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Compact Non-Chiral Dielectric Metasurfaces to Manifest Enormous Chirality based Optical Responses

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Abstract

The chiro-optical effects are commonly linked with the chiral structures, which simultaneously break rotational and mirror symmetries. In recent years, the chiral metasurfaces (2D equivalent of metamaterials) emerged due to their exceptional ability to manipulate electromagnetic (EM) waves. Although many efforts have been made for highly efficient chiral meta-devices yet the realization of compact all-dielectric meta-devices at optical wavelengths is still challenging. In this work, we have demonstrated a non-chiral all-dielectric meta-device permitting enormous chirality based optical responses. The basic building block of the proposed meta-device comprises a pair of distinct subwavelength meta-atoms with a relative rotation angle of 45 degrees. The novel design strategy leads to a compact all-dielectric meta-device that offers a giant chiro-optical effect in terms of asymmetric transmission and optical activity at a wide-angle of the incident light. In our opinion, the proposed meta-device can find application in integrated chiral optical systems, polarization rotators, optical displays, and chiral sensing.

1 Introduction

Metasurfaces are composed of subwavelength artificially engineered nanostructures, which lead to strong light-matter interactions. This ability made them a suitable candidate for full dimensional manipulation of electromagnetic (EM) waves in terms of polarization, amplitude, and phase as well [1]. To that extent, numerous applications have been realized, such as meta-reflectarrays [2, 3], holography [4-6], lensing [7], and light structuring [8-10] with high efficiency and compactness, which can be hardly realized by natural materials.

Chirality is ubiquitous in biological and chemical species such as proteins, sugar, macroscopic crystals, and DNA [11-13]. Moreover, the chiral molecules are used in the pesticide and pharmaceutical industry for enantiomer's selection [14-16]. In optics, the chiral molecules can discriminate between two spins of photons for circularly polarized (CP) illumination, which leads to a chiro-optical effect. In this regard, chiral metasurfaces show promising abilities for spin-selective absorption which ultimately have many applications in CD spectroscopy and chiral sensing [17-19].

Previously, most chiral metasurfaces presented were based on plasmonic meta-atoms, which have limited applicability in advanced optics due to their strong ohmic losses [2, 20]. So far, very few works have been based on single-layered all-dielectric metasurfaces [19, 21-23]. To the best of the author's knowledge, no one has designed a compact single-layered all-dielectric meta-device based on non-chiral meta-atoms generating enormous chiro-optical effect in the visible regime.

Here, we demonstrate a non-chiral all-dielectric meta-device to manifest chirality based optical responses. In forward propagation, the proposed meta-device transmits cross-polarized light for right circularly polarized (RCP) light illumination whereas fully absorbs the cross-polarized parameter for left circularly polarized (LCP) light and reflects the co-polarized parameter with small efficiency. In contrast, the reverse phenomenon occurs for backward propagation with negligible reflectance.

2 Design Methodology and Results

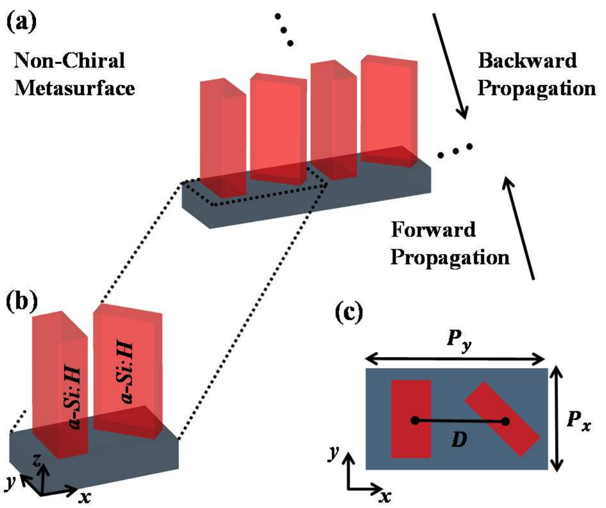

Figure 1. (a) Design principle of the non-chiral dielectric metasurface. (b) 3-D view of the basic building block of the metasurface (c) The top view of the basic building block.

The design principle of the proposed non-chiral dielectric meta-device is depicted in Fig. 1. The proposed metasurface designed using the optimized basic building block (Fig. 1b) comprises distinct non-chiral meta-atoms. The mutual contribution of the non-chiral meta-atoms simultaneously breaking rotational and mirror symmetries induce enormous chirality based optical responses for CP illumination. The top view of the basic building block is shown in Fig. 1c. The chiro-optical response of the metasurface depends on the parameters like length and width of the meta-atoms, periodicity P_i, rotation angles and the inter-spacing D. The metasurface contains hydrogenated amorphous silicon (*a-Si:H*) [9] meta-atoms placed on silicon dioxide (SiO_2) substrate. The meta-atoms in the basic building block of meta-device are optimized in such a way that they can provide giant chiro-optical effects.

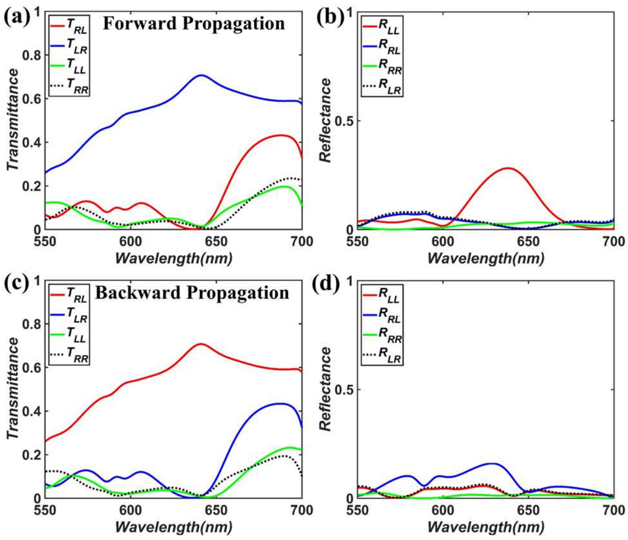

Figure 2. The proposed non-chiral dielectric metasurface's transmittance parameters for CP illumination in (a) forward direction (c) backward direction. The proposed non-chiral dielectric metasurface's reflectance parameters for CP illumination in (b) forward direction (d) backward direction.

The transmittance and reflectance parameters of the proposed non-chiral dielectric metasurface for CP illumination in the forward and backward direction is depicted in Fig. 2. The metasurface shows maximum transmittance of cross-polarized component (T_{LR}) for RCP incident light and minimum transmittance for all other components in forward propagation (Fig. 2a). The metasurface shows opposite behavior for illumination in a backward direction, as depicted in Fig. 2c. The reflectance for CP illumination in the forward and backward direction is demonstrated in Fig. 2b and Fig. 2d, respectively. In the forward direction, the metasurface shows reflectance for the co-polarized component of LCP incident light. In contrast, it shows negligible efficiency for all the reflectance parameters in the backward direction.

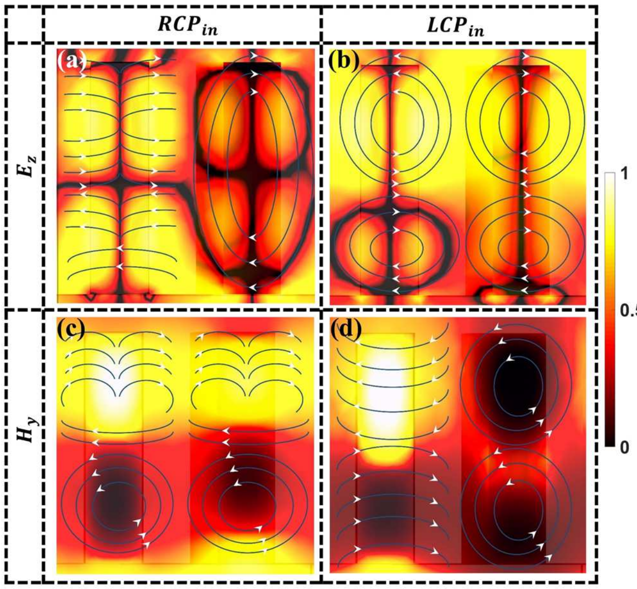

Figure 3. Normalized electromagnetic field distribution for the proposed basic building block in *xz*-plane at the wavelength of 633nm for CP illumination in the forward direction. $\boldsymbol{E_z}$ field distribution along with the direction of electric currents (blue lines with white arrows) for (a) RCP and (b) LCP illumination. $\boldsymbol{H_y}$ field distribution for (c) RCP and (d) LCP illumination.

Fig. 3 illustrates the normalized electromagnetic (*EM*) fields distribution in the proposed non-chiral dielectric metasurface to confirm the nature of dominant modes for CP illumination in the forward direction at the wavelength of 633nm. These *EM*-field distributions are shown in *xz*-plane at the center of the basic building block in the *y*-plane. The normalized electric field distribution is depicted for RCP and LCP illumination in Fig. 3a and 3b, respectively. Likewise, the normalized magnetic field distribution is plotted in Fig. 3c and 3d. The white arrows show the direction of electric currents. The CP illumination on the proposed non-chiral dielectric metasurface exhibits constructive and destructive interference, hence leading to enormous chiro-optical effects as depicted in Fig. 2.

Usually, the chiral metasurfaces deteriorate results except for the normal incidences of light, but the proposed meta-device performs well for a wide-angle of the incident illumination. Fig. 4 demonstrates the absorption for a wide range of incident angles (0-80 degrees) of light in the forward direction in *xz* and *yz*-plane. Fig. 4a and 4b illustrate the perfect absorption for the cross-polarized parameter of LCP incidences at varying incident angles in *xz*-plane and minimum absorption for RCP incidences, respectively. Fig. 4c and 4d depict the perfect absorption for the cross-polarized parameter of LCP incidences at varying incident angle in *yz*-plane and minimum absorption for RCP incidences at working wavelength of 633nm from 0-40 degrees of incident angle, respectively.

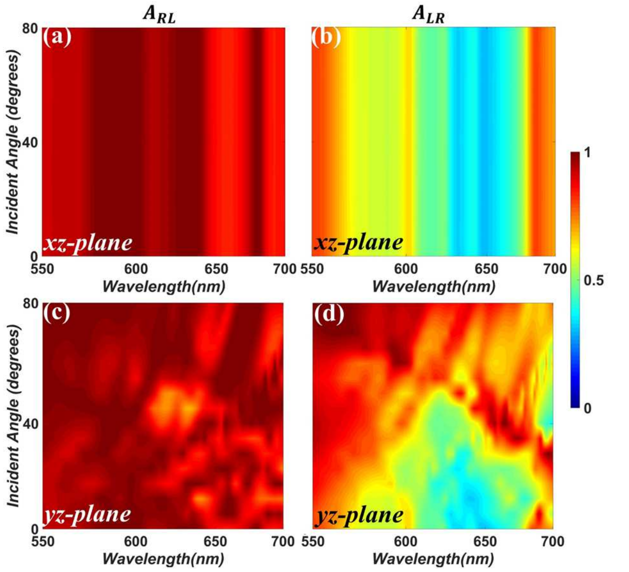

Figure 4. The cross-polarized absorption parameters for CP illuminated in a forward direction without considering the reflectance at a wide range of incident angles (0-80 degrees). Absorption vs. wavelength for (a) LCP and (b) RCP incident light at a wide range of incident angles in the *xz*-plane. Absorption vs. wavelength for (c) LCP and (d) RCP incident light at the wide range of incident angles in *yz*-plane.

3 Conclusion

We have demonstrated a single-layered non-chiral all-dielectric meta-device to generate an enormous chiro-optical effect. The novel design strategy of basic building blocks leading to giant circular dichroism and asymmetric transmission provides an extra degree of freedom by coupling non-chiral meta-atoms. The meta-device works efficiently in both forward and backward directions and provides spin-selective transmission and absorption. The results of the proposed meta-device prove that it can have application in CD spectroscopy, chiral sensing, ultrathin polarizers for integrated photonics, and polarized optical displays.

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5 References

1. S. S. Bukhari, J. Vardaxoglou, and W. Whittow, “A metasurfaces review: Definitions and applications,” *Appl. Sci.*, vol. 9, no. 13, 2019.

2. H. S. Khaliq, M. R. Akram, K. Riaz, M. A. Ansari, J. Akbar, J. Zhang, W. Zhu, D. Zhang, X. Wang, M. Zubair, and M. Q. Mehmood, "Single-Layered Meta-reflectarray for Polarization Retention and Spin-encrypted Phase-encoding," *Opt. Express* 2021.

3. H. S. Khaliq, K. Riaz, M. Zubair, M. A. Ansari, M. R. Akram, T. Naeem, J. Zhang, W. Zhu, D. Zhang, X. Wang, and M. Q. Mehmood, "Highly efficient metamirror with circular dichroism and wavefront engineering," in *Proceedings of SPIE - The International Society for Optical Engineering* (2020), Vol. 11344.

4. M. A. Ansari, I. Kim, D. Lee, M. H. Waseem, M. Zubair, N. Mahmood, T. Badloe, S. Yerci, T. Tauqeer, M. Q. Mehmood, and J. Rho, "A Spin-Encoded All-Dielectric Metahologram for Visible Light," *Laser Photonics Rev.* **13**, 1–9, 2019.

5. M. A. Ansari, I. Kim, I. D. Rukhlenko, M. Zubair, S. Yerci, T. Tauqeer, M. Q. Mehmood, and J. Rho, "Engineering spin and antiferromagnetic resonances to realize an efficient direction-multiplexed visible meta-hologram," *Nanoscale Horizons* **5**, 57–64, 2020.

6. Z. Li, I. Kim, L. Zhang, M. Q. Mehmood, M. S. Anwar, M. Saleem, D. Lee, K. T. Nam, S. Zhang, B. Luk’Yanchuk, Y. Wang, G. Zheng, J. Rho, and C. W. Qiu, "Dielectric Meta-Holograms Enabled with Dual Magnetic Resonances in Visible Light," *ACS Nano* **11**, 9382–938, 2017.

7. X. Chen, M. Chen, M. Q. Mehmood, D. Wen, F. Yue, C. W. Qiu, and S. Zhang, "Longitudinal Multifoci Metalens for Circularly Polarized Light," *Adv. Opt. Mater.* **3**, 1201–1206, 2015.

8. M. Q. Mehmood, S. Mei, S. Hussain, K. Huang, S. Y. Siew, L. Zhang, T. Zhang, X. Ling, H. Liu, J. Teng, A. Danner, S. Zhang, and C. W. Qiu, "Visible-Frequency Metasurface for Structuring and Spatially Multiplexing Optical Vortices," *Adv. Mater.* **28**, 2533–2539, 2016.

9. N. Mahmood, I. Kim, M. Q. Mehmood, H. Jeong, A. Akbar, D. Lee, M. Saleem, M. Zubair, M. S. Anwar, F. A. Tahir, and J. Rho, "Polarisation insensitive multifunctional metasurfaces based on all-dielectric nanowaveguides," *Nanoscale* **10**, 18323–18330, 2018.

10. K. Huang, H. Liu, S. Restuccia, M. Q. Mehmood, S. T. Mei, D. Giovannini, A. Danner, M. J. Padgett, J. H. Teng, and C. W. Qiu, "Spiniform phase-encoded metagratings entangling arbitrary rational-order orbital angular momentum," *Light Sci. Appl.* **7**, 17156–17157, 2018.

11. S. Vignolini, E. Moyroud, B. J. Glover, and U. Steiner, "Analysing photonic structures in plants," *J. R. Soc. Interface* **10**, 20130394, 2013.

12. V. Sharma, M. Crne, J. O. Park, and M. Srinivasarao, "Structural origin of circularly polarized iridescence in jeweled beetles," *Science* **325**, 449–451, 2009.

13. R. M. Hazen and D. S. Sholl, "Chiral selection on inorganic crystalline surfaces," *Nat. Mater.* **2**, 367–374, 2003.

14. I. Čorić and B. List, "Asymmetric spiroacetalization catalysed by confined Brønsted acids," *Nature* **483**, 315–319, 2012.

15. Sekhon, "Exploiting the Power of Stereochemistry in Drugs: An Overview of Racemic and Enantiopure Drugs," *J. Mod. Med. Chem.* 2013.

16. D. J. Cordato, L. E. Mather, and G. K. Herkes, "Stereochemistry in clinical medicine: A neurological perspective," *J. Clin. Neurosci.* **10**, 649–654, 2003.

17. J. Hu, M. Lawrence, and J. A. Dionne, "High Quality Factor Dielectric Metasurfaces for Ultraviolet Circular Dichroism Spectroscopy," *ACS Photonics* **7**, 36–42, 2020.

18. M. L. Solomon, J. Hu, M. Lawrence, A. García-Etxarri, and J. A. Dionne, "Enantiospecific Optical Enhancement of Chiral Sensing and Separation with Dielectric Metasurfaces," *ACS Photonics* **6**, 43–49, 2019.

19. T. Naeem, A. S. Rana, M. Zubair, T. Tauqeer, and M. Q. Mehmood, "Breaking planar symmetries by a single layered metasurface for realizing unique on-chip chiroptical effects," *Opt. Mater. Express* **10**, 3342, 2020.

20. V. K. Valev, J. J. Baumberg, C. Sibilia, and T. Verbiest, "Chirality and chiroptical effects in plasmonic nanostructures: Fundamentals, recent progress, and outlook," *Adv. Mater.* **25**, 2517–2534, 2013.

21. M. L. Solomon, J. Hu, M. Lawrence, A. García-Etxarri, and J. A. Dionne, "Enantiospecific Optical Enhancement of Chiral Sensing and Separation with Dielectric Metasurfaces," *ACS Photonics* **6**, 43–49, 2019.

22. F. Zhang, M. Pu, X. Li, P. Gao, X. Ma, J. Luo, H. Yu, and X. Luo, "All-Dielectric Metasurfaces for Simultaneous Giant Circular Asymmetric Transmission and Wavefront Shaping Based on Asymmetric Photonic Spin–Orbit Interactions," *Adv. Funct. Mater.* **27**, 1–7, 2017.

23. T. V. Raziman, R. H. Godiksen, M. A. Müller, and A. G. Curto, "Conditions for Enhancing Chiral Nanophotonics near Achiral Nanoparticles," *ACS Photonics* **6**, 2583–2589, 2019.