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A Novel Reconfigurable Spiral-Shaped Monopole Antenna for Biomedical Applications

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Abstract—In this paper, a new reconfigurable antenna is introduced. This antenna is a printed spiral-shaped monopole antenna with a compact structure. By embedding microwave switches in the structure of the antenna, different resonance frequencies can be achieved in different states of the switches. The introduced antenna is capable to cover two standard frequency bands for biomedical applications, i.e., Medical Implant Communication Service (MICS) and Industrial, Scientific and Medicine (ISM) bands. MICS band covers 402 MHz to 406 MHz and ISM covers 2.4 GHz to 2.5 GHz frequency range. The proposed antenna has a compact size of 32 mm $\times$ 50.3 mm $\times$ 1.8 mm, and it is fabricated on an FR4 substrate. The measurement results are in a good agreement with the simulations.

1. INTRODUCTION

Reconfigurable antennas are widely employed in multi-standard communication systems such as military and biomedical applications. Dynamically, modifications of antenna radiation characteristics, such as resonance frequency, bandwidth, radiation pattern, and polarization, are the major advantages of reconfigurable antennas over traditionally fixed operating antennas [1, 2]. Design methodology of these antennas encounters some challenges. For developing an antenna with a specific radiation pattern, the current distribution on the antenna surface can be useful [3–5]. However, changing in the current distribution can change the operating frequency of the antenna which can be counted as a drawback for these kinds of antennas. Although it is possible to alter spatial distribution of the radiation pattern while the operating frequency is fixed, it is a difficult task to accomplish [6–8]. Many commonly used antennas, such as linear antennas, loop antennas, slot antennas, and microstrip antennas, usually operate in their resonance frequencies. The effective electrical length of these antennas has great influence on the operating frequency and bandwidth of these antennas. Therefore, it is possible to achieve different frequency bands by changing the electrical length of these antennas. This reconfigurability is usually classified in continuous and switched methods [9, 10]. Both of these techniques use a common theory, changing in the effective electrical length of the antenna. However, the obtained results from these two methods are different. Continuous frequency tunable antennas obtain smooth transitions within or between operating bands without jumps. Switched tunable antennas use some switching mechanisms such as optical switches, PIN diodes, GaAs FETs, and RF MEMS (Radio Frequency Micro Electro Mechanical Systems) switches to operate at separated frequency bands [11]. The effective length of the antenna, hence its operating frequency, can be changed by shortening or lengthening the antenna through electronic, optical, or mechanical switches [11, 12]. One of the important usages of these antennas can be in the biomedical applications. Since each part of the body has an optimum frequency, for on-body wireless communication it is necessary to have different operating frequencies which enable the antenna to operate on various parts of the body [13]. In the wireless systems, an antenna is required for transmit or pick up a signal into or from the body. The most critical part of the biotelemetry systems

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is the structure of the antenna which is implanted in or attached to the body [14–18]. By means of the reconfigurable antennas, a single antenna can be used for different biomedical applications [19]. The compact size and ability to operate at the standard frequency bands of biomedical applications are the major advantages of these antennas. In [20], the proposed antenna can be employed in the MICS band which can be attached to human skin easily. In this paper, a novel monopole spiral shaped antenna is proposed which operates in many resonance frequencies such as MICS and ISM. By using three switches, the reconfigurable characteristic is achieved. The switch placement on the antenna structure is investigated.

2. THE STRUCTURE OF THE ANTENNA

Figure 1 shows the detailed structure of the antenna. For achieving compact size and broadband frequency response, a spiral-shaped monopole antenna is selected. The electrical length of this antenna mainly depends on its physical length. Therefore, by changing the electrical length, the resonance frequency of the antenna can be changed. Using this characteristic and by means of microwave switches, a reconfigurable antenna can be achieved. Defected ground plane of this antenna introduces broadband response. A rectangle with dimensions of $w_1 \times l_2$ is cut from this ground for the purpose of impedance matching (Fig. 1(a)). As a result, the achieved reconfigurable antenna can operate in wide ranges of frequencies by using switches in its structure. The locations of these switches have great impact on the frequency bands.

The antenna design parameters including the number of spiral turns, line width, and line space are optimized through commercial software. This antenna is investigated in two states: in free space and when it is attached to a multilayer box which emulates human tissue in order to show that the proposed antenna operates on two biomedical bands i.e., MICS and ISM bands. The introduced antenna is simulated with two substrates: Macor and FR4. The simulations are done using Ansoft HFSS software. The Macor substrate shows better results in terms of frequency bandwidth. The experimental results of this antenna are presented using an FR4 substrate and are in good agreement with the simulations. The line space and line width of the spiral section are represented by t and s, respectively (Fig. 1(a)).

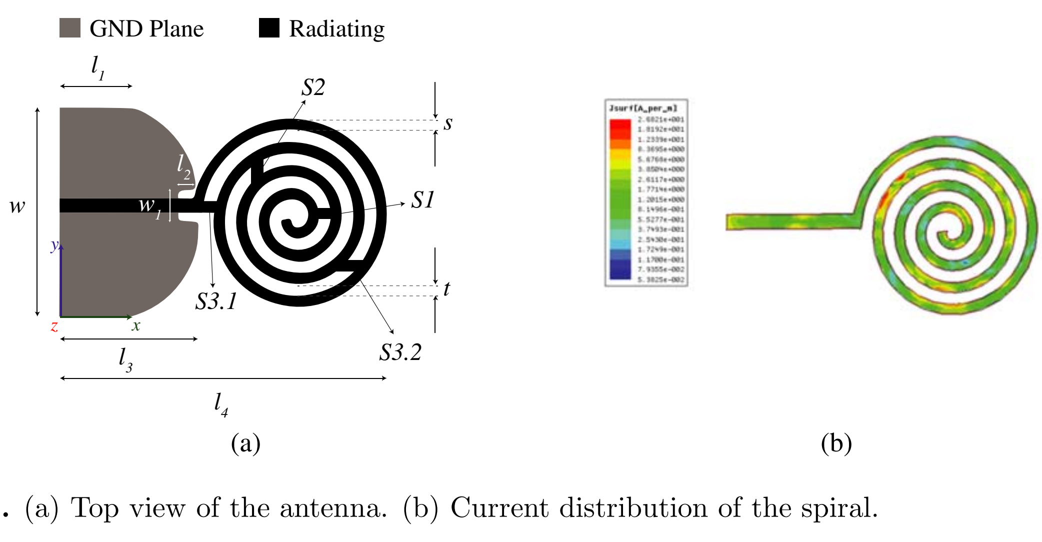


Figure 1. (a) Top view of the antenna. (b) Current distribution of the spiral.

Table 1. Parameter values of the antenna. All the parameters are in millimeters.

s	t	w	w_1	l_1	l_2	l_3	l_4
1.95	1.62	32	4.62	11	3.03	21.9	50.33

The parameter values of the antenna are given in Table 1.

Current distribution on the antenna at 2.4 GHz is illustrated in Fig. 1(b). As pointed earlier, the switch positions are selected according to the current distributions. According to the desired frequency bands, different places for each switch are tested, and the best places for them are selected. The current distribution on the surface of the antenna determines the radiation characteristics of the antenna. Switches are located where the current distribution decreases in order to have the most influence on the performance of the antenna. By placing the switches at different places, current distribution changes, and it results in a new electrical length and new resonance frequency band. The positions of the switches are given in Table 2. As shown in Fig. 1(a), two places for switch 3 are considered, and according to these places, two different antennas are introduced. '$S3.1$' and '$S3.2$' denote two different locations of switch 3 in antenna 1 and antenna 2, respectively. Gain of the antenna at 2.4 GHz is shown in Fig. 2.

Figure 3 shows the fabricated prototypes. Here, ideal switches are used instead of microwave switches. '0' represents the OFF state and '1' the ON state for each switch.

Table 2. The center coordinates of the switches with respect to the origin.

Swithches	(x (mm), y (mm))
$S1$	(42.5, 15)
$S2$	(31, 21)
$S3.1$	(25, 15.5)
$S3.2$	(47, 7)

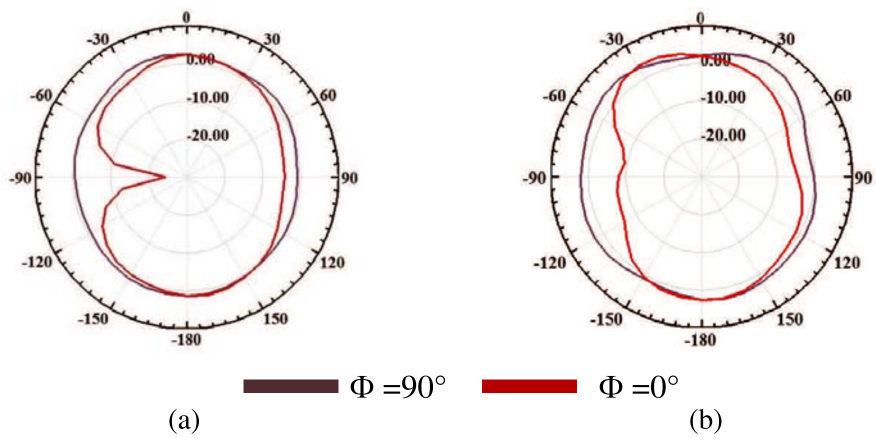


Figure 2. Radiation pattern for proposed antenna on (a) FR4 substrate, (b) Macor substrate.

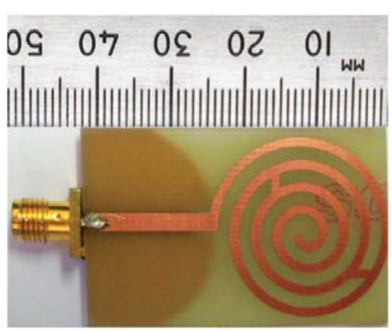
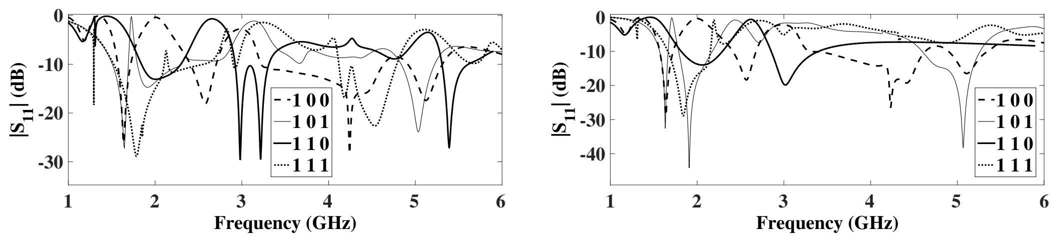


Figure 3. Top view of the fabricated antenna.

3. RESULTS

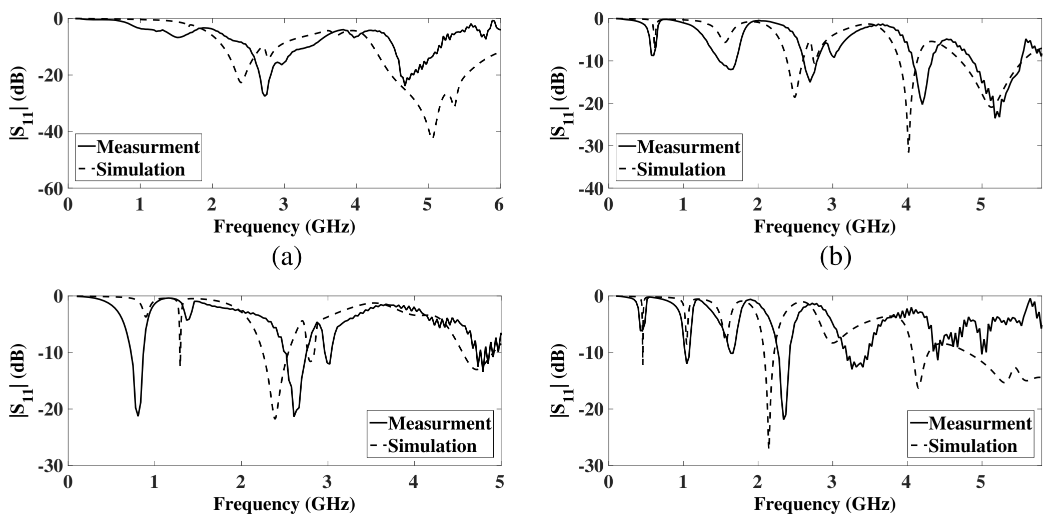
The diagrams of $|S_{11}|$ versus frequency for different states of the switches for Macor substrate are shown in Fig. 4. The different states of the switches create different electrical lengths. As a result, different resonance frequencies are obtained for both antennas, which is the purpose of the reconfigurable antennas. Fig. 4 represents that in 1–6 GHz frequency range, many resonances with different bandwidths can be achieved for different states of the three switches.

To validate the performance of the proposed antennas, the experimental results are presented. The experimental results of the proposed antenna fabricated on an FR4 substrate is shown in Fig. 5. The measurement results match the simulated results.



(a) (b)

Figure 4. Simulation results of S_{11} vs. frequency. Four different states of (a) antenna 1 and (b) antenna 2.



(a) (b)

(c) (d)

Figure 5. Comparison between the measurement and the simulation results of (a) antenna 1, state '111', (b) antenna 1, state '100', (c) antenna 1, state '010', (d) antenna 2, state '011'.

Table 3. Parameters of the multilayer tissues.

Layer	Thickness (mm)	Conductance (S/m)	Relative Permittivity
Skin	4	0.69	46.7
Fat	4	0.08	11.6
Muscle	75	0.84	58.8

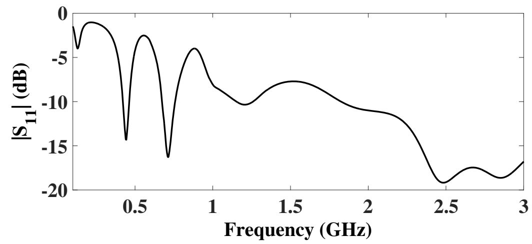


Figure 6. $|S_{11}|$ of the antenna attached on human tissue.

In the simulation, the human body is modelled by a box with three layers: muscle, fat and skin. The thickness of these layers, relative permittivities, and conductances are shown in Table 3. Here, the state '100' of the antenna is used for simulation. The cross section of this model is 150 mm × 150 mm. The antenna is attached to the skin, and the simulated $|S_{11}|$ is shown in Fig. 6. This figure illustrates that there are two resonances at the two standard bands, MICS and ISM.

4. CONCLUSION

In this paper, a new reconfigurable spiral antenna with three switches is introduced. The new antenna can be used in biomedical applications. By means of switches, the antenna can operate in different frequency bands such as MICS and ISM. The simulated and measurement results are presented and compared. The practical results ensure wideband response of the proposed antenna.

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