Highly Reflective Mirror Based on Noble Metal 2D Babinet Metasurface

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Abstract. We study optical properties of plasmonic 2D nanostructures (metasurfaces) constructed by analogy with Babinet’s principle – combinations of a perforated noble metal thin film and a complementary array of nanodiscs. Despite of large absorption in either the perforated films or the arrays of nanodiscs, the considered metasurfaces were highly reflective. The effect of increased reflectance is attributed to mutual cancellation of electric and ‘magnetic’ dipoles induced in antiphase, thus suppressing absorption; and a spacer in between the dipoles influences the spectral and incidence angle ranges for the effect observation. We show that a chosen metasurface can have an angle- and polarization-independent response in a wide spectral range.

1. Introduction
In optics, a basic formulation of Babinet’s principle [1] is that the sum of a wave transmitted through a screen and a one transmitted through a complementary screen (e.g., a hole in a metal film and a metal disc of the same diameter) is exactly the incident wave. In the simplest case of a thin metal screen, a complementary screen is obtained via interchanging the metal and the holes in the initial screen configuration, i.e. via the structural inversion. Babinet’s principle has been extensively used for designing the antennas with constant input impedance, studied in radio frequency. Subsequent modern applications in optics were due to the polarization-independent and spectrally-flat response of a self-complementary structure. At present, Babinet’s principle is extended to absorbing and impedance surfaces, replacing the structural inversion with the impedance one in the latter case. Thin layers of substance structured at sub-wavelength level is commonly referred to as a metasurface (planar metamaterial) [2]. Babinet’s principle in its initial formulation is valid for thin ($l \ll \lambda$) screens with large apertures in it ($d \gg \lambda$) and should be clarified if a substance under study is structured at sub-wavelength level. Structuring the substance at sub-wavelength level results in peculiarities in the optical response. Extraordinary optical transmission of periodic metallic structures has been known since the early works by Ebbesen [3] and Pendry [4]. Modern designs of metasurfaces include...
checkerboard-type [5] and kagome [6] lattices. In [7], an effective lumped circuit model was developed for wavefront shaping on the basis of a complementary plasmonic structure.

In this paper we study the optical properties of plasmonic 2D Babinet-type nanostructures. We discuss the mechanism for increased reflectance and attribute it to the local field interaction between the grating plasmon resonances in the perforated metal film and those in ensembles of metal discs.

2. Model and numerical results

Let us consider two separated complementary 2D metasurfaces embedded into a thin dielectric film (BK7 glass) and a Babinet one, when adjoining them (Figure 1). Metasurface A is a periodic array of silver discs with the following parameters: lattice constants of \(a = b = 350\ \text{nm}\), a disc radius varied in a range of \(r_{\text{disc}} = 30–100\ \text{nm}\) and a disc height of \(h_{\text{disc}} = 30\ \text{nm}\). Metasurface B is a perforated silver film: lattice constants of \(a = b = 350\ \text{nm}\), a hole radius varied in a range of \(r_{\text{hole}} = 30–100\ \text{nm}\) and a film thickness of \(h_{\text{hole}} = 30\ \text{nm}\). Both metasurfaces A or B demonstrate a grating plasmon resonance (GPR)-modified spectra where interaction in the ensemble of discs or holes governs the spectral position of corresponding bands as shown in Figures 1(a) and 1(b). For the chosen \(a = b = 350\ \text{nm}\), these reflection spectra change with the radius of discs (or holes) as the effective refractive index of the metasurface changes [8]. For the sake of simplicity, the Babinet metasurface (C) was situated on a BK7 substrate (Figure 1(d)); the dielectric constant \(\varepsilon_{\text{BK7}} = 1.51^2\) of the BK7 glass was used in the calculation models for all studied metasurfaces. Spacing \(dH\) between A and B varied from 10 to 100 nm. The total thickness of the considered metasurfaces was of the order of ~100 nm. Reflectivity of a Babinet-type structure is presented in Figure 1(c) for \(dH = 20\ \text{nm}\). We shall limit the spectral range to 600–1000 nm where GPR features are observed; spectra were calculated at normal and oblique incidence (\(\alpha\) – the angle of incidence).

![Figure 1](image)

**Fig. 1** (a) Normal-incidence reflection spectra for various disc radii for metasurface A. The reflectivity of a non-processed Ag film of the same thickness is shown with a red line. (b) Normal-incidence reflection spectra for various hole radii for metasurface B. Overlap takes place (shown with a red arrow) between transmission (2D metal disc array, dashed red curve) and reflection (perforated metal film) when \(r_{\text{disc}} = 70\ \text{nm}\) and \(r_{\text{hole}} = 60\ \text{nm}\). Transmission spectrum for B \((r_{\text{hole}} = 60\ \text{nm})\). (c) Reflectivity \(R\) and loss \((A = 1 - R - T)\) spectrum at normal incidence for a Babinet-type structure (metasurface C) formed by a stacking A and B with \(dH = 20\ \text{nm}\) spacing in between. R and A for a non-processed Ag film are shown for the same (30nm, dash-dotted line) and increased (50nm, circles) thickness values. (d) General view of a Babinet-type structure.
When an array of nanodiscs is illuminated, the induced electric dipoles interact via the electromagnetic waves along the surface. The resonant wavelength (see Figure 1(a)) is governed by a diffraction grating condition at the order \( m = \pm 1, \pm 2, \ldots \): 
\[ m \lambda_{\text{GPR}} = n_{\text{EFF}} D. \]
Here, \( \lambda_{\text{GPR}} \) is a vacuum wavelength, \( D \) is the period of the structure, and \( n_{\text{EFF}} \) is an effective permittivity of the medium, which can be calculated [9] in the frame of Maxwell-Garnett approximation. In the case of a perforated metal film, a number of mechanisms affect the resonance position [10] apart from the grating plasmon resonance; among them are the cavity modes and spoof plasmons. Arguably, the response of a single hole in a metal film can be described as a magnetic dipole [11]. Our modelling results (Figures 1(a) and 1(b)) suggest that metal discs of metasurface A can act as electric dipoles, while holes of metasurface B can be represented as magnetic dipoles and their transmission \( (T_A) \) and reflection spectra \( (R_B) \) can be quantitatively same, \( T_A = R_B \). Note, also, that polarized light coupling to metasurfaces A and B goes differently at oblique incidence. The GPR band spectrally shifts in the s-polarized spectra of metasurface A and does not shift in the p-polarized ones as the angle of incidence changes [9]. One can observe the opposite behaviour in polarized spectra of metasurface B; the GPR band shifts for the p-polarization. This is why we may expect an unusual polarization-independent optical response for metasurface C.

Plot 1(b) illustrates that, taking the exactly complementary metasurfaces A and B, the GPR features in their reflection and transmission spectra do not coincide. However, by simply changing \( r_{\text{disc}} \), which means influencing the effective refractive index, one can tune the spectral position of the transmission peak in the spectrum of metasurface A and adjust it to that in the spectrum of metasurface B. It was found that the best overlap takes place when the holes were slightly smaller than the discs, \( r_{\text{hole}} = 60 \text{ nm} \) and \( r_{\text{disc}} = 70 \text{ nm} \). Note that the reflection minimum for spectra of metasurface B is due to SPR excitation which is eventually associated with absorption. A reflection spectrum of metasurface C having \( r_{\text{hole}} = 60 \text{ nm} \), \( r_{\text{disc}} = 70 \text{ nm} \), \( H = 30 \text{ nm} \) and \( dH = 30 \text{ nm} \) is shown in Plot 1(c). The interaction between electric and ‘magnetic’ dipoles placed in the close vicinity unexpectedly resulted in an effect of increased reflectance for metasurface C. The rise of reflection in the range of 700–900 nm can be associated with suppression of strength of plasmon near fields, diminishing light attenuation via two channels – surface plasmon polaritions on the surfaces of metasurface B and electric dipoles in the discs of metasurface A. Thus, the reflectance from metasurface C was up to 10 percent larger than that of a conventional silver film with a thickness of 30 nm; the effective thickness of silver film is increased to 50 nm. Near-zero energy flow through the metasurface C occurs due to the fact that the electric dipole induced in B is in an antiphase [12] with the external field, as opposed to electric dipole in A. Near-field interaction between adjoined complementary metasurfaces A and B results in the cancellation of the transmitted wave.

We have observed several \( dH \)-dependent features in reflection spectra [Figure 2(a)]: (i) there is an optimal value of \( dH \) where the reflectance tends to maximum (see line 3), (ii) a wavelength range of the increased reflection shortens as \( dH \) increases, (iii) there is a band associated with resonant light coupling of the “disc–hole metaatom” in a range of 600-700 nm—an electric dipole resonance, which is not observed in spectra of metasurfaces A and B, and (iv) a magnetic dipole resonance of the “disc–hole metaatom”. Figure 2(b) illustrates robustness of the effect of increased reflection from metasurface C having \( dH = 30 \text{ nm} \). Here, the presented curves show a normalized variation of reflectance \( (\Delta R/R) \) under variation of the BK7 refractive index \( (\Delta n_{\text{BK7}} = 0.01) \), hole \( (\Delta r_{\text{holes}} = 2 \text{ nm}) \) and disc \( (\Delta r_{\text{disc}} = 2 \text{ nm}) \) radii variation, and the variation of \( \Delta R/R \) in s- and p-polarized spectra at for oblique incidence, \( \Delta \alpha =10^\circ \). We attribute the increase in reflectivity to the manifestation of an interaction between two ‘decoupled’ sheets, one exhibiting electric dipole interaction properties while the other one manifesting the magnetic dipole ones. To validate this assumption, we varied numerically the gap distance \( dH \) between the layers. Increase in the gap distance \( dH \) leads to lowering in the reflection, as shown in Figure 2(a).
Figure 2. (a) Reflectivity ($R$) and loss ($A = 1 - R - T$) spectra of a Babinet-type structure for different spacing distances $dH$ between complementary metasurfaces. Metal film thickness is 30 nm, $r_{\text{disc}} = 70$ nm, $r_{\text{hole}} = 60$ nm. Increase in the line thickness (as shown with dashed arrow) corresponds to increase in $dH$ from 10 nm to 40 nm in 10 nm steps. Dashed line shows the reflectivity of a 30nm-thick Ag film without (nano-) structuring. (b) Spectral changes in reflection spectra of a ‘Babinet-type’ structure due to small variations of structure parameters and interaction geometry.

3. Summary

Near-field interaction between adjoined complementary metasurfaces – 2D arrays of discs and holes separated by a gap – results in the cancellation of the transmitted wave, thus significantly increasing reflectance as compared to that of the initial thin non-structured silver film. For such Babinet-type metasurface, the observed effect can be attributed to destructive interference of grating plasmon resonances originated from collective excitation of electric and ‘magnetic’ dipole modes of discs and holes. The resulting structure had a flat spectral response that was polarization-independent in a wide spectral range (~700-900nm). This spectral range was limited from the short/long wavelengths by bands associated by collective responses of “disc-hole metaatoms”. When increasing the gap between the adjoined metasurfaces, the effect of increased reflectance was diminished, and the Babinet-type metasurface became absorbing and transmitting.

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