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Unidirectional second harmonic generation based on electromagnetic induced transparency-like phenomenon derived from standing waves

Yueyun Hu [a], Chunhua Xue [b,*], Yong Sun [c]

[a] COMAC Shanghai Aircraft Design and Research Institute, Shanghai 201210, China
[b] School of Computer Science & Communication Engineering, Guangxi University of Science and Technology, Liuzhou, Guangxi 545006, China
[c] Key Laboratory of Advanced Micro-structure Materials, MOE, School of Physics Science and Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

The nonlinearity and one-way response associated with an electromagnetically induced transparency-like (EIT-like) phenomenon based on a standing wave are theoretically analyzed and experimentally measured. The dark-meta-atom's strong energy localization results in strong second harmonic generation (SHG), while input for the opposite direction elicits no EIT-like response and a 20 dB decrease in SHG strength. The second-order standing wave can be tuned to affect the efficiency of SHG. The results presented here may represent a novel approach to designing nonreciprocal devices such as high signal-to-noise ratio electromagnetic diodes.

1. Introduction

Nonreciprocal optical devices are highly valuable in optical communication and information processing. The electromagnetic (EM) diode is one such typical transmission device that allows light to travel in only one direction. Over the past several years, numerous studies have been conducted on nonreciprocal optical device fabrication; a variety of new physical concepts and methods have been established accordingly. Examples include the dynamic modulation of photonic structures [1–3], nanometer-scale magneto-optic [4] and acousto-optic effects [5], and nonlinear PT symmetry breaking [6–8]. Recently, a new mechanism for one-way optical transmission has attracted widespread research attention. The nonreciprocity of any device fabricated via this technique originates in the nonlinearity of EIT-like phenomena [9]. An atomic EIT is an archetypal quantum coherent process with extremely steep normal dispersion in the narrow transparent spectral window [10] that can dramatically reduce the group velocity of light, resulting in a high nonlinearity [11–13]. The EIT-like phenomenon was first obtained with surface plasmon resonance, in which a bright (dark) resonator mimics the bright (metastable) state and the interference of the electromagnetic (EM) wave mimics the quantum coherent process [14]. EIT-like effect can tightly bound the EM light on the subwavelength scale which exhibits "slow light" phenomena [14–16]. EIT-like phenomena have been recognized in many other systems including multiple coupled cavities [17], fishnet structures [18], negative-magnetic metamaterials [19] and other plasmonic structures [3,20,21]. Relevant EIT analogies extend the EIT concept into a frequency range running from the infrared to microwave regime, allowing for stunning visual effects and applications such as perfect narrow-band absorption [22], sensor [23], storage and retrieval of EM waves [24], ultra-low threshold nonlinear devices [25,26] and EM diodes [9].

In this study, we explore the one-way second harmonic generation (SHG) originated from the nonlinear EIT-like effect. We employ a microwave transmission line with a standing wave structure side-coupled to split ring resonators (SRRs) which is used for mimicking meta-atoms. The EIT-like response hence was achieved by forming an equivalent three-level system with a metastable state [27]. For fundamental frequency response, our system exhibits a reciprocal transmission behavior but nonreciprocal reflection and EIT-like response. The localized field strengths of the dark meta-atoms were vastly different for different incident directions. In results, these differences give rise to unidirectional SHG signal transmission when nonlinear harmonic responses of meta-atoms are excited. Unlike a traditional device, the incident EM wave of our sample one-way transmission is at double frequency, which completely avoids the impact of said EM wave. This endows the diode with a high signal-to-noise ratio. Because this structure exists in the microstrip line system, it has both a low profile and can

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* Corresponding author.
E-mail address: davies2000@163.com (C. Xue).

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be easily integrated into existing technologies, making it ideal for practical application.

This paper is organized as follows: In Sec. 2, we present the theoretical analysis and experimental results of the unidirectional EIT-like phenomenon. The EIT-like phenomenon can be observed only if two meta-atoms are arranged in the sequence node-antinode. In Sec. 3, we experimentally measure the one-way SHG based on the unidirectional EIT-like phenomenon. Then we discuss the tuning of one-way SHG by introducing an extra meta-atom to adjust the standing wave field. Finally, we conclude in Sec. 4.

2. Fundamental frequency response

Our experiment setup is carried out in a microstrip transmission line system. Samples are fabricated on a 1.57-mm-thick FR-4 copper-clad substrate ($\varepsilon_r = 4.4$, $tan\delta = 0.01$) using laser direct structuring technology (LPKF ProtoLaser 200), as shown in Fig. 1(a). A microstrip line with length of 210 mm and width of 0.2 mm is used for constructing the standing wave field and is connected to a 50Ω microstrip transmission line. Two pairs of split-ring resonators (SRRs) made of the same wire arrange symmetrically on the two sides of the microstrip, which acts as two meta-atoms [28, 29]. When an atom is located within a standing wave, the atom's radiation will strongly depend on the field strength of standing wave. The radiation of atoms located at the node of standing wave is rather weak, which can be seen as a dark atom. On the contrary, the radiation of atoms located at the anti-node of standing wave is rather considerable, which can be seen as a bright atom. Here we set the left pair of SRRs at the node of standing wave which acts a dark meta-atom. Its parameters are $W = 10$ mm, $H = 2$ mm, $s = 0.3$ mm, and $c = 2.48$ pF, respectively. The right pair of SRRs is set at the anti-node of standing wave and thus acts a dark meta-atom. Its parameters are $W' = 10$ mm, $H' = 2$ mm, $s' = 0.3$ mm and $c' = 2.16$ mm, respectively. Here the capacitance values are the unbiased values of the varactor (Infinion-BBY52-02W). In addition, we consider the power of input EM wave as −14 dBm, a rather weak value. In this case, the system at fundamental frequency can be seen as a linear one and we just need to consider the small signal harmonic generation (SHG).

First we theoretically analyze this system. This system can be investigated quantitatively by using transfer matrix method (TMM) in conjunction with coupled-mode theory. The theoretical model is presented in Fig. 1(b). The cavity is divided into three layers by two meta-atoms. Supposing that EM waves propagate along the z direction, and the magnetic field in layer j ($j = 0, 1, 2, 3, 4$) can be described with the overlying of forward wave $H_j^+(z,\omega)$ and backward wave $H_j^-(z,\omega)$. Together they take the form $H_j^\pm(z,\omega) = |H_j^\pm| e^{\pm(ik_j z - i\omega t)}$, in which k_j is wave number. The dark meta-atom (left circle) is coupled with the cavity with resonant frequency ω_1 (without any bias voltage), scattering loss γ_1 and dissipative loss Γ_1, while the bright meta-atom (right circle) has resonant frequency ω_2, scattering loss γ_2 and dissipative loss Γ_2. For left incidence, the field coefficients $[H_0^+(z,\omega), H_0^-(z,\omega)]^T$ and $[H_4^+(z,\omega), H_4^-(z,\omega)]^T$ (where superscript T denotes the transposition operation) are related by a 2 × 2 transfer matrix M

$$\begin{bmatrix} H_0^+(z,\omega) \\ H_0^-(z,\omega) \end{bmatrix} = M \begin{bmatrix} H_4^+(z,\omega) \\ H_4^-(z,\omega) \end{bmatrix}, \tag{1}$$

where the transfer matrix M can be obtained from the propagation matrices D_j and the transmission matrices $M_{j\to j+1}$

$$M = M_{0\to1} D_1 M_{1\to2} D_2 M_{2\to3} D_3 M_{3\to4}. \tag{2}$$

The propagation matrices are determined with the layer length d_j, which is given by

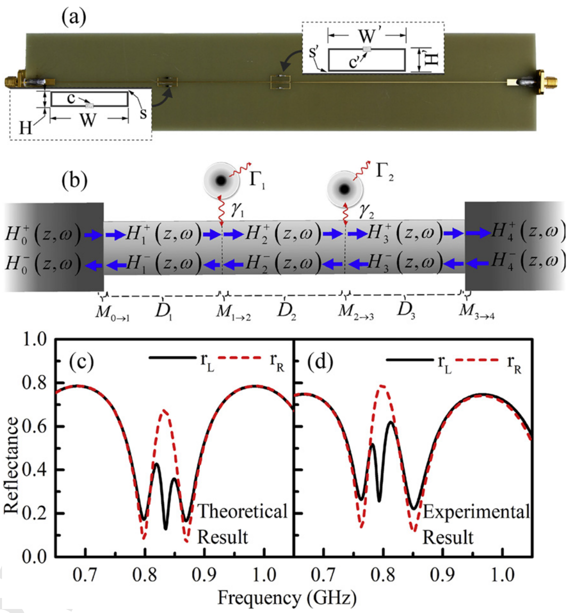

Fig. 1. (a) Photograph of sample realizing EIT-like phenomenon with meta-atom-1 at left and meta-atom-2 at right. The parameters are given in the text. (b) Theoretical system model. (c) The calculated reflectance spectrum of the system for left incidence (black solid line) or right incidence (red dashed line). (d) The experimental reflectance spectrum of the system. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

$$D_j = \begin{bmatrix} e^{-ik_j d_j} & 0 \\ 0 & e^{ik_j d_j} \end{bmatrix}. \tag{3}$$

As the two ports are symmetrical, the transmission matrices near the ports satisfy $M_{3\to4} = M_{0\to1}^{-1}$ and are written as follows

$$M_{0\to1} = \frac{1}{2} \begin{bmatrix} 1+\eta_{0\to1} & 1-\eta_{0\to1} \\ 1-\eta_{0\to1} & 1+\eta_{0\to1} \end{bmatrix}, \tag{4}$$

where $\eta_{0\to1} = \eta_0/\eta_1$. The corresponding transmission matrices can be obtained by using reflection coefficient r_j and transmission coefficient t_j of the meta-atoms, in which $j = 1, 2$ denotes meta-atoms 1 and 2, respectively. The matrices yields to

$$M_{j\to j+1} = \frac{1}{t_j} \begin{bmatrix} 1 & -r_j \\ r_j & 1+2r_j \end{bmatrix}. \tag{5}$$

In order to obtain the reflection coefficient r_j, we need to analyze the resonance of varactor-loaded dark meta-atom with nonlinear oscillator model. The voltage V of the varactor can be expanded in a Taylor series in terms of the normalized charge q, namely $V \approx q + \frac{\alpha}{\omega_1^2} q^2 + \frac{\beta}{\omega_1^2} q^3$, where ω_1 is the linear resonant frequency of dark meta-atom, $q = Q/c$ with Q the charge and c the linear capacitance of varactor. α and β denote the second- and third-nonlinear susceptibility of the varactor, respectively. The equation of motion thus can be written as $\frac{d^2q}{dt^2} + \gamma \frac{dq}{dt} + \omega_1^2 q + \alpha q^2 + \beta q^3 = -\omega_1^2 \varepsilon(t)$, where $\varepsilon(t)$ is the excitation voltage on the varactor [30], and $\gamma = \gamma_1 + \Gamma_1$ is the total loss of dark meta-atom. This is now a nonlinear driven oscillator problem.

In such nonlinear driven oscillator problem, the resonant frequency of dark meta-atom yields the form $\omega_1 + \Delta\omega$, where $\Delta\omega$ is the nonlinear frequency shift. $\Delta\omega$ is caused by the nonlinear q^2 and q^3 terms and can be written as $\Delta\omega \approx \left(\frac{3\beta}{8\omega_1} - \frac{5\alpha^2}{12\omega_1^3} \right) |q_1|^2$ [30–32] with q_1 being the normalized charge quantity at the fundamental frequency. Thus the equation of motion can be rewritten as $\frac{d^2q_1}{dt^2} + \gamma \frac{dq_1}{dt} + (\omega_1 + \Delta\omega)^2 q_1 = -\omega_1^2 \varepsilon(t)$. Assume harmonic ex-

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