Anisotropic Time-varying Metasurface for Real-time Polarization Conversion

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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 \( |CP \rangle \), linear polarization \( |LP \rangle \), and elliptical polarization \( |EP \rangle \) 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.

![Figure 1](image)

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

$$a_0 = \sum_{n=1}^{L} R^n \cdot$$ \hspace{1cm} (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.

![Figure 2](image1)

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 $|LP\rangle$, $|CP\rangle$, and
$|EP\rangle$ states can be successfully realized. We will present
more details and experimental results in the presentation.

![Figure 3](image2)

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

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.

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References


