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Design of a Meander Line Omni-directional Loop Antenna for Biomedical Applications

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Abstract: The exploration of new medical diagnostic techniques, for instance the digestive tract monitoring wireless capsule endoscopy (WCE) has been emerged as a sophisticated technique. In WCE, wireless communication through a miniaturized antenna is a crucial element. Therefore, in this paper, the design of a compact planar meander-line micro strip patch antenna for WCE application has been presented. The dimension of the proposed antenna is 20.6 mm × 20.25 mm × 0.254 mm. Polyimide with the dielectric constant of $\mathcal{E}_r$=3.5 and loss tangent of tan δ = 0.0027 has been selected as the substrate material for this antenna. The proposed antenna has been resonated at the frequency of 1.78 GHz in the human body model and 2.62 GHz in the free space. The resultant reflection coefficients in the human body model and the free space are -16.04 dB and -40.31 dB respectively. The obtained bandwidth of this antenna is 90 MHz in the body model and 198 MHz in the free space. This antenna has given almost omni-directional radiation pattern in both environments. Moreover, the calculated specific absorption rate (SAR) with the proposed antenna is obtained as 1.03056 W/Kg inside the body model.

Keywords: *Wireless capsule endoscopy (WCE); Meander-line micro strip patch; Reflection coefficient; Omni-directional; Specific absorption rate (SAR).*

Introduction: Biomedical implantable devices have played a vital role in some remote continuous monitoring of important physiological parameters such as blood flow rate, concentration of blood glucose and blood oxygen level [1-3]. For this, some techniques include endoscopy, tomography, MRI, ultrasound, etc. have been required as an imaging system in the medical science. However, two forms of endoscopy such as colonoscopy and esophagogastroduodenoscopy (EGD) are not appropriately accomplished for examining the middle portion of the digestive tract. Therefore, wireless capsule endoscopy (WCE) could be considered more systematic in this purpose. WCE is a wireless endoscopy system where the images of human gastrointestinal (GI) tract are captured for identifying the specific diseases [4]. Though in some diagnoses and medical treatments, wired endoscopy systems are generally used, it causes several problems. Medical examinations by using wired endoscopies are reluctant, time consuming and painful to patients. Moreover, it has limited test coverage because of finite length of wired endoscopy. On the other hand, WCE is painless and noninvasive. In addition, it is capable of going through the deepest areas of the GI tract. Therefore, wireless capsule endoscopy systems have been offered to overcome the limitations of the wired endoscopies [5].

A traditional endoscopy named as colonoscopy is a lower endoscopy technique. In this system, a long flexible tube is inserted through the rectum of the digestive tract. It can record images of the colon and distal portion of the small intestine. In the same way, another traditional method named as EGD is used a small flexible tube to examine the esophagus, stomach and the first part of the small intestine [6]. On the contrary, wireless capsule endoscopy is a modern system as it does not require any external tube. Capsule endoscopy is a procedure that uses a tiny wireless camera to diagnose the diseases inside the human body [7]. Therefore, one of the important possible applications of wireless implantable devices is WCE which is used to record images of the digestive tract for diagnosis as shown in Fig. 1 [8, 9]. The figure shows that a capsule shaped pill is swallowed by the patient where a small camera is attached for taking images of the digestive tract. In WCE system, the capsule should be small enough to be swallowed through the patient's throat [10]. In order to transmit those internal images of the human body to an external receiver by means of wireless communications, various elements including the camera, transceiver, LEDs,

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battery, etc. are contained in the capsule. When the images are captured through the camera, an antenna inside the capsule is worked as a transmitting device for transmitting the image signal. And the receiving device which is placed outside the human body, are received the images from the transmitting antenna. Then these images of GI tract are interpreted by the physicians [4]. This procedure can be done even if the patients are doing their daily and usual works. Hence, omni-directional antenna can be selected for this wireless communication.

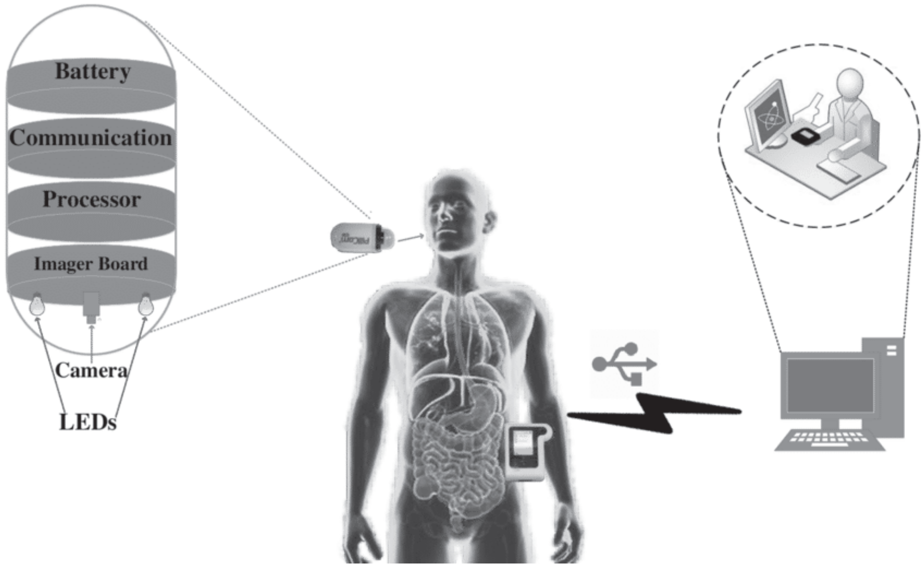


Fig. 1: Wireless capsule endoscopy system [9].

A loop antenna can be used as a wideband antenna. A meandered loop antenna can be chosen for WCE, since this antenna operates in both MICS (Medical Implant Communications Service) and ISM (Industrial, Scientific and Medical) bands. It can provide stable performance in the variable environments even inside the human body. For WCE, the size of the antenna should be miniaturized that can be obtained by combining with the use of meander line. Also, the antenna can be tuned to operate in the desired bands, if the width of meander lines and the gaps between them are properly adjusted [11]. In addition, this type of antenna requires low power to propagate through the human body and it can be achieved an omni-directional radiation pattern which is usually advantageous for this purpose.

Numerous researches have been conducted on antenna for wireless endoscopy. For instance, Nikolayev et al. [12] proposed 434 MHz in-body capsule antenna with the length of 10 mm and the diameter of 7 mm. The antenna matched below -10 dB in a wide range of body tissues. The achieved bandwidth for -10 dB was 17 MHz in this work. The radiation efficiency reached to 0.4% including the gain of -22 dBi. The radiation performance of this antenna exceeded most of the counterparts however its impedance characteristics were more robust. In another study, Hosain et al. [13] designed a multi-layer dipole antenna for implantable biomedical application. The dimension of this antenna was π *(10)2 *2.8 mm^3. The antenna had been obtained an omni-directional radiation pattern and its bandwidth was found as 10 MHz at the return loss of -10 dB. A fat arm spiral structured antenna was proposed by Lee and Yoon [14] for wireless capsule endoscopy system. The antenna was very small in size and it had wideband characteristics. The height of the antenna was 4 mm and the diameter was 10 mm. This antenna produced an omni-directional radiation pattern and its bandwidth was found as 460 ~ 535 MHz (75 MHz) for VSWR < 2. The antenna obtained fractional bandwidth of 15 % in the liquid tissue phantom with the relative permittivity of 56.7 and the conductivity of 0.94. Another small antenna for wireless-capsule endoscopy system was invented by Kwak et al. [15]. This work designed a small spiral structure and obtained its wideband characteristics. The size of the antenna was 10.1 mm in diameter and 3 mm in height. It provided an isotropic radiation pattern and the impedance bandwidth of the antenna was from 430 to 500 MHz for VSWR < 2. Furthermore, Lee et al. [16]

presented a dual spiral antenna for wideband capsule endoscopy system. This dual resonance structure was composed of two different spiral elements and a single feed wire connected these elements. The impedance bandwidth of the antenna was obtained as 98 MHz and it produced an isotropic radiation pattern.

In this work, a meander line omni-directional loop antenna is selected which is designed with the dielectric material of Polyamide. The dielectric constant of this material is 3.5 and the loss tangent is 0.0027. This types of antenna is usually light weight and low cost. In this work, the antenna is simulated inside a model of human GI tract where multi-layer tissues such as skin, fat, muscle have been used. The simulation is integrated through "Finite Integration Technique". The environment of our human body model is closer to the actual human body. Thus, the obtained results are more accurate compare to the human body model with single-layer. Our proposed antenna for WCE is offered: (1) size miniaturization, (2) increasing the bandwidth with optimized resonant frequency, (3) omni-directional radiation pattern, and (4) providing patient safety.

The paper is organized as follows. Firstly, the design of the proposed antenna and the human GI tract model including their simulation setups are presented. Secondly, the performances of the proposed antenna in the free space and inside the body model with GI tract are analyzed. Moreover, a discussion has been given at the end of this section. Thirdly, the calculation of the specific absorption rate (SAR) has been illustrated. And finally, the concluding remarks and future recommendations are provided.

Design and Model:

A. Configurations of Proposed Antenna: The structure of our proposed antenna is designed in "Finite Integration Technique" microwave studio. The proposed antenna is made up of a meandered conducting line, a substrate and a ground plane. In this design, the substrate is placed between the patch and ground as sandwiched. The schematic view of the meandered conducting line dimension has been shown in Fig. 2.

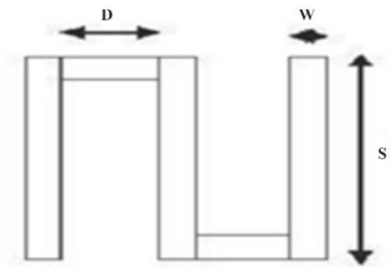


Fig. 2: Dimension of the meandered line [17].

The dimension of the meander line antenna is calculated from the following equations [18]:

$$s = 0.102\,\lambda g \tag{1}$$

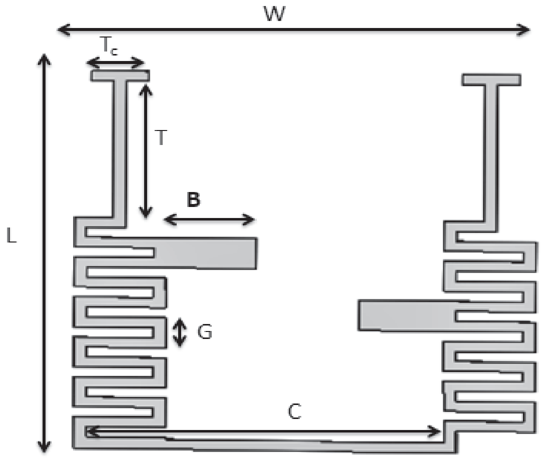
$$d = 0.046\,\lambda g \tag{2}$$

$$w = 0.013\,\lambda g \tag{3}$$

Where, λg is the guided wavelength (m).

The dimension of the designed antenna is about 20.6 mm × 20.25 mm × 0.254 mm in size. Fig. 3(a) presents the structure of the proposed antenna. Moreover, the specifications of the antenna are mentioned in Table 1. In this work, Polyimide is chosen as a substrate because of its relative permittivity (ε_r= 3.5) and loss tangent (tanδ = 0.0027) which helps to decreasing the resonant frequency, in order to operate it in the ISM band. On the other hand, the selected material of the patch and ground are both chosen as copper. In this design, a meandered conducting line is used to increase the current conduction path to bring the resonant frequency in the desired position, as well as to reduce the size of the antenna. To enhance the bandwidth, discrete port transmission line is applied at the top.

In order to insert the proposed antenna in the body model, this designed antenna has been bended as 5 mm radius which is shown in Fig. 3(b). The transmission line connectors of both ends are connected together through the discrete port feed to form a bend shape.



(a)

(b)

Fig. 3: (a) Design of the proposed antenna and (b) Bended antenna after capsule insertion.

Table 1. The specifications of the proposed antenna.

Parameter	Size (mm)
Substrate width, W	20.6
Substrate length, L	20.25
Conductor brick, B	6.87
Loop connector, C	15.2
Transmission line connector, T_c	2.5
Gap between conductor loop, G	1.65
Transmission line, T	7.4

B. Design of Human GI Tract Model: The ingestible capsule antenna travels along the human GI tract. Thus, the performance of the proposed antenna needs to be analyzed inside the human GI tract model. In this work, a HUGO human body model has been used for simulation which is shown in Fig. 4(a). The GI tract of the body model consists of several layers of human tissues such as Esophagus, Stomach, Small Intestine, Large Intestine, muscle, fat and skin. The schematic cross sectional view of the GI tract model comprises with different tissues has been presented in Fig. 4(b).

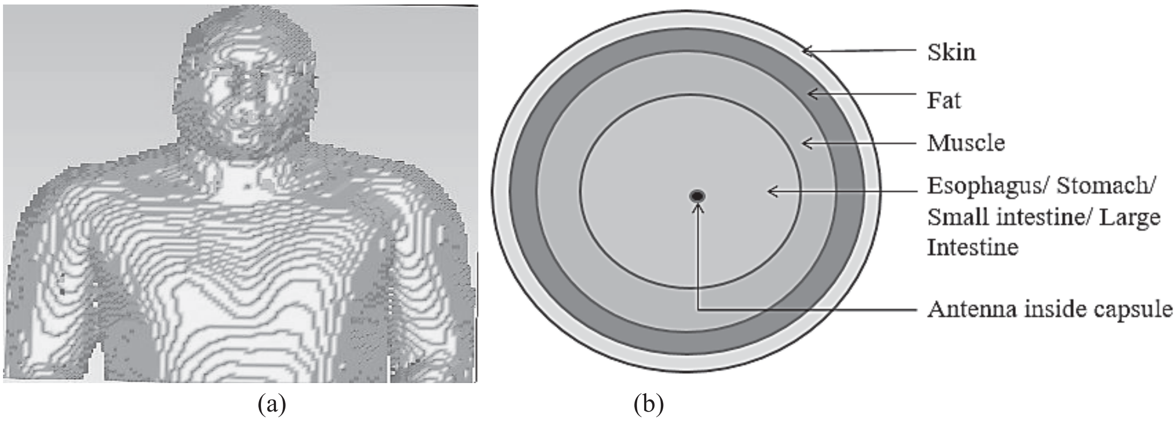


Fig. 4: (a) Upper section of HUGO body model consisting of all tissue elements and (b) Schematic cross-sectional view of the GI tract model.

During simulation, different tissues of the GI tract have been absorbed different quantity of microwaves because of their own properties. Thus, the specifications of all tissues play an important role to detect different tissues. The properties of all tissues including their relative permittivity, conductivity and loss tangent are given in Table 2. The calculations of the electric conductivity (σ) and the dielectric constant (ε_r) are found in [19]. From the following equations, it is stated that the electrical properties of the tissues are influenced by the frequency (*f*).

$$\varepsilon_r = 1.71 \,.\, f^{-1.13} + 4 + \frac{\varepsilon_s - 4}{1 + \left(\frac{f}{25}\right)^2} \quad (4)$$

$$\sigma = 1.35 \,.\, f^{0.13} \,.\, \sigma_{0.1} + \frac{0.0222 \,.\, (\varepsilon_s - 4) \,.\, f^2}{1 + \left(\frac{f}{25}\right)^2} \quad (5)$$

Table 2. The properties of tissues used in this simulation at 5 GHz [20, 21].

Tissue	**Relative Permittivity**	**Conductivity(S/m)**	**Loss Tangent**
Esophagus	57.89	5.16	0.32
Stomach	57.89	5.16	0.32
Small intestine	49.98	5.75	0.41
Large intestine	46.4	4.7	0.36
Muscle	49.54	4.04	0.29
Fat	5.03	0.24	0.17
Skin	35.77	3.06	0.31

C. Simulation Setup: Human GI tract with surrounding tissues will be simulated through "Finite Integration Technique". For this, the proposed antenna is placed in the small intestine of HUGO body model. The simulation is carried out to investigate the performances of the antenna. Fig. 5 shows the proposed antenna inside the tissue model to obtain SAR. The SAR is the rate of the energy which is absorbed by the human body when the electromagnetic field of radio frequency (RF) has been exposed. It is the power absorbed by the human body per unit of the volume, in the presence of an incident electromagnetic field. Therefore, it depends on the mass density of the tissues and it is proportional to the ratio between the conductivity and the density of the exposed tissue. The unit of SAR is expressed in watts per kilogram (W/Kg) and the value of the SAR has been calculated by the following equation [22]:

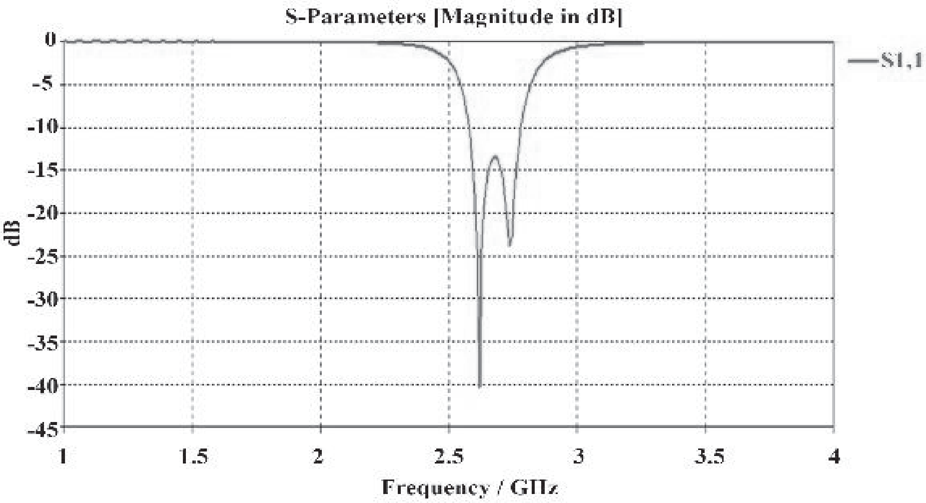
$$\text{SAR}=\frac{P}{\rho}=\frac{\sigma\left|E^2\right|}{\rho} \tag{6}$$

Where, P is the absorbed power in the tissue (W), ρ is the mass density of the human tissue (Kg), σ is the conductivity of the tissue (S/m) and E is the intensity of the electromagnetic field (V/m).

Fig. 5: The placement of the designed antenna into the small intestine of HUGO body model.

Result Analysis and Discussion: The evaluation of the proposed antenna for WCE application depends on the safety properties of the antenna. To analysis this, the proposed antenna is operated in free space and inside the human body model i.e. gastrointestinal tract model. The performance parameters of the proposed antenna such as reflection coefficient (S_{11} parameter), impedance, VSWR, gain, antenna's efficiency, radiation pattern are analyzed in both environments, which are described below:

A. S Parameter: The resonant frequency is the frequency for which the refection coefficient is lowest that means the frequency at which the maximum energy is radiated. The bandwidth of an antenna is generally determined by the range of frequencies over which the reflection coefficient is less than -10 dB because the radiated power up to this level is acceptable. The reflection coefficients ($|S_{11}|$) of the ingestible capsule antenna in the free space and inside the human body model are examined through the simulation, which are demonstrated in Fig. 6.



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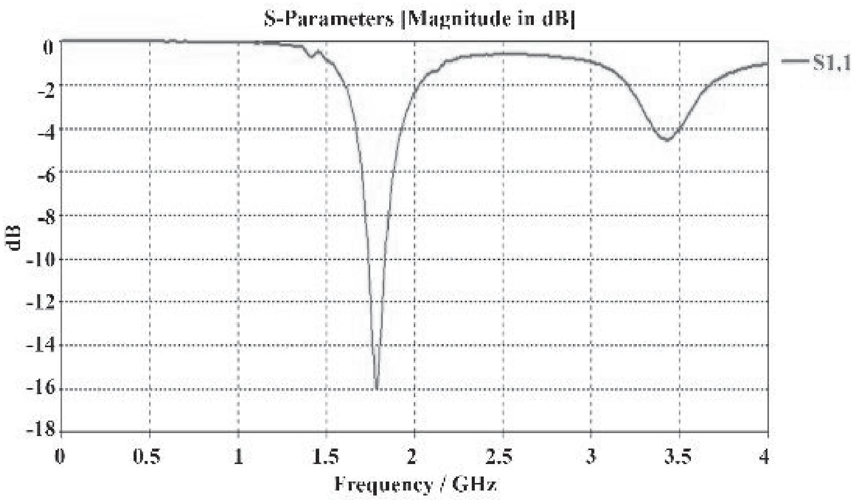
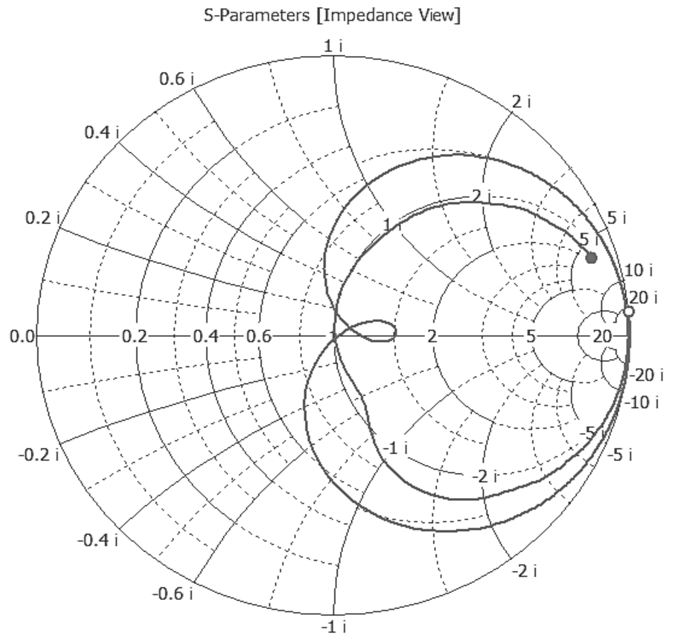


(b)

Fig. 6: S_{11} parameter: (a) in the free space and (b) inside the human body model.

It is cleared that the antenna resonates at a frequency of 2.62 GHz in the free space and 1.78 GHz in the human body model. All of these frequency bands are supported by IEEE 802.15.6 standard. The minimum magnitude of reflection coefficient ($|S_{11}|$) of the ingestible antenna is -40.31 dB with -10 dB bandwidth of about 198 MHz ranging from 2.58 GHz to 2.78 GHz in the free space. Similarly, -16.04 dB of minimum magnitude of reflection coefficient ($|S_{11}|$) is achieved with -10 dB bandwidth of about 90 MHz ranging from 1.74 GHz to 1.83 GHz in the human body model. The fractional bandwidth of the antenna can be calculated by taking the ratio of the bandwidth to the resonant frequency.



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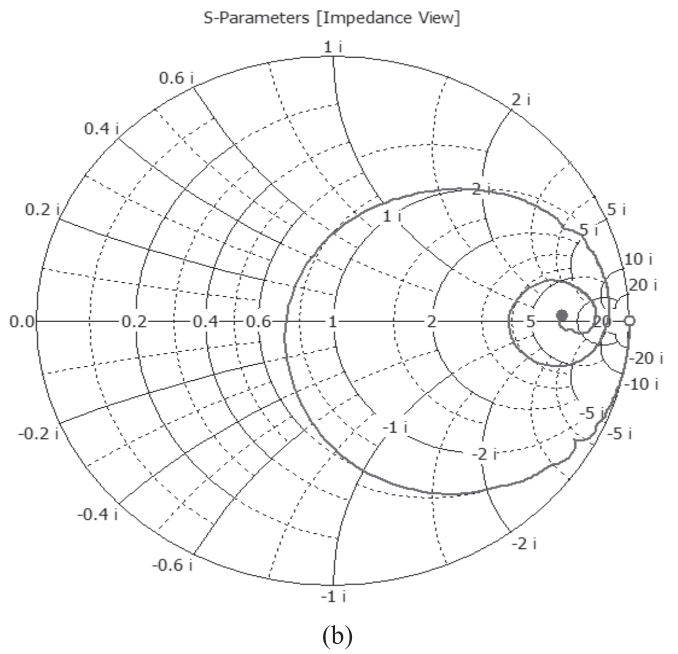
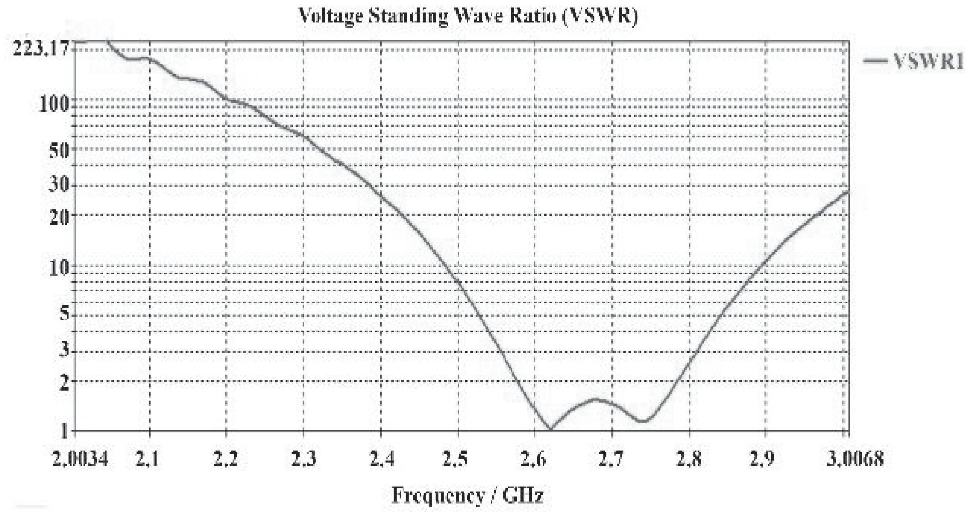


(b)

Fig. 7: Smith chart for proposed antenna: (a) in the free space and (b) inside the human body model.

B. Smith Chart: To solve the problems with the transmission lines and the matching circuits, the smith chart can be used. Fig. 7 shows the smith chart of S_{11} parameter for both environments. Moreover, the smith chart can be used to calculate the voltage standing wave ratio (VSWR). It is found that the impedance of the proposed antenna is as 50 Ω which is suitable for the biomedical applications.



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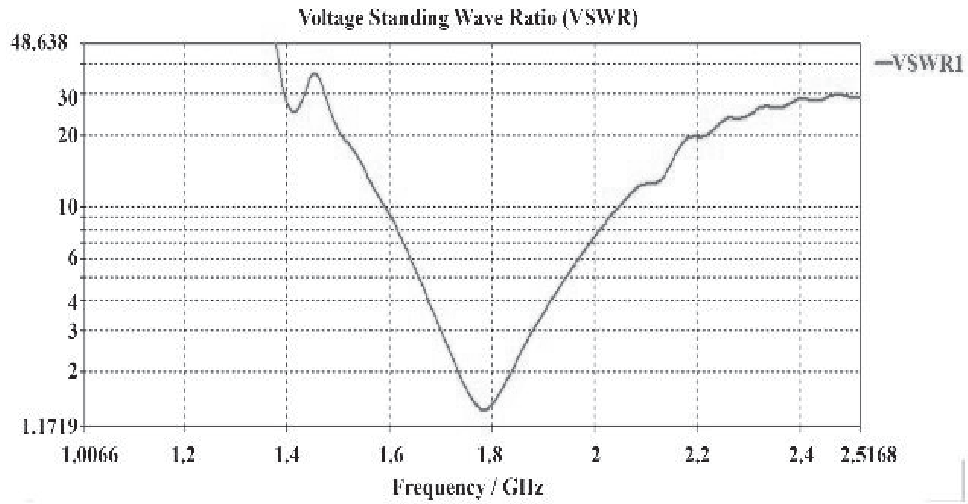


(b)

Fig. 8: VSWR of the proposed antenna: (a) in the free space and (b) inside the human body model.

C. Voltage Standing Wave Ratio (VSWR): The reflected power of an antenna is described by VSWR. VSWR indicates how much the antenna's impedance is matched with the RF transmission line impedance and the more power is delivered to the antenna. The mismatch of the antenna impedance with the RF transmission line can cause of power loss and reflected energy. Therefore, it can be stated that it is a function of reflection coefficient. VSWR is always real and positive number. For an ideal antenna, VSWR is 1 i.e. no power is reflected from the antenna. The values of VSWR for the proposed antenna in the free space and inside the human body model are analyzed (as shown in Fig. 8). It is seen that the VSWRs of the antenna in free space and in the human body model are 1.03 and 1.37 respectively, which is below 2 in the entire operating frequency range. As a result, it is acceptable to design an antenna for biomedical applications

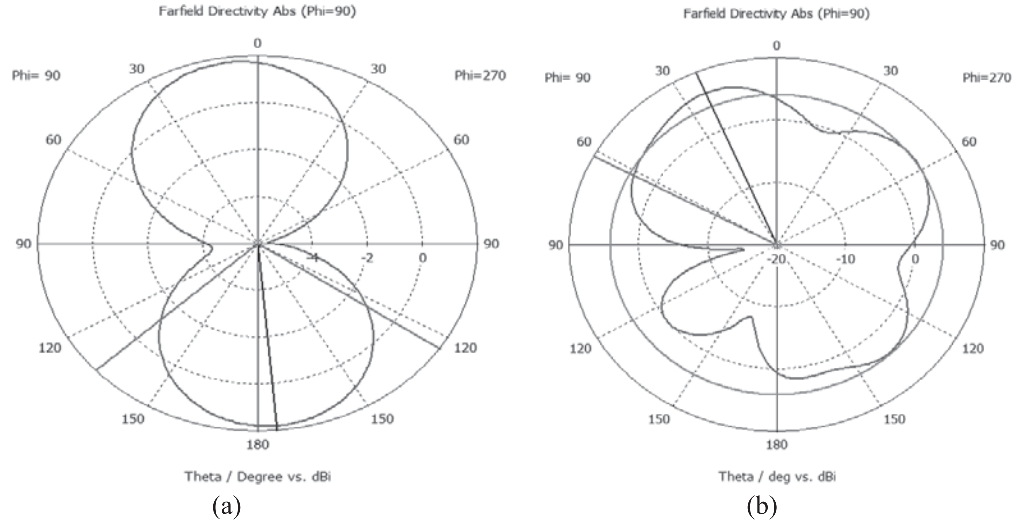


Fig. 9: Far-field directivity pattern of the proposed antenna at E-plane: (a) in the free space and (b) inside the human body model.

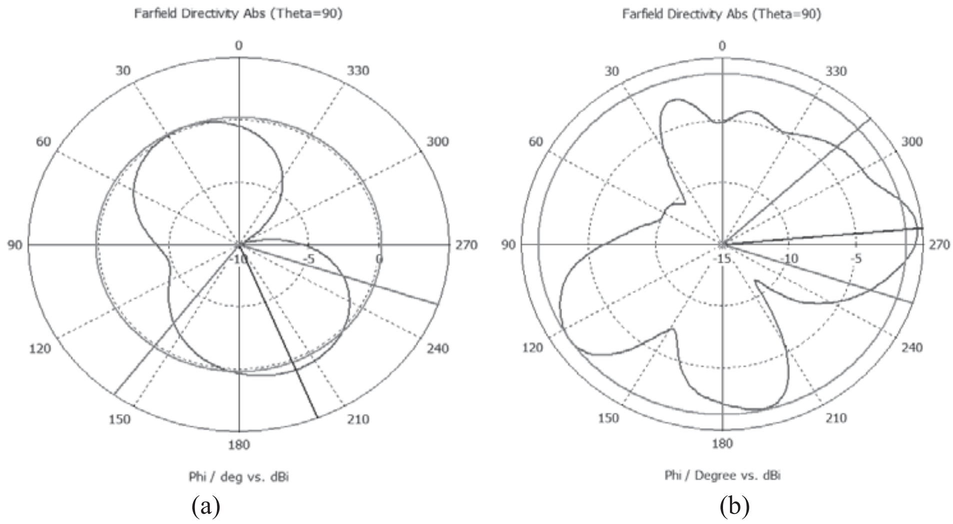
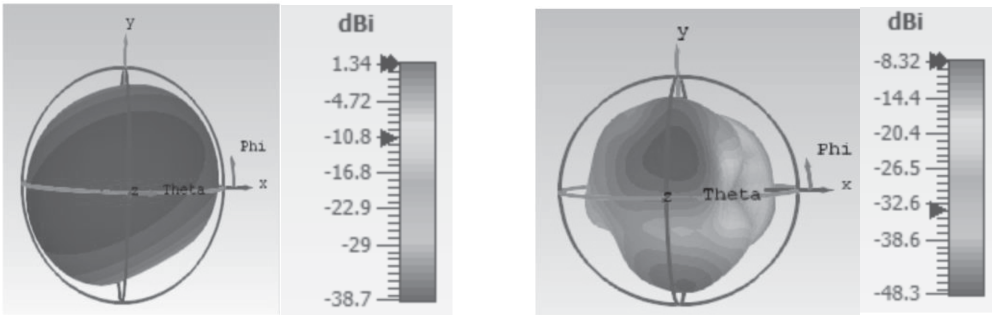


Fig. 10: Far-field directivity radiation pattern of the proposed antenna at H-plane: (a) in the free space and (b) inside the human body model.

D. Radiation Pattern: The variation of the radiated power by an antenna as a function of the direction away from the antenna is known as radiation pattern. The 2D far field radiation patterns of the antenna in E-plane and H-plane for both environments at the resonant frequency are displayed in Fig. 9 and Fig. 10 respectively.

From these radiation patterns, it can be summarized that the antenna has not provided equal radiation in all directions. Hence, it does not show the isotropic radiation pattern. It is also seen that the antenna does not radiate more strongly in some directions than the others. Therefore, it does not show the directional radiation pattern characteristics as well. It is observed that the antenna exhibits omni-directional radiation pattern throughout the GI tract for both of the two planes. Thus, the antenna will be able to transmit information in all directions. That means it is independent of the direction and orientation of the capsule which is essential for biomedical application such as wireless capsule endoscopy.

E. Gain and Efficiency: The gain is a useful analysis that describes the performance of an antenna. The ratio of the radiation intensity in a given direction to the radiation intensity of an isotropic source is defined as gain. Gain is related to the directory and the radiation efficiency of an antenna. The 3D radiation patterns of the proposed antenna in the free space and inside the human body model are presented in Fig. 11.



(a) (b)

Fig. 11: The 3D far field radiation pattern of the gain of the proposed antenna: (a) in the free space and (b) inside the human body model.

The gain of the designed antenna is found to be 1.33 dB in the free space and –8.31 dB in the human body. In the free space, the value of the radiation efficiency and total efficiency of the antenna is same as 0.46 dB. Additionally, the radiation efficiency and total efficiency for the human body model are -14.86 dB and -14.98 dB respectively. It can be concluded that the radiation efficiency and total efficiency are both decreased inside the human body model because of the super lossy tissue medium.

A comparative analysis of the performances of the antenna inside the human body model and the free space has been exhibited in the following Table 3. It is obtained that the resonant frequency in the human body model is low which is quite good for wireless capsule endoscopy as well as for any biomedical applications. In addition, the bandwidth of the proposed antenna exists in ISM band which is acceptable for this application.

Table 3. Comparative analysis of simulated results for human body model and free space.

Parameter	**Human Body Model**	**Free Space**
Resonant frequency (GHz)	1.78	2.62
$\|S_{11}\|$ dB	-16	-40
-10 dB bandwidth (MHz)	90	198
VSWR	1.37	1.03
Maximum gain (dB)	-8.31	1.33
Radiation efficiency (dB)	-14.86	0.46
Total efficiency (dB)	-14.98	0.46

Previously different designs of antenna have been offered for WCE purpose. Some of these provided relatively low performances compared to our proposed design. Therefore, a comparative discussion is made by the performance parameters when the antenna is encapsulated inside the human body model. The parameters of the antenna include the size, increasing the bandwidth with highest resonant frequency, radiation efficiency and the radiation pattern. Though the size of the proposed antenna is 20.6 mm × 20.25 mm × 0.254 mm, this overall size has been optimized by bending the antenna in 5 mm radius before encapsulation inside the human body model which is miniature compared to others [12, 14, 16]. On the other hand, the proposed antenna has bandwidth of 90 MHz with the highest resonant frequency as 1.78 GHz for human body model whereas the resonant frequency of the existing researches [12-15] is 434 MHz, 915 MHz, 500 MHz and 440 MHz respectively. In addition, the radiation efficiency in the free space of the designed antenna is 46% which is much better than the radiation efficiency of 0.4% [12] and 40.75 % [13]. Moreover, the radiation pattern of the proposed antenna is omni-directional which is same as some existing works [13, 14]. However, other existing works provides dipole-like or isotropic radiation pattern [12, 15, 16].

SAR and Safety Analysis:
To keep the patient safe from the radiating elements, SAR analysis has been done. According to IEEE C95.1-2005 standard limits l0g-avg SAR to 2 W/Kg and the IEEE C95.l-1999 standard limits 1g-avg SAR to 1.6 W/Kg. The calculation of the SAR is accomplished for input power of 1 W throughout the GI tract in “Finite Integration Technique” averaged over 10 g of tissue. The value of SAR in our human body model is obtained as 1.03056 W/Kg. Therefore, it is summarized that the maximum allowable net input power for the proposed design of the capsule antenna is 0.474135W which is matched with IEEE C95.l-2005 standard.

Conclusions: This paper presented a meander line omni-directional loop antenna for WCE application. The shape of the proposed antenna was miniaturized which allowed it to fit inside a capsule model and swallowed through the patient’s throat. The performance of the antenna was analyzed in the free space and inside the human GI tract model which was made with multiple tissues. The antenna in the free space had a resonant frequency of 2.62 GHz, -10 dB bandwidth of 198 MHz, VSWR of 1.03, the maximum gain of 1.33 dB, and total efficiency of 0.46 dB. On the other hand, the antenna inside the GI tract model had a resonant frequency of 1.78 GHz, -10 dB bandwidth of 90 MHz, VSWR of 1.37, the maximum gain of -8.31 dB, and total efficiency of -14.98 dB. This antenna provided omni-directional radiation pattern for both environments. Moreover, the calculated SAR was obtained as 1.03056 W/Kg inside the body model which maintains the safety standard. After a successful simulated evaluation, the proposed antenna can be used for biomedical application such as WCE. Therefore, future work will be involved it to manufacture a prototype of this antenna.

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