gold (Au) brick-shaped nanoantennas and bottom continuous Au film. When a linearly-polarized light is normally incident on the meta-atom, surface plasmons are excited on the metal-dielectric interfaces, and then strongly coupled to each other due to the subwavelength spacer, forming the “so-called” magnetic resonance or GSP resonance with strong magnetic fields in the middle dielectric spacer and antiparallel current oscillations in two metallic layers. Due to the termination of the MIM structure, the GSP resonance is a lateral standing-wave type resonance that results from counter-propagating waves reflected back and forth at structure terminations. As such, the GSP resonance can be described by a simple Fabry-Perot resonator formula:

$$w \frac{2\pi}{\lambda_0 n_{\text{gsp}}} + \varphi = p\pi$$  \hspace{1cm} (1)

where $w$ is the width of the nanobrick, $\lambda_0$ is the wavelength in free space, $n_{\text{gsp}}$ is the real part of the effective GSP mode index, $\varphi$ is an additional phase induced by reflection at the termination, and $p$ is an integer defining the order of the GSP mode. From the above formula, it is evident that the resonant mode depends on the dimensions of the nanobrick. For a certain GSP resonator with specifically-designed dimensions ($L_x$ and $L_y$), multiple GSP resonances with different orders might be simultaneously induced at different wavelengths, which helps to ease the fabrication constraints for multiband metasurfaces which typically involve multilayered structures or complicated meta-atoms with small features to support the first-order resonances corresponding to short wavelengths. Furthermore, near the GSP resonances, the nanobrick dimensions $L_x$ and $L_y$ allow us to independently control the phase of reflected light within the whole coverage of up to $2\pi$ for the respective orthogonal linear polarizations. Therefore, by
considering the nanobricks that support multiple GSP modes and engineering their phase responses, one can realize dual-band metasurfaces, and demonstrate polarization-controlled beam steering at two discrete wavelengths simultaneously, as shown in Figure 1b,c.

To accommodate multiple GSP resonances within the meta-atom and eliminate the diffraction orders, we choose a suitable large period of $A = 450$ nm and calculate the reflection coefficients for nanobricks with varied widths at two designed wavelengths of $\lambda_1 = 633$ nm and $\lambda_2 = 1450$ nm, respectively. For simplicity, we first show the results of isotropic nanobricks with identical widths along the $x$- and $y$-directions (i.e., $L_x = L_y$) for two different wavelengths in Figure 1d. The two dips in reflection amplitude along with phase variation at $\lambda_1 = 633$ nm clearly indicate that the nanobrick supporting first-order GSP mode ($p = 1$) has a width of $\sim 90$ nm and the width becomes approximately 3 times larger ($\sim 270$ nm) when the third-order GSP mode ($p = 3$) is excited, which is consistent with the formula. However, such a GSP resonator can only support the first-order GSP mode at the longer wavelength of $\lambda_2 = 1450$ nm. To verify the different GSP modes, Figure 1e displays the electric and magnetic field distributions at the $x$-$z$ planes under $x$-polarized incidence, illustrating the excitation of the third-order and first-order modes at the wavelengths of 633 nm and 1450 nm, respectively. Additionally, the reflection phases and amplitudes for two wavelengths have similar profiles, indicating the potential for achieving dual-band phase-gradient metasurfaces with such a simple GSP meta-atom design.

**Figure 1.** Working principle of the dual-band metasurface using multiple GSP resonances. (a) Schematic of the GSP unit cell consisting of Au nanobricks on top of thin SiO$_2$ layer and optically thick Au film, illuminated by a linearly-polarized light at normal incidence. The fixed
dimensions are: $t_n = 50$ nm, $t_s = 40$ nm, and $A = 450$ nm. $E_x$ and $E_y$ represent the $x$- and $y$-polarizations, respectively. (b) The GSP metasurface 1 (MS1) for dual-band polarization-independent beam steering, which comprises of isotropic nanobricks ($L_x = L_y$) to reflect $x$- and $y$-polarized light into the same diffraction order (+1) for both wavelengths of $\lambda_1 = 633$ and $\lambda_2 = 1450$ nm, respectively. (c) The GSP metasurface 2 (MS2) for dual-band polarization-splitting using anisotropic nanobricks to reflect $x$- and $y$-polarized light into the +1 and −1 diffraction orders for both wavelengths of $\lambda_1 = 633$ and $\lambda_2 = 1450$ nm, respectively. (d) Calculated reflection amplitudes and phases as a function of the dimensions of the isotropic nanobricks at two wavelengths of $\lambda_1 = 633$ and $\lambda_2 = 1450$ nm. The incident wave is $x$-polarized. (e) Simulated field distributions in the $x$-$z$ plane at wavelengths of $\lambda_1 = 633$ and $\lambda_2 = 1450$ nm with the dimension $L_x = L_y$ being ~ 270 nm.

Employing the multiple GSP modes, a polarization-independent phase-gradient dual-wavelength metasurface (refer as MS1 in the following text) is first designed, which can steer both $x$- and $y$-polarized waves to +1 diffraction order in the far-field for two discrete wavelengths of 633 nm and 1450 nm, as shown in Figure 1b. Specifically, the polarization-insensitive MS1 consists of isotropic meta-atoms with equal $L_x$ and $L_y$ that have constant phase steps for both $x$- and $y$-polarizations, as marked with circles in Figure 1d. The selected five nanobricks that collectively form a supercell are schematically represented in Figure 2a. From the reflection phases and amplitudes of all five chosen nanobricks (Figure 2b), one can observe similar phase gradients for two orthogonal linear polarizations with a phase step of 66° at $\lambda_1 = 633$ nm and 74° at $\lambda_2 = 1450$ nm to cover a maximum phase span up to $2\pi$. For each meta-atom, the reflection amplitude at $\lambda_1 = 633$ nm is lower, which is attributed to the higher loss of the third-order GSP mode as well as Ohmic loss of Au in the visible range. Full-wave numerical simulations show that practically the majority of the reflected light for both polarizations are routed to the corresponding +1 diffraction order (Figure 2c, d). The anomalous reflection angle $\theta_r$ of MS1 can be calculated by considering the supercell arrays as phase blazed gratings by equating the generalized refraction laws with diffraction theory, similar to previous works. Based on the design, the calculated $\theta_r$ is found to be 16.3° at $\lambda_1 = 633$ nm and 40.1° at $\lambda_2 = 1450$ nm, respectively. The calculated $\theta_r$ can be adjusted by selecting different phase steps (Supporting Information S1). Here it should be noted that the distortion of the reflected wavefronts for $x$-polarization is mainly ascribed to the near-field coupling between adjacent elements which is not taken into account during the simulation. Additionally, the increased variations in reflection amplitudes of the third-order GSP meta-atoms degrade the performance.
at $\lambda = 633$ nm. Although there are distortions, the reflected fields assemble well-defined planar wavefronts for both polarization at two wavelengths.

As a final comment, we emphasize that our strategy to select meta-atoms has focused on covering the maximum phase coverage while ensuring that the phase steps are nearly identical for both wavelengths. In particular, we first do multiple simulations by taking all the available geometrical parameters into considerations and then carefully select the proper parameters, which can provide similar phase gradients at two wavelengths simultaneously. Additionally, the possible amplitudes at two wavelengths should be as high as possible, which is required for achieving highly-efficient meta-devices.

**Figure 2.** Design of MS1 for dual-band polarization-independent beam steering. (a) The supercell of isotropic meta-atoms to span the $2\pi$ phase gradient for both linear polarizations. The widths are 120, 250, 270, 290, and 390 nm, respectively. (b) Reflection amplitudes and phases of five selected isotropic meta-atoms at two wavelengths. The incident light is $x$-polarized. (c, d) The $x$- and $y$-components of the reflected electric fields at the designed wavelengths of (c) 633 and (d) 1450 nm when the linearly-polarized wave is normally incident on the metasurface.

The MS1 was fabricated using the standard electron beam lithography (EBL) and a lift-off process (see the Methods for more details). Figure 3a displays the scanning electron microscope (SEM) image of one of the fabricated supercells with square shapes of the nanobricks being well-formed. The roughness and rounding at the edges of nanobricks are the only possible ways that lead to additional losses. Following the fabrication, the optical characterization was performed using a home-built optical set-up (see the Methods for more details). In Figure 3b-e, we show the total diffraction efficiency and the amount of light reflected into different diffraction of the designed MS1 for polarization-independent beam steering at two spectrum ranges [i.e. 575 – 675 nm in the visible and 1350 – 1550 nm in the telecom] for both $x$- and $y$-
polarizations, respectively. Generally, most of the light is diffracted into +1 order and the light in the zero-order is suppressed when the operating wavelength is close to the designed values for both linear polarizations. In addition, the numerical simulations are in good agreement with the experimentally measured results. For the telecom range corresponding to the first-order GSP mode, an efficiency of > 65% is experimentally achieved in the +1-order diffraction at the designed wavelength of $\lambda_2 = 1450$ nm for both polarizations. Importantly, it is impressive that MS1 shows a broadband response with excellent performance in the wavelength range of 1350-1550 nm, where > 50% of the incident light is routed to the +1 diffraction and other diffraction orders are greatly suppressed. Such excellent performance is ascribed to the higher reflectivities and quasi-linear phase gradient (Supporting Information S1). For visible range, the simulated efficiency of the +1-order diffraction is ~ 30% for $x$-polarization and ~ 40% for $y$-polarization while the measured efficiency is only ~ 20% for both polarizations at $\lambda_1 = 633$ nm. Worse still, the zero-order is not completely suppressed in the experiment. Nevertheless, the measured efficiency for the reflected light in the desired +1 diffraction order is above 10% within a broad bandwidth from 575 to 675 nm in the visible range. The differences between simulated and measured results can be attributed to both the large losses associated with third-order GSP mode, approximate material parameters considered for Au at visible wavelengths, as well as the titanium (Ti) adhesion layers between dielectric-metal interfaces, which make it difficult to predict the performance accurately. Additionally, the third-order resonance is more sensitive to the geometric parameters. Thus, a smaller discrepancy in the fabricated meta-atoms can lead to a larger deviation between simulation and experimental results. Compared with previous work for beam steering, the efficiencies achieved for both visible and IR dual-bands are in good agreement, which is achieved by using a compact single design based on multiple GSP modes as seen from our study.
Figure 3. Optical characterization of fabricated MS1 for dual-band polarization-independent beam steering. (a) SEM image of a supercell of the fabricated MS1. The scale bar is 500 nm (b-e) The amount of light reflected in diffraction orders for normally incident light of $x$- (b, d) and $y$-polarizations (c, e) at two different bands. The dashed line and solid line indicate the experimental and simulated results, respectively.

We now discuss the second metasurface (refer as MS2) designed for dual-band polarization-splitting, namely, polarization-dependent beam steering, which is important to demonstrate how the same design strategy based on multiple GSP modes can be used for metasurfaces with different functionalities. The MS2 is designed to anomalously reflect light by routing $x$-polarized light to +1 diffraction order and $y$-polarized light to −1 diffraction order (Figure 1c). To achieve polarization-splitting functionality, the meta-atoms require opposite phase gradients for two orthogonal linear polarizations. The respective phase lines are shown on amplitude maps at dual-wavelengths of $\lambda_1 = 633$ nm and $\lambda_2 = 1450$ nm, respectively, where the selected nanobricks with the required phase values are marked with squares (Figure 4a, b). Note that the phase and amplitude maps are obtained from reflection coefficients of individual meta-atom, with the same design procedure followed by MS1. The collective meta-atoms forming the supercell for MS2 is shown in Figure 4c. Figure 4d displays the phase and amplitude values of the selected anisotropic nanobricks at $\lambda_1 = 633$ nm and $\lambda_2 = 1450$ nm, which supplies the opposite phase gradients for two linear polarizations at each wavelength. Numerical simulations
of MS2 shows that the reflected light for \(x\)-polarization is contained within the \(+1\)-diffraction order while the reflected light for \(y\)-polarization is routed to \(-1\)-order at the two designed wavelengths (Figure 4e, f), indicating the good performance of polarization-splitting.

**Figure 4.** Design of MS2 for dual-band polarization-splitting. (a, b) Calculated reflection amplitude and phase distribution as a function of the nanobrick dimensions for (a) \(\lambda_1 = 633\) nm and (b) \(\lambda_2 = 1450\) nm, respectively. The map represents the reflection amplitude under \(x\)-polarization, while lines are contours of the reflection phase with constant phase values for \(x\)-(solid curves) and \(y\)-polarizations (dashed curves). (c) The supercell of anisotropic meta-atoms with opposite phase gradients for dual-band polarization splitting. The widths along the \(x\)-axis \((L_x)\) are 125, 250, 275, 295, 340 nm, and the widths along the \(y\)-axis \((L_y)\) are 350, 300, 280, 250, 170 nm, respectively. (d) Reflection amplitudes and phases of five selected anisotropic meta-atoms at two wavelengths for both polarizations. (e, f) The \(x\)- and \(y\)-components of the reflected electric fields at the designed wavelengths of (e) 633 and (f) 1450 nm when linearly-polarized waves are normally incident on the metasurface.

With the above numerical simulations illustrating the capability of polarization-splitting with MS2, we now move on to the experimental verification. Figure 5a displays a representative...
SEM image of the fabricated supercell of MS2 composed of rectangular nanobricks, with a reasonable correlation between the designed supercell regardless of visible discrepancies. Similarly, the performance of MS2 is quantitively determined by measuring the corresponding zero- and first-order diffraction efficiencies as shown in Figure 5b-e. In general, we observe a reasonable agreement between the measured and calculated diffraction efficiencies, demonstrating the polarization-splitting over two broadband spectrum ranges, albeit with a reduced efficiency of ~10% and non-vanishing zero-order diffraction in the visible band from 575 to 675 nm. Such discrepancies are mainly attributed to the aforementioned loss channels and the fabrication errors which greatly affect the performance of third-order GSP metasurface in visible. In spite of the bigger deviation in the visible band, the MS2 sample shows excellent performance in the telecom band, with >50% diffraction efficiencies for the desired diffraction orders within 1350-1550 nm IR range.

![SEM image of the fabricated supercell of MS2](image)

**Figure 5.** Optical characterization of fabricated MS2 for dual-band polarization-splitting. (a) SEM image of a supercell of the fabricated MS2. The scale bar is 500 nm. (b-e) The amount of light reflected in diffraction orders for normally incident light of $x$- (b, d) and $y$-polarizations (c, e) at two different bands. The dashed line and solid line indicate the experimental and simulated results, respectively.
Conclusion

To summarize, we have proposed the use of multiple GSP resonances for the realization of dual-band multifunctional metasurfaces by designing GSP meta-atoms that would resonate at two different wavelengths, without significant modifications of the conventional GSP configurations. Capitalizing on this concept, we have successfully demonstrated phase-gradient GSP metasurfaces for polarization-independent beam steering and polarization-splitting simultaneously at telecom (1350 – 1550 nm) and visible (575 – 675 nm) wavelengths. The fabricated metasurfaces exhibit good performance with > 65% diffraction efficiency at the first-order resonant wavelength of 1450 nm and over 50% efficiency within the telecom range of 1350 – 1550 nm, while at the third-order resonant wavelength of 633 nm the diffraction efficiency is 20% and > 10% in visible spectrum ranging from 575 to 675 nm. Since the concept of multiple-order GSP modes requires only minimal modifications to the already well-developed design approach, it can readily be employed as a flexible and robust approach for all complex multiple functionalities in diverse applications, such as polarization-modulated devices.30-32

Methods

Fabrication. We used the standard EBL nanofabrication technique to fabricate the metasurfaces. First, a 3-nm-thick Ti, a 200-nm-thick Au, and a 3-nm-thick Ti were deposited onto a silicon substrate using electron-beam evaporation. Then a 40-nm-thick SiO_2 spacer layer was deposited via radio frequency (RF) sputtering. After that, a 100-nm-thick poly(methyl methacrylate) (PMMA) (2% in anisole, Micro Chem) layer was spin-coated on the prepared substrate and baked at 180°C for 2 min. The step followed is to exposure the PMMA layer at an acceleration voltage of 30 kV using the JEOL JSM-6490LV electron microscope equipped with an ELPHY Quantum lithography system. Next, the resist was developed for 30 s in a 3:1 mixture of isopropanol (IPA) and methyl isobutyl ketone (MIBK). The Au nanobricks were obtained by deposition of 3-nm-thick Ti and 50-nm-thick Au using e-beam evaporation and subsequent 10 hours incubation in PG-remover (commercially obtained solution) for lift-off of unexposed resist. The fabricated metasurfaces were imaged using JEOL JSM-6490LV SEM to confirm their actual dimensions and correct for imperfections.

Numerical Simulations. All numerical simulations were performed using Comsol Multiphysics (version 5.2) based on the finite-element method. In the simulations, we modeled a single unit cell (Figure 1, Figure 2b and Figure 4a,b,d) or supercell (Figure 2c,d, Figure 3, Figure 4e,f and
Figure 5) by applying periodic boundary conditions on the vertical sides of the cell. The excitation and collection ports were applied above and below the unit cell, followed by perfectly matched layers in order to minimize reflections. In the excitation port, a linearly-polarized plane-wave was used. In all simulations, the edges of Au bricks were rounded with a 10 nm radius of curvature to eliminate the singularities. The permittivity of Au was taken from Johnson and Christy database, while the refractive index of the SiO$_2$ spacer layer was assumed to be 1.45. The medium above the nanobricks is chosen to be air with a refractive index of 1. Regarding the reflection coefficients of the homogenous GSP metasurfaces (Figure 1d and Figure 4a,b), the phase is determined at the top surface of the Au bricks. The diffraction efficiencies (Figure 3b-e and Figure 5b-e) were obtained by calculating the reflected power into different diffraction orders.

**Optical characterization.** The experimental characterization of the fabricated metasurfaces was performed by directly measuring the light reflected at different diffraction orders (Supporting Information Figure S2). The incident white light source was obtained from SuperK EXTREME laser (NKT, 400-2400 nm), combined with SuperK SELECT acousto-optic tunable filter. The incident light was then weakly focused on the sample with the diameter in the range of 20-40 µm using a convex lens with a focal length of 50 mm (Thorlabs, LA1131-ML), ensuring that the incident beam could cover most of the metasurface area and did not exceed the metasurface boundaries. To achieve desired linear polarization, the incident beam was filtered using Glan Thomson polarizers (Thorlabs, GT15). A beam splitter (Thorlabs, CCM1-BS015/M, CCM1-BS013/M) was placed right after the lens to separate the incident light from zero-order diffracted light. The intensity measured at different diffracted angles was normalized with incident light intensity. The polarization of the different diffraction orders upon reflection from metasurface was checked with linear polarizers (Thorlabs, LPVIS100-MP2).

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**Competing financial interests:**

The authors declare no potential conflicts of interest.
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