Analysis of the THz response of a simple periodic graphite-based structure

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Abstract: We report the observation of the dichroism effect in simple wire grid structures made of graphite on a paper substrate, i.e. we investigate the feasibility of drawing polarizers for the THz band using conventional graphite-based lead pencils. The displacement of the maximum frequency of the selective absorption phenomenon by varying the wire pitch hints at a polarizing behavior. Measurements of the maximum and minimum of transmission efficiency, extinction ratio and degree of polarization are carried out with a transmission fiber THz-TDS setup. Experimental results show a 9 dB extinction ratio for an inexpensive (<1$) home-made component.

OCIS codes: (300.6495) Spectroscopy, terahertz; (050.1930) Dichroism; (310.5448) Polarization, other optical properties.

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1. Introduction

The terahertz band gap (from 300 GHz to 10 THz) is a poorly exploited region of the electromagnetic spectrum. Many efforts are being made in this field to develop THz components that allow the manipulation and control of THz beams. Beam splitters [1], wave plates [2], filters [3] and polarizers [4] are examples of now commercially available THz components. Further work is being carried out to develop robust and durable THz components with better and better performance and, especially, with a lower cost. In particular, the knowledge of the polarization state of a THz beam is of fundamental importance to study the anisotropic THz response of a material, to develop sensitive nondestructive inspection techniques or to characterize novel metamaterials [5]. Among the various techniques used to implement polarizers, metal wire grids, both deposited on a lossless substrate or as a free standing structure, are probably the most widely used.

Photolithography followed by etching mode [6], deep ultraviolet interference lithography [7] or nanoparticles deposition [8] have been employed to develop polarizers but they have the drawback of being relatively expensive and complicated processes. Some innovative results have been achieved in nanotechnology with aligned carbon nanotubes [9–11] and efforts are being made to fabricate wave plates and beam splitters, by means of unconventional and economic methods [12–17].

In this letter we follow this low-cost approach and we analyze the polarizing behavior due to the dichroism effect in a periodic structure drawn using graphite-lead pencil on a common sheet of paper.

These graphite-based periodic structures are characterized by standard time-domain terahertz spectroscopy (TDS-THz). Periodic grids of 1, 0.8 and 0.6 millimeter wire pitch are designed and studied. With the aim of enhancing the devised dichroism effect, different configurations are experimented, such as bi-layers grid, or double and triple stack grids.

2. Experimental results

In the THz region, signal wavelengths comprises frequencies between 100 GHz and 10 THz, which correspond to wavelengths ranging from 30 μm to 3 mm. Pencil line widths are in the order of this wavelength range. In particular, lead pencils are of interest due to the conducting properties of graphite. Pencils with the highest content of graphite are more suitable for this application, so 8B lead pencils will be used in the experiment. Due to the transparency of the paper to the THz [12] and the high graphite content of the pencil [18], the designed structures can be considered as a metal wire grid with a response in the THz frequency range.

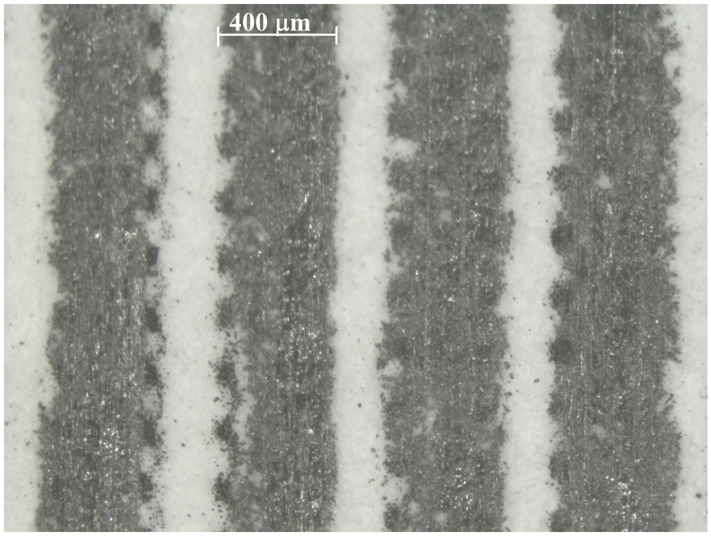


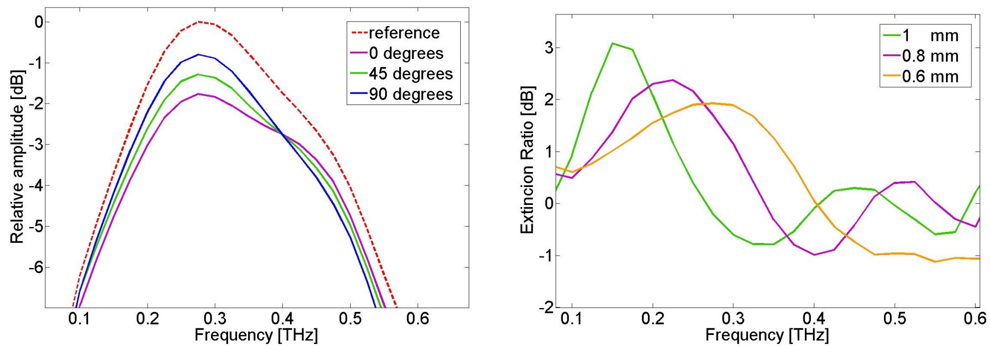
Fig. 1. Optical microscope image of the 0.8 mm pitch grid structure with 0.4 millimeters wire width (fill factor ranging from 0.5 to 0.8). Black graphite wires alternate with blank paper spacings.

The pattern with the required wire periodicity is printed on blank paper, that is used as a reference throughout the whole presented work. Then, the periodic graphite structure is drawn using an 8B lead pencil (Fig. 1). The samples are squares of $35mm \times 35mm$ with a fill factor ranging from 0.5 and 0.8 and a pitch of 1 *mm*, 0.8 *mm* and 0.6 *mm*, corresponding respectively to an expected maximum frequency of polarization of 300 GHz, 375 GHz and 500 GHz. Polarizers of larger size can be easily developed.

To characterize the samples, a standard transmission fiber THz-TDS setup is used. Each grid is stuck on a graduated rotational holder placed in the free air path of the THz beam. The angle formed between the polarization axis of the incoming THz beam and the grid long axis, defined as the axis parallel to the wires direction, respect which the grid is symmetrical, is set by rotating the grid holder. For each sample, the THz time signal is recorded at 0 degrees (parallel condition), 45 degrees and 90 degrees (perpendicular condition).

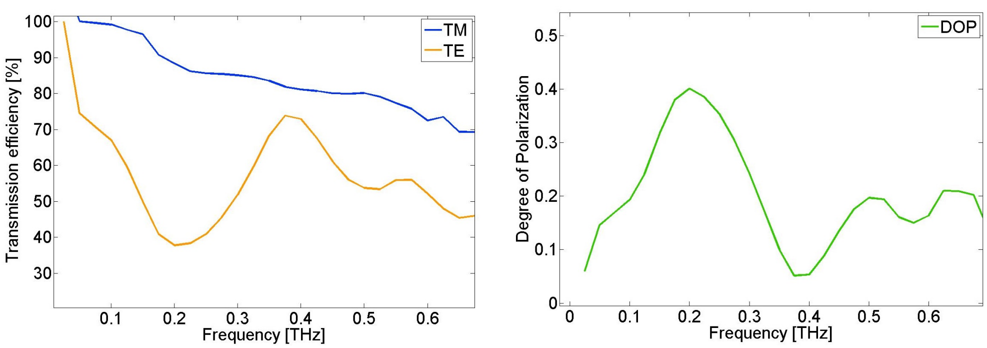
The relative amplitude of the THz spectra (referred to the spectrum of a blank sheet of paper) is displayed in Fig. 2(a). As the incoming wavelength λ is much greater than the grid periodicity d, a difference in the relative amplitude of the spectra is noticeable, ascribable to a polarization effect due to the selective absorption phenomenon (dichroism effect). The pitch determines the maximum frequency below which the effect is relevant. As it can be seen in Fig. 2, a decrease of the periodicity corresponds to a shift towards higher frequencies of the structure bandwidth. Fig. 2(b) shows the extinction ratio of the structures ($ER = 10log_{10}\frac{T_\perp}{T_\parallel}$ [19]), where $\perp$ and $\parallel$ refer to the TM and TE polarization, respectively. With a single structure, an ER of only 3 dB is achieved (see Fig. 2(b)) which is far below the required features for a commercial polarizer, that is at least 20 dB [4].

The evaluation of transmission efficiency reveals a decreasing trend as the THz incoming wavelength becomes comparable with the grid periodicity. In addition, the transmission efficiency in the case of parallel condition exhibits a maximum of transmission for $\lambda = d$. Instead of the expected lowpass response, a bandpass behavior is shown in Fig. 2, due to the bandwidth limitation of the THz characterization setup (low emitted power below 100 GHz).



(a) (b)

Fig. 2. Fig. 2(a) Frequency transmission spectra achieved by Fourier transforming the time-dependent THz electric field. The dotted red line represents the reference blank paper signal, whereas the other three traces are the 90° (blue line), 45° (green line) and the 0° (purple line). Fig. 2(b) shows the variation of the frequency of maximum ER as a function of the pitch dimensions.



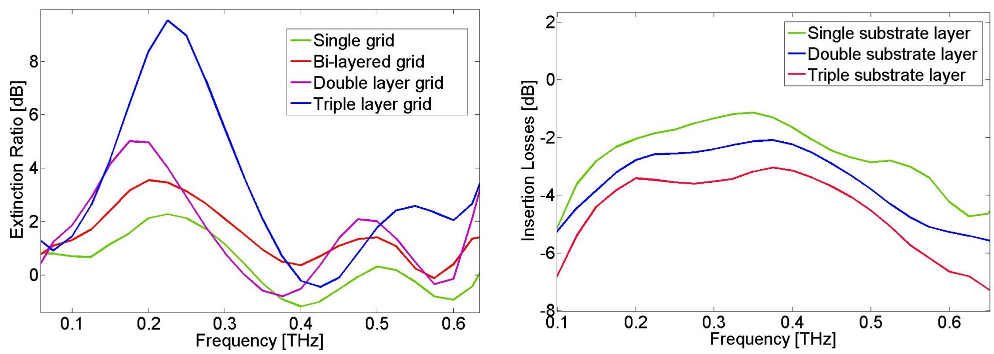
(a) (b)

Fig. 3. Fig. 3(a) Transmission efficiencies for the 0.8 *mm* pitch structure. The maximum transmission efficiency exhibits a decreasing trend as the incoming THz wavelength becomes comparable to the pitch dimension. In addition to this behavior, the minimum transmission efficiency shows a maximum of transmission when $\lambda = d$. Fig. 3(b) displays the Degree of Polarization of the 800 μm pitch wire grid with a single layer structure.

Finally the Degree of Polarization is analyzed. Fig. 3(b) shows that the graphite wire grid only partially polarizes the incoming THz beam, reaching a 40% polarization at the frequency of maximum ER.

The good conductivity of pure graphite is affected by the presence in the pencil of clay and other binders. The resistivity ρ of the compound on the sheet of paper (measured as the averaged resistivity value of each drawn line) results to be 1694 Ωm. This value is several orders of magnitude above the pure graphite resistivity value that is $7.837 \times 10^{-6} \Omega m$ [20] or common metals such as copper (ρ=$1.69 \times 10^{-8} \Omega m$). This last value of resistivity implies skin depths that ranges from 4.45 μm at 100 GHz to 2.57 μm at 300 GHz.

Three different configurations have been tested for the 0.8 *mm* pitch pattern to improve its performance. The first design is obtained by depositing graphite on both sides of the same substrate (sheet of paper), whereas the other two structures are the result of sticking together two and three one-faced periodic structures, respectively. In these cases, particular attention is payed to superimpose them precisely.



(a) (b)

Fig. 4. The ER of three different structures and the corresponding IL are shown and compared with the basic one. The used wire grids are the 800 μm pitch. The ER value increases as the number of structure grows, reaching almost 10 dB.

Results for the ER and the correspondent Insertion Loss ($IL = 10log_{10}T_{\perp}$ [21]) are shown in Fig. 4. The increase of the ER in the three-layer structure suggests that THz polarizers with moderate performance could easily be developed following this very simple approach. To test the durability of this method, the wire grid structures have been measured again after one month, checking that there has been no significant changes in performance.

3. Summary

The polarizing effect due to the dichroism phenomenon is studied in simple periodic structures drawn with lead pencil on blank paper. The display of the selective absorption phenomenon when modifying the angle between the polarization axis of the incoming THz beam and the long axis, and the displacement of its maximum frequency according to the pitch variation hints at a polarizer behavior. Extinction Ratio up to 9 dB are shown using an extremely simple low-tech approach based on low-cost materials with an estimated cost of less than one dollar.

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