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Anisotropic Time-varying Metasurface for Real-time Polarization Conversion

Qi Hu, Ke Chen*, and Yijun Feng
School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China
*ke.chen@nju.edu.cn

Abstract

Manipulating the polarization of electromagnetic waves is important for modern science and technology. Here, we propose an anisotropic time-varying metasurface for realizing dynamic conversion between input and output waves with different polarizations. The metasurface's anisotropy can be dynamically tuned at will just by controlling the time-varying reflection phases of the metasurface for two orthogonally-polarized linear waves. A series of examples have been designed to verify polarization conversion among circular, linear, and even elliptical polarizations. The proposed method may provide a new way for versatile polarization manipulations that may have potential uses in many applications.

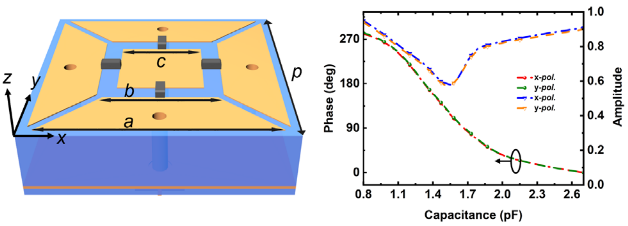
1. Introduction

Controlling the polarization state of light is of paramount importance in tailoring light-matter interactions, which has been used in many applications such as high-resolution imaging, spectroscopy diagnostics, and communications. The conventional way for controlling light's polarization is realized by natural birefringent materials, with bulky volume and limited abilities. Recently, metasurfaces composed of artificially engineered inclusions with sub-wavelength thickness have been used to manipulate the electromagnetic wave in desired manners through locally designing field discontinuities across the interface [1]. Most of the existing metasurfaces involve with linear-polarized waves, circular-polarized waves, and their inter-conversions. For example, by optimizing the topology of a freeform meta-structure, the output light polarization can be continuously changed from linear birefringence to elliptical birefringence, determined by the angle of the incidence [2]. Other methods of geometric phase or combination of geometric phase and propagation phase can also enact versatile polarization control [3-4]. However, most of them are limited to a few polarization functions because they are made of passive dielectric/metallic structures whose electromagnetic characteristics are fixed once fabricated. Although a few studies have proposed tunable metasurfaces capable of dynamically manipulating the polarization state of light [5], they are limited by either circularly or linearly birefringent, just constituting only a small subset of all possibilities.

Here, we proposed an anisotropic metasurface with time-variant reflection controlled by external bias voltages. The metasurface can enact dual-polarized-independent amplitude and phase control, which are further used for dynamic and flexible polarization conversion between two distinct polarizations. As the design examples, dynamic conversion between circular polarization |*CP*⟩, linear polarization |*LP*⟩, and elliptical polarization |*EP*⟩ states are demonstrated. The proposed method may provide a new way for dynamic polarization optics that may be further used in applications of optical/wireless detection and communication, integrated systems, etc.

2. Element design and theory

The key step herein to obtain conversion between different polarizations is realizing arbitrary amplitude and phase control for orthogonal polarizations. The proposed anisotropic time-varying meta-atom is shown in Fig. 1, which has a symmetric configuration about the axes, providing independent electromagnetic responses for x-linearly and y-linearly polarized waves. The dielectric substrate is selected with $\varepsilon_r = 2.2+0.001i$. Varactors (SMV-1405) controlled by the external voltage are loaded to the top metallic layer. The two varactors along x-direction and the two along y-directions are independently modulated by two external bias voltage sources.



(a) (b)

Figure 1. (a) Schematic of the tunable meta-atom loaded with varactors. (b) Simulated reflection phase and amplitude of the proposed meta-atom.

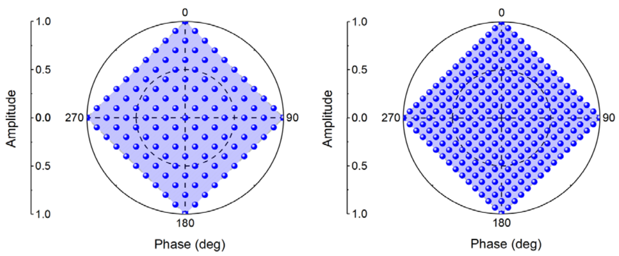
We have performed full-wave simulations to optimize the structure of the meta-atom with realistic lossy materials. When the reverse bias voltage varies from 0 to 18 V, the capacitance of varactors varies from 0.77 to 2.67 pF according to the data-sheet, and simulated reflection responses at 5.5 GHz are shown in Fig. 1b. Both the amplitude and phase responses are almost identical for x- and y-linear polarizations. As the reverse bias voltage is varied from 0 to 18 V, the reflection phase of the meta-atom is gradually changed from 0° to 282°. At the same time, the amplitude is higher than 0.8 in most cases.

Once the external voltage is changed rapidly, we can get a time-varying metasurface with variant behavior of reflection phases. Hence, it is important to analyze the effective reflection properties from a time-varying metasurface. Assume the time-modulation speed of the voltage onto the metasurface is much slower in time scale than the incident wave, the effective reflection $R(t)$ from the metasurface can be written as a periodic function of time. Therefore, the reflection wave will have a line spectrum with the lines separated in the frequency axis by a repetition frequency that is determined by the modulation speed of the external voltages. Moreover, the line spectrum is centered about the incident frequency. In other word, when a monochromatic incidence shines onto the time-varying metasurface, the output waves will have various frequency components. For the fundamental frequency (incident frequency), the effective reflection coefficients can be reduced as

$$a_0 = \sum_{n=1}^{L} \frac{R^n}{L} \ . \tag{1}$$

Here, the parameter L (positive integer) represents the periodic length of time-varying sequence. We can find that the effective reflection is the time averages of the time-varying coefficients at fundamental frequency that is irrelevant to the sequence order. Meanwhile, the length L has a significant influence on the effective reflection coefficients. More detailed derivation can be found in [6-9].

We use the proposed meta-atom as a 2-bit time-varying metasurface that means by setting the external voltages with four different values, we can realize four different phase responses with an interval of 90 degrees. For simplicity, we first consider an ideal lossless case that the amplitude responses are unitary while the phase can be dynamically tuned by the voltage. Then, we traverse all possible time-varying sequences applied onto the metasurface and then calculate the attainable effective reflection. The time-varying sequences is composed of 2-bit phases and has a periodic length L=10 and L=15. The attainable effective reflection are shown in Fig. 2a and 2b.



(a) (b)

Figure 2. Attainable reflection responses when the metasurface is modulated with a time-varying reflection phases. (a) Sequences formed by 2-bit phases (phase interval of 90°) and the length is L = 10, and (b) L = 15.

We can observe that more combination of reflection phase and amplitude can be realized when the sequence length is improved; however, all possible reflection responses are still located in the same area formed by the four vertexes, indicating that arbitrary state in such area are attainable when the time-varying sequence is sufficiently long. In this case, the shortest absolute distance between two reflection responses and the sequence length L are in inverse proportion.

3. Results of polarization conversion

In this section, we use the proposed time-varying metasurface to achieve mode conversion between two distinct polarizations. Because an arbitrary full-polarized wave can be decomposed into x- and y-polarized wave, the conversion between different waves can be viewed as manipulating the x- and y-polarized components by flexible amplitude and phase control. For example, when the conversion is set between circular and linear polarizations, we only need to add an additional phase of 90 degrees to x- or y-polarized component.

Fig. 3 shows some design examples of mode conversion between output and incidence with different polarizations at fundamental frequency. Different to previous studies that generate dynamic polarization for a given incidence with certain polarization, here we extend the metasurface to a more general platform that enacts dynamic conversion between different waves with flexible input and output polarizations. The left column shows a fraction of the time-varying sequences utilized to modulate the metasurface. And consequently, the conversion between |LP⟩, |CP⟩, and |EP⟩ states can be successfully realized. We will present more details and experimental results in the presentation.

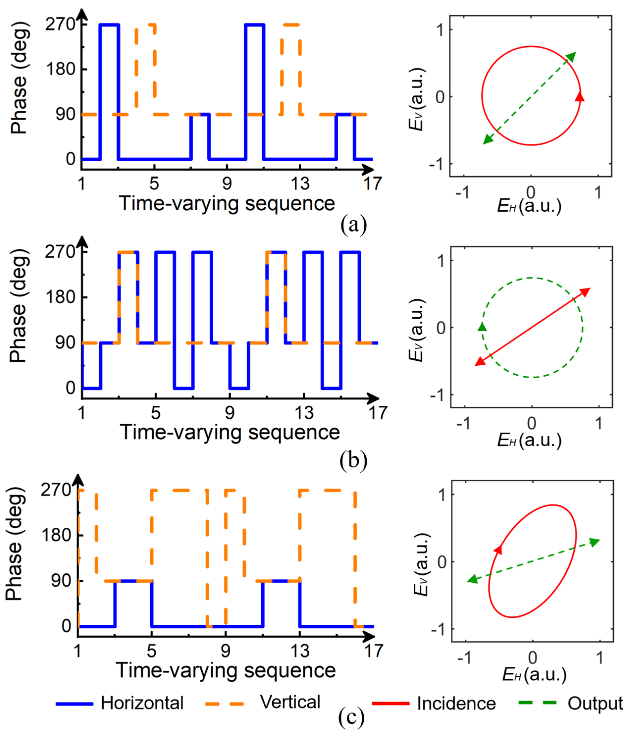


Figure 3. Examples of polarization conversion between distinct input and output polarizations. The left panels show the required time-varying sequences of the reflection

phases and the right panels show the normalized theoretical results of the output wave under different input waves. (a) Polarization conversion between $|45°\rangle$ output and $|RCP\rangle$ input. (b) Polarization conversion between $|LCP\rangle$ output and $|33.7°\rangle$ input. (c) Polarization conversion between $|17.5°\rangle$ output and elliptical-polarized input with ellipticity angle of 30° and orientation angle of 60°.

4. Conclusion

In summary, we have proposed an anisotropic time-varying metasurface for dynamic conversion between different input polarization and output polarization. The change of the metasurface's anisotropy is determined by the varactors loaded on the metasurface and eventually controlled by the external voltages. The proposed method may enable a new platform for versatile polarization optics and may have potential uses in such as quantum information, optical or wireless communication, and imaging.

5. Acknowledgements

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References

[1] N. Yu et al., "Light propagation with phase discontinuities: generalized laws of reflection and refraction," Science, 334, 6054, February 2011, pp. 333-337, doi: 10.1126/science.1210713.

[2] Z. Shi et al., "Continuous angle-tunable birefringence with freeform metasurfaces for arbitrary polarization conversion," Sci. Adv., 6, 23, June 2020, eaba3367, doi: 10.1126/sciadv.aba3367.

[3] F. Ding, "Versatile polarization generation and manipulation using dielectric metasurfaces", Laser Photonics Rev., 14, 11, November 2020, doi: 10.1002/lpor.202000116.

[4] Arbabi E, et al., "Full-Stokes imaging polarimetry using dielectric metasurfaces". ACS Photonics, 5, 8, August 2018, pp. 3132-3140, doi: 10.1021/acsphoton ics. 8b00362.

[5] K. Chen, et al., "Active anisotropic coding metasurface with independent real-time reconfigurability for dual polarized waves," Adv. Mater. Technol., 5, 2, February 2020, p. 1900930, doi: 10.1002/admt.201900930.

[6] A. Tennant and B. Chambers. "Time-switched array analysis of phase-switched screens," IEEE Trans. Antennas Propag., 57, 3, March 2009, pp. 808-812, doi: 10.1109/TAP.2009.2013448.

[7] Q. Hu et al., "Arbitrary and dynamic Poincaré sphere polarization converter with time-varying metasurface," Adv. Opt. Mater., 2101915, December 2021, doi: 10.1002/adom.202101915.

[8] J. K et al., "Linear and nonlinear polarization syntheses and their programmable controls based on anisotropic time-domain digital coding metasurface," Small Struc., 2, 1, January 2021, doi: 10.1002/sstr.202000060.

[9] W. Kummer, A. Villeneuve, T. Fong, and F. Terrio, "Ultra-low sidelobes from time-modulated arrays," IEEE Trans. Antennas Propag., 11, 6, November 1963, pp. 633 - 639, doi: 10.1109/TAP.1963.1138102.