Electromagnetically induced transparency and lattice resonances in metasurfaces composed of silicon nanocylinders

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Abstract

Densely packed metasurfaces composed of cylindrical silicon nano-resonators were found to demonstrate the phenomenon of electromagnetically induced transparency at electric dipolar resonances. It was shown that this phenomenon is not related to overlapping of dipolar resonances or to the Kerker's effects. The observed transparency appeared to be related to interference between waves scattered by nano-resonators and by additional scattering centers including the electric branch of lattice resonances. Coupled resonance fields were also found to contribute to observed phenomena.

1. Introduction

We have recently shown [1, 2] that electromagnetic responses of metasurfaces (MSs) composed of cylindrical silicon nano-resonators (NRs) drastically depend on the lattice constant characterizing the periodicity of these arrays. At fixed diameters of nano-resonators, chosen to be 240 nm, densely packed MSs with the lattice constant Δ of about 300 nm revealed strong interactions between neighboring NRs. On the contrary, in sparsely packed MSs with Δ = 450 nm, meta-atoms conserved autonomous behavior and remained unaffected by neighboring resonances.

From the analysis of recent literature devoted to studies of silicon MSs [3, 4] it could be concluded that most intriguing results, such as full transmission and 2π phase control at specific NR and MS geometries, providing for coincidence of electric (EDR) and magnetic (MDR) dipolar resonances, could be obtained only in densely packed MSs. However, varying resonator geometry in [3, 4] was accompanied by simultaneous varying of array lattice constant that complicated the interpretation of the results. Our studies of the influence of NR geometry on MS responses at fixed lattice constants did not confirm the benefits observed in [3, 4] at overlapping of EDR and MDR in NRs. In particular, spectral changes in waves scattered from MSs did not demonstrate effects, which could be related to π-value jumps in phases at two dipolar resonances and did not testify in favor of realizing the Kerker's condition at joint resonance frequency. In addition, we have found that full transmission through MSs at Δ = 300 nm could be obtained at various NR geometries, irrelevant to coincidence of the resonance frequencies of EDR and MDR. Here we present the results of investigation of this newly observed phenomenon.

2. Electromagnetically induced MS transparency

S-parameter spectra of MS with Δ = 275 nm, presented in Fig. 1, reveal narrowband full transmission at 633 nm. Sharp peak of S21 is accompanied by a deep drop of S11 that is typical for observation of electromagnetically induced transparency (EIT) in metamaterials [5]. Another S11 drop seen at 900 nm is defined by destructive interference of waves backscattered from red tails of EDR and MDR at the 1st Kerker's condition [6].

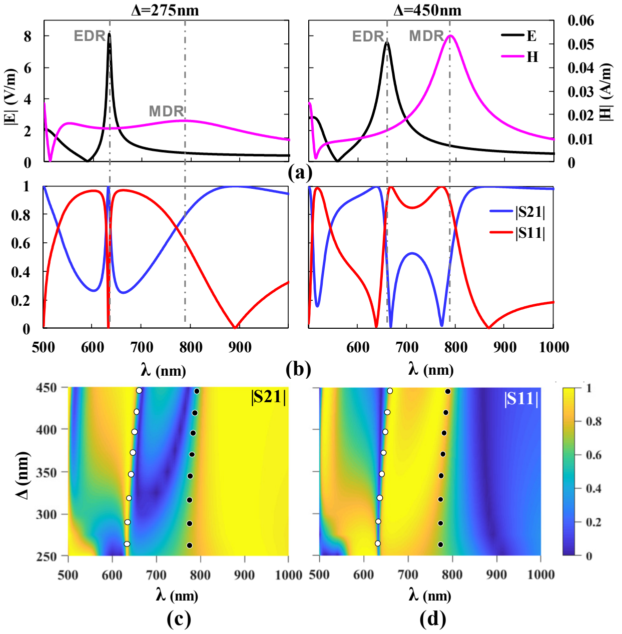

Fig. 1. (a) Spectra of signals from field probes in NRs of MSs with Δ=275nm and Δ=450nm at NR heights of 160 nm; (b) S-parameter spectra; (c) and (d) spectra of |S21| and |S11| coefficients in dependence on MS lattice constant.

As seen in Fig. 1, S-parameter spectra of MS at Δ = 450 nm also demonstrate similar Kerker's effect, however, near EDR, these spectra has nothing in common with EIT-like response of dense MS at 633 nm. Presented in Fig. 1c changes of spectral distributions of S21 values at varying MS lattice constants show that the bandwidth of EIT-like phenomenon becomes especially narrow at Δ less than 325 nm. At higher Δ, the bandwidth increases while S21 plot loses its symmetry. As seen in Fig. 1d, S11 spectra conserve deep drops at EDRs at increasing values of Δ up to 350 nm.

3. Bright and dark resonance modes

Although EIT has been originally detected in atomic systems at destructive interference of parallel electron transitions, it is now recognized as the phenomenon similar to that observed in metamaterials at interference between waves scattered from so-called bright resonance modes, coupled with incident waves, and from dark modes, participating due to coupling with bright modes. I was shown in [7] that EIT in metamaterials with electric dipole response could be described by using the two oscillator model. While EDRs in NRs could be considered as bright oscillators, to apply the model, dark oscillators should also be defined. Recently, it was shown [8] that EDRs in MSs can be coupled with so-called lattice resonances (LRs) originating from interaction of surface waves with the lattice. This coupling was assumed affecting the formation of EDRs and causing changes of EDR frequency at varying Δ, similar to our earlier observations [1].

Fig. 2a presents E-field pattern in the planar cross-section of dense MS at the EDR frequency and Fig. 2b - similar pattern at the frequency corresponding to zero signal in the spectrum of the probe placed at NR center (at point P1 in the inset of Fig. 2c). As seen in the figures, the pattern obtained at the EDR frequency demonstrates confined in resonators dipolar fields along with E-fields in the gaps between NRs in X-oriented rows of MS. The latter fields are apparently due to LRs interacting with EDRs in a wide range of Δ restricted only by the Rayleigh anomaly [8].

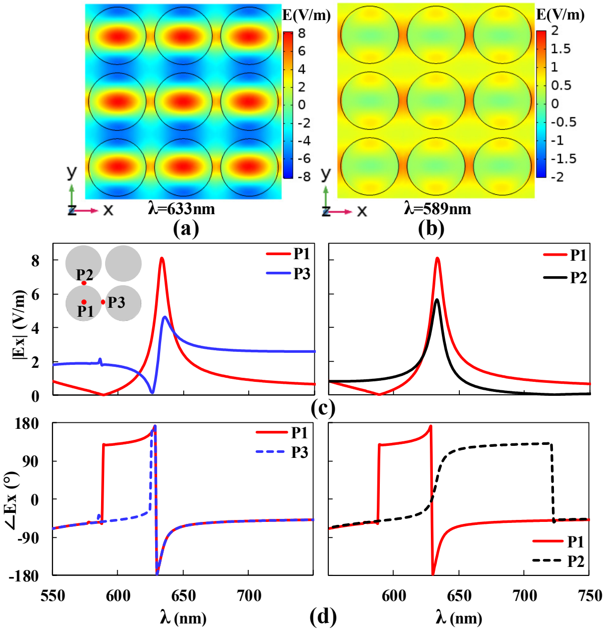

Fig. 2. (a) and (b) E-field patterns in XY cross-section of dense MS at EDR frequency (a) and at the frequency of zero probe signal at point P1(b); (c) spectra of probe signals in the points shown in the inset; (d) spectral changes of signal phases in points P1-P3.

It is interesting to note that LRs remain visible in the field patterns obtained at $\lambda<\lambda_{EDR}$ (Fig. 2b), when EDRs cannot be registered. Fig. 2c (left) shows that the probe signal in the point P3 centered in the area of LS responses has Fano shape. This fact is in favor of suggestion that LSs interfere with waves scattered from other sources. Fig. 2d (left) confirms the possibility of destructive interference between waves scattered by LSs and EDRs, as it demonstrates the π-value phase difference of probe signals characterizing responses of these resonances below the EDR frequency.

The field pattern presented in Fig. 2a allows for suggesting that additional involvement in the interference phenomena can be expected from dipolar-type fields concentrated in the gaps between resonators in Y-oriented columns of MSs. Presented in Fig. 2c (right) spectrum of signal from the probe placed in such gap (at point P2 shown in the inset of Figs. 2c) also has Fano shape, which looks as mirrored with respect to the shape of signal spectrum for the probe placed inside NR (at point P1). This specifics could be related to the π-value difference between phases of E-fields inside NRs and in the Y-oriented gaps that is illustrated by Fig. 2d. Such difference is capable of causing destructive interference between waves scattered in backward direction from NRs and from fields in the gaps.

4. Conclusion

Conducted studies have demonstrated an opportunity for realizing EIT-like phenomenon in dense silicon MSs and have identified centers of scattering capable of providing in destructive interference of waves backscattered from MS.

Acknowledgements

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