Monopole resonators in planar plasmonic metamaterials

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Abstract: We first present a new phenomenon: the quarter-wavelength resonance of an electromagnetic field in planar plasmonic metamaterials consisting of asymmetrically coupled air-slot arrays, which is essential for a monopole resonator. The anti-nodal electric field intensity of the quarter-wavelength fundamental mode is formed by strong charge concentrations at the sharp metallic edges of the crossing position of the air-slots, and the nodal point of the electric field intensity naturally occurs at the other end of the air-slot. By tuning the structural asymmetry, the quarter-wavelength resonances were successfully split from the half-wavelength resonance, experimentally and numerically.

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1. Introduction

Resonance is a fundamental physical phenomenon in nature and occurs when a system interacts with energy that can easily transfer to one or more storage modes in the system. A structure has its own resonance frequencies at which the amplitude stationarily oscillates at high amplitudes. The phenomenon has been widely exploited in various areas, such as acoustic resonance in musical instruments, electrical resonance in tuned electronic circuits, and optical resonance in laser cavities, etc.

The resonance behavior is also found in the material system in which the resonance is related to the energy band of the materials. Recently, metamaterial is widely investigated because it is an artificial material for realizing a desired resonance for the purpose of control and manipulation of electromagnetic wave [1]. Especially, subwavelength-aperture resonators or plasmonic antennas as planar plasmonic metamaterials have attracted considerable interest in researching the characteristics of strong electric field enhancement, extreme light concentration and manipulation [2–8]. The fundamental mode, that is the lowest resonant frequency mode of a vibrating system, is important in that it determines the characteristics and the performances of the metamaterial devices. In the planar plasmonic metamaterials, the wavelength of the fundamental mode is typically determined by twice the length of the elements such as a plasmonic air-slot or a metal rod, which is called a half-wavelength resonance [9,10].

On the other hand, in the case of standing longitudinal sound waves vibrating in a closed air column (open at one end, closed at the other), a fundamental mode occurs with a wavelength of four times the length of the column. This is named a quarter-wavelength resonance. Many natural phenomena, such as the howling sound from tree branches and manmade noises such as those from basic musical instruments such as clarinets, are associated with the quarter-wavelength resonance. Recently, a few studies have explored the phenomenon that occurs in metallic rod-shaped monopole antennas [11,12]. These structures are based on three-dimensional geometries which restrict the applicability on various types of optical devices that require size-reduction technology. Therefore, in electromagnetic waves, the fundamental mode having one-quarter resonant wavelength in two-dimensional (planar) geometries should be realized in any structures such as planar plasmonic metamaterials.

In this paper, we present a new phenomenon: the quarter-wavelength resonance occurring in planar plasmonic metamaterials with asymmetrically coupled air-slot arrays in a thin aluminum (Al) film at terahertz (THz) frequencies. The quarter-wavelength resonance is similar to the fundamental acoustic mode allowed in a closed air column. At the crossing position of the air-slots, the charge carriers are highly concentrated and then the electric fields are strongly enhanced. The intensity of the electric field of the quarter-wavelength resonant mode at the crossing position is therefore greater than anywhere else in the air-slots. This can be regarded as the anti-nodal distribution of the electromagnetic field. The quarter-wavelength resonance can be generated by the formation of an artificial electromagnetic anti-node at the crossing position and a node at the end of the slots at once. The strong electric-field enhancement is also associated with the effects of sharp edges located near the crossing position of air-slots. From numerical simulations, we found that the phenomenon is caused by the strong concentration of the induced charges at the sharp metal edges formed by the asymmetric crossing of the air-slots. Moreover, in the THz experiments, we clearly observed the quarter-wavelength resonance in the structures and demonstrated the tunability of the quarter-wavelength resonance by changing the geometrical parameters. Monopole resonators, which are realized based on the quarter-wavelength resonance phenomenon, may enable the design of size-reduced, photonic, and optoelectronic devices.
2. Experimental details

We first designed composite planar plasmonic metamaterials that consist of a periodical arrangement of asymmetrically coupled air-slot arrays in 30-μm-thick Al film as shown in Fig. 1. Generally, the rectangular air-slot in a thin perfect-metal film has a fundamental mode, of which the wavelength is approximately one half the length of a longer rectangular side. We intended to realize the generation of both the well-known half-wavelength fundamental mode, \( \lambda_1 \), in the air-slots and the quarter-wavelength resonant mode, \( \lambda_f \), due to the planar metamaterial structure together. The half-wavelength resonant mode, \( \lambda_1 = 2L_1 \), due to the oblique slots with the total length, \( L_1 \), can be strongly driven by the incident THz radiation with the electric field polarized perpendicular to the air-slot. Simultaneously, we set the length, \( L_2 \), from the crossing position to the end of the slot lying on the symmetric axis of the metamaterial structure, for the quarter-wavelength fundamental mode, \( \lambda_f = 4L_2 \). For the clear observation of the fundamental modes, the structures were designed asymmetrically, since in the case of symmetric structures the resonant peaks of two fundamental modes cannot be separated. The ratio between the lengths from the crossing position to each end of the air-slot, denoted as asymmetric scale, is one-to-three.

![Fig. 1. Schematic of a planar plasmonic metamaterial comprising a unit cell in vertical view. The structure was designed to have a periodical arrangement of asymmetrically coupled air-slots where the angle, \( \theta \), between the center air-slot and the side air-slots is 20 degrees. The lengths of the air-slots are varied from 300 to 800 μm for realizing the tunability of each fundamental mode.](image)

The structures were fabricated by using the femtosecond laser machining method, which is based on laser ablation performed by amplified femtosecond laser pulses [13]. Figure 2(a) shows microscopic images of the samples with geometric parameters of: (upper) \( L_1 = 600, L_2 = 450 \), (middle) \( L_1 = 600, L_2 = 330 \), and (lower) \( L_1 = 600, L_2 = 270 \), in microns. The widths of the perforated slots are at least less than 20 μm. The air-slots are perforated in a 30 μm-thick aluminum film and the angle between the slots is 20 degrees. The anti-nodal distribution at the crossing position is optimized at small angles between the air-slots. Nevertheless, it is difficult to obtain the angles less than 20 degree due to the limitation of fabricating the sample structures using the femtosecond laser machining method. The angle of 20 degree is an optimal condition for our experiments. The unit cells are arranged to form a square lattice with the periods of 400 and 1000 μm along the x and y axes, respectively, in order to avoid the wood anomaly near two fundamental resonances. The THz transmission measurements were performed with a standard THz time-domain spectroscopy system based on a photoconductive antenna as a detector and a p-type InAs wafer as an emitter [14,15].
transmission spectra were obtained by normalization of the Fourier spectra of measured signals from samples with those of a measured signal through a typical open reference cell.

3. Results and discussion

Figure 2(b) shows the experimental spectra from the three samples described in Fig. 2(a). The two oblique air-slots in each sample have an equal length of $L_1 = 600 \, \mu m$, in which the fundamental mode (the longest wavelength among resonances), $\lambda_c = 2L_1$, appears at 0.25 THz in the ideal case. However, in the experimental spectra, the resonance peaks were found near 0.24 THz, corresponding to the half-wavelength fundamental mode. Compared with the spectral peak position in the ideal case, the measured peaks shift to a slightly longer wavelength, since the incident THz wave senses that the coupled structures composed of the two oblique slots are effectively longer than a single air-slot with the same length. Meanwhile, the length of the center slot, $L_2$, along the symmetry axis of the two oblique air-slots, is varied successively as 450, 330, and 270 \, \mu m [Fig. 2(a)], while the length of the oblique air-slots is fixed at $L_1 = 600 \, \mu m$. According to the condition of the quarter-wavelength fundamental mode as $\lambda_q = 4L_2$, the peaks should be found at 0.17, 0.23, and 0.28 THz. In Fig. 2(b), we can see the resonant peaks that exist as distinct from the peaks of the half-wavelength fundamental mode, appearing at 0.19, 0.24, and 0.30 THz [red arrows, Fig. 2(b)]. Basically, the intensity of the half-wavelength resonance is stronger than one of the quarter-wavelength resonance when the resonances are far enough away from each other as shown in upper figures in Fig. 2(b) and 2(c). This is because the half-wavelength resonance is related to the two outer slots whereas the quarter-wavelength resonance is only associated with a part of the center slot (from the crossing position to the edge of the long arm in the center slot). On the other hand, when the two resonances are not far enough away from each other, the intensities of both resonances are significantly changed by the effect of Fano-type interference caused by the coupling between two adjacent resonance modes.

Indeed, this is also confirmed by numerical simulations performed based on a three-dimensional finite-difference time-domain (FDTD) method. Periodic boundary conditions are applied in the in-plane direction of the film, in the $x$ and $y$ directions, and the perfectly matched layers are employed in the normal direction of the film, the $z$ direction. In the THz frequencies, most metals can be regarded as perfect conductors. We can therefore extract the values of the permittivity of the Al, the plasma frequency, and the damping constant, using the Drude model [16]. Figure 2(c) shows the zero-order transmission spectra obtained using
the numerical simulations. The spectral peak positions [red arrows, Fig. 2(c)] correspond well to the experimental results.

![Simulation spectrum](image)

**Fig. 3.** (a) Simulated transmission spectrum through the planar metamaterial composed of the air-slots with the lengths: \( L_1 = 600 \), \( L_2 = 450 \), in microns. Simulation results for the quarter- (b)-(e) and half-wavelength fundamental mode (f)-(i). (b) and (f) Intensities of electric near-field distributions on the xy plane. (c) and (g) Intensity profiles of the electric near-field in the cross-section of the lines through the points A and B shown in (b) and the points C and D shown in (g), respectively. The dotted red curves represent the square and the cosine function corresponding to the intensities of the quarter- and half-wavelength fundamental modes, respectively. (d) and (h) The intensities of current density distributions on the xy plane. (e) and (i) Y-axis current density distributions.

For further insights into the existence and characteristics of the quarter-wavelength fundamental mode, we examined the electric field intensity distribution at the center of the Al film, and the induced current density distributions on the surface of the film at the fundamental resonance. For the planar metamaterial designed to be \( L_1 = 600 \) \( \mu m \) and \( L_2 = 450 \) \( \mu m \), the simulated spectrum [Fig. 3(a)] distinctly shows the two resonant peaks resulting from the half- and quarter-wavelength fundamental modes: one appearing at 0.23 THz is due to the half-wavelength resonance and the other appearing at 0.16 THz is due to the quarter-wavelength resonance. To visualize the spatial patterns of the fundamental modes, we plot the...
electric near-field distributions at each resonant frequency [Figs. 3(b) and 3(f)]. Figures 3(c) and 3(g) show the intensities of the electric near-field along the center axes of air-slots from point A to point B in Fig. 3(b) and from point C to point D in Fig. 3(f), respectively. The patterns show cosine-like intensity variations, exactly guided by the squares of cosine function corresponding to $\lambda_i = 4L_2$ [dotted red curve, Fig. 3(c)] and $\lambda_i = 2L_1$ [dotted red curve, Fig. 3(g)], respectively. Unlike a full half-cycle as shown by the intensity variation plotted in Fig. 3(g), a rapid drop of the intensity appears at the crossing position of the air-slots [Fig. 3(c)]. At this position, the strongly concentrated electric charges oscillate in time across the gap region of the air-slot and induce the maximum amplitude of electric fields. We therefore conclude that the crossing position corresponds to an anti-node of a standing electromagnetic wave, similar to a displacement anti-node of the sound wave existing at the open end of an air column.

To further our understanding, the current density distributions were calculated as shown in Figs. 3(d) and 3(h). The current density of the half-wavelength mode distributes over all the air-slots shown in Fig. 3(h). Especially, the amplitude of the current density is minimized at the center of each air-slot [Fig. 3(h)] and the sign of the y-axis current density is changed at the centers [Fig. 3(i)], not the crossing position. These results demonstrate that the concentrated electric field across the air-slot is maximized at the center of each air-slot, which ensures the existence of the half-wavelength fundamental mode. In contrast, for the quarter-wavelength fundamental mode, the current density concentrates mainly on the right side of the air-slots, the region between the node and anti-node of the resonant mode.

The strong concentration of the electric field near the crossing position is associated with sharp edge effects of a metal gap. The right side of the designed structure [Fig. 3(d)] can be considered as a structured metal plate with two tapered sections. Our structures differ from typical tapered gaps in that the gap width from end to end is the same in our structures and the gap is closed at the position of the typical gap inlet for the incident light [17,18]. For these reasons, the electromagnetic anti-node is excited at the sharp edge of two tapered sections, i.e. the crossing position of the air-slots, where the concentration of the THz radiation is maximized, and the nodal point is created at the closed end of the air-slot at the same time. As a result, the requirements for the excitation of the quarter-wavelength fundamental mode are fully satisfied.

In addition, the realization of high tunability is important to validate our observations and to intensify our understanding. We numerically investigated the dependence of the resonance frequency on the length of air-slots independently. First, we controlled the peak position of
the quarter-wavelength fundamental mode by changing the length $L_2$, as shown in Fig. 4(a). In this case, the length $L_1$ is set to be the same in order to fix the half-wavelength resonance frequency. The half-wavelength resonant frequency is therefore almost independent on $L_2$ [red squares, Fig. 4(a)]. Figure 4(a) shows the tunability of the quarter-wavelength fundamental mode, following the guided curve of $\lambda_f = 4L_2$ well [dotted black curve], except for the slight peak position shift due to the strong coupling between the two adjacent resonant modes. In the same way, we realized the tunability of the half-wavelength fundamental mode in the condition of $L_2 = 270$ $\mu$m as shown in Fig. 4(b). The tunability characteristics verify that each fundamental mode is independently excited under the corresponding structural parameters: the length $L_1$ of the oblique air-slots for the half-wavelength mode and the length $L_2$ from the crossing position to the end of the center air-slot for the quarter-wavelength mode.

4. Conclusion

In conclusion, we have presented new phenomenon, the quarter-wavelength resonance behavior in planar plasmonic metamaterials consisting of asymmetrically coupled air-slots. Based on the phenomenon, the monopole resonators have been achieved and the tunability of the resonators has been realized by the appreciable variation in geometrical parameters such as the length of air-slots. According to the THz experiments and simulation results, the origin of the quarter-wavelength fundamental mode is associated with the formation of an artificial electromagnetic anti-node at the crossing position of the air-slots and a nodal point at the end of the air-slot. The electromagnetic anti-node appears at the crossing position of air-slots where the strong concentration and oscillation of the electric field occurs due to the effect of the sharp edge of the two tapered metal plates. The planar plasmonic metamaterial structures that generate the quarter-wavelength fundamental mode provide a new method for controlling the light-matter interactions and open the possibility for designing and developing photonic devices that require further size reduction technology.

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