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Effect of Fragmenting Dielectric Metasurfaces on their Dipolar and Lattice Resonances

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Abstract – **Parameters of unit cells in metasurfaces (MSs) are usually determined by applying the infinitely periodic conditions in numerical analysis. However, real-world samples of MSs are implemented with finite number of resonators. We conduct studies to reveal the effects of fragmenting MSs, comprised from n × m low-loss identical dielectric disks, on their electromagnetic responses. It is seen that in fragmental MSs, new odd-mode dipolar resonances with extraordinary intensity and Q-factors can appear that were not detected in infinite MSs. Such modes are associated with out-of-phase oscillations in neighbor resonators. Meanwhile, presented results demonstrate that fragmenting the MSs does not deteriorate the formation of lattice resonances at approaching the Rayleigh anomaly (RA) in very sparse fragments. In RA area, conventional even-mode dipolar resonances show red-shifting while odd-modes are spectrally stable. Responses of MS fragments can make them promising platforms for developing applications such as sensing, imaging, and absorption.**

I. INTRODUCTION

Surface waves (SWs) in dielectric metasurfaces (MSs) are considered as caused by in-plane radiation from dipolar resonances, formed in MSs at normal wave incidence [1]. SWs, in turn, are responsible for the formation of lattice resonances (LRs) due to cooperative phenomena of interactions with MS lattices. Generation of LRs is enhanced, when MS lattice constants become comparable with incident wavelengths that marks approaching Rayleigh anomalies (RAs). Analysis of field patterns in infinite periodic dielectric MSs [2] allowed us to reveal accumulation of scattered SWs in inter-resonator gaps at LR formation. In this work, we investigate LRs and dipolar resonances in fragments of MSs composed of ceramic resonators. We have earlier shown that responses of MSs in microwave range can be reproduced in details in optical range by using scaled MSs composed of silicon nano-resonators [3].

II. LR FORMATION IN INFINITE MSS WITH SQUARE AND RECTANGULAR LATTICES

MSs under study were composed of disk resonators with relative permittivity of 37.2, diameter of 6 mm, and height of 3 mm. Incident plane wave was normal to MS planes (XY-planes), with electric field E directed along X-axis. In the simulation models, fragmented MSs comprising finite numbers of disks were inserted in empty computational domains terminated by perfectly matching boundaries. These models represented the infinity of free-space around MS fragments. For simulating infinitely periodic MSs, a conventional single unit cell model with periodic boundary conditions applied at XZ and YZ faces of the cell was employed. Figure 1(a) shows that electric dipolar resonance (EDR) responses in infinite MSs with square lattices experience red-shifting at increasing lattice constants L above 27 mm and then follow the curve, asymptotically approaching RA line ($L = \lambda$). It can be noticed in Figure 1 that the strength of EDR responses decreases after the turn of their spectral line. Similar changes are seen at increasing Ly in MSs with rectangular lattices. Figure 1(b) illustrates as red-shifting of EDR responses, so decreasing of the strengths of probe signals in resonator centers with increasing lattice constant. On the contrary, probe signals in X-oriented gaps between resonators demonstrate an increase of field intensity at increasing Ly, at similar red-shifting as that of signals from probes in resonator centers. This result points out at interplay between EDR and LR formation. Taking into account the fact that EDRs are associated with the formation of X-directed electric dipoles in DR centers, maximal radiation from dipoles is expected in Y-direction. Correspondingly, SWs should propagate along Y-axis and scatter by X-oriented resonator rows. Interplay between EDR and LR fields can be responsible for increasing the wavelengths of combined resonances in MSs at increasing Ly.

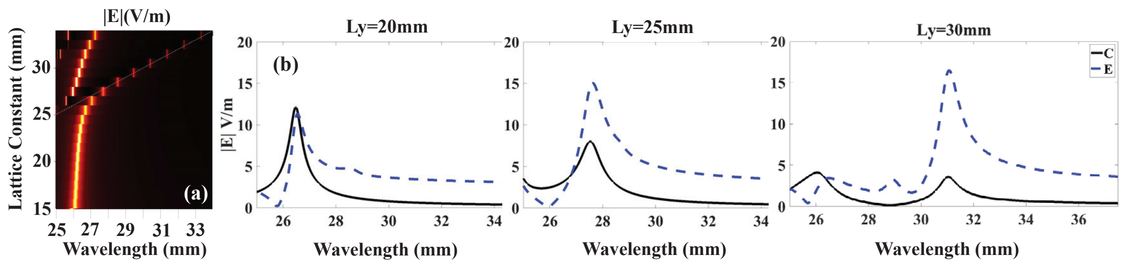

Fig. 1. Effects of increasing lattice constants on the spectra of EDR responses in infinite MSs modeled by using periodic boundary conditions: (a) signal spectra from probes located in DR centers of MSs with square lattices; (b) signal spectra from probes located in MSs with rectangular lattices, when Lx was kept equal to 10 mm while Ly was changed from 20 mm to 25 mm and to 30 mm. Solid curves: probes placed in DR centers, dashed curves: probes placed in X-oriented gaps nearby one of DRs to represent LR formation

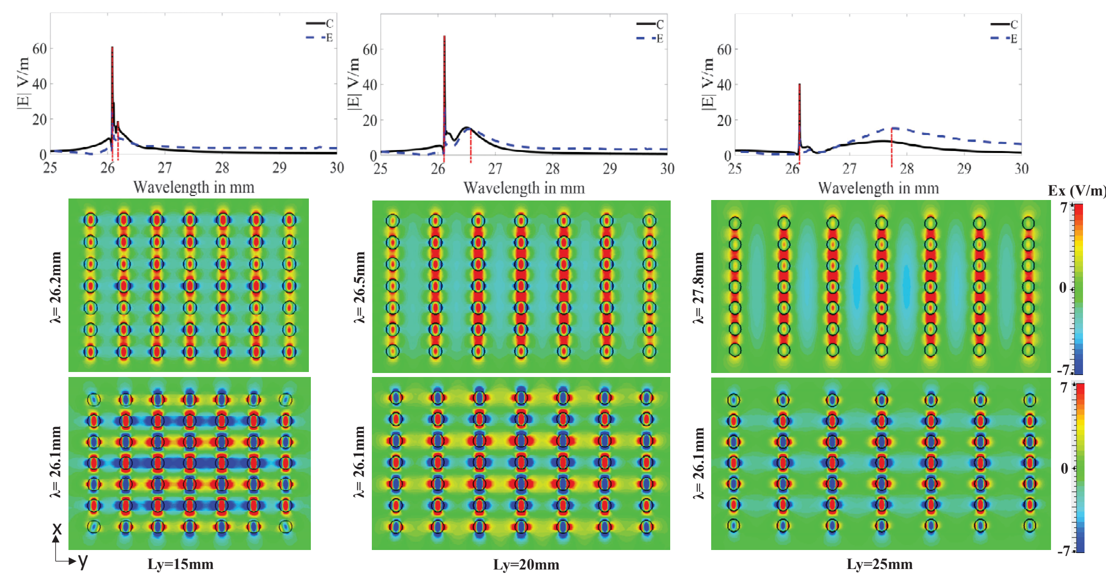

Fig. 2. Resonance responses in fragments of MSs with rectangular lattices incorporating 7 × 7 resonators; Lx = 10 mm and Ly is varied: (left column) 15 mm, (middle column) 20 mm, and (right column) 25 mm. Upper row: Spectra of signals from E-field probes placed (C) in the center of central resonator in fragments (solid curves) and (E) near the central resonator in X-oriented gap between resonators (dashed curves). Lower row: E-field patterns in median XY-cross-sections of MS fragments at wavelengths, which are marked in probe signal spectra.

III. Specifics of LRs in Fragmented MSs with Rectangular Lattices

The studies of the specifics MS fragments present an interest, because experiments are always performed for the samples of finite size. Figures 2(a)-(c) show probe signal spectra and field patterns observed in median cross-sections of MSs composed of 7 × 7 resonators at various Ly. As seen from probe signal spectra, MS fragments support EDR resonances exactly at the same wavelength, at which they appeared in infinite MSs at small lattice constants (and which is similar to resonance wavelength of single resonator), however, both the strengths and Q-factors of these resonances are very high and could be additionally increased at incorporating more resonators in MS fragment. For example, fragments composed of 9 × 9 or 11 × 11 resonators were found to have the strength of resonance responses increased up to 2 times compared to that of 7 × 7 fragments. Field patterns in median cross-sections of MSs show that high-Q responses are related exclusively to the formation of odd resonance modes. At small Ly, even modes are observed almost at the same wavelengths as odd modes, however at increasing Ly, they exhibit red-shifting, similar to that observed in infinite MSs. As in infinite MSs, this shifting is apparently the result of LR formation. Thus, in fragmented MSs, we observe two resonance modes, one being a high-Q odd mode and another one-an even mode, which is pretty similar to that observed in infinite MSs. There is a question, why odd-mode resonances demonstrate no signs of LR appearance. From our point of view, this is the result of destructive interference of waves radiated by dielectric disks resonating out of phase. Therefore, the intensity of LRs disappear at the wavelength corresponding to the original EDR excitation. These circumstances should support an increase of Q-factors at odd-type resonances.

IV. Conclusions

We show that fragmenting dielectric MSs does not deteriorate the formation of lattice resonances and related red shifting of even dipolar resonance modes. The new peculiarity, not observed in infinite MSs, is appearance of additional odd resonance modes with extremely high intensity and Q-factors. The revealed variety of resonance responses from MS fragments can extend the opportunities for their applications in sensing, imaging, and absorption.

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