A 2 GHz Polypyrrole Microstrip Patch Antenna on Plexiglas™ Substrate

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***Abstract* — A Microstrip Patch Antenna (MPA) has been fabricated using a Conducting Polymer (CP), Polypyrrole (PPy) as radiating patch on a transparent 3mm thick Plexiglas™ substrate. The bulk DC conductivity of the PPy patch is 2000 S/m and its thickness 120 µm. The MPA was designed for operating at 2 GHz. A similar antenna with Copper (Cu) patch on Plexiglas™ was also fabricated for validating the simulation of PPy antenna and comparing its performance. The results show that the PPy antenna reaches a gain of 5.01 dB at 2.18 GHz as against 6.26 dB at 2.2 GHz for a corresponding Cu patch antenna. The conduction efficiency of Cu-patch antenna is around 80% while that of PPy-patch antenna is around 60%. The results suggest that it might be possible to use CPs in other passive microwave circuit applications.**

***Index Terms* — Conducting Polymer, Microstrip Patch Antenna.**

I. Introduction

Recent advances in electrical conductivity and impressive improvements in stability are making conducting polymers (CPs) very attractive as alternatives to copper (Cu) for planar antennas. This is particularly so in applications where light weight, inexpensive and/or wearable/conformal antennas are a consideration. There have been isolated efforts in the past towards using CP as material for antenna design. In particular, Solberg Jr. *et al.* [1] used a Conducting Polymer (CP) composite to build a non-planar direction-finding antenna operating in the frequency range of 30 MHz to 1 GHz. Cichos *et al.* [2] has tried using polymeric film with silver flakes for designing low cost RFID coil antennas. Rmili *et al.* [3] has reported fabricating a rectangular microstrip patch antenna with the radiating element made of Polyaniline (PANI), a CP having a bulk DC conductivity of 6000 S/m.

Conductive polymers are emerging as one of the most important materials of our time. They have moved from purely passive materials such as coatings to active materials with very interesting optical, electrical and mechanical properties. The conductivity of CP is typically in the range: 10^{-10} to 10^{7} S/m, which place it between the conductivity of classic insulators such as glass, and that of metallic conductors such as copper. CPs are usually described as the cation salts of highly conjugated polymers, which are obtained by electrochemical polymerization to produce film or chemical polymerization to produce powder. Therefore, CPs are popularly known as "organic metals". However, unlike metals, a polymer does not possess free electrons that can move through the polymer lattice when subjected to electrical field. In CPs, electrical conduction takes place through overlapping π molecular orbits, when one or more π electrons are removed from the polymer chain. Trends in the available literature on CPs indicate that the bulk conductivity of CPs may, in a foreseeable future, become equal to that of copper if not better. Currently, CPs are impacting upon a number of fields, some of which are: polymeric batteries [4, 5], photovoltaics [6], electro-chromic devices [5] and ion selective membranes [7], EMI shields [8, 9], radar absorbers [10], electrical wires [11], corrosion inhibitors [5, 6], bio-sensors, and electrochemical actuators (for e.g. artificial muscles [12]).

In this paper we explore the possibility of using Polypyrrole (PPy) for application at microwave frequencies, in particular as a resonant patch on a planar Microstrip Patch Antenna (MPA). This research is part of our work on re-configurable antennas using CPs. This investigation is a first step towards a better understanding of the numerical simulation, design and fabrication issues associated with antennas using these materials for various future applications.

II. Conducting Polymer (PPy) Film Preparation

The PPy film for the antenna patch was obtained from The Defence Science and Technology Organization (DSTO) in Melbourne, Australia. It was prepared in accordance with the procedure indicated by Truong *et al.* [13]; i.e. by conducting electrochemical polymerization in an aqueous solution. Sodium *p*-toluene sulphonate (*p*-TS) was used as dopant. The polymerization solution contained freshly distilled pyrrole (0.1 M) and the abovementioned dopants (0.1 M) in distilled water. Electrodes of stainless steel were used for growing the film in a nitrogen environment. A current density of 2.8 mA/cm^2 was passed through the solution for about 2 hours. The films obtained by the above procedure were 120 µm thick and were washed in acetonitrile/water (1:1 solution) to remove excess dopant. The films were then allowed to dry.

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Using the four-probe technique, the DC conductivity of the film sample was measured as 2000 S/m.

III. ANTENNA DESIGN

The selection of Plexiglas™ as a substrate for this antenna was on the premise that a successful antenna design on Plexiglas™ could lead to development of some interesting low-cost conformal and planar future designs, including optically transparent microwave antennas. The fabricated Cu and PPy-patch MPA are shown in Fig. 1.

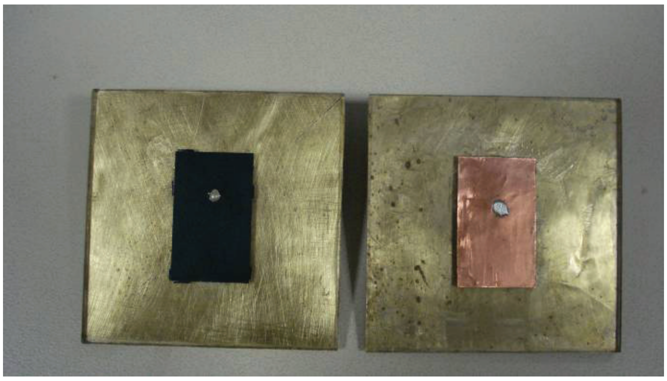

Fig. 1. PPy (left) and Cu (right) MPAs on Plexiglas™ substrate with Cu foil as ground plane.

The permittivity of Plexiglas™ substrate at microwave frequencies is not accurately available from the manufacturer's data sheets and therefore an indirect approach for determining permittivity was adopted. The schematic diagram in Fig. 2 shows the configuration of the MPA used in this study. An identical Cu-MPA was fabricated as reference.

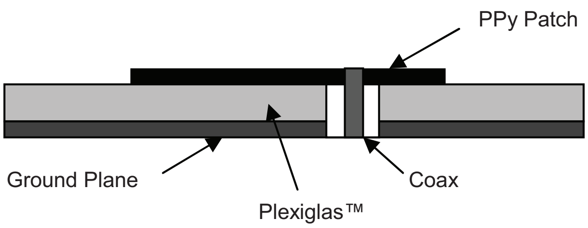

Fig. 2. A cross sectional view of the MPA.

A. Determination of the permittivity of Plexiglas™

The relative permittivity value of Plexiglas™ indicated in the literature varies from 2.4 to 3.7. As the material library of the electromagnetic simulation tool CST™ indicates the relative permittivity value of Plexiglas™ of 3.4, initial design and simulations were made using this value. Actual measurements on a reference Cu-MPA indicated a large discrepancy between the resonance frequencies of the simulated and measured results (as shown in Fig. 3). Adjustment to permittivity and loss tangent (tan δ) value of Plexiglas™ used in simulations was undertaken towards matching of the measured Cu-MPA results. Through this process, which involved the first two resonances of the patch, the Plexiglas's permittivity was estimated to be 2.5, with a loss tangent of 0.001. This permittivity value for the substrate was taken as a basis for the design of the PPy-MPA. The accurate match of simulation and measurement results subsequently obtained for the designed PPy-MPA (as shown in Fig. 4) further validated the permittivity value of 2.5 and tan = 0.001 for the Plexiglas™ substrate.

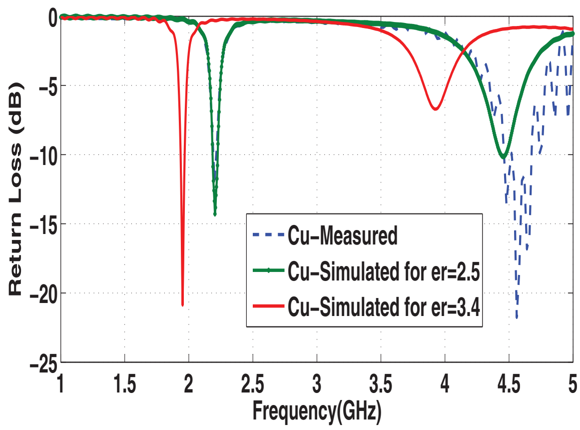

Fig. 3. Simulated (CST™) and measured return loss of Cu MPA on Plexiglas™ substrate for different permittivity values.

B. Simulations and design optimization

The effect of the patch thickness for less conductive material (such as PPy) is an important consideration in this design. Most antenna designers would consider a couple of skin depths thickness for PPy (or similar less conductive material) patch as essential. However, two key questions that need to be considered here are: (1) How to simulate thin materials using EM simulators (such as CST™ and HFSS™), (2) what is the minimum fraction of skin depth for the patch (of less conductive material) that could be used for acceptable antenna performance. An in-depth investigation of these questions will be the focus of further study. At present, it is important to state that simulations in this work were undertaken by assuming zero thickness of the patches. PPy was simulated as a sheet with finite conductivity of 2000 S/m. The Cu and PPy MPA designs were separately optimized for good impedance matching using CST™ and HFSS™. The optimized design parameter values are indicated in Table I.

C. Antenna Fabrication

Two MPAs were fabricated: The first one out of Cu and the other one with PPy as a patch. The ground plane in both cases was a Cu foil pasted on the Plexiglas™ back side using epoxy-based glue. Cu and PPy patches were also pasted to the Plexiglas™ using the same glue. The SMA connector in the case of Cu-MPA was directly soldered to the ground plane and the patch. However, being a plastic, PPy can not withstand high soldering temperatures; therefore, the SMA centre pin was pasted to the PPy patch using silver-loaded epoxy glue. The jacket of the SMA was soldered to the PPy-MPA ground plane.

TABLE I
DESIGN DATA FOR COPPER AND PPY MICROSTRIP PATCH ANTENNA

Parameters	Copper-MPA	PPy-MPA
Substrate		
• Thickness	3 mm	3 mm
• Estimated ϵ_r	2.5	2.5
• Estimated tan δ	0.001	0.001
• Dimensions	80x80 mm	80x80 mm
Patch		
• Length	40.1 mm	40.1 mm
• Width	24.46 mm	24.46 mm
Coaxial Feed		
• Off center	4.0 mm	6.67 mm

IV. RESULTS

The return loss measured on the PPy antenna is presented in Fig. 4 together with the predicted curves from both simulation tools used. The good agreement in terms of resonant frequencies and associated bandwidths validate the design procedure, including the determination of the material parameter of the Plexiglas™ substrate.

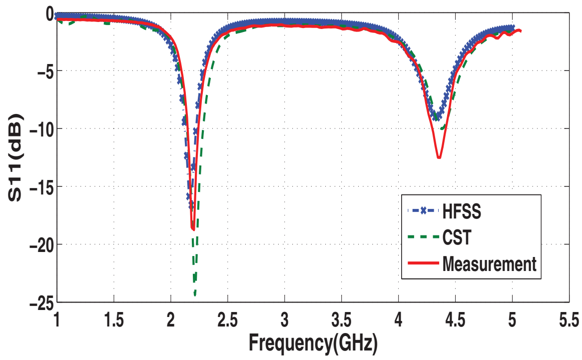

Fig. 4. Simulated and measured return loss for PPy-MPA.

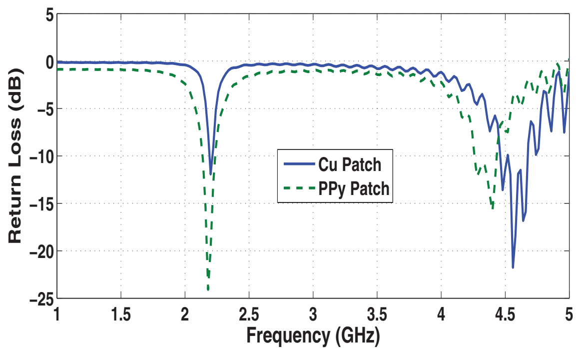

Fig. 5. Comparison between measured return loss for Cu and PPy-MPA.

A direct comparison of the return loss from the PPy antenna and the Cu antenna is shown in Fig. 5. The Cu-patch MPA is resonant at 2.2 GHz, while the PPy-patch MPA has a resonance frequency of 2.18 GHz with a -10 dB BW of about 100 MHz or 4.5%. Considering that the Cu-MPA was designed using an inaccurate substrate permittivity, and that it was primarily used as tool for estimating permittivity of Plexiglas™, it is clear that the low return loss observed in Cu-MPA (Fig. 3 and 5) is due to poor input impedance match. The consistency of the results is further validated by the comparison of the shape of the measured and simulated radiation pattern of Cu-MPA shown in Fig. 6. The discrepancy between the curves is attributed to fabrication imperfections.

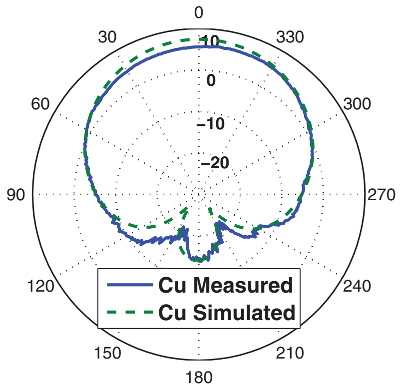

Fig. 6. Simulated (CST™) and measured E-plane radiation pattern for Cu-MPA.

The measured E and H-plane co- and cross-polarized patterns of the Cu and PPy patch antenna are presented in Fig 7 and 8 respectively.

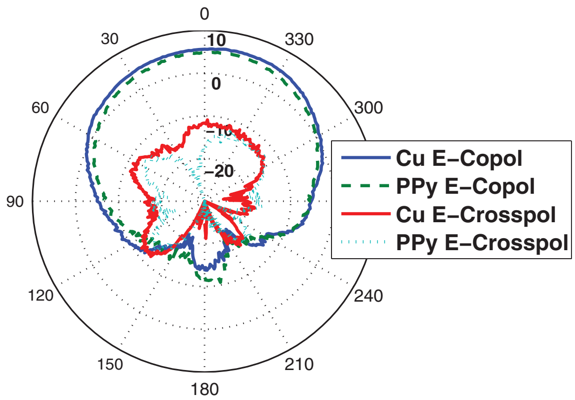

Fig. 7. E-plane Co-pol and Cross-pol radiation pattern measurements for Cu and PPy MPA.

The measured realized gain of the Cu MPA antenna is 5.91 dB as against 4.99 dB for PPy MPA. Further, the cross polarization is measured to be below -15 dB and the radiation patterns for both PPy and Cu MPA are identical in shape. Taking reflection efficiency into account, the measured gain of the Cu-MPA is 6.26 dB as against 5.01 dB for PPy- MPA.

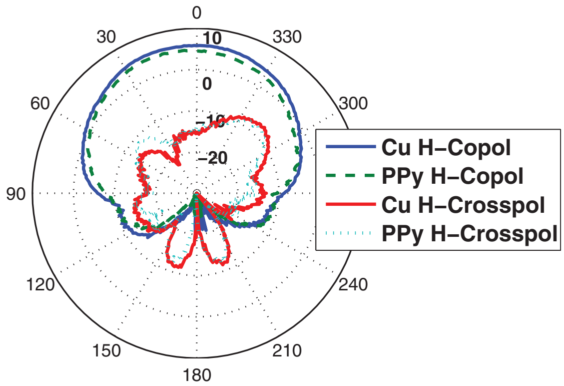

Fig. 8. H-plane Co-pol and Cross-pol radiation pattern measurements for Cu and PPy MPA.

On the basis of those data, the radiation efficiency for the Cu MPA is estimated to be around 80%, most of the losses being attributed to the dielectric losses in the substrate. The efficiency is reduced by replacing the Cu patch by the less-conductive PPy material to a value of around 62%.

V. Discussion

Construction of a MPA using a less conductive material (such as PPy) on a non-standard substrate (such as Plexiglas™) has some interesting design aspects from the point of view of patch thickness (i.e. skin depth), fabrication issues and characterization of permittivity of substrate.

The computed value of skin depth for a patch with a DC conductivity of 2000 S/m at 2 GHz is 251.6 µm, which is about twice the thickness of PPy patch used in the MPA. However, it is important to consider that the mechanism of electrical conduction and dispersion of electrical conductivity in CPs is different from that of metals [14]. Epstein et al. [14] has also described in detail the mechanism of conduction and its dispersion with frequency in CPs. The observed performance of the PPy-MPA in this work is suggestive of an increase in bulk AC conductivity of the patch with frequency.

Current literature [15] on PPy indicates DC conductivities up to 20,000 S/m, which would noticeably improve the performance reported in this paper. Furthermore, other CPs such as PEDOT, PANI and PA can provide much higher conductivity than PPy. However, designs techniques with relatively low-conductivity materials and their associated fabrication issues need further investigation.

VI. Conclusion

This paper has presented results of a CP based MPA on a non-standard substrate such as Plexiglas™. The results of PPy patch were compared with an identical Cu MPA used as reference. The obtained performances indicate that a PPy based microwave antenna is feasible. It is further emphasized that the MPA design, as a resonant structure, provides a good tool for understanding exotic materials. Enhancement in our understanding of the microwave properties of CP materials could eventually lead to their usage in passive microwave circuits in the future.

Acknowledgement

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