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All optical SRR switch using carbon nanotube composite

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ABSTRACT

This paper presents a new design for all optical SRR metamaterial switch with carbon nanotube (CNT) composite as the nonlinear layer. Because of strong nonlinear effects of CNT composite layer, a low threshold power pump for switching is achieved. The possible fabrication of CNT composite besides the tunable applied frequency, are the main advantages of new designed structure.

1. Introduction

Metamaterials with unavailable optical properties in nature such as the negative refraction, have been studied extensively from optical to microwave frequency ranges [1]. They show a wide range of new applications such as sub wavelength image [2], slow light and cloaking [3]. In many cases, metallic resonators such as split ring resonators (SRRs) and fishnet structures are used to demonstrate the negative index metamaterial [4,5].

The design of all optical switches based on SRRs has attracted a great deal of attention in recent years, however only a limited number of materials have been used in their design and fabrication. For example, Chen et al. [6] have proposed a structure for terahertz electro optical switch based on SRRs and Gong et al. [7] have investigated theoretically an all optical absorption switch using an effective medium which its strong Kerr nonlinear effect has been discussed in [8].

Since their discovery in 1991 by Ijima [9], CNTs have found practical applications in several fields. It is well known that, materials with large third order optical nonlinearities are required for photonic applications including all optical switching, data processing, eye and sensor protection. Due to superior electrical and optical characteristics, the CNT structures and composites have been attracted by the researchers for using in electrical and optical devices [10–15]. Also the optical switching properties of CNT composites have been discussed in [16]. But all optical metamaterial switch structure based on the Kerr effect of CNT composite which is presented and discussed in this paper is a new idea which has not been introduced before.

The strong third order optical nonlinearity of CNT-paraffin composite provides it as a good candidate for nonlinear optical applications. CNTs have third order susceptibility (χ^3) dependent on the nanotube radius. In order to prevent the inter-band absorption and achieve a transparent region for the CNT composite, there is a low frequency limit where the incident photon energies satisfy the condition $\hbar\omega_i << \varepsilon_g$. For the case of CNT-paraffin composite, the imaginary part of $\chi^{(3)}$ is equal to zero and thus no inter-band absorption is occurred, whereas its real part is obtained about 10^{-7} esu [17]. This value is appropriate for practical applications in nonlinear optical devices.

In this paper, we introduce a novel structure for all optical SRR switch based on metamaterial which the CNT composite has been used as the nonlinear layer. For the three-dimensional simulation of switching performance we need to have the optical parameters of CNT composite layer. In [18], the permittivity dispersion of single wall CNT (SWCNT) has been calculated using some experimental results for the grapheme permittivity. Here we combine some methods to calculate theoretically the effective parameters from experimentally verified references. In addition, two kinds of nonlinear layer including CNT-paraffin and CNT-$BaTiO_3$ have been implemented and studied in the structure, which latter choice has a higher third order nonlinear susceptibility than former one [19]. So our work is a combination of several efforts such as the calculation of effective parameters for MWCNT and MWCNT composite, the structure design for an all optical switch and the simulation of switching performance.

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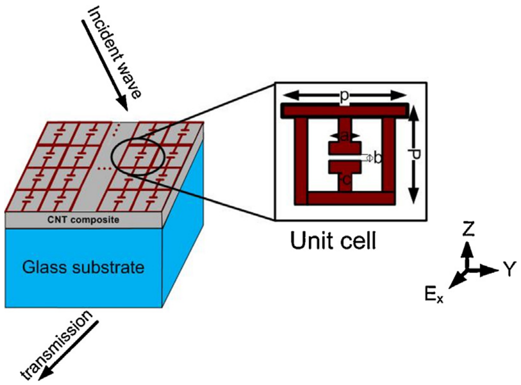

Fig. 1. The schematic of total structure and the related unit cell for the proposed all optical SRR switch, with $a = 10$, $b = 2$, $c = 4$ and $p = 50$ nm.

The paper is organized as follows: In Section 2, the proposed structure for the all optical SRR switch is introduced and discussed. Section 3 discusses about the effective optical parameters of CNT composite. Then in Section 4, the simulation results are presented. In this section, two cases for the nonlinear layer are considered: in one case, Paraffin has been used as the host media for the CNT composite, and in the other case, $BaTiO_3$ has been used. Finally in Section 5, the paper is concluded.

2. The proposed structure

Fig. 1 shows the schematic of total structure and the related unit cell for the proposed all optical SRR switch. The implemented unit cell in the structure is based on a recently presented electric analog to split ring resonators (SRRs) which consists of two single golden SRR put together on a split gap side [6–20]. In our proposed structure, this unit cell is placed on a CNT composite layer deposited on the glass substrate.

It should be noted that, the switch structure is illuminated from the top of it, as indicated in Fig. 1. The schematic of total structure and the related unit cell for the proposed all optical SRR switch, with $a = 10$, $b = 2$, $c = 4$ and $p = 50$ nm, and consequently the output wave as the switch response (transmission) will be obtained and detected by a detector placed under the switch structure.

Fig. 3 shows the equivalent circuit model for the split ring resonator (SRR) unit cell. A capacitor-like structure couples to the electric field and is connected in parallel with two loops, which each provides an inductance to the circuit model, as discussed in [21]. This configuration allows the electric field to drive the LC resonance providing both positive and negative electric polarizations at different frequencies along the resonance curve, where the phase of resonator response is in phase and out of phase with the driving field, respectively [20]. The two inductive loops are connected in parallel, so the equivalent inductance will be $L/2$. Now, the resonance frequency can be calculated as $\omega = \sqrt{2/(LC)}$. The resistance R in Fig. 2 models the dissipation in the golden split rings.

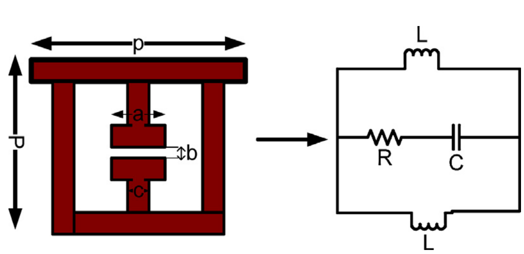

Fig. 2. The equivalent circuit model for the SRR unit cell.

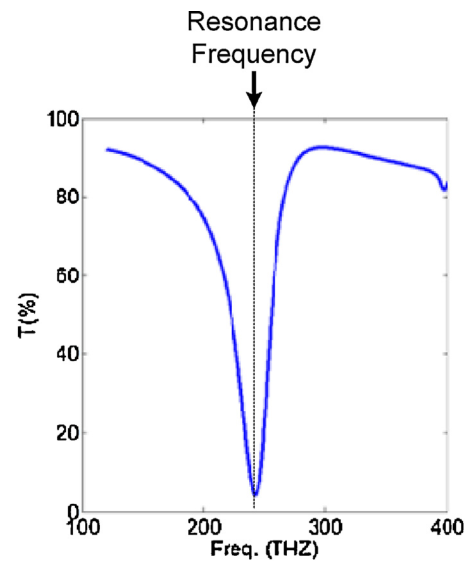

Fig. 3. The transmission coefficient versus the resonance frequency for the SRR unit cell.

Fig. 3 shows the transmission coefficient versus the frequency for the SRR unit cell with the geometric parameters as in Fig. 1. As it is clear, the transmission (output signal) falls to zero at the resonance frequency of about 240 THz, which is due to the impedance matching.

It should be noted that, in the proposed all optical switch, the probe signal is tuned on at the resonance frequency, so the output signal will be normally zero at this frequency. In this method, a high power pulse (pump) is used to change the switch state from off to on due to the nonlinear effects of CNT composite (Kerr effect) [22]. This subject will be discussed completely in Section 4.

3. The effective optical parameters of CNT composite

The widely used descriptions for the effective dielectric function are the Bruggeman and Maxwell–Garnett effective medium theory (EMT) [18,23]

$$\frac{f(\varepsilon_{CNT} - \varepsilon_{eff})}{\varepsilon_{eff} + L(\varepsilon_{CNT} - \varepsilon_{eff})} + \frac{(1-f)(\varepsilon_h - \varepsilon_{eff})}{\varepsilon_{eff} + L(\varepsilon_h - \varepsilon_{eff})} = 0 \quad (1)$$

$$\varepsilon_{eff_{\shortparallel}} = \varepsilon_h + f(\varepsilon_{\shortparallel} - \varepsilon_h) \quad (2)$$

$$\varepsilon_{eff\perp} = \varepsilon_h + \left[\frac{f(\varepsilon_\perp - \varepsilon_h)}{\varepsilon_h} + \left(\frac{1}{2}\right)(1-f)(\varepsilon_\perp - \varepsilon_h)\right] \quad (3)$$

where ε_{CNT} and ε_h are the complex dielectric constant of CNT and host material, respectively. Also ε_{eff} is the effective dielectric constant of CNT composite, f is the volume fraction of CNT contained in the composite, and L is the depolarization factor of each CNT in the composite.

3.1. CNT-paraffin composite

First we have used the vertical and parallel permittivities of graphite given in [24] for calculating the permittivity of MWCNT using Eq. (1) [25], then using Eqs. (2) and (3) we have calculated the effective permittivity of CNT-paraffin composite. Figs. 4 and 5 show the parallel and vertical effective permittivities of CNT-paraffin composite respectively, calculated using Eq. (1).

Figs. 6 and 7 show the effective parallel and vertical permittivities of CNT-paraffin composite respectively, which are calculated using Eqs. (2) and (3).