Resonant Response in Tunable Metasurface Based on Crossed All-Dielectric Grating

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Abstract — We theoretically demonstrate mechanical tuning of the spectral response of a Mie-like resonant dielectric metasurface consisting of crossed all-dielectric strip gratings. We use two array of parallel dielectric strips superimposed on each other to mechanically alter the crossing angle between them thereby changing the position of the maximum of the spectral response in a wide frequency range. The metasurface structure is considered as a doubly-periodic system in an oblique mesh. This mechanically controllable metasurface can be perspective in developing of a flexible polarization-sensitive optical devices.

Keywords — mechanically tunable metasurface, Mie-like resonant, optics.

I. INTRODUCTION

The metasurface is a two-dimensional analogue of metamaterials with extraordinary properties not found in natural materials [1], [2]. Unlike conventional materials, which have a weak response to external influences and, as a consequence, are able to demonstrate dynamic control of properties in an extremely limited range, metasurfaces open the way to obtain the desired controllability of scattered field properties due to both the cell geometry reconﬁguration and material property dynamic changes. As a rule, a change in the geometry of the cell occurs due to mechanical operation. Reversible stretching metasurfaces based on a stretchable substrate resulting in manipulation of transmission spectra by putting a strain along the surface of the polydimethylsiloxane substrate [3], [4]. The use of a micro-electro-mechanical system MEMS extends the functionality of mechanically tunable metasurfaces [5], [6]. Thus, the mechanical reconﬁguration of the periodic cell of the metasurface is important. In particular, the effectiveness of this approach to controlling the resonant frequencies without additional external stimuli such as thermal, electrical, magnetic, optical, chemical, or electrochemical and others, discussed, for instance, in [7], [8], [9].

With the shortening of the scattering wavelength from microwave to optics, metal periodic structures become less efficient as a result of increasing thermal loss in the metal. One of the most popular research topics for the enhancing efficiency of metasurfaces relates to high-index all-dielectric planar structures with the possibility of expanding their functionality through the use of their reconfigurable properties. Dielectric metasurfaces consist of volumetric elements in which an incident electromagnetic wave excites polarization current resonances associated with magnetic and electric dipole Mie-resonances [10], [11], [12]. Recently, metamaterials and metasurfaces with moire conﬁgurations, which are regulated by rotation in the plane of superimposed layers, have drawn attention to the extraordinary optical properties of such quasi-periodic structures, including multiband and broadband responses and optical activity [13], [14].

In our letter we continue our research of the mechanical tunable crossing gratings. In [15] we demonstrate for metallic crossing strip gratings moving resonant peak along frequency scale through altering the angle of crossing. This resonance is associated with the length of the rhombus side of the structure cell when the lattice symmetry is broken. In contrast with those resonances when replacing metal strips with a dielectric one we observe volumetric Mie-like resonance that leads to the same effect namely moving resonant peak along frequency scale through altering the angle of strips crossing.

II. FORMULATION OF THE PROBLEM

In Fig. 1 we present the scheme of an all-dielectric metasurface formed by the intersection of two identical periodic arrays (a is arrays period) of parallel dielectric strips of rectangular cross section. To simplify the physical analysis of the formation of the response of such metasurface to electromagnetic excitation, substrates on which periodic arrays can be located are excluded from consideration.

The periodic cell of the metasurface under study has the shape of a rhombus with an acute angle β and a side

\[
L = L_x = L_y = a/sin(\beta)
\]

that defines the period of the metasurface along the Ox1 and Oy1 axes. Dielectric strips of thickness \( h = 0.05a \) and width \( D = a/3 \) are considered to be made of non-magnetic material with \( \mu = 1 \) and with a dielectric constant that corresponds to the dielectric constant of silicon at the terahertz range \( \varepsilon = 11.0 \) and \( tan\delta = 10^{-3} \) (the time dependence is assumed in the form \( exp(-\omega t) \)). The metasurface can be tuned by mechanically rotating one of the arrays at an arbitrary angle relative to the other. We assume that the backward array \( (0 \leq z \leq h) \) contains strips that are
oriented along the $Oz$ axis and are fixed, and the front array ($h \leq z \leq 2h$) can be rotated in the $xOy$ plane. It is clear that different metasurfaces will be formed by varying the values of angles $0 \leq \beta \leq 90^\circ$. A plane electromagnetic wave incidents on the metasurface from the upper region $z > 2h$ in the opposite direction to the $Oz$ axis. We will distinguish cases of $x$- and $y$-polarized waves.

### III. THE NUMERICAL SIMULATIONS

Analysis of the resonant response of the studied structure to electromagnetic excitation was performed on the basis of numerical simulated scattering of a plane wave on a periodic structure, using the well-tested method of integral functionals [16]. The method uses volume integral equations for equivalent electric and magnetic polarization currents induced by the incident wave field in the periodic layer. Integral equations are solved numerically with the help of integral functionals related to the distribution of the polarization current and the technique of Floquet-Fourier series double decomposition. At the final stage of the solution, we obtain scattered fields as a superposition of diffraction harmonics in the following form:

$$E_r^x(x, y, z) = \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} E_{pq}^x e^{i(\xi_{pq} y + \gamma_q z - \kappa_{pq} z)}, \quad (1)$$

$$E_r^y(x, y, z) = \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} E_{pq}^y e^{i(\xi_{pq} y + \gamma_q z + \kappa_{pq} z)}, \quad (2)$$

where

$$\gamma_q = \frac{2\pi q}{L_{x1}}, \quad \xi_{pq} = \frac{2\pi}{L_{x1}} \left( \frac{p}{L_{x1}} - \frac{q}{L_{y1}} \cos \beta \right), \quad \kappa_{pq} = \sqrt{k^2 - \xi_{pq}^2 - \gamma_q^2}.$$  

are the wave vector components of a diffracted order $p$ and $q$, $E_{pq}^x$ and $E_{pq}^y$ that are the magnitudes of the electric field of the reflected and transmitted waves.

Fig. 2 shows the reflection coefficients for the case of normal incidence on the investigated structure of $x$- and $y$-polarized waves for different values of the angle $\beta$. We see that the difference in the dependence of the reflection coefficients $r_{xx}$ and $r_{yy}$ becomes noticeable for angles less than $70^\circ$. Fig. 3 demonstrates in more detail this difference.

One can see that for angles $\beta < 70^\circ$, an additional resonance of reflection appears. The frequency of this resonance is strongly depends from value of $\beta$ and it demonstrates huge red shift with decreasing of the angle $\beta$. At the same time, the initial resonance remains frequency. Moreover, additional reflection resonance is characterized by polarization sensitivity. For $y$-polarized wave his amplitude is comparable with main resonance and for $x$-polarized it is very small.

The appearance of additional reflection resonance for such ultra thin dielectric structure ($h = 0.05a$) should be associated with the exciting of additional eigen oscillation of the structure. At the same time, eigen oscillation result in forming strong local field and appearance of absorption peak for dissipative structure. Therefore, in order to analyze the eigen oscillations of the system, the field distributions in the periodic cell were calculated at frequencies of absorption maxima (Fig. 4). One can see that the electric field has a maximum in the region of the dielectric strips overlapping and field distribution has form inherent to the dipole moment pattern. In this case, with some assumptions, the eigen oscillations of periodic cell can be associated with Mie resonances of the dielectric rhombus formed by the overlapping of the silicon strips. It is easy to see that the absorption maxima appears when the directions of the equivalent electric dipoles coincide with the diagonals of the rhombus. This allows us to assume that the reflection resonances of the considered structure under...
are caused by the interaction of these self-oscillations. Then for $\beta = 90^\circ$ these oscillations are degenerate, and therefore their superposition gives oscillations of the same frequency. This is confirmed by the polarization independence of the reflection coefficient when the wave is normally incident on such structure. For the $\beta < 90^\circ$, the eigen oscillations have different frequencies, and the resonances observed in studied system are results of their interaction. The interaction leads to the appearance of oscillation, which significantly depends on the difference between the eigen oscillations of the rhomboid particle. As one can see, with an $\beta$ increase this oscillation rapidly shifts to the high frequency band. Moreover, due to the symmetry of the problem, this eigen-oscillation has an high electromagnetic coupling with the $y$-polarized wave unlike with the $x$-polarized. Thus, resonance for the case of $x$-polarization has much smaller amplitude. To confirm our conclusions in the presentation at the conference, we plan to provide an analysis of the results of the study of the intrinsic polarization states of the structure.

![Fig. 4. Distributions of the amplitudes (color map) and vectors (arrows) of the electric field in the unit cell at the frequencies of the absorption maxima of the metasurface (a, b correspond to $a/\lambda = 0.80$, c, d - $a/\lambda = 0.76$) with a rhombic cell ($\beta = 60^\circ$) for the case (a, d) $y$-polarized, (b, c) $x$-polarized waves.](image)

The conversion into cross-polarization electromagnetic waves is almost the same, for both polarized waves which allows us to speak about the polarization independence of the polarization-transformation properties of such structures (Fig.5). Note that the polarization-transformation properties of such structures also posses a resonant character and for the reflective metasurfaces, in which the strips array can be placed on a metal substrate, these patterns are preserved.

For any value of the angle $\beta$ except for $\beta = 0$ and $\pi/2$, the investigated structure manifests properties inherent to objects with a volume chirality. The relevant properties appear as a result of electromagnetic coupling between closely placed gratings of a double-layered structure [17]. Obviously, the sign of chirality is defined by the sign of the angle $\beta$. A circular dichroism and an optical activities of the metasurface may be observed as consequence of chirality. Both effects are controllable in the proposed metasurface.

In terms of circular polarised waves, a transmission matrix may be presented by using calculated transmission coefficients of linear polarised waves in accordance with the following expression [18].

$$
\begin{pmatrix}
  t_{++} & t_{+-} \\
  t_{-+} & t_{--}
\end{pmatrix} = \frac{1}{2} \begin{pmatrix}
  t_{xx} + t_{yy} + i(t_{xy} - t_{yx}) & t_{xx} - t_{yy} - i(t_{xy} + t_{yx}) \\
  t_{xx} - t_{yy} + i(t_{xy} + t_{yx}) & t_{xx} + t_{yy} - i(t_{xy} - t_{yx})
\end{pmatrix}
$$

where indexes $+$ and $-$ denote right-handed and left-handed circularly polarised waves respectively.

The circular dichroism can be calculated by expression

$$
D = |t_{++}|^2 - |t_{--}|^2.
$$

The polarisation azimuth angle can be found by formula

$$
\Phi = -\frac{1}{2} [\arg(t_{++}) - \arg(t_{--})].
$$

![Fig. 5. The normalised frequency dependences of the cross-conversion coefficients $|r_{ij}|^2$ for the cases of normal incidence on the structure of the (a) $y$- and (b) $x$-polarized waves with different angle $\beta$. Here the indices $i$ and $j$ take on the values $x, y$.](image)

IV. CONCLUSION

In summary, in this paper, we present for the first time achieving mechanical tuning of the resonant response of an all dielectric metasurface at the terahertz range by removing the degeneracy of the electric dipole resonance of crossed arrays with silicon strips through their rotation relative to each other. Mechanical frequency tuning of the resonant peak position occurs in a fairly wide frequency range. This kind of metasurfaces can be a key component in planar configurable optical devices.

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