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Negative refraction of a single-layer metamaterial inserted with dual-coaxial waveguides array

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ABSTRACT

Single-layer metamaterials consisting of a hexagonal close-packed array of Ag/GaP/Ag/GaP/Ag dual coaxial waveguides are investigated by simulation, focusing on both the negative-index property and transmission performance at visible frequencies. Numerical simulations indicate that the negative index mode, the same as the one identified in the Ag/GaP/Ag coaxial waveguides arrays (Nat. Mater. 9, 407, 2010) perfectly conserves and exhibits two negative index bands centered at 400 and 800 THz, respectively. The transmission peaks of the Fabry–Perot resonance at 400 THz and the transmission intensity of the resonance at 800 THz are closely related to the thickness of the silver film. Moreover, the coupling of the two coaxial waveguides can dominate the negative refraction and optical transmission of the constructed metamaterial, only by changing the distance of the two annular apertures. The present configuration can provide more approaches to tune its properties than the single coaxial waveguide array.

1. Introduction

Metamaterials with artificial electromagnetic properties have got increasing interests in the fields of both electromagnetism and photonics. Benefited from a free choice of geometries and compositions, metamaterials have presented extraordinary properties such as enhanced transmission, abnormal dispersion of light, backwards phase propagation and negative refraction, which can be used in sensing applications, sub-diffraction imaging, invisibility cloaking and so on [1–4]. Metamaterials with negative refractive index provides opportunities for integration of true-nanoscale optical components on semiconductor chips and perfect imaging [5]. To implement the functions of negative-index metamaterials (NIMs), it is essential to find out how to achieve the NIMs with both high figure of merit (FOM) and simple topology structures. At present, among all the topology structures for NIMs in visible optical spectrum, the fishnet configuration and its variations are the main and promising designs to achieve negative refractive index due to their advantages on fabrication and measurement [6]. However, in order to increase the operating frequency up to the visible region, the unit cell of the fishnet configuration has to been scaled down to nanoscale [7]. Moreover, for the sake of either low loss or special function, the fishnet structure is usually cascaded to a stack of multiple layers, which increase the fabrication procedure [8–11], and restricts further development of the fishnet metamaterial. It is meaningful to search for other configuration for NIMs except the fishnet configuration [12,13]. Recently, a coaxial waveguides configuration is studied on negative index and homogeneous along the coaxial axis.

By using a coaxial waveguides configuration, a conceptually different approach was proposed to achieve a negative refractive index in the optical spectral range. The coaxial MIM (metal/insulator/metal) waveguides, composed of a metal core surrounded by a dielectric cylinder clad by a metal outer layer, can confine light in all transverse directions [14,15]. By measuring the optical transmission of single coaxial waveguides, the dispersion diagram for these nanoscale waveguides was determined [16]. Rodríguez-Fortuño et al. verified theoretically that a square array of coaxial waveguides could support backward propagating modes at visible frequencies [17]. At nearly the same time, the negative-index modes of a hexangular array of coaxial M/I/M plasmon waveguides were demonstrated theoretically and these modes would dominant other waveguide modes for a wide range of frequencies above the surface plasmon resonance frequency [18,19]. The finding in Ref. [19] indicated that the negative index of refraction benefits from the couple of the arrays of coaxial hole. Inspired by this finding, we want to explore, if we add an annular channel surrounding the former coaxial hole (i.e. dual-coaxial waveguide) as shown in Fig. 1, how will the dual-coaxial holes array effect the negative index of the whole matematerial. In this paper, it is verified that negative index can be preserved by the dual-coaxial waveguide array as good as the former coaxial waveguide array. Moreover, the optical performance can be modulated by more optional choices.

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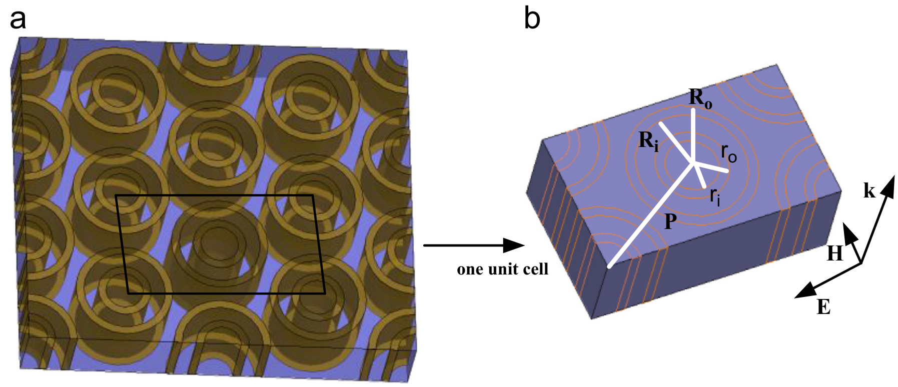

Fig. 1. (a) Diagram of the hexagonal close-packed Ag/GaP/Ag/GaP/Ag dual coaxial waveguides array embedded in silver film. (b) The scheme of one unit cell of our configuration. All geometrical parameters, the polarization and propagation direction are indicated in the figure.

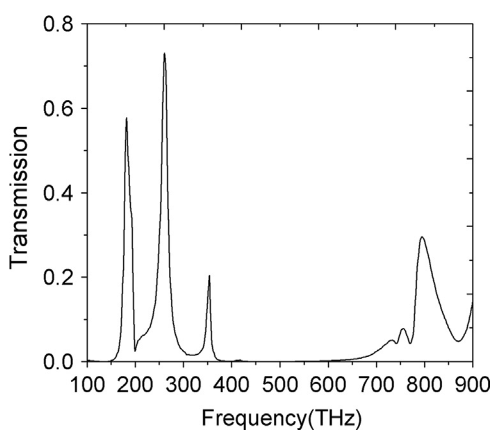

Fig. 2. Transmission spectra of the studied structure with 100 nm thick silver film.

2. Sample configuration

To be comparable to the previous reported results, the dual-coaxial waveguide, composed of GaP annulus, is arranged in a hexagonal closed-packed array, and is set at a pitch of $p = 165$ nm in a 100 nm-thick silver film as Ref. [19], as shown in Fig. 1(a). One unit cell is diagramed in Fig. 1(b). The inner diameter of the big annulus and the small annulus is $2R_i = 125\ nm$ and $2r_i = 60\ nm$, their outer diameter is $2R_0 = 147\ nm$, $2r_0 = 82\ nm$ respectively, and can be changed conveniently for the sake of later parameter study. The same thickness $d = 11$ nm is chosen for the two GaP annular channels so that some conventional waveguide modes connected with channels thickness are the same [15]. The optical performance of the above structure is simulated by using the finite element method. In simulation, the optical constants for silver and gallium phosphide are taken from the tabulated literature data in Refs. [20,21], respectively. In simulation, we refine the mesh of the annular channels further more to get the higher precision.

3. Simulation and analyzing

3.1. Transmission results and analysis

Fig. 2 shows the transmission of the structure at normal incidence with polarization shown as Fig. 1(b). A few transmission peaks ranging from 150 to 400 THz are observed, and even more important, a transmission peak at 800 THz in the ultraviolet band is found. It is well known that the silver coaxial waveguide have two different guide modes, one is the conventional guide mode, and the other is the surface plasmon guided mode. The small thickness $d = 11$ nm of the two annular channels in our design has greatly reduced the conventional guided mode in the studied frequency range. Moreover, the largest cutoff wavelength of the first conventional guide mode is given by

$$\lambda^{c}_{TE_{11}} = \pi(R_o + R_i) \tag{1}$$

where R_o and R_i is the outer and inner radius of annular channel respectively. Therefore, a larger annulus possesses a longer cutoff wavelength (smaller cutoff frequency) than a smaller annulus does. Let the outer radius $R_o = 73.5\ nm$ and the inner radius $R_i = 62.5\ nm$ of the big annulus in Eq. (1), the longest cutoff wavelength $\lambda^{c}_{TE_{11}} \approx 427\ nm$, i.e., the lowest cutoff frequency $f^c \approx 703\ THz$, is acquired for the two coaxial waveguides. Therefore, the transmission peaks over the frequency range from 200 to 400 THz result certainly from the surface plasmon guided modes. To distinguish the transmission peak around 800 THz, we simulate the transmission of the smaller annulus array, that is the dual coaxial waveguide without the bigger annulus. The result indicates that this transmission peak also exists. However, the maximum cutoff wavelength of the conventional guide mode of the smaller annulus is less than 300 nm, corresponding to the minimum cutoff frequency more than 1000 THz. Therefore, the high frequency peak at 800 THz is verified to be also from the surface plasmon guided mode.

In Fig. 2, the three adjacent transmission peaks are typical Fabry–Perot resonances, which come from the interference between forward and backward propagating of low order surface plasmon guided modes by fulfilling the condition

$$|2Hk_{spp}(\omega) + \Delta\varphi_1 + \Delta\varphi_2| = 2\pi m \tag{2}$$

where H is the length of the coaxial waveguide, $k_{spp}(\omega)$ is the wave vector of the surface plasmon at frequency ω, $\Delta\varphi_1$ *and* $\Delta\varphi_2$ are the phase shifts as a result of plasmon reflection at either end of the waveguide, and m is the mode number. From Eq. (2), the resonant peaks will change as H changes, and the decrease of H will reduce the number of the resonance peaks. To verify this, the transmission of 70 nm thick coaxial waveguide silver film is simulated as shown in Fig. 3. The simulated results indicate that two of the three resonance peaks are preserved, which is in agreement with Eq. (2). It is worthwhile to note that the transmission intensity is effectively amplified, whereas the band width of the high order plasmon guided mode is effectively enlarged. Specially, the transmission intensity is twice as much as that of the former, and is the same as that of the low order peaks, which is valuable for frequency mode.

In order to further understand the high order transmission peak, we reduce the distance of the dual coaxial waveguide while the gap $d = 11$ nm of the annulus and the radius of the small annulus is fixed. The dispersion of the transmission peak as a