High refractive index metamaterials using corrugated metallic slots

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Abstract: We report on a method for realizing high refractive index metamaterials using corrugated metallic slot structures at terahertz frequencies. The effective refractive index and peak index frequency can be controlled by varying the width of the air gap in the corrugated slot arrays. The phenomenon occurs because of the secondary resonance effect due to the fundamental inductive-capacitive resonance, which generates a red-shift of the fundamental resonance determined by twice the length of the corrugated metallic slots. In addition, multiple gaps in the corrugated slots act as plasmonic hotspots which have the properties of three-dimensional subwavelength confinement due to extremely strong enhancement of the terahertz waves. The versatile characteristics of the structures may have many potential applications in designing compact optical devices incorporating various functionalities and in developing highly sensitive spectroscopic/imaging systems.

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The exploitation of the characteristics of resonance in metallic structures, at scales much smaller than the wavelength of light, has attracted much attention recently. The aim is creating artificial materials, called metamaterials, with effective electromagnetic responses; and manipulating light for realizing advanced optical devices and systems. Until now, metamaterials have realized unusual optical phenomena, such as negative refractive index [1–4], optical cloaking [5], unnaturally high refractive index [6–8], superlens effect [9, 10], perfect absorber [11], and so on. The unit cells, called meta-atoms, consisting of metamaterials are taken to be subwavelength and the geometrical dimensions generate...
structural resonances. Therefore, controlling the electromagnetic properties of metamaterials is directly connected to the structural design and dimensions of the unit cells.

Split-ring resonators form basic unit cells of negative-index metamaterials and assembled metal rod structures are used to generate negative permeability for negative-index metamaterials, to manipulate resonance properties for plasmonic rulers, and to realize electromagnetically induced transparency-like phenomenon [2, 12, 13]. More recently, specifically designed unit cells have been proposed for realizing optical devices with customized functionalities in a wide range of wavelengths [7, 8, 14–20]. In particular, an “I” shaped metallic patch structure was used to realize unnaturally huge refractive index [7, 8]. M. Choi et al. reported that a broadband, high refractive index could be achieved by terahertz (THz) metamaterials composed of unit cells that are formed by “I”-shaped metallic patches [8]. For potential applications in biology and optoelectronics requiring highly sensitive spectroscopic/imaging systems, new functional devices with subwavelength, controllable, large field enhancement, still having the property of high index of refraction, should be developed [21]. The corrugated structures are a candidate for realizing the devices, because metamaterials based on the structures have widespread availability in the way that the structural diversity and new optical phenomena, such as localized spoof plasmons, can be realized [22–28]. The plasmonic air-slot enabling the optical manipulation of resonance mode was therefore modified to have multiple subwavelength areas formed by corrugating the sidewalls of the slots.

In this paper, we demonstrate a method for realizing high refractive index metamaterials, using corrugated metallic slot structures, with multiple plasmonic hotspots attributed to three-dimensional subwavelength confinement of the electromagnetic waves. The corrugated air-slots were designed to have several narrow air-gaps inside the slot area. The overall length of the slots determines the characteristics of the fundamental mode having a half-resonant wavelength. The narrow air-gaps are shown to be capable of strongly confining the THz waves in three-dimensional subwavelength areas, similar to hotspots on a bare metal surface. As the width of the air-gaps decreases, the spectral resonance peaks shift to the longer wavelength region and the field enhancement in the plasmonic hotspots extremely increases. The corrugated metallic slot structures can be therefore considered a metamaterial with effective high refractive index, while showing multiple, three-dimensional, subwavelength, extremely strong confinement of the THz waves. This originates from the secondary resonance effect due to the fundamental inductive-capacitive resonance appearing in facing semi-loop metallic shapes [29–32]. The theoretical simulation results using the three-dimensional finite-difference time-domain (FDTD) technique are well consistent with their corresponding experimental results.

2. Experimental details

The corrugated slot structures that consist of a periodic arrangement of air-slots were fabricated on 10-μm-thick stainless steel film as shown in Fig. 1. The structures were directly fabricated by femtosecond pulsed laser micromachining method. The corrugated air-slots were arranged in a rectangular pattern with x- and y-axis periods of $P_x = 400$ μm and $P_y = 500$ μm, respectively. The corresponding Rayleigh frequencies of $f_R = c/P_x$ (or $c/P_y$) at normal incidence were designed to be outside the spectral region of interest. The unit cell with its relevant dimensions is shown in the inset of Fig. 1. The vertical and horizontal lengths of a basic air-slot aperture are $L_y = 400$ μm and $L_x = 80$ μm, respectively. The fundamental resonance mode, also-called half-wavelength resonance, is determined by twice the length of the slots. When the polarization of the THz waves is along the x-direction, the corresponding half-wavelength resonance mode, $\lambda_y = 2L_y$, is located at the frequency of 0.38 THz.

Five pairs of two facing rectangular bumps with width $a_1 = 10$ μm were designed perpendicularly to the both walls of the slot. The bumps are symmetrically arranged around the center of the slot and the gap width $d$ formed by the two facing bumps is varied from 20 to
5 μm. The key feature of this structure is that the geometrical regions between the two facing bumps are extremely smaller than the wavelength. The incident light can be strongly confined in a three-dimensional region of subwavelength dimensions due to local capacitor effect [32]. The five gap regions with width even up to 5 μm, as shown in the inset of Fig. 1, are expected to show strong subwavelength confinement of the THz waves.

The measurements are performed using a standard THz time-domain spectroscopy technique [33–35]. A p-type InAs wafer and photoconductive switching antenna are employed for generating and detecting THz pulses in the frequency range of 0.1–2.0 THz, respectively. All measurements are performed at normal incidence with the collimated THz waves between two parabolic mirrors. Using the fast-Fourier transform method, the measured time-domain signals are transformed to the frequency-domain spectra. To reveal the numerical characteristics of the structure, numerical simulations based on the finite-difference time-domain (FDTD) method are performed. In simulation, the metallic film is regarded as a perfect conductor because most metals act as a perfect conductor in THz frequency. The complex dielectric constant of the metallic film is extracted from the optical constant of Al using the Drude model [36]. The electric-near field distributions and transmission spectra are simulated under the conditions of periodic boundary in the in-plane direction and of perfectly matched layers in the normal direction of the film.

3. Results and discussion

Figure 2(b) shows the measured transmission spectra from the corrugated slot structures with different gap width of \(d = 80 \, \mu m\) (Sample E), 20 μm (Sample C), 10 μm (Sample B), and 5 μm (Sample A), shown in the microscopic images of Fig. 1(a). All the structures have an equal length of \(L_y = 400 \, \mu m\) and, therefore, fundamental resonance can be expected at the same frequency of 0.38 THz due to the half-wavelength resonance mode determined by \(\lambda_y = 2L_y\). However, in the measured spectra, aside from the resonance shift due to the difference between the widths of the straight slots (Sample D and E) [37, 38], the resonance peaks
strongly shift to a longer wavelength region when the gap width of the air-slots decreases. We note that the gradual red shift of the resonance peak is distinguished from that of the result measured from the straight slot structures of $L_x = 5 \mu m$ [Sample D, shown in the green curve in Fig. 2(b)]. This implies that the strong red shift is not directly associated with the reduction of the total slot width, but has relevance to the bumps in the corrugated slot structures. The simulated transmission spectra shown in Fig. 2(c) are almost identical with a very good agreement with the experimental results, except for the relatively stronger red shift of the spectral peak values and amplitudes.

![Fig. 2. (a) Microscopic images of the unit cells of five metamaterials with different gap width of $d = 5 \mu m$ (Sample A), 10 \mu m (Sample B), 20 \mu m (Sample C), and 80 \mu m (Sample E). The unit cell of Sample D has a straight slot of the width 5 \mu m. (b) and (c) Normalized transmission amplitudes measured from five metamaterials and simulation results based on FDTD method, respectively. (d) Resonance peak values extracted from experimental (blue triangles) and simulation (blue squares) results and scale parameters S (blue circles). The red ones represent the corresponding effect dielectric constants. All the curves indicate the fitting curves. (e) Electric field intensity distribution simulated with Sample A.]

The resonant frequencies extracted from the experimental and simulation results shown in Fig. 2(b) and 2(c) are presented in Fig. 2(d). From the corresponding resonance wavelengths $\lambda_{res}$ and the half-wavelength resonance mode $\lambda_c$ due to the fundamental slot with the length of $L_y = 400 \mu m$, we calculate the effective dielectric constants given by $\varepsilon_{eff} = \sqrt{\varepsilon_{ref} \lambda_c / \lambda_{res}}$, as shown in the red triangles and squares in Fig. 2(d). This implies that the corrugated air-slots can be regarded as straight slots filled with the effective medium with the effective dielectric constant. In other words, the optical properties observed in the structures correspond to the results measured in the samples with effectively longer air-slots than the original ones.

The red-shift arises from the secondary resonance effect due to the fundamental resonance frequency of split-ring resonators (SRRs) formed by the bumps on the walls of air-slots, approximately given by $\omega_0 = 1/\sqrt{LC}$, where $L$ is the loop inductance and $C$ is the air-gap capacitance. The major contribution to the resonance shift is the change of the air-gap...
capacitance, since the increase of the loop inductance is not prominent when the air-gap width varies from 20 to 5 μm, whereas the air-gap capacitance dramatically increases with decreasing gap width. We expect the air-gap capacitance to be roughly in inverse proportion to the gap width according to local capacitor model [32]. To understand quantitatively the degree of the contribution to relative change of the resonance peaks, a scale parameter $S$ can be defined as:

$$ S = \frac{\alpha}{\sqrt{C_o + \beta C_j}}, $$

where $\alpha$ is a constant that makes the values of $S$, the corresponding resonance frequencies obtained from this modeling method. $C_o$ indicates the effective capacitance corresponding to a primary resonance, which is the half-wavelength mode of the straight air-slot without bumps. $C_j$ indicates the air-gap capacitance appearing in the corrugated slot structures with SRRs. In the case of the straight slot, the value of $\beta$ becomes zero, whereas with decreasing gap width, the value of $\beta$ increases. This means that the value of $\beta$ at gap width of 5 μm is roughly four times larger than the one at gap width of 20 μm. Figure 2(d) shows the values of the scale parameter for all the samples and the corresponding effect dielectric constants. The overall tendency in the resonance red shift is well consistent with the experimental and simulation results.

Another important merit of the corrugated slot structures is that the electric field could be confined in extremely small subwavelength volumes at desired points as shown in Fig. 2(e). The electric field distribution shows strong subwavelength confinement inside the air-gaps formed by bumps. The thickness in the z-axis and the area of air-gap regions in the xy plane are much smaller than the wavelength of incident THz waves. In the case of Sample A, the degrees of field confinement along the x, y, and z-axes, given by $\lambda_{res}/d$ (or $a_j, t$) is roughly 220, 110, and 110, respectively. The volume area occupied by the confined electric fields versus unit volume for a single wavelength, $d a_j/\lambda_{res}^3$, is about $3.8 \times 10^{-7}$, which are surprisingly high three-dimensional subwavelength confinement. This arises from lighting rod effect induced by the electric field accumulation of a light source near subwavelength metal edges such as a metal gap [32]. The number and spatial position of the electric field confinement in a single slot are extremely controllable by designing proper structures. The designed narrow gaps in the corrugated slots can be therefore acted upon as multiple plasmonic hotspots, which have the same function as electromagnetic hotspots on metal surfaces. The corrugated slot structures can be exploited for hotspot engineering for many potential applications in developing highly sensitive spectroscopic/imaging systems.

After analyzing the properties of high refractive index metamaterials with multiple plasmonic hotspots, we carried out a numerical study in metamaterials with corrugated slots having the length $L_y = 800$ μm (twice the length of Sample A-E) to understand the mechanisms for optimization of the effective refractive index for a range of structural designs. The inset of Fig. 3(b) shows the resonance peak values extracted from the simulated amplitude spectra [Fig. 3(a)] of the THz wave transmission for metamaterials composed of the corrugated slots with length 800 μm. As shown in Fig. 3(b), the electromagnetic responses tuning the effective refractive index in the 800-μm-slot based metamaterials are more effective than in the 400-μm-slot based ones. The multiple plasmonic hotspots are still generated in a three-dimensional subwavelength region [Fig. 3(c)] and the efficiency of the near-electric field confinement is even strongly improved as shown in the intensity profile of the electric near-field [Fig. 3(d)]. It is quite obvious that further property improvement of effective high-refractive index and multiple plasmonic hotspots can be realized by increasing
local capacitance by reducing the width of air-gaps and by fabricating the metamaterial structures with proper designs.

![Image](image.png)

Fig. 3. (a) Simulated amplitude spectra of the THz wave transmission for metamaterials composed of the corrugated slots with the length of 800 µm. The gap width \(d\) is varied from 90 µm to 5 µm, while keeping the other parameters constant. (b) The effective dielectric constants calculated using the resonance peak values of the simulation results shown in (a) (black squares) and ones shown in Fig. 2(c) (red circles). The inset shows the resonant peak values extracted from the simulation results. (c) Spatial field distribution of the electric field intensity at a unit cell of the corrugated slot structure. (d) The intensity profile of the electric near-field in the cross-section at the center of the slot along the y-axis.

4. Conclusion

In conclusion, we have demonstrated a method for achieving high refractive index metamaterials with multiple plasmonic hotspots in three-dimensional subwavelength regions. The metamaterials composed of corrugated metallic slots with several narrow air-gaps inside the slot area have shown effective high-refractive index and multiple plasmonic hotspots formed by extremely strong confinement of the THz waves. The properties occur due to the secondary resonance effect originating from the fundamental inductive-capacitive resonance appearing in facing semi-loop metallic shapes of the corrugated air-slots. Optimizing the properties of effective refractive index and multiple plasmonic hotspots is possible by reducing the width of air-gaps and tuning the resonance peak by varying the length of the air-slots. The results, especially realizing the multiple plasmonic hotspots formed by a huge field enhancement in metamaterials, have offered invaluable insights into exploiting the metamaterials for hotspot engineering for potential applications in developing highly sensitive spectroscopic/imaging systems and for the realization of versatile optical devices including various functionalities.

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