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Lattice Resonances in Metasurfaces Composed of Silicon Nano-Cylinders

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Abstract – **We investigate lattice resonances (LRs) in metasurfaces (MSs), composed of silicon nano-cylinders. It is revealed that LRs can be detected through concentration of fields at specific locations in the gaps between nano-cylinders. Formation of LRs appears to significantly modify the resonance responses of MSs, transforming elementary responses into collective phenomena. Their contribution in red-shifting of resonances at increasing the lattice constants and in phenomena, associated with Rayleigh anomalies, are discussed.**

I. INTRODUCTION

Silicon metasurfaces (MSs) demonstrate unique capabilities for controlling light propagation and scattering at the formation of Mie resonances in constituent posts or disks. The properties of MSs can be employed for realizing various photonic functionalities in sensing, imaging, light-guiding, and holographic applications [1-5]. Originally, plasmonic MSs have been developed and utilized for these purposes [2]. However, employing metal in their design caused excessive losses in optical range. Alternative MSs, composed of dielectric resonators (DRs), were found free from similar drawbacks that had opened a window for implementing efficient optical components and led to advances in photonics [1]. However, recent works on the resonance phenomena in dielectric MSs have revealed that in addition to elementary resonances, such as electric and magnetic dipolar and quadrupolar resonances (EDR, MDR, and MQR) in constituent particles, MSs are capable of supporting complicated resonance phenomena, which integrate the entire lattice due to the propagation of surface waves [3-5]. The studies of the effects of lattice periodicity on these phenomena have shown that at lattice constants, comparable to the wavelengths of radiation, diffraction of surface waves, which are initiated by elementary electric and magnetic resonances, leads to appearance of so-called lattice resonances (LRs), which significantly affect MS responses [4, 5]. Realization of LRs opens up new perspectives for developing various applications demanding field-localization or high-Q resonances [5]. This work aims to provide a deeper insight into the formation and the effects of LRs in silicon MSs. Special attention is paid to the realization of the Kerker's effects.

II. RESULTS AND DISCUSSION

MSs under study had square lattices and were composed of silicon nano-posts with the diameters of 240 nm and with variable heights. Unit-cells of MSs with periodic boundary conditions were simulated by using COMSOL Multiphysics software package. Electric and magnetic components of the incident wave were polarized, respectively, along X and Y axes, while Z-directed wave-vector was normal to the plane of lattice. Fig. 1 presents spectral changes of MS responses at increasing the lattice constants Δ. It is seen in the figure that both electric and magnetic resonance responses, registered by the probes, located in DRs' centers, demonstrate red spectral shifts in MSs with bigger Δ. As the result, the curves, representing dependences of resonance positions on Δ, turn towards longer wavelengths and gradually approach the lines, corresponding to Rayleigh anomalies (RAs), which play the role of asymptotes for respective dependencies. Similar effects were earlier noticed in [4] at studying planar arrays of spherical silicon resonators, organized in rectangular cells. Authors of [4] related the obtained data to an interplay of elementary dipolar resonances with surface lattice resonances. However, presented below data do not confirm integrating of these resonances. As seen from the presented in Fig. 1 S-parameter spectra, red shifting of electric responses creates an opportunity for realizing both electric and magnetic responses at the same wavelengths of incident light. However, at an obvious presence of LRs in MSs, such overlapping does not lead to realizing any special effects in MS transmission or reflection spectra. It should be noted that LRs, formed by surface waves, propagating in MS plane, are not expected to directly affect transmission of waves at normal incidence. Kerker's effect, caused by interference of EDR and MDR radiations, is well seen as deep drops in the presented S11 spectra at wavelengths, exceeding the resonance wavelengths (see dark-blue line to the right from MDRs in Fig. 1).

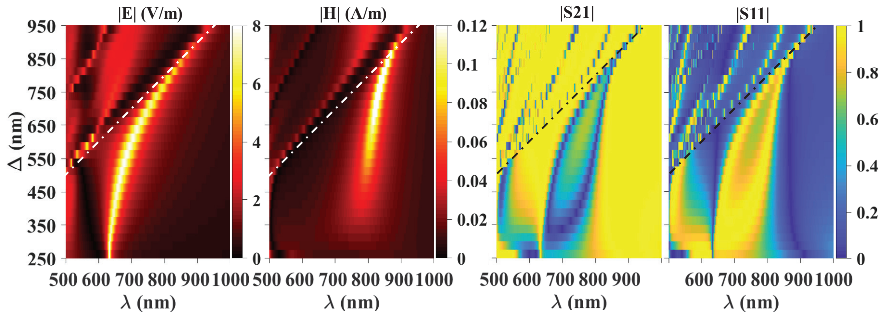

Fig. 1. Red shifting of electric and magnetic resonance responses of square-latticed MSs at increasing their lattice constants and representation of resonance responses by color images of S-parameter spectra. The heights of silicon posts were 160 nm. Positions of Rayleigh anomalies are shown by dashed-dotted lines.

According to [4], LRs gain their strength in spectral regions close to the RA lines. Thus, the data presented in Fig. 1 could be used to determine the range of lattice constants, at which clear signs of LR appearance could be expected in field distributions of MSs. Considering the electric lattice resonance, it can be concluded from Fig. 1 that the presence of LRs should be expected in E-field distributions of MSs with lattice constants in the range from 450 nm to 750 nm. These distributions in planar (XY) and normal to the MS plane (ZX) and (ZY) cross-sections are presented in Fig. 2.

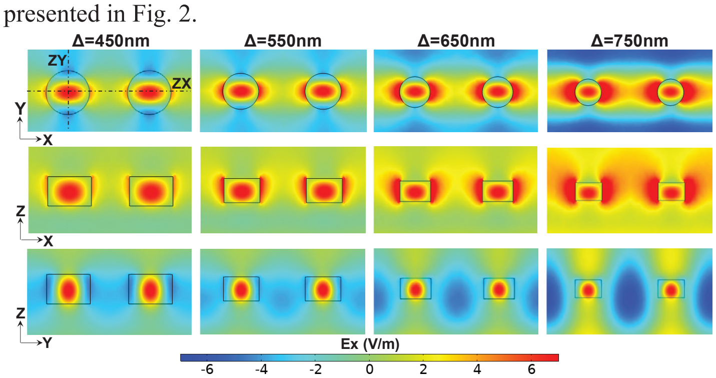

Fig. 2. Changes of gap-edge field configurations at increasing the lattice constants Δ in square-latticed MSs, composed of DRs with the heights of 160 nm and diameters of 240 nm. Field patterns in three rows were obtained, respectively, in XY, XZ and YZ cross-sections passing through DR centers. Z-axis is normal to MS plane, X- and Y- axes are co-directed with E- and H-fields of incident waves. Dashed lines show positions of ZX and ZY cross-sections.

As seen in the figure, at Δ = 450 nm, strong fields can be observed in the centers of MS resonators in all three cross-sections. The distributions of these fields correspond to the formation of the electric dipolar resonances in DRs. However, at Δ = 550 nm, the field patterns change. In addition to dipolar fields, an appearance of field spots in X-oriented gaps between resonators can be observed. These field spots look adjacent to the resonator bodies and having maximal intensity at outer surfaces of resonators. They are called further the gap-edge fields. These fields spread in air in both Z and X directions and do not look as an extension of the dipolar fields. At bigger Δ, they become much stronger, than dipolar fields inside resonators, the intensity of which does not experience visual changes. It is worth mentioning that gap-edge fields, formed at two sides of resonators, do not overlap, and therefore, can be considered as independent entities. On the other hand, the field patterns in ZY cross-section allow for suggesting that the gap-edge fields in X-oriented gaps affect the fields in Y-oriented gaps between resonators. While at Δ = 450 nm, the fields in Y-oriented gaps have relatively low intensity, being defined by dipolar fields, circling in air around resonators, then at bigger Δ, the intensity of Y-gap fields experiences a significant enhancement correlated with an enhancement of gap-edge fields in X-oriented gaps. The mechanism of this correlation has to be investigated additionally.

To ensure that the gap-edge fields can serve as the markers of LRs, the spectra of E-field signals from probes placed in special points of MSs have been simulated. As evident from the schematic in Fig. 3, P1 probe characterizes the dipolar resonance formation, P2 probe represents incident wave field within MS, and P3 probe provides information about the formation of gap-edge fields. From the data in Fig. 3 it is well seen that the peak intensity of the dipolar resonance in point P1 experiences no changes at increasing Δ, despite red shifting of the spectral positions of peaks. Intensity of background radiation (point P2) becomes less at bigger Δ, as it is expected, while the strength of the gap-edge fields in point P3 grows up significantly, so that its dual peaking even exceeds the resonance peak in point P1. Spectral positions of P3 peaks coincide with positions of electric and magnetic dipolar resonances that agrees with the suggestion that LRs are caused by the diffraction of surface waves, launched by resonance radiation.

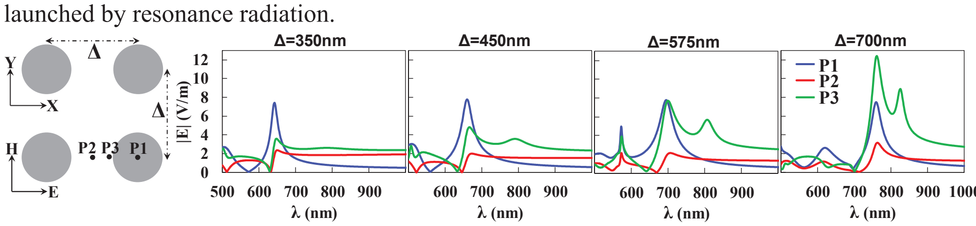

Fig. 3. Schematic of probe location and spectra of signals from respective E-field probes placed at points P1, P2, and P3 of square-latticed MSs having different lattice constants Δ. Resonator heights were 160 nm and diameters - 240 nm.

III. Conclusive Remarks

According to the obtained results, resonances inside DRs conserve their strength at the conditions, which cause strong enhancement of LRs. Thus, the formation of LRs does not inevitably affect dipolar resonances inside DRs. It could be then presumed that surface waves, responsible for the formation of LRs, do not interact with DRs in the same manner, as the plane waves, incident normally to the MS plane. Under such assumption, the formation of elementary resonances inside DRs, on one hand, and the formation of gap-edge fields, as LR markers, on the other hand, should be controlled by physically different processes. At the same time, surface waves should experience scattering at their interaction with DRs, located on their path, even though this scattering could not affect the strength of resonance fields inside DRs. Scattered fields are, most probably, collected in the spots of gap-edge fields near the centers of scattering, i.e. DRs. However, the physics underlying appearance of resonance-like field enhancements in these spots still needs clarification. Additional question, which requires further clarification, is the nature of red shifting of the resonance responses at increasing the lattice constants. Since this shifting proceeds without changing the strength of resonance fields in DR centers, it should be related to some geometric factors. In particular, it could be suggested that shifting of electric responses to longer wavelengths could be defined by coherent oscillations of dipolar fields, formed inside DRs, and gap-edge fields, formed in X-oriented gaps. Such coherence could increase the effective wavelengths of oscillations controlling the formation of resonances in the centers of DRs.

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