Diffractionless High-Directional Transferring of Localized Electromagnetic Signal via Microwave Hyperbolic Metasurface

Artem Hrinchenko, *Student Member, IEEE*, Oleh Yermakov, *Member, IEEE*

***Abstract*—Hyperbolic metasurfaces exhibit unique dispersion and polarization properties, making them promising for a plethora of photonic applications. However, engineering hyperbolicity through predefined spectral positions of structural resonances remains a challenge. In this work, we investigate the resonant properties of optical metasurfaces based on square arrays of gold rectangular nanopatches depending on their geometric parameters. We show that the spectral bandwidth of the hyperbolic regime increases first linearly and then quadratic with nanopatches stretching, indicating extreme anisotropy. We also demonstrate plasmon canalization for a specific metasurface design which is important for in-plane signal transferring.**

***Index Terms*—Metasurface, anisotropy, hyperbolic dispersion, plasmon canalization.**

I. Introduction

Hyperbolic metasurfaces (HMS) offer diverse applications in far- and near-field optics, including negative refraction, hyperlensing, sensing and etc [1], [2]. However, their design requires the extensive numerical simulation, which can be time-consuming and require significant effort.

In this work, we analyze the spectral positions of the resonances and the bandwidth of the hyperbolic regime for dozens of plasmonic metasurface designs based on gold nanopatches. Starting with nanopatches of a square cross-section, we gradually stretch them into gratings, introducing anisotropy. We show that one of the resonant wavelength and spectral bandwidth initially grows linearly with the stretching but transition to a quadratic dependence at extreme anisotropy. Finally, we demonstrate plasmon canalization near resonance, highlighting the relevance of HMS engineering for in-plane optical signal transfer. The results obtained are supported by the IEEE MTT-S Undergraduate/Pre-Graduate Scholarship program and are partially published in [3] with the related acknowledgments to this program.

II. The Design and Methods

We consider a metasurface composed of a periodic array of gold nanopatches with a rectangular cross-section, arranged in a square lattice at the interface of a quartz substrate (Fig. 1a$_1$-a$_4$). The dispersion of gold follows experimental data for thin films [4]. Initially, we analyze nanopatches with a square cross-section, then stretch them along the x-axis, transforming them into rectangles while preserving the cross-sectional area. The long and short sides are defined as $a_x = a\,\eta$ and $a_y = a/\eta$, where η characterizes the anisotropy. We introduce a filling factor $f_x = a_x/p$ to describe the stretching. The limiting cases correspond to an isotropic metasurface and an extreme anisotropic regime, effectively forming a grating with period p and width a_y. The metasurface is described

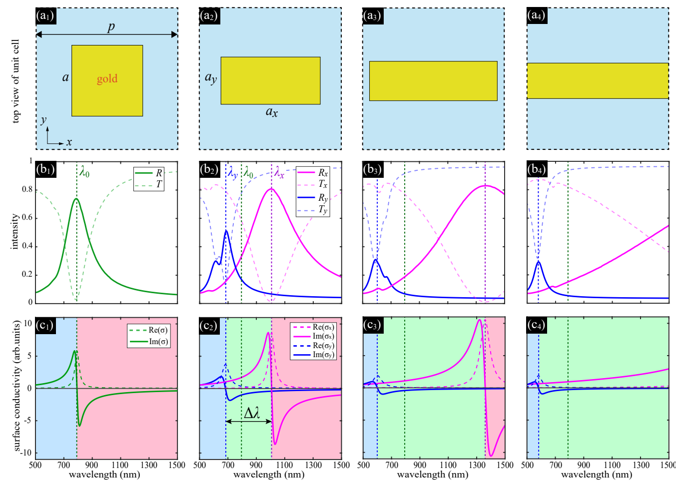

Fig. 1. (a$_1$)–(a$_4$) The metasurfaces' unit cells of a period p = 300 nm with (a$_1$) a square cross section of a side a = 150 nm, (a$_2$) and (a$_3$) a rectangular cross section of the long and short sides a_x and a_y, and (a4) grating p of a width a_y. (b$_1$)–(b$_4$) The R and T spectra of the metasurfaces shown in (a$_1$)–(a$_4$). (c$_1$)–(c$_4$) The blue, red, and green regions correspond to $\mathrm{Im}\,(\sigma_x) > 0, \mathrm{Im}\,(\sigma_y) > 0$, $\mathrm{Im}\,(\sigma_x) < 0, \mathrm{Im}\,(\sigma_y) < 0$ and the hyperbolic regime $\mathrm{Im}\,(\sigma_x)\,\mathrm{Im}\,(\sigma_y) < 0$, respectively. The resonant wavelengths for the isotropic and anisotropic cases are shown by green (λ_0), purple (λ_x) and blue (λ_y) dashed lines.

by an effective surface conductivity tensor, whose dispersion follows the Drude-Lorentz model [5]. By deriving the Fresnel equations for a 2D conducting layer, the reflectance can be expressed through the surface conductivity parameters.

$$R_i = \frac{(\sigma_0^i)^2 + (\beta_i^2 + \gamma_i^2)\zeta_-^2 + 2\gamma_i\sigma_0^i\zeta_-}{(\sigma_0^i)^2 + (\beta_i^2 + \gamma_i^2)\zeta_+^2 + 2\gamma_i\sigma_0^i\zeta_+}, \tag{1}$$

where the index $i = x, y$ components, $\sigma_0^{x,y}$ is the normalized dimensionless amplitude of surface conductivity, $\beta_{x,y} = 1 - \Omega_{x,y}^2$; $\Omega_{x,y}$ and $\gamma_{x,y}$ are the dimensionless resonant frequency and the bandwidth of the resonance, respectively, normalized per the angular frequency ω, $\zeta_{+,-} = n_s \pm 1$, n_s is the refractive index of substrate.

We calculate reflectance and transmittance spectra (Fig. 1b$_1$-b$_4$) for normally incident waves using the finite-element method and retrieve the surface conductivity components σ_x and σ_y (Fig. 1c$_1$-c$_4$) via least-squares fitting. Finally, we define the spectral bandwidth of the hyperbolic regime (SBHR) as the difference between the resonance wavelengths of the conductivity components:

$$\Delta\lambda = \lambda_x - \lambda_y. \tag{2}$$

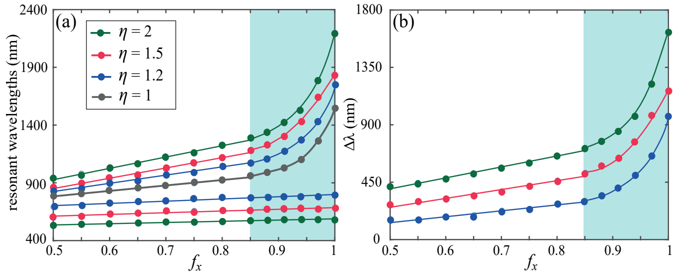

Fig. 2. The dependencies of (a) the resonant wavelengths λ_0 (gray lines), λ_x (upper solid lines) and λ_y (lower dashed lines) and (b) $\Delta\lambda$ on the f_x along the stretching direction for the fixed p and η.

III. Results

We analyze the spectral positions of the resonances and the SBHR during the stretching of the nanopatches up to the extreme near-grating case characterized by $f_x = 0.99$. By varying one parameter and fixing the other two, we demonstrate a quadratic dependence of one of the resonances when the electric field is oriented along the stretching direction (x-axis) (Fig. 2a) . Therefore, the SBHR dependence also becomes quadratic (Fig. 2b) in the extreme anisotropy regime for the range $0.85 < f_x < 0.99$ is associated with the strong mutual interaction between the nanoparticles leading to the substantial modification of the eigenmodes dispersion [5].

Finally, we demonstrate the typical near-resonant spatial field distribution of the surface plasmon-polariton excited by the vertical (z-oriented) dipole and propagating in the canalization regime along the plasmonic nanopatch-based metasurface (Fig. 3b and Fig. 3d). We plotted the spectral dependence of $\mathrm{Im}(\sigma_x)/\mathrm{Im}(\sigma_y)$ (Fig. 3a) pronounced peak near 1000 nm. At the large peak, σ_x is resonant while σ_y is near-zero, supporting divergenceless propagation of surface plasmon-polaritons. The optimum canalization occurs slightly shifted to 1100 nm due to high absorption losses near the resonance, as shown by the real part of the surface conductivity (red dashed line). The spatial distributions of the normal component of the magnetic field H_z (Fig. 3b and Fig. 3d) demonstrate collinear propagation along the x-axis with small decay, verifying the canalization regime. We extracted isofrequency contours (Fig. 3c) via two-dimensional Fourier transform from the H_z-field distribution of a 15×15 nanopatch metasurface and compared them with analytical calculations using the dispersion equation and surface conductivity tensor from (Fig. 1c$_2$). The good coincidence indicates a flat isofrequency contour, marking the topological transition between elliptical and hyperbolic shapes. These findings demonstrate the engineering of plasmonic metasurface resonances and efficient plasmon canalization, applicable to hyperbolic optics and surface wave excitation.

IV. Conclusion

We investigated plasmonic metasurfaces based on gold nanopatches, varying their size, degree of anisotropy, and period from isotropic (square) to extremely anisotropic (gratings). The quadratic dependence of the spectral bandwidth of one of the resonances on the anisotropy at an electric field oriented along the stretching direction is determined. This

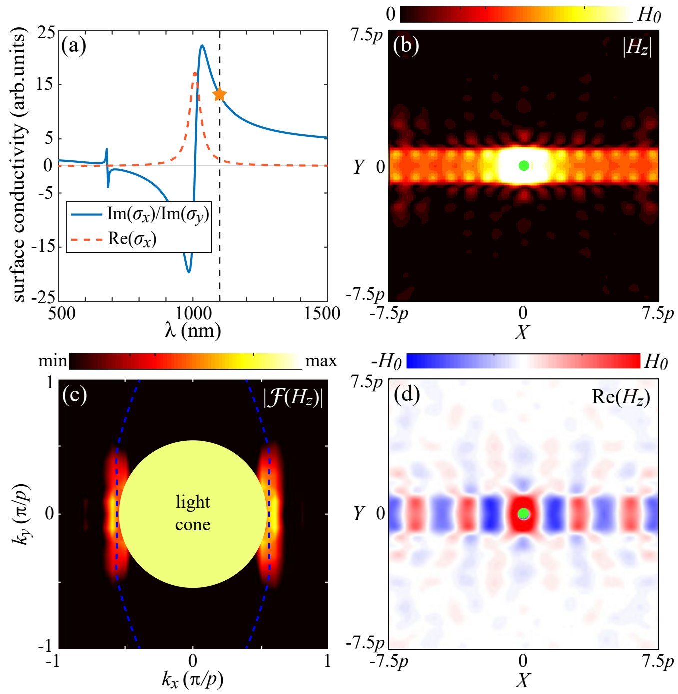

Fig. 3. (a) The dependence of the $\mathrm{Re}(\sigma_x)$ and the ratio $\mathrm{Im}(\sigma_x)/\mathrm{Im}(\sigma_y)$ on the λ. (b) and (d) The spatial in-plane distribution of the (b) amplitude $|H_z|$ and (d) real part of the normal component of the magnetic field $\mathrm{Re}(H_z)$ of the magnetic field for the surface plasmon-polariton excited by the vertical magnetic dipole at the $\lambda = 1100$ nm. (c) The Fourier spectrum of the magnetic field spatial distribution shown in (b,d) within the first Brillouin zone.

leads to a broad bandwidth between the resonances, which corresponds to the hyperbolic regime of the metasurface. Plasmon canalization near the engineered resonance is demonstrated as an example of a possible application. These results may be useful for optical research and engineering of HMS plasmon resonances. Finally, one can extend the horizons of the related applications from to infrared and microwave frequency ranges.

V. Impact Statement and Future Plans

The MTT-S scholarship provided me with the opportunity to carry out this long-term and meaningful project, which contributed to advance my knowledge and research skills in the field of plasmon canalization. The results obtained have been published and highlighted by the front cover of the Journal of Applied Physics [3]. I will continue study this topic within my PhD studies.

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