A Highly Flexible and Efficient Dipole Antenna Realized in Methanol-Treated Conductive Polymers

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***Abstract*—A highly flexible and efficient 2.45-GHz dipole antenna realized in methanol-treated conductive polymers PEDOT:PSS (PEDOT) is presented. The originally highly conductive PEDOT thin films have been further treated by immersion in a methanol solution, to realize a significant conductivity improvement from approximately 3500 S/m to 18500 S/m. As a result, a more than 25% antenna efficiency enhancement is attained, which brings the averaged efficiency up to 91.4% of the efficiency of a copper reference antenna with identical geometry. This simple treatment shows a practical and affordable solution to significantly improve conductivity for conductive polymers and make this type of materials even more suitable for antenna applications, particularly in conformal and flexible configurations. To verify the performance improvement, three identical antennas realized in copper, untreated and treated PEDOT have been fabricated and experimentally characterized. The results are in very good agreement with the full-wave simulations and confirm the expected improvement.**

I. INTRODUCTION

Metallic materials such as copper and gold are conventionally utilized as antenna conducting materials since they have very high conductivity, stability and robustness. However, due to the lack of reproducible mechanical flexibility, they have limitations as conducting materials for flexible antennas [1]. Recently, due to the dramatic increase in the demand for flexible electronics, including antennas, various suitable conducting materials offering desired characteristics such as high conductivity and non-destructive mechanical conformability have been emerging. These materials include embroidered conductive threads [2], [3], conductive fabrics [4], [5], conductive inks [6], [7], silver nanowires [8] and conductive polymers [9], [10]. In particular, in spite of the limitations in obtaining sufficient thickness and satisfactory conductivity simultaneously [11], conductive polymers have become one of the promising classes of conducting materials for flexible microwave devices such as antennas [12] and sensors [13], with steadily improving high electrical conductivity and plastic-like reproducible mechanical flexibility.

Conductive polymeric materials have been initially utilized for various antenna designs in the last two decades [14], [15], and some potential soldering methods have been investigated as well [16]. A few year ago, a proximity-coupled microstrip antenna whose radiating patch was made of polyaniline (Pani) film has been reported to have 56% efficiency [17]. Similarly, two microstrip patch antennas using Polypyrrole (PPy) as their patch materials have also been demonstrated with efficiencies of 62% [18] and 65% [19] respectively. Moreover, an ultra-wideband (UWB) antenna design using PPy as all conducting materials has been demonstrated with a remarkably higher efficiency of 79.2% [11]. Such satisfactory efficiency was attributed to the sufficient thickness and conductivity in the PPy as well as a non-resonant antenna structure [20]. To further lift the antenna efficiency and make better use of conductive polymers' reversible mechanical flexibility, a planar trapezoidal UWB antenna based on a PEDOT thin film has been proposed very recently, with exceptional mechanical conformability and a measured efficiency of nearly 90% [21]. Such promising performance is obtained through combination of a unique PEDOT preparation allowing to achieve substantial thickness and outstanding conductivity, and a non-resonant antenna design optimized for efficiency.

As mentioned in the above literature review, usually lossy-material-based resonant antennas achieve a lower efficiency compared to non-resonant designs. Thus, much higher conductivity in the conducting materials is necessary for resonant antennas to attain an efficiency above 90% compared to non-resonant antennas. Therefore, in this paper, a simple yet robust methanol-solution-based treatment [22] is applied to a highly conductive PEDOT thin film to further enhance its conductivity. Then a 2.45 GHz resonant dipole antenna is designed and prototypes are fabricated using both untreated and treated PEDOT, as well as copper for reference. The experimental characterization of the antenna performance shows that the treated material allows to achieve a radiation efficiency of above 91% of the copper antenna efficiency. This represents a 25% efficiency improvement with respect to the antenna made of the untreated materials. These results emphasize that, with a simple and stable treatment, conductive polymers can be even more suitable for antenna applications, with significantly enhanced conductivity.

II. THE ANTENNA

The resonant antenna test bed is a 2.45-GHz dipole antenna and its realizations in copper, untreated and treated PEDOT

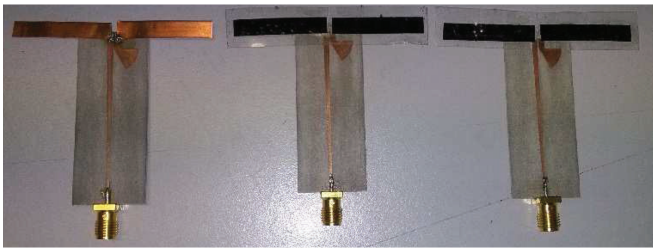

Fig. 1. Antenna realizations in copper (left), original (middle) and treated (right) PEDOT.

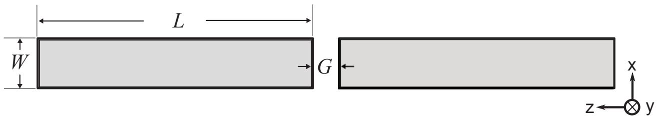

Fig. 2. Antenna configuration and its dimensions: L = 27.3 mm, W = 5 mm, G = 1.5 mm.

are shown in Fig. 1. The three prototypes are fed with a 50-Ω microstrip line to 78-Ω balanced coplanar strips impedance transition which is employed as a balun [23], [24]. The antenna dimensions are also illustrated in Fig. 2. The dipole arm length L is inversely proportional to the resonance frequency while the width W is proportional to the impedance bandwidth. The gap G between the two arms determines the input impedance of the antenna. Therefore, L and W are determined to obtain resonance at 2.45 GHz and to ensure ease of fabrication respectively, while G is chosen such that the input impedance is 78 Ω. The copper antenna arms are soldered whereas the polymeric arms are glued with conductive epoxy for connection to the balun. In order to achieve high accuracy in fabrication, the antennas are trimmed with a laser milling machine (LPKF: Protolaser_S). Sticky tape is used as a substrate for the PEDOT antennas which provides a straightening support. The impact of this tape on the antenna performance is negligible owing to its very small thickness. Thanks to the plastic-like flexibility of the PEDOT film, the antennas feature an exceptional reproducible non-destructive mechanical conformability, as illustrated by the two bending configurations shown in Fig. 3. Therefore, seamless integration in flexible electronic systems is possible with this type of polymeric antennas.

III. THE CONDUCTIVE POLYMERS

As mentioned previously, conductive polymers inherently hold a process-limited thickness and a relatively lower conductivity compared to metallic materials. The free-standing PEDOT thin film used in this work is quite challenging to achieve since it has a substantial thickness of 113 μm and a relatively high estimated dc-conductivity of 3500 S/m. This unique combination of thickness and conductivity enables a sufficiently low sheet resistance of approximately 2.5 $\Omega/\square$. Such competitive materials are prepared with Clevios PH1000 (Heraeus) solution and ethylene glycol using a solvent casting method. All residual solvent is eliminated completely from the films through a 130°C annealing process. The PEDOT film thickness is approximately two thirds of the skin depth at 2.45 GHz which is around 170 μm. This fact implies an increase in conductor ohmic loss and consequently a decrease in antenna efficiency. This loss in efficiency can be partially overcome by using well established techniques to enhance the conductivity [25].

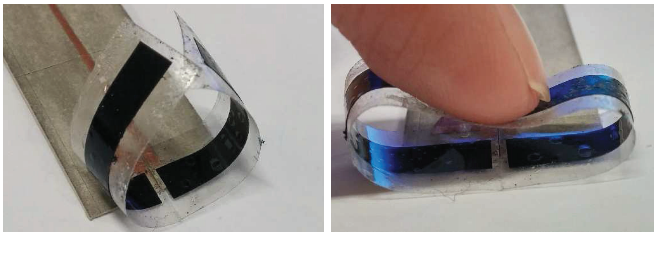

Fig. 3. PEDOT antenna in two bending configurations.

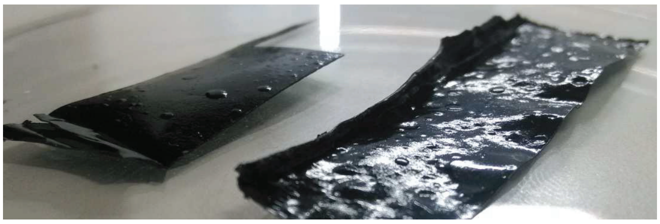

Fig. 4. The original (left) and methanol-treated (right) PEDOT:PSS.

IV. THE METHANOL TREATMENT

To further increase the conductivity, a simple, stable and economic treatment with methanol solution immersion reported in [22] is deployed. In this method, samples were immersed in methanol overnight and dried at room temprature. It is shown that this simple technique can enhance the conductivity of the samples by 2-3 orders of magnitude [22]. Changes to morphology, improved alignment of the PEDOT particles and removal of excess insulating PSS from the PEDOT:PSS film are the often mentioned main mechanisms for the high conductivity enhancement.

The original and the treated PEDOT thin films are shown in Fig. 4. Some sort of distortions in the treated PEDOT film are observed, which might become problematic for antenna designs requiring large areas. However, this could be solved by clipping or flattening during treatment with dedicated tools. Resistance measurement with a four-probe measuring system has been conducted and the resulting DC-conductivity of the original and the treated PEDOT has been determined to be around 3500 S/m and 18500 S/m respectively. Therefore, the sheet resistance of the treated PEDOT film is estimated to be approximately 0.5 $\Omega/\square$, which is about one fifth of the untreated film.

V. EXPERIMENTAL RESULTS

The prototype PEDOT antennas have been experimentally characterized and compared with the reference copper antenna to investigate the performance improvement due to the material treatment. The results have been analyzed together with corresponding simulations performed using CST Microwave Studio 2015 (CST). They show encouraging improvements in antenna performance in terms of matching and antenna efficiency, as described in the following.

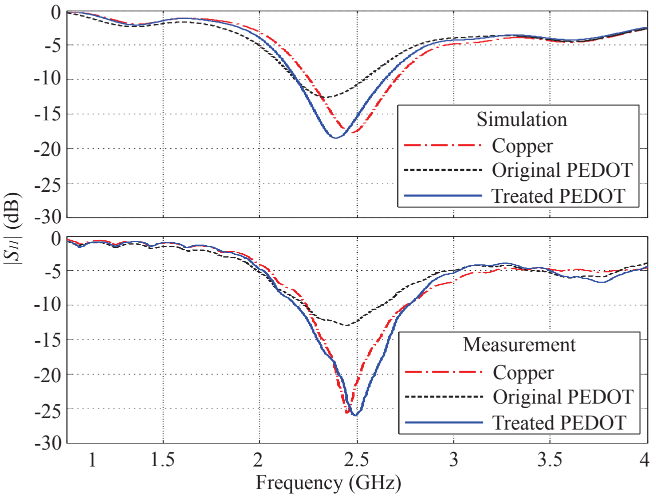

Fig. 5. Antenna reflection coefficient comparison. Top: simulations. Bottom: measurements.

A. *Reflection coefficient*

The simulated and measured reflection coefficients are depicted in the top and bottom sub-figures in Fig. 5 respectively. The simulated and measured curves for corresponding devices are in good agreement. Slight resonances shifts are observed which can be attributed to fabrication tolerances. The similarity in the reflection coefficient of the copper and treated PEDOT antenna suggests that they should have comparable performance in terms of efficiency.

B. *Radiation patterns*

The measured radiation patterns at 2.45 GHz in xy-, xz- and yz-plane are shown in Fig. 6, normalized to the overall maximum gain of the copper reference antenna. The co-polarization and cross-polarization components are depicted in the left-hand side and the right-hand side columns, respectively. The striking similarity in the shape of the patterns for the copper and treated PEDOT antennas suggests a similar antenna efficiency. As expected for a dipole antenna, the patterns in xy-plane is omnidirectional and zeros are observed at $\theta = 0^\circ,\ 180^\circ$, along the z axis. The asymmetry of the co-polar components in the xz-plane is introduced due to the presence of the SMA and a right angle connectors in the measurement path.

C. *Antenna radiation efficiency*

The antenna efficiency is estimated through an approximate gain-directivity measurement relative to the reference antenna. Comparisons of the radiation patterns in xz- and yz-plane, as shown in Fig. 6, indicate that the antennas have nearly identical directivity since the patterns are of the same shape. To compare the gains, the radiated power is averaged over all elevation angles, assuming 100% efficiency for the copper antenna. The PEDOT antenna efficiency is then evaluated through [11]

$$e_c \approx \frac{\Sigma_\phi \Sigma_\theta G_{PEDOT}(\theta,\phi)\sin\theta\Delta\theta\Delta\phi}{\Sigma_\phi \Sigma_\theta G_{Copper}(\theta,\phi)\sin\theta\Delta\theta\Delta\phi}. \tag{1}$$

The simulated and estimated efficiencies are both illustrated in Fig. 7. A good correspondence between simulated efficiencies and pattern-based estimations is observed. Over the operation band, the antenna made from the original PEDOT yields an averaged 65% efficiency whereas the one realized with the treated polymer holds an averaged 91.4% efficiency. The last value is, to the best of our knowledge, the highest reported efficiency for this type of resonant polymeric antenna. An efficiency increase of more than 25% is achieved through the conductivity enhancement fulfilled with a simple methanol treatment.

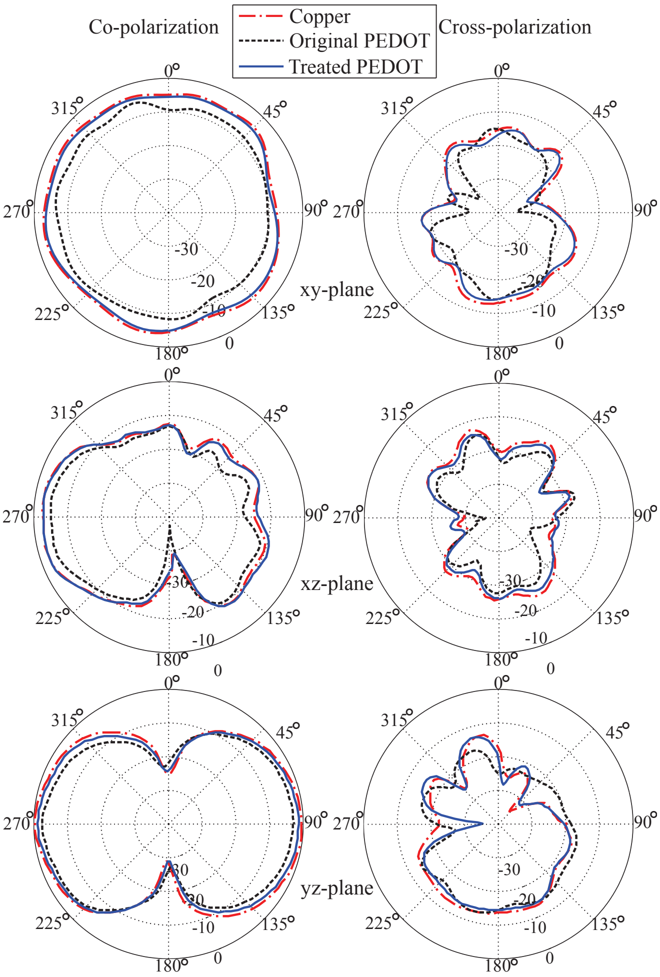

Fig. 6. Measured radiation patterns at 2.45 GHz in principal planes. Left: co-polarization. Right: cross-polarization. All patterns are normalized to the overall maximum gain of the copper antenna.

VI. CONCLUSION

A highly flexible and efficient 2.45-GHz dipole antenna realized with methanol-treated PEDOT has been presented, demonstrating a promising and simple method to significantly enhance conductivity in conductive polymers. Three identical antenna designs realized in copper, standard and treated PEDOT have been fabricated and experimentally characterized. The PEDOT antennas exhibit an exceptional plastic-like reversible mechanical flexibility, and the resulting reflection coefficient measurements and gain-directivity efficiency estimations are in a good agreement with CST simulations. The methanol-solution-based treatment of the PEDOT thin film

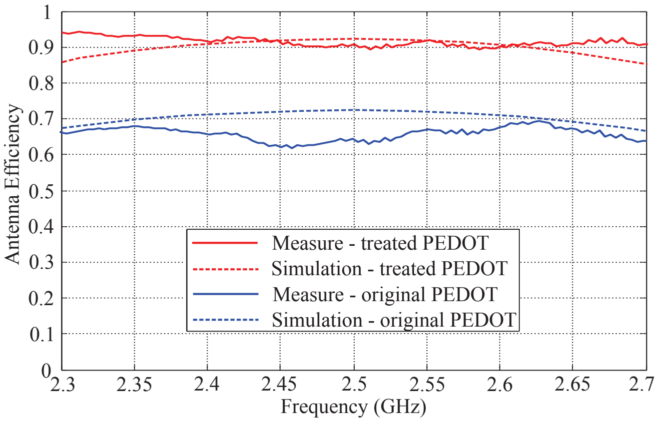

Fig. 7. Simulated and measured antenna efficiency relatively to the copper reference antenna.

boosts the antenna efficiency by 25% to an averaged value of 91.4% over the operation band. The result is remarkable in conjunction with a resonant design, and is, to the best of our knowledge, the highest value reported for this type of polymeric antennas. All these facts emphasize the promising potentials of conductive polymers in microwave antenna applications, particularly in conformal and flexible configurations.

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