Actively Tunable and Polarization-Independent Toroidal Resonance in Hybrid Metal-Vanadium Dioxide Metamaterial

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Abstract
A tunable toroidal resonance generated in hybrid metal-vanadium dioxide metamaterial, which is composed of rectangular aluminum split ring interconnected with VO₂ strips, is proposed and illustrated in this paper. Simulation results show that the toroidal dipolar resonance is generated by two reversed closed-loop poloidal currents co-excited by aluminum and vanadium dioxide, and the toroidal dipolar resonance is insensitive to the polarization angle because of symmetrical structure. In addition, the calculated scattered powers show that the toroidal dipolar resonance is remarkable and plays a dominant role in the vicinity of transmission dip. Moreover, the amplitude of toroidal resonance can be actively tuned by conductivity of VO₂, and theoretical fitting is carried out to further reveal the physical mechanism. The fitting results indicate that the physical mechanism can be attributed to the variation of overall damping rate caused by tuning conductivity of vanadium dioxide. This work can enrich the actively tunable toroidal dipolar metamaterial and have potential applications in terahertz high-Q-factor sensors.

Keywords Toroidal resonance · metamaterial · vanadium dioxide · actively tunable · polarization-independent

Introduction

Toroidal resonance, which can be produced by two reversed closed-loop poloidal currents, was initially proposed by Zel’dovich in 1957,¹ and is found in nuclear physics and solid state physics.² It has unique electromagnetic characteristics, such as a high Q-factor and circular dichroism,³ and is considered as a counterpart of fundamental electric and magnetic resonance. However, toroidal dipolar resonance is always accompanied by electric and magnetic resonance in natural materials, and its electromagnetic scattering power is usually masked by electric and magnetic dipoles.³ Therefore, its wider application has faced difficulties, and relevant studies almost came to a standstill until the emergence of metamaterials. Metamaterials are usually composed of artificial resonators scaled in sub-wavelength and have many unusual characteristics that are unattainable in natural materials. Therefore, metamaterial is regarded as an emerging field for extensive exploration of novel electromagnetic devices.¹⁻¹¹

Recently, the toroidal dipolar response caused by 3D metamaterial in the microwave regime was observed in experiment,¹² in which toroidal dipolar resonance is remarkably strengthened and higher than other multipoles. Hence, toroidal resonance in metamaterials has attracted considerable attention and unveils a new perspective in toroidal resonance applications.¹³⁻¹⁹ Currently, actively tunable electromagnetic characteristics in metamaterial have attracted considerable attention for practical requirements, and various approaches are proposed.²⁰⁻²⁶ In these approaches, phase change materials are incorporated into metamaterials to achieve active manipulation of toroidal resonance, which is considered an efficient method. For instance, Zhou et al. proposed a Si array and Ge₂Sb₂Te₅ (GST) hybrid metamaterial and investigated the radiation manipulation of toroidal resonance via tuning the crystallization states of GST.²⁶ Among phase change materials, vanadium dioxide (VO₂) is regarded as representative because of its excellent transition behavior, which can change in the insulator phase and the metal phase by external triggering, such as optical, thermal and electrical excitation. Therefore, active manipulation in toroidal resonance metamaterial can be realized due to the transition behavior of VO₂. Song et al. gained active modulation of toroidal dipolar resonance by putting a VO₂ layer beneath...
the Au-based toroidal resonance structures. In these hybrid metal-VO₂ metamaterials with toroidal resonance, VO₂ mainly acts as a dielectric layer, and toroidal resonance is fairly sensitive to polarization, while polarization-independent toroidal metamaterial, especially based on metal and VO₂ hybrid resonators, is rarely proposed.

In this paper, polarization-independent toroidal resonance metamaterial is proposed, and its transmission spectra could be actively manipulated via phase transition of VO₂. Compared with previous hybrid metal-VO₂ metamaterial, VO₂ is acted as part of the hybrid resonator, which jointly excites toroidal resonance. Thus, the tuning characteristic is contrary to previous toroidal metamaterial hybrids with metal-VO₂. Therefore, this work is beneficial in enriching actively tunable toroidal dipolar metamaterial and has potential applications in terahertz high-Q-factor sensors.

**Structure Design and Simulation**

The proposed toroidal resonance metamaterial is a periodic hybrid structure based on SiO₂ substrate, and the unit cell includes an aluminum-based rectangular ring with four pairs of symmetrical split gaps and four VO₂ strips interconnected with middle aluminum strips, as shown in Fig. 1a. The dimensions of the cell are \( P_x = 150 \) µm and \( P_y = 150 \) µm in \( x \) and \( y \) directions, respectively, and the rectangular ring are \( L = 110 \) µm and \( W = 10 \) µm, as shown in Fig. 1b. The lengths of aluminum and VO₂ strips are \( W_1 = 28 \) µm and \( L_1 = 30 \) µm, and the gaps is \( g_1 = 2 \) µm. The thickness of aluminum-based rectangular ring, VO₂ strips and SiO₂ substrate are same (10 µm).

The simulation based on the commercial CST Microwave Studio package is carried on to validate the resonance behaviors of the proposed toroidal dipolar metamaterial. In the simulation, \( x \) and \( y \) axes are set as unit cell boundary, the \( z \) axis is set as a perfect match layer. The Drude model is adopted to expressed the optical characteristics of VO₂, \( \varepsilon(\omega) = \varepsilon_\infty - \frac{\sigma_0}{\omega^2 + i\gamma \omega} \), where \( \varepsilon_\infty \) and \( \gamma \) are 12 and 5.575 × 10⁴ rad/s, respectively. The plasma frequency \( \omega_p \) can be expressed by \( \omega_p^2(\sigma) = \frac{\sigma_0}{\omega_p^2(\sigma_0)} \) with \( \sigma_0 = 3 \times 10^4 \Omega^{-1} \text{cm}^{-1} \) and \( \omega_p(\sigma_0) = 1.4 \times 10^{15} \text{rad/s} \). While permittivity of aluminum is derived by Drude model with plasma frequency \( \omega_{PAL} = 2.24 \times 10^{16} \text{rad/s} \) and the damping constant \( \gamma_{PAL} = 1.22 \times 10^{15} \text{rad/s} \). In this paper, the conductivities of VO₂ are set from 1×10³ s/m to 2×10⁵ s/m.

**Results and Discussion**

When the initial conductivity of VO₂ is 2×10⁵ s/m, the transmission spectrum of proposed metamaterial with different polarization angles is shown in Fig. 2. As shown in Fig. 2, the proposed metamaterial resonates obviously at 1.45 THz, and quality factor \( Q \), which is defined as ratio of central frequency to resonant line width, is 96.4. Moreover, it exhibits polarization-independent properties when the polarization angle \( \phi \) varies from 0° to 90°, which can be attributed to its structural symmetry.

To further investigate forming mechanism, the electric fields, magnetic fields and surface current distributions of toroidal dipolar resonator at 1.45 THz for different polarization angles are simulated and displayed. Figure 3 shows the case when polarization angle \( \phi \) is 0°. As observed from Fig. 3a-c, a pair of opposite electric charges emerge in neighboring edges of horizontal VO₂ strips, and two reversed closed-loop poloidal currents are produced, which are distributed in sections I-II and sections III-IV. As a
result, magnetic dipoles with head-to-tail arrangement are produced, and a toroidal dipolar resonance along the x-direction is excited. The above mechanism is briefly demonstrated in Fig. 3d. Figure 4 shows the case when polarization angle $\phi$ is 90°. As shown in Fig. 4a to c, because of the symmetrical structure, a pair of opposite electric charges emerge in vertical VO$_2$ strips, and two reversed closed-loop poloidal currents are produced and distributed in sections I-IV and sections II-III. Therefore, magnetic dipoles arranged head-to-tail are produced, and a toroidal dipolar resonance along the y-direction is excited. The corresponding diagrammatic sketch of forming mechanism is shown in Fig. 4d. Meanwhile, the forming mechanism of toroidal dipolar resonance when polarization angle $\phi$ is 45° has also been studied and is demonstrated in Fig. 5. Magnetic dipoles arranged in head-to-tail are distributed in diagonal sections, so toroidal dipolar resonance is excited when the polarization angle $\phi$ is 45°.

As we previously mentioned, toroidal dipolar resonance in metamaterial is remarkably strengthened and higher than other multipoles. In order to quantitatively analyze its
contribution, the scattered powers excited in the proposed unit cell metamaterial are calculated by current density displacement. Figure 6 shows the calculated scattered powers when conductivity of VO$_2$ is $2 \times 10^5$ s/m and polarization angle $\varphi$ of incident plane wave is 0°, including electric dipole $P_y$, magnetic dipole $M_z$, toroidal dipole $T_y$, electric quadrupole $Q_e$ and magnetic quadrupole $Q_m$. In the vicinity of 1.45 THz, toroidal dipolar resonance strengthens remarkably and plays a prominent role, while the electric dipole $P_y$ is suppressed strongly; hence, resonance at 1.45 THz in transmission spectra can mainly be attributed to toroidal dipolar excitation.

Moreover, the proposed toroidal dipolar phenomena were able to be actively modulated by VO$_2$, as shown in Fig. 7. It can be clearly seen that the amplitude of toroidal resonance decreases as $\sigma$ of VO$_2$ decreases. Specifically, the toroidal resonance vanishes when $\sigma$ of VO$_2$ is 1000 s/m. It should be pointed out that this tuning characteristic is contrary to previous toroidal metamaterial hybrids with metal-VO$_2$. Meanwhile, the frequency of toroidal resonance exhibits a slight red shift, which can be attributed to the increase of resistance in split-ring resonators (SRRs) according to the resonant frequency expression $f = \frac{1}{2\pi} \left( \frac{1}{LC} - \frac{R^2}{4L^2} \right)^{\frac{1}{2}}$, where $L$, $C$ and $R$ are effective inductance, capacitance and resistance, respectively. To further investigate the physical mechanism underlying the tuning characteristic, the transmission features of the proposed toroidal resonance metamaterial are fitted by the Fano formula:

$$T = \left| a_1 + ia_2 + \frac{b}{\omega - \omega_0 + iy} \right|$$  \hspace{1cm} (1)

where $a_1$, $a_2$ and $b$ are constant, $\gamma$ and $\omega_0$ are the damping rate and resonant frequency respectively. It is clear that the fitted curves in Fig. 8 agree well with the simulated curves in Fig. 7. Figure 9 shows the damping rates of toroidal resonance cell when $\sigma$ of VO$_2$ is $2 \times 10^5$ s/m, 2x$10^4$ s/m, etc.
It can be clearly seen that damping rate $\gamma$ increases remarkably as $\sigma$ of VO$_2$ decreases, which is the main cause for tuning characteristics of the proposed toroidal dipolar metamaterial.

**Conclusions**

In conclusion, an actively tunable and polarization-independent toroidal resonance in hybrid metal-VO$_2$ Metamaterial is proposed and illustrated. Different from former hybrid metal-VO$_2$ metamaterial, the toroidal dipolar phenomenon is excited by metal and VO$_2$ hybrid resonator, which is composed of a rectangular aluminum split ring interconnected with four VO$_2$ strips. Simulation results show that the toroidal dipolar resonance is generated by two reversed closed-loop poloidal currents co-excited by aluminum and vanadium dioxide, and the toroidal dipolar resonance is insensitive to the polarization angle because of the symmetrical structure. The calculated scattered powers show that the toroidal dipolar resonance is remarkable and plays a dominant role in the vicinity of transmission dip. Moreover, the amplitude of toroidal resonance can be actively tuned by conductivity of VO$_2$. As conductivity of VO$_2$ decreases, the amplitude of toroidal resonance decreases and frequency exhibits a slight red shift. Specifically, the toroidal resonance disappears when the conductivity of VO$_2$ is 1000 s/m. To further reveal the physical mechanism, theoretical fitting is carried out, which indicates that the main reason is variation of overall damping rate caused by tuning the conductivity of vanadium dioxide. This work can enrich the actively tunable toroidal dipolar metamaterial, with potential applications in high-Q-factor terahertz sensors.

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**Conflict of interest** The authors declare that they have no conflict of interest.

**References**

1. I.B. Zeldovich, Electromagnetic interaction with parity violation. *Sov. Phys. JETP.* 6, 1184 (1958).
2. V.M. Dubovik, and V.V. Tugushev, Toroid moments in electrodynamics and solid-state. *Phys. Rep.* 187, 145 (1990).
3. M.H. Li, L.Y. Guo, J.F. Dong, and H.L. Yang, Resonant transparency in planar metamaterial with toroidal moment. *Appl. Phys. Express* 7, 082201 (2014).
4. E. Ponizovskaya Devine, Mid-infrared photodetector based on 2D material metamaterial with negative index properties for a wide range of angles near vertical illumination. *Appl. Phys. A* 127, 209 (2021).
5. S. Indrajeet, H. Wang, M.D. Hutchings, B.G. Taketani, F.K. Wilhelm, M.D. LaHaye, and B.L.T. Plourde, Coupling a superconducting qubit to a left-handed metamaterial resonator. *Phys. Rev. Appl.* 14, 064033 (2020).
6. M. Bakir, M. Karaaslan, F. Dincer, K. Delihacioglu, and C. Sabah, Tunable perfect metamaterial absorber and sensor applications. *J Mater Sci: Mater Electron* 27, 12091 (2016).
7. J.S. Hummelt, X. Lu, H. Xu, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, Coherent Cherenkov-cyclotron radiation excited by an electron beam in a metamaterial waveguide. *Phys. Rev. Lett.* 117, 237701 (2016).
8. D. Ziemiañiewicz and S. Zeliñska-Racyñska, Complex Doppler effect in left-handed metamaterials. *J. Opt. Soc. Am. B* 32, 363 (2015).
9. J.S. Mei, Q. Wu, and K. Zhang, Multifunctional complementary cloak with homogeneous anisotropic material parameters. *J. Opt. Soc. Am. A* 29, 2067 (2012).
10. W.C. Harris, D.D. Stancil, and D.S. Ricketts, Improved wireless power transfer efficiency with non-perfect lenses. *Appl. Phys. Lett.* 114, 143903 (2019).
11. J. Li, P. Yu, H. Cheng, W. Liu, Z. Li, B. Xie, S. Chen, and J. Tian, Optical polarization encoding using graphene-loaded plasmonic metasurfaces. *Adv. Opt. Mater.* 4, 91 (2016).
12. T. Kaelberer, V.A. Fedotov, N. Papasimakis, D.P. Tsai, and N.I. Zheludev, Toroidal dipolar response in a metamaterial. *Science* 330, 1510 (2010).
13. S. Xu, A. Sayanskij, A.S. Kupriyanov, V.R. Tuz, P. Kapitanova, and H.B. Sun, Experimental observation of toroidal dipole modes in all-dielectric metasurfaces. *Adv. Opt. Mater.* 6, 1801166 (2018).
14. Z. Liu, S. Du, A. Cui, Z.C. Li, Y.C. Fan, and S.Q. Chen, High-quality-factor mid-infrared toroidal excitation in folded 3D metamaterials. *Adv. Mater.* 29, 1606298 (2017).
15. J. Li, J. Shao, X. Li, Z. Shi, and Y.J. Wang, Incident-angle-insensitive toroidal metamaterial. *Opt. Express* 30, 8510 (2022).
16. C. Chen, K. Kaj, Y. Huang, X. Zhao, R.D. Averitt, and X. Zhang, Tunable toroidal response in a reconfigurable terahertz metamaterial. *Adv. Opt. Mater.* 9, 2101215 (2021).
17. T. Lei, T.Y. Xiang, J. Wang, R.S. Zhou, and X.W. Zhu, Dual-toroidal analog EIT with metamaterial. *Appl. Phys. Express* 14, 067001 (2021).
18. T. Guo, C. Chen, F. Yan, R. Wang, and L. Li, Controllable terahertz switch using toroidal dipolar mode of a metamaterial. *Plasmonics* 16, 933 (2021).
19. T. Xiang, T. Lei, T. Chen, Z. Shen, and J. Zhang, Low-loss dual-band transparency metamaterial with toroidal dipole. *Materials* 15, 5013 (2022).
20. B. Gerislioglu, A. Ahmadiavand, and N. Pala, Tunable plasmonic toroidal terahertz metamodulator. *Phys. Rev. B* 97, 161405 (2018).
21. M. Gupta, Y.K. Srivastava, and R. Singh, A toroidal metamaterial switch. *Adv. Mater.* 30, 1704845 (2018).
22. X. He, L. Tian, Y. Wang, J. Jiang, and Z. Geng, Active modulation and switching of toroidal resonance in micromachined reconfigurable terahertz metamaterials. *Results Phys.* 17, 103133 (2020).
23. Y. Sun, D. Liao, J. Xu, Y. Wu, and L. Chen, Active switching of toroidal resonances by using a Dirac semimetal for terahertz communication. *Front Phys.* 8, 602772 (2020).
24. X. Chen and W. Fan, Study of the interaction between graphene and planar terahertz metamaterial with toroidal dipolar resonance. *Opt. Lett.* 42, 2034 (2017).
25. Z. Liu, S. Du, A. Cui, Z. Li, Y. Fan, S. Chen, W. Li, J. Li, and C. Gu, High-quality-factor mid-infrared toroidal excitation in folded 3D metamaterials. *Adv. Mater.* 29, 1606298 (2017).
26. C.B. Zhou, S.Y. Li, M.H. Fan, X.F. Wang, Y.L. Xu, W.W. Xu, S.Y. Xiao, M.Z. Hu, and J.T. Liu, Optical radiation manipulation of Si-Ge2Sb2Te5 hybrid metasurfaces. Opt. Express 28, 9690 (2020).

27. Z. Song, Y. Deng, Y. Zhou, and Z. Liu, Tunable toroidal dipolar resonance for terahertz wave enabled by a vanadium dioxide metamaterial. IEEE Photonics J. 11, 1 (2019).

28. Z. Song, Y. Deng, Y. Zhou, and Z. Liu, Terahertz toroidal metamaterial with tunable properties. Opt. Express 27, 5792 (2019).

29. S. Xiao, T. Wang, T. Liu, X. Yan, Z. Li, and C. Xu, Active modulation of electromagnetically induced transparency analogue in terahertz hybrid metal-graphene metamaterials. Carbon 126, 271 (2018).

30. J. Huang, J. Li, Y. Yang, J. Li, J.H. Li, Y.T. Zhang, and J.Q. Yao, Broadband terahertz absorber with a flexible, reconfigurable performance-based hybrid-patterned vanadium dioxide metasurfaces. Opt. Express 28, 17832 (2020).

31. S. Malthesh and N. Krishnaswamy, Improvement in quality factor of double microring resonator for sensing applications. J. Nanophotonics 13, 026014 (2019).

32. G. Sun, S. Peng, X. Zhang, and Y. Zhu, Switchable electromagnetically induced transparency with toroidal mode in a graphene-loaded all-dielectric Metasurface. Nanomaterials 10, 1064 (2020).

33. G.D. Liu, X. Zhai, S.X. Xia, Q. Lin, C.J. Zhao, and L.L. Wang, Toroidal resonance based optical modulator employing hybrid graphene-dielectric metasurface. Opt. Express 25, 26045 (2017).

34. H.T. Chen, H. Yang, R. Singh, J.F. O’Hara, A.K. Azad, S.A. Trugman, Q.X. Jia, and A.J. Taylor, Tuning the resonance in high-temperature superconducting terahertz metamaterials. Phys. Rev. Lett. 105, 247402 (2010).

35. W.D. Wang, and J.G. Qi, Polarization-independent Fano metasurface with directional toroidal dipole for magnetic field tunability. Appl. Phys. Express 12, 065004 (2019).

36. A. Bhattacharya, K.M. Devi, T. Nguyen, and G. Kumar, Actively tunable toroidal excitations in graphene based terahertz metamaterials. Opt. Commun. 459, 124919 (2020).

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