Optical Activity Effect on Planar Chiral Metamaterials

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Abstract. Metamaterial is an artificial material which has a negative refractive index. Both of permittivity and permeability have a negative value to possess negative refraction. The breakthrough of metamaterial development was present as the invention of planar chiral metamaterials. This research was focused on the development of a new design of planar chiral metamaterial with different depth. The developed metamaterial design was analyzed by chirality analysis in relation to the optical activity characteristics. The planar chiral metamaterial development was following a design, a structure examination, and a fabrication process using a focused ion beam system. Chirality characterization were measured using a femtosecond Ti:Sapphire pumped terahertz emission spectroscopy system. THz signal was occurred due to the optical rectification process as a result of an intense femtosecond laser pulses radiation on planar chiral metamaterial sample. The samples were capable to generate a THz emission over a frequency range of 0 – 2.24 THz, while the THz signal was measured as ~5 ps. The effect of optical activity was able to rotate the polarization plane on a frequency range of 0 – 1.4 THz for both of the clockwise and the counter-clockwise samples. The maximum polarization plane rotation were +13° and −18° at a frequency 1.35 THz. It can be concluded that the new design planar chiral metamaterial with different depth has been successfully obtained with its elliptic polarized THz emission characteristic.

Key words: Optical Activity, Planar Chiral Metamaterials, Polarization Plane

1. Introduction

Metamaterials can be describe as the arrangement of artificial dielectric elements or magnetic elements in order to get unusual electromagnetic properties [1]. Unlike natural materials, metamaterials must be builded to gain negative permittivity and negative permeability simultaneously. Negative refraction can be constructed from the dielectric metamaterials (as a negative permittivity) and the magnetic metamaterial (as a negative permeability). Chiral metamaterials, in the other hand, has a different way to get the negative refraction [2]. The chiral metamaterials possess a difference response for a left circularly polarized wave and a right circularly polarized wave [3]. Chiral structure will do significant effect when they interact with the electromagnetic field, such as polarized the field. For example, the optical activity, which is caused by a difference in indices of refraction between left/right-handed circularly polarized wave [4].

To satisfy the increasing demand of chiral materials with strong optical properties availability, nanostructured metamaterials are used to construct the chiral materials. We can obtain negative
refraction in chiral metamaterials with large chirality without the need to have negative permittivity and negative permeability simultaneously. The polarization plane of a linearly polarized wave will rotate when it passes through the planar chiral metamaterials. The phase between two circularly polarized waves will increase as their superpositioned. The polarization change from linear to circular are characterized with its ellipticity [5]. When the ellipticity is large, the linearly polarized wave will strongly distorted then become elliptically polarized, as shown in fig. 1.

![Figure 1. Schematic of ellipticity](image1)

Chiral metamaterials will rotate the polarization plane of a linearly polarized light which passes through it. These metamaterials optical properties are called optical activity and the polarization mechanism is shown in fig. 2. Optical activity is shown by the polarization angle of elliptically polarized wave. The polarization angle can be determined from the angle between the polarization ellipsoid major axis and the horizontal axis [6].

![Figure 2. Mechanism of optical activity](image2)

Research on planar chiral metamaterials also emerge at the terahertz region and the developed metamaterials are consider as a new class of metamaterials [7]. Todays advancement of a high-field terahertz source lead to the chance to explore many nonlinear effect including optical rectification. Rectification will generate terahertz frequencies from optical pulses [8]. Nevertheless, the experiments in planar chiral metamaterials at the terahertz region still face major challenges due to the the geometry complexity [9]. Nowadays, advances in nanoscale fabrication have made the possibility to create artificially nanostructured materials with extraordinary optical properties [10]. In this paper, we report the analysis of planar chiral metamaterial with different depth. The structure was experimented using terahertz emission and its polarization angle spectra analysis in relation to the optical activity effect.

2. Sample preparation & experimental setup

The planar chiral metamaterial development was conducted following the steps as follows: first, we begin with a design mechanism, followed by a structure examination, then a fabrication process using an FB2200 Focused Ion Beam system. THz emission and chiral metamaterials optical activity effect were determined using THz emission spectroscopy. The planar chiral metamaterial samples which
were used have dimensions $1.2 \, \mu m \times 0.3 \, \mu m \times 0.3 \, \mu m$. We have developed two type of a 1200 periodic square pattern samples of a planar chiral metamaterials. Samples was builded with a period formed by a square pattern of chiral with different depth on a silver thin film with a clock-wise (CW) and a counter clock-wise pattern. The single pattern of a chiral unit and its dimension were shown in Figure 3 [11].

A standard THz generation setup as shown in fig. 4. were using to the experiments. The technical spesification of the Laser source were as follows: Ti:Sapphire oscillator (Scientific XL, Femtolasers), generates pulses with 50 fs duration, wavelength 800 nm, repetition rate 11 MHz, and average power output 800 mW. Laser beam was directed to the beam splitter which transmit 80% intensity to use as the pumping beam and 20% use as the sampling beam. The pumping beam will focused to an approximately 2 mm spot size on the sample surface, at 45° angle of incidence. The generated THz radiation were gained using an off-axis paraboloidal mirror. The reflection were focused to a ZnTe detection crystal. At the same time, the copropagating sampling pulse was synchronized to the detection crystal. The THz electric field will elliptically polarizes the probe beam. The ellipticity was determined using a differential detection setup that consist of a quarter wave plate, a Wollaston prism, and a differential detector.

As described before, the polarization was transform from linear polarization to circularly polarization. The intensity difference between probe pulse s and p wave was determined after the probe pulse transmit through the quarter wave plate. The polarization states then were analysed using polarization state experiment, as shown in figure 5.
We could describe left-hand circular polarization as an electric field vector that do an anti-clockwise rotation at a fixed point, as observed along the beam. The ellipticity was yielded as [12]

\[ \eta = \frac{|E_R| - |E_L|}{|E_R| + |E_L|} \]  

\( E_R \) shows the amplitude of right-hand circularly polarization and \( E_L \) shows the left-hand. The gained polarization angle was the angle between the polarization ellipsoid the major axis and the horizontal axis.

3. Discussion

Femtosecond laser pulses which were radiated to a planar chiral metamaterials sample will generate THz signal. THz signal occurred due to the non linear optical rectification process. The developed chiral metamaterial samples capable to generate THz emission signal at ~5 ps. A Fourier transform process to the signal’s time-domain traces has successfully determined that the signal was emitted with a frequency of 2 THz. The emitted THz electric field from the planar chiral metamaterial have a single-cycle shape followed by an oscillating tail as shown in Fig. 6. The weakened oscillations were suspected originate from absorption and re-emission of THz light by water vapor molecules in the atmosphere.

![Schematic of the Polarization states experiment](image)

Figure 5. Schematic of the Polarization states experiment

![Waveform of the THz pulse](image)

Figure 6. Waveform of the THz pulse

Second order dependence in these experiments are interesting to explore. The THz amplitude were convincingly non linearly increase and the second-order non linear process was consider involve with the THz emission. Figure 7 shows the rotation angle of THz emission spectra from every sample. It can be stated that the chirality of the sample chiral structure will determine the polarization rotation and its rotation direction. The strong oscillating appearance for the right-hand and the left-hand sample was raised to define the angle for the almost elliptic polarized wave.
Figure 7. Polarization angle spectra

The sample optical activity was able to rotate the polarization plane on a frequency range of 0 – 1.4 THz for both of the clockwise and the counter-clockwise samples. The maximum polarization plane rotation were +13° and −18° at a frequency 1.35 THz. More importantly, we are succesfully observed polarization reversal of ellipticity in each sample. The opposite polarity stated that the absorbance value of a clock-wise and a counter clock-wise sample was different. The planar chiral metamaterial has been constructed and posses THz emission with elliptically polarization.

4. Conclusion

This new structure design of a chiral metamaterial has shown a promising result as it simple and easy to fabricate. The developed sample were successfully performed that the optical activity was depend on their chirality. The planar chiral metamaterial samples were capable to generate THz signal under an intense femtosecond laser pulses radiation. The generated THz emission were ranging from a frequency of 0 to 2.24 THz, and its THz signal was ~5 ps. The optical activity effect was able to rotate the polarization plane on a frequency range of 0 to 1.4 THz for both of the clockwise and the counter-clockwise samples. The maximum polarization plane rotation were +13° and −18° at a frequency 1.35 THz. We have the conclusion that the planar chiral metamaterial has been builded and posses THz emission with elliptically polarization.

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