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Citation: Applied Physics Letters 109, 031103 (2016); doi: 10.1063/1.4959032
View online: http://dx.doi.org/10.1063/1.4959032
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/109/3?ver=pdfcov
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Optical isotropy at terahertz frequencies using anisotropic metamaterials

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(Received 10 March 2016; accepted 25 June 2016; published online 18 July 2016)

We demonstrate optically isotropic filters in the terahertz (THz) frequency range using structurally anisotropic metamaterials. The proposed metamaterials with two-dimensional arrangements of anisotropic H-shaped apertures show polarization-independent transmission due to the combined effects of the dipole resonances of resonators and antennas. Our results may offer the potential for the design and realization of versatile THz devices and systems. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4959032]

During the past several years, optical devices based on artificial optical materials, such as plasmonic metamaterials, have attracted increasing attention for their potential use in electronics, photonics, and biotechnology.1–4 Each unit cell forming the artificial optical materials acts as a meta-atom which is the basis of all plasmonic metamaterial structures. Meta-atoms are fundamentally designed with subwavelength metallic elements such as circular or rectangular holes and c-shaped metallic rods that exhibit effective electric and magnetic responses.5 The optical characteristics of plasmonic metamaterials, such as extraordinary optical transmission, wavelength filtering, and the ability to manipulate polarization and directionality, are determined by the structural properties of meta-atoms.6–9 Early studies on plasmonic metamaterials were focused on relatively simple and symmetric structures of meta-atoms.6–8 Recently, many functionalyzed composite structures for forming meta-atoms have been proposed to have specific optical properties for achieving customized functionalities for use in devices or systems in a wide range of wavelengths.10–21 In particular, achieving anisotropic transmission in the plasmonic metamaterials composed of asymmetric meta-atoms has become a remarkable research topic as much as achieving isotropic transmission in symmetric meta-atom structures.22–24 Therefore, realizing isotropic optical properties in anisotropic metamaterial structures became one of the challenging topics. This is particularly important to achieving reliable performances from devices such as optical filters, attenuators, perfect absorbers, and other optical devices.25–29

In this letter, we demonstrate a method for realizing optical isotropy at terahertz (THz) frequencies using structurally anisotropic plasmonic metamaterials that are based on the two-dimensional arrangements of H-shaped apertures. The integrated apertures form one-dimensional linear chains of plasmonic air-slot resonators of H-shaped and rod-shaped antennas. The resonance from the resonators and the antennas is related to their structural dimensions. The wavelength of the fundamental mode, which is the lowest resonant frequency mode of a vibrating system, is commonly twice the length of the plasmonic components, which is called dipole resonance.12,30 However, the directions of the movement of the oscillating charges on the slot resonators and antennas are different because the charges in the antennas oscillate along the antenna structure whereas the slot resonators cause charge oscillations across the edges of the resonator gap. Therefore, the proposed metamaterials may have polarization-independent transmission due to the combined effects of the dipole resonances of the slot resonators and the antennas.

We designed structurally anisotropic metamaterials comprising two-dimensional arrangements of H-shaped apertures in a 10-μm-thick stainless-steel film, as shown in Fig. 1(a). The structures were fabricated using the femtosecond laser micro-machining technique, which is laser ablation by amplified femtosecond laser pulses.31 The schematic diagram in Fig. 1(b) indicates the relevant dimensional data of the fabricated H-shaped aperture. The apertures were arranged in rectangular lattices with periods of Px = 350 μm and Py = 630 μm, and the horizontal and vertical lengths of the H-shaped aperture were lx = 80 μm and ly = 600 μm, respectively. The width of vertical slots along the y-axis was a = 20 μm and the width of the air gap between the two straight air slots consequently becomes d = 40 μm. A different type of anisotropic metamaterial, comprising two-dimensional arrangements of II-shaped apertures, was fabricated to have the same values of structural parameters, except for not having the air gap between the two straight air slots. We cannot, therefore, expect the dipole resonance due to the rod-shaped antennas in the metamaterial. The polarization-independent transmission of the structures may not be achieved for that reason. The polarization-independent features of the anisotropic metamaterials composed of H-shaped air-slots are systematically compared with those of the structures composed of II-shaped air-slots.

Figure 1(c) is a microscopic image of an array of H-shaped apertures, clearly showing the anisotropic metamaterial structure of one-dimensional linear chains of the H-shaped air slots. The sum of the lengths b and w equals the fixed value of Py = 630 μm, but each length is varied to

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manipulate the condition of wavelength filtering. Each pair of adjacent apertures forms rod-like metallic antennas, as indicated by the yellow area in Fig. 1(c), that lie in the same direction as the H-shaped slot resonators. Two different mechanisms for wavelength selection are responsible for the behavior of the resonance: (1) the incident light polarized at 0° couples with the H-shaped slot resonators and (2) the incident light polarized at 90° the rod-like metallic antennas. The selected wavelength of the electromagnetic waves is varied by tuning b and w.

We performed experiments using THz time-domain spectroscopy.32,33 We measured the polarization-dependent THz transmission amplitudes by rotating the samples, where the polarization of the incident THz radiation was set to zero in the direction along the x-axis. To investigate the numerical characteristics of structurally anisotropic metamaterials, we also performed a three-dimensional finite-difference time-domain (FDTD) simulation. The parameters of the metallic film in the THz frequency range were extracted using the Drude model, because most metals can be regarded as perfect conductors in the THz frequency range.34 The electric-field distributions on the surface of the designed metamaterials and zero-order transmission spectra were obtained using the simulation method.

The polarization-dependent characteristics of the resonant transmission in anisotropic metamaterial structures composed of one-dimensional linear chains of the II- and H-shaped slots are presented in Figs. 2(a) and 2(b), respectively. Figure 2(a) shows the resonant peak corresponding to the wavelength of the fundamental mode, \( \lambda_r = 2l_y \), determined to be twice the whole length of the II-shaped air slots only at polarization angle 0°. This is seen in Fig. 2(c), where the values of the cross-sectional profile along the line A approach zero as the polarization angle approaches 90°. On the other hand, the spectral characteristics dependent on polarization, presented in Fig. 2(b), and the cross-sectional profile along the line B, shown in Fig. 2(d), show that there is still resonant transmission at the frequency of 0.29 THz over all polarizations, despite being partly reduced and having a narrow spectral width.

This behavior is verified by simulating the spectral characteristics that are dependent on the polarization angle and the electric-field and current density distributions at the resonance frequency (0.27 THz) taken at the xy-plane on the surface of the metamaterials. The values of b and w were fine-tuned to obtain optical isotropy at a specific frequency. Figure 3(b) shows that the value of normalized transmission amplitude is over 0.93 even for 0°-polarized incident light at the frequency of 0.27 THz, without any change in the spectral peak position. This means that the transmission amplitude remains high over all polarization angles. This is important because, even though the metamaterial structures are composed of one-dimensional linear chains of the H-shaped air slots that exhibit two-fold rotational symmetry,
Figure 3. (a) Simulated polarization-dependent transmission amplitude spectra of the sample in Fig. 2(b). The lengths \( b \) and \( w \) of the H-shaped slots are 150 \( \mu m \) and 480 \( \mu m \), respectively. (b) Cross-sectional profiles of the simulated polarization-dependent transmission amplitude spectra at on-resonance (black squares) and off-resonance (red circles) spectral positions of 0.28 and 0.37 THz, respectively. (c) and (d) Simulated electric-field distributions on the x-axis (\( E_x \), left panels), induced current density distributions on the y-axis (\( J_y \), middle panels), and schematic diagrams depicting electric charge distributions predicted on the basis of electric field and current density characteristics, at the frequency of 0.28 THz for 0°- and 90°-polarized incident light, respectively. The red and blue arrows indicate the directions of the electric field inside the slots and the induced current density within the rod-shaped area, respectively.

excellent non-directional resonant mode of THz transmission can be achieved. The numerical simulation results provide the non-directionality of the resonant transmission as well as do not affect the phase of the THz wave for all directions of polarization (see supplementary material).

To examine the underlying mechanisms of the non-directionality of the resonant transmission, we simulated the electric-field and current density distributions on the surface of the metamaterials for 0°- and 90°-polarized incident light, as shown in Figs. 3(c) and 3(d), respectively. For 0°-polarized incident light, the electric fields on the x-axis were in one direction only at a fixed time. The amplitude of the electric field and its oscillations approaches zero toward the edges of the air slots. Therefore, the electric charge distribution, which provides a clear picture of the origin of the behavior of the resonance, can be predicted, as shown in the schematic diagram on the right side of Fig. 3(c). It implies that the half-wavelength fundamental mode (called dipole resonance), which is determined to be typically twice the length of the elements (in our case, the length of the major axis of the II- and H-shaped apertures), occurs at the polarization.

On the other hand, with 90°-polarized incident light, the induced surface current along the y-axis appears to be in only one direction at a fixed time and within the rod-shaped metallic area [depicted by the yellow rectangle in Fig. 1(c)], as shown in the schematic diagram on the right side of Fig. 3(d). The resonance mode at this polarization has a dipole-like charge current distribution on the surface of the rod-shaped metallic area. The amplitude of the current density is at its maximum near the area between two vertically adjacent H-shaped slots, which corresponds to an antinode of the oscillating current, whereas it is at its minimum at the edges of the rod-shaped metallic area. The resonance mode makes it look like the incident THz waves are coupled to an electric dipole due to the current oscillations in the rod-type antenna. This implies that the non-directional transmission of the THz waves that appear at a specific frequency, which can be considered an optically isotropic property, originates from the individual contributions of the dipole resonances. These resonances are due to the arrangement of the air-slot resonators and rod-type metallic antennas along only one direction and thus form the anisotropic metamaterial structure.

After analyzing the properties and mechanisms of optical isotropy at THz frequencies, we performed a parametric study of the effect of varying the length \( w \) of the rod-shaped metallic area. Figures 4(b)–4(e) show the measured and simulated transmission amplitude spectra of the four samples shown in Fig. 4(a). In Figs. 4(b) and 4(c), the shapes of the measured and simulated transmission spectra are almost indistinguishable for the samples with different length \( w \). By contrast, the resonance spectral peaks shown in Figs. 4(d) and 4(e) are clearly distinguishable. Sample A that does not have a rod-shaped metallic area does not even show a specific resonance peak at the polarization angle of 90°. The spectral position of the resonance peak shifts to higher frequencies at the polarization angle of 90° when \( w \) is decreased, as seen in Fig. 4(f). Unlike the realization of tunable spectral resonance at polarization, the half-wavelength resonant frequency due to the vertical aperture components of the H-shaped air slots, as shown in the inset of Fig. 4(f), remains almost constant for all the samples at the polarization angle of 0°. The tunability characteristics verify that the dipole resonances due to the air-slot resonators and the rod-like antenna structures are independently excited by the incident THz waves with vertical and horizontal polarization, respectively, under the corresponding structural parameters as a result.

In conclusion, we have demonstrated optical isotropy at a specific frequency in the THz frequency range using anisotropic metamaterial structures composed of anisotropic H-shaped air slots with two-fold rotational symmetry. According to the
results of the THz experiments and the simulations, the origin of the optically isotropic property is associated with the combined effects of the half-wavelength resonance modes (called dipole resonance) of the air-slot resonators and rod-like antennas. In addition, spectral tunability can be achieved by fine-tuning the structural parameters. This may be useful for designing and realizing versatile THz devices and systems.

See supplementary material for demonstrating the absence of the phase difference.

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education, Science and Technology (Nos. KRF-2014R1A1A2057920 and 2013R1A1A2074801). This study was also financially supported by Chonnam National University in 2014.

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FIG. 4. (a) Optical microscopy images of four samples with different combinations of lengths b and w. Sample A: b = 0 μm and w = 1 μm; Sample B: b = 100 μm and w = 530 μm; Sample C: b = 150 μm and w = 480 μm; Sample D: b = 200 μm and w = 430 μm. (b) and (c) Experimental and simulated normalized transmission amplitude spectra at the polarization angle of 0°, respectively. (d) Experimental and simulated normalized transmission amplitude spectra at the polarization angle of 90°, respectively. (f) Spectral peak positions obtained from the results presented in (d) and (e). The inset presents the spectral peak positions obtained from the results shown in (b) and (c).