

Design of Wideband Monopole Antenna Loaded with Small Spiral for Using in Wireless Capsule Endoscopy Systems

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Abstract—In this paper, a new antenna is designed in order to use in the wireless capsule endoscopy (WCE) system. This antenna consists of two parts; the small monopole part and the small spiral. Having the omnidirectional radiation pattern for covering the stochastic motions of the capsule into gastrointestinal and also, appropriate gain and wide bandwidth to achieve high resolution images must be considered in designing procedure. In this design, a good radiation pattern is obtained from small monopole, and using the spiral structure leads to an appropriate wide bandwidth and a miniaturized antenna. By simulating this antenna in the human body environment and considering four different body tissues and their results, the antenna has the bandwidth of 360 MHz (39.3% relative bandwidth) at 928 MHz center frequency which covers the ISM band (868.0–868.6 MHz and 902.8 to 928.0 MHz). The radiation pattern of the antenna is omnidirectional. The maximum gain of the designed antenna is -23 dB, over the frequency band that is suitable for using as a transmitter antenna in the WCEs.

1. INTRODUCTION

Endoscopy capsule or video pill is a camera with the same shape and size of an oral capsule, and it can be a valuable diagnostic tool in the hands of gastric diseases professionals with providing a unique endoscopic technique [1, 2]. In this method, the painless endoscopic imaging of the small bowel surgery can be done with the help of a small wireless swallow video camera; therefore, the doctors will be able to see the parts of the intestine that cannot be seen with other tools such as Computed Tomography scan [3].

In the WCE system, the task of the antenna is sending the images taken by the camera to the receiver located in the outside of the body [4]. However, due to the wave propagation in the body environment that has high permittivity and losses coefficients, the designing procedure of a sufficient antenna for WCE faces some challenges. The capsule enters in the digestive system after being swallowed by the patient and then, is driven forward with the help of the expansions and contractions of the digestive system. Therefore, all of the movements and orientations of the capsule are stochastic along its path [5]. Consequently, having an appropriate radiation pattern is one of the major challenges in the procedure of designing capsule antennas. The radiation pattern should be such that the process of sending out signals is not disturbed, and the communication links between the capsule and the external receiver have been continuous during the stochastic movements of the capsule. Therefore, a proper radiation pattern for the designed antenna is omnidirectional in order to cover all random motions of the capsule [6]. Hence, all of the designed antennas for this application have omnidirectional radiation pattern or close to it. The patch antenna placed on the wall of the capsule has omnidirectional radiation pattern. However, the bandwidth of this antenna is about 2% which is not wide enough for WCE system [7]. Also, the pattern of dual spiral antenna is omnidirectional, but the amount of $S_{11} < -14$ dB is in the frequency band 350–450 MHz [8] which is too low for capsule antennas. The spherical helix

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and spherical spiral antennas [10] have appropriate radiation pattern, but the gains of these antennas are about -32 dB, which is lower than permitted gain for capsule antenna (-28 dB [9]).

Having wide bandwidth is one of the other challenges of the capsule endoscopy antennas. The bandwidth must be high enough to improve the image resolution [9]. The other proposed antennas have satisfied this important requirement slightly. For example, the trapezoidal conformal antenna is ultra-wideband, but its frequency range is not within the standard frequency band (3 to 4.8 GHz) of the in body antennas [10].

The minimization of the antennas dimensions is the last challenge in the design procedure, because it is easy to swallow a small capsule. Therefore, the capsule should be designed in the smallest possible size [11]. For example, a spiral antenna has good characteristics such as omnidirectional radiation pattern and wide bandwidth, approximately 35% of the center frequency of 433 MHz, but it occupies a lot of space inside the capsule [12].

In this paper, a monopole antenna loaded with small spiral is designed to satisfy the requirements of the video pills in the best way. The antenna's structure consists of two parts; the monopole part and spiral part. The monopole part of the designed antenna creates omnidirectional radiation pattern which is very suitable for use in capsule endoscopy. According to this feature, the stochastic motions of the capsule are covered as much as possible. On the other hands, with placing a small spiral part to this monopole antenna, the small size is achieved, which is suitable for capsule endoscopy system. Also, using this structure leads to a bandwidth of 370 MHz at 927 MHz center frequency (39% relative bandwidth) and then has a better quality of the images. Consequently, due to the small size of the proposed antenna, it is considered as embedded antennas types. Therefore, this antenna can be used in a capsule endoscopy system as a transmitter antenna because of its desirable radiation characteristics. All simulations have been done with HFSS EM full wave simulator software. Also, in order to show the validity of the achieved results, the simulations have been confirmed with the CST EM full wave simulator.

2. REVIEW OF THE SIMPLE MONOPOLE ANTENNA RADIATION IN AIR AND BODY

The proposed monopole antenna has omnidirectional radiation pattern due to its geometric form. Therefore, according to the need of such a model, the monopole antenna is used for the capsule antenna's basic designing. A $\lambda/4$ monopole antenna fed with 50 ohm coaxial cable, which radiates in free space, has omnidirectional radiation pattern. In order to use this antenna in capsule endoscope it is necessary to study it in the human body. As mentioned earlier, the capsule moves inside the human body. Therefore, the antenna sends signals out through the body tissues. The tissues of the human body have a high dielectric and losses coefficient. Hence, as the signals pass through the tissues, the path losses rise, and the antenna's performance will be reduced compared to when it radiates at free space.

Therefore, the simulation should be done in the human body [13]. Since the characteristics of the tissues change with frequency variations, according to the antenna frequency range, the single-layer tissue model is chosen ($\epsilon_r = 56$, ϵ_r is the dielectric of the body tissues, Conductivity = 0.8 s/m [16]) for modeling the body. Because the dielectric of the human body tissues is very high, it is known that the wavelength decreases in the body environment, thus the dimensions will be decrease.

$$\lambda_{in\ body} = \frac{\lambda_{in\ air}}{\sqrt{\epsilon_r}} \quad (1)$$

Therefore, the $\lambda/4$ monopole should have a length of 32 mm to radiate at a frequency of 1 GHz in the body environment. Figure 1(a) shows the antenna simulation and return loss of this antenna in the body environment, and Figure 1(b) represents the radiation pattern.

To simulate the antenna, it is placed in the center of a sphere which contains materials with similar body tissues properties. As expected, the monopole antenna's radiation pattern is omnidirectional in the body environment, and the maximum gain value is -23 dB. According to the simulation results, the antenna is not well matched with this structure. Moreover, its size is not suitable for using in the wireless capsule endoscopy systems. How to reduce the size and increase the bandwidth of this antenna is described in the next section.

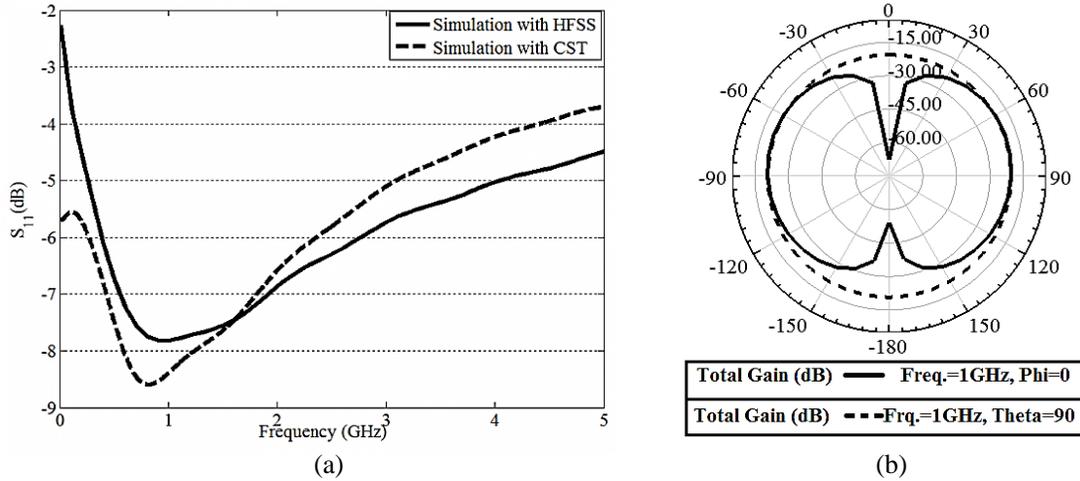


Figure 1. (a) $\lambda/4$ Monopole antenna S_{11} in body environment and (b) its radiation pattern in body environment.

3. MINIATURIZATION AND IMPROVEMENT THE BANDWIDTH OF THE ANTENNA

The size of the $\lambda/4$ monopole antenna is large for radiation at frequency 1 GHz in the WCE application. Also, the S_{11} characteristic obtained from the antenna does not have an acceptable value in the considered band. In this section, the effect of adding the spiral part to the antenna is studied. Due to the figure of the spiral part, it is simple to adjust it at the desired frequency by adjusting the length of the flow path. In this paper, the following antenna is designed by combining the spiral part with the monopole antenna. Therefore, the appropriate characteristics of each part will be used. As mentioned before, since the size of the antenna is limited in the capsule, the chosen length for the monopole part should be as small as possible. Hence, the length of the monopole part is chosen 0.0016λ in order to resonate in lower frequencies. Then, a spiral part with 0.15 mm space between turns and a variable number of the turns will be added on the top of shorted monopole. In this situation, the antenna can be modeled as parallel RLC circuit in which R , L and C are the equivalent resistance, inductance and capacitance of the antenna structure, respectively. When only the monopole antenna is considered without adding the spiral part, the total L and C impedances tend to be zero at the resonant frequency, and the value of its resistance is very large. For a good impedance matching by adding the spiral part to the monopole antenna with 0.0016λ length, the imaginary part of the impedance of the antenna is adjusted to close to zero at resonant frequency. The real and imaginary parts of the impedance of the antenna are shown in Figures 2(a) and (b). In the first case, the spiral part (with different number of turns) is used in the structure of the monopole antenna. However, it is supposed that the spiral part is not used in the second case.

As seen in Figure 2, the imaginary part of the impedance of the antenna in the absence of the spiral part is about 50 ohms. The value of imaginary part tends to be zero by adding the spiral part to this structure. It means that according to the variation of the value of the impedance imaginary part from 50 to 5 ohms, the spiral part shows inductive property, and the antenna impedance tends to the line impedance (i.e., 50 ohms).

By increasing the number of turns of the spiral part, the inductance increases and the resonant frequency will be decreased.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

The simulations are done with different numbers of turns in order to achieve a good value for the number of turns to have a broadband at a center frequency of 1 GHz. Figure 2 shows the variations of the number of turns in spiral part. In addition to an appropriate bandwidth, the antenna gain should be

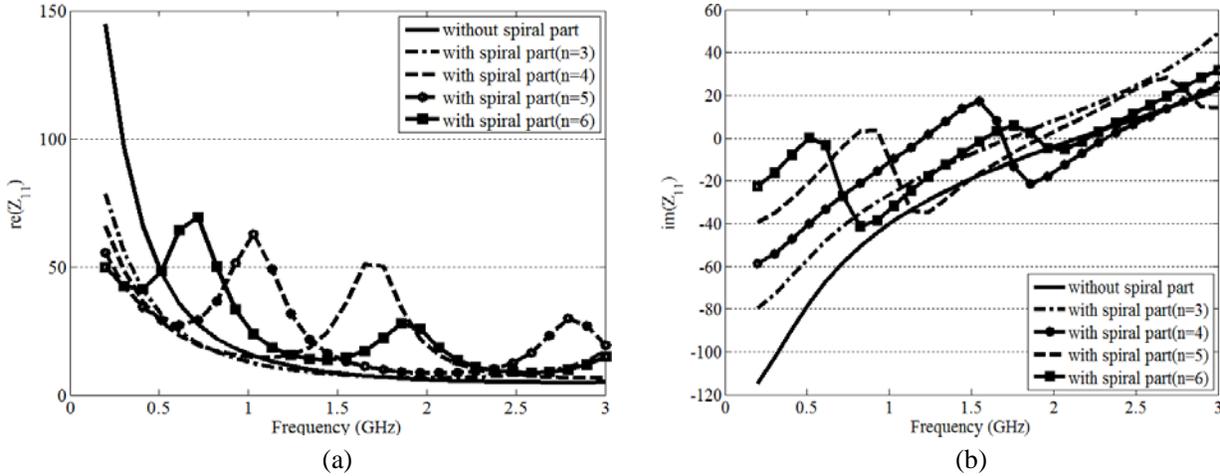


Figure 2. The impedance of the antenna in two cases including the existence of the spiral part (with a different number of turns) and the antenna without using the spiral part in terms of frequency. (a) The imaginary part of the impedance. (b) The real part of the impedance.

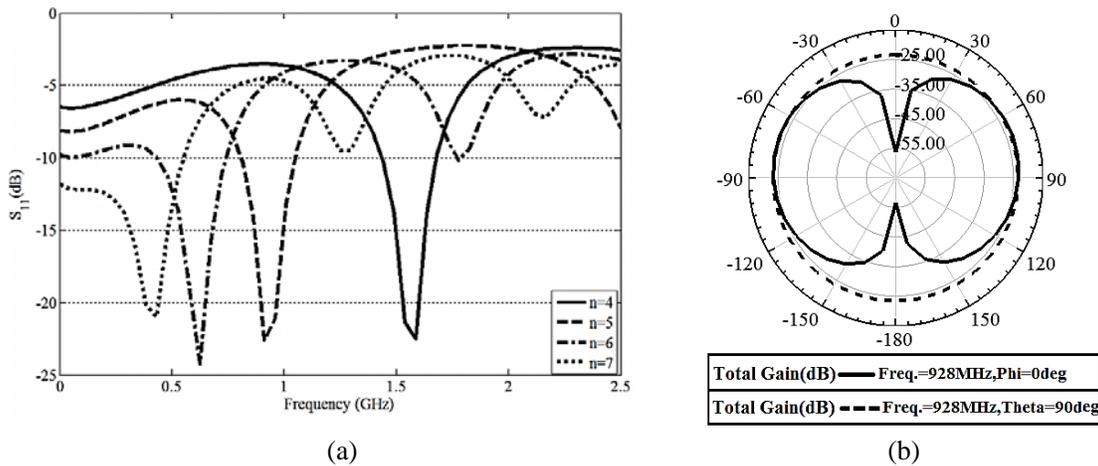


Figure 3. (a) Antenna return loss for a number of different turns. (b) Antenna radiation pattern for $n = 5$ at 928 MHz.

noted also in a frequency band. According to Figure 3(a), when the number of turns is 7, the antenna has the best bandwidth; however in this case, the antenna gain is about -38 dB which is much less than capsule antennas admissible gain. The same issue is true for the number of turns 6. In the case of 5 turns, the antenna resonates at frequency of 1 GHz and also has a bandwidth of 360 MHz (36% relative bandwidth). According to Figure 3(b), the antenna gain is -23 dB (medium frequency band), which is 5 dB greater than the extent permitted. Thus, a very small spiral part, with 5 turns with the distance of 0.15 mm between rounds is placed on top of the short monopole antenna. By placing this part, the current path changes its direction and then enters the spiral part.

Since the capsule endoscopy is a swallowed capsule, it is important to choose a good material for the capsule's cover such that it does not cause any inflammation in the patient's body. Therefore, the material of the capsule's body is considered from a biocompatible material such as polyethylene with dielectric coefficient 3.15 [15]. The antenna design is done in a capsule coated with polyethylene material with thickness of 0.5 mm. Figure 4 represents the placement of the antenna inside the capsule.

After placing the antenna in the capsule, it is placed inside the chamber that contains materials with similar characteristics of the human body. The chamber is considered as a sphere with diameter of

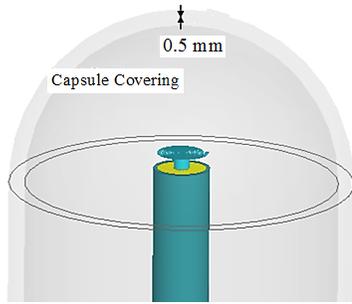


Figure 4. Spiral antenna geometry and placement of the capsule.

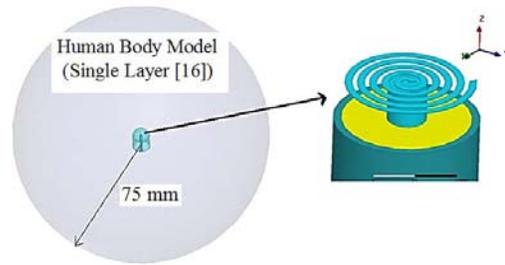


Figure 5. The desired antenna and its position in the body.

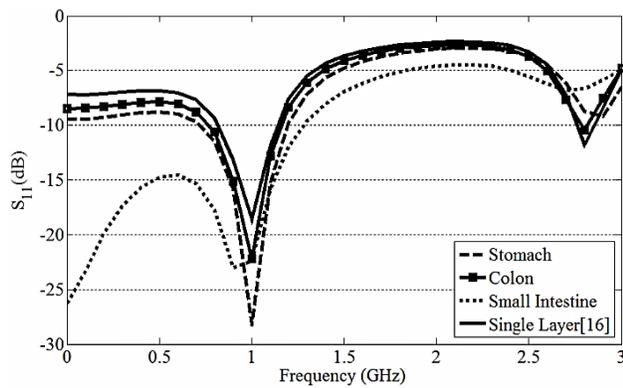


Figure 6. Antennas return loss in several body tissues.

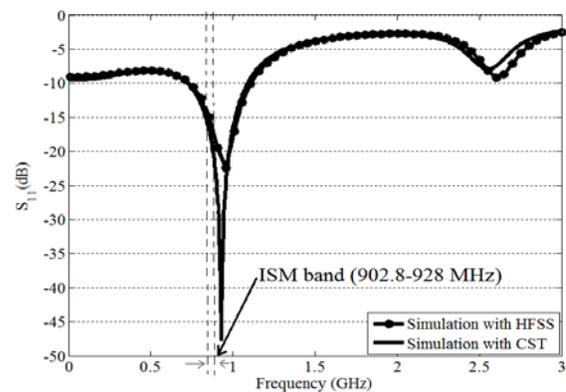


Figure 7. Proposed antennas return loss in HFSS and CST software.

Table 1. Characteristics of the various tissues at 0.928 GHz frequency [14].

	Relative permittivity (at 928 MHz)	Conductivity [S/m] (at 928 MHz)
Stomach	64.8	1.23
Small Intestine	58.8	2.2
Colon	57.5	1.12
Single Layer [16]	56	0.8

150 mm, and its electrical characteristic is similar to the single-layered tissue mentioned in [16]. Figure 5 denotes the antenna design and placement of the single-layer tissue model.

The digestive system has a number of different tissues with different specifications. These tissues include the stomach, small intestine, colon, etc. These tissues have different characteristics at different frequencies. The single layer model of the body tissues specifications that are roughly equivalent to the human body are given in [16]. The results of the antenna simulations in several body tissues models and also in the air are compared in Figure 6. As can be seen, there are only small differences in the results of the different tissue models. Table 1 shows the characteristics of different tissues in 0.928 GHz frequency. The resonant frequency in free space is 7 GHz.

The antenna is simulated in the single layer of tissue in [16]. In order to confirm the final results, the final antenna is simulated by two softwares. Figure 7 shows the return loss of the proposed antenna

with these two softwares. As can be seen, the results of both the softwares HFSS and CST confirm each other.

According to Figure 7, it can be seen that the antenna bandwidth is 360 MHz at the resonant frequency of 928 MHz, thus, the relative bandwidth is approximately 39%.

This bandwidth covers one of the standard medical equipment bands, i.e., ISM, (902.8–928 MHz and 868.0 to 868.6 MHz).

These bands belong to the low frequency bands presented by the FCC for medical devices [17]. This bandwidth is large enough for transmitter WCE antenna and guarantees receiving high quality images in the receiver.

A monopole antenna has an omnidirectional radiation pattern. This radiation pattern is appropriate for using in the wireless capsule endoscopy system. This radiation pattern is required in order to cover all random motions of the antenna in the gastrointestinal tract. Therefore, the most important feature of the monopole part used in the proposed antenna is its omnidirectional radiation pattern. To illustrate the role of the monopole and spiral parts in the proposed antenna, the fields of the radiation of each part must be considered. Three radiation patterns can be seen in the Figure 8. Each of these patterns is plotted at 928 MHz frequency. According to this fact that changing the frequency will lead to changing in behavior of the antennas radiation characteristics, the considered radiation pattern has been plotted within the limited permitted ISM band and resonant frequency, since the behavior of the antenna is

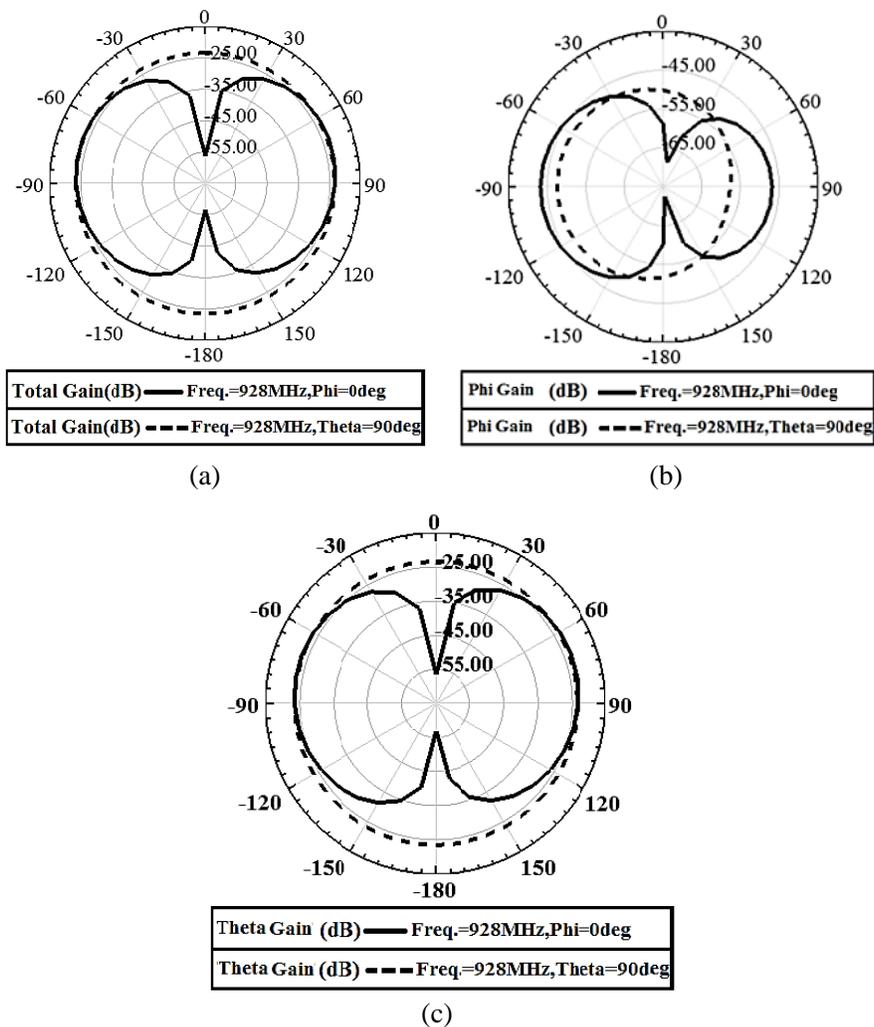


Figure 8. Antenna radiation pattern, (a) total gain, (b) Phi gain, and (c) Theta gain.

Table 2. The radiation characteristics of the proposed antenna and some other WCE antennas.

	The proposed antenna	Single arm spiral antenna [12]	Fat arm spiral antenna [18]	Conical helix antenna [6]	Compact patch antenna [14]
Bandwidth	360 MHz (39.2%)	110 MHz (24.1%)	75 MHz (15%)	101 MHz (22%)	> 50 MHz
Frequency band	ISM, (902.8–928 MHz and 868.0 to 868.6 MHz)	400–510 MHz	460–535 MHz	418–519 MHz	ISM (Resonance freq = 2.4 GHz)
Size	Spiral with 0.15 mm gap and 5 turns and 0.5 mm monopole length	Diameter = 10.5 mm, width conductor = 0.5 mm	spiral arm = 3 mm wide and separated from the ground plane with 1 mm of air gap	Radius sphere = 5 mm	10.5 × 10 (mm)
Gain	–23 dB				–5.2 dB
Location in capsule	The upper dome capsule	The upper dome capsule	The upper dome capsule	The upper dome capsule	Outer wall capsule

more important in this area. Each of the radiation patterns, shown in Figure 8, is plotted in two x - y ($\theta = 90^\circ$) and x - z ($\phi = 0^\circ$) planes. In $\theta = 90^\circ$ plane, the value of θ is constant and equal to 90° , and ϕ varies from 0° to 180° . In these dots of the space, the values of the total gain and the gain due to the E_θ and E_ϕ components are calculated and plotted in polar diagrams in Figure 8. Also, when $\phi = 0^\circ$, the value of ϕ is equal to 0° , and the θ varies from 0° to 180° . By measuring the values of the gain, the polar curve is obtained the same as before, which can be seen in Figure 8. The maximum amount of the three radiation patterns of the total gain and the gain due to E_θ and E_ϕ components are equal to -23 dB, -43 dB and -23 dB, respectively. It is expected that the radiation field of the monopole is along the E_θ , and the spiral part is E_ϕ . It can be seen that the Total gain and the gain due to E_θ component are similar which represents the dominant role of monopole section in the radiation pattern polarization. Thus, the spiral antenna plays the role of a load for the monopole antenna and leads to compression and impedance matching of antenna. The maximum gain of the antenna is -23 dB, which is 8 dB greater than that permitted for WCE transmitter antennas [9].

Table 2 compares the radiation characteristics of the proposed monopole antenna loaded with small spiral antenna with some other WCE antennas. According to this table, it can be seen that the proposed antenna is more appropriate in terms of size, the capsule occupied space and the bandwidth with respect to the other antenna which has been designed. Therefore, this antenna can satisfy the requirements of the WCE antenna.

4. CONCLUSION

In this paper, the radiation performance of a small dipole antenna loaded with spiral section was described. It was designed for using in wireless capsule endoscopy system. Because of the specific usage of this antenna, the design challenges were explained. One of these challenges was the miniaturization of the antennas. This problem was solved by adding the small spiral to monopole antenna. Therefore, the size of the antenna was reduced, and also an appropriate bandwidth was obtained. The 39% bandwidth and omnidirectional radiation pattern with a maximum gain of -23 dB were some of the good characteristics that made the proposed antenna suitable for using as a transmitter antenna in WCEs. The simulations were done with two HFSS and CST softwares to verify the validity of the results.

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