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Research Article

Optically Controlled Reconfigurable Filtenna

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This work is regarding the development of a novel antenna called optically controlled reconfigurable filtenna, which is based on the integration of a broadband printed antenna with a bandpass reconfigurable RF filter. The filter is designed by applying defected microstrip structure (DMS) technique and positioned in printed antenna feeding line in order to keep the same size of the original antenna. The filtenna bandwidth is optically reconfigurable by using two photoconductive silicon switches excited by CW laser at 808 nm. Numerical results rely on independent and switchable operational modes through the 2.4 and 5.1 GHz ISM bands, whereas measurements demonstrate two reconfigurable modes based on single-band/dual-band operation over the same frequency bands. The proposed device is validated by theoretical, numerical, and experimental results.

1. Introduction

The term cognitive radio (CR) was introduced by Joseph Mitola III as a technology able to dynamically and opportunistically provide frequency spectrum access to unlicensed users [1, 2]. CR is an intelligent wireless communication system able to self-learn and self-adapt as a function of the radio environment by taking advantage of software-defined radio (SDR) platforms. Spectrum sensing is one of the most important stages in CR applications [3]. Using this technique, users can measure, evaluate, learn, and be aware of the transmission environment related parameters. For instance, we have recently reported a successful implementation of an Adaptive and Cognitive Radio over Fiber (ACRoF) architecture in a geographically distributed optical-wireless network [4]. It consists of a central office, which centralizes all network functionalities, and simple remote antenna units based on optically controlled reconfigurable antennas for data transmission and broadband antennas for performing spectrum sensing. From the antenna point of view, CR applications require using two different antennas: a broadband antenna for spectrum sensing and a reconfigurable narrowband antenna after selecting the operation channel.

Reconfigurable antennas are able to reconfigure at least one electromagnetic property, such as operation bandwidth, radiation pattern, and/or polarization [5]. The reconfiguration techniques are based on different approaches [5, 6]: PIN diode and varactor; RF MEMS; FET transistor; structural alteration; permittivity or permeability variable materials; and photoconductive switch [7]. Optically Controlled Reconfigurable Antenna Arrays (OCRAAs) are typically composed of photoconductive switches, which provides few microseconds of switching time, electromagnetic transparency, and easy integration to optical backbones and backhauls. OCRAA main advantages rely on linear response without harmonic and intermodulation distortion generation and no biasing circuit, which usually degrades antenna performance [8].

This work presents the concept and development of an optically controlled reconfigurable filtenna, which represents the integration of a broadband printed antenna with DMS filter. The paper is divided into six sections. Section 2 concerns the broadband printed antenna design, whereas the DMS bandpass filter, responsible for filtenna operation frequency selection, is described in Section 3. Section 4 presents the reconfigurable filtenna design. The proposed optically controlled reconfigurable filtenna concept and its

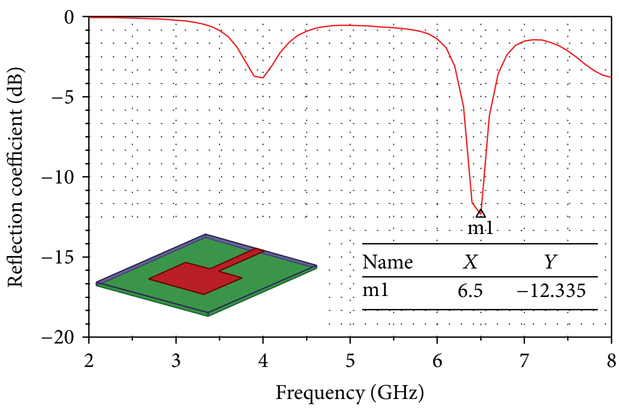


Figure 1: Conventional patch antenna reflection coefficient.

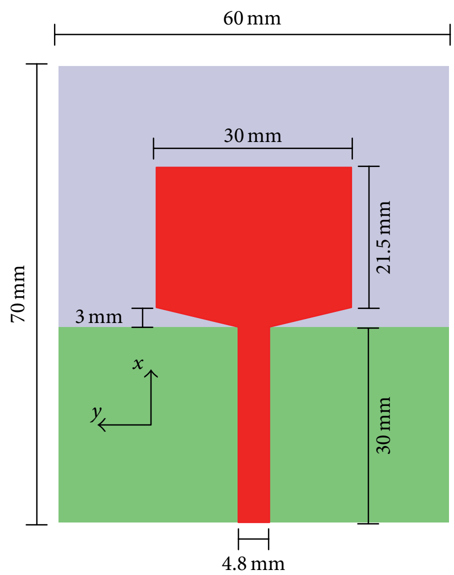


Figure 2: The broadband printed antenna.

main numerical and experimental results are reported in Section 5. Finally, conclusions and final comments are elucidated in Section 6.

2. Broadband Printed Antenna

This section is focused on the printed antenna design, which is going to be the radiating element of the proposed filtenna. This kind of antenna is widely used due to its simple format and attractive characteristics as [9] easy construction; low profile; low-cost, and others [9]. However, printed antennas typically provide narrow fractional bandwidth (FBW) of a few percent [9]. Many works propose multilayers patch antennas to enhance FBW [10, 11]. Nasimuddin et al. reported a 48,8% microstrip antenna using multilayer parasitic elements [11]. Nevertheless, multilayer antennas suffer from high dimensions, which can limit some applications.

Initially, a conventional patch antenna has been designed using an Arlon DiClad 880 substrate, as illustrated in Figure 1. Its main properties are dielectric constant of 2.2; thickness of 1.524 mm; and loss tangent of 9×10^{-4}. Numerical results of the antenna reflection, obtained using ANSYS HFSS, are reported in Figure 1. The antenna initial bandwidth is only 1,54% centered at 6.5 GHz. Figure 2 shows the modified patch antenna based on a truncated ground plane and a taper impedance matching structure between the antenna feeding line and patch radiator [12–14]. Truncated ground plane is responsible for creating a capacitive load for compensating the patch inductance, making the antenna input impedance approximately real over a wide bandwidth. The taper structure smoothes the abrupt impedance transition between antenna feeding line and patch, with the purpose of further improving the impedance matching. Truncated ground plane and tapered microstrip line dimensions have been obtained using ANSYS HFSS. The antenna reflection coefficient is presented in Figure 3. A wide bandwidth from 1.917 to 7.387 GHz (FBW = 117.58%) has been obtained. According to Figure 2, the broadband antenna is printed in the x-y plane; therefore it radiates x-oriented linear polarization. The antenna radiation patterns are going to be analyzed in the two

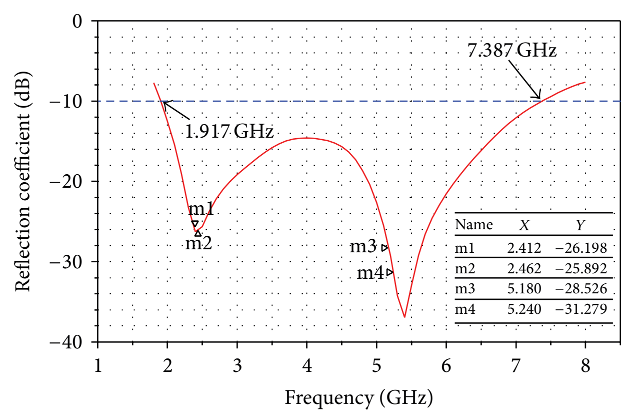


Figure 3: The broadband printed antenna reflection coefficient.

main planes, namely, azimuth (the y-z plane) and elevation (the x-y plane).

3. DMS Bandpass Filter

A bandpass RF filter based on the defected microstrip structure (DMS) technique [15] has been proper developed in order to be incorporated into the 4.8 × 30 mm antenna feeding line. We had decided to apply this technique due to the size limitations. The filter structure has been designed using a uniform slot insertion in a microstrip line with length L and width W. DMS technique is also applicable to amplifier harmonic suppression [16], microstrip antenna size reduction [17], and microstrip line longitudinal size reduction [18]. Figure 4 presents the DMS slot format, which has the following design parameters: upper slot length L_1 and width W_1 and lower slot length L_2 and width W_2.

The T-shape slot insertion in the microstrip line disturbs the current distribution, increasing the effective inductance. Therefore, microstrip line electrical length is also increased

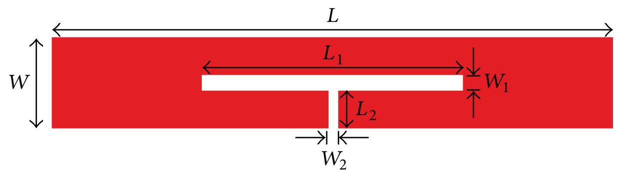


Figure 4: T-shape DMS structure: $L_1 = 14$ mm, $W_1 = 0.8$ mm, $L_2 = 2$ mm, $W_2 = 0.6$ mm, $L = 30$ mm, and $W = 4.8$ mm.

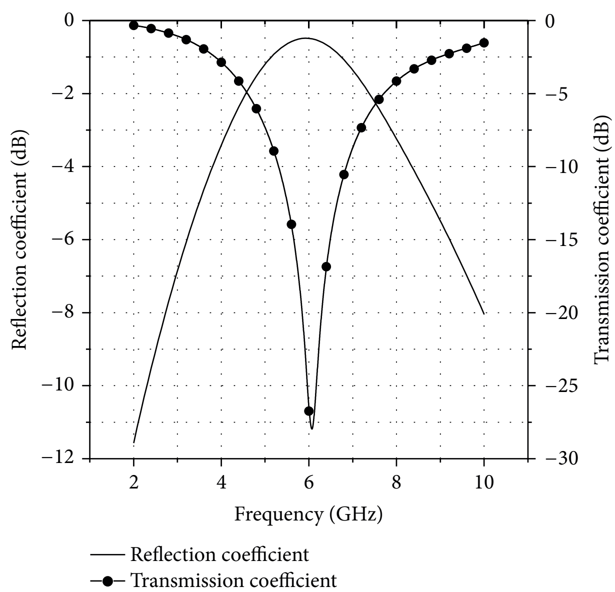


Figure 5: T-shape DMS structure frequency response.

[19], as well as its slow-wave due to DMS structure properties, thus providing band-stop [20] and low-pass [21] filter design. Figure 5 reports the T-shape DMS frequency response, characterized as a band-stop filter. The DMS band-stop behavior can be changed to a bandpass response by adding a series of capacitive structures. For frequencies lower than band-stop resonance, the inductive impedance is combined with series of capacitance to create LC series resonator for ensuring a bandpass filter frequency response [22].

Our main goal is making the DMS filter response manageable for enabling the antenna frequency reconfigurability over the 2.4 and 5.1 GHz ISM bands. The capacitance tunability for making the antenna bandwidth reconfigurable is obtained by using microstrip gap lines and discrete SMD (surface-mount device) capacitors, as described in Figure 6. The discrete capacitors are used to tune the 2.4 GHz band, whereas the microstrip gap lines are applied to enable an antenna operation in the 5.1 GHz band. If the gap lines are short-circuited (Figure 6(a)), the RF filter operates in the bandpass configuration for the 2.4 GHz frequency band. On the other hand, if the gap lines are in operation (Figure 6(b)), the capacitances associated with SMD capacitors reconfigure the operation frequency to the 5.1 GHz band, since the gap capacitance (0.13 pF) is smaller than discrete capacitance (1.8 pF). The DMS T-shape final dimensions are $L_1 = 6.841$ mm, $W_1 = 1.143$ mm, $L_2 = 2$ mm, and $W_2 = 0.428$ mm.

Figure 7 presents the proposed reconfigurable bandpass filter frequency response. The proposed DMS RF filter provides two possible narrowband configurations: operation in the 2.4 or 5.1 GHz ISM bands. The optically controlled filtenna is based on the use of photoconductive switches placed in gap capacitance regions, as shown in Figure 6(c) and explained in the next section.

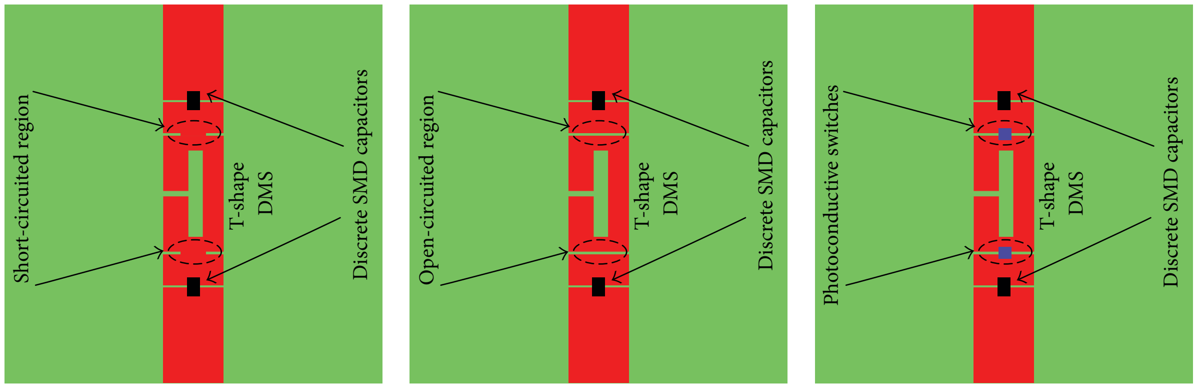
4. The Reconfigurable Filtenna Design

A filtenna is an integration of an antenna with RF filter, usually positioned in the antenna feeding line or ground plane [23]. Filtennas allow reconfiguring the bandwidth without disturbing the radiating element. Our reconfigurable filtenna design relies on the combination of a reconfigurable DMS bandpass filter with a broadband printed antenna, as shown in Figure 8. In the filtenna numerical model, the photoconductive switches have been implemented in the following ways: as a piece of silicon for the “OFF” state and as PEC (perfect electrical conductor) boundary condition for the “ON” state. The proposed filtenna provides two operational modes through the 2.4 and 5.1 GHz ISM bands. Figure 9 presents the numerical simulations of the filtenna reflection coefficient (S_{11}), with the purpose of illustrating its two operational modes: the first bandwidth centered at approximately 2.45 GHz and the second one centered at 5.18 GHz. These simulated results demonstrate that the filtenna bandwidth can be reconfigured through two ISM frequency bands by manipulating the gap line capacitances.

The filtenna radiation pattern has also been numerically analyzed using ANSYS HFSS in order to evaluate the impact of integrating the DMS structure into the antenna feeding line. Figure 10 presents a comparison between the filtenna and original printed antenna patterns in the azimuth (y-z) and elevation (x-y) planes at 2.4 and 5.1 GHz. In all cases, no significant degradation in the radiation pattern is observed, demonstrating that the proposed structure makes the frequency response reconfigurable without disturbing the antenna main electromagnetic properties. The filtenna provides a maximum gain of 3.34 and 3.77 dBi for 2.4 and 5.1 GHz, respectively.

5. Optically Controlled Reconfigurable Filtenna

The optically controlled reconfigurable filtenna is based on the use of two photoconductive switches for manipulating the gap line capacitances. Therefore, using the two silicon photoconductive switches (Figure 11(a)), the filtenna presented in the previous section (Figure 11(b)), and discrete SMD capacitors ensures the bandwidth reconfigurability. The silicon switches are diced from high resistivity silicon wafer ($\rho > 6000\,\Omega \times$ cm) [8], which might imply high insertion loss in the microwave band. For this reason, we have implemented tiny dices of 2×2 mm. Photoconductive switches can change from insulator state to near conductor state if they are properly illuminated [8]. In this way, the silicon conductivity is increased and its dielectric constant is



(a) DMS filter configuration for 2.4 GHz band

(b) DMS filter configuration for 5.1 GHz band

(c) Reconfigurable DMS filter based on photoconductive switches

FIGURE 6: T-shape DMS bandpass filter.

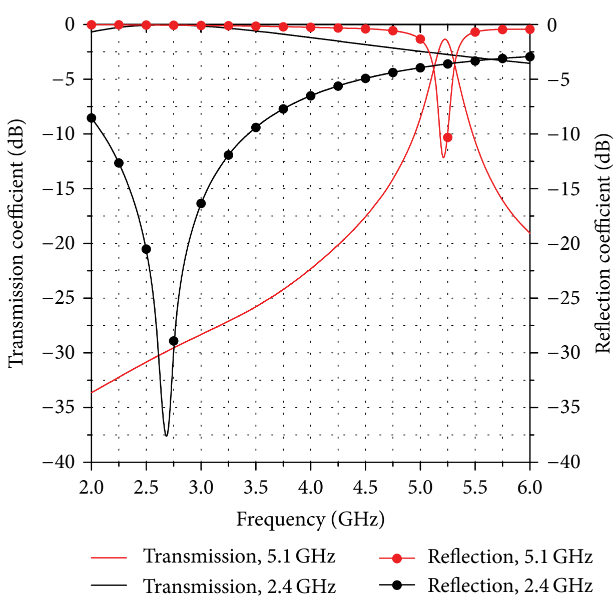


FIGURE 7: T-shape DMS reconfigurable bandpass filter frequency response.

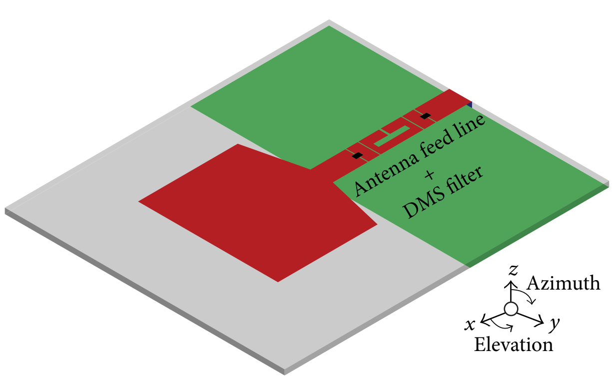


FIGURE 8: The reconfigurable filtenna concept.

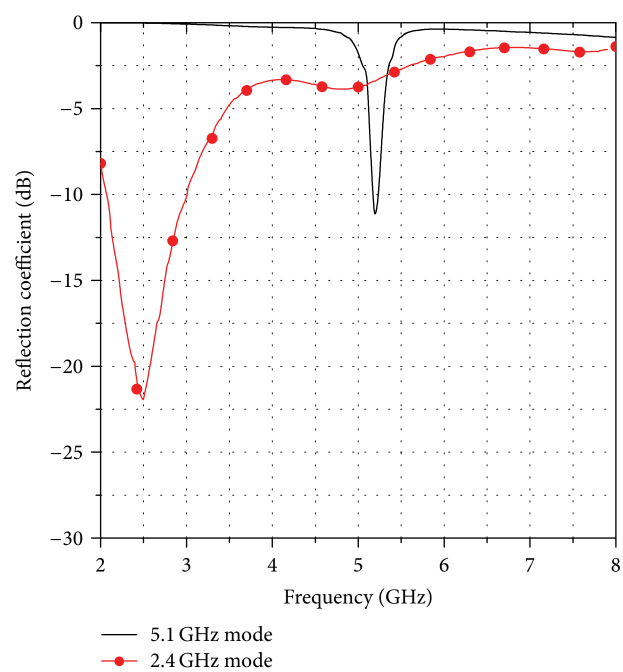


FIGURE 9: Numerical results of the reconfigurable filtenna reflection coefficient.

reduced [24]. The incident photons must have enough energy to allow electrons movement from valence to conduction band in order to create new electron-hole pairs. Near-infrared light region is adequate for this process, providing a balance between absorption coefficient and light penetration depth [25]. We have excited our photoconductive switches using 808 nm CW laser at an average power of 500 mW [26].

The proposed filtenna frequency response has been experimentally evaluated as function of laser optical power. Nevertheless, in the first trial, we could not obtain a reasonable impedance matching ($S_{11} < -10$ dB) in the two required frequency bands due to the resultant impedance imaginary

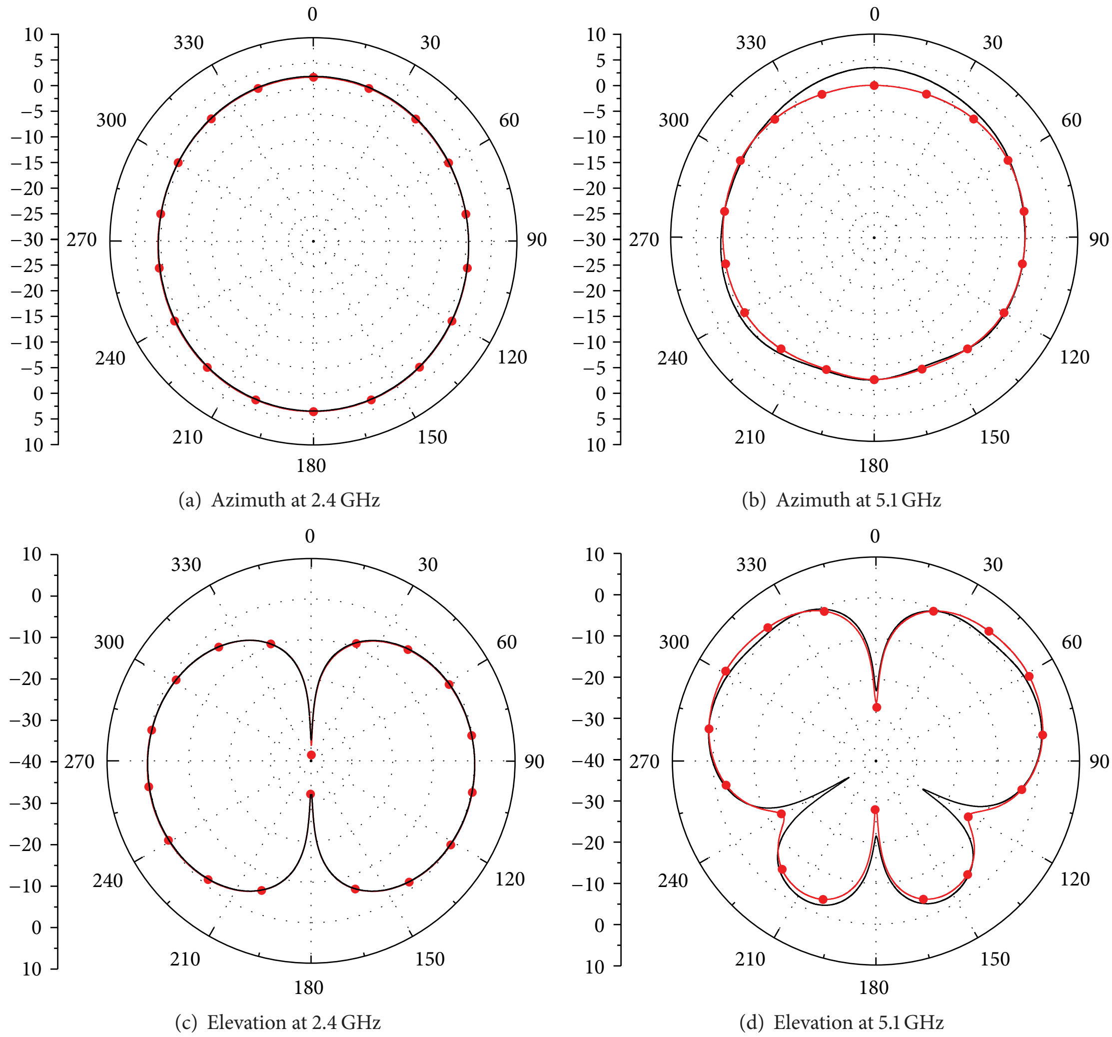
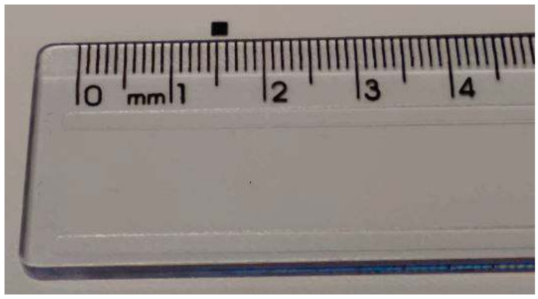


Figure 10: Radiation pattern comparisons: original printed antenna (red curve with circles) and filtenna (black continuous curve).

part, which depends on the silicon switches capacitance and that of the SMD capacitors. This impedance alteration implied a detuning of our DMS RF filter at 2.4 and 5.1 GHz ISM bands. For this reason, we have redesigned our DMS filter in order to compensate this problem by means of reducing the T-shape upper slot length L_1 from 6.841 to 3.35 mm and increasing the SMD capacitors from 1.8 to 2.2 pF, as reported in Figure 11(c).

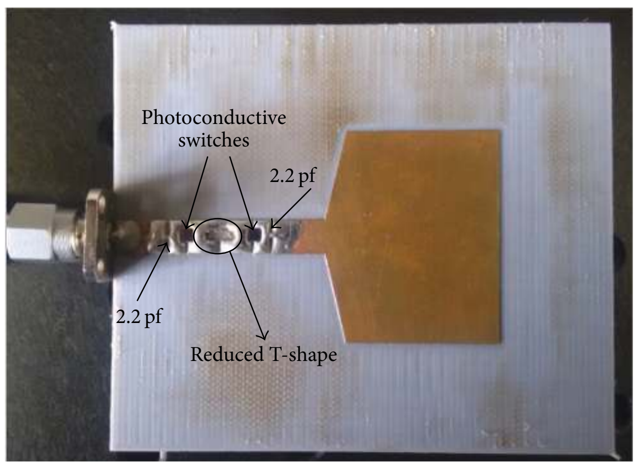
The optically controlled filtenna is based on two different states of the photoconductive switches: "OFF" state when they are not illuminated and "ON" state when both switches are illuminated by the 808 nm laser, as reported in Figure 12, which shows the two pieces optical fibers used to launch light into them. Real incident light can be observed into the two photoconductive switches. A unique laser and a power splitter have been used to simultaneously control the incident light into both silicon dices. Figure 13 reports measurements of the filtenna frequency response for the "OFF" and "ON" states. A measured bandwidth from 4.18 to 5.56 GHz has been obtained when the laser has been turned off. On the other hand, as soon as laser power has been set to 500 mW, two operational bandwidths have been observed: the first bandwidth from 1.8 to 3.1 GHz and the second one from 4.3 to 5.8 GHz. Therefore, contrarily to the filtenna designed in Section 4 that provides a unique bandwidth in one of the ISM bands, the optically controlled reconfigurable filtenna enables the two following modes: single-band operation in the 5.1 GHz ("OFF" state) or dual-band operation in both ISM bands ("ON" state). This difference might be attributed to the silicon nonlinear effects, which can significantly change the switch complex permittivity. These measured results prove the successful development of the first optically controlled reconfigurable filtenna reported in literature, which is potential for cognitive radio applications and broadband communications.

The proposed optically controlled reconfigurable filtenna is very promising to be applied to the ACRoF architecture [4] in order to enable dual-band spectrum sensing over two ISM bands and data transmission using one or two bands, depending on the traffic demand. The ACRoF system can take advantage of lower spectral density of the 5.1 GHz band by using the filtenna single-band mode. Additionally, in case of



(a) Example of 2 × 2 mm photoconductive switch

(b) The first filtenna prototype



(c) Optically controlled filtenna

Figure 11: Optically controlled reconfigurable filtenna prototype.

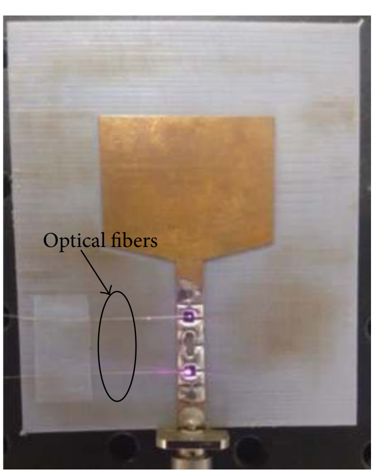


Figure 12: Optically controlled reconfigurable filtenna operating in the 2.4 GHz band (photoconductive switches on "ON-state"): real incident light can be observed into the two photoconductive switches.

increase in the number of users and/or traffic demand, the filtenna can switch to dual-band operation mode to allow communications using both bands.

The filtenna radiation patterns in the azimuth (y-z) and elevation (x-y) planes have been measured in a semianechoic chamber. Figure 14 displays comparisons of the simulated and measured patterns at 2.4 and 5.1 GHz. There is an excellent agreement between simulation and experimental results in the azimuth plane for both frequencies. A good accordance is also observed for the elevation plane at 2.4 GHz (Figure 14(c)). The small discrepancies noted for the elevation plane at 5.1 GHz, presented in Figure 14(d), might be due to imprecision in the fabrication process.

6. Conclusions

The concept of an optically controlled reconfigurable filtenna has been successfully demonstrated and validated by numerical simulations and experiments. The proposed filtenna

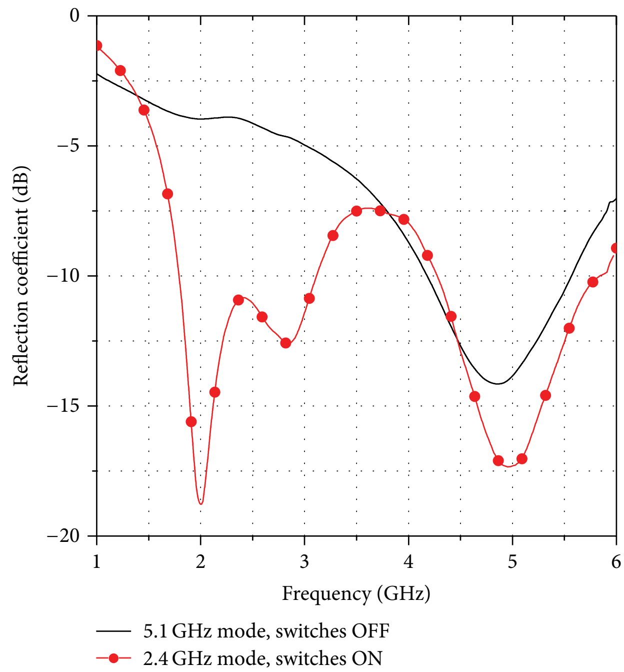
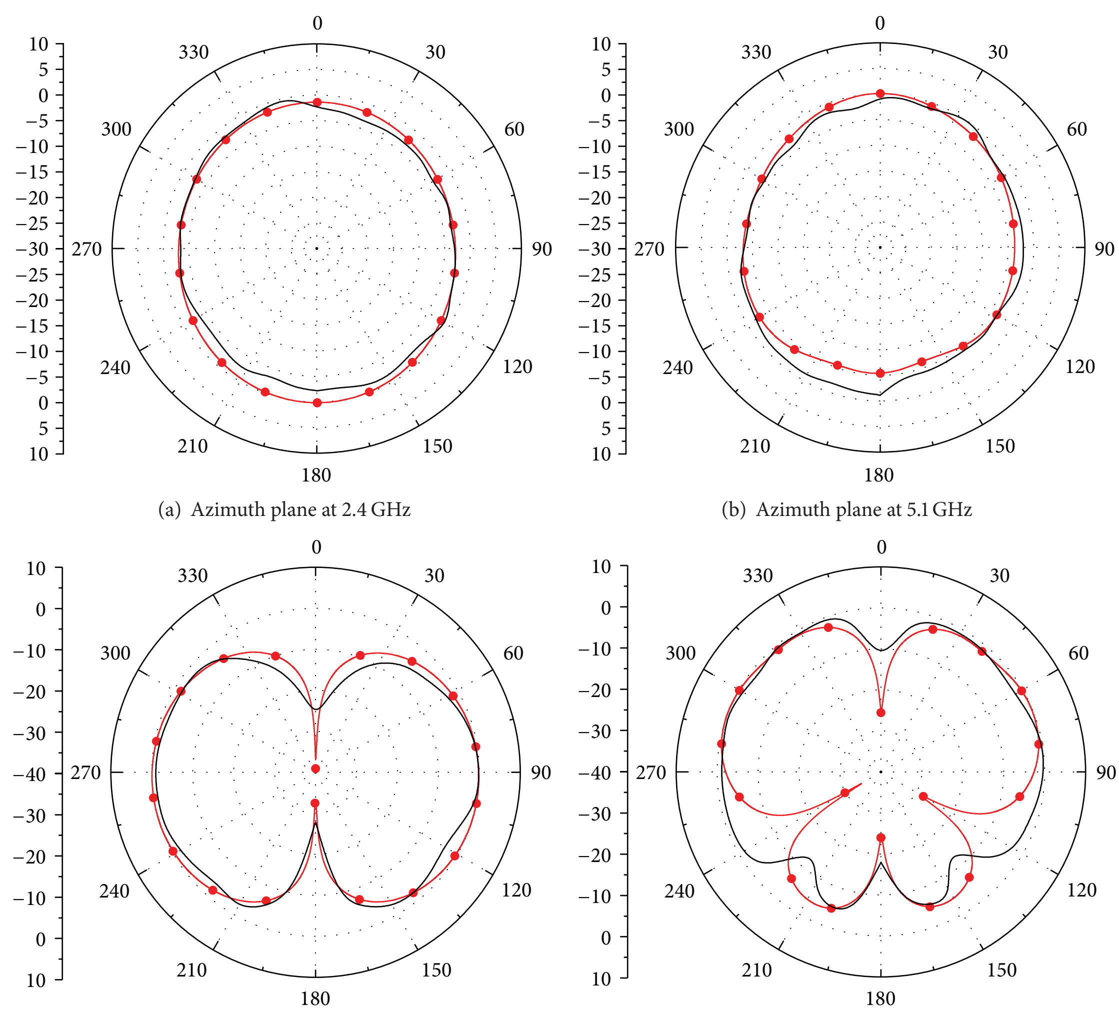


Figure 13: Two operational modes of the optically controlled reconfigurable filtenna.



(a) Azimuth plane at 2.4 GHz

(b) Azimuth plane at 5.1 GHz

(c) Elevation plane at 2.4 GHz

(d) Elevation plane at 5.1 GHz

Figure 14: Optically controlled reconfigurable filtenna radiation pattern: simulation (red curves with circles) and measurements (black continuous curves).

consists of an integration of a broadband printed antenna and DMS bandpass filter. It provides reconfigurable frequency response based on two different operational modes, namely, single-band operation in the 5.1 GHz ("OFF" state) or dual-band operation in both ISM bands ("ON" state). The reconfigurable filtenna principle has been validated from 1.0 to 6.0 GHz in order to illustrate the bandwidth reconfigurability over the 2.4 and 5.1 GHz ISM bands, without changing any antenna dimensions. Moreover, comparisons of the filtenna radiation pattern and that of the original printed antenna in the azimuth and elevation planes have not shown any significant degradation, demonstrating the proposed structure frequency reconfigurability without disturbing the antenna main electromagnetic properties. Simulated and measured results of the filtenna radiation patterns at 2.4 and 5.1 GHz have been shown to be in excellent agreement. The proposed filtenna can be considered potential for broadband communications networks and cognitive radio applications. For instance, it can be applied to the ACRoF architecture [4] for making the implementation of new functionalities possible, such as multiband radiofrequency spectrum sensing and dynamic resource allocation over different bandwidths. Future work regards a detailed electromagnetic characterization of the silicon photoconductive switches as a function of the incident optical power.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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