Periodic Array of Chiral Metamaterial-Dielectric Slabs for the Application as Terahertz Polarization Rotator

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Abstract

This study proposes a stratified chiral metamaterial as a polarization rotator for terahertz regime. Combination of chiral constituent with dielectrics permits optimization of spectral filter and polarization rotation properties. The lack of suitable wave-plates for terahertz region opens the way for novel component/devices enabling polarization control. With the aid of a new class of metamaterials, the capability of the fabrication of multilayer structures for polarization rotator realization can be increased. We can generate either polarization-rotation combs or narrow rotation bands with very good and broad sideband suppression, of interest for example for data transmission or sensing purposes.

1. Introduction

Electromagnetic metamaterials are artificially structured composites that can be engineered to have desired electromagnetic properties, while having other advantageous material properties [1]. The concept of artificial materials appears to begin in the late nineteenth century with the study of optical activity [2]. Later on, K. F. Lindman worked on artificial chiral media by embedding many randomly oriented small wire helices in a host medium [3]. Then, W. E. Kock made lightweight microwave lenses by arranging conducting spheres, disks, and strips periodically and effectively tailoring the effective refractive index of the artificial media [3]. After that, several studies appeared in the literature on electromagnetic artificial materials including so-called single/double-negative metamaterials and their potential applications. For details one can check the References of [4] and [5]. As a definition, double-negative metamaterials (DNG-MTMs) are composite materials in which both the permittivity and the permeability are simultaneously negative over a certain frequency band. In the single-negative (SNG) MTMs either the permittivity or the permeability is negative, but not both. These are epsilon-negative (ENG) and mu-negative MTMs in which either the permittivity is negative while the permeability is positive (in the case of ENG MTMs) or the permittivity is positive while the permeability is negative (in the case of MNG MTMs). SNG/DNG MTMs have interesting properties when they are composed of stratified SNG/DNG and dielectric slabs embedded between semi-infinite conventional media. If an additional chirality parameter is included to the structure, the unusual properties of the configuration can be increased.

In this study, the multilayer structure formed by MTM and dielectric slabs with different material properties for designing a polarization rotator for the terahertz (THz) regime is presented. The incident THz wave is assumed to be a monochromatic wave with arbitrary polarization. The transfer matrix method is used in the analysis. After obtaining the electric and magnetic fields both inside and outside the stratified structure, and imposing the boundary conditions, the transfer matrix can be obtained. Note that the elements of the transfer matrix are expressed as a function of the incidence angle, the structure parameters, the thickness of each slab, and the frequency. Then, the incident, reflected, and transmitted powers can easily be determined. As a result, the scattering characteristics of the stratified structure for the THz wave with any arbitrary polarization for the realization of a polarization rotator is computed and presented in the numerical results. First, the conventional stratified structure with the known parameters will be considered. Then, the structure will be re-arranged to form a combination of SNG MTMs and dielectrics to observe the effect of the SNG material on the reflection and transmission characteristics of the configuration. At last, chirality will be added to the configuration and the effect of the chirality will be investigated. The results show that the study can easily be used for the production of polarization rotator for THz regime.

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2. Theoretical Analysis

In this section, the theoretical approach to investigate a planar stratified structure comprised of SNG, dielectric, chiral, and chiral MTM layers and different combinations thereof to obtain high reflection, high transmission, and polarization rotation is presented. All computations are based on the theory of stratified structures. In the analysis, the transfer matrix method, which gives all required relations among the fields in all regions, is used [6, 7]. First, the configuration of the stratified structure is constructed by embedding between two semi-infinite dielectric media. Next, the constructed configuration is analyzed using the transfer matrix formulation which is applied to compute the reflectance and transmittance. The stratified structure with different material properties and thicknesses considered in this paper is shown in Figure 1. For this structure, the transfer matrix formulation can be given as:

\[
\begin{bmatrix}
E_{i\perp} \\
E_{r\perp} \\
E_{i//} \\
E_{r//}
\end{bmatrix} = [U]
\begin{bmatrix}
E_{i\perp} \\
E_{i//}
\end{bmatrix}
= \begin{bmatrix}
u_{11} & u_{12} \\
u_{21} & u_{22} \\
u_{31} & u_{32} \\
u_{41} & u_{42}
\end{bmatrix}
\begin{bmatrix}
E_{r\perp} \\
E_{r//}
\end{bmatrix}
\]

(1)

where the subscripts // and \( \perp \) refer to the parallel and perpendicular components of the electric field vector, respectively. Note that \([U]\) = \([A]\) \([B_1]\) \([B_2]\) \([B_3]\)\ldots\([B_{n-1}]\) \([C]\). Here, \([A]\) and \([B_m]\) are both square matrices of order 4, \([C]\) is a 4×2 matrix and \([U]\) is in the form of 4×2 matrix. The elements of \([A]\), \([B_m]\), and \([C]\) are expressed as a function of the incidence angle, the structure parameters, the thickness of each slab, and the frequency. Note that the conservation of the power is fulfilled in all computations.

\[d_1\]

\[d_2\]

\[n_1\]

\[n_2\]

\[\cdots\cdots\]

\[E_i\]

\[E_r\]

\[E_t\]

Figure 1: Schematic representation of the investigated stratified structure.

3. Numerical Results

In this section, the numerical results for four different cases will be presented. The investigated structure is composed of five alternating layers with different combinations. The structure is stacked as XDXDX where D stands for dielectric with the dielectric constant of 2.2 and X will stand for dielectric, chiral, and chiral MTM in which it will be changed from one case to another one in that order. The optical thickness (\(n \times d\)) of all layers is arranged to be \(\lambda_o/4\) where \(\lambda_o\) is the free-space wavelength at the operation frequency. All computations are performed for an incident electric field with \(p\)-polarization (\(E_{i\perp} = 0\)).

In the first case, the power reflection and transmission characteristics of the five-layer structure composed of dielectric materials are investigated. In this first step, we set out with a conventional interference filter. The dielectric constant of the medium X is selected to be 4.5. The frequency response of the power reflection and transmission of the structure is shown in Figure 2. As it is seen from the figure, the parallel component of the reflection (transmission) becomes unity (zero) at around 1.0 THz and 3.0 THz with the bandwidth of 0.72 THz. The transmission is unity at some frequencies, namely at 0, 0.34, 0.64, 1.36, 1.66, 2.0 THz and then again at 2.34, 2.64, 3.36, 3.66, 4.0 THz. The corresponding reflection is zero at these frequencies. In addition, there are more ripples in the frequency behavior of the structure. Note that the perpendicular component of the power reflection and transmission is zero since the structure is excited by a \(p\)-polarized electric field. As a result, the structure behaves as
a band-pass filter or high-reflection coating at some frequency bands for the reflection wave while it acts as an anti-
reflection (full-transmission) filter at other frequencies.

![Figure 2: Frequency response of five-layer all-dielectric structure.](image)

In the second case, the frequency response of the five-layer structure is investigated with the same
arrangement as in the previous case except for the X medium. This medium now is considered as a chiral medium in
which it has the same dielectric constant of 4.5 with the additional chirality parameter of \(-2 \times 10^{-3}\). Figure 3 shows the
power reflection and transmission as a function of frequency. The same observation as in the case before for the
reflection character of the structure can be seen. The structure acts as a band-pass filter and a high-reflection coating
for the reflection wave at around 1.0 THz and 3.0 THz as in the previous example. The parallel component of the
transmission is now decreased, in comparison with the previous one, and it reaches to zero at 2.0 THz. At the same
time, the perpendicular component of the transmission is enhanced and it reaches to unity at 2.0 THz although the
incident electric field has no perpendicular component. At this frequency, a parallel-perpendicular polarization
conversion occurs for the transmitted wave. Therefore, we can say that the second structure acts as a polarization-
conversion transmission filter in some THz frequency band. Note that there are also some ripples in the reflection
and transmission as in the previous example.

![Figure 3: Power reflection and transmission as a function of frequency for five-chiral-dielectric-layer structure.](image)

As a third example, a five-layer structure is investigated as in the first two cases, but here the medium X is
arranged to be a SNG-MTM with the dielectric constant of \(-4.5\). The power reflection and transmission versus
frequency are shown in Figure 4. In this case, the pass-bands are larger in comparison with the previous examples.
The reflection and transmission have only pass-bands. The structure has no ripples which means the frequency
response of the structure is now improved. The present structure is well-studied as a narrow-band transmission filter
with excellent rejection outside the pass-bands.

At last, the five-layer structure composed of dielectric and chiral MTM (X medium) is analyzed. In this case,
the chiral MTM has a dielectric constant of -4.5 and a chirality parameter of \(-2 \times 10^{-3}\). Figure 5 presents the reflection
and transmission data. The reflection and transmission have the same ripple-free features as in the previous example.
The parallel component of the transmission is minimized at around 2.0 THz and the perpendicular component has a
high peak at this frequency. Complete polarization conversion occurs at 2.0 THz.
The frequency response of the periodic stratified structure composed of four different combination of materials: dielectric, chiral, SNG-MTM, and chiral MTM, is presented. The filtering, high-reflection-coating, polarization-conversion features of the structure for the THz region are observed from the numerical results. The optimum conditions for the mentioned features are also provided. As a result, the proposed structure can be used for filtering, coating, and especially polarization conversion devices in the THz regime.

5. References