Switching of plasmonic resonances in multi-gap resonators at terahertz frequencies

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Abstract

Switching plasmonic resonance modes in metamaterials have drawn enormous attention in recent years due to its great potential in applications in electromagnetic modulation and sensing. The switching process is essentially dependent on the connection way in the gaps of the metamaterial structure. In this work, we experimentally investigate the resonance switching effect in a multi-gap metamaterial structure at terahertz frequencies. It is found that a new inductor-capacitor circuit (LC) resonance would generate if the center gaps are totally connected. By decomposing the types of the connection in the center gaps, it is found that under horizontally polarized incidences, such switching effect is attributed to the horizontal connection (HC), while the vertical connection (VC) cannot bring any change in the transmission. This characteristic is further theoretically generalized to an active modulator by replacing the metallic HC to vanadium dioxide (VO2) HC, where the dynamic switching effect is observed. The detail study in the resonance switching effect may broaden the avenues toward the control of terahertz waves and the development of modulators and sensors in the terahertz band.

1. Introduction

Metamaterials have attracted great attentions in recent years, due to their unusual and exotic electromagnetic features that natural materials cannot realize [1]. They have been widely applied to control the radiations in the optical, infrared, terahertz and microwave ranges [2–11]. In the terahertz band, extensive studies on functional metamaterial devices have been well demonstrated, including invisibility cloaks, sensors, lenses, filters, modulators, etc [12–25]. In a general way, the essential rule for designing metamaterials is to build up certain resonance modes in the unit cell, such as inductor-capacitor circuit (LC) resonance, Fano resonance, dipolar resonance, and so forth. Each resonance mode has its unique properties and applications. The LC resonance is achieved by mimicking an LC oscillator, such as using a split-ring resonator (SRR), whose resonance frequency and resonance strength can be easily tuned by changing the gap width [26]. The Fano resonance is generally derived from asymmetric spit-ring resonators (TASRs), which can support extremely high-quality (Q) factor resonances with low radiative losses [27, 28]. The dipolar resonance can be directly excited by the external electromagnetic wave, and usually exhibit a robust resonance which is hardly to be altered [15]. However, these studies mainly focus on independent resonance and rarely consider the resonance switching effect. It is of particular importance to study the resonance switching effect in metamaterials, which can significantly promote the applications of all kinds of resonances on the way from metamaterials to metadevices. To date, there have been a few works reporting such switching effect [29–39]. For example, an optically implemented broadband blueshift switch was realized by incorporating silicon as elements of the metamaterial resonators [29]. In addition, the resonance switch induced by the polarization conversion was observed in a metamaterial composed of liquid crystal and metallic wire grating [30]. Moreover, an ultrahigh Q-factor switch with large
tuning range is achieved by stretching the polydimethylsiloxane (PDMS) based parabolic-shaped metamaterial (PSM) [31]. In these researches, it is very important to understand the inner relationships between different resonance modes since the switching effect could be applied in the designs of plasmonic devices and metamaterial sensors.

In this work, we experimentally and theoretically demonstrate the resonance switching effect in passive planar metamaterials consisting of an array of multi-gap resonators in the terahertz band. It is observed that under horizontally polarized incidence, the VC in the gaps can only preserve the dipolar resonance at higher frequencies while the HC supports a new resonance —— LC resonance. By changing the types of the connections, it is found that the emergence of the LC resonance only happens under HC. The resonance is independent of the number of connections in the same category. To further apply such ability, we theoretically design an active resonance switch by incorporating phase change material vanadium dioxide (VO₂) HC into the multi-gap resonator. This particular scheme would tremendously expand the scope of novel metamaterial-based terahertz photonic devices.

2. Structure design

Figure 1 (a) illustrates the schematic of the designed multi-gap metamaterial. The metamaterial has two layers. The first layer is 630-μm-thick high-impedance silicon substrate, and the second layer is 200-nm-thick metallic structures. In order to reduce the non-radiation loss of the metal, we use aluminum with low joule loss as the metal material. Figure 1 (b) illustrates the schematic of the unit cell. The lateral dimension of the structure is \(a = 40\) μm with a square periodicity of 50 μm. There are four gaps in the outer square ring with the gap width \(g = 5\) μm, and one cut circle in the middle with radius \(r = 5\) μm. The line width of the structure is \(w = 4.5\) μm. Conventional photolithography was employed to fabricate the multi-gap metamaterial samples. Each sample consists of 200 × 200 unit cells. A microscopic image of the part of the fabricated sample is shown in figure 1 (c).

3. Sample characterization

The characterization of the metamaterial samples was carried out using confocal terahertz time-domain spectroscopy (THz-TDS) system with available band ranging from 0.1 to 3 THz [40]. Four parabolic mirrors in the THz-TDS system focuses the terahertz beam to a waist with a diameter of 3.5 mm, allowing the transmission of the terahertz beam through the 10 mm × 10 mm metamaterial samples at normal incidence. In order to avoid the absorption of terahertz waves by the water vapor in the atmosphere, all the measurements were carried out in a dry air environment with the humidity <5%. The amplitude transmission is extracted by \(|\tilde{r}(\omega)| = |\tilde{E}_s(\omega) / \tilde{E}_r(\omega)|\), where \(\tilde{E}_s(\omega)\) and \(\tilde{E}_r(\omega)\) are the Fourier transformed transmitted terahertz electric field of the sample and the reference (bare silicon with same thickness), respectively.

4. Results and discussion

The red curve in figure 2(a) illustrates the measured amplitude transmission \(|\tilde{r}(\omega)|\) through the multi-gap metamaterial with \(r = 5\) μm under x-polarized incidence. It can be seen that there is only one obvious resonance located at high frequency range around 2.51 THz. This high frequency resonance is dipolar resonance since it is derived from a dipole like charge distribution in the metamaterial structure, which will be discussed in detail at a later stage. Its relatively broad line shape is due to the strong radiative coupling to the free space. However, when
that the two-HCs metamaterial have more energy loss. This inference can be confirmed by the different surface current distributions extracted from simulations.

Figure 2. Measured (a) and simulated (b) amplitude transmission spectra of the metamaterial with \( r = 5 \, \mu m \) (red curve) and \( r = 0 \, \mu m \) (black curve), respectively.

In order to understand the inner mechanism of the above resonance variation behavior, we performed full-wave numerical simulations using finite-element time-domain (FDTD) method. In the simulations, the incident direction of the terahertz wave is set to along the \(-z\) direction, the polarization is along the \(x\) direction, as shown in figure 1(a). The simulation frequency range is set to 0 to 3 THz. The silicon substrate was modeled as a lossless dielectric with permittivity \( \varepsilon = 11.78 \), and the metal was modeled as aluminum with conductivity \( \sigma = 3.72 \times 10^7 \, S \, m^{-1} \). As illustrated in figure 2(b), the simulated amplitude transmission spectra \( \vert I(\omega) \vert \) of the metamaterials with different \( r \) agree well with the measured results in figure 2(a). This indicates that we could analyze such responses based on the electric field distributions and surface current distributions extracted from simulations.

Figure 3(a) illustrates the surface electric field distribution at the dipolar resonance frequency (at 2.51 THz) with \( r = 5 \, \mu m \). It can be seen that the electric field of the dipolar resonance mainly distribute at the gaps in the \(x\) direction. In order to look into the carrier distribution in detail, the corresponding surface current distribution is also extracted, as shown in figure 3(b). The symmetrical current distribution with respect to the \(x\) axis reveal four in-phase dipoles in the metamaterial structure (see the insets in figure 3(b)). When the center part is all connected, namely \( r = 0 \, \mu m \), it can be seen that there still exist dipolar effect, as shown in figures 3(c) and (d). Owing to the connections in the center, the effective length of the dipoles increases, resulting a redshift of the resonance frequency (see figure 2). The main difference in these two metamaterial structure cases is the newly emerged resonance at the low frequency of about 0.86 THz in the metamaterial with \( r = 0 \, \mu m \). It can be clearly observed in figure 3(e), the intense electric fields at 0.86 THz are confined in the top and bottom split gaps of the metamaterial. Moreover, with a closer look at the surface current distribution as shown in figure 3(f), we observe accumulation of opposite charges in these gaps, which means that they behave as two effective capacitors. All of these features indicate a clear LC resonance.

To acquire further understanding of the inner connecting characteristics in the cut circle, we partially connect the center of the metamaterial structure by using \( 8 \, \mu m \times 3 \, \mu m \) aluminum bars. When the connection bar is perpendicular to the direction of the electric field (see the first and second optical images at the right column of figure 4). The measured and simulated amplitude transmission spectra (see figures 4(a) and (b), respectively) and the corresponding surface current distributions (see figures 5(a) and (b), respectively) with one and two VCs are nearly the same as the case of the above investigated unconnected metamaterial structure. From their transmission contrast, it is found that the number of VC has no effect on the dipolar resonance. When the connection bar is parallel to the direction of the electric field (see the third and fourth optical images at the right column in figure 4). It can be seen from the measured and simulated amplitude transmission spectra (see figures 4(c) and (d), respectively) that the LC resonance and dipolar resonance can both appear regardless of one or two HCs. However, the LC resonance width of the two-HCs metamaterial is broader than that of the one-HC metamaterial. Specifically, the Q factor of the former is 2.7, and that of the later is 4.8, respectively, which means that the two-HCs metamaterial have more energy loss. This inference can be confirmed by the different surface...
current distributions shown in figures 5(c) and (d). The parallel surface current distributions of the two-HCs unit cell form two current loops, which would roughly lead to twice energy loss as compared to the one-HC case with only one current loop.

Based on the above analysis on the emergence of the LC resonance, an active modulator is further designed theoretically by replacing the connection made from metal to that made from phase change material VO₂, which has been widely used in composing active metamaterials in a broad spectral range. The conductivity of VO₂ is

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**Figure 3.** Simulated surface electric field (a), (c), (e) and surface current distributions (b), (d), (f) at the dipolar resonance frequency of 2.51 THz with $r = 5 \mu m$ (left), dipolar resonance frequency of 2.37 THz with $r = 0 \mu m$ (middle) and LC resonance frequency of 0.86 THz with $r = 0 \mu m$ (right), respectively. Insets of (b), (d) and (f): the black arrows illustrate the surface current direction, the '+' and '-' represent the sign of the accumulated charges at the end of the gaps.

**Figure 4.** Measured (a), (c) and simulated (b), (d) amplitude transmission spectra of the metamaterials with different types of connections. The right column: optical images of the metamaterials with different types of connections.
strongly dependent on temperature, which behaves as insulator at low temperature while conductor at high temperature. Specifically, its conductivity is around $10 \, \text{S m}^{-1}$ at room temperature ($23^\circ \text{C}$), and can increase to the order of $10^5 \, \text{S m}^{-1}$ as temperature increases [41]. The corresponding critical insulator-to-metal transition temperature is around $67^\circ \text{C}$, which is easy to achieve [42–46]. Here, in order to show a more basic integration, we simply give an example based on the one-HC metamaterial. As shown in figure 6(a), the VO$_2$ connection is integrated under the multi-gap resonator with dimensions of $l = 8 \, \mu\text{m}$, $d = 3 \, \mu\text{m}$, and thickness $t = 150 \, \text{nm}$.

We carried out numerical simulations to characterize the performance of this active modulator of resonance switching, in which the conductivity of VO$_2$ is changed. To make the simulated results reliable and achievable, the varying range of the VO$_2$ conductivity (from $5 \times 10^4$ to $5 \times 10^5 \, \text{S m}^{-1}$) was taken from the reported

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Simulated surface current distribution of the metamaterials with (a) One VC at the dipolar resonance frequency of 2.51 THz, (b) Two VCs at the dipolar resonance frequency of 2.51 THz, (c) One HC at the LC resonance frequency of 0.83 THz, and (d) Two HCs at the LC resonance frequency of 0.91 THz, respectively. Insets: the black arrows illustrate the surface current direction.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{(a) Schematic of the unit cell of the active modulator. The red bar is made of VO$_2$. (b) Simulated amplitude transmission spectra of the active modulator with different VO$_2$ conductivities.}
\end{figure}
experimental work in the terahertz regime, corresponding to the variation of temperature from about 51 to 88 °C [46]. Figure 6(b) illustrate the simulated amplitude transmission spectra of this structure. It can be seen that the LC resonance is gradually getting stronger as the temperature increases. At higher VO₂ conductivities, the gap is well connected, and thus the charges can easily flow across the gap. In this case, strong surface current loops are formed, as shown in the figures 7(a) and (b), indicating strong LC resonances. However, at lower conductivities, the charges at the gap hardly flow through the VO₂ connection. Thus, the surface current loops are very weak (see figures 7(c) and (d)), leading to reduced LC resonance strength.

5. Conclusions

In conclusion, the switching effect of plasmonic resonance modes in multi-gap resonators was experimentally demonstrated in the terahertz regime. Detail analysis proves that the resonance switching effect mainly depends on the HC instead of the VC under horizontally polarized incidences. It can be deduced from the structure symmetry that under vertically polarized incidences, the mode transition effect will mainly depend on the VC. A distinct modulation behavior at the LC resonance is observed by theoretically incorporate the VO₂ in the gap of the metamaterial. The proposed metamaterial structure demonstrates a new scheme to alter the resonance mode which could lead to the development of novel terahertz modulators and sensors.

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