Optical bistability involving planar metamaterials with broken structural symmetry

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We report on a bistable light transmission through a planar metamaterial composed of a metal pattern of weakly asymmetric elements placed on a nonlinear substrate. Such structure bears the Fano-type sharp resonance response of a trapped-mode excitation. The feedback required for bistability is provided by the coupling between the strong antiphased trapped-mode-resonance currents excited on the metal elements and the intensity of inner field in the nonlinear substrate.

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The optical transmission bistability is a phenomenon whereby a system changes its transmission from one value to another in response to properties of light passing through.[1] The switch between the two stable states of transmission is usually induced by the intensity of the incident light, and, luckily, the switch may exhibit a hysteresis. The light intensity driven systems must have an intrinsic nonlinear susceptibility and feedback to provide optical bistability. This effect can be used to realize all-optical switches, limiters, and logic gates. The issue of the day is to reduce the size of such all-optical devices, decrease their switching times and the required intensity of light.

Typically, all-optical devices include a Fabry-Perot resonator to provide feedback[2] although the systems without such resonator can be used too. An example of such structures is the nonlinear photonic crystal microresonators[3,4] and the devices based on the surface plasmon polaritons in metal nanostructures.[5,6] They offer a unique mechanism for confining light, giving rise to a combination of high-quality factors and small modal volumes that is helpful to stronger nonlinear effects and reduce the size of the all-optical devices.

There is another promising way to develop the small-size all-optical switching devices without electromagnetic cavities and surface plasmons field enhancement. Here the case in point is the planar metamaterials (also known as metafilms) with active constituents. Typically, these systems are surface structures which consist of some metal or dielectric resonance elements arranged as a periodic array and placed on a layer thin in comparison to the wavelength. One way to obtain the nonlinear response of a planar metamaterial is to introduce some nonlinear individual resonance elements in the structure (see, for instance, Ref. 7). Thus in Ref. 8, the elements are made nonlinear and tunable via the insertion of diodes with a voltage-controlled capacitance. However, in the optical range the manufacturing of such structures is associated with considerable technological difficulties. Another simpler way is to arrange the proper resonance elements on a nonlinear substrate.

The main feature of the planar metamaterials, essential for the optical switching applications, is a resonance character of their transmission and reflection spectra. The usual resonance field enhancement inside a planar metamaterial may be extremely enlarged by involving structures which bear so-called trapped or dark modes.[9,10] The excitation of high-quality-factor trapped mode resonances in planar double-

periodic structures with a broken symmetry was shown both theoretically[11,12] and experimentally[13] in microwaves. In particular, these typical peak-and-trough Fano spectral profile resonances are excited in the periodic structure consisted of asymmetrically split metal rings. A small asymmetry of the metal elements of such structure results in the excitation of the strong mode of antiphased currents, which provides low radiation losses and therefore high Q-factor resonances. Recently, the trapped mode resonances were investigated in similar planar structures in the near-IR range.[14] It was shown that the special choice of geometry parameters of the structure enables to increase the Q factor of the trapped mode resonance by several times in comparison with the ordinary plasmon-polariton resonance. Such high-Q resonance regime is promised to observe a bistability in the near-IR range, if the structure is to include a nonlinear material.

In this report, we propose and study an all-optical switching device based on the bistability in a planar metamaterial made of complex shaped resonance particles placed on a substrate of nonlinear material in the regime of a trapped mode excitation. The studied structure consists of the identical subwavelength metal inclusions in the form of asymmetrically split rings (ASRs) arranged in a periodic array and placed on a thin nonlinear dielectric substrate (see Fig. 1). Each ASR contains two identical strip elements opposite to one another. The right-hand split between the strips φ_1 is a little different from the left-hand one φ_2 so that the square
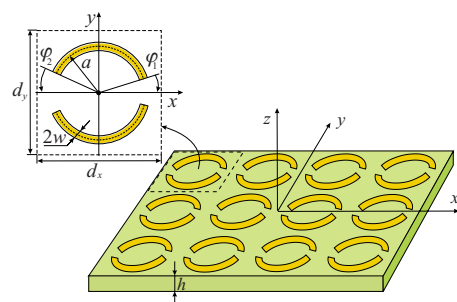

FIG. 1. (Color online) Fragment of the planar metamaterial and its elementary cell. The size of the square translation cell is $d=d_x=d_y=900$ nm. The asymmetrically split metal rings are placed on the top face of $h=0.1d$-thick nonlinear dielectric layer. The radius and the width of metal rings are $a=0.4d$ and $2w=0.06d$, respectively. The angle sizes of ring splits are $\varphi_1=15°$ and $\varphi_2=25°$.
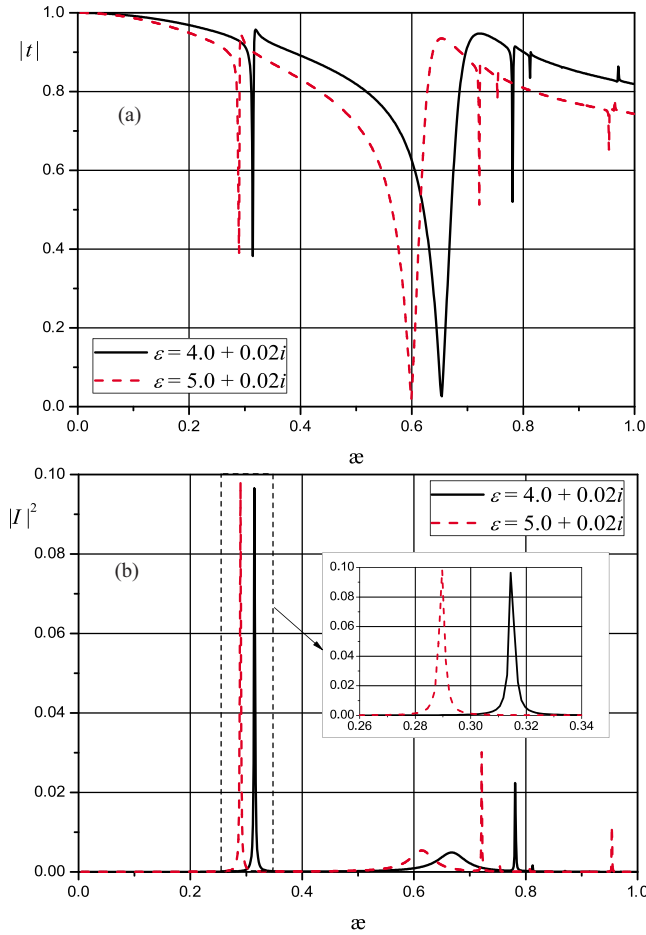
FIG. 2. (Color online) (a) The frequency dependences of the magnitude of the transmission coefficient and (b) the square of the current magnitude (a.u.) averaged along the metal pattern in the case of the linear permittivity ($\varepsilon_2=0$) of the substrate.
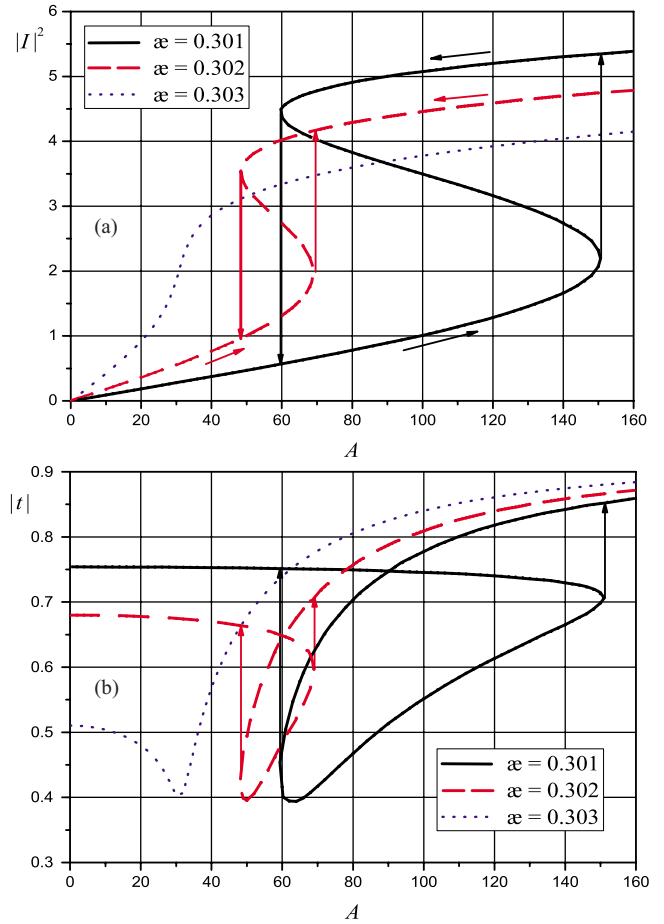

FIG. 3. (Color online) (a) The square of the current magnitude in a.u. averaged along split ring and (b) the magnitude of the transmission coefficient versus the incident field magnitude in the case of the nonlinear permittivity ($\varepsilon_1=4+0.02i$ and $\varepsilon_2=5\times10^{-3}$) of the substrate. The arrows indicate the bistable loop.

unit cell is asymmetric with regard to the y axis. A normally incident plane wave polarized transversely to the array symmetry axis (x axis) can excite the trapped mode resonances. Therefore we consider the structure excitation by y-polarized plane wave. Suppose, that the incident field has an amplitude A and a frequency ω.

As usual, actual optical array structures are mounted into a dielectric host or placed on a thick dielectric substrate. Two things happen with the trapped mode resonance frequency ω_0, when a dielectric substrate is added next to the structure. First, the resonant frequency ω_0 changes. If the structure is completely inside the dielectric material with relative dielectric constant ε_r, the resonant frequency will reduce in frequency with the factor $\sqrt{\varepsilon_r}$.[15] If the structure is placed between dielectric slabs of finite thickness, the resonant frequency will change to somewhere between ω_0 and $\omega_0/\sqrt{\varepsilon_r}$. And, at last, if we have a dielectric only to one side of the structure, the resonant frequency shifts downward to be near $\omega_0/\sqrt{(\varepsilon_r+1)/2}$. Second, the finite thickness of a practical substrate (of about 0.3–0.5 mm) results in the appearance of some additional interference resonances. However, as shown in Ref. 14, the trapped mode resonance can be easily separated against the interference resonances back-

ground. Thus the presence of the thick dielectric substrate has no effect on the trapped mode resonance qualitatively and we consider further a "free-standing" structure configuration of a metal array placed on a thin nonlinear substrate, in order to simplify explanation.

The algorithm based on the method of moments was proposed earlier[11] to study the resonance nature of the structure response, under the assumption of such a small amplitude A that the dependence of the substrate permittivity ε on the field intensity is infinitesimal. The algorithm requires that, at the first step, the surface current induced in the metal pattern by the field of the incident wave is to be calculated. The metal pattern is treated as a perfect conductor while the substrate is assumed to be a lossy dielectric. In particular, assuming $A=1$ v/m the magnitude of the current I averaged along the single element can be determined as a function

$$I = Q(\omega,\varepsilon). \qquad (1)$$

At the second step, the found surface current distribution is used to calculate the transmission and reflection coefficients as $t=t(\omega,\varepsilon)$ and $r=r(\omega,\varepsilon)$.
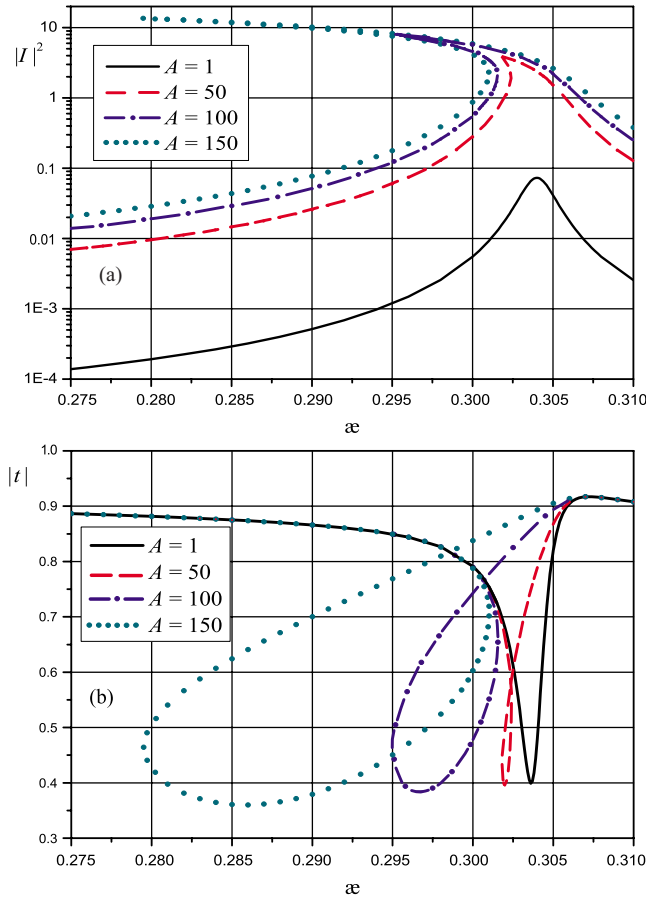
FIG. 4. (Color online) Frequency dependences of the square of (a) the current magnitude averaged along split ring (on the logarithmic scale) in a.u. and (b) the magnitude of the transmission coefficient in the case of the nonlinear permittivity ($\varepsilon_1 = 4 + 0.02i$ and $\varepsilon_2 = 5 \times 10^{-3}$) of the substrate.

To introduce the nonlinearity (the third-order Kerr effect), let us assume that the permittivity ε of the substrate depends on the intensity of the electromagnetic field inside it. In our approximate approach to the nonlinear problem solution, first assume that the inner intensity is directly proportional to the square of the current magnitude averaged over a metal pattern extent. Second, in view of the smallness of the translation cell of the array, we suppose that the nonlinear substrate remains to be a homogeneous dielectric slab under intensive light. Thus, the intensity-dependent permittivity of the substrate is given further as

$$\varepsilon = \varepsilon_1 + \varepsilon_2 |I|^2.$$

Note, since the substrate permittivity is proportional to the current value in the metal pattern, the nonlinearity effect reaches its maximum under the ASR resonance condition.

If the amplitude A of the incident field differs from the unity, the appropriate average current magnitude for a given ε can be found using Eq. (1) as

$$I = A \cdot Q(\omega, \varepsilon). \tag{2}$$

Since the substrate permittivity ε depends on the average

current value I, the relation in Eq. (2) can be rewritten as follows:

$$I = A \cdot Q(\omega, \varepsilon_1 + \varepsilon_2 |I|^2). \tag{3}$$

Expression (3) is a nonlinear equation related to the average current value in the metal pattern. The incident field magnitude is a parameter of the Eq. (3). At a fixed frequency ω, the solution of this equation is the average current value dependent on the magnitude of the incident field $I = I(A)$, where the function $I(A)$ is presumably multivalued.

On the basis of the current $I(A)$ found by a numerical solution of the Eq. (3), it is possible now to determine the permittivity of the nonlinear substrate $\varepsilon = \varepsilon_1 + \varepsilon_2 |I(A)|^2$ and to calculate the reflection and transmission coefficients

$$t = t(\omega, \varepsilon_1 + \varepsilon_2 |I(A)|^2), \quad r = r(\omega, \varepsilon_1 + \varepsilon_2 |I(A)|^2)$$

as the functions of the magnitude of the incident field.

At first we consider the transmission through the array of ASRs placed on a linear substrate (see Fig. 2).[12–14] If a normal incident wave is polarized in y direction, at the dimensionless frequency nearly $\text{æ} = d/\lambda \sim 0.3$, a sharp reflection resonance occurs. This resonance corresponds to the excitation of a trapped mode because equal and opposite directed currents in the two arcs of each complex particle of array radiate a little in free space. The resonance has a high-quality factor and the current magnitude reaches the maximum at this frequency. As the permittivity of the substrate increases, the resonance frequency shifts to low values. Note, if the incident field is x polarized or the splits between the strips are the same, only a symmetric current mode is excited. The corresponding resonance has a low quality factor and this configuration is not suitable to observe a bistability because the current magnitude is small at this frequency.

Suppose that the trapped mode resonance frequency is slightly higher than the incident field frequency. As the intensity of the incident field rises, the magnitude of currents on the metal elements increases. This leads to increasing the field strength inside the substrate and its permittivity as well. As a result, the frequency of the resonant mode decreases and shifts toward the frequency of incident wave, which, in turn, enhances further the coupling between the current modes and the inner field intensity in the nonlinear substrate. This positive feedback increases the slope of the rising edge of the transmission spectrum, as compared to the linear case. As the frequency extends beyond the resonant mode frequency, the inner field magnitude in the substrate decreases and the permittivity goes back toward its linear level, and this negative feedback keeps the resonant frequency close to the incident field frequency.

The curves in Fig. 3(a) are a plot of the square of the current magnitude averaged along ASR element versus the incident field magnitude at fixed frequencies. As an example, let us consider the incident field frequency $\text{æ} = 0.301$ (solid line). As the incident field amplitude increases, the current magnitude (and proportionally the inner field intensity) gradually increases along the bottom branch of the curve, until it reaches about $|I|^2 \approx 2$. At this point, the current magnitude jumps to around $|I|^2 \approx 5.5$ due to the instability of the system at the interior branch of the curve. This transition is

shown in the figure with an arrow directed upward. The incident field magnitude decreasing results in flowing the square of the current magnitude along the upper branch of the curve down to $|I|^2 \approx 4.5$, where it drops to a value of about $|I|^2 \approx 0.5$. Similarly, this transition is displayed as an arrow directed downward. The dramatic current variation from high to low level produces a switching from high to low transmission [see Fig. 3(b)].

The frequency dependence of the transmission coefficient magnitude manifests also some impressive discontinuous switches to different values of transmission, as the frequency increases and decreases in the resonance range for the sufficiently large intensity of the incident wave. The shifting of the peak of the resonance and the onset of a bistable transmittivity through the ASR structure is similar to that of the reflection from a Fabry-Perot cavity [Fig. 4(a)]. However, the trapped-mode resonance is Fano shaped[16] rather than the Lorentzian, as is the characteristic of one-dimensional Fabry-Perot cavities. This Fano resonance can lead to a peculiar transmission spectra and bistable behavior.[17] In particular,

the transmission resonance of the ASR structure may loop back on themselves [Fig. 4(b)]. Such a form of the hysteresis loop of transmittivity is similar to the behavior of the reflection spectra of a photonic crystal in the presence of a nonresonant downstream scattering source in microcavities;[17] where the Fano resonances arise due to the interference between two (or more) different scattering pathways. From the analogy between these two systems, it can be concluded that the peculiar bistable loop in the transmission is the result of a superposition of resonant and nonresonant contributions. In conclusion, a planar nonlinear metamaterial composed of a metal array placed on a nonlinear dielectric substrate, which bears a sharp resonance response by an excitation of a trapped mode due to a broken symmetry of the pattern is a challenging object for all-optical switching applications.

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