Enhancement of absorption bistability by trapping-light planar metamaterial

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Abstract
We propose to achieve a strong bistable response of a thin layer of a saturable absorption medium by involving a planar metamaterial specially designed to bear a high-$Q$ trapped-mode resonance in the infrared region.

Keywords: absorption, bistability, metamaterial, trapped mode

(Some figures may appear in colour only in the online journal)

1. Introduction

The effect of optical bistability (or multistability) is a basis of numerous applications such as optical switching, differential amplification, unidirectional transmission, power limiting, pulse shaping and optical digital data processing [1]. A common way to obtain optically bistable devices is by using a resonant cavity containing a Kerr-type or saturable absorption material whose complex refraction index depends on the input light intensity. In the first case, the dispersion bistability appears as a result of the nonlinear increasing or decreasing of the optical path length as the field intensity inside the resonator rises. In the second one, the dependence of power absorption of the material inside the cavity on the input field intensity leads to the saturable absorption bistability. In the present paper we mainly focus our attention on the latter phenomenon.

The mechanism of saturable absorption is related to the possibility of a material absorbing more than one photon before relaxing to the ground state. Also, two-photon and multiphoton absorptions are known under a sufficiently high light intensity. In addition, population redistribution induced by intense laser fields leads to the interaction of stimulated emission and absorption in complex molecular systems and the generation of free carriers in solids [2, 3]. These phenomena are manifested in both reduced (saturable) and increased (reverse saturable) optical absorption.

The basic principle of obtaining optical bistable switching consists in using a saturable absorber to detune a resonant cavity by variation of the input light intensity [1, 4]. At low intensity, the saturable absorber is characterized by high attenuation which detunes the cavity and, thereby, causes the cavity to reflect and absorb substantially all the incident wave power. At an intensity above a threshold level of the system, the attenuation decreases abruptly, and the cavity transmits substantially all the incident wave energy. As light intensity is decreased, the cavity continues to transmit light until a lower threshold level is reached, at which point the medium again becomes a high absorber and the cavity once again is detuned. The described process is characterized by a dependence between the input and output intensities in the form of a hysteresis loop.

The threshold levels and the total change in attenuation depend upon the kind of material. The key parameters for a saturable absorption material are its wavelength range (where it absorbs), its dynamic response (how fast it recovers), and its saturation intensity and fluence [5]. Semiconductor materials, combined with proper epitaxial growth and correct optical design of the structure, can achieve a broad range of desired properties for nearly ideal saturable absorber structures for all-solid-state lasers. Also, glasses doped by...
rare-earth elements or semiconductor quantum dots (QDs) have been proposed as saturable absorbers to obtain optical switching in the IR range [6, 7].

Typically, a saturable absorber is integrated inside a Fabry–Perot structure or an optical ring cavity [8, 9]. In further realizations, the intracavity saturation absorber is integrated into a more general mirror structure that allows for both saturable absorption and negative dispersion control, which is now generally referred to as semiconductor saturable absorber mirrors (SESAMs) [10]. In a general sense the design problem of SESAMs is reduced to the analysis of multilayered interference filters for a desired nonlinear reflectivity response. But, in any case, some resonant cavity is used to provide the field confinement and the nonlinear response enhancement.

A prospective way to reduce the cavity size and the input field intensity required for optical bistable switching lies in using plasmonic and metamaterial technologies [11]. It is known that the planar metamaterials can create an environment equivalent to a resonant cavity which allows us to achieve the required field confinement within a system to provide the nonlinear effect enhancement. To date there are a set of publications [12–18] where the properties of nonlinear metamaterials formed by integrating nonlinear components or materials into the metamaterial are studied both theoretically and experimentally. Typically, such structures are composed of metallic inclusions in the form of symmetrical split-ring resonators which are resonant because of an internal capacitance and inductance within each element. These elements are made nonlinear and tunable via the insertion of diodes with a voltage-controlled characteristic in the capacitive gaps of the metamaterial elements. To the best of our knowledge, in this way only a dispersion bistable response in the metamaterials is realized. A straightforward homogenization procedure is applied to describe such nonlinear systems as a composite medium with expression of its material properties via some effective parameters. It should be noted that the main drawbacks of such structures are the low quality factor of the resonances and considerable technological difficulties in their manufacturing in the optical range.

Hence, the metamaterials which are capable of supporting the trapped-mode resonant excitation [19–21] can be a successful alternative. The trapped-mode resonances appear in planar metamaterials designed on the basis of multiple-elt periodic arrays which typically consist of identical subwavelength metallic inclusions structured in the form of double-rings (DRs) [22] or asymmetrically split rings or squares [23, 24]. These particles are arranged periodically and placed on a thin dielectric substrate. The trapped-mode resonance is a result of the antiphase current oscillations in the particles of a periodic cell and they have a high quality factor due to the weak interaction with free space. The nonlinearity can be included in such a system in the form of a substrate made of some Kerr-type or saturable absorption nonlinear material.

This concept was recently confirmed experimentally in [25, 26], where the metamaterials which bear trapped-mode resonances were proposed to realize an enhancement of QD luminescence and electro-optic switching. The main advantage of the studied structures is the fact that a significant field enhancement is achieved in a thin planar system. Note that in these structures an active medium was used as a substrate of planar metamaterial. Also, in our previous publications [27, 28] the features of a dispersion bistable response of metamaterials with asymmetrical and symmetrical particles placed on a nonlinear substrate were studied. It is shown that the effect of nonlinearity appears as the formation of closed loops of bistable transmission within the frequency of the trapped-mode resonance due to the strong field localization in the system.

The goal of this paper is to show an enhancement of absorption bistability in a planar metamaterial which bears the trapped-mode resonances in sight to design the improved saturable absorption mirror. An array of metallic double-ring elements is chosen to construct the metamaterial due to the polarization insensitivity of this structure at the normal incidence of an exciting wave.

2. Problem statement and method of solution

The square unit cell of the structure under study has a size $d = d_x = d_y = 800$ nm and consists of one metallic DR (figure 1). The radii of the outer and inner rings are fixed at $a_1 = 290$ nm and $a_2 = 230$ nm, respectively. The width of both rings is $w = 40$ nm. The array is placed on a dielectric substrate with permittivity $\varepsilon$ and thickness $h = 150$ nm. Suppose that the normally incident plane monochromatic wave has a frequency $\omega$ and a magnitude $A$.

When the intensity of input light is small, i.e. in the linear regime, in order to calculate the optical response of the metamaterial, two different techniques based on the method of moments (MoM) [29] and the pseudo-spectral time-domain (PSTD) method [24] were proposed earlier. The MoM is a numerical–analytical method that involves solving an integral equation which is related to the surface currents induced on the metallic pattern by the incident electromagnetic wave,
then calculating the scattered fields produced by the currents as a superposition of partial spatial waves. In the framework of this method the metallic pattern is treated as a thin perfect conductor. On the other hand, the PSTD is a direct numerical scheme which uses a spatial spectral expansion of fields and the differentiation theorem for Fourier transforms to calculate the spatial derivatives. It is significant that the PSTD allows us to take into account the strong dissipation and dispersion of the metal permittivity of the elements. Nevertheless, in [24] it was revealed that the results obtained with both techniques are in good agreement with each other down to the mid-IR region where the trapped-mode resonances are still well observed and have a high Q factor.

So we restrict our study within this region and use the MoM because it allows us to calculate the magnitude of currents along the DR element since it is important to estimate the inner field magnitude inside the system. On the other hand, such a numerical–analytical treatment enables us to clearly understand the physics of the phenomena under investigation. Thus, by virtue of the MoM, the magnitude of the current $J$, the reflection $R$, transmission $T$ and absorption $W = 1 - |R|^2 - |T|^2$ coefficients can be determined numerically as functions of the frequency and permittivity of the substrate and presented in the symbolic form

$$u = F_u(\omega, \varepsilon),$$

where $u = J, R, T$, or $W$.

Next we should note that, at the trapped-mode resonance, due to the specific current distribution on the metallic pattern, the electromagnetic energy is symmetrically confined to a very small region between two half-arcs of the rings, where the energy density reaches substantially high values. The latter feature allows us to construct approximate model based on the transmission line theory to estimate the inner field intensity caused by rings [28]. According to this theory, in each unit cell, the DR is symmetrically divided into two parts where the half-arc of the inner and outer conductive rings are considered as two wires with a distance $b = a_1 - a_2 - 2w$ between them. Along these wires the currents with equal magnitude flow in opposite directions. Thus, the electric field strength is defined as

$$E_{in} = V/b = ZJ/b,$$

where $V$ is the line voltage, $J$ is the magnitude of current induced in the DR element and $Z$ is the impedance of the line. The impedance is determined at the resonant frequency $\omega_0 = d/\lambda_0$ as

$$Z = \frac{60\pi\varepsilon_0}{dC_0},$$

where $l = \pi(a_1 + a_2)/2$ and

$$C_0 = \frac{1}{4} \ln \left[ \frac{p}{2w} + \sqrt{\frac{p}{2w}} - 1 \right]$$

is the capacity in free space per unit length of the line, $p = a_1 - a_2$. In view of the small size of the translation cell of the array in comparison with the wavelength, we suppose that the nonlinear substrate remains a homogeneous dielectric slab under intense light. Thus, from this model it is possible to evaluate the relation between the inner electric field strength and the current magnitude $J$ averaged along one half-arc of the DR element.

Next, in the nonlinear regime, we suppose that the structure’s substrate is a material whose absorption property depends on the intensity of the electric field $I_n = (1/2)\varepsilon_0\varepsilon_0^*|E_{in}|^2$ inside it. Here the complex refractive index $n = \sqrt{\varepsilon}$ of the substrate is defined in the form [30]

$$n = n' + in'' = n' + \frac{i}{2\omega} \alpha,$$

where $\alpha$ is an absorption index. Thus, the permittivity $\varepsilon$ of the substrate can be found as a function of $\alpha$, $\varepsilon = \varepsilon(\alpha)$.

As a saturable absorbing material for the structure’s substrate we consider chalcogenide glasses doped with quantum dots of other elements such as Ge, As and Sb due to their wide availability for the mid-IR range [6, 7]. It is known that systems based on quantum dots have discrete energy levels. To describe the effects of saturation in such systems a two-level model is widely used. Further, the simple two-level model is developed in three directions. The first direction consists in use of the three- and four-level models, which is important in studying the process of creating a population inversion in lasers. The second direction of the model development is taking into account the inhomogeneous broadening of spectral lines due to the fact that every quantum structure element (molecule, ion, quantum dot, etc) is in the fields of its neighbors, which may be different. Finally the third direction is considering the dynamic Stark shift of the energy levels of molecules under the action of light. As usual, the two-level model is preferable when studying bistable devices because in many cases it gives good agreement with experiments [6, 7], and due to its simplicity.

Thus, to describe the dependence of permittivity $\varepsilon$ on the absorption index $\alpha$ we use a two-level model of a fast relaxing absorber whose absorption index $\alpha$ is described by the formulae [31]

$$\alpha(\omega, I_n) = \frac{0.25\omega_0^2}{(\omega - \omega_0)^2 + 0.25\gamma^2(1 + I_n/I_{sat})},$$

where $\omega_0$ is the weak-field absorption index, $\gamma$ is the weak-field absorption line broadening, $I_{sat}$ is the saturation intensity and $\omega_0$ is the frequency of the center of the spectral absorption line. The absorption curve defined by equation (4) has a Lorentzian shape, and when $I_n = I_{sat}$ the absorption index is reduced to half of the peak of the absorption line. Here the terms describing the dynamic Stark shift are discarded under an assumption that the effect of the dynamic Stark shift occurs under light intensities much larger than those required for saturation of absorption [31]. The absorption line broadening depends on the inner field intensity as $\gamma/\sqrt{1 + I_n/I_{sat}}$. In the center of the spectral line, the absorption index is $\alpha(\omega_0, I_n) = \alpha(0)/(1 + I_n/I_{sat})$, whereas on the distant sides of the absorption line, $\omega - \omega_0 \gg \gamma$, the value of $\alpha(\omega, I_n)$ is practically the same as $\alpha(\omega, 0)$, i.e. under a certain intensity level, the most pronounced decreasing of absorption is reached in the center of the
line. Hence it follows that the best way to obtain strong interaction of the metamaterial with a nonlinear substrate lies in tuning the trapped-mode resonant frequency to the frequency of the center of the spectral line of a saturable material. This fact is also proved with experimental results of the QD’s luminescence enhancement in the plasmonic metamaterial [25].

As the absorption index $\alpha$ is a function of the inner field intensity $I_{\text{in}}$, so, too, is the permittivity of the substrate, $\varepsilon = \varepsilon(I_{\text{in}})$. According to equation (2), the inner field intensity is a function of the averaged current magnitude, $I_{\text{in}} = I_{\text{in}}(\bar{J})$. Thus, the nonlinear equation on the averaged current magnitude in the metallic pattern can be obtained in the form [27]

$$\bar{J} = \hat{A}F_2(\omega, \varepsilon(I_{\text{in}}(\bar{J}))),$$

(5)

where $\hat{A}$ is a dimensionless coefficient which depicts how many times the incident field magnitude $A$ is greater than 1 V cm$^{-1}$. Thus, the magnitude $A$ is a parameter of equation (5), and, at a fixed frequency $\omega$, the solution of this equation is the average current magnitude $\bar{J}$ which depends on the magnitude of the incident field ($\bar{J} = \bar{J}(A)$).

Further, on the basis of the current $\bar{J}(A)$ found by a numerical solution of equation (5), the permittivity of the nonlinear substrate $\varepsilon = \varepsilon(I_{\text{in}}(A))$ is obtained and the reflection, transmission and absorption coefficients are calculated as functions of the frequency and magnitude of the incident field.

### 3. Numerical results and discussion

Typical frequency dependences of the current magnitude, reflection, transmission and absorption coefficients calculated in the linear regime under the assumption of a nondispersive substrate with the method of moments are given in figure 2. One can see that a sharp resonance appears in the band where the maximum of current magnitude occurs. At this frequency band, the induced currents in the inner and outer rings oscillate in opposite directions. An electromagnetic field of two closed strips of the rings is similar to the nonradiating field of a double-wire line of resonant length. Thus, the oppositely directed but almost equal currents of the inner and outer rings of the array yield an electromagnetically trapped mode. The scattered field produced by such a configuration of current is very weak in comparison with an intensity of the stored field and, as a consequence, the coupling of the planar metamaterial to free space is small and, therefore, radiation losses are reduced, which ensures a high quality factor resonant response. Evidently, as the value of Joule losses in the metamaterial increases, the magnitude of current and quality factor of the resonance decrease but, nevertheless, the resonance remains to be well observed [32]. By this means, we suppose that, near the frequency of trapped-mode excitation, such a metamaterial will strongly react on the intense incident wave when the substrate is made of a nonlinear dielectric even in the case when the dielectric is dissipative. Also, in figure 2(b) (figure 2(c)), one can see the evolution of the approximately symmetric close to
Lorentzian profile of the transmission (reflection) resonance to an asymmetric Fano one [33–35] when the losses decrease, which is very suitable to realize abrupt switching in the nonlinear regime.

Thus, in the case of the array placed on the substrate whose complex permittivity depends on the field intensity, the dependences of the inner intensity versus the incident field magnitude in the case of the nonlinear permittivity of the substrate. For this and further calculations, we use the experimental results obtained in [6]. Thus, the saturation intensity is chosen to be \( I_{sat} = 60 \text{ kW cm}^{-2} \), which is typical for the phosphate glasses doped with 6 nm PbS QDs in the IR range. \( \gamma = \gamma_d/(2\pi c) = 1 \), \( n' = \sqrt{4/T} \). The dimensionless frequency \( \omega \) corresponds to the trapped-mode resonance and to the peak of the absorption line, \( \omega = \omega_0/(2\pi c) = 0.3 \).

\[ \text{Figure 3.} \] Dependences of the inner intensity versus the incident field magnitude in the case of the nonlinear permittivity of the substrate. For this and further calculations, we use the experimental results obtained in [6]. Thus, the saturation intensity is chosen to be \( I_{sat} = 60 \text{ kW cm}^{-2} \), which is typical for the phosphate glasses doped with 6 nm PbS QDs in the IR range. \( \gamma = \gamma_d/(2\pi c) = 1 \), \( n' = \sqrt{4/T} \). The dimensionless frequency \( \omega \) corresponds to the trapped-mode resonance and to the peak of the absorption line, \( \omega = \omega_0/(2\pi c) = 0.3 \).

peculiarity is that the resonance in the Fabry–Perot cavity has the Lorentzian-shape whereas the trapped-mode resonance in the DR-structure has the Fano-shape and the latter one is characterized by an asymmetrical peak-and-trough profile.

From the classical point of view [33], the resonant conditions of the studied structure can be described using two weakly coupled harmonic oscillators, where one of them is driven by a periodic force (see, for an example, figure 2(a) in [34]). In such a system, in general, the spectrum of the forced oscillator consists of two resonances, and while the first resonance is characterized by a symmetric profile, described by a Lorentzian function, the second one is characterized by an asymmetrical Fano profile. At a certain frequency, the amplitude of the forced oscillator becomes zero, as a result of destructive interference of oscillations from the driving force and coupled oscillator.

In our case, the different current distributions in the metallic pattern lead to the appearance of similar resonant conditions (figure 2(b)). Thus, the resonant feature I is a result of resonant excitation of a predominantly dipole mode (i.e. current oscillations symmetric with respect to the symmetry axis of DR) in either the outer or inner ring and this resonance is described by a Lorentzian function. At feature II, both rings are excited equally, while the induced currents in the inner and outer rings oscillate in opposite phases, yielding an electromagnetically trapped mode [22, 32] whose resonance has an asymmetrical profile.

Such an asymmetrical spectral profile of the transmission coefficient which varies from low to high over a very narrow frequency range can be very useful in all-optical switchings since there are gently sloping bands of the high reflection and transmission before and after the resonant frequency [34, 35]. This peculiarity of spectra manifests itself in the stepwise variation of magnitudes of reflection, transmission and absorption coefficients calculated versus the incident field amplitude (figure 4). These figures also illustrate another effect of the shape asymmetry of the trapped-mode resonance, namely the formation of the hysteresis with closed loops in the curves of both reflection and absorption coefficients (figure 4(b)). In particular, a closed loop appears when the level of reflection (absorption) before the threshold amplitude is greater than that one after it. Thus when the hysteresis is formed, the part of the curve that corresponds to the rising edge remains above the part of the curve that corresponds to the falling edge.

4. Conclusions

In conclusion, a planar nonlinear DR metamaterial, which bears a high quality factor Fano-shape trapped-mode resonance is a promising object for the realization of a polarization-insensitive absorption bistable switching. The main advantage of the studied structure is the possibility to achieve the bistable transmission at low input intensity, due to a large quality factor of the trapped-mode resonance.
Figure 4. Dependences of the magnitudes of the reflection, transmission and absorption coefficients versus the incident field amplitude for different absorption index $\alpha_0$ in the case of the nonlinear permittivity of the substrate: $J_{sat} = 60 \text{ kV cm}^{-2}$, $\gamma = yd/(2\pi c) = 1$, $n' = \sqrt{\mathcal{T}}$, and $x = x_0 = 0.3$.

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