Effect of Film Thickness on the Radiation Efficiency of a 4.5 GHz Polypyrrole Conducting Polymer Patch Antenna

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Abstract — **Microstrip antenna performance is affected by the conductivity and thickness of the patch. Generally the patch thickness is expected to be at least a couple of skin depths thick for reasonable antenna performance. However, planar microwave antennas based on conducting polymers (CP) can exhibit reasonable antenna performance despite a relatively low conductivity and a thickness below a skin depth. In this paper, a detailed study on the effect of CP patch thickness on overall antenna performance is presented. Microstrip antennas for 4.5 GHz operation were fabricated on a 3.2 mm thick FR-4 substrate using polypyrrole patches with a constant electrical conductivity of 2000 S/m. The antennas were identical apart from using four different patch thicknesses ranging from 40 to 140 µm. In all cases, the thickness of the patches used in this study is less than one skin depth (168 µm). The gain and radiation efficiency of the antennas was measured. The lowest gain observed was 2.42 dB for 40 µm thickness with a radiation efficiency of 38%, and the highest gain observed was 4.63 dB for 140 µm thickness with a radiation efficiency of 65%. Results presented in this paper clearly indicate that it is possible to obtain reasonable antenna performance, even if the patch thickness is a fraction of skin depth.**

Index Terms — **Conducting polymers, polypyrrole, microstrip patch antenna.**

I. Introduction

Conductive polymers (CPs) are emerging as one of the most important materials of our time. They have moved from applications as purely passive coating and packaging materials to take a promising role as active materials with very interesting optical, electrical and mechanical properties. The conductivity σ of CP is typically in the range 10^{-10} to 10^{7} S/m, which places it between the conductivity of classic insulators such as glass ($\sigma \approx$ 0.2-0.3x 10^{-12} S/m), and that of metallic conductors such as copper ($\sigma = 5.8\text{x}10^{7}$ S/m). Recent advances in electrical conductivity and impressive improvements in stability are making CPs very attractive as alternatives to copper (Cu) for the manufacture of planar antennas. This is particularly so in applications where light-weight, inexpensive and/or wearable/conformal antennas are a consideration.

Study of the use of CPs in antenna technology, particularly in the design of planar microwave antennas is presently in its infancy. Most of the earlier reported works [1-4] were explorative in nature and therefore did not dwell sufficiently on issues such as: (a) the minimum fraction of skin depth for a microstrip antenna patch (of less conductive material) that could be used for acceptable antenna performance, or (b) how to *accurately* simulate very thin materials using EM simulators (such as CST™ and HFSS™). Furthermore, due to the inherent limitation of present techniques for fabricating thick CP films, it is necessary to clearly understand the effect of CP patch thickness on CP based planar microwave antennas. In this paper we investigate this aspect using PPy patches of different thicknesses in a 4.5 GHz microstrip antenna.

II. Conducting Polymer (PPy) Film Preparation

The polypyrrole (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.* [5]; i.e. by electrochemical polymerization in an aqueous solution. Sodium *p*-toluene sulphonate (*p*-TS) was used as dopant. The details of the film preparation are also described in [2].

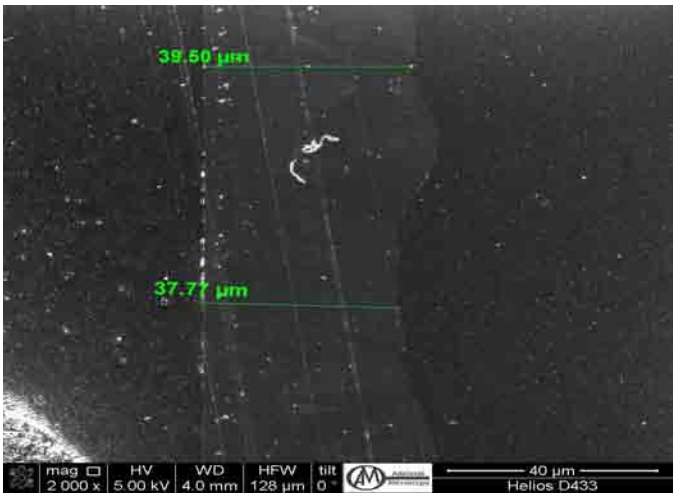
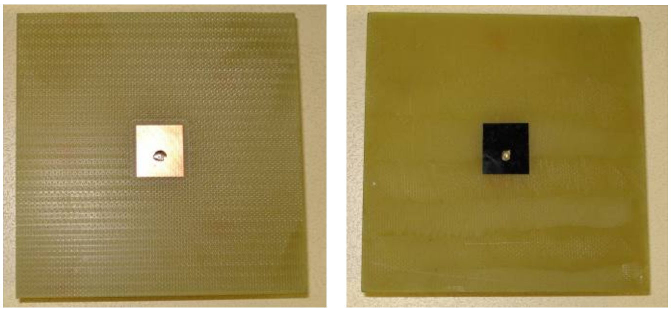


Fig. 1. Scanning Electron Microscope (SEM) measurement of Polypyrrole film thicknesses.

Using the four-probe technique, the DC conductivity of PPy films obtained by the above procedure was measured to be 2000 S/m. The thickness of the films was measured using a Scanning Electron Microscope (SEM) Philips XL 30, as illustrated for a section of 40 µm PPy film in Fig. 1.

III. ANTENNA DESIGN

Four PPy patches and one equivalent Cu-patch antenna were fabricated on FR-4 substrate. Examples of fabricated Cu and PPy-patch microstrip antennas are shown in Fig. 2.



(a) (b)

Fig. 2. 4.5 GHz microstrip antennas on FR-4 substrate with co-axial feed: (a) Cu-patch, (b) PPy patch

The permittivity of the FR-4 substrate at microwave frequencies is not accurately available from the manufacturer's data sheets and it varies from panel to panel. An indirect approach was therefore applied for determining the permittivity of the specific FR-4 samples used in our study at the frequency of interest (i.e. 4.5 GHz).

A. Determination of the permittivity of FR-4 substrate

The relative permittivity value of FR-4 indicated in the literature varies from 4.0 to 4.9. The material library of the electromagnetic simulation tool CST™ indicates the relative permittivity value of FR-4 to be 4.9, while the HFSS™ simulation material library indicates a value of 4.4. Initial design and simulations were made using this value 4.4. Actual measurements on a reference Cu patch antenna indicated a large discrepancy between the resonant frequencies of the simulated and measured results. An adjustment to permittivity and loss tangent (tan) value of FR-4 used in simulations was undertaken towards matching of the measured Cu patch antenna results. Through this process, the FR-4's permittivity was estimated to be 4.1, with a loss tangent of 0.001(Fig. 3).

This permittivity value for the substrate was taken as a basis for the subsequent design of the four PPy patches on FR-4 substrate. All the PPy films had a DC conductivity of 2000 S/m, which translates into a DC volume resistivity of $5x10^{-2}$ •cm. The resulting DC surface resistivity of the PPy film samples is shown in Table I. For accurate simulation of the PPy-patch antennas, the film thickness and its surface resistivity must be accurately known.

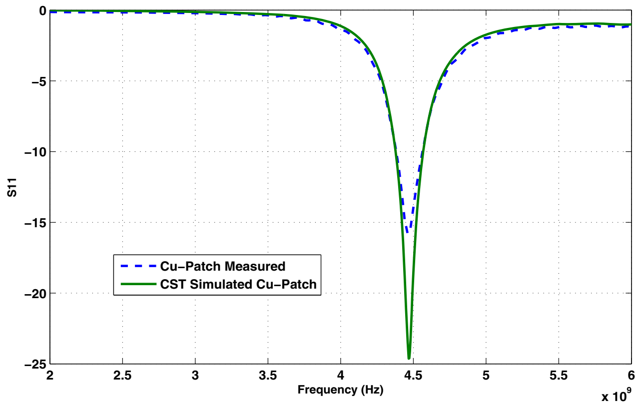


Fig. 3. Simulated and measured S11 for a Cu patch antenna on a FR-4 substrate with permittivity $_r$ =4.1

TABLE I

SURFACE RESISTIVITY OF POLYPYRROLE FILM SAMPLES

PPy Film Thickness (µm)	DC Surface Resistivity (ohms/square)
140	3.57
90	5.56
50	10
40	12.5

B. Simulations and design optimization

The antenna design was optimized for good impedance match. In the case of PPy patches, the same microstrip antenna design and feed position were used for all samples, in order to isolate the effect of patch thickness on antenna performance. The design parameters for the microstrip patch antenna are indicated in Table II

TABLE II

MICROSTRIP ANTENNA DESIGN DATA

Parameters	Cu	PPy			
		140µm	90µm	50µm	40µm
Substrate					
• FR-4 (ε_r)	4.1				
• Thickness	3.2 mm				
• Dimension	80x80mm				
Patch Design					
• Length (mm)	14.26	14.16			
• Width (mm)	12.9	12.9			
Feed point (off center in mm)	2.09	2.53			

The effect of the patch thickness for less conductive material (such as PPy) is an important consideration in this design. The PPy patches have been simulated as impedance sheets with finite thickness using both CST™ and HFSS™ as EM simulators. It is pertinent to mention here that the EM solvers, while simulating the CP material (or any other material with finite thickness and conductivity), take into account its thickness only in the frequency-domain solution and discard the effect of thickness in the time-domain solution. The microstrip antenna with CP material was therefore simulated in the frequency domain.

C. Antenna fabrication

The fabrication of the microstrip antenna using the free-standing PPy patch proved challenging because of the mechanical properties of the material. The PPy film is very delicate and tends to shear along the cut edges. This therefore makes it hard to cut the film to exact patch size or drill holes using computer-assisted tools. The inaccuracies of the fabrication process often affect the optimised design of the antenna. The PPy patch was cut to the desired size by hand using a suitable template. Since systematic fabrication errors affected the realisation of the optimised parameters, the simulation was later adjusted according to actual dimensions of the fabricated devices. The systematic error had a mildly detrimental effect on the matching of the fabricated antennas, which could be solved through refinement of the manufacture procedure.

IV. RESULTS

An accurate match of simulation and measurement results was obtained for the designed PPy patch antennas (Fig. 4) , which further validated the permittivity value of 4.1 and tan = 0.001 for the FR-4 substrate.

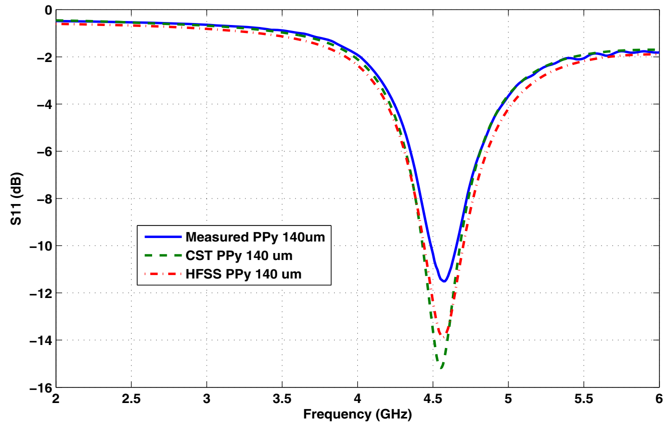


Fig. 4. Simulated and measured S11 for a PPy patch antenna on a FR-4 substrate with permittivity $_r$=4.1.

The co-polarized (co-pol) radiation patterns of the PPy patch antennas and equivalent Cu patch antenna are shown in Fig. 5 and 6 for the E- and H-plane. The IEEE gain and estimated radiation efficiency of the PPy patch antenna are listed in Table III. The radiation efficiency of the PPy patch antennas was estimated by comparing measured gain against that of the equivalent Cu patch antenna. The radiation efficiency of the copper patch antenna was determined from measurement and simulation.

TABLE III
MEASURED GAIN AND RADIATION EFFICIENCY

PPy-Film Sample	Gain (dB)	Radiation Efficiency (%)
40 μm	2.42	38.5
50 μm	3.4	47.8
90 μm	3.8	52.3
140 μm	4.63	64.8
Cu (17μm)	5.45	99.6

The Cu patch antenna is resonant at 4.46 GHz, with a -10 dB bandwidth of about 300 MHz or 6.7%. The resonant frequencies of the PPy patch antenna are within 1% of 4.5 GHz. The consistency of the results is further validated by the comparison of the shape of the measured and simulated radiation pattern of Cu patch antenna and PPy patch antennas.

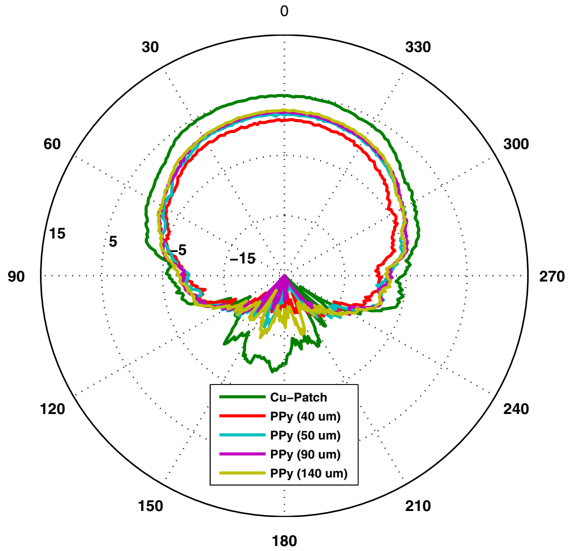


Fig. 5. Measured E-plane co-pol antenna gain patterns.

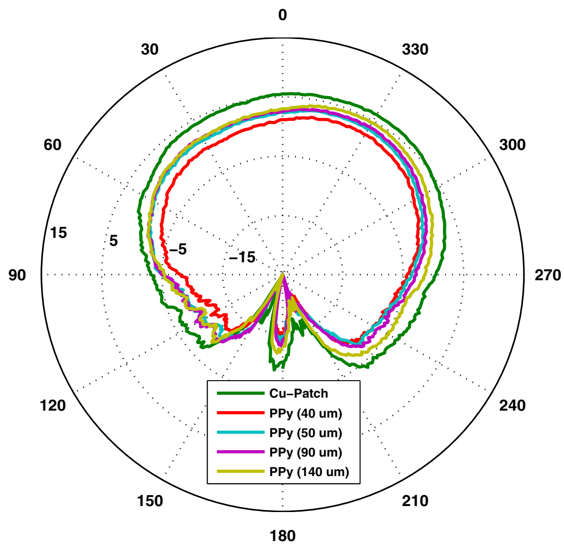
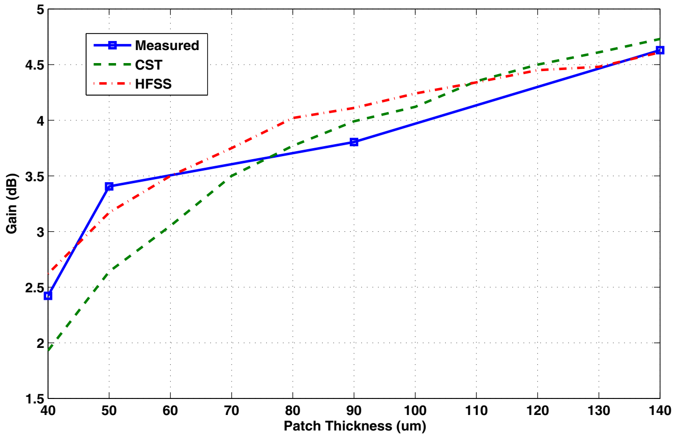
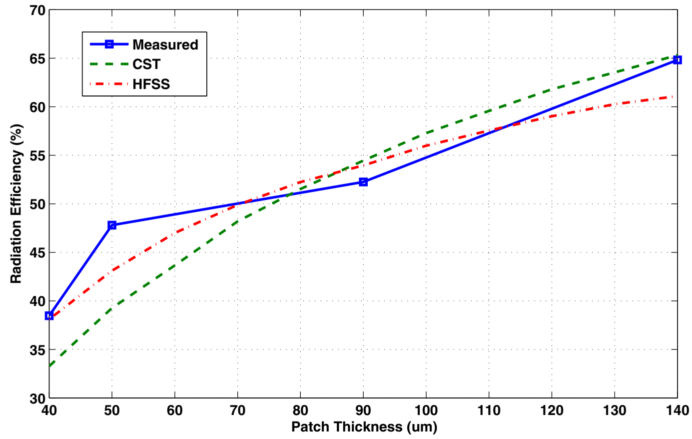


Fig. 6. Measured H-plane co-pol antenna gain patterns.

The measured IEEE gain and radiation efficiencies were compared to simulated values obtained using CST™ and HFSS™. The variations of antenna gain and radiation efficiency against patch thickness and surface resistivity are shown in Fig. 7. The good agreement validates the simulation procedure.



(a)



(b)

Fig. 7 Variation of (a) antenna gain with PPy patch thickness (b) antenna radiation efficiency with PPy patch thickness

V. Discussion

The classical antenna design for patch materials with low conductivity requires that the patch thickness should be at least a couple of skin depths. The skin depth at 4.5 GHz for 2000 S/m conductivity is 168µm. However, it emerges from the present study that reasonable antenna performance is possible with patch thicknesses less than one skin depth. Furthermore, the effect of low patch conductivity and patch thickness could be mutually off-set (within limits) by either increasing conductivity of the conductive polymer or by increasing the patch thickness closer to at least one skin depth, or both. Alternatively, for higher frequency designs the effect of patch thickness could be offset. These considerations are particularly important in the development of reconfigurable microwave antennas with CPs.

VI. Conclusion

The performance of PPy-based 4.5 GHz antennas was presented and compared with an equivalent copper microstrip antenna. The lowest gain observed was 2.42 dB (for 40 µm thickness with a radiation efficiency of 38%), the highest gain observed was 4.63 dB (for 140 µm thickness with a radiation efficiency of 65%). The equivalent copper antenna gain was 5.45 (with a radiation efficiency close to 100%).

In this paper it clearly emerges that CP-based microwave antennas are possible albeit with some limitations in terms of gain and radiation efficiency. However, the advantages of light weight, low cost, conformal design, bio-compatibility and degradability make these antennas very attractive in certain applications, such as optically transparent antennas, wearable and conformal antennas, indoor MIMO applications and bio-medical applications.

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