THz and infrared metamaterial polarization converter with tunable ellipticity

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Abstract

In this contribution we present the metamaterial based polarization converter from linear to elliptical polarization with a desired ellipticity and ellipse orientation. We show two designs with the conversion efficiency 50% for the frequencies around 1 THz and 193 THz. The proposed device is realistic for fabrication and can be used as a polarizer or a polarization compensator.

1. Introduction

Metamaterials provide exciting possibilities for light manipulation and new functionalities, which are especially needed in the young field of terahertz (THz) science and technology, due to limitations of natural material properties. THz radiation has a lot of applications, for example, in communication systems, food quality control, defense, biomedical imaging and chemical spectroscopy. In this work we focus on a polarization converter. A large number of devices had already been studied: transmission polarizers [1],[2], wave retarders in reflection [3], plasmonic lenses [4] or even nanoantennas [5]. However, all this devices have a serious drawback: they are not flexible enough to obtain arbitrary light polarization. The goal of this contribution is to develop a tunable polarizer that converts linearly polarized light into elliptically polarized light with a desired ellipticity and ellipse orientation.

2. Methodology

The principle of operation of the polarizer is the following. Let's consider an incident linearly polarized plane wave which enters the device along Z-axis from air (Fig.1A). In order to obtain elliptically polarized light at the output the outgoing wave has to consist of two linearly polarized waves with a phase difference $\Delta\phi$ between the components E_x and E_y, namely

$$E_x = A_x \cdot \cos(\omega t),\ E_y = A_y \cdot \cos(\omega t + \Delta\phi), \tag{1}$$

where A_x and A_y denote the amplitudes of the electric field and ω is the angular frequency.

If the phase difference $\Delta\phi = 90^\circ$, Eq.(1) becomes a parametric equation for an ellipse with the axis along x- and y-coordinates:

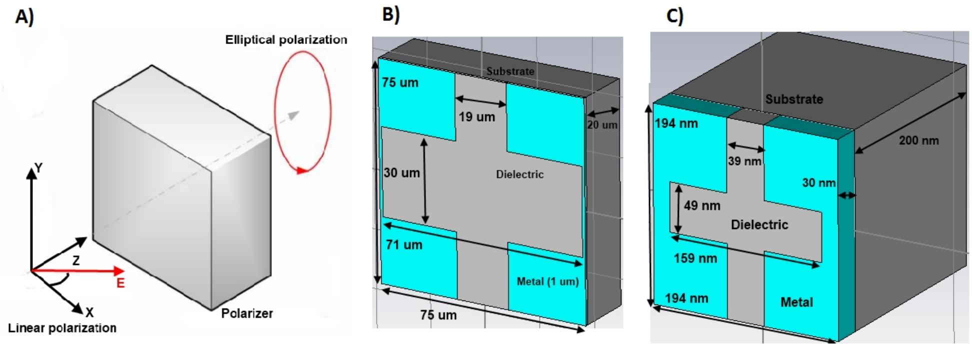

Fig. 1: (A) Operation principle of the polarization converter. An incoming linearly polarized wave is converted into an elliptically polarized. Design of the metamaterial polarizer unit cell for the (B) 1 THz and (C) 193 THz.

$$\left(\frac{E_x}{A_x}\right)^2 + \left(\frac{E_y}{A_y}\right)^2 = 1 \tag{2}$$

Rotating the linear incoming polarization we can change the amplitudes A_x and A_y and therefore ellipticity:

$$k = \frac{A_x}{A_y} \tag{3}$$

In this way we can obtain any polarization starting from linear to circular. Rotating the device together with the polarization we can change the ellipse direction.

3. Results

In order to obtain the desired functionality, we developed the metamaterial designs (See Fig.1B,C). To show the scalability of the design to different frequency range, we tuned it to 1 THz (Fig.1B) and 193 THz (Fig.1C). Its unit cell consists of metallic mesh with dielectric resonant slots. Varying different geometric parameters one can achieve the desired phase shift and transmittivity level. Unit cell of the metamaterial polarizer for 1 THz is shown on Fig.1B. The structure consists of a substrate made of silica or polymer with the refractive index n=1.5 and a cross-shaped slot in a metallic film on top of it. The slot is also made of silica with n=1.5 and metal is approximated via Drude model for silver $\left(\epsilon_\infty = 5, \omega_p = 1.37e^{16}\frac{rad}{s}, \gamma = 1.6e^{13}Hz\right)$. Numerical simulations were made in CST Microwave studio [6].We used the periodic (unit cell) boundary conditions in for x- and y- and open space (perfectly matched layers) for z- direction. The calculations were done in the frequency domain. The structure was excited with x-and y-polarized plane waves. Transmission coefficients (S_{21} - parameters) were calculated for each polarization. We define the working range of the device as the frequency range where the phase shift between polarizations varies from 80 to 100° and the transmittivity changes to $\pm 10\%$ from the working point. Technical characteristics of the polarizer (Fig.1B) are presented in the Fig. 2. At the frequency 1 THz transmittivities for different polarizations are almost equal: T_x=0.515 ; T_y=0.494. This results in 50% total transmittivity and ellipticity k = 1 when the incident wave is linearly polarized at 45° with respect to the x-axis.Together with phase shift close to 90° it makes the difference between idealized ellipse (violet line in the Fig.2C) and the one obtained with polarizer (blue line) negligible. The working range of the device is 0.83 - 1.11 THz. However, the phase shift remains in the designated frames in the region 0.5-1.15 THz, and that allows tuning to another frequency. Characteristics of the polarization converter for telecom infrared frequency 193 THz (Fig.1C) are shown below in the Fig.3. For the incident polarization at 45° at the frequency 193.4 THz we obtain nearly 50% total transmittivity and k=0.95. The working range of the device is 170-200 THz; phase range is 160-270 THz. So, this design is also easily tunable to a required frequency.

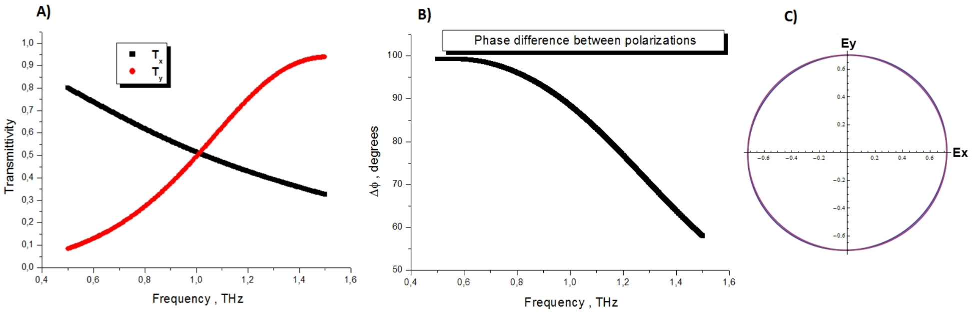

Fig. 2: Characteristics of the polarizer for the frequency range around 1 THz. Transmittivities for x- and y- polarizations (A) and phase shift between polarizations (B). The output wave polarization ellipse (C) for the incident linearly polarized wave with the angle between **E** and Ox equal to 45°

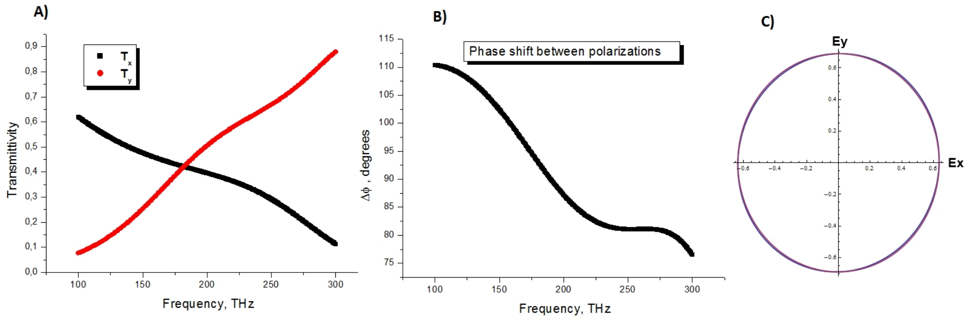

Fig. 3: Characteristics of the polarizer for the infrared telecom range around 193 THz. Transmittivities for x- and y- polarizations (A) and phase shift between polarizations (B). The output wave polarization ellipse (C) for the incident linearly polarized wave with the angle between **E** and Ox equal to 45°

4. Conclusion

We proposed the metamaterial polarization converter capable to convert linearly polarized incident radiation into elliptically polarized with a desired ellipticity. The device has a high transmittivity around 50%, stable phase shift within the bandwidth, a simple geometry, and it can be fabricated with the standard clean room facilities. It is reciprocal, so it can work in the opposite direction, converting elliptical polarization into linear. We believe the device will find its application as a polarization converter or compensator.

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