Tunable circular dichroism of chiral metamaterial based on phase transition of vanadium dioxide (VO$_2$)

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Abstract

The circular dichroism effect characterized by different optical responses between left-handed and right-handed circularly polarized lights is widely applied for biological monitoring, analytical chemistry, and plasmonic sensing. Despite the fact that circular dichroisms are achieved by many conventional chiral and anisotropic metamaterials, dynamic and efficient modulation of circular dichroisms is still challenging. In this paper, we demonstrate a VO$_2$ embedded metamaterial enabling tunable chirality by taking advantages of the VO$_2$ phase transitions between insulators and metals. Specifically, by changing the laser power and the irradiated position on the metamaterial, the VO$_2$ phase transition takes place at the irradiated region and induces a tunable circular dichroism effect. This work provides a strategy for the active control and modulation of circular polarizations, which pays the way for applications in terahertz and microwave regions.

1. Introduction

In recent years, chiral metamaterials have been proposed and studied extensively for their unique electromagnetic (EM) properties, such as asymmetric transmission [1, 2], negative refractive [3, 4], circular dichroism (CD) [5–9], electromagnetic induced transparency [10, 11], and polarization conversion [12, 13]. Circular dichroism reflecting the difference in the absorption of circularly polarized light of opposite handedness, has been researched theoretically and practically in the aspect of biological monitoring, analytical chemistry, and plasmonic sensing [14–18]. Many researches have been carried out to pursue a large circular dichroism from microwave to visible regions. Three-dimensional and planar chiral metamaterials such as helix-shaped and L-shaped MMs [15, 19–21], bilayered structures [17, 22, 23], kirigami-based structures [24] and chiral oligomers [25, 26] have been designed to study the effect of CD and other chiroptical responses. However, for most traditional metamaterials, CD responses are untunable as soon as the structures are fabricated, which limits their applications in programmable metamaterial, holography and electromagnetic phase modulations.

To this end, functional materials such as graphene, liquid crystal, as well as GeSbTe (GST) and vanadium dioxide (VO$_2$) [27–34] are utilized to pursue dynamic controls of the CD effect based on their unique properties. Among which VO$_2$ stands out with an abrupt insulator-metal transition leading to dramatical changes in electromagnetic properties at temperatures around 68 °C, which makes the VO$_2$ phase transition a new approach to control CD. Recent researches on VO$_2$ based metamaterials have been reported. However, previous works only show CD tunability in the aspect of intensity, and the controllable frequency selectivity is still not involved.
In this paper, we report tunable CD effects with both intensity and frequency selectivity in VO₂ based chiral metamaterial. The proposed bilayered metamaterial is composed of periodic VO₂ arcs on the top layer and periodic silver arcs on the bottom layer. By adjusting the laser energy and irradiation position on the VO₂ arc, the insulator-metal transition takes place at the irradiated region that generates tunable CD responses. The flexible structure promises potential applications in CD switches, filters, and modulators.

2. Design and experiments

The schematic view of the chiral VO₂ metamaterial is shown in figure 1. The VO₂ based metamaterial is based on a bilayered double-arc resonator (DAR) structure which consists of periodic VO₂ arcs on the top layer and periodic silver (Ag) arcs on the bottom layer of the glass substrate, as shown in figures 1(b) and (c). The VO₂ arc and the Ag arc arc are concentric at Z-axis with the same radius of r = 2.9 mm and the same width of w = 0.8 mm. The central angles of the VO₂ and Ag arcs are θ = 120° and φ = 90°, respectively. The period of the unit cell period is p = 10 mm and the height of the SiO₂ substrate is h = 2 mm.

In the simulation, the commercial finite integration package (COMSOL Multiphysics) is used to investigate the electromagnetic wave propagations. The periodic boundary conditions are applied along the x–y plane (x and y directions). The relative permittivity of SiO₂ substrate with negligible loss is set 3.9, and the silver arc is taken as a perfect conductor in microwave region. The VO₂ film can be regarded as a mixture of an insulting matrix and a conductive phase, and its complex dielectric properties in the microwave band can be described with the Bruggeman–Drude model [42] as
\[
\varepsilon = \varepsilon_2 + \frac{(1 - \phi)^2[(\varepsilon_2 / \varepsilon_1) - 1]^2}{2} - \varepsilon_1[(\varepsilon_2 / \varepsilon_1) - 1] \\
\times \sqrt{(1 - \phi)^4[(\varepsilon_2 / \varepsilon_1) - 1]^2 / 4 + (1 - \phi)^2(\varepsilon_2 / \varepsilon_1)}
\]

where φ is the volume fraction of the conductive phase, and ε₁, ε₂, ε₃ are the complex dielectric constants of the matrix and conductive phase, respectively. However, the dielectric mixture behavior of VO₂ thin films at microwave frequencies is not strongly frequency dependent, and it is not significantly affected by the value used for ε₁ and ε₂. Therefore, in this work, the permittivity of VO₂ arc (ε₃) can be treated as constant of ε₃ = 9 for both insulting and metallic states [38], and the conductivity of VO₂ is set as 200 S m⁻¹ when it is in the insulating state.

In the sample fabrication, the VO₂ arc is deposited on the top layer of the glass substrate by E-beam evaporation with thickness around 2 μm, and the Ag arc is then deposited on the bottom layer by thermal evaporation. The fabricated sample is inserted into the rectangular X band (10 ~ 22 GHz) waveguide to obtain...
transmission parameters of RCP and LCP incidence. In the experiment, a femtosecond laser with a center wavelength of 1040 nm is applied to irradiate the VO$_2$ arc. By changing the laser power, the laser induces phase transitions at the positions when the local temperature exceeds the critical threshold. The pulse duration is 50 fs, repetition rate is 100 MHz and the spot diameter (at 1/e$^2$) is adjustable. By applying the half-wave plate, the laser power can be adjusted between 0 and 1 W.

Figure 2. Transmission and CD properties of DAR under circular polarized wave excitation with $\theta = 120^\circ$ and VO$_2$ conductivity of $\sigma_{\text{VO}_2} = 10^5$ S m$^{-1}$. (a) Transmission spectra. (b) CD spectrum.

Figure 3. The electric current density and electric field distributions of the top and bottom arcs at resonant frequencies of 13.3 GHz and 16.6 GHz.
3. Simulation and discussion

By COMSOL Multiphysics simulation, the complex frequency-dependent $S$ parameters ($S_{11}$ and $S_{21}$) are obtained and the transmission is calculated by $T(\omega) = |S_{21}|^2$. In particular, circular dichroism (CD) is defined as $CD = T_{RCP} - T_{LCP}$, where $T_{RCP}$ and $T_{LCP}$ denote the transmission of RCP and LCP light. Figure 2 depicts the simulated transmission and the CD spectrum of the chiral metamaterial with $\theta = 120^\circ$ and the VO$_2$ conductivity of $\sigma_{\text{VO}_2} = 10^5$ S m$^{-1}$, assuming the metal state of the VO$_2$. Two distinct transmission valleys are observed at approximately 13.3 GHz and 16.6 GHz for RCP and LCP incidence, respectively. The transmission difference of $T_{RCP}$ and $T_{LCP}$ lead to the CD effect. As a consequence, one evident CD peak appears at 16.6 GHz with a relatively large CD value of 0.719, and one evident CD valley appears at 13.3 GHz shown in figure 2(b).

For a better understanding of the CD effect, the electric current density and electric field distributions of the metamaterial structure under RCP and LCP incidence is studied with the setting of $\theta = 120^\circ$ and $\sigma_{\text{VO}_2} = 10^5$ S m$^{-1}$. As shown in figure 3, at 13.3 GHz the stronger current flow and electric field distributions emerge under RCP incidence, which indicates a powerful twisting effect compared with the LCP condition. The two arcs are strongly coupled and further induce a lower RCP transmission. The similar phenomenon shows up under LCP incidence at 16.6 GHz, then a lower LCP transmission are observed in the spectra. Therefore, inside the metamaterial structure the DAR can be regarded as a coupled resonator system in which the strong chiral response comes from the coupling between the two arcs. Moreover, the surface currents on the top and bottom arcs flow in the same direction at 13.3 GHz and against each other at 16.6 GHz. The dotted arrows represent the equivalent electric dipole moments in the arcs and reveal both the bonding and antibonding modes are excited in the DAR structure under LCP and RCP incidence, respectively [43].

Figure 4. Measured and numerical simulated CD spectra with whole VO$_2$ arc irradiated by the laser spot. (a) Experimental CD spectra under different laser powers. (b) Simulating CD spectra with various conductivity of VO$_2$ ($\sigma_{\text{VO}_2}$).
The circular dichroism spectra of the hybrid chiral metamaterial are experimentally and theoretically characterized under different laser powers at room temperature (25 °C) and the whole VO₂ arc is covered by the laser spot. As the incident laser power is increased, the CD peak increases sharply with small frequency deviation. When the incident power is 0 mW, the valley and peak numbers of CD are −0.125 and 0.287, respectively. The CD effect is strengthened gradually with continuous increasing of the laser power. When the incident power is increased to 978 mW (the highest available power), the valley and peak numbers are −0.374 and 0.674, respectively. The simulated CD spectra of the metamaterial are shown in figure 4(b) with the conductivity of VO₂ ranging from 200 to 1 × 10⁵ S m⁻¹. The magnitude at CD peak increases with the conductivities, which coincides with the experiment results. It is worth noting that the result of simulated CD at 200 S m⁻¹ is smaller than that of the experimental result at 0 mW. This is probably due to the impurities in vanadium dioxide during fabrication, which induces a raise of the electrical conductivity. This findings indicate that the conductivity of the VO₂ improves with the increasing laser powers, which the metallic VO₂ induces a stronger coupling between the two arcs and a larger CD effect.

The chiral metamaterial also exhibits frequency tunability of the CD effect by manipulating the laser irradiation on the top arc. The laser power is set as 978 mw with a spot size of 6 mm. By changing the laser spot position on the VO₂ arc, the central angle of the arc under laser irradiation is adjusted from 70° to 120° with a step of 10°. Figure 5(a) is the schematic diagram of the phase transition process with different laser coverage angles. It is assuming that the VO₂ phase transition takes place in the laser irradiated region and the other part of the arc remains insulating state. Therefore, in the simulation the conductivity of the metallic part with laser spot on is set to 10⁵ S m⁻¹ and the other part is set to 200 S m⁻¹. The other settings are the same as the previous simulation. Figure 5(b) shows the experimental and simulated CD spectra with different laser irradiation angles on the VO₂ arc. It is clear that the simulation results are in good agreements with the performed experiments, which verifies the active tuning of the chiral structure designed. It is noticable that the experimental CD results

Figure 5. (a) Schematic diagram of the laser coverage central angles(θ) changing from 70° to 120°. (b) Measured (under 978 mW power) and numerical simulated (σ_{VO₂} = 10⁵ S m⁻¹) CD spectra of the chiral metamaterial with different coverage angles on the VO₂ arc.
are a little bit smaller than the corresponding simulation ones. This is mainly due to the manufacturing errors and the loss of laser energy in the experiment. The CD effect can be adjusted in a long range and the peak values more than 0.6 are observed from the experiment results. In order to attain the connection between laser spot position and the tunable CD effect, more detailed simulations are performed by changing the laser coverage angles on the VO₂ arc from 60° to 120° in step of 10°. Figure 6 shows the CD map of the chiral metamaterial with different laser irradiation conditions on the VO₂ arc. It can be seen that as the coverage angles increase, the CD peaks undergo a red shift from 21 GHz to 16 GHz. Therefore, the working frequency of the CD effect is tunable by adjusting the laser coverage position on the VO₂ arc. In other words, the laser induced phase transition process of VO₂ enables the tunable CD effect to meet different requirements of working conditions.

4. Conclusion

In conclusion, we have numerically studied and experimentally verified a VO₂ based metamaterial to achieve dynamic and efficient control of circular dichroisms. The tunable CD effect is observed in the chiral metamaterial from both simulation and experiment results, and the tunability originates from the laser induced ITM transition of VO₂. In particular, by changing the laser power and the irradiated position on the VO₂ arc, the phase transition may take place where the temperature is above the critical number and the operating frequency can be dynamically adjusted over a wide wavelength range. This study provides a general platform for the design

Figure 6. The 3-dimensional (a) and 2-dimensional (b) CD colormaps of the chiral metamaterial with different laser coverage angles(θ).
of active control and modulation of circular polarizations, which can be used in the fields of enantiomer recognition, analytical chemistry and molecular sensor.

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