Circular-polarization-sensitive absorption in refractory metamaterials composed of molybdenum zigzag arrays

MEIYAN PAN,1 QIANG LI,1,* YU HONG,1 LU CAI,1 JUN LU,1,2 AND MIN QIU1

1State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China
2phylujun@zju.edu.cn
*qiangli@zju.edu.cn

Abstract: Circularly polarized light (CPL) is utilized in various fields, including optical communication and biological imaging. To overcome the lack of circular-polarization-sensitive absorbers working at high temperature, a refractory and circular-polarization-sensitive absorber comprised of molybdenum zigzag arrays is proposed. At certain resonant wavelengths, one component of circular polarization is absorbed by confining electromagnetic field in the dielectric layer, while the other component is backscattered. The circular-polarization-sensitive absorber could be applied as a CPL thermal radiator as well as a reflective linear-to-circular polarizer. As a CPL thermal radiator, left-handed circular radiation and right-handed circular radiation are dominant at different temperatures, respectively. As a linear-to-circular polarizer, both perfect left-handed circularly polarized light and nearly perfect right-handed circularly polarized light are obtained.

© 2018 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

OCIS codes: (130.3060) Infrared; (130.5440) Polarization-selective devices; (160.3918) Metamaterials.

References and links

1. C. Wagenknecht, C. Li, A. Reingruber, X. Bao, A. Goebel, Y. Chen, Q. Zhang, K. Chen, and J. Pan, “Experimental demonstration of a heralded entanglement source,” Nat. Photonics 4(8), 549–552 (2010).
2. E. Karimi, S. A. Schulz, I. De Leon, H. Qassim, J. Upham, and R. W. Boyd, “Generating optical orbital angular momentum at visible wavelengths using a plasmonic metasurface,” Light Sci. Appl. 3(5), e167 (2014).
3. C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirtlyuk, A. Tsukamoto, A. Itoh, and T. Rasing, “All-optical magnetic recording with circularly polarized light,” Phys. Rev. Lett. 99(4), 047601 (2007).
4. S. M. Kelly and N. C. Price, “The use of circular dichroism in the investigation of protein structure and function,” Curr. Protein Pept. Sci. 1(4), 349–384 (2000).
5. L. Huang, X. Chen, H. Muhlenbernd, H. Zhang, S. Chen, B. Bai, Q. Tan, G. Jin, K. Cheah, C. Qiu, J. Li, T. Zentgraf, and S. Zhang, “Three-dimensional optical holography using a plasmonic metasurface,” Nat. Commun. 4(1), 2808 (2013).
6. J. Yeom, B. Yeom, H. Chan, K. W. Smith, S. Dominguez-Medina, J. H. Bahng, G. Zhao, W. S. Chang, S. J. Chang, A. Chuvilin, D. Melnikau, A. L. Rogach, P. Zhang, S. Link, P. Král, and N. A. Kotov, “Chiral templating of self-assembling nanostructures by circularly polarized light,” Nat. Mater. 14(1), 66–72 (2015).
7. Y. Zhao and A. Alù, “Tailoring the dispersion of plasmonic nanorods to realize broadband optical metawaveplates,” Nano Lett. 13(3), 1086–1091 (2013).
8. P. Ginzburg, F. J. Rodríguez Fortuño, G. A. Wurtz, W. Dickson, A. Murphy, F. Morgan, R. J. Pollard, I. Jorsh, A. Atrashchenko, P. A. Belov, Y. S. Kivshar, A. Nevet, G. Ankonina, M. Orenstein, and A. V. Zayats, “Manipulating polarization of light with ultrathin epsilon-near-zero metamaterials,” Opt. Express 21(12), 14907–14917 (2013).
9. M. Decker, M. W. Klein, M. Wegener, and S. Linden, “Circular dichroism of planar chiral magnetic metamaterials,” Opt. Lett. 32(7), 856–858 (2007).
10. A. Shaltout, J. Liu, V. M. Shalaev, and A. V. Kildishev, “Optically active metasurface with non-chiral plasmonic nanoantennas,” Nano Lett. 14(8), 4426–4431 (2014).
11. S. Kruk, B. Hopkins, A. Kravchenko II, A. Miroshnichenko, D. N. Neshev, and Y. S. Kivshar, “Invited article: broadband highly efficient dielectric metadevices for polarization control,” APL Photonics 1(3), 030801 (2016).
12. K. A. Bachman, Y. J. Peltzer, P. D. Flammer, T. E. Furtak, R. T. Collins, and R. E. Hollingsworth, “Spiral plasmonic nanoantennas as circular polarization transmission filters,” Opt. Express 20(2), 1308–1319 (2012).
13. Y. Cui, L. Kang, S. Lan, S. Rodrigues, and W. Cai, “Giant chiral optical response from a twisted-arc metamaterial,” Nano Lett. 14(2), 1021–1025 (2014).
14. R. Ji, S. W. Wang, X. Liu, X. Chen, and W. Lu, “Broadband circular polarizers constructed using helix-like chiral metamaterials,” Nanoscale 8(31), 14725–14729 (2016).
15. J. K. Gansel, M. Thiel, M. S. Rill, M. Decke, K. Bade, V. Saile, G. von Freymann, S. Linden, and M. Wegener, “Gold helix photonic metamaterial as broadband circular polarizer,” Science 325(5947), 1513–1515 (2009).
16. J. K. Gansel, M. Latzel, A. Frolich, J. Kaschke, M. Thiel, and M. Wegener, “Tapered gold-helix metamaterials as improved circular polarizers,” Appl. Phys. Lett. 100(10), 101109 (2012).
17. I. Sakellari, X. Yin, M. L. Nesterov, K. Terzaki, A. Xomalis, and M. Farsari, “3D chiral plasmonic metamaterials fabricated by direct laser writing: the twisted omega particle,” Adv. Opt. Mater. 8(16), 1700200 (2017).
18. J. W. Lee and C. T. Chan, “Circularly polarized thermal radiation from layer-by-layer photonic crystal structures,” Appl. Phys. Lett. 90(5), 051912 (2007).
19. Z. Wang, H. Jia, K. Yao, W. Cai, H. Chen, and Y. Liu, “Circular dichroism metamirrors with near-perfect extinction,” ACS Photonics 3(11), 2096–2101 (2016).
20. Y. Yang, R. C. Costa, M. J. Fuchter, and A. J. Campbell, “Circularly polarized light detection by a chiral organic semiconductor transistor,” Nat. Photonics 7(8), 634–638 (2013).
21. T. Yokoyama, T. Dao, K. Chen, S. Ishii, R. P. Sugavaneshwar, M. Kitajima, and T. Nagao, “Spectrally selective mid-infrared thermal emission from molybdenum plasmonic metamaterial operated up to 1000 °C,” Adv. Opt. Mater. 4(12), 1987–1992 (2016).
22. M. A. Ordal, R. J. Bell, R. W. Alexander, Jr., L. A. Newquist, and M. R. Querry, “Optical properties of Al, Fe, Ti, Ta, and Mo at submillimeter wavelengths,” Appl. Opt. 32(1), 209–215 (1993).
1. Introduction

Circularly polarized light (CPL) has many applications in various fields including quantum-based optical computing and communication [1–3], biological imaging [4], holography [5] and nanofabrication [6]. There have been numerous research on plasmonic circular polarizers with symmetric structures [7–11] and chiral structures [12–17]. However, only a few have focused on achieving circular-polarization-sensitive absorption, i.e., absorbing left-handed circularly polarized (LCP) or right-handed circularly polarized (RCP) component of incident light while reflecting the other component. Several structures involving circular-polarization-sensitive absorption have been proposed so far: a layer-by-layer photonic crystal [18]; a circular dichroism metamirror [19]; an organic field-effect transistor where intrinsically chiral organics work [20]; a theoretical circular dichroism bolometer [21] and a CPL detector [22] based on chiral metamaterials. For the layer-by-layer photonic crystal [18], circular-polarization-sensitive absorption is achieved by the photonic band-gap effect for one circular polarization. Hence the operating frequency can be scaled with the dimensions of the structure and can also be tuned by changing the dielectric ratio of the photonic crystal. For the circular dichroism metamirror [19], simultaneously perfect LCP reflectance and almost complete RCP absorption are performed by combining two layers of anisotropic metamaterial structures. However, the fabrication is difficult for these two structures due to the rotation between two adjacent layers. For the organic field-effect transistor [20], the intrinsic chirality of helicenes is used, thus the operating frequency cannot be tuned by changing the geometric parameters. For the chiral metamaterial based on a metal-insulator-metal (MIM) structure [21, 22], where metallic nanopatterns and a metallic film are separated by a thin dielectric film [23], extreme absorption can be achieved by concentrating the electromagnetic field in the dielectric gap and the size can be reduced into a sub-wavelength scale due to strong magnetic resonances. However, although the CPL detector [22] is experimentally demonstrated, it cannot work at high temperatures because of low melting points of PMMA (approximately 100 °C [24]) and nano-sized silver pattern [25] (below 200 °C for silver films with a thickness of about 20 nm [26]). Therefore, the applications of this device to a system at high temperatures are limited.

Aiming at the lack of a circular-polarization-sensitive absorber that can work at high temperatures, a MIM structure comprised of zigzag arrays is proposed. Molybdenum (Mo) and aluminum dioxide (Al₂O₃) are utilized because both of them in nanoscale are reported to be thermally stable at 1000 °C [27]. At resonant wavelengths, one CPL is absorbed by confining electromagnetic field in the dielectric layer, while the other is reflected. The circular-polarization-sensitive absorber could be applied as a CPL thermal radiator as well as a reflective linear-to-circular polarizer. As a CPL thermal radiator, LCP radiation and RCP radiation are dominant at different temperatures, respectively. As a reflective linear-to-circular polarizer, perfect LCP and nearly perfect RCP are both obtained. The proposed circular-polarization-sensitive absorber may further be applied to biological imaging and sensing, quantum-based optical computing and communication, etc., using a highly integrated photonic platform.
2. Simulation model and results

![Schematic of the proposed circular-polarization-sensitive absorber](image)

As depicted in Fig. 1(a), a Mo zigzag array and a Mo film is separated by the same zigzag Al₂O₃ array. The simulations are performed with a commercial numerical software, FDTD Solutions. The optical parameters of Mo are taken from Ref [28]. The CPL plane wave illumination is achieved by setting two plane waves with orthogonal polarization and a phase difference of $\pi/2$. The thicknesses of the top Mo zigzag array ($t$) and the bottom Mo film are set 170 nm and 200 nm, respectively, and the thickness of Al₂O₃ insulator layer ($h_d$) is 550 nm. Other parameters are: $v_1 = 570$ nm, $v_2 = 2450$ nm, $v_3 = 930$ nm, $p_x = 2300$ nm, $p_y = v_2 + v_3 = 3380$ nm. As shown in Fig. 1(b), the chiral geometry brings about circular-polarization-sensitive absorptions at different wavelengths. In particular, LCP is strongly absorbed around the wavelength of 4.6 $\mu$m (the strength of the LCP absorption is about five times that of the RCP absorption) while RCP is strongly absorbed around the wavelength of 2.6 $\mu$m (the strength of the RCP absorption is about five times that of the LCP absorption). A weak circular polarization sensitivity also occurs around the wavelength of 3.4 $\mu$m, which nearly corresponds to the periodicity along the $y$ axis of the grating. Circular dichroism (CD), defined as the difference between LCP and RCP response, is usually introduced to describe the circular polarization sensitivity [22, 29]. As the result, the CD value is about $-0.53$ and $0.55$ at the wavelengths of 2.6 and 4.6 $\mu$m, respectively.

3. Discussions

It is clear that the CPL absorption can be explained by the destructive and constructive interference between the unconverted and converted scattered fields [21]. To unveil the physics behind varied CPL absorption at different wavelengths, the corresponding electromagnetic fields are shown in Figs. 2(b) and 2(d).

Firstly, at the wavelength of 4.6 $\mu$m, where LCP absorption is dominant, the electromagnetic field is localized in the Al₂O₃ layer and confined around the chiral structure. It is illustrated in Fig. 2(b) that an electric dipole is excited on the surface of the Mo zigzag pattern, where the notation “+” and “−” represents the positive and negative charges, respectively. Hence, electromagnetic field normal to the $x$ axis is investigated. As illustrated in Fig. 2(d), the LCP absorption at 4.6 $\mu$m is generated from two antiparallel magnetic resonances (the second order magnetic resonance), excitation of which is rarely observed at normal incidence [30, 31] because of a destructive interference. However, the destructive
interference fails in this structure because these two magnetic resonances are misaligned by the asymmetric geometry.

Secondly, at the wavelength of 2.6 μm, where RCP absorption dominates, the electromagnetic field is localized in the Al₂O₃ layer but mostly confined around the Mo zigzag pattern. A couple of electric dipoles are excited and a weak magnetic resonance in high order is also observed. This resonance is a hybridization of a lattice resonance and a magnetic resonance.

Thirdly, at the wavelength of 3.4 μm, where the circular-polarization-sensitive absorption is not effective, the electromagnetic field is concentrated on the air side of the Mo zigzag pattern and diffuses to air, as shown in Figs. 2(b) and 2(d). The electromagnetic field profiles and the value of resonant frequency both imply that absorption at 3.4 μm is induced by a lattice mode resonance.

![Fig. 2. Simulated normalized electromagnetic field profiles at the three peak absorption wavelengths.](image)

The resonant modes could also be deduced from the dependence on incident angle, which is depicted in Fig. 3.

As shown in Fig. 3(a), the LCP resonance around 4.6 μm at normal incidence is almost insensitive to the incident angle θ for oblique incident in the x-z plane, indicating a magnetic resonance. On the other hand, the resonance displays a good linear relationship between the resonant wavelength and the incident angle φ for oblique incidence in the y-z plane [see Fig. 3(c)].

When θ increases, the RCP resonance around 2.6 μm at normal incidence splits [see Fig. 3(b)] for an oblique incidence in the x-z plane, where a lattice mode and a magnetic mode can be distinguished. This implies that the absorption at 2.6 μm at θ = 0° is due to a hybridization of a magnetic resonance and a lattice mode resonance.

In addition, the fact that the resonance around 3.4 μm at normal incidence is a lattice mode can be deduced from the drastic shift of the absorption peak with oblique incidence. It
is a property of lattice mode resonance because the needed wave vector compensation is different for different angles of incidence.

Furthermore, it is worth noting that the good linear relationship between the resonant absorption wavelengths and the incident angle \( \phi \) could be further applied in CPL spatial angle measurement. The difference between two dispersions of different polarizations only remains on intensity.

![Fig. 3. Dependence of the absorptivity by the proposed chiral metamaterial on the incident angle with (a) and (c): LCP incidence; (b) and (d): RCP incidence. The 3D schematics of the oblique incidences to the simulated structure in a periodic unit are shown on the left.](image)

It is feasible to fabricate the circular-polarization-sensitive absorber. A Mo film with thickness of 200 nm could be deposited with magnetron sputtering technique first and then the zigzag arrays including the middle \( \text{Al}_2\text{O}_3 \) and top Mo could be fabricated by one-step of electron beam lithography and lift-off process [32, 33]. The smallest width of the structure is about 344 nm as shown in Fig. 1(a), which is not challenging for electron beam lithography technique. As far as the fabrication is concerned, accurate dimensions of the hybrid nanostructure are challenging to meet. In particular, the accurate sharp corner is very difficult to be achieved by electron beam lithography. Nevertheless, the simulated performance would be easy to be obtained in the experiment once the structure is fabricated because of the high intrinsic fabrication tolerance. As shown in Fig. 4, with round corner (with a radius of 200 nm) [Fig. 4(a)] and other variations of geometric parameters including \( h_d \) (thickness of the \( \text{Al}_2\text{O}_3 \) layer), \( v_1, v_2, v_3 \), the changes of CPL absorptions are quite slight. Furthermore, the periodicity along \( x \) axis and thickness of Mo patterns have little effect on the CPL absorption. That is to say, the performance of the proposed absorber is very robust to the fabrication errors on the geometry.
Fig. 4. CPL absorption for the proposed structure by varying the geometric parameters: (a) radius of corners: 0 (sharp) and 200 nm (round); (b) periodicity along the x axis; (c) thicknesses of Mo zigzag pattern; (d) thickness of the insulator Al₂O₃ layer; (e) v₁; (f) v₂ and (g) v₃ which determine the periodicity along y axis. Positive/negative value means that the corresponding parameter is larger/smaller than that of the optimized design, whose features are illustrated by the black curves. Responses to LCP are illustrated by solid lines while that to RCP are illustrated by dash lines.
4. Applications

4.1 A CPL thermal radiator

According to Kirchhoff’s law of thermal radiation, at thermal equilibrium the emissivity of a subject is equal to its absorptivity. The absorbers can also be used as thermal emitters, which show great potential in a wide range of energy-harvesting applications [34–39]. Therefore, the circular-polarization-sensitive absorber radiates energy as described by their absorptivity, including the polarization and direction. The radiation intensity spectra are calculated by multiplying the blackbody radiation at the given temperature with the dispersive emissivity, i.e., \( I(\lambda, T) = \varepsilon(\lambda)I_b(\lambda, T) \), where \( \varepsilon(\lambda) \) is the emissivity of the circular-polarization-sensitive absorber and \( I_b(\lambda, T) \) is the blackbody radiation spectrum at temperature \( T \). The calculated results are plotted in Fig. 5. As shown in Fig. 5(b), when the circular-polarization-sensitive absorber is at low temperatures (\( T = 100 \ ^\circ\text{C} \) and \( T = 360 \ ^\circ\text{C} \)), LCP radiation at the wavelength of around 4.6 \( \mu\text{m} \) dominates (for instance, at \( T = 100 \ ^\circ\text{C} \), LCP radiation at 4.6 \( \mu\text{m} \) is 36 times higher than RCP radiation at 2.6 \( \mu\text{m} \)). With the increasing temperature from 100 \(^\circ\text{C}\) to 844 \(^\circ\text{C}\) (at which nanosized molybdenum and aluminum dioxide are both thermally stable [25, 27]), a dominant LCP radiation at 4.6 \( \mu\text{m} \) is replaced by a dominant RCP radiation at 2.6 \( \mu\text{m} \) (at \( T = 884 \ ^\circ\text{C} \), RCP radiation at 2.6 \( \mu\text{m} \) is twice as high as LCP radiation at 4.6 \( \mu\text{m} \)). That is to say, the radiated circular polarization (although with the corresponding wavelength) is alternative by changing the heating temperature. In addition, for the wavelength range we interested, the total energy of LCP radiation always exceeds that of RCP radiation unless the temperature is higher than 1050 \(^\circ\text{C}\) [Fig. 5(b)]. The average emissivity within the wavelength range is also considered: \( \bar{\epsilon}(T) = \frac{\int_\lambda^{5.3 \mu\text{m}} I_b(\lambda, T) d\lambda}{\int_\lambda^{5.3 \mu\text{m}} I_b(\lambda, T) d\lambda} \), where \( I_b(\lambda, T) \) is the blackbody radiation intensity. As indicated in Fig. 5(c), the average emissivity of LCP radiation decreases while that of RCP radiation increases with increasing temperature.
4.2 A reflective linear-to-circular polarizer

Fig. 6. (a) Sketch of the application of the proposed structure as a reflective linear-to-circular polarizer. (b) Schematic drawing of the circular-polarization-sensitive absorber from the top view. The linearly polarized light is normally incident and the polarization angle is indicated as \( \Phi \). (c) Effect of polarization angle on the ellipticities (\( \chi \)) at 2.6 \( \mu \)m and 4.6\( \mu \)m.

The circular-polarization-sensitive absorber presented in this report could also act as a reflective linear-to-circular polarizer. To investigate the performance of the proposed structure as a linear-to-circular polarizer, a criterion for the ellipticity of the reflected wave is defined as

\[
\chi = 2|E_x||E_y|\sin\phi/\left(|E_x|^2 + |E_y|^2\right) [40],
\]

where \( E_x \) and \( E_y \) components are extracted from the reflected wave, and \( \phi \) is the phase difference. Another definition is

\[
\chi = |a_R|^2 - |a_L|^2 [41],
\]

where \( a_L \) and \( a_R \) are the amplitudes of LCP and RCP, respectively. When \( \chi = -1 \), the reflected wave is a LCP light and when \( \chi = 1 \), the reflected wave is a RCP light.

As shown in Fig. 6(c), the proposed circular-polarization-sensitive absorber shows a good performance as a linear-to-circular polarizer. For the resonant wavelengths (2.6 \( \mu \)m and 4.6 \( \mu \)m), the linearly polarized light can be regarded as a superposition of LCP and RCP, so the linear-to-circular polarization conversion is achieved by absorbing one CPL while reflecting the other. When the polarization angle (\( \Phi \)) is about 135°, a nearly perfect RCP light (\( \chi =1 \)) at 2.6 \( \mu \)m can be obtained. When \( \Phi =110^\circ \), a perfect LCP light (\( \chi = -1 \)) at 4.6 \( \mu \)m can be obtained. Note that at these two resonant wavelengths, around half of the light energy is absorbed by the linear-to-circular polarizer. Besides, the dependence of \( \chi \) on the polarization angle \( \Phi \) results from the interference of reversed and unreversed polarizations of the reflected light.

5. Conclusions

In summary, a refractory and circular-polarization-sensitive absorber based on chiral plasmonic metamaterials is proposed. At the resonant wavelengths, one circular polarized component of light is absorbed by confining electromagnetic field in the dielectric layer, while the other is reflected. The proposed circular-polarization-sensitive absorber shows a good tolerance to toughness and can be applied as a CPL thermal radiator as well as a reflective linear-to-circular polarizer. With the proposed structure acting as a CPL thermal radiator, LCP radiation and RCP radiation is alternative (at respectively corresponding wavelengths) by changing the heating temperature. With the proposed structure acting as a linear-to-circular polarizer, perfect LCP and nearly perfect RCP are both achieved.

Funding

National Key Research and Development Program of China (2017YFA0205700); National Natural Science Foundation of China (NSFC) (61425023, 61575177, 61775194).

Acknowledgment

We are indebted to Hao Luo and Wei Wang for the investigation experiments for properties of molybdenum.