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New frequency-reconfigurable microstrip antenna composed of organic semiconductor polymer

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ABSTRACT

A novel frequency-reconfigurable microstrip antenna composed of organic semiconductor polymer (P3HT) is proposed. Resonance frequency of the antenna is tuned in 6.8–7.73 GHz band, by changing the light illumination intensity of a 5 W/cm^2 white light source. Behavior of the antenna under different light intensities is investigated and compared to a reference copper antenna. Measured radiation patterns are identical in higher and lower resonant bands. Measured radiation efficiency and gain of the proposed antenna are compared in higher and lower bands. The results indicate that, it is possible to obtain reasonable performance albeit with modest radiation efficiencies.

1. Introduction

With the rapid development of wireless communications, especially the in-depth research on MIMO techniques, reconfigurable antennas are gaining increased attention. Different characteristics (such as resonant frequency [1,2], radiation pattern [3], polarization [4]) of these antennas can be reconfigurable through making changes in the geometrical or electrical properties. The concept of reconfigurable antennas first appeared in 1983 [5]. Many concepts of the reconfigurable antenna structures have been proposed. Their common feature is the application of some switching elements, i.e. PIN diodes or MEMS switches. Each type of switching element has its advantages and drawbacks. Many designs have been proposed that use the variable reactance property of varactor diodes, but these are normally accompanied by biasing lines and high biasing voltages [6,7]. PIN diodes in reconfigurable antennas have also gained in popularity, as they require lower biasing voltages [8,9].

MEMS are limited by low-power handling capabilities and mechanical failure due to moving parts. All these designs require metallic biasing lines to be attached to the antenna which can interfere with the radiation patterns [10,8]. Using fiber optic cables instead to activate optical switches have the advantage of being electromagnetically transparent and so do not interfere with the radiation patterns of the antenna [11]. They also provide thermal and electrical isolation between the antenna and the control circuitry. Recently, there has been a growing interest in exploiting conducting polymers (CP) for planar antennas [12–16].

In this research, we propose a novel frequency reconfigurable microstrip antenna composed of P3HT (3-hexylthiophene). Organic semiconductors [17] are a class of solids displaying semiconductor properties based entirely on organic components. Organic semiconductor polymers have been the focus of many studies because they have shown many advantages, such as easy fabrication, mechanical flexibility and tunable optical properties. In recent years, the potential application of P3HT in polymer electronics and optoelectronic applications has gained significant attention [18]. Because of its good spectral overlap with optical wavelength irradiation and high charge-carrier mobility as well as having a low band gap [19].

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These features are relatively stable in ambient conditions and it has excellent solubility in common organic solvents. An important characteristic of P3HT is its small band gap. It has been reported to be approximately 1.9 eV, and its corresponding absorption peaks between 450 and 600 nm in the visible part of the spectrum. It is thus possible to photogenerate charges within the dielectric, and these charges are able to move reasonably rapidly.

The optically controlled frequency response of the antenna can be achieved by using the organic semiconductor as the patch material. When the organic polymer is being illuminated by the light source whose photon energy is greater than the band gap energy of the semiconductor material, an electron–hole plasma region will be induced. This leads to a different permittivity from that of the non-illuminated region. As a result, the dielectric property of organic material will be changed through these activated regions, and the resonant properties of the antenna will be changed. Thus, the performance of the antenna can be controlled by the intensity of the optical illumination. P3HT has a high absorption coefficient close to the maximum photon flux in the optical spectrum, peaking between the blue green (450 nm) and green yellow (600 nm). The UV–Vis absorption spectra for a thin film of pure P3HT indicates two peaks at 493 and 517 nm and one shoulder at 572 nm. These three bands can be attributed to the transition from valence band to conduction band. Therefore a general white-light source is sufficient for optical applications without particular equipment requirement.

The paper is organized as follows. In Section 2, we describe design procedure of the proposed antenna and talk about the influential parameters on its performance. In Section 3, experimental and simulation results are presented. Conclusions are made in Section 4.

2. Antenna design procedure

To start the design procedure, first of all, we have to choose a specific configuration (e.g. rectangular, circular, etc.). This selection depends on the application of the antenna. The simplest microstrip patch configuration is undoubtedly the rectangular patch. Since it was an elementary study on the application of organic polymers in antennas, we did not want to increase the complexity of the design process by choosing an odd configuration for the patch, so we chose the rectangular configuration. Then, a reference copper (Cu) rectangular patch antenna was fabricated and tested, to obtain its resonance frequency. This reference metallic antenna is used for validation of the simulation and for the direct comparison of the relative performance of the P3HT antenna. To achieve a reasonable comparison, we try to make Cu and P3HT antennas as similar as possible (in terms of dimensions and substrate material). Patch width has a minor effect on resonance frequency and radiation pattern of the antenna. It affects the input resistance and bandwidth to a larger extent. It has been suggested that [20,21].

$$1 < \frac{\text{Length}}{\text{Width}} < 2 \quad \text{(for metallic patches)} \tag{1}$$

The patch length determines the resonance frequency, and is a critical parameter in design because of the inherent narrow bandwidth of the patch. To a zero-order approximation, the patch length L for the TM_{10} mode is given by:

$$L = \frac{c}{2f_r\sqrt{\varepsilon_r}} \quad \text{(c is the speed of light, } f_r \text{ is the resonance frequency, } L \text{ is patch length)} \tag{2}$$

The factor $\sqrt{\varepsilon_r}$ is due to the loading by the substrate.

Dimensions of the copper antenna are chosen to be 14 mm × 13.5 mm. It is mounted on 1.8 mm thick Ultralam® 2000 substrate ($\varepsilon_r = 2.4$). To match the input impedance of the antenna to 50 ohms, the feed point selected to be 1.28 mm off center, which was determined by trial and error. The change in feed location gives rise to a change in the input impedance and hence provides a simple method for impedance matching. The resonance frequency of the Cu antenna was measured to be 6.9 GHz.

Most microstrip antenna designers would consider a couple of skin depths thickness for metallic (Cu) patches as essential. The skin depth of copper at 6 GHz is 0.85 μm, and the thickness of the reference copper antenna metallization was chosen to be 17 μm, which is about 20 times of its skin depth. The skin depth of less conductive materials (like P3HT) is usually very high in contrast to conductors. In [22] it has been shown that, for conducting polymer antennas, it is possible to obtain a reasonable antenna performance, even if the patch thickness is a fraction of its skin depth. The DC conductivity of the material (P3HT) used in our experiment is 1000 s/m and its skin depth at 6 GHz is 205 μm. So we chose the thickness of P3HT film to be 100 μm (around one half of the skin depth). It is possible to use thinner P3HT films, but the radiation efficiency and antenna gain will dramatically decline with thinner patches [22].

The configuration of the proposed (P3HT) antenna is shown in Fig. 1. The antenna was excited by a coaxial line feed. It consists of a 100 μm film of P3HT polymer on a 1.8 mm Ultralam® 2000 substrate. Antenna was designed to be 15 mm × 15 mm, to make it as much as similar to the reference antenna. The feed point is located 3 mm from the center (to match the input impedance to 50 ohms). The light source shown in the figure is an ordinary white light projector and produces white light illumination of approximately 5 W/cm^2.

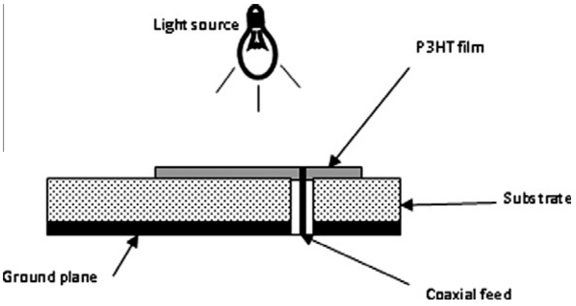

Fig. 1. Cross section of the proposed patch antenna.

The illuminated P3HT polymer will have a complex permittivity different from that of non-illuminated material. So the tunable response of the antenna can be achieved by switching from optical illumination to non-illumination. The permittivity of P3HT under illumination is difficult to calculate accurately, so we measured it in laboratory (using reflective coaxial method [23]) in illuminated and non-illuminated states. The empirical values are: $\varepsilon_r = 3.17$, $\tan\delta = 0.02$ for non-illuminated; $\varepsilon_r = 2.72$, $\tan\delta = 0.12$ for illuminated.

In Eq. (2), ε_r is the effective permittivity of the substrate material. Since the permittivity of P3HT decreases as the illumination intensity increases (from 3.17 to 2.72), the effective permittivity (in Eq. (2)) will be affected too. Thus, it can be predicted that, by increasing the light illumination intensity, P3HT antenna will resonate at higher frequencies (because of inverse relation of ε_r and f_r). The value of ε_r also affects the amount of radiated power. A low value of ε_r will increase the fringing fields at the patch periphery, and thus the radiated power.

3. Experimental and simulation results

The antenna design was optimized for 50 ohms impedance match. The resonant frequency of the antenna, when the light source was off (ambient conditions), measured to be 6.85 GHz. Fig. 2 depicts a comparison of measured and simulated return loss for P3HT antenna. Simulation was performed using FEM-based commercial software, HFSS by ANSOFT. When the light source was turned on, the resonant frequency was shifted to 7.73 GHz. Fig. 3 shows experimental and simulation results for illuminated antenna. CPs exhibit dispersion in their electrical conductivity with frequency [24–26]. Therefore, the measured results differed from the simulated results not only due to fabrication errors, but also due to dispersion in electrical conductivity. Table 1 compares measured antenna gain and radiation efficiency for reference copper antenna, illuminated and non-illuminated P3HT antennas. Fig. 4 shows measured E and H plane radiation patterns for non-illuminated and illuminated antennas. As it can be seen, radiation patterns are nearly identical, in lower and upper bands. The Cu patch antenna is resonant at 6.9 GHz with a 10 dB bandwidth of 250 MHz. The non-illuminated P3HT antenna has 10 dB bandwidth of 420 MHz around it resonant frequency, while the illuminated P3HT antenna has 10 dB bandwidth of 700 MHz.

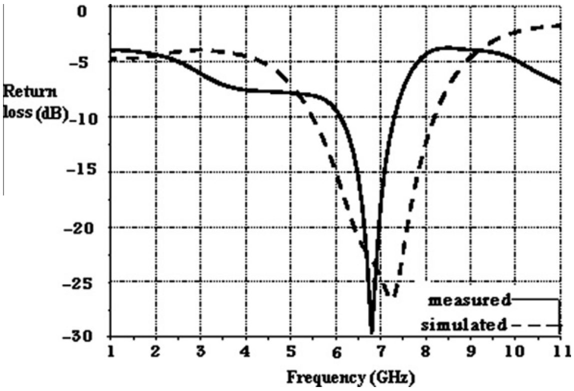

Fig. 2. Measured and simulated return loss of the proposed antenna when the light source was off.

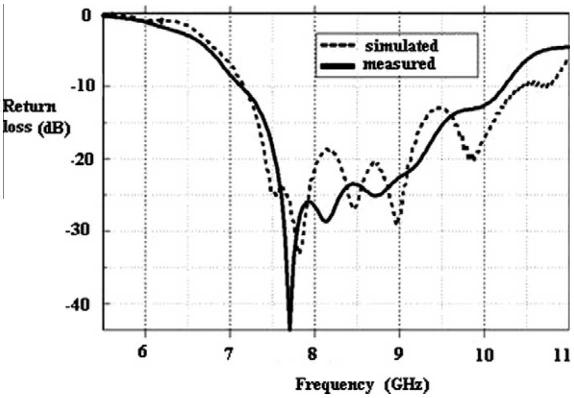

Fig. 3. Measured and simulated return loss of the proposed antenna when the light source was on.

Table 1
Comparison between the parameters of reference copper, illuminated P3HT, and non-illuminated P3HT antennas.

Patch type	Gain (dB)	Radiation efficiency (%)	Resonant frequency (GHz)
Reference copper	7.5	96.5	6.9
P3HT (non-illuminated)	6.25	50.22	6.85
P3HT (illuminated)	2.25	56.52	7.73

To better illustrate the behavior of the antenna under different illumination intensities, three light filters were used to decrease the light intensity by 35%, 50% and 70%. Resonant frequencies of each case were measured, and are illustrated in Fig. 5. Interestingly, the resonant frequency can be adjusted simply by adjusting the intensity of optical illumination. The switching speed between frequency bands is very fast, it is almost instantly switched by changing illumination intensity. The proposed antenna is a very good candidate for multi-frequency applications. Also, the antenna is suitable for frequency-sweeping applications, as its resonant frequency changes very gradually by light intensity. Optical control of the proposed antenna is driven by the need for dynamic control, fast response, immunity from electromagnetic interference and good isolation between the controlling and controlled devices. From practical point of view, the antenna can be tuned to operate under different light intensities and at desired resonant frequencies. A control circuit can be implemented to adjust the light source intensity proportional to the desired operating frequency.

Too many parameters (e.g. light intensity, light wavelength, P3HT film thickness, patch dimensions, and substrate material) affect the behavior of the proposed

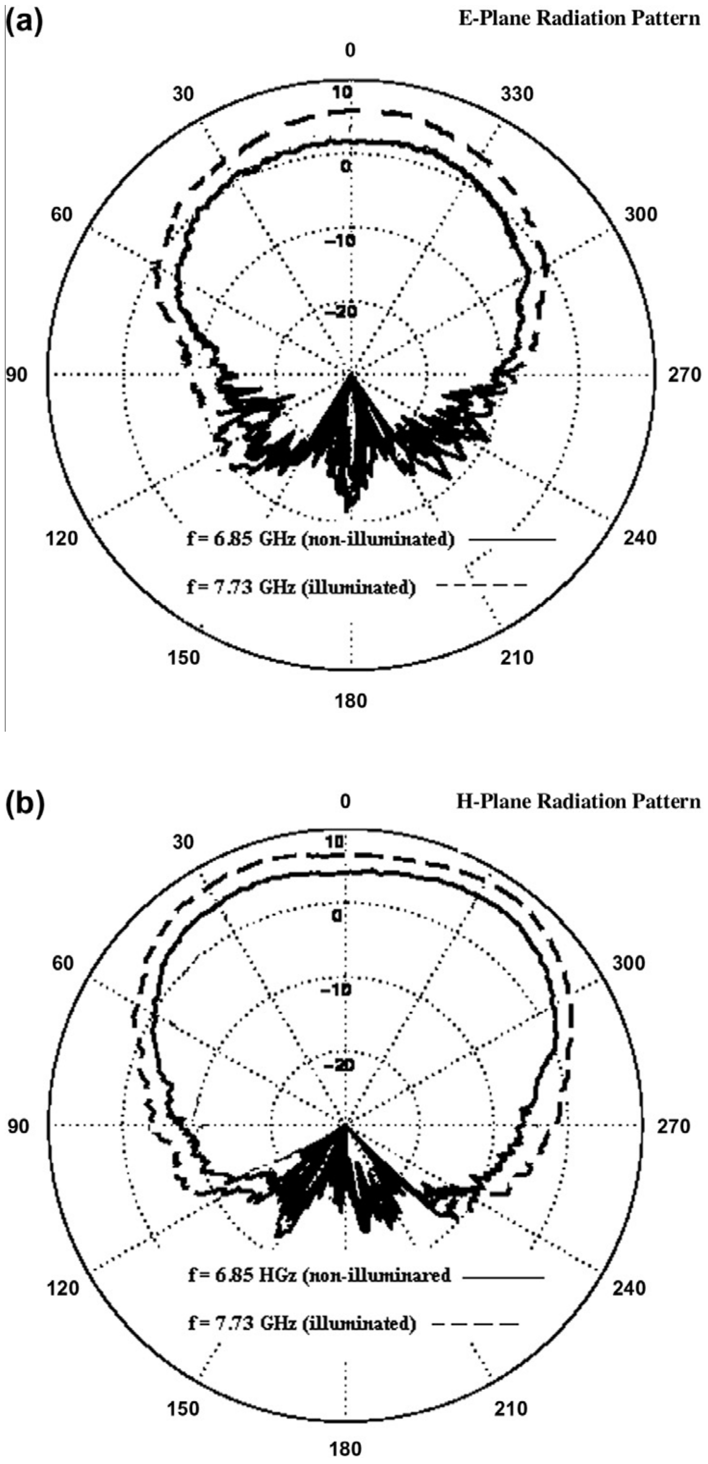

Fig. 4. E-plane (a) and H-plane (b) radiation patterns for non-illuminated (f = 6.85 GHz) and illuminated (f = 7.73 GHz) antennas.

antenna. It is difficult to incorporate all of these parameters in a single mathematical formula. But, it can be predicted that, as has been shown in [22] for a Polypyrrole Conducting Polymer Patch, the radiation efficiency and antenna gain of the proposed antenna, will increase by increasing patch thickness.

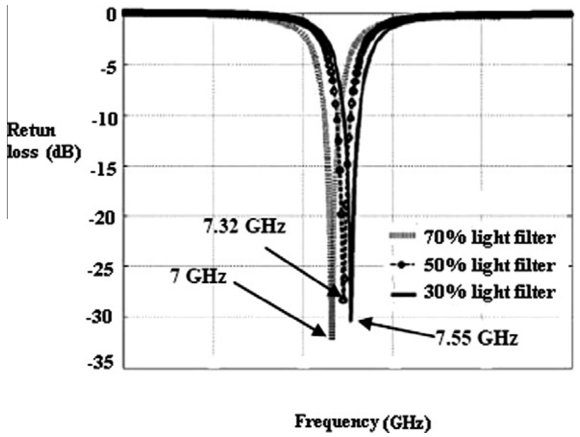

Fig. 5. Measured resonance frequencies of the proposed antenna under different light intensities.

4. Conclusions

A novel frequency-reconfigurable microstrip antenna using P3HT organic polymer has been investigated. Resonant frequency of the antenna changes as a function of optical illumination intensity. The frequency shift of the proposed antenna is in 6–7 GHz bands. By changing its dimensions, P3HT film thickness, and substrate material, it will operate at other desired frequency bands. Based on the presented results, organic polymers are potential candidates to incorporate in patch antennas. Despite the modest radiation efficiency of the proposed antenna (when compared to metallic patches), it has the interesting property that its resonant frequency can be changed by an external stimuli (light illumination).

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