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Flexible twist polarizer based on ultrathin multi-layered polymer-carbon nanotubes composite films

Yann Danlée[1,2] | **Isabelle Huynen**[1] | **Christian Bailly**[2]

[1] Information and Communications Technologies, Electronics and Applied Mathematics (ICTEAM), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

[2] Institute of Condensed Matter and Nanosciences (IMCN), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

Correspondence
Information and Communications Technologies, Electronics and Applied Mathematics (ICTEAM), Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium.
Email: yann.danlee@uclouvain.be

Abstract

We present an ultrathin and flexible microwave broadband polarization transformer concept based on oriented carbon nanotubes dispersed in a polycarbonate matrix. Stacking anisotropic composite films with a controlled angle mismatch between successive layers produces a twist polarizer able to change the orientation of the electric field over broad frequency range in the microwave domain. The smart organization confers to the multilayer a high efficiency measured as a degree of twist, which reaches 75.1% at GHz frequencies for a 420 μm thick seven-layer stack.

KEYWORDS

carbon nanotubes, microwave polarization, multilayer, polymer, twist polarizer

1 | INTRODUCTION

Polarization transformers have numerous applications, for instance, in radar/antenna engineering. A variety of polarization transformers have been described for different applications, such as circular polarization (CP) selectivity,[1,2] polarization rotation of a linearly polarized (LP) plane wave,[3] and LP to CP conversions.[4] This work focuses on a twist-polarization transformer which forces the electric field of electromagnetic waves to rotate towards a predefined angle. The current literature proposes different polarization transformers at microwaves but there is no systematic way of designing such devices.[5,6] In optics, the phenomenon is commonly used in the liquid crystal screen, where it is referred to as the twisted nematic field effect.[7] Researches have proved that the integration of carbon nanostructures brings a noteworthy enhancement to the optical nematic polarizer,[8,9] and opens the way to many applications.[10–12] At microwave frequencies, rotating the polarization is possible by the method of twisted waveguides, but those systems are large and operate on a narrow band.[13] Niemi et al.[14] has published the simulation of a twist polarizer comprising an array of chiral elements, i.e. pairs of orthogonal canonical helices. The device drastically increases the efficiency with respect to the state of the art but only for a very specific frequency. Broadband polarization transformers are made of successive metal grid plates stacked at incremental angles in order to force the rotation of the polarization. They are simple and adaptable to a lot of radar applications but their thickness always exceeds a few cm.[15] Furthermore, the metal is not suited to maximize the transmission because of its high reflectivity which indubitably reduces the efficiency.[16] Our original strategy uses stacks of oriented-CNT films at a constant angle increment to twist the polarization. Carbon nanotubes (CNTs) allow a fine interaction with the electric field[17] required for polarization like metal grid, but without considerably reflecting the energy as a metal.[18] Currently, polymer-CNT composites are widely used for broadband absorption[19] or microwave polarization.[20] Our twist polarizer operates over the GHz-range and has the advantage of a thickness ∼100 times lower than the wavelength. The multilayer is quantified in the following sections of the article and then some perspectives are given with the help of simulations.

2 | SAMPLE FABRICATION AND CHARACTERIZATION METHODS

2.1 | Process of implementation

Oriented-CNT films are produced from a custom-made compound (Makrolon 2805 polycarbonate reinforced with 2%wt. of CNTs NC7000) provided by the company NanoCyl.

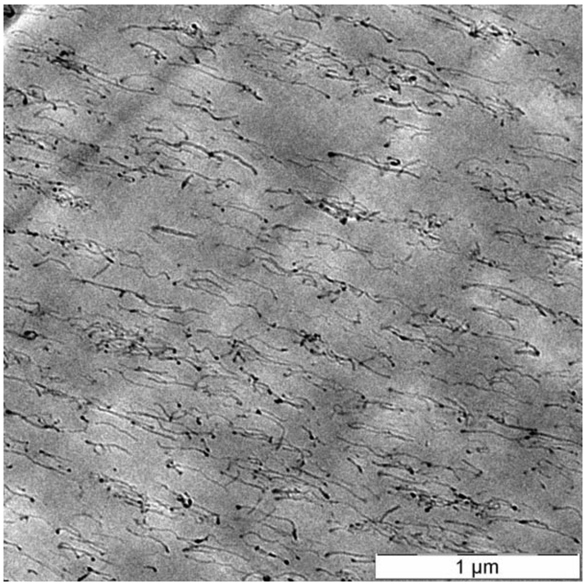

FIGURE 1 TEM images 5000× of oriented CNT by stretching. The composite is 2%wt. CNT blended in polycarbonate

Compounded pellets are continuously fed into a micro 15 DSM microcompounder operating at 150 RPM and 280°C while the material comes out through a film die. The hot film is directly connected to a stretching roll (DSM Xplore roller). The outgoing ribbon is driven by a take-up reel which stretches the nanocomposite. The rolling speed and torque are imposed at respectively 700 mm/min and 30Nmm. The thickness after stretching is about 40× smaller than at the die. The elongational flow between the die and the stretching roll strongly aligns the CNT in the strain direction.

2.2 | Characterization techniques

We use a Keithley K2400 or K6430 4-contact probe for the measurement of in-plane DC conductivity σ. The frequency response of the samples is characterized using different methods for the in-plane and out-of-plane configuration: conductivity in the direction perpendicular to the film (out-of-plane σ) is extracted from measurements using a Keysight PNA-X N5247A (Agilent) Vector Network Analyzer operating up to 70 GHz in a microstrip line configuration, while the in-plane corresponding parameters are obtained from a waveguide configuration. The two techniques are explained and illustrated in refrence.[21]

TEM has been performed on nanocomposites with the help of a Zeiss Leo 922 working at 200 KV and equipped with an Omega-A filter. The samples were beforehand embedded in epoxy resin and sliced at 90 nm thickness by a Leica EM UC6 ultramicrotome.

3 | MEASUREMENT OF FREQUENCY RESPONSE

We elaborate an anisotropic material at the nanoscale thanks to the uniaxial orientation of the nanofillers in the plane of the film. The optimal concentration of CNT was determined thanks to preliminary EM characterizations detailed in reference.[22] The in-plane DC conductivity measured parallel and perpendicular to the CNT orientation is quite close to those of pure polymer. This weak DC conductivity makes sense when considering the CNT organization in the PC matrix (Figure 1). They are not in any way connected to each other, implying a very low conductivity in all directions. We thus need to characterize AC properties to see a significant electrical anisotropy. Indeed, at high frequencies, the coupling capacitance between CNTs ends acts as a short-circuit, creating virtual conductive aligned strips whereas capacitive coupling is much lower in the orthogonal directions.

The in-plane conductivity is measured at microwaves frequencies along the two perpendicular axes in the plane. Let's assume that the nanotubes are oriented along the z-axis in the yz plane. The waveguide measurements give the conductivity (in z-direction) parallel to the fillers and (in y-direction) perpendicular to the fillers. The microstrip measurement gives the out-of-plane conductivity (along x-direction) which is perpendicular to the plane (and to the fillers). Figure 2 shows that the measurements in x- and y-direction are close to each other. The conductivity parallel to the CNT is higher which proves the influence of the uniaxial orientation.

We now build a twist polarizer by stacking oriented films with a given angle increment between two neighboring layers. The first layer has nanofillers oriented along the z-axis, for instance. Layer by layer, the CNT are progressively rotated until the nanofillers in the end layer are aligned in the y-direction. Let's assume that an unpolarized wave comes in at port 1 (see top part of Figure 3), the electric field will progressively align along the y-direction. If the incoming wave

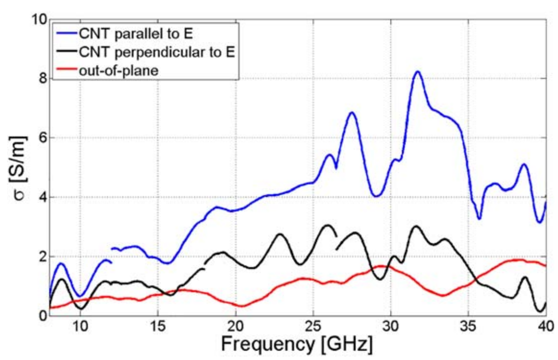

FIGURE 2 AC characterization of aligned CNT composite. Conductivity is given for the electric field oriented in parallel and perpendicularly to the CNT in-plane and out-of-plane. [Color figure can be viewed at wileyonlinelibrary.com]

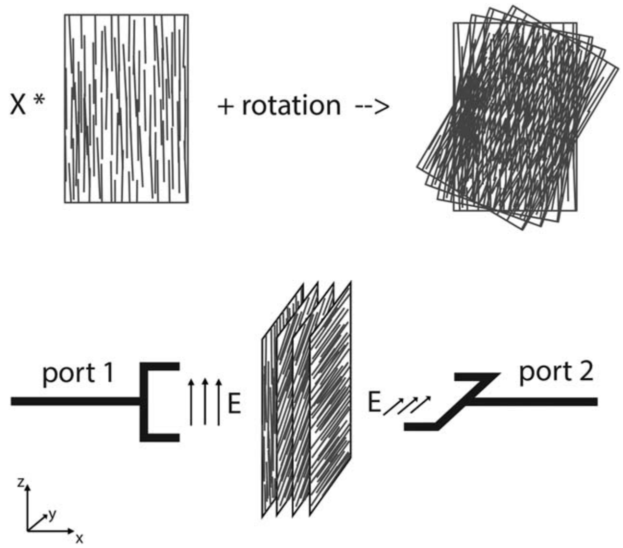

FIGURE 3 Scheme of the polarizer multilayer (stack of X layers with incremental rotation) and the orientation of the ports for EM characterization

is already polarized along y, the interaction with the multilayer will be weak so that no rotation or absorption will be effected. In short, the polarizer imposes an orientation of the electric field without significant absorption.

The waveguide set-up used for this particular characterization is schematized in the bottom part of Figure 3. The port 1 emits/measures z-polarized waves while the receiver/emitter of the port 2 is polarized in the y-direction. In the absence of a twist polarizer between the two ports, almost nothing is transmitted. The reflection is total for the same reason. This is the reference which we compare the effect of samples with. It means that almost nothing is transmitted without the help of a polarizer. This reference transmission measurement is first compared in Figure 4 with the situation where a twist polarizer is inserted between the ports. The polarizer is built from a multilayer stack of three CNT-oriented composites films, each 60 μm thick. The first film of the stack (close to port 1) has its nanofillers aligned with the incoming electric field, while the second and third films are respectively rotated by 45° and 90°. The polarized transmission of this three-layer twist polarizer increases ∼15 dB by comparison with the reference transmission depending on frequency. A second multilayer is built from seven CNT-oriented films, with a rotation increment of 15° from layer to layer is shown in Figure 4 too. The reflection S_{11} (not shown) is close to −10 dB for the two multilayers. This low reflectivity is explained by the specific stack organization of the multilayer (see details in reference[23]). The polarizer is more efficient if we use more layers since the S-Parameters of the seven-layers system demonstrate that the polarized transmission through the sample is enhanced. The polarizer transformers can be quantified by the "degree of twist" (DOT) defined as

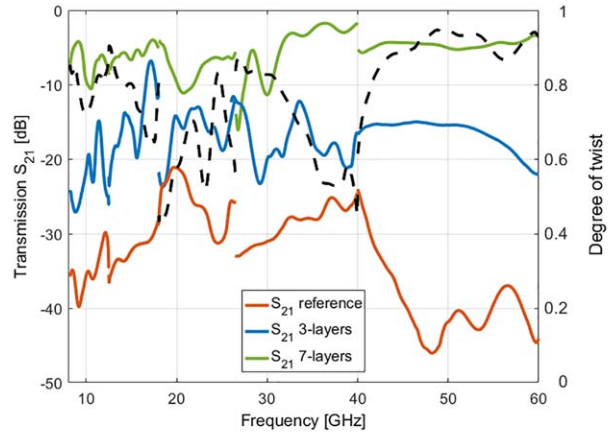

FIGURE 4 Transmission S_{21} of the three- and seven-layer twist polarizers compared with the reference (i.e. transmission through perpendicular-crossed wave guide). The DOT of the seven-layer twist polarizer is displayed in dotted line. [Color figure can be viewed at wileyonlinelibrary.com]

$$\mathrm{DOT}=\frac{|S_{21\mathrm{ml}}|-|S_{21\mathrm{ref}}|}{|S_{21\mathrm{ml}}|+|S_{21\mathrm{ref}}|} \tag{1}$$

where $S_{21\mathrm{ml}}$ and $S_{21\mathrm{ref}}$ are respectively the transmission S_{21} through the multilayer and reference. The three- and seven-layers twist polarizers have a DOT averaged over the considered frequency range equal to 0.64 and 0.75, respectively, for a thickness of 180 and 420 μm. Figure 4 shows the DOT depending on the frequency of the 7-layer twist polarizer. Reference[16] describes a metal mesh based polarization transformer which provides a transmission of −28 dB for an E-field rotation of 90° while we get < −10dB with our seven-layer twist polarizer. No DOT (or reflectance) is given for this structure but our multilayer exhibits a certain advantage in term of transmission (and probably reflection). Niemi et al.[14] have proven that a transmission close to 0 dB (and hence a DOT close to 1) is feasible by metallic patterned structures but this performance is effective over a very narrow band only. A photo of the seven-layer twist polarizer is exhibited in Figure 5 to visualize our flexible structure.

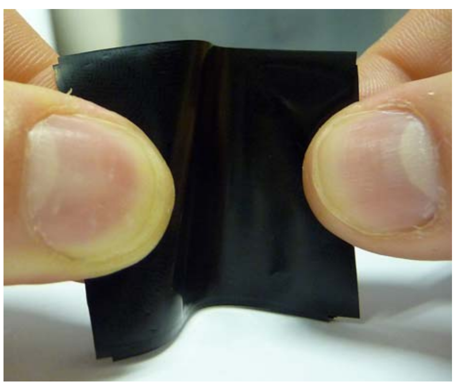

FIGURE 5 Photo of the seven-layer twist polarizer. [Color figure can be viewed at wileyonlinelibrary.com]

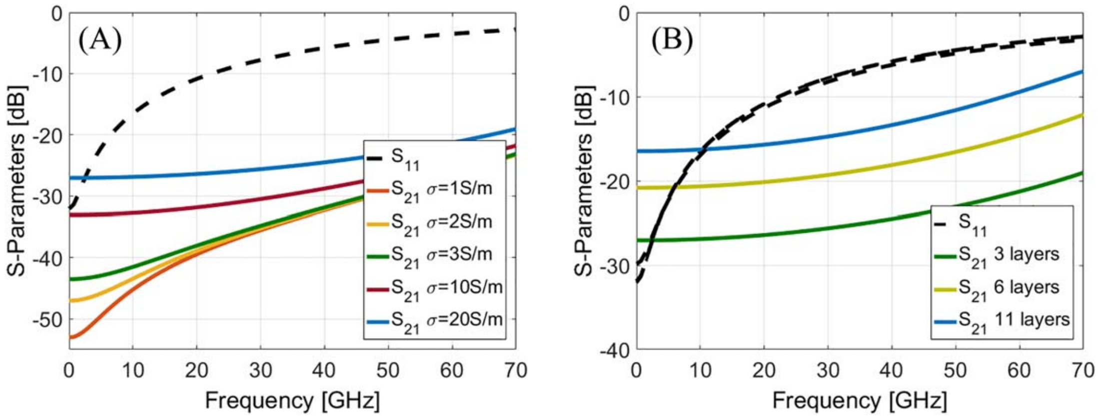

FIGURE 6 Comsol simulations of several polarizing structures. In (A), only conductivity changes and structural arrangement is fixed. In (B), the number of equivalent layer varies. [Color figure can be viewed at wileyonlinelibrary.com]

4 | OPTIMIZATION OF PERFORMANCES

Comsol simulations have been performed to provide guidance toward an optimal homogeneous structure. The effect of anisotropy in term of conductivity and the number of stacked layers are studied. We have explored the impact of conductivity in one direction from 1 up to 20 S/m whereas the conductivity in other directions is fixed at 10^{-5} S/m. The thickness of all films is set at 25 μm. Figure 6A proves that increasing conductivity improves the transmission for three-layers polarizers. In Figure 6B, we start from the three-layers polarizer with $\sigma = 20$ S/m. This is now compared with multilayers where the number of stacked layers increases (at same conductivity). We quickly conclude that it is advantageous to stack layers maximizing anisotropic conductivity and to increase the number of those successive layers (and correspondingly reduce the angle increment between successive layers).

This system could hence be optimized by using thinner films with higher CNT concentration and extremely high anisotropy. The enhancement of the stretching process should provide better alignment and thinner films which are advantageous for decreasing the loss. The low thickness of the layers could be compensated by a higher quantity of films in order to maximize the transmission and to keep a good mechanical resistance.

5 | CONCLUSION

We have demonstrated a concept based on stacks of oriented-CNT composite films to control microwave polarization. From layer to layer, the electric field of the wave rotates up to a defined angle independently of frequency. The DOT (defined earlier) of our seven-layers polarizer has been measured at 0.75 and it operates over a wide spectrum from 8 to 60 GHz. This performance fills the gap of GHz-frequencies in the field of polarizer transformer. The efficiency is due to an effective polarized transmission of the waves without significant reflection and the very low thickness compared to wavelength considerably avoids unwanted absorption. The composite films benefit from the advantage of the polycarbonate matrix in terms of mechanical properties such as flexibility and strong resistance. The implementation process is simple and could be improved to yield the potential improvements suggested by the simulations.

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Dual-end opened slot antenna design for dual-band WLAN uses on handsets

Chih-Kai Chang | **Chi-Yuan Yao** | **Wen-Jiao Liao**

Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

Correspondence
Chi-Yuan Yao, Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan.
Email: d10407009@mail.ntust.edu.tw

Abstract

A novel slot antenna configuration is proposed for applications on mobile terminals. The slot has both ends opened and can be placed on circuit board edges or incorporated with a handset's metal body. The antenna is loaded with one capacitor at the slot's opening and an inductor right next to the feed. Functions of loadings include size reduction, band broadening, and matching improvement. A compact design of 15 mm × 5 mm is devised for dual-band WLAN uses. Simulated and measured results validate that good matching and radiation efficiency are achieved with moderately directive patterns in both bands. A two-antenna scheme is also provided for MIMO uses. A mobile device can take advantage of the proposed antenna's compact volume and directive pattern to achieve good isolation and diversity performances.

KEYWORDS

handset antennas, lumped element loadings, MIMO, miniaturized antennas, slot antennas