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Design of Microstrip-Fed Proximity-Coupled Conducting-Polymer Patch Antenna

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Abstract: A conducting-polymer patch antenna was fabricated by a screen-printing technique. Polyaniline (Pani) films of conductivity 6000 S/m, permittivity 6000 and thickness 100 µm have been used as a radiating patch. HFSS was used as a design tool to validate the experimental measurement of the Pani-patch antenna. Measured and simulated results of the resonant frequency, return loss, gain, bandwidth and radiation patterns are presented. Simulations and measurements have been performed on both copper- and Pani-antennas for comparison. Details of the design considerations, simulation and experimental results are presented and discussed.

Keywords: conducting-polymer, HFSS simulation, patch antenna.

1. Introduction

Conducting polymers has attracted considerable interest for several decades due to their potential applications in microelectronics (Karg & al., 1996), (Angelopoulos & al. 1993), (Yoshimo & al., 1987). Conducting polymers show a number of advantages over traditional inorganic microwave conducting materials (copper, gold...) such as lower surface mass, easy complex and processing, as well as adjustable electromagnetic parameters by chemical manipulation of the polymer backbone, by the nature of the dopant, by the degree of the doping, and by blending with other polymers (Skotheim & al.,1998).

Among the conducting polymers, polyaniline (Pani) has been demonstrated to provide a new route to metallization, particularly in printed circuit board (PCB) technology (Clarke & al., 1981), (Berry & al., 1985). Pani can be processed on mass scales by techniques such as ink-jet printing and screen printing, which offers an opportunity for low-cost manufacturing of polymer-based, passive microwave electronic devices, such as filters and antennas.

In this paper, we report the design of Pani-patch antenna. We present the designed, simulated and measured results of the rectangular microstrip-fed proximity-coupled antenna where the Pani-radiating patch was printed by a screen printing technique. Since the electric properties of the radiating film influence the antenna characteristics, Pani-films were characterized at microwave frequencies (Rmili & al., 2004). The measured conductivity and permittivity over X-band are 6000 S/m and 6000, respectively.

2. Screen-printing technique

2.1. Copper-antenna

The thick-film ink used to print copper-patches contains at least three main ingredients: an active mineral material (copper), a mineral binder generally added to provide adhesion to the substrate and the organic vehicule (Vest & al., 1991). The screening agent consists of high molecular weight polymer (acrylic resin) dissolved in a low vapour pressure solvent (butyl acetate).

A layer of some tens of microns thickness is obtained by the transfer of the ink on the substrate through a patterned screen. The wet film can then level within 20 min at room temperature due to the pseudoplastic and thixotropic properties of the ink.

Then a drying cycle of 20-30 min at 398-423 K is often used to eliminate most of the solvents contained in the levelled films. Next, screen printed layers are fired in a belt furnace whose temperature profile and atmosphere are carefully controlled. Using a standard temperature cycle of approximately 60 min, the samples may be peak heated at 1273 K for 10-15 min. Typical heating and cooling rates range from 318-373 K min^{-1}.

At room temperature, the mechanical pressure may reduce the thickness of the oven-dried layers by as much as 30 %. The reduction roughly corresponds to the volumic percentage of the organic sovents eliminated during the drying process. After removal of the solvents, the sreen printed substrate is introduced into a stainless steel die of 2,5 cm diameter. Uniaxial pressure up to 5.10^8 Pa is then applied to the sample using a hydaulic press.

2.2. Pani-patch

The Pani-solution, used as thick-film ink for printing of conducting-polymer patches, was synthesized according to the method described in (Olinga & al., 2000). 1,2-benzenedicarboxylic acid, 4-sulfo, 1,2di(2-ethyl hexyl) ester (DEHEPSA) was used as dopant. Dichloroacetic acid (DCAA) was used as the solvant in preparing polyaniline solution for film casting. Four grams of Pani /DEHEPSA complex was dissolved in 100 g of dichloroacetic acid (DCAA) and the solution was stirred for 12 h at room temperature.

Conducting-polymer films were prepared as follow: A 15 ml of Pani-solution (4 wt % of Pani /DEHEPSA) was spread out on a teflon slide and the solvent was allowed to evaporate in a vacuum oven for a period of 24 h at 60 °C. Measurements were performed at microwave frequencies using several microwave techniques (resonant cavity, open-ended coaxial probe, and reflection/transmission) in order to determinate the electric properties of Pani-films (Rmili & al., 2005). The obtained Pani-films of thickness 100 µm, have a conductivity of 6000 S/m and a permittivity of 6000.

3. Antennas design

The geometry of the microstrip-fed proximity-coupled antenna is shown in Figure 1. The rectangular patch is fed by proximity coupled microstrip line placed between two dielectric layers of antenna substrate (Pozar & al., 1987). The antenna was designed to operate with a center frequency around 10 GHz and input impedance of 50 Ω. Table 1 shows the design parameters for both the top and bottom substrates. Table 2 shows the design parameters for the Pani-film used as a resonating patch.

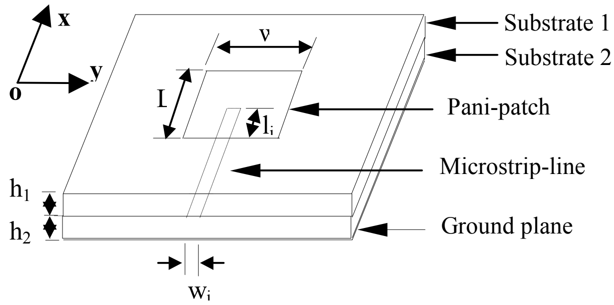


Figure 1. *Structure of the square microstrip-fed proximity-coupled antenna.*

Parameter	Value
Substrate	Alumina
Substrate thickness, h (mm)	0.635
Permittivity, ε_r	9.6
Loss tangent, tan δ	10^{-3}

Table 1. *Design data of the two substrates.*

Parameter	Value
Patch	polyaniline
Film thickness, e (mm)	0.1
Conductivity, σ (S/m)	6000
Permittivity, ε_r	6000

Table 2. *Design data of thePani-film.*

A square radiating Pani-film of dimensions 5 mm × 5 mm was printed by screen printing technique on the top substrate, whereas on the grounded substrate, a microstrip feed made of copper was printed. The microstrip line is 0.635 mm wide and 7.5 mm long. Both the top and the bottom substrates are of dimensions 25.4 mm × 25.4 mm. A copper film of thickness 50 µm, was used as the ground plane of the antenna.

A good impedance matching can be obtained, using Ansoft HFSS software, by selecting proper value of the microstrip line width (W_i = 0.635 mm) and by adjusting the length l_i under the square resonator. The copper-antenna was realized with the same parameter design by printing copper-patch (σ = 5.7 10^7 S/m).

4. Simulation design

4.1. Copper and Pani antennas

HFSS-model for Pani-patch antenna was designed according to experimental parameters design. The simulations use 100 µm layer of conductivity 6000 S/m, permittivity 6000 as radiating rectangular patch. Two identicals layers of alumina (ε_r = 9.6, tg δ = 10^{-3}) of thickness 0.635 mm are used to model substrates. A thin copper layer of thickness 5 µm was used to model the groundplane.The box representing air has the dimensions 20 mm × 20 mm × 15 mm. The antenna is placed in the middle. Air is modelled by vacuum in all simulations.

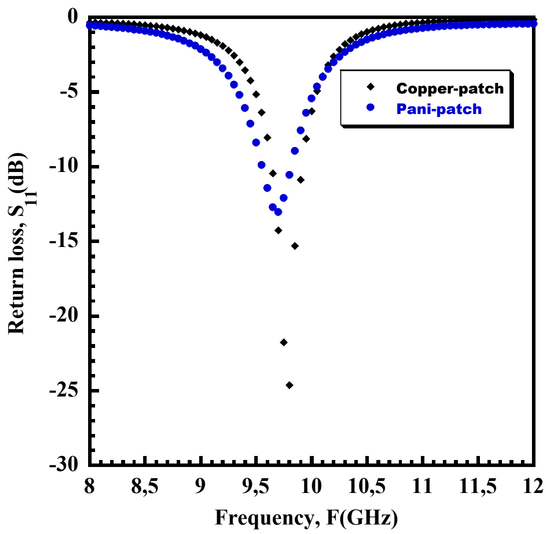
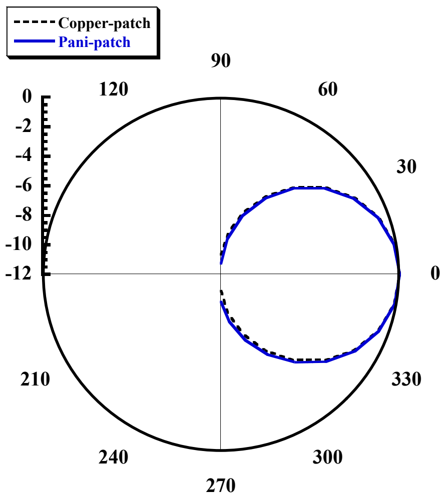


Figure 2. *Simulated return loss versus frequency for Pani- and copper-patch antennas.*

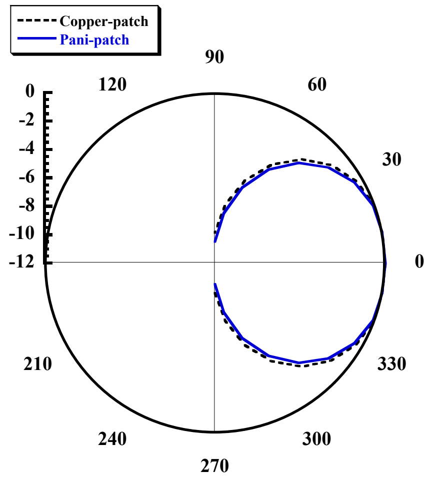
The comparison of simulated return loss between Pani- and copper-antennas versus frequency is presented in Fig. 2. It shows that the return loss for Pani-antenna was about –13 dB, at 9.7 GHz, which is higher than that of the copper-antenna. This increase may be attributed to the decrease of the patch conductivity.

Radiation characteristics of the antennas are also studied. Fig. 3 illustrates the simulated far-field of both Pani- and copper-antennas in H- and E- planes, respectively.

The half-power beamwidth (HPBW) of the Pani-antenna at 9.7 GHz for the H- and E- planes are found to be 95° and 135°, respectively.



(a)



(b)

Figure 3. *Simulated radiation patterns in both E- (y-z plane) and H- (x-z) planes at, (a) : Copper-patch (f_r = 9.8 GHz) antenna; (b) : Pani-patch antenna.(f_r = 9.7GHz)*

Compared to copper-patch antenna, the Pani-patch antenna has similar radiation characteristics (Fig. 3). From this observation, we can conclude that the patch conductivity does not affect the radiation behavior since the skin depth of the electromagnetic microwave ($\delta \approx 65$ µm at 10 GHz) is inferior then the patch thickness (100 µm)). Fig. 3 points out that radiation patterns in H- and E- planes of the conducting-polymer antenna are also symmetric. This symmetry is rather obvious, as that property dependends only on the geometry of the antenna and not on the conductivity of the patch.

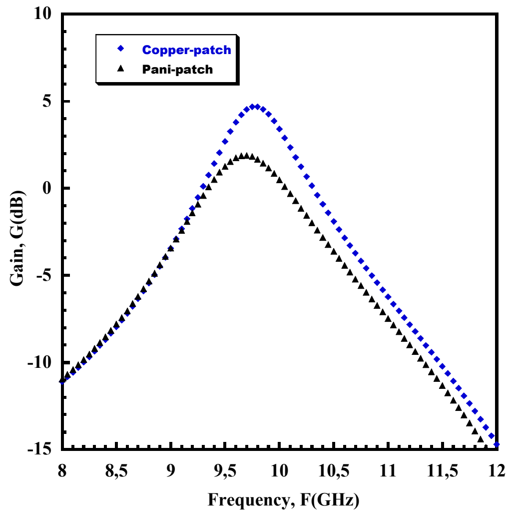


Figure 4. *Simulated antenna gain for both Copper- and Pani-patch antennas.*

The simulated gain of both Copper- and Pani-patch antennas are shown in Fig. 4. We can see that the gain of the conducting-polymer antenna is about 1.88 dB, which is less than the case of the metallic antenna (4.69 dB). This drop of the gain may be due to the increase of the dissipated power in the conducting-polymer film. This result can be confirmed in Fig. 5, which gives the variation of the simulated effeciency of both conducting-polymer and metallic antennas versus frequency. In fact, the effenciency of the Pani-antenna at the frequency resonant is about 65 % which is less than that of the copper antenna (98%).

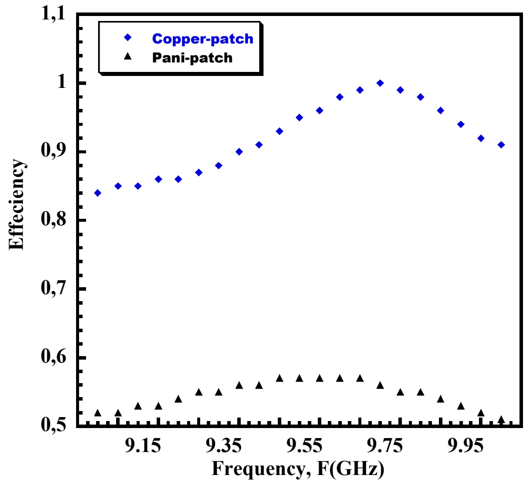


Figure 5. *Ansoft-HFSS simulation for the efficiency of both Copper- and Pani-patch antennas.*

The simulated electric-field distribution, on the upper side of the top substrate, at the same phase φ = 60°, in both copper and Pani antennas is presented in Fig. 6.

Because symmetry is used to speed up the simulations, only one half the patch is plotted in figures 6 and 7. We can observe that high fields are localized under the microstrip and at the edges of the patch where the electric field should be radiated in theory. The magnitude of the electric field on the Pani-patch's surface is less than that on the copper one, which can explain the decrease in the excited surface current magnitude as shown in Fig. 7.

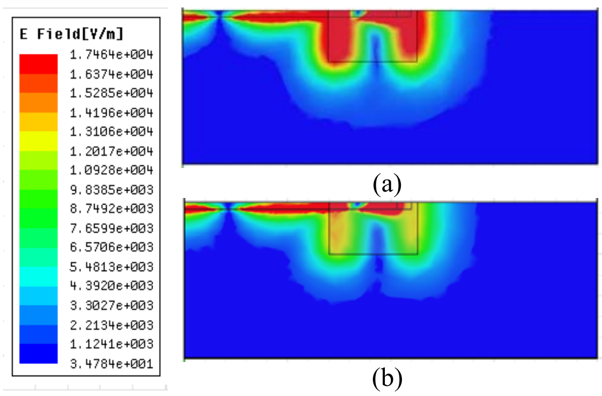


Figure 6*. The simulated magnitude of the electric field on the upper side of the top substrate, at the resonance frequency F_r and at the phase $\varphi = 60°$.*
(a) Copper-patch antenna (F_r = 9.8 GHz); (b) Pani-patch antenna (F_r = 9.7 GHz).

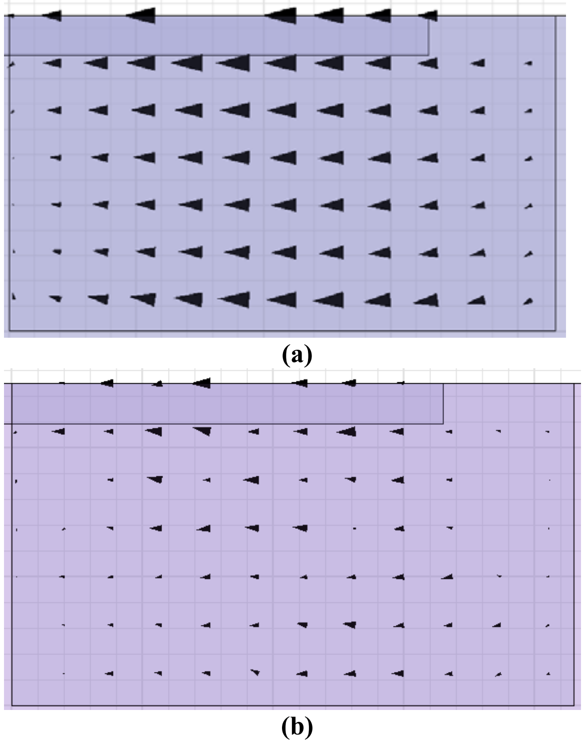


Figure *7. Simulated current distributions on the top surface of the patch, (a): Copper-patch, (b): Pani-patch.*

The excited patch's surface current distribution of the proposed antenna is also studied by using Ansoft-HFSS. Fig. 7 shows the simulated patch's surface current distribution for both Pani- and copper-antennas. It is seen that both organic and metallic structures have similar surface current distributions on the rectangular patch, whereas the current density at the Pani-patch surface is smaller then that at the copper-patch surface.

These characteristics agree with simulated results that similar radiation patterns for the two materials and a drop in both gain and efficiency of the conducting-polymer antenna are reported.

4.2. Copper and Pani microstrips

In order to study the dissipated energy in the conducting-polymer material, simulations of a Pani-microstrip structure were performed. The HFSS-model of the structure is presented in Fig. 8. A thin layer of conductivity 6000 S/m and permittivity 6000 was used to model the microstrip. This absorbing-material layer is of width 0.635 mm, length 11 mm and thickness 100 µm. The substrate was modeled by a layer of alumina (ε_r = 9.6, tg δ = 10^{-3}) of thickness 0.635 mm. The box representing air has the dimensions 7 mm × 25 mm × 5 mm. The same structure was simulated by replacing the Pani-patch by a copper one, for comparison.

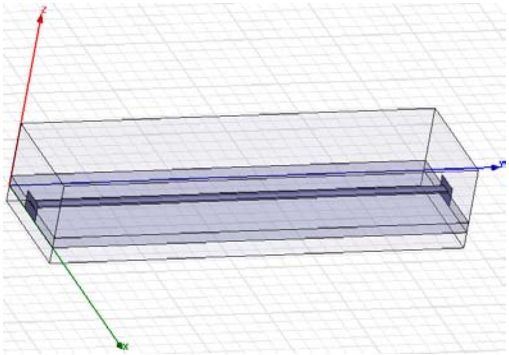


Figure 8. HFSS-model of the Pani-microstrip structure.

The evolution of simulated reflection and transmission coefficients of both Pani and copper structures, over the X-band frequency, is given in Fig. 9.

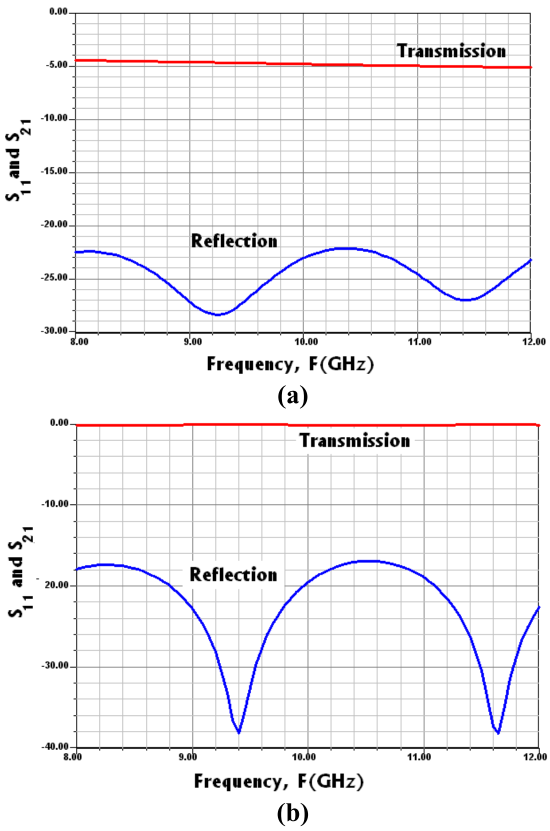


***Figure 9.** HFSS-simulated reflection and transmission coefficients, (a): Pani-microstrip; (b): Copper-microstrip*

As shown in Fig. 10, the reflection coefficients of Pani- and copper-microstrips at 10 GHz are about –23 dB and –38 dB, respectively, which proof the good adaptation of these structures. The transmission coefficient is about –5 dB for a Pani-microstrip of length 25 mm (Fig. 9(a)), wheareas this coefficient is very small (S_{21} < -0.1 dB) in the case of the metallic-microstrip (Fig. 9(b)). We can conclude that, the incident energy decreases as the microwave progresses along the Pani-microstrip, because of the dissipated energy in the conducting- polymer film. These energy losses can be evaluated from Fig. 9(a) as 2dB per cm at 10 GHz. This high value of the dissipated energy in propagation does not allow the realisation of a Pani-microstrip for the microstrip-fed proximity-coupled patch-antenna. For this raison, the microstrip was made of metallic conductor (copper).

5. Experimental results

The antenna under test was characterized by measuring the resonant frequency, return loss (Fig. 10), and gain, using HP 8510 C network analyser.

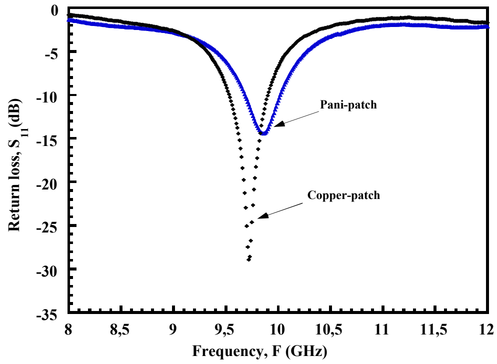
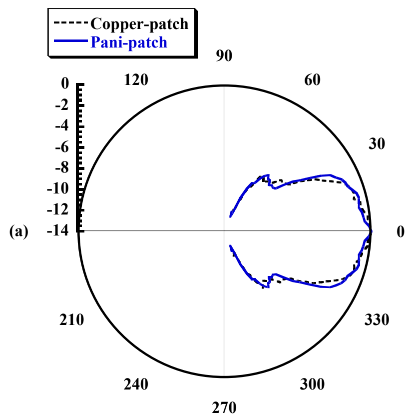


Figure 10. *Measured return loss versus frequency.*

The measured gain is 3.4 dB at 9.85 GHz, in the broad side direction (θ = 0°). The bandwidth is about 3 % for $|S_{11}| \geq -10$ dB. Figure 11 presents the measured radiation patterns in H- and E- planes, respectively, at the center frequency f_r = 9.85 GHz for Pani- antennas and at f_r = 9.72 GHz for copper-antenna. The HPBW of both Pani- and copper-antennas for the H- and E- planes are found to be 62° and 75°, respectively. The cross polarisation level is less than 16 dBi in the principal planes at the resonant frequency.

Due to the mechanical limitation of the stepper motor, radiation patterns could not be measured over the angular range 90°-270°. The 3-dB beam width of both E plane and H plane radiation patterns is 62° and 75°, respectively.



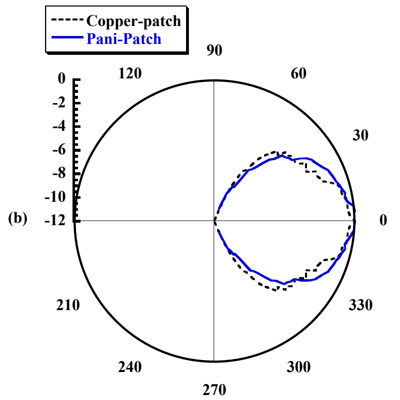


Figure 11. *Measured radiation patterns in the two principal planes for Pani and copper-patch antennas, (a): H-plane; (b): E-plane.*

6. Discussions

Measured and simulated results on the resonant frequency return loss, bandwidth, gain, efficiency and the half-power beamwidth (HPBW) of radiation patterns are presented in Table 3.

Parameter	*Simulations*		*Measurements*	
	Pani	*Cu*	*Pani*	*Cu*
Resonant Frequency	9.70	9.80	9.85	9.72
Return loss	-13.0	-24.6	-14.2	-29.0
Bandwidth	2.7%	2.7%	3.1%	3.4%
Gain	1.88	4.69	3.42	5.50
HPBW (H-plane)	95	90	62	62
HPBW (E-plane)	135	140	75	75
Efficiency	56%	98%	-	-

***Table 3**. Tabulated comparison of the experimental and simulated results.*

As shown in Table 3, the Pani-antenna resonates at 9.85 GHz against the calculated value of 9.7 GHz. The difference in resonant frequencies may be attributed to the fabrication tolerances. The resonant frequency shift can be compensated with a small change of the patch length. Since this frequency-shift is small, the needed change of the patch length is so small that it does not affect the antenna parameters (gain, return loss, bandwidth…).

Despite the measured return loss of the antenna increases when we replace the copper-patch by the Pani one, we consider that S_{11}values less than –10 dB ($(S_{11})_{Pani}$ = -14.2 dB) are satisfying to realize patch-antenna. The comparison of simulated and measured values of the return loss is satisfying.

We can observe also from Table 3, that the measured bandwidth, which is the frequency range where the S_{11} parameter is smaller than –10 dB, is slightly affected by a change in the patch's conductivity, whereas no significant effect was reported in simulated results.

The measured gain of the Pani-patch antenna is 3.42 dB which is only 2.0 dB lower than that of the copper antenna despite that the Pani conductivity is many orders of magnitude lower than that of copper (σ_{Pani} = 6000 S/m, σ_{cu} = $5.7.10^7$ S/m). In fact, the decrease of the patch conductivity leads to an increase in the dissipated energy in the conducting-polymer film, which affects the gain and the efficiency of the structure.

The difference between simulated and measured values of the gain may be attributed especially to two reasons. First, the use of finite reflecting-groundplane of dimensions 50 mm $\times$ 37 mm to ovoid back radiation, whereas the simulation uses an infinite one. Second, the presence of a metallic support used to fix the antenna on the experimental device.

These two experimental constraints affect the measured radiation patterns by increasing the directivity of the antenna in the front side, which gives measured gain values superior to those simulated. As a result, measured radiation characteristics of the antenna are slightly different to those simulated.

Comparison between measured and simulated HPBW values for the two antennas confirms this explanation. In fact, measured HPBW values are narrower compared to those deduced from simulated patterns.

As shown in Table 3, there is no significant difference, in both simulation and measurements, between HPBW values when we substitute the copper patch par the conducting-polymer one. In addition to the similar radiation patterns of the two antennas, we can conclude that the patch's conductivity does not affect radiation patterns since the skin depth ($\delta \approx 65$ μm at 10 GHz) is inferior than the thickness (e = 100 μm) of the film.

Conclusion

In this paper, we have designed, simulated and characterized a new conducting-polymer patch antenna operating at around 10 GHz. Polyaniline film, of conductivity 6000 S/m and permittivity 6000, was used as resonating square patch to realize a microstrip-fed proximity-coupled antenna.

Results show that Pani-patch antennas can be realized with relatively good characteristics. The return loss of the realized Pani-antenna is about –14.2 dB, the bandwidth is found to be 3.1% and the gain of the antenna is about 3.42 at 9.85 GHz.

The only 2 dB-drop in the measured gain for a Pani-patch of conductivity 6000 S/m and permittivity 6000 can be consider as an encouraging result since the conductivity of other conducting-polymer films can achieve 10^5 S/m (Pomfret & al., 1999), (Theophilou & al., 1989).

On the other hand, the high dissipated energy in the Pani-film of conductivity 6000 S/m and permittivity 6000 does not allow the realization of micristrips with this level of conductivity. Therefore, we think that these higher values of losses can be reduced by using more conductive films.

The comparison of simulated results between Pani-antennas and Pani-microstrip, allows us to conclude that the use of conducting-polymers in wireless system is more adapted for resonating structure such as antennas, resonators, filters then microstrip-structures.

We think also that use of conducting-polymer for the design of resonating structures operating at high frequencies (e.g. millimetric-band) is better. In fact, at higher frequencies, the dimensions of the realized structures are much little, which reduce the interaction of the microwave field with the conducting-polymer materials, and then reduce losses of electromagnetic energy.

Finally, measured results are satisfying concerning matching, bandwidth and the gain for a Pani-film of conductivity 6000 S/m and permittivity 6000. However, further improvement is needed in the synthesis process of Pani-solutions to fabricate more high and stable conducting films, and in the fabrication process to realize antenna with better characteristics.

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