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Research Article

Efficiency of a Compact Elliptical Planar Ultra-Wideband Antenna Based on Conductive Polymers

Thomas Kaufmann,[1] Akhilesh Verma,[1] Van-Tan Truong,[2] Bo Weng,[3] Roderick Shepherd,[4] and Christophe Fumeaux[1]

[1] *The University of Adelaide, Adelaide, SA 5005, Australia*
[2] *Defence Science and Technology Organisation (DSTO) Melbourne, Fischermans Bend, VIC 3207, Australia*
[3] *University of Wollongong, Wollongong, NSW 2522, Australia*
[4] *The University of Sydney, Sydney, NSW 2006, Australia*

Correspondence should be addressed to Thomas Kaufmann, thomaska@eleceng.adelaide.edu.au

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A planar antenna for ultra-wideband (UWB) applications covering the 3.1–10.6 GHz range has been designed as a test bed for efficiency measurements of antennas manufactured using polymer conductors. Two types of conductive polymers, PEDOT and PPy (polypyrrole), with very different thicknesses and conductivities have been selected as conductors for the radiating elements. A comparison between measured radiation patterns of the conductive polymers and a copper reference antenna allows to estimate the conductor losses of the two types of conductive polymers. For a 158 μm thick PPy polymer, an efficiency of almost 80% can be observed over the whole UWB spectrum. For a 7 μm thick PEDOT layer, an average efficiency of 26.6% demonstrates, considering the room for improvement, the potential of this type of versatile materials as flexible printable alternative to conductive metallic paints. The paper demonstrates that, even though the PEDOT conductivity is an order of magnitude larger than that of PPy, the thicker PPy layer leads to much higher efficiency over the whole UWB frequency range. This result highlights that high efficiency can be achieved not only through high conductivity, but also through a sufficiently thick layer of conductive polymers.

1. Introduction

Recent advances in material research have enabled the synthesis of a wide range of conductive polymers with characteristics that make them interesting for electromagnetic applications. Increasingly high electrical conductivity and mechanical elasticity, combined with the potential of low-cost mass production, make these types of materials highly interesting for the manufacture of antennas as integrated components for emerging all-polymer electronic devices. Additionally, some electroactive conductive polymers have the ability to change their properties through the application of a bias voltage, suggesting applicability for future designs of reconfigurable antennas. In this perspective, conductive polymers appear as an increasingly relevant type of materials with the potential to allow the creation of mechanically flexible, electrically reconfigurable antennas at a low cost. Conductive polymer films can be manufactured and patterned with conventional inkjet printing or screening technology. It is expected that through the progress in composite polymers, a further increase in the present conductivities at room temperature will be achieved.

Previous work on conductive polymers includes numerous implementations from UHF to mm-waves. Often these antennas have been designed as proof of concept, whereas quantitative studies on the efficiency are less common. The following selection of publications on antennas constructed with less conductive materials illustrates the status of research, with some of the contributions providing efficiency estimations. Regarding the electromagnetic properties of conductive polymer for use in antenna design, previously published work at microwave frequencies has considered

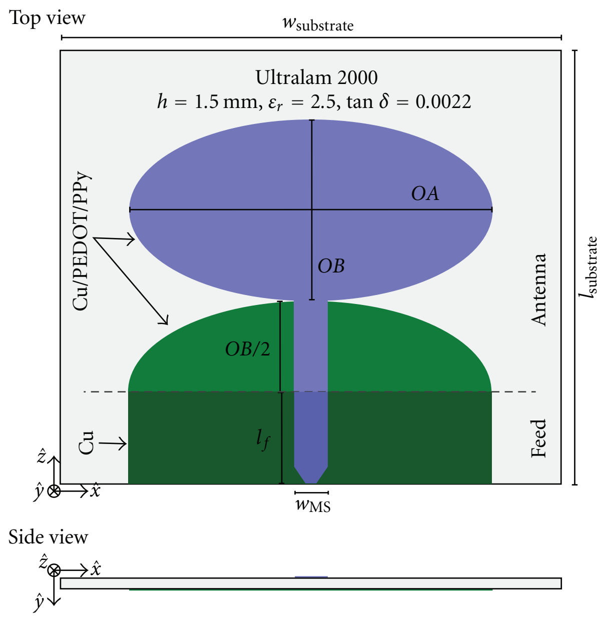


FIGURE 1: Schematic of the antenna. In all manufactured antennas, the feeding section was produced in copper, and the radiating elements have been manufactured alternatively in copper, PEDOT, or PPy.

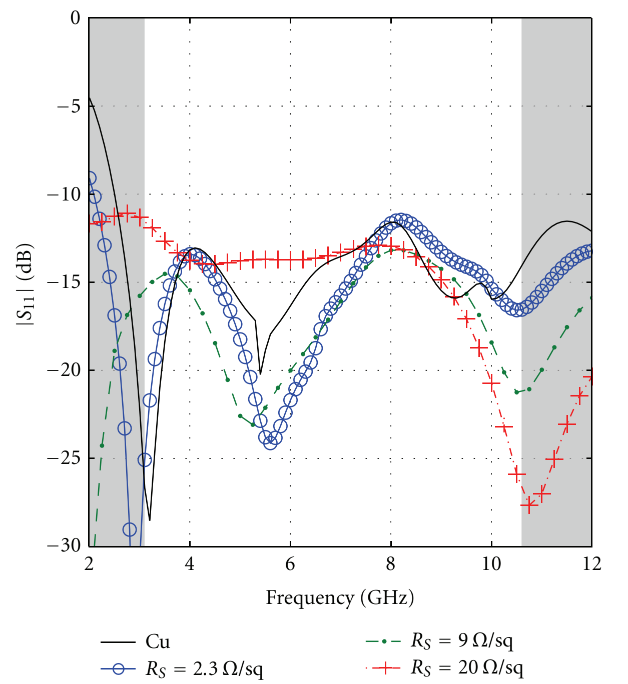


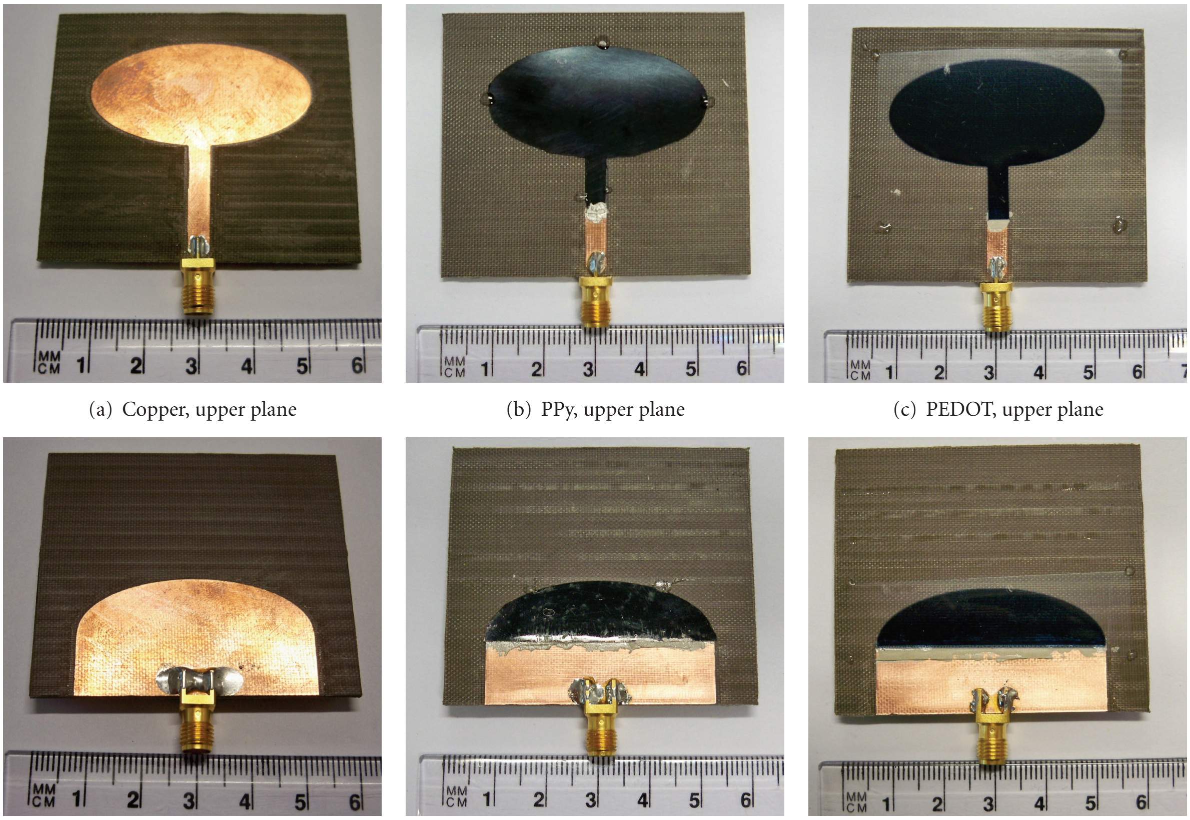
FIGURE 2: Simulated input reflections for different values of the sheet resistance of the conductive polymer antenna section. For PPy, the estimated sheet resistance is $R_S = 2.3\,\Omega$/sq, and, for PEDOT, it is calculated as $R_S = 9\,\Omega$/sq.

narrowband microstrip patch antennas in [1–3]. In particular, the latter two references estimated the efficiency degradation due to the use of a top patch manufactured from different conductive polymers. Using a very promising type of conductive polymers, a carbon-nanotube- (CNT-) based textile microstrip patch antenna has been presented in [4], where the efficiency has been estimated at −2 dB compared to an ideal patch antenna. The application of a CNT ground plane for microstrip antennas, rather than for the resonant element, has been investigated in [5]. Another implementation of conducting textiles as a building block of antennas has been presented in [6] at the high VHF/low UHF range with conductive polymer-coated fibres. In a real-word application, the performance of a MIMO ad hoc network with transparent conductive polymer antennas [7] has been estimated at 2.5 GHz with promising results. At a lower frequency range, conductive polymer-based RFID antennas have been introduced in [8, 9] with evaluation of radiation performance. For these lower frequencies, the conductivity and thickness of the materials is often still quite low, leading to rather small efficiencies. In the realm of flexible, printed antennas, an inkjet-printed ultra-wideband (UWB) antenna based on conductive (metallic) ink with a paper substrate has been introduced in [10]. Also, a new printing process for metallic conductors has been introduced in [11] for 2.4 GHz applications, implemented on printed microstrip patch antenna with a plastic substrate. In the millimeter range, an extensive range of studies on the efficiency of CNT monopole antennas have been performed [12].

The characterization of conductive polymer antennas for high-frequency applications is in its infancy, and this paper explores the impact of losses in a practical antenna setup, due to the use of nonideal conductors with thickness below requirement. Especially the relevant comparison between a conductor with low conductivity/large thickness (PPy) and high conductivity/small thickness (PEDOT) will shed some light of the efficiency of these conductors in relation to the skin depth in the UWB spectrum.

Two types of these conductors, PEDOT and polypyrrole (PPy), have been selected for the manufacture of the antennas presented in this paper. The PEDOT exhibits the highest conductivity and has the ability to directly be inkjet-printed on a carrier substrate, however with a feasible thickness presently limited to a few micrometers. PPy on the other side has lower electrical conductivity but can be produced in significantly thicker films. In the present form, PPy requires manual manufacture for small-scale prototype production.

The goal of this paper is to estimate the efficiency of antennas based on conductive polymers over a large frequency range. Therefore, a planar UWB antenna has been designed for operation from 3.1 to 10.6 GHz. This design acts as a test bed for the two different conductive polymers. By comparison with the same design built in copper for reference, the efficiency of the polymer conductors at various frequencies can be experimentally evaluated. The results show different performance for the two conductive polymer approaches explored here. With the knowledge of the present limitations in terms of conductivity and layer thickness, more elaborate antennas based on conductive polymers can be designed in the future.



(a) Copper, upper plane (b) PPy, upper plane (c) PEDOT, upper plane

(d) Copper, lower plane (e) PPy, lower plane (f) PEDOT, lower plane

Figure 3: Upper and lower planes of the three antennas.

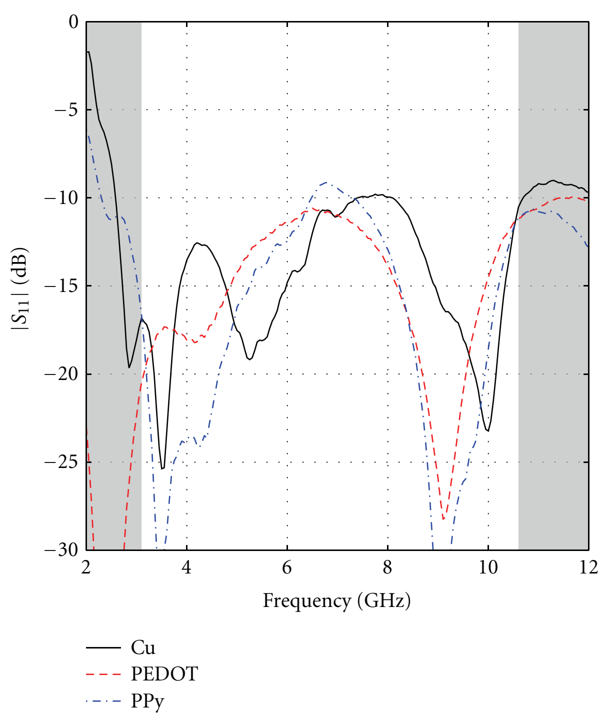


Figure 4: Input reflections for the antennas. The nonshaded area designates the operation UWB spectrum from 3.1 to 10.6 GHz.

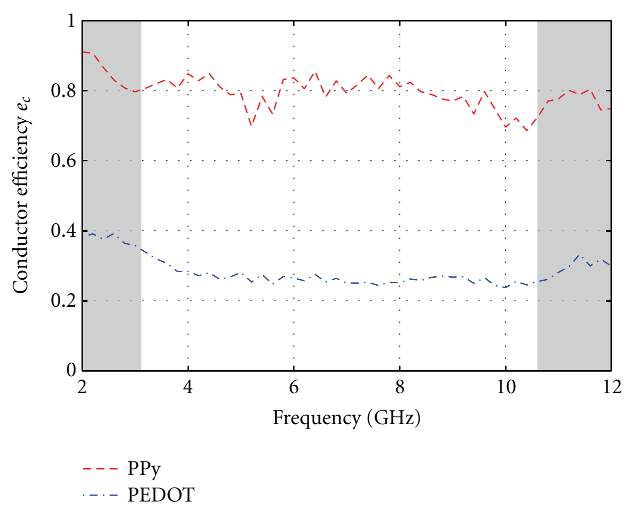
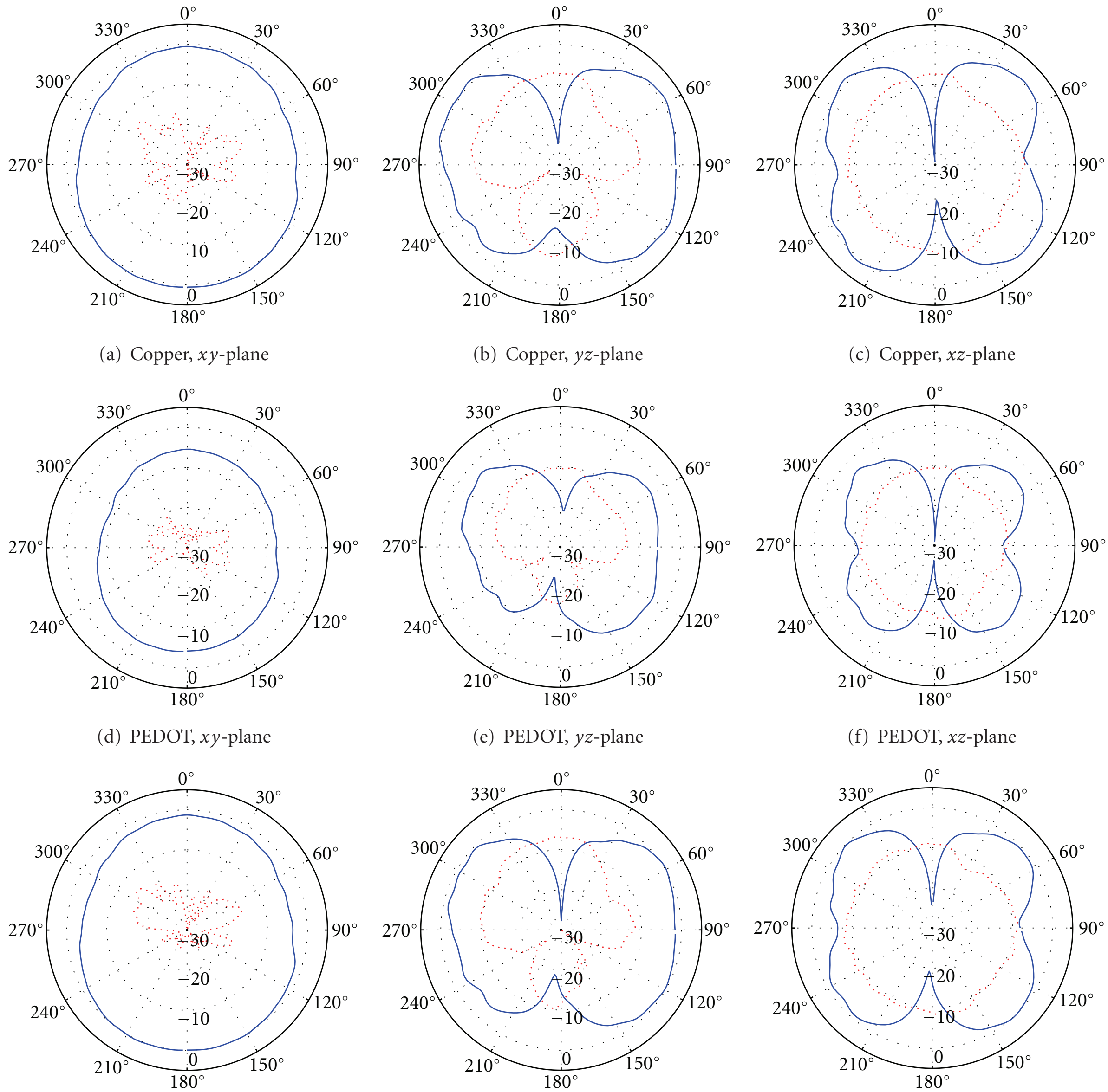


Figure 5: Efficiency for averaged gains in the *xz*-plane for the PPy and PEDOT antennas. The nonshaded area designates the UWB spectrum.

2. Conductive Polymers

Polymers are large organic molecules that are omnipresent in nature, for example, in DNA and proteins. They are also



(a) Copper, xy-plane (b) Copper, yz-plane (c) Copper, xz-plane

(d) PEDOT, xy-plane (e) PEDOT, yz-plane (f) PEDOT, xz-plane

(g) PPy, xy-plane (h) PPy, yz-plane (i) PPy, xz-plane

FIGURE 6: Radiation patterns for the antennas with the three different conductors at a frequency of 3.1 GHz. The solid line represents the copolarization and the dotted line the cross-polarization.

very important synthetic materials, including the class of plastic materials. Polymers are composed of large chains of carbon-based molecules linked by covalent bonds. Since the original demonstration of electrical conductivity in synthesized polymer materials [13], research efforts have resulted in a steady increase of the dc-conductivity of conductive polymers through improvement in their intrinsic properties or through the use of composite and doped polymers [14]. Long-term predictions arguably state that doped polymers or composites could approach metals in terms of dc-conductivity at room temperature. But beyond the promise in terms of electrical conductivity, conductive polymers such as PEDOT or PPy are very attractive materials because of the possibility to pattern them as thin films through low-cost printing (screen or inkjet) and because of their flexibility.

The rapid developments in conductive polymer science provide a strong motivation for using these materials as alternatives to classical metallic conductors in the design and fabrication of electromagnetic devices as components in flexible electronics. Despite the fact that the conductivity of these polymers remains below that of metals, it has been proven to be high enough to build antennas [11, 15]. Clearly, antenna technology can strongly benefit from the exploitation of low-cost, flexible, light-weight plastic-like electrical conductors with suitable processing and patterning

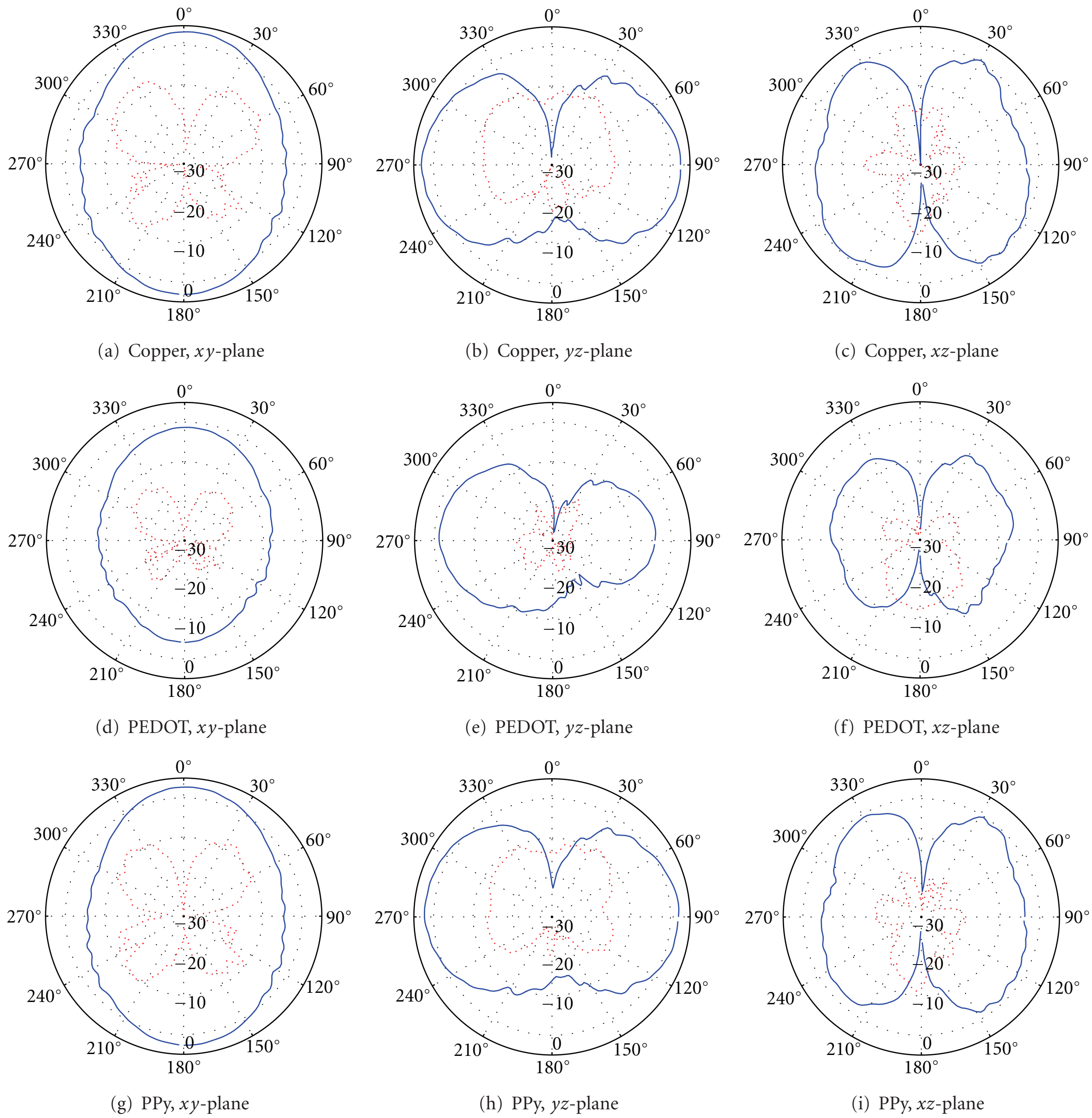
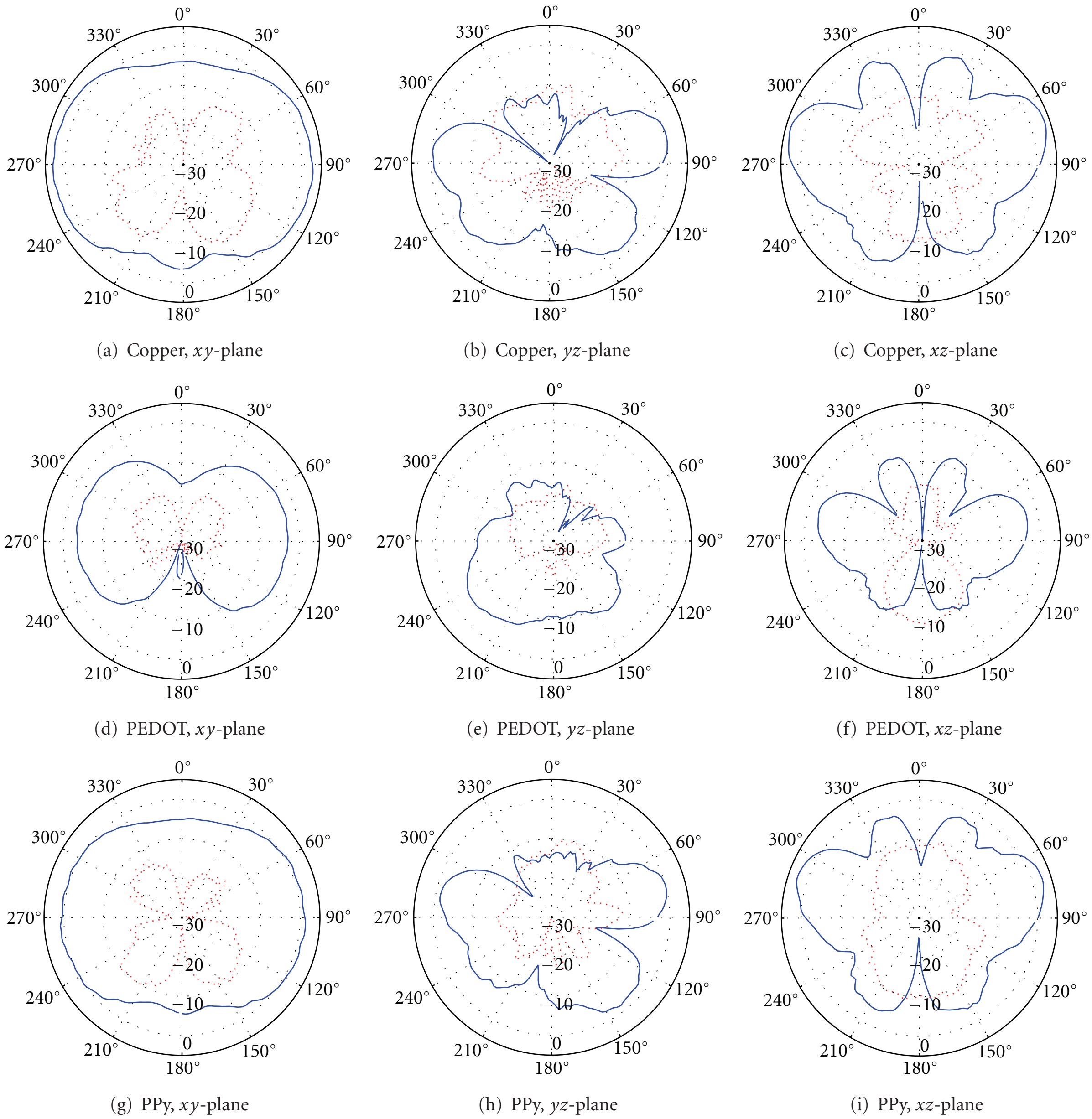


Figure 7: Radiation patterns for the antennas with the three different conductors at a frequency of 5 GHz. The solid line represents the copolarization and the dotted line the cross-polarization.

technology. But beyond these particular properties, there are also the promises of three other unique characteristics that are potentially realizable with conductive polymer materials. The first one is the optical transparency, which could allow the integration of antennas onto windshields, solar panels or displays. The second one is the biocompatibility and biodegradability, which, when combined to the flexibility, opens the door to wearable and biodegradable implantable devices [16]. The third one is the possibility of dynamically controlling the electrical properties of polymers in electroactive cells, which suggests the possibility of low-cost flexible reconfigurability in antenna applications. Such devices would be able to adapt to multiple functional requirements, that is, work at multiple frequencies and/or dynamically adapt to their environment through polarization or space diversity.

The two different polymer materials employed in the present investigation are described in the following. They are representative of very different approaches, with different strengths and challenges.

2.1. PEDOT. PEDOT:PSS is a stable conductive polymer available as an aqueous dispersion for a variety of coating and printing methods including inkjet, flexographic, gravure, slot die, and screen. DC conductivities as high as 100,000 S/m



(a) Copper, xy-plane (b) Copper, yz-plane (c) Copper, xz-plane

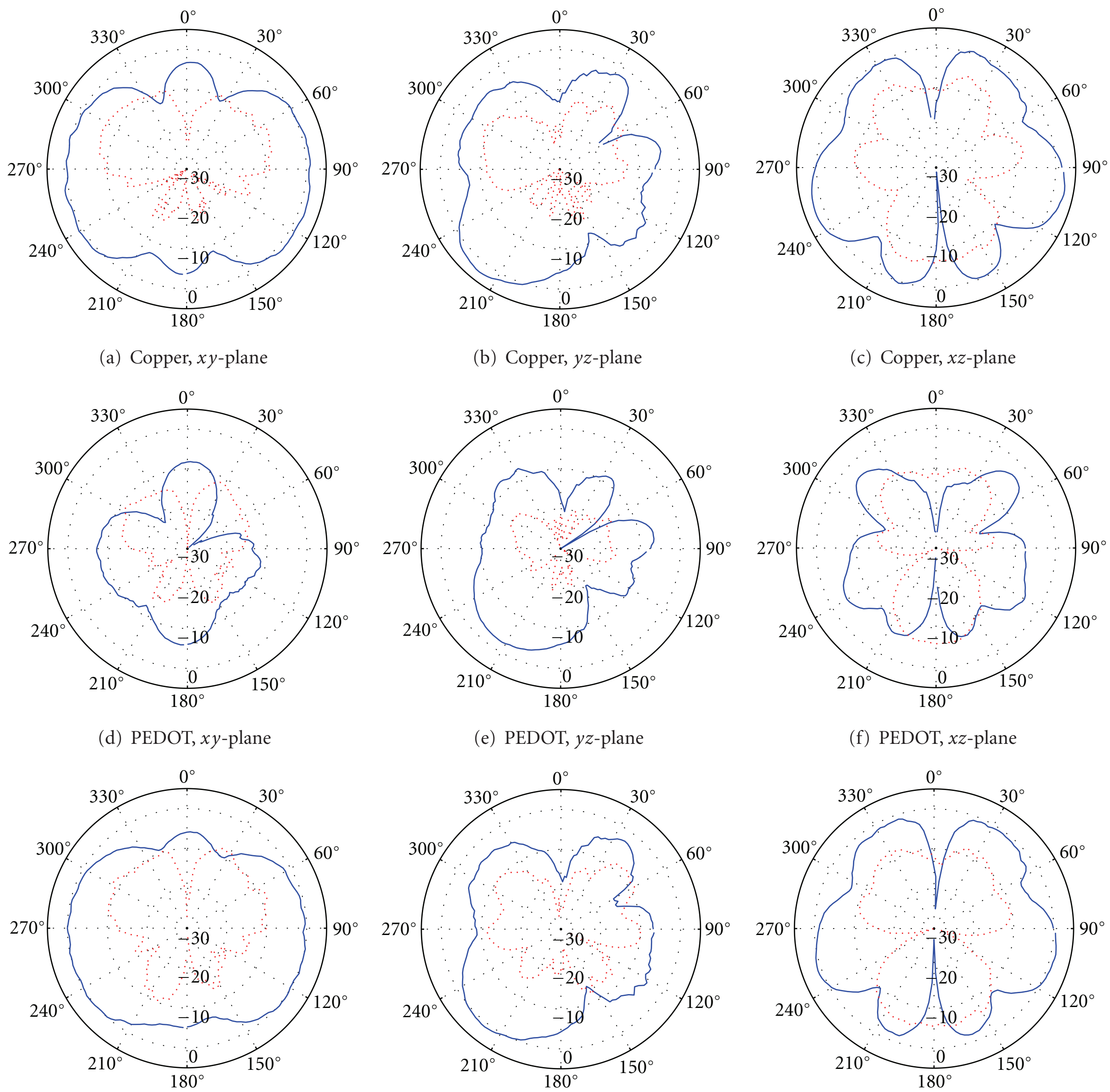
(d) PEDOT, xy-plane (e) PEDOT, yz-plane (f) PEDOT, xz-plane

(g) PPy, xy-plane (h) PPy, yz-plane (i) PPy, xz-plane

Figure 8: Radiation patterns for the antennas with the three different conductors at a frequency of 7 GHz. The solid line represents the copolarization and the dotted line the cross-polarization.

are achievable from commercial formulations, and, after low-temperature annealing, very stable films are produced. Film thicknesses are very much dependent on the processing method and typically range from 50 nm to 100 μm. In this work, we employ inkjet printing as this method provides greatest design flexibility when optimizing device geometry and allows for printing complex patterns.

A Dimatix DMP2800 inkjet printer was used to process a commercial PEDOT ink Clevios P Jet HCv2 [17] and pattern a film of 7 μm thickness on a 100 μm polyethylene terephthalate (PET) substrate. The printed PEDOT film has a dc-conductivity of 16, 000 S/m. The inkjet system employed is capable of printing very thin films (50 nm) of PEDOT. However, for antenna applications, film thicknesses of the order of micrometers are required, and therefore multiple layers were printed consecutively on top of each other. After heat annealing, the thickness of the final multilayer printed film was measured using a Dektak contact profiler. The inkjet system employed uses printheads with only 16 jets (0.6–0.8 mm print swathe width), and, as a result, the fabrication process is currently quite time consuming. Using wider format printheads with increased print swathe width would significantly reduce fabrication time even with multilayer patterning. Also, as PEDOT:PSS is available for a wide



(a) Copper, *xy*-plane (b) Copper, *yz*-plane (c) Copper, *xz*-plane

(d) PEDOT, *xy*-plane (e) PEDOT, *yz*-plane (f) PEDOT, *xz*-plane

(g) PPy, *xy*-plane (h) PPy, *yz*-plane (i) PPy, *xz*-plane

FIGURE 9: Radiation patterns for the antennas with the three different conductors at a frequency of 9 GHz. The solid line represents the copolarization and the dotted line the cross-polarization.

range of processing methods, once final antenna designs are chosen, other approaches can be employed to scale the fabrication process for industrial applications.

2.2. Polypyrrole (PPy) Conducting Polymers. PPy is one of the most popular conducting polymers used in applications owing to its thermal/environmental stability. Depending on the method of polymerization, PPy can be synthesized as free-standing films or powder. In the current form, free-standing film samples are used and must be patterned manually. In this case, the simple shapes have been carved out using a scalpel.

The PPy samples are obtained from the Defence Science and Technology Organization (DSTO) in Melbourne, Australia. The polymer was prepared in accordance with the procedure indicated by Truong and Ternan [18]; that is, through electrochemical polymerization in an aqueous solution. Sodium p-toluene sulphonate (p-TS) was used as the dopant. Electrodes of stainless steel were used for growing the film in a nitrogen environment. The films obtained by the above procedure are between 57 and 158 μm thick and have been washed in acetonitrile/water (1 : 1 solution) to remove excess dopant. The films were then allowed to dry. In the present investigation, a free-standing sample with a

Table 1: DC conductivity and skin depths of the applied conducting materials at the lower and upper margins of the UWB spectrum.

	Copper	PEDOT	PPy
σ	$5.8 \cdot 10^7$ S/m	16,000 S/m	2,720 S/m
δ (3.1GHz)	1.2 μm	71.5 μm	173.3 μm
δ (10.6 GHz)	0.6 μm	38.6 μm	93.7 μm

thickness of 158 μm is used. Using the four-probe technique, the dc-conductivity of the film sample could be measured as 2, 720 S/m, that is, roughly one order of magnitude below the conductivity of the PEDOT sample. The thickness of the PPy film was accurately measured using a Scanning Electron Microscope (SEM) Philips XL 30.

3. UWB Antenna

The antenna design presented in this paper is an adaptation of a circular UWB dipole antenna [19]. The most important criteria for this layout is established by the availability of conductive polymer samples: due to the limited areas of free-standing PPy samples and the long printing times for patterned PEDOT films, the conductive area of the designed antenna has been minimized. Additionally, simple shapes were favoured to facilitate the manual cutting of PPy films. As low-loss substrate, Rogers Ultralam 2000 with a thickness of 1.5 mm (60 mil) has been selected as it exhibits accurately specified permittivity ($\varepsilon_r = 2.5 \pm 0.1$) and allows for milling of the copper reference antenna as well as the contacting structure of the polymer antennas. A short feeding microstrip line section built in copper has been included in the present design to allow soldering of an SMA connector. The antenna starts after this launching section and is then manufactured using the two mentioned conductive polymers.

All numerical simulations for optimization of the present design have been performed using the finite-element frequency-domain solver of HFSS. The copper layers can be simulated using the traditional model with finite conductivities. The polymer conductors however are in the range of or much thinner than a skin depth (as shown in Table 1) in the chosen frequency range; therefore, the finite conductivity model is not applicable. Instead, the conductive polymers have been modeled as a thin layer of finite impedance with the sheet resistance R_S estimated through the dc-conductivity σ as [20]

$$R_S = \frac{1}{\sigma d}, \quad (1)$$

where d designates the thickness of the conductor film. For the printed PEDOT conductor, a thickness of $d = 7\,\mu$m and conductivity of $\sigma = 16$ kS/m lead to a sheet resistance of $R_S = 9\,\Omega$/sq. For the PPy sample, the sheet resistance could be estimated as $R_S = 2.3\,\Omega$/sq ($d = 158\,\mu$m, $\sigma = 2,720$ S/m).

3.1. Design. After consideration of several design options, a microstrip line fed structure on two planes has been selected as shown in Figure 1 with a shape adapted from [21, 22]. This arrangement minimizes the impact of production tolerances, in comparison to a coplanar waveguide feed.

On the upper plane, the microstrip line is connected to an elliptically shaped conductor. On the lower plane, the ground plane evolves into a half-ellipse (Figure 1). The width of the ground plane has also been minimized to reduce the amount of conducting material required. The opening slot between the ellipsoidal shapes on the two planes acts as a broadband radiating structure with a predominantly vertical linear polarization. The microstrip line is fed through a coaxial SMA connector, which is soldered onto a copper feeding structure.

The dimensions of the antenna have been optimized to give acceptable input reflections ($|S_{11}| < -10$ dB) for all different conductivities of the radiating elements while retaining a minimal size. For the antenna as shown in Figure 1, the ellipse with an axial ratio of AR = 0.5 has a major axis of OA = 44 mm and a minor axis of OB = 22 mm. The feeding structure has a length of $l_f = 11$ mm to allow the feeding microstrip mode to establish after the transition from the coaxial SMA connector. For a 50 Ω impedance, the width of the microstrip line has been kept constant as $w_{\text{MS}} = 4$ mm to facilitate the manufacturing process. A short taper (2 mm) at the transition between the coaxial connector and the microstrip line avoids coupling effects from the metallic connector case. The size of the substrate has been chosen sufficiently large to accommodate the antenna with a width of $w_{\text{substrate}} = 60$ mm and a length of $l_{\text{substrate}} = 52$ mm.

The simulated input reflections for a variation of sheet resistances $R_S = [2.3, 9, 20]\,\Omega$/sq and the metallic copper conductor are shown in Figure 2. The following observations can be made for increasing conductor losses. At first, the input reflections decrease with increasing sheet resistance. This happens up to a point where the mismatch between the copper and polymer microstrip line becomes too large (i.e., towards $R_S = 20\,\Omega$/sq), which manifests in generally larger reflections. Additionally, a shift of the first resonance to lower frequencies can be observed.

3.2. Manufacture. Three separate antennas have been manufactured. First, an all-copper antenna has been built for verification of the design and to provide a reference for efficiency estimations. Using classical milling technology, the shapes were cut from an all-copper layer on the Ultralam substrate.

For the second antenna, the antenna part in Figure 1 has been realized with a printed PEDOT layer. The initial transition from the coaxial SMA connector to the feed section remains in copper. Conductive epoxy has been used to establish a permanent galvanic connection between the feeding line/ground plane and the radiating elements. The thin PET substrate is facing away from the substrate so that the conductor can be directly connected to the feeding line. Due to the low dielectric constant ($\varepsilon_r < 3$), low losses, and thin dimension, the effect of the PET layer can be neglected.

For the third antenna, the radiating part of the antenna has been manufactured in PPy. Using a prefabricated template, the shapes have been cut with a scalpel from the flexible free-standing PPy sample. The conductive polymer has then been fixed onto the substrate with a few dots of regular epoxy, and an electrical connection to the copper microstrip feeding line has been established through a small area of conductive epoxy at the feed/antenna transition. Due to the manual production process, deviation from the original design must be expected. Also, slight discrepancies in the alignment could not be avoided. Figure 3 shows the manufactured antennas.

4. Measurements

To characterize the antennas, the input reflections (S_{11} parameter) and radiation patterns of all three antennas have been measured. The absolute gain patterns provides the basis for the estimation of the polymer antennas' efficiency by comparing their radiation performance with that of the reference copper device.

4.1. Input Reflections. The maximum acceptable input reflections correspond to $|S_{11}| = -10$ dB. As shown in Figure 4, this has been nearly fulfilled for all antennas. The copper antenna shows a good correspondence with the simulated results. For the polymer antennas, the results somewhat deviate from the simulated values. This is attributed to tolerances in the manufacture, misalignment of the conductors and a nonideal transition using conductive glue from the microstrip feeding line to the polymer layers. Nevertheless, a shift of the resonances towards lower frequencies can be observed demonstrating consistency with the simulated results.

4.2. Patterns. The radiation patterns are shown in Figures 6, 7, 8, and 9 at the end of this paper for the frequencies $f = [3.1, 5, 7, 9]$ GHz in form of the total realized gain.

A dipole-like behavior is expected, which should translate as an omnidirectional pattern in the xy-plane (subfigures (a), (d), and (g)). This is indeed observed at lower frequencies, while the omnidirectional characteristics slightly deteriorates towards the upper end of the UWB spectrum. As anticipated, the patterns in the xz- and yz-plane exhibit a zero along the dipole axis, that is, towards 0° and 180°. Again, the patterns deteriorate towards higher frequencies, where deviations in manufacturing quality have a larger impact.

It can generally be observed that all patterns exhibit similar characteristics. The xz-plane patterns offer the best similarity between the different conductors, and the patterns in the yz-plane show largest discrepancies between all antennas at all frequencies.

4.3. Efficiency. The efficiency e_{cd} of an antenna is included in the definition of the gain G in terms of its directivity D as

$$G = e_{cd}D, \qquad e_{cd} = e_c e_d, \tag{2}$$

where the efficiency e_c is related to conductor losses and e_d to dielectric losses. In this paper, the goal is to estimate the losses that occur because of the relatively low conductivity of the conductive polymer, that is, to characterize the efficiency e_c at microwave frequencies. A straightforward method is to directly compare the radiation performance of the copper and polymer antennas. The dielectric substrate materials are identical and therefore show identical dielectric losses and associated dielectric efficiencies e_d. The losses of the copper can be assumed negligible, that is, $e_c \approx 1$. Therefore, the difference of the gains between the copper and the two polymer antennas is an indicator of the losses in the respective conductive polymer.

The efficiency is estimated here based on the performance in the xz-plane pattern where the patterns have the same shape, that is, the same directivity. The averaged total received power over all azimuthal angles is used as a measure of the average gain, and the efficiency can then be approximated as

$$e_c \approx \frac{\sum_\phi G_{\mathrm{Polymer}}(\theta = 90^\circ, \phi)\Delta\phi}{\sum_\phi G_{\mathrm{Cu}}(\theta = 90^\circ, \phi)\Delta\phi}. \tag{3}$$

This simplified approach avoids performing measurements with a Wheeler Cap notoriously difficult through the UWB range or carrying out involved measurements of the whole three-dimensional pattern for a gain/directivity comparison [23, 24].

Figure 5 shows the resulting conductor efficiencies as a function of the frequency for the antennas based on PEDOT and PPy. The average efficiency over the whole UWB frequency band is $e_c = 26.6\%$ for the PEDOT and $e_c = 79.2\%$ for the PPy antenna. This is in good agreement with the results based on a microstrip patch antenna for the same two materials at 6 GHz in [3].

The same observation can be done with the patterns in the xy- and yz-plane, but, due to a divergence of the patterns towards higher frequencies (especially for the yz-plane), the curves are more noisy and the results are less reliable above 7 GHz. Nevertheless, these results are highly encouraging in a demonstration of the general feasibility of using these types of materials as conductor in microwave antenna structures.

5. Conclusion

Conductive polymers are promising materials for the manufacture of low-cost and mechanically flexible antennas with potentially complex geometries. In this paper a planar antenna design realized with conducting polymer for ultra-wideband applications has been presented. The design has been simplified to minimize the area of polymer samples required and allow for manual manufacture. A tapered elliptical aperture acts as radiating element between the two conductors.

Three antennas have been manufactured with a short feeding structure made out of copper for easy connection. The body of the radiating structure is built, respectively, in copper, PEDOT, or PPy conductive polymers. A reasonably omnidirectional dipole-like radiation pattern over a large frequency bandwidth with low-input reflections has been observed for all three antennas. The similarity of the patterns allowed to estimate the conductor losses by comparing the gain patterns.

For the PPy antenna, a very satisfying efficiency of $e_c = 79.2\%$ averaged over the whole UWB spectrum could be measured. This good performance is due to the large thickness of the free-standing conductive polymer film. The disadvantage of this arrangement is however the (currently) manual manufacture of the geometry. The PEDOT technology allows for the direct printing of complex geometries onto a carrier substrate. However, the process is still presently limited in terms of achievable thicknesses, and, therefore, despite a higher conductivity compared to the PPy, less satisfactory performances were achieved. For this antenna, an efficiency of $e_c = 26.6\%$ has been measured, which nevertheless encourages further investigation in this type of material given its potential.

It has been demonstrated in the present study that even though the PPy conductor exhibits a conductivity lower by an order of magnitude compared to PEDOT, this drawback can be compensated by increasing substantially the film conductor thickness to reach values close to the skin depth. This approach has resulted in an efficiency loss of only around 1 dB for the PPy antenna compared to a copper antenna. As for the PEDOT antenna, the currently achieved thickness of 7 μm in inkjet printing needs to be increased as it is well below skin depth.

The research on the material side currently mainly focus on increasing conductivity, for example, in composite form with carbon nanotubes or graphene. The present results demonstrate the need for further research on improving the processability for achieving thicker layer thicknesses, as complementary path.

The degradation of efficiency coming about through the use of conducting polymers in the fabrication of antennas has to be put into the perspective of the attractive properties of the materials, such as plastic-like mechanical flexibility, processability, and potential for low-cost patterning. Potential designs will also benefit from the biocompatibility and biodegradability for medical applications and from the electroactivity for reconfigurable designs. Finally, polymer antennas could be seamlessly integrated in low-cost all-polymer electronic devices.

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