Optics Communications 401 (2017) 66–70

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The role of current loop in harmonic generation from magnetic metamaterials in two polarizations

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ARTICLE INFO

Keywords:
Metamaterials
Second harmonic generation
Third harmonic generation
Nonlinear optics

ABSTRACT

In this paper, we investigate the role of current loop in the generation of second and third harmonic signals from magnetic metamaterials and we are clarifying why two polarized harmonics are generated from magnetic metamaterials. We show that the current loop formed in the magnetic resonant frequency acts as a source for nonlinear effects. The current loop that has a circular shape can be divided into two orthogonal parts, where each of these parts acts as a source for generating a harmonic signal parallel to itself. The type of harmonic signal is determined by the metamaterial's inversion symmetry in that direction. This claim is also supported by the experimental results of another group.

1. Introduction

Considering the recent rapid growth of photonic science and the birth of newly designed photonic devices, the needs for new photonic elements have been increasing. Ones of such elements are nonlinear metamaterials, which are artificially structured materials which are capable of generating nonlinear effects in very small thickness. Researchers have been trying to find metamaterials for generating nonlinear effects for the past decades, and some designs have been introduced for second harmonic generation [1–5], and some designs were also suggested for how to amplify them [6,7]. Some others have used the nonlinear photonic elements such as diodes for generating nonlinear effects [8,9]. Other nonlinear effects like solitons are also seen in metamaterials [10], and tunable nonlinear metamaterials are also made by using liquid crystals [11].

In this paper, we show how magnetic metamaterials generate harmonic signals in two polarizations. Magnetic metamaterials produce their magnetic response by inducing a magnetic dipole in the opposite direction of the incident magnetic field. This magnetic dipole is created by a loop of current in the magnetic resonance of the metamaterial [12]. Here, we investigate the effect of this current loop on harmonic generation which is supported by the numerical analysis of nanostrips as an example of magnetic metamaterials. We also brought a reference that shows the similar experimental results of harmonic generation from SRRs. We discussed how our theory conforms with the experimental results that was achieved in that reference.

2. Theory

In general, the optical properties of metamaterials can be described by their transmittance and reflectance spectra (see Fig. 1(a)). From the spectra not only we can get their negative refractive index regions and their effective permittivity and permeability [13,14], but also we can determine their resonant frequencies. We have two resonant frequencies in metamaterials, electric and magnetic resonant frequency. These frequencies are in the maximum values of the absorption curve. We show that the amplified polarization currents in the magnetic resonant frequency can be used to generate second and third harmonic signals in two different polarizations.

The highest amount of polarization currents in the metamaterials occurs in their magnetic resonant frequency. In the magnetic resonance, the incident magnetic field induces a current loop in the metamaterial (see Fig. 1(b)). This situation can also be visualized as an LC circuit, which is operating at its resonant frequency (see the inset of Fig. 1(b)). The metallic parts form a loop which acts like an inductance and the gaps act like capacitors. In the resonant frequency of LC circuits, the impedance reaches its minimum and thus the highest amplitude of

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http://dx.doi.org/10.1016/j.optcom.2017.05.040
Received 23 April 2017; Received in revised form 14 May 2017; Accepted 16 May 2017
0030-4018/

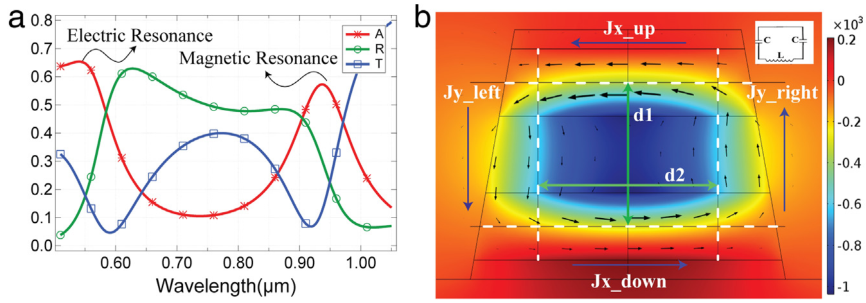

Fig. 1. (a) Transmission, reflection and absorption spectra of nanostrips. The peaks in the absorption curve determine the resonant frequencies. (b) Magnetic field distribution and electric field displacement (black arrows) in magnetic resonant frequency. The external magnetic field induces a current loop which can be divided into two orthogonal parts. The current loop components are measured on the white dashed lines. The separation between these lines are shown by d_1 and d_2. The inset shows the equivalent circuit.

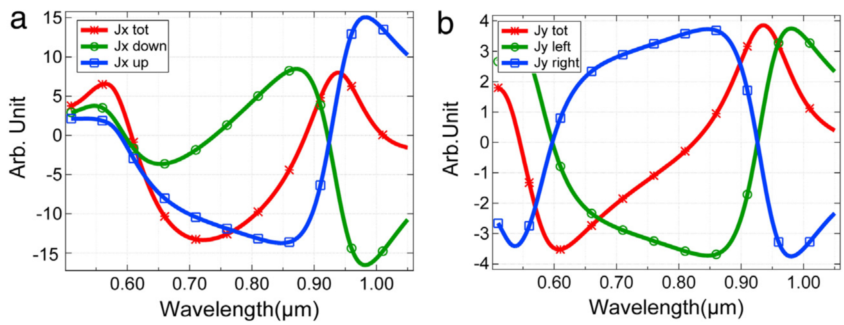

Fig. 2. (a) Polarization currents in the upper and lower metallic parts (J_x up and down), and the $J_{x,tot}$.(b) Polarization currents in the left and right metallic parts (J_y left and right), and the $J_{y,tot}$. Both components of J_{tot} has the same maximum as the absorption curve in Fig. 1(a).

currents can be seen [15] which means that a strong current loop will be formed. The induced currents (or the equivalent electric fields) are much stronger than the background field in the metallic parts (This can be seen schematically in Fig. 1(b), in which the arrows that show the strength of the electric field, are much bigger in the metallic parts in comparison to the background electric field). Based on the fact that the nonlinear properties of metamaterials originate from the nonlinear behavior of metallic parts [1], the current loop will act as a source for nonlinear effects. Now we show that how this current loop generates nonlinear effects in two polarizations. We divide the current loop into two parts. Upper and lower currents, and left and right currents (see Fig. 1(b)). As mentioned above, the polarization currents act as the sources for nonlinear effects. Each group of polarization currents (left and right or up and down) creates a nonlinear field perpendicular to the other one. Although the currents in these parts and the corresponding generated fields are antiparallel (e.g. J_y left and right), the added phase factor ($e^{ik_0 d}$) caused by their separation leads to a constructive field (see Fig. 2, and Eqs. (1) and (2)).

To show the effect of currents, we measure the average currents on four lines on the upper ($J_{x,up}$) and lower ($J_{x,down}$) metallic parts, and left ($J_{y,left}$) and right ($J_{y,right}$) metallic parts of the nanostrips. To prove this claim, we measure two quantities. First of all, we measure the currents in four lines (white dashed lines) (see Fig. 1(b)). The separation between the horizontal lines is d_1 and the separation between the vertical lines is d_2. Now, we measure the following two quantities:

$$J_{x,tot} = J_{x,up} \times \exp(-ik_0 d_1) + J_{x,down} \tag{1}$$

$$J_{y,tot} = J_{y,left} \times \exp(-ik_0 d_2) + J_{y,right}. \tag{2}$$

As can be seen from Fig. 2(a) and (b), although the individual currents have maximums in different frequencies compared to the nanostrips' absorption curve, but $J_{x,tot}$ and $J_{y,tot}$ have a maximum in the same frequency as the nanostrips' absorption curve. These two perpendicular currents are responsible for creating the nonlinear effects.

Now we discuss the required equations which are necessary for the simulation of nonlinear behavior of metals. The linear behavior of noble metals at different frequencies is described by Drude model, which is based on the equation of motion of free electrons in metals [16]:

$$m\ddot{\vec{r}}(t) + m\Gamma\dot{\vec{r}}(t) = -e\overrightarrow{E_0}e^{-i\omega t}. \tag{3}$$

The right-hand side term is the driving force caused by the exciting wave, and the middle term is the damping force. By substituting $\overrightarrow{P(t)} = ne\vec{r}(t)$ and $\overrightarrow{J_p} = \frac{\partial \vec{P}}{\partial t}$ we have:

$$\frac{\partial \overrightarrow{J_p}}{\partial t} + \Gamma\overrightarrow{J_p} = \varepsilon_0 \omega_p^2 \vec{E} \tag{4}$$

where $\omega_p = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m}}$ is the plasma frequency. The above equation is solved simultaneously with Maxwell equations followed, and then we have the linear behavior of noble metals at different frequencies:

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E} \tag{5}$$

$$\frac{\partial \vec{E}}{\partial t} = c^2 \vec{\nabla} \times \vec{B} - \frac{\overrightarrow{J_p}}{\varepsilon_0}. \tag{6}$$

In order to consider nonlinear effects we should also add three physical effects to the Eq. (3), which are the electric and magnetic components of Lorentz force and the convective derivative of the electron-velocity field:

$$\frac{\partial \overrightarrow{J_p}}{\partial t} = -\Gamma\overrightarrow{J_p} + \varepsilon_0 \omega_p^2 \vec{E} + \sum_k \frac{\partial}{\partial r_k}\left(\frac{\overrightarrow{J_p} J_{pk}}{\omega_p^2 m_e \varepsilon_0 / e - \rho}\right) - \frac{e}{m_e}\left[\rho\vec{E} + \overrightarrow{J_p} \times \vec{B}\right]. \tag{7}$$

The above model is presented in [17] and it is verified experimentally for 5 different metallic nanoparticles like SRRs and T-shape particles. Some other models are also presented in the literature [18–21]. Hence, the final set of the equations to be simulated simultaneously are (5)–(7). As can be seen from the Eq. (7) the nonlinear effects originate from the polarization currents.