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Artificial magnetism of cross shaped metamaterial in green light frequencies

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ABSTRACT

We theoretically investigate the magnetic response of a cross-shaped metamaterial at green light frequencies. Such a structure supports a strong magnetic resonance, which results in a large negative permeability and hence a band of negative refractive index over 50 THz. The structure is low loss and exhibits a high FOM of 3.75 at 570 THz. The magnetic resonance can be effectively tailored both in operation frequency and resonance strength by means of adjusting the geometric dimensions, which is well described by the equivalent circuit model. The proposed structure may offer an effective means to realize the magnetic devices at visible frequencies.

1. Introduction

Naturally occurring substances have negligible response to the magnetic component of the electromagnetic wave above terahertz frequencies. Artificial magnetism which originates from the magnetic resonance of man-made composites known as metamaterials, however, can be induced within a wide band ranging from microwave to optical frequencies [1–6]. The permeability of artificial metamaterials can attain the negative values nearby the magnetic resonance. Motivated by the extraordinary effects related to the negative permeability, such as negative refraction [7–9], enhanced MRI imaging [10,11] and invisible cloak [12,13], etc., a wide range of magnetically responsive metamaterial structures are devised in recent years. However, realizing strong magnetic response at the visible light band is still a challenging research problem. In addition to the complex fabrication process, the difficulty in achieving negative permeability at visible region mainly comes from two limitations. The one is that the blueshift of the resonance frequency tends to saturate in the visible band owning to the role of kinetic inductance [14,15]. The other limitation arises form the increased metallic loss, which highly dampens the magnetic resonance and hence fails to produce negative permeability.

There has been a continuous effort to push up the operation frequency of metamaterials deep into the visible frequencies. The multi-layer fishnet metamaterial is known as an effective approach to achieve negative permeability with low losses up to optical frequencies [7,16–19]. Nonetheless, at even higher visible frequencies, the magnetic resonance is not strong enough to support large negative permeability. Surface plasmon waveguide is another promising strategy to produce strong magnetic resonance and hence negative refractive index over a wide visible band [20–22]. Yet its two-dimensional architecture renders itself difficult to be integrated into compact three-dimensional optical devices. Recently, much attention is moved to the Mie scattering of dielectric nanowires or nanoshells, which can also give rise to magnetic response in the visible frequencies [23,24].

In this work, we proposed a visible frequency magnetic metamaterial which is composed of periodic cross-shaped metallic nanoantennas. Strong magnetic resonance is excited due to the near-field coupling between neighboring unit cells. The resulted permeability takes a large negative value of -2 around 570 THz (520 nm) in the green light region. Combined with the negative permittivity caused by the electric resonance, a negative index frequency band covering 50 THz is obtained with a peak figure of merit (FOM) of 3.75. The enhancement of the magnetic field, resonance amplitude and the operation frequency of magnetic resonance can be effectively tailored by adjusting the geometric sizes of the structure. The proposed structure may offer a promising approach for achieving artificial magnetic at visible frequencies.

2. Model and simulation method

The schematic and the geometric sizes of a unit cell of the proposed structure are shown in Fig. 1(a). The cross-shaped silver nanoantennas (yellow part) are periodically arranged in the X

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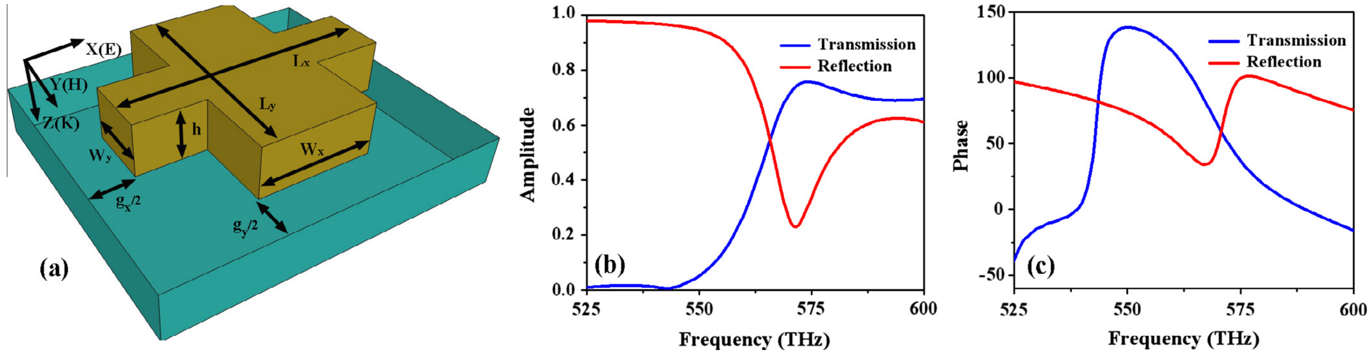

Fig. 1. (a) Schematic of the cross-shaped metamaterial. The geometric dimensions are taken as $L_x = 170$ nm, $L_y = 185$ nm, $W_x = 50$ nm, $W_y = 120$ nm, $g_x = 70$ nm, $g_y = 120$ nm and $h = 90$ nm. (b) and (c) The magnitude and phase (deg) of transmission and reflection spectra of the structure.

and *Y* directions on the quartz substrate (green part). Such a structure was previously employed as a color filter owning to its plasmon resonance driven by the electric field [25]. But its magnetic response, to out knowledge, has not been reported. This structure can be fabricated by employing evaporation techniques and standard electron-beam lithography. The incident light propagates normal to the array with the electric and magnetic field directed in the *X* and *Y* directions, respectively. The simulation is implemented using the finite difference time domain (FDTD) method. The periodic boundaries are applied in the *X* and *Y* directions and the perfect matched layer (PML) boundary is used in the *Z* direction. The dispersive dielectric constant of silver is taken from the empirical data measured by Johnson and Christy [26], and the refractive index of quartz substrate is chosen as 1.5.

3. Results and discussion

Fig. 1(b) and (c) plot the calculated transmission (blue curve) and reflection (red curve) of the structure. The refractive index (n) and the effective impedance (z) of metamaterials can be retrieved from the transmission (T) and reflection (R) according to the following relationship, where k and h are the free-space propagation constant and structure thickness, respectively.

$$n = \pm\frac{1}{kh}\cos^{-1}\left(\frac{1-R^2+T^2}{2T}\right) \tag{1}$$

$$z = \pm\sqrt{\frac{(1+R)^2-T^2}{(1-R)^2-T^2}} \tag{2}$$

Once n and z are evaluated, effective permittivity (ε) and permeability (μ) are calculated using $\varepsilon = n/z$ and $\mu = nz$ [27]. It is shown in Fig. 2(a) that the permittivity $Re(\varepsilon)$ (red curve) takes negative values within the frequency band of interest. It results from the plasmon resonance under which the excited electric field inside the nanoantenna oscillates in the incident polarization direction, as previously investigated in the color filter [25]. Meanwhile the negative permeability $Re(\mu)$ is achieved in the region between 563 THz and 580 THz and takes a large negative value of −2 at 565 THz. The bandwidth of negative permeability is much narrower than that of the negative permittivity because the magnetic response is normally much weaker than the electric response [5]. In the double-negative region, where both the permeability and permittivity take negative values, the structure has the negative refractive index. Fig. 2(b) presents the real part (blue solid curve), imaginary pert (blue dashed curve) of refractive index and the figure of merit (FOM = $-Re(n)/Im(n)$) (red curve). The negative refractive index $Re(n)$ covers a wide frequency band ranging from 540 THz to 590 THz. The FOM is an important measure to evaluate the loss performance of negative index metamaterials. The higher value it takes, the lower loss the structure exhibits. The FOM herein reaches as high as 3.75 at 570 THz ($n = -1.39 + 0.37i$), which compares with that obtained with other highly low-loss metamaterials operating in the green light band [17,18]. Nearby the double-negative band, the refractive index also takes negative values although $Re(\mu) < 0$ is *not* fulfilled. It is known to be caused by the large imaginary part of permeability $Im(\mu)$ [28], and the FOM is relatively low within this region since the large $Im(\mu)$ leads to large dissipative losses.

In order to understand the underlying mechanism of the magnetic response, the field distribution at the cutting plane of $Z = 0$ is analyzed at the magnetic resonance frequency (570 THz). The electric field under magnetic resonance mainly oscillates in the *Z* direction. Fig. 3(a) exhibits that the electric field E_z is mostly concentrated at the edges of the horizontal bar of the cross nanoantenna. E_z near the adjacent parallel plates of the neighboring crosses oscillates 180° out of phase. Such an anti-symmetric electric field distribution gives rise to a magnetic dipole, which counteracts the incident magnetic field at resonance and hence produces the negative permeability. Different from the magnetic resonance mode, at the electric resonance the structure serves as an equivalent electric dipole along the *X* axis (not shown here). The electric dipole oscillates against the incident electric field and gives rise to the negative permittivity if the resonance is strong enough. As shown in Fig. 3(b), the magnetic field H_z is highly localized and enhanced in the gap between the neighboring nanoantennas. To better visualize the magnetic field distribution, the normalized magnetic field along the *X* axis ($Y = 0$) is plotted in Fig. 4(a), where $(X, Y) = (0, 0)$ corresponds to the center point of the gap region. The H_y has the maximum magnitude near the boundary of the gap and slightly decreases toward the middle point. Since the magnetic resonance is caused by the near field coupling between adjacent unit-cells, the magnetic response of the structure is highly sensitive to the variation of the gap width (g_x). Fig. 4(b) shows the normalized intensity of magnetic field $|H_z/H_0|^2$ as a function of gap width g_x, which is measured at the center point of the gap. All other geometrics sizes are kept the same with those chosen in Fig. 1. A large field enhancement is obtained at a narrow gap, with a peak 100-fold enhancement for $g_x = 20$ nm. As the gap becomes wider, the enhancement factor initially decreases dramatically and then keeps almost fixed at a level of 20.

In addition to the field enhancement, the resonance frequency is also strongly dependent of the gap width. Fig. 5(a) shows the color map of permeability as a function of frequency and gap width. The white dashed curve outlines the contour of $Re(\mu) = 0$. For ease of comparison, the permeability at $g_x = 30$ nm, 90 nm and 150 nm is extracted and shown in Fig. 5(c). As the gap width