Bistable transmission of nonlinear planar metamaterial with high structural symmetry via trapped-mode excitation

S. L. Prosvirnin[1,2] and V. R. Tuz[1,2]

[1]Institute of Radio Astronomy, National Academy of Sciences of Ukraine
4, Krasnoznamennaya st., Kharkiv 61002, Ukraine; email: prosvirn@rian.kharkov.ua
[2]School of Radio Physics, Karazin Kharkiv National University
4, Svobody Square, Kharkiv 61077, Ukraine; email: vladimir.r.tuz@univer.kharkov.ua

Abstract

We argue the possibility of realization of a polarization insensitive all-optical switching in a planar metamaterial composed of a 4-fold periodic array of two concentric metal rings placed on a substrate of nonlinear material. It is demonstrated that the switching may be achieved between essentially different values of transmission nearly the frequency of the high-quality-factor Fano-shape trapped-mode resonance excitation.

1. Introduction

Considerable recent attention has been focussed on the phenomena of optical bistability due to the possibility of its practical application to completely optical logic circuits, switches, limiters, optical transistors and diodes. In passive bistable devices, the nonlinear medium is placed inside some optical cavity, and control of operating conditions of the light propagation is provided with light [1].

The issue of the day is to reduce the size of such optical devices, decrease their switching times and the required intensity of light. To do that, photonic crystal microcavities, plasmonic and quantum well structures were proposed to enhance the nonlinear effects as well as to reduce the material volume. In all these cases, the excitation of high-quality-factor resonances in the systems is provided to obtain efficient switching. Exceptionally strong and narrow resonances are also possible to obtain in planar metamaterials designed on the basis of multi-element periodic arrays via engaging trapped-modes [2]. In the regime of quasi-trapped-mode excitation of an actual structure, the field is strongly localized to the structure plane and the resonant transmission and reflection have a large quality factor due to very small radiation of electromagnetic energy in a comparison with stored one.

Typically, metamaterials which can bear trapped-modes consist of identical subwavelength metallic inclusions structured in the form of asymmetrically split rings [2, 3] or split squares [4]. These elements are arranged periodically and placed on a thin dielectric substrate. The characteristic feature of such metamaterials is the dependence of their spectra on the polarization and the angle of incidence of input wave. In [5, 6, 7], the polarization and incidence direction insensitive structures were also proposed. One of such structures consists of a planar array which periodic cell element consists of two concentric rings (double-ring (DR) structure). Remarkably, at the trapped-mode resonance in the DR structure the electromagnetic energy is confined to a very small region between the rings, where the energy density reaches substantially high values. It provides the response of the metamaterial operating in the trapped-mode regime extremely sensitive to the dielectric properties of the substrate. This feature can be used for enhancing optical nonlinearity response in the nanoscaled version of the metamaterial [8].

ISBN 978-952-67611-0-7

In this paper we argue the possibility of realization of a polarization insensitive bistable device on the basis of a metamaterial which consists of double-ring array placed on a substrate of nonlinear dielectric in the regime of trapped-mode excitation.

2. Problem statement and solution

The square unit cell of the structure under study has a size $d = d_x = d_y = 800$ nm and consists of one DR (Fig. 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 the both metal rings is $2w = 40$ nm. The array is placed on a dielectric substrate with thickness $h = 150$ nm and permittivity ε. Suppose that the normally incident field is a plane monochromatic wave of a frequency ω and an amplitude A.

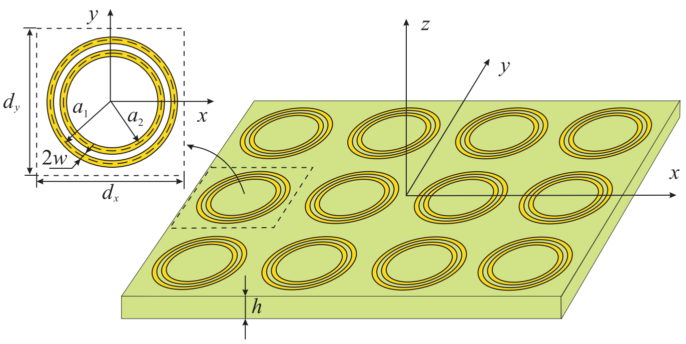

Fig. 1: Fragment of the planar metamaterial and its elementary unit cell.

In the linear case the optical response of the metamaterial under study is calculated using the well established method of moments [9]. This numerical method involves solving an integral equation on the surface current induced in the metallic pattern by the incident electromagnetic wave, then calculating the scattered fields produced by the current as a superposition of partial spatial waves. The metallic pattern is treated as a very thin perfect conductor which is acceptable for most metals in the mid-IR region. As a result, the magnitude of the current J along the single DR element, the reflection r and transmission t coefficients can be determined in the form $J = J(\omega, \varepsilon)$, $t = t(\omega, \varepsilon)$, and $r = r(\omega, \varepsilon)$, respectively.

Next we suppose that the structure substrate is a Kerr nonlinear dielectric which permittivity ε depends on the average intensity of electric field I_{in} inside it. As mentioned above, at the trapped-mode resonance, electromagnetic energy is confined to a very small region between the rings and the crucial affect of the permittivity on the system properties occurs in this place. Therefore, the approximation based on the transmission line theory can be used here to estimate the field intensity between the rings. According to this theory, conductive rings are considered as two wires with a distance $b = a_1 - a_2 - 2w$ between them. Thus the electric field strength is defined as $E_{in} = V/b$, where $V = Z_0 J$ is the line voltage, J is the current magnitude, and Z_0 is the impedance of line. The impedance is determined at the resonant frequency $æ_0 = d/\lambda_0$, $Z_0 = 60 l æ_0/dC_0$, where $l = \pi(a_1 + a_2)/2$, and $C_0 = \ln[p/2w + \sqrt{(p/2w)^2 - 1}]/4$ is the capacity per unit length of line, $p = a_1 - a_2$.

From this model it follows that the electric field strength between the rings is directly proportional to the current magnitude J. Thus, the nonlinear equation on the current magnitude in the metallic pattern is obtained in the form $J = A \cdot J(\omega, \varepsilon_1 + \varepsilon_2 I_{in}(J))$. The incident field magnitude A is a parameter of this equation. At a fixed frequency ω, the solution of this equation is the current value which is dependent on the magnitude of the incident field, $J = J(A)$. After a numerical solution of the nonlinear equation, the permittivity of the nonlinear substrate $\varepsilon = \varepsilon_1 + \varepsilon_2 I_{in}(A)$ is determined and the reflection and transmission coefficients versus the frequency and magnitude of the incident field are calculated.

In the case of the nonlinear permittivity of substrate, the transmission coefficient magnitude versus the incident field magnitude has the form of hysteresis (Fig. 2a). At a certain intensity of the incident field, the transmission coefficient changes stepwise its value from small to large level. The frequency dependences of the transmission coefficient magnitude also manifest discontinuous switching from small to

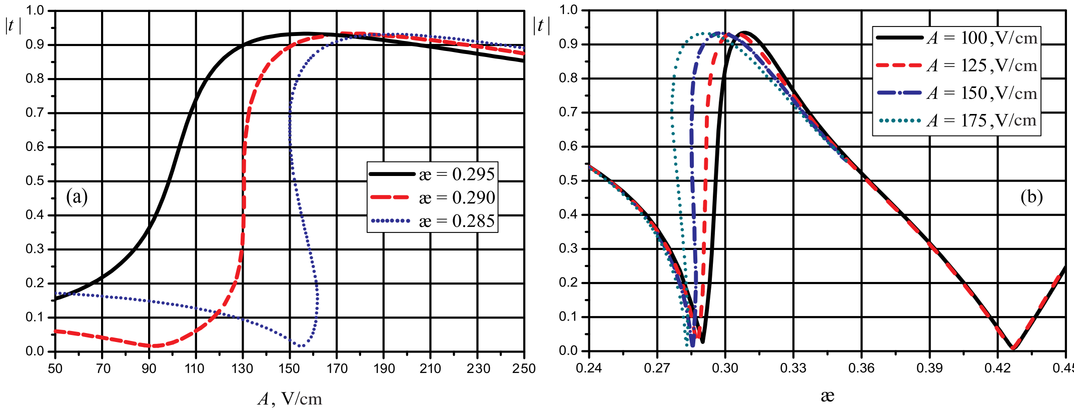

Fig. 2: Transmission coefficient versus the incident field magnitude (a) and frequency (b) ($\varepsilon_1 = 4.1 + 0.02i$ and $\varepsilon_2 = 5 \times 10^{-3}$ cm^2/kW)

large level with frequency increasing/decreasing (Fig. 2b). This switching appears closely to the resonant frequency of the trapped-mode excitation. The main peculiarity is that the trapped-mode resonance in DR-structure has the Fano-shape. This form of resonance appears in the presence of the interference between a high-quality resonance and a much smoother, continuum-like spectrum and it typically exhibits a sharp asymmetric line shape with the transmission coefficients varying from 0 to 1 over a very narrow frequency range. The resonance of such kind is very suitable to obtain great amplitude of switching since there are gently sloping bands of the high reflection and transmission before and after the resonant frequency.

In conclusion, a planar DR nonlinear metamaterial, which bears a high-quality-factor Fano-shape trapped-mode resonance is promising object for a realization of a polarization insensitive all-optical switching.

This work was supported by the National Academy of Sciences of Ukraine under the Program Nanotechnologies and Nanomaterials, the Project no. 1.1.3.17.

References

[1] H.M. Gibbs, *Optical Bistability: Controlling Light with Light,* Orlando, USA: Academic Press, 1985.

[2] S. Prosvirnin and S. Zouhdi, *Resonances of closed modes in thin arrays of complex particles,* in Advances in Electromagnetics of Complex Media and Metamaterials, edited by S. Zouhdi and M. Arsalane. Kluwer: pp. 281–290, 2003.

[3] V.A. Fedotov, M. Rose, S.L. Prosvirnin, N. Papasimakis, and N.I. Zheludev, Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry, *Phys. Rev. Lett.,* vol. 99, p. 147401, 2007.

[4] V.V. Khardikov, E.O. Iarko, and S.L. Prosvirnin, Trapping of light by metal arrays, *J. Opt.,* vol. 12, p. 045102, 2010.

[5] S. Prosvirnin, N. Papasimakis, V. Fedotov, S. Zouhdi, and N. Zheludev,*Trapped-mode resonances in planar metamaterials with high structural symmetry,* in Metamaterials and Plasmonics: Fundamentals, Modelling, Applications, edited by S. Zouhdi, A. Sihvola, and A.P. Vinogradov. Springer: pp. 201–208. 2009.

[6] N. Papasimakis, Y.H. Fu, V.A. Fedotov, S.L. Prosvirnin, D.P. Tsai, and N.I. Zheludev, Metamaterial with polarization and direction insensitive resonant transmission response mimicking electromagnetically induced transparency, *Appl. Phys. Lett.,* vol. 94, p. 211902, 2009.

[7] M.N. Kawakatsu, V.A. Dmitriev, and S.L. Prosvirnin, Microwave frequency selective surfaces with high Q-factor resonance and polarization insensitivity, *J. Electromag. Waves Appl.,* vol. 24, pp. 261–270, 2010.

[8] V.R. Tuz, S.L. Prosvirnin, and L.A. Kochetova, Optical bistability involving planar metamaterials with broken structural symmetry, *Phys. Rev. B,* vol. 82, p. 233402, 2010.

[9] S.L. Prosvirnin, Transformation of polarization when waves are reflected by a microstrip array made of complex-shaped elements, *J. Commun. Techn. Electron.,* vol. 44, no. 6, pp. 635–639, 1999.