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Switchable supercavity modes in metasurfaces based on phase change materials

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Abstract. The paper considers a switchable high-index metasurface made of $Ge_2Sb_2Te_5$ compound. Varying the lattice spacing between the scatterers, we examined the fundamental dipole-type mode defining the metamaterial properties. At a certain lattice spacing, the structure has the reliable resonance in spectrum for the case of crystalline phase of $Ge_2Sb_2Te_5$, while the resonance in the case of amorphous phase degrades completely.

Keywords: bound states in the continuum (BIC), supercavity modes, metasurface, GST

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Материалы конференции
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Переключаемые суперрезонансные состояния в метаповерхностях на основе материалов с фазовой памятью

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Аннотация. Мы исследуем переключаемую высокоиндексную метаповерхность на основе соединения $Ge_2Sb_2Te_5$. Мы изменяем параметр решетки между рассеивателями и исследуем основную моду дипольного типа, определяющую метаматериальные свойства структуры. При определенном периоде решетки система поддерживает резонансное состояние для случая кристаллической фазы $Ge_2Sb_2Te_5$, тогда как в случае аморфной фазы резонанс полностью деградирует.

Ключевые слова: связанные состояния в континууме (ССК), суперрезонансные моды, метаповерхность, GST

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Introduction

The problem of electromagnetic waves confinement in small volume has a great applied potential for creating sensors, lasers, modulators, and other nonlinear devices. The study of high-quality (Q) resonance modes provides an opportunity to find a solution.

Recently, considerable attention has been paid to research of bound states in the continuum (BIC), which appeared to be perfect resonances with no radiation losses into free space [1]. It was established theoretically that no perfect resonances can exist in finite structures given that permittivity does not take extremal values. However, practical systems still allow for BIC-related supercavity modes with a high-Q factor limited by saturation due to size.

Metasurfaces made of high-index materials were reported to support BIC caused by Mie resonances arising in individual structural elements [2]. Many promising photonic devises require elements with switchable optical properties [3]. Composite phase transition materials based on the Ge-Sb-Te (GST) compound attract significant interest because of high modulation of dielectric index with non-volatile transition between crystalline and metastable amorphous phases. The most studied compound, $Ge_2Sb_2Te_5$, exhibits a change in dielectric permittivity from 15 (amorphous phase) to 35 (crystalline) in the infrared range [3]. Metamaterial properties are known to emerge in periodic systems when the dielectric index of structural elements reaches a certain critical value [4]. Thus, a GST-based structure might become a metasurface supporting BIC under the transition in the phase change material.

Results

We have previously studied metasurface-supported supercavity modes. The metasurface consists of silicon cylinders with a circular profile [5]. In this work, we consider a metasurface containing parallel composed of GST microblocks which have the width w = 300 μm, the height h = 300 μm and the lattice constant a = 750 μm (Fig. 1). The metasurface is shown in Fig. 1. We study TE polarized waves, that is, the electric field oscillates along the axis z. In contrast to cylindrical structural elements, allowing to describe the system analytically, metasurfaces made of $Ge_2Sb_2Te_5$ composite microblocks with a square profile represent a system with a more technologically accessible configuration for lithographic methods.

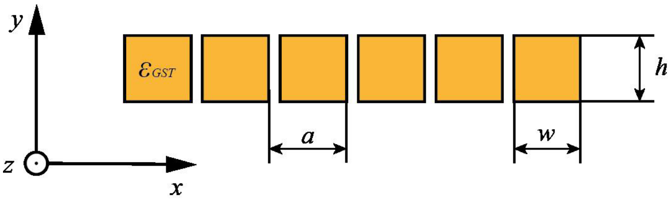

Fig. 1. Schematic view of GST metasurface composed of microblocks with rectangular profile

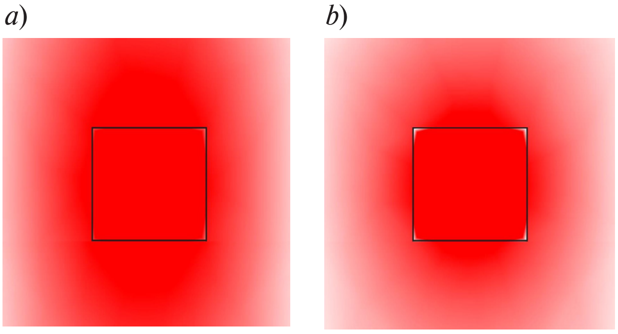

Fig. 2. Magnetic field distribution of the dipole type mode for amorphous GST phase (a) and crystalline GST phase (b). TE polarization, a = 1.75 mm, h = 500 μm, w = 500 μm

Here we consider a dipole-type mode supported by the structure. Fig. 2 compares magnetic field distribution for crystalline and amorphous GST microblocks which were simulated with COMSOL Multiphysics software. We assume that GST permittivity in the terahertz spectral range has no losses, $\varepsilon = 35$ in the crystalline phase and $\varepsilon = 15$ in the amorphous phase with no frequency dispersion. The block with a higher index exhibits stronger field localization, since the mode frequency is lower and near-field penetration into the outer space is linear to the wavelength in vacuum.

We analyze the reflection spectra of the metasurface whose properties are related to the dipole resonance sustained by each structural element, which is a GST microblock. Since the modes lie under the light cone, we shift half of the blocks by $a/20$ along the x direction. The spectra were simulated by means of rigorous coupled wave analysis (RCWA) involving over 100 plane waves in the x direction, which is sufficient for reliable convergence.

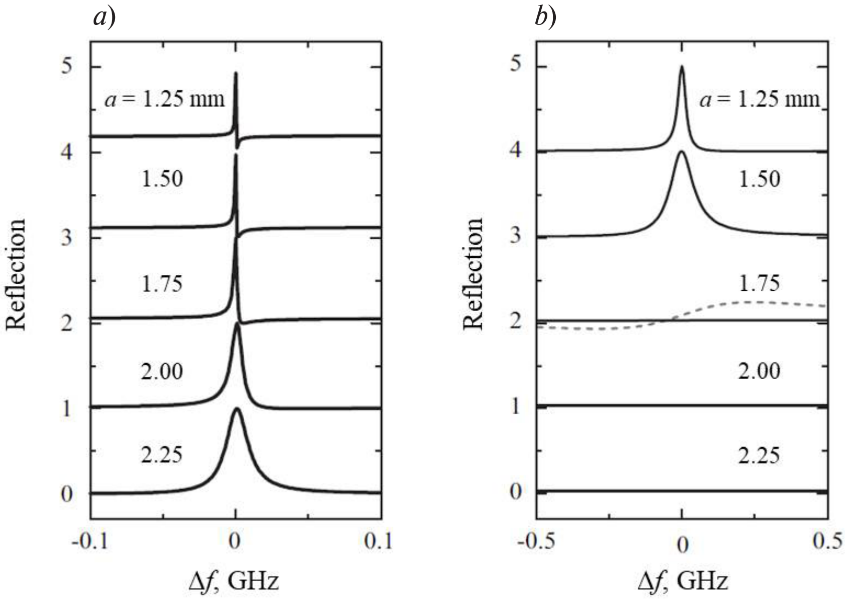

Fig. 3. Reflection spectra of GST-based metasurfaces as a function of lattice spacing: amorphous phase of GST (a) and crystalline phase of GST (*b*). The spectra are shifted along the vertical axis for convenience. The horizontal axis is the frequency detuning. The additional reflection spectra of the structure with $a = 1.75$ mm are shown in panel (*b*) at 50x magnification (dashed curve)

Fig. 3 shows the reflection spectra around the resonance depending on the lattice spacing a, while the sizes of microblocks are kept unchanged. The resonance position shifts to lower frequencies with an increase in lattice spacing (Fig. 4). For the case of crystalline GST, the dipole peak in reflection is clearly seen in the entire range of the lattice spacing from 1.25 to 2.25 mm. The quality factor of the mode decreases with a. The amorphous GST structure exhibits a different dependence. The dipole peak is observed in the structures with $a < 1.75$ mm and disappears for greater lattice spacings. At $a = 1.75$ mm, the resonance can be recognized with a 50x magnification. Thus, the structure ceases to be a metasurface operating due to dipole resonance.

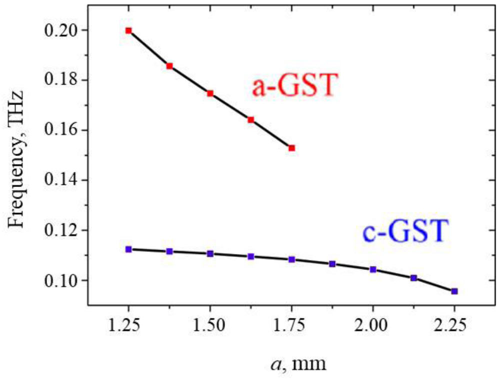

Fig. 4. Shift of the dipole resonance with a change in the lattice period for both amorphous and crystalline phases. The data was calculated with RCWA solver

When the distance between neighboring microblocks is small, a collective mode is formed and the structure acts as a metasurface. For large distances, the microblocks scatter the electromagnetic waves almost independently, so they cannot be regarded as a single system. Studies of a dimer [7] and especially photonic phase transitions to a metamaterial regime [4, 6] reveal that there exists a critical distance between the structural elements for a collective mode to form. Fig. 3, *b* shows that the collective dipole mode responsible for the metasurface regime exhibits rapid degradation when the distance approaches the critical distance about $a_{cr} \sim 1.75$ mm. In our structure, the critical distance increases with the dielectric permittivity of the scatterer similar to other systems [4, 6, 7] in spite of stronger localization of the electromagnetic fields in the structural elements. It is therefore possible to switch the system between metasurface and independent scatterer regimes by means of nonreversible transition of GST.

Conclusion

To summarize, we have demonstrated on/off switching for the metasurface regime. The switching is conditioned by amorphous-to-crystalline phase transition of $Ge_2Sb_2Te_5$. It is important for applications that this transition occurs fast and is nonreversible: that is, the structure does not return to its previous state for arbitrary time after switching. We have found that the chain of amorphous GST microblocks ceases to be a metasurface when the lattice spacing exceeds $a = 1.75$ mm, while crystalline GST microblocks allow for the metasurface regime at least for the lattice spacing $a = 2.5$ mm and larger.

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