Flexible Sub-THz Metal Wire Grid Polarizer Based on an $EGaIn_{24.5}$ Alloy

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***Abstract*—A flexible sub-THz polarizer based on an eutectic Gallium-Indium alloy ($EGaIn_{24.5}$) on a vinyl acetate substrate is fabricated and tested. The $EGaIn_{24.5}$ alloy shows low melting point, good wettability and high conductivity, resulting in a low cost alternative to conductive inks based on metal nanoparticles. These properties are exploited to draw metal wire grid polarizers by using a technical pen on a bendable sheet of vinyl acetate monomer. Measurements are carried out with a transmission THz-TDS setup in the frequency range from 0.1 to 0.6 THz, showing an Extinction Ratio (ER) up to 20 dB. This approach allows a quick low-tech and cost effective implementation of flexible polarizers in the sub-THz band.**

***Index Terms*—terahertz spectroscopy, submillimeter wave polarizer, metal alloy.**

I. Introduction

WAVES in the THz band are of interest in a variety of scientific and technological fields. Among other features, their no-ionizing nature and the transparency of some common materials, such as cotton and plastic, in this spectral region, make THz signals very appealing for nondestructive inspection, characterization of a wide range of materials and so on [1]. As the control of the polarization state of the generated THz beam allows the extraction of additional information through polarimetric analysis [2], efforts are being made to provide cost-effective and high performance polarizers, helping in this key task [3], [4]. Most THz polarizers are based on metal wire grid structure, both free-standing and on a substrate. In parallel, work is being carried out to develop flexible polarizers [5]–[8], inspired by the emergent field of flexible electronics, to improve the mechanical robustness of these components [6]. Polarizers based on ink-jet printing exploit the conductive properties of metal inks based on Silver or Aluminum nanoparticles [7], [8]. The former type requires a rather complex and expensive process of fabrication in addition to specific printers of considerable cost [8], [9]. On the other hand, Aluminum based inks are more affordable, but they provide lower performance than Silver based ones [8], because of their higher resistivity ($\rho_{Ag} = 1.59 \cdot 10^{-6}\Omega cm < \rho_{Al} = 2.65 \cdot 10^{-6}\Omega cm$ [10]).

In this letter, it is shown that an $EGaIn_{24.5}$ alloy can be used as a simple and low cost alternative to the implementation of polarizers in the THz region on flexible substrates. The alloy properties allow straightforward drawing of metal wire grids on flexible substrates using common technical pens, which behave as polarizers in the THz band.

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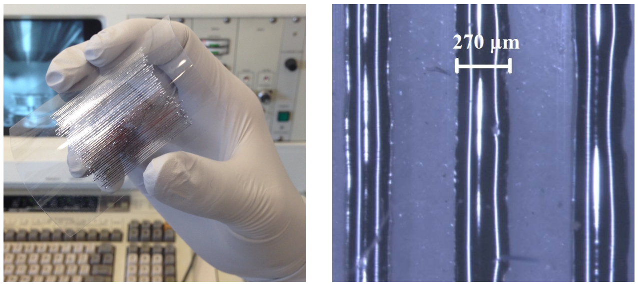
II. Experimental results

The first step in the fabrication of the metal wire grid polarizer is the preparation of the $EGaIn_{24.5}$ metal alloy. Following the procedure described by Zheng et al. [11], 99.9% pure Gallium is melted in a beaker on a hot plate and then stirred with 99.9% pure Indium with a glass rod. Metals are weighted 75.5:24.5 and they are kept in de-ionized water to reduce the development of oxide skin that specially characterizes Gallium and its alloys [12]. As the $EGaIn_{24.5}$ is liquid at room temperature and has high surface tension, sheets of vinyl acetate monomer offer good adherence, avoiding the formation of droplets of alloy that can blur the result [9].

Technical pens with highly precise nib widths can be used to deliver the ink by hand on the substrate. In particular, a technical pen with 0.8 mm nib size is used in the experiments [13]. The inner part of the refillable pen is previously treated with an HCl solution, trying to remove the oxide skin that quickly forms in the metal alloy as it comes in contact with oxygen. Additionally in this way, the metal ink surface tension is reduced, making it to flow smoothly from the pen. The compatibility between the amount of alloy deposited with the pen and the high adhesion of the chosen substrate allows a direct drawing process.

Several studies deal with the determination of the role of the alloy oxidation, when studying its rheological properties [9], [12], [14]. The solid-like response of $EGaIn_{24.5}$ and its high wettability are actually due to the compact, stable and homogeneous oxide skin that quickly forms on the droplet surface when it is exposed to air, avoiding the oxidation of the whole alloy (i.e. the alloy naturally passivates itself). The expected resistivity value of the eutectic alloy at room temperature is ρ=29$\mu\Omega cm$ [11], [15], that is two orders of magnitude lower than that of silver-based inks in the same environmental conditions. The actual resistivity of the alloy used in the experiments is determined with the four point probe method [16]. A 3.5 x 3.5 cm^2 thin layer of the alloy is deposited by hand on an acetate sheet. The wire thickness is estimated to be (74.20 ± 0.02) μm, but it is affected by the nib flux, whereas the substrate thickness is evaluated in 0.110 mm by mean of a digital caliper with an accuracy of 0.001 mm and a resolution of 0.02 mm. Repeated measurements are taken in five different areas of the same sample to determine the homogeneity of the deposition process. The measurements provides a resistivity value of ρ=167$\pm$24$\mu\Omega cm$. The deviation from the expected theoretical value is probably due to an excess of Gallium oxide in the alloy.

Figure 1 shows the periodic structure developed with the



(a) (b)

Fig. 1. a) Photograph of the bendable nominal 500 μm pitch metal wire grid polarizer, with wire width ranging from 100 μm to 300 μm and a fill factor from 0.2 to 0.6, based on $EGaIn_{24.5}$ alloy on an acetate vinyl monomer sheet. b) Optical microscope image of the same structure.

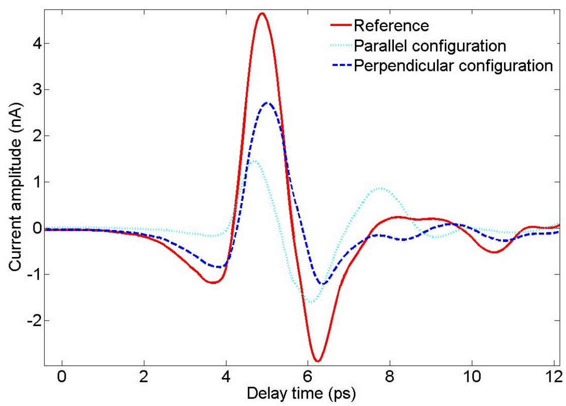


Fig. 2. Current signals comparison among the bare vinyl substrate and the signals of both perpendicular and parallel polarization.

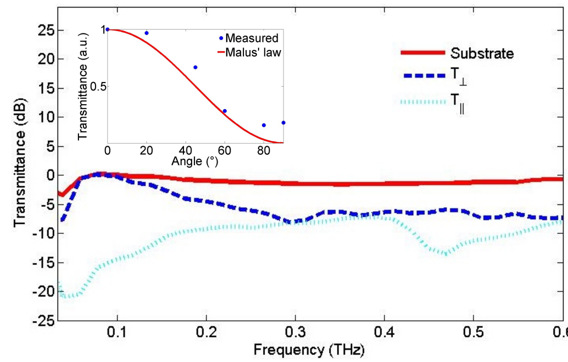


Fig. 3. Comparison of transmittance of both perpendicular and parallel configurations and the substrate of the 500 μm wire pitch structure in the 0.1 - 0.6 THz frequency range. Inset: Normalized transmittance as a function of the angle between the transmission axis of the polarizer and the incoming THz electric field at 100 GHz and Malus' law.

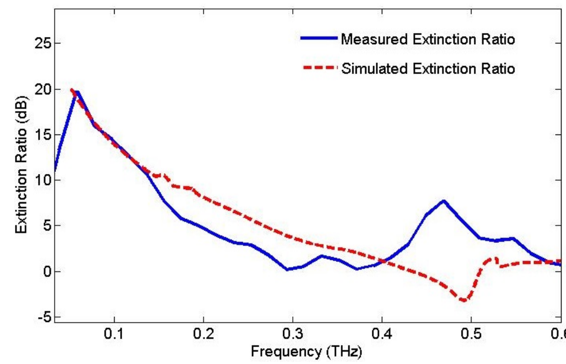


Fig. 4. Solid line: measured extinction ratio of the wire grid structure drawn with a target 500 μm pitch pattern in the 0.1 - 0.6 THz frequency range. Dashed: simulations of a wire grid structure with irregularities both in the wire and pitch lengths.

proposed technique. Wires approximately 270 μm wide and 3.5 cm long and with a nominal periodicity of 500 μm are drawn on a vinyl acetate sheet. Wire and pitch standard deviation is estimated in approximately 23% and 24% of the nominal value. In order to achieve a polarizing behavior based on the selective absorption phenomenon, i. e. the dichroism effect, a pitch lower than the incoming waves is required [17], [18]. To test the performance of the periodic structure as a polarizer the metal wire grid is stuck on a rotational holder and the transmission at normal incidence is analyzed using a conventional all-fiber TDS-THz time domain spectroscopy setup based on photoconductive antennas [1]. This instrument has been in-house developed using commercial fiber-pigtailed photoconductive antennas by Menlo Systems GmbH, optimized for operation in the telecom band. A femtosecond laser providing optical pulses at 1550 nm and 100 fs with a repetition rate of 100 MHz has been used as optical source. Measurements were performed with a single polarizer placed in the focus point of the optical system, consisted on four THz TPX lenses, plano-convex and bi-convex types. Figure 2 compares the temporal waveforms of the substrate and a single polarizer in parallel and perpendicular orientations. The parallel configuration describes the one in which the angle formed by the long axis of the grid and the incoming THz electric field is 0°, whereas in the perpendicular configuration this angle is 90°.

The polarizer performance is expressed as Extinction Ratio (ER), that is the ratio between the perpendicular and the parallel transmittance expressed in dB, calculated as $ER = 10 \cdot log_{10} \frac{T_\perp}{T_\parallel}$.

Figure 3 shows the transmittance of bare vinyl acetate, that is mostly transparent in the considered band. A higher transmission coefficient is detected when the angle formed by the long axis of the grid (parallel to the wire direction) and the incoming THz electric field is 90°, whereas a lower trend is achieved when the two directions are at 0°. The inset of Fig. 3 shows the angular dependency of the transmittance, following Malus' law.

Figure 4 shows the corresponding ER trace in the frequency range between 0.1 and 0.6 THz. The ER reaches up to 20 dB, comparable with results collected in [19]. As expected, it reflects the transmittance behavior in addition to a decay as the wire periodicity becomes of the order of the incoming THz wavelength. At low frequencies the ER cannot be measured due to the very low power emitted by photoconductive antennas below 50 GHz. Simulations were performed with a FDTD simulation tool (CST Microwave Studio), for terahertz frequencies in Normal background condition. The measured optical parameters of the substrate and the alloy conductivity, as well as the irregularity of the wire width and pitch were also considered.

To test the durability of the device, the polarizer went through a second set of measurements after a two week period of exposition to air. No significant change in the ER evolution is seen. The ER shows just a small decrease of its maximum (less than 1dB) and the bandwidth is roughly the same.

The capability to bend the polarizer has been studied following [20], where it was shown that bending a polarizer introduces Rayleigh-Wood anomalies that might degrade its performance. This anomaly is a redistribution of energy of forbidden diffraction modes of higher orders among the lower ones, so it negatively affects the transmission properties of the polarizer. It can be shown that above a given minimum bending radius the degradation can be avoided. This degradation due to strong bending of the structure has been tested by bending the polarizer. Equation (8) in [20]

$$R > R_{min} = \frac{S_{WGP}}{2\arcsin|n_S - (\lambda/\Lambda)|}$$

With S_{WGP} total wire grid polarizer dimension and Λ representing the pitch structure, states that the radius of the polarizer can be calculated in order not to incur in the anomaly in a specific frequency band. With a radius of curvature of 2.25 cm, frequencies below 454 GHz will show degradation due to this effect and a decrease of 7% in the ER peak amplitude was experimentally observed.

III. Conclusion

A low-tech and cost-effective method to easily develop polarizers in the THz band has been proposed. This approach is based on common, inexpensive and easily available materials. The combination of high electrical conductivity and good wettability makes $\mathrm{EGaIn}_{24.5}$ an efficient, low-cost and no toxic conductive ink that allows direct drawing of THz polarizers on flexible substrates. This approach could also be employed to draw other components such as THz mesh filters. Besides increased robustness in terms of normal and shear stress, the the flexibility of both substrate and metal alloy offers the capability of implementing flexible electromagnetic components. Better performance in terms of repeatability (and therefore bandwidth) could be reached through the use of a more complex method for ink delivery based on hardware and software modifications on affordable commercial printers [22].

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