Controlling high-\(Q\) trapped modes in polarization-insensitive all-dielectric metasurfaces

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We reveal peculiarities of the trapped (dark) mode excitation in a polarization-insensitive all-dielectric metasurface, whose unit super-cell is constructed by particularly arranging four cylindrical dielectric particles. Involving group-theoretical description we discuss in detail the effect of different orientations of particles within the super-cell on characteristics of the trapped mode. The theoretical predictions are confirmed by numerical simulations and experimental investigations. Since the metasurface is realized from simple dielectric particles without the use of any metallic components, they are feasibly scalable to both micro- and nanometer-size structures, and they can be employed in flat-optics platforms for realizing efficient light-matter interaction for multiple hotspot light localization, optical sensing, and highly-efficient light trapping.

I. INTRODUCTION

Today, with the advancements of nanotechnology, the science and engineering of subwavelength light-matter interactions move to design and fabrication of nanostructures with desired optical properties\(^1\). It allows one to construct optical components with previously unattainable characteristics. These also include planar metamaterials (metasurfaces) made of metallic (plasmonic) particles which are extremely important parts of sensors, slow light and beam steering devices, holographic displays, near-IR tunable filters, fast optical inter-connectors, switches, and amplitude modulators.

A particular class of novel metasurfaces based on dielectric nanoparticles has several significant advantages compared to plasmonic ones, especially concerning their low losses and fabrication techniques targeting to higher frequencies of operation\(^2,3\). They are so-called all-dielectric\(^4\) metasurfaces composed of subwavelength dielectric particles made of high-refractive-index material\(^5\). The particles are arranged into a lattice where each particle behaves as an individual resonator\(^6\) sustaining a set of electric and magnetic dipolar and multipolar modes (referred to Mie-type modes\(^7\)). An appearance of these modes can be spectrally controlled and engineered independently\(^8\).

Due to the unique features of optically induced electric and magnetic Mie-type modes of the dielectric particles, the all-dielectric metasurfaces are expected to complement or even replace different plasmonic components in a range of potential applications\(^9,10\). However, metasurfaces based on the Mie-type modes are still not sufficiently thin to compete with their metallic counterparts. An alternative approach is to access trapped (dark) modes of the dielectric resonators, which allow deeper subwavelength thicknesses while still preserving a sharp resonant response\(^11,12\) in the electromagnetic theory\(^12\) the trapped modes are considered as some degenerate states that are not directly coupled to the field of incoming radiation, whereas they can be excited indirectly by removing the degeneracy.

In particular, in order to lift the degeneracy and provide a necessary coupling of an incoming radiation with a trapped mode, some structural asymmetry can be introduced into the particles forming the metasurface\(^13,14\) (recently, the trapped modes in such asymmetrical structures were referred to the phenomenon of bound states in the continuum (BIC) originated from distortion of the symmetry-protected bound state in the continuum\(^20\)). As a side effect of the method, the resulting metasurface composed of asymmetrical particles becomes to be polarization sensitive even for a normally incident electromagnetic wave. It reduces the practical applicability of the metasurfaces based on trapped modes. In order to overcome this drawback, several designs of the metasurfaces composed of thin metallic particles have been proposed\(^21,23\) whereas for the all-dielectric metasurfaces they are quite rare\(^24,31\). It is due to a greater flexibility available in designs of thin metallic resonators. They can be given a rather complicated shape that provides a specific configuration of the surface currents flow, which is impossible to realize in the volumetric dielectric resonators for the displacement (polarization) currents. Therefore, in order to access a trapped mode in polarization-insensitive all-dielectric metasurfaces another approach should be applied.
As such a design of polarization-insensitive all-dielectric metasurfaces\(^\text{32–36}\) a multi-layer configuration of dielectric resonators can be mentioned. In this configuration, in order to access a trapped mode, two additional scatterers of a particular form are attached diagonally to the upper and lower sides of the resonators forming metasurface. A multistep lift-off and deposition procedure is suggested for the resonators fabrication. While the metasurfaces consisting of ordinary (single-layer) asymmetric particles are fabricated and investigated\(^\text{30}\) the structure composed of the multi-layer resonators has been investigated only numerically. Apparently this is due to the fact that the technology of their production, although feasible, is quite complex.

Alternatively, a trapped mode can be excited in the polarization-insensitive metasurfaces whose unit cell comprises several particles arranged specifically (so-called super-cell\(^\text{32–36}\)). Although these metasurfaces possess a more complicated unit cell, their production complexity is the same as for the metasurfaces based on the ordinary single-particle unit cells.

Following the concept of super-cell metasurfaces, in the present paper we employ group-theoretical predictions\(^\text{37,38}\) numerical simulations and experimental study for both far-field and near-field characteristics to reveal conditions of the trapped mode excitation in a polarization-insensitive metasurface. We distinguish several super-cell’s designs which provide efficient coupling of the all-dielectric metasurface with a linearly polarized incident wave via the trapped mode. They utilize particles with a short coaxial-sector notch made in a form of smile since they can efficiently support the trapped mode\(^\text{10}\).

II. THEORETICAL DESCRIPTION

In order to ensure the completeness of our study, we start the discussion by demonstrating a polarization-sensitive response of the trapped mode excited by a linearly polarized wave in the metasurface. We consider that the metasurface under study is illuminated by a normally incident (\(\vec{k} = \{0, 0, k_z\}\)) linearly polarized wave with the electric field vector directed either along the \(x\)-axis (\(\vec{E} = \{E_x, 0, 0\}\), \(x\)-polarized wave) or along the \(y\)-axis (\(\vec{E} = \{0, E_y, 0\}\), \(y\)-polarized wave) (see Fig. 1).

The numerical simulations of the electromagnetic response of the metasurface were performed with the use of RF module of commercial COMSOL Multiphysics\(^\text{9}\) finite-element electromagnetic solver. The Floquet-periodic boundary conditions were imposed on four sides of the unit cell to simulate the infinite two-dimensional array of resonators.\(^\text{30}\)

The point symmetry of the super-cell depends on the orientation of notches of the four disks. For the first design, symmetry of the super-cell in the \(x − y\) plane is described by the group \(C_h\) (in Schönflies notation\(^\text{39}\)) which contains only one vertical plane of symmetry \(x = 0\). Under such a problem statement, the trapped mode appears to be excited only for the \(x\)-polarized wave (see Fig. 2a) and the Supplemental Material\(^\text{41}\). In the spectra of the metasurface the trapped mode manifests itself as a peripheral lowest frequency (red-shifted\(^\text{13}\)) resonance (the corresponding resonance is distinguished on the spectral curves by the green arrows). The resonance acquires a sharp peak-and-trough (Fano) profile where extremes of transmission and reflection approach to 0 and 1 alternately, since in the simulation the losses in materials forming the metasurface are considered to be absent.

From the analysis of the polarization current and magnetic field distributions in the middle plane (\(x − y\) plane at \(z\) coordinate corresponding to the half height of the particles) it is revealed that the identified trapped mode resembles the characteristics of the lowest transverse electric (TE\(_{01}\)) mode of the individual cylindrical dielectric resonator (see the color maps in Fig. 2a) and the Supplemental Material\(^\text{41}\). At this state there is a specific distribution of the electromagnetic field within each particle, where the polarization currents have a circular flow twisting around the particle’s center, whereas the magnetic field direction in the particle centers is oriented orthogonally to the metasurface plane forming out-of-plane magnetic dipole moment. All magnetic moments induced in the metasurface are oriented in the same direction demonstrating a dynamic ferromagnetic order\(^\text{12}\).

The most straightforward way to construct a polarization-insensitive metasurface based on the same particles is to rearrange them within the \(2 \times 2\) super-cells, similarly to those proposed for the split ring based metasurfaces\(^\text{31,32,35}\). For the normal wave incidence,
symmetry of the super-cell in the $x-y$ plane is described by the group $C_4$ which consists of the four-fold axis for rotation around the $z$-axis (Fig. 2(b)). It is mathematically proven that for the metasurfaces whose unit cell symmetry belongs to the rotational groups $C_n$, for $n>2$ there is polarization independence of the structure. In Fig. 2(b) one can see that the spectral characteristics of the metasurface corresponding to excitation with two different polarizations are indeed identical.

For each polarization, the trapped mode is supported by a pair of active particles placed diagonally, while the remaining two resonators are inactive. In the color maps of Fig. 2(b) (Multimedia view) an active pair of particles is presented for the $x$-polarized wave. Another pair is active for the $y$-polarized wave and has the similar field distributions (are not presented here). Since only two particles are active within the super-cell, the lattice appears to be somewhat ‘sparse’. The out-of-plane magnetic moments induced in the active particles are oriented in the opposite directions resembling a dynamic antiferromagnetic order that leads to a shift of the resonance to the low frequency region in comparison with the $C_s$ design.

Next it is our goal is to find the polarization-insensitive configuration when all particles in the super-cell are active. For the metasurface under study there is a possibility to further increase the symmetry order of the super-cell via the design transition from the group $C_4$ to the group $C_{4v}$. The latter contains additionally four vertical planes of symmetry passing through the $z$-axis. They are $x=0$, $y=0$ and two diagonal planes. For this design the notches of the particles should be oriented either inward or outward the center of the super-cell. These two configurations are in fact identical, since the disks are situated equidistantly in the two-dimensional lattice, and thus there is arbitrariness in the super-cell choice. Remarkably, for such a design all four particles in the super-cell are active ones for the waves of both orthogonal polarizations.

The spectra of the metasurface whose unit cell possesses the higher symmetry and is described by the group $C_{4v}$ is presented in Fig. 2(c). It can be seen that in the frequency band of interest, the spectral curves for metasurfaces describing by the group $C_4$ and the group $C_{4v}$ are almost the same. The corresponding field distributions at the resonant frequency are presented in the color
III. EXPERIMENTAL VERIFICATION

In order to verify the polarization-insensitive appearance of a trapped mode, the prototypes of metasurface were fabricated and experimentally investigated in the microwave frequency range. As a dielectric material the Taizhou Wangling TP-series microwave ceramic characterized by the relative permittivity $\varepsilon_d = 24$ and loss tangent $\tan \delta_d \leq 1 \times 10^{-3}$ at 10 GHz has been used. The dielectric particles with the sizes mentioned in the caption of Fig. 2 were fabricated with the use of precise mechanical cutting techniques. To arrange them, an array of holes was milled in a custom holder made of a Styrofoam material whose relative permittivity is $\varepsilon_s = 1.1$ and thickness of the plate is $h_s = 20.0$ mm. The metasurface prototypes were constructed of $12 \times 12$ super-cells (so we used 576 particles in total) arranged in a lattice having the period $d = 22$ mm.

At the first step the transmission and reflection spectra have been measured for all the metasurface prototypes. The common technique when the measurements are performed in the radiating near-field region and then transformed to the far-field zone has been used. During the investigation the prototype was fixed on the 2.0 m distance from a rectangular linearly polarized broadband horn antenna as shown in Fig. 3(a). The antenna generates a quasi-plane wave with required polarization. It is connected to the port of the Vector Network Ana-
The magnetic moments are orthogonally oriented relative to the metasurface plane and demonstrate different patterns with respect to the particular resonator orderings. Thus, we have measured the magnetic near-field distribution for all the proposed designs. For that purpose we slightly changed the experimental setup. We used a small magnetic probe placed in the $x-y$ plane instead of the electric one (see Fig. 3(b)). The normal component ($H_z$) of the magnetic near-field has been scanned over the area of $20 \times 44$ mm with 1 mm step covering $1 \times 2$ super-cells. The near-field scanning was performed on the distance of 1 mm above the metasurface prototypes. The color maps of the measured near-field distribution confirming discussed above trapped mode resonant conditions and orientations of the out-of-plane magnetic moments are shown in Fig. 5.

IV. CONCLUSIONS

In conclusion, we have studied the appearance of a trapped mode in several polarization-insensitive designs of the all-dielectric metasurface under the normal wave incidence condition. The super-cell configuration for these designs is related to the symmetry groups $C_s$, $C_4$, and $C_{4v}$. Three different distributions of the magnetic moments are found to exist within the super-cell which resemble either ferromagnetic or antiferromagnetic order. An unexpected behaviour is that for the design related to the group $C_4$ only two particles are active in the super-cell, while other two are inactive.

Although in our designs the particles with coaxial-sector notch in the shape of a smile are used, we argue the considered effects have a common nature and will also exist in particles with holes of a simpler shape, for example, in resonators with an off-centered round or rectangular hole that are easier to fabricate at the nanoscale. We believe that proposed designs can be useful in highly sensitive sensors, filters, and strong light matter interaction applications where polarization-insensitivity feature provides additional benefits.

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