Rotationally reconfigurable metamaterials based on moiré phenomenon

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Abstract: Exploiting moiré interference, we make a new type of reconfigurable metamaterials and study their transmission tunability for incident electromagnetic waves. The moiré pattern is formed by overlapping two transparent layers, each of which has a periodic metallic pattern, and the cluster size of the resulting moiré pattern can be varied by changing the relative superposition angle of the two layers. In our reconfigurable metamaterials, both the size and structural shape of the unit cell can be varied simultaneously through moiré interference. We show that the transmission of electromagnetic waves can be controlled from 90% to 10% at 11 GHz by experiments and numerical simulation. The reconfigurable metamaterial proposed here can be applied in bandpass filters and tunable modulation devices.

OCIS codes: (160.3918) Metamaterials; (350.2460) Filters, interference.

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1. Introduction

Metamaterials have attracted much interest in recent years due to their distinctive material properties, which are not found in nature, such as negative refraction, extreme chirality, and perfect absorption [1–3]. The artificial atoms forming metamaterials should be designed to be much smaller than the wavelength of incident light (typically less than one-tenth of wavelength) so that the metamaterial can be considered as a homogeneous medium for electromagnetic (EM) waves. Novel optical properties can be realized through the electric and magnetic responses of ingeniously designed metallic structures in the metamaterial while fulfilling the basic requirements of effective homogeneity. Typically, metal wires, split-ring resonators, and fishnet structures have been widely used as subwavelength structures (meta-atoms) of metamaterials to induce strong electromagnetic coupling between metamaterials and incident EM waves [4–7]. Through the intensive studies over last decade, metamaterials have been proven to be useful in cutting edge technologies such as cloaking, imaging beyond the diffraction limit, and graphene photonics [8–12].

Despite the versatile capabilities of metamaterials, their applications are limited by the lack of tunability and narrow operating bandwidth. Hence, tunable metamaterials have recently appealed to many researchers because of their active controllability and wide frequency range of operation [13]. To date, various types of tunable metamaterials have been proposed, such as phase-transition-driven metamaterials, metamaterials that are reconfigurable by electromechanical structure changes, electro-tunable metamaterials with carbon nanotubes and graphene, and stretchable metamaterials [12, 14–16].

Metamaterials that can be reconfigured through the structural transformation of meta-atoms allow us to control the transmission, reflection, and absorption of incident EM waves [17, 18]. However, previous works have focused only on the alteration in the resonance characteristics through changes in the shape and structure of the meta-atoms while maintaining the size of the unit cell and the lattice constant of the metamaterials. Therefore, the application fields of conventional reconfigurable metamaterials have been restricted by the low tuning depth and narrow bandwidth.

Here, we propose a new type of reconfigurable metamaterials using moiré interference to overcome aforementioned drawbacks. Moiré patterns are interference patterns formed when two or more periodic patterns or gratings are overlapped; they are very widely used in various industrial and optical science applications, such as super-resolution microscopy, image processing, and holographic interferometry [19–23]. By superimposing two identically patterned layers at various relative angles, a variety of interference patterns can be produced.

If we apply moiré interference to the design of metamaterials, the reconfigurable metamaterials with various sizes and shape of unit cell can be easily obtained without additional fabrication processes. Since the geometrical shape and size of the meta-atom are the crucial factors that determine the resonance feature of the metamaterials, we can control the transmission of electromagnetic waves by tuning the resonance frequency continuously via the structural change in the resulting moiré patterns. Our reconfigurable metamaterials are distinguished from previously suggested reconfigurable metamaterials in that both the lattice size and the shape of the cluster or unit cell can be changed simultaneously. As a result, these meta-devices exhibit high tunability and wide bandwidth.

2. Reconfigurable meta-device based on moiré patterns

A property of moiré patterns is that periodic clusters of various sizes and shape can be created by continuous changes in the superposition angle of two layers. For two layers with the same square lattice pattern, the periodicity of the newly created cluster is related to the angle between the two layers as follows,

$$p = \frac{p_0}{\sin(\theta / 2)} \qquad (0^\circ \leq \theta < 90^\circ),$$

where p_0 is the lattice constant of the original layers

For superposition with an arbitrary rotation angle, the clusters of the interference patterns do not form exact unit cells but make an overall statistically recursive quasi-periodic pattern. In other words, the k-space profile in the Fourier transform of the interference pattern has a broad distribution instead of a delta-function-type peak owing to their quasi-periodicity. Here, the maximum value in the k-space profile corresponds to the statistical periodicity.

As an illustrative example of our approach, we select a disk array as a basic pattern of the moiré reconfigurable metamaterials, although a variety of new moiré patterns can be made from other basic patterns. When the pattern element of each layer is a disk, as shown in Fig. 1(a), various moiré patterns are created with other periods that differ from the original lattice constant p_0, for the arbitrary superposition angle of 15°, 20°, 30°, 40°, and 45° as shown in Fig. 1(b)-(f), respectively. One can notice that the larger the superposition angle θ becomes, the more smaller clusters in new periodic patterns are obtained. In this paper, we focus on the specific superposition angles at which the cluster element of the moiré pattern becomes an exact unit cell for convenience of numerical simulation.

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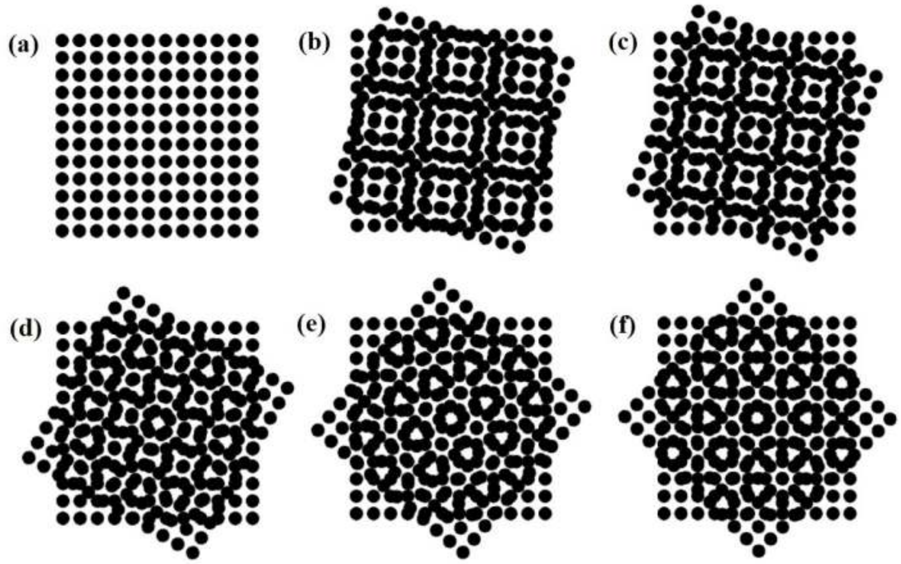

Fig. 1. Schematic view of two-layer superposition with periodic structure of metallic disks (radius of the disk: 1.2mm, unit cell: 3mm) for various rotation angles: (a) $\theta = 0°$, (b) $\theta = 15°$, (c) $\theta = 20°$, (d) $\theta = 30°$, (e) $\theta = 40°$, (f) $\theta = 45°$ (see Visualization 1).

3. Numerical simulation

As mentioned above, the generic moiré patterns have a statistical periodicity that is not exactly recursive when one layer is rotated by an arbitrary angle. Particularly, the cluster becomes an exact unit cell at specific angles $(2\times\sin^{-1}(1/\sqrt{(2m-1)^2+1}),\ \ m=1, 2, 3, 4,\ldots)$, as shown in Fig. 2(a)-(c). We numerically simulated transmission of EM waves for three of these cases [case 1: $\theta = 0$, case 2: $\theta = 2\times\sin^{-1}(1/\sqrt{10})$, and case 3: $\theta = 2\times\sin^{-1}(1/\sqrt{26})$]. Because the resonance frequency of the reconfigurable metamaterials depend on the size of the unit cell of the moiré pattern, we set the radius of the disk to 1.2 mm and the lattice constant to 3 mm in order to obtain a resonance frequency between 10 and 20 GHz.

The finite-difference time-domain method is used in all of the simulations in the microwave frequency regime. The thickness and permittivity of the base substrate made of Teflon are set to 240 μm and 2.17, respectively, which coincide with the real material parameters of the substrate. Unit cell images of the moiré pattern are shown in the Fig. 2(a)–(c). The simulated transmission and surface current densities in each case are depicted in Fig. 2(d) and 2(e), respectively.

In all of the cases, the lowest resonance mode of each reconfigurable metamaterial exhibits the characteristics of the typical Lorentz oscillator model which explains classically the interaction between EM waves and matter with bound electrons (i.e., a dielectric medium), because the metallic clusters are of isolated ring shapes. The resonance frequency of the lowest resonance mode of the meta-atoms in the transmission spectra decreases as the size of the cluster increases, as shown in Fig. 2(d). Figure 2(e) shows the simulated electric current and electric field intensity of the moiré interference pattern in cases 2 and 3. The gap between the meta-atoms formed by moiré interference dramatically decreases as the unit cell size of the meta-atoms becomes large, so very strong electric fields are induced between the gaps, as shown in Fig. 2(e). The narrow gap leads to a large increase in the capacitance of the meta-atom [24]. Thus, the above behavior of resonance frequency in the reconfigurable metamaterial stems from the changes in the capacitance as well as the inductance for different cluster sizes and shapes.

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In case 2, the electromagnetic resonance is located at 27 GHz, and in case 3, two electromagnetic resonances at 11 GHz and 17 GHz are observed in the simulation frequency regime of interest (Fig. 2). The second resonance at 17 GHz [Fig. 2(e)-III] in case 3 is a higher-order resonance distinguished from the fundamental dipole-type resonances [Fig. 2(e)-I in case 2 and Fig. 2(e)-II in case 3]. The intense fluctuation in the transmission spectrum at frequencies above 25 GHz in case 3 [Fig. 2(d)] are meaningless because in this frequency regime, the unit cell size becomes comparable to the wavelength of incident EM wave. (In other words, the unit cell size no longer satisfies the homogenous medium requirement that the unit cell size of a metamaterial should be sufficiently smaller than the wavelength.)

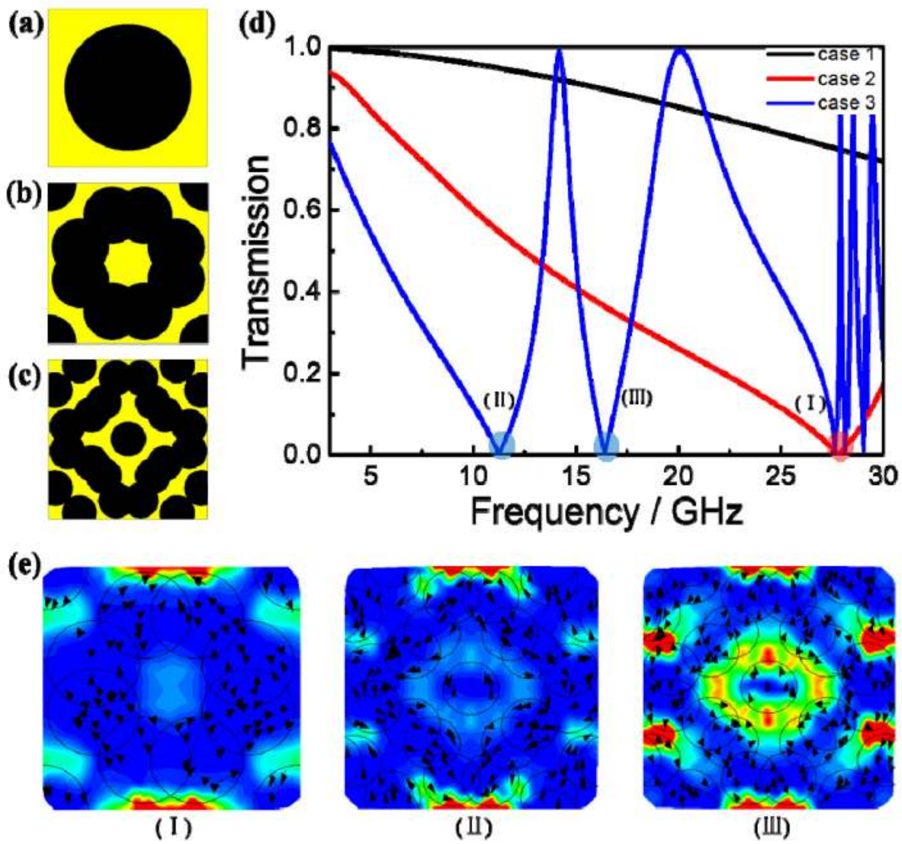

Fig. 2. Simulation results of transmission properties of the reconfigurable metamaterial based on moiré interferences: Schematic view of unit-cell structures for various rotation angles (a) 0° (case 1) (b) $2\times\sin^{-1}(1/\sqrt{10})^{\circ}$ (case2), and (c) $2\times\sin^{-1}(1/\sqrt{26})^{\circ}$ (case 3), (d) Simulated transmission spectra in case 1 (black line), case 2 (red line) and case 3 (blue line), (e) Surface current density plots in the meta-atom at resonance frequencies (I) in case 2 (at 27 GHz), (II) in case 3 (at 11 GHz), and (III) in case 3 (at 17 GHz). (The arrows indicate the directions of the surface currents and the red color means high intensity region of electric field.)

4. Experimental results and discussion

As the substance of the metallic pattern, Cu was etched on a commercially available Teflon substrate (Taconic TLY-5a) with a thickness of 18 µm. The radius of the disk-shaped unit cell is set to 1.2 mm, and the lattice constant is 3 mm, as in the simulation. The sample is 15 cm × 15 cm in size. For the setup of superimposed metamaterial layers, we need two subsidiary functional components. The first is a rotation stage that rotates one of the metamaterial layers with respect to the other by an arbitrary angle. The other is vacuum packing equipment made

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of polyethylene to compress the two overlapping layers. This compression process is important to reduce the surface contact resistance between the two metamaterial layers. Here, the vacuum pressure was set to 500 Torr.

We measure the transmission of EM waves to confirm the changes in the electromagnetic resonance of the reconfigurable metamaterial based on moiré interference. The experiment are performed using a typical RF transmission measurement setup. In the measurement, the sample is placed in the center between broadband horn antennas (LB-20245) with a working frequency range of 2–25 GHz. Microwave network analyzers (Agilent PNA-L) are used to analyze the transmission. The transmission value is obtained by dividing the measured value by the air transmission value without the sample.

Images of the metamaterial samples and transmission spectra obtained from the simulation and experiment in the three cases are depicted in Fig. 3. The black squares indicate the experimental data, and the red lines indicate the simulation results. The measured values in the experiment shown in Fig. 3 are consistent with the simulation results. Discrepancies between the simulation and experimental data can be explained by the unavoidable contact resistance between the two metal layers, which is not considered in the numerical simulations, as well as slight rotational misalignment, etc.

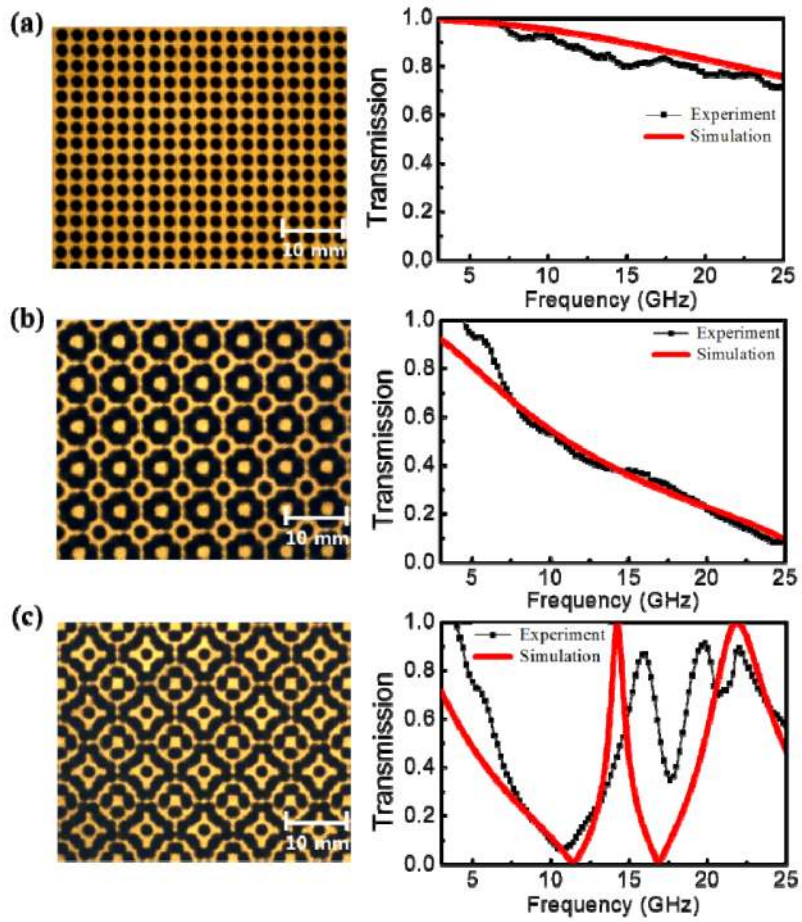

Fig. 3. The real images of the reconfigurable metamaterial for various rotation angles (on the left), experimental results (the black squares in the right graph) and numerical results (the red line in the right graph) of transmission spectra for each case 1 (a), case 2 (b), and case 3 (c), respectively.

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5. Conclusion

In summary, we designed a new type of reconfigurable metamaterial in which the size and shape of the cluster (or unit cell) can be changed simultaneously using moiré interference. We experimentally and numerically verified that the resonance feature of the reconfigurable metamaterial can be controlled through variable cluster structures in the gigahertz frequency range. In particular, the transmission of normally incident EM waves can be controlled from 90% to 10% at 11 GHz. Our reconfigurable metamaterial has a strong advantage over previously reported ones in that it is tunable in a wide frequency range and provides deep modulation depth. The design scheme of reconfigurable metamaterials using a moiré pattern is not limited to a disk array as the basic pattern of each constituent layer, but can be extended to various shapes such as a polygon, an oval, and a chiral shape. We expect that the reconfigurable metamaterials proposed here can be applied in various tunable EM filters and modulation devices.

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