UWB Elliptical Antenna Using Fractal Geometry For Wireless Capsule Endoscopy

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Abstract. In this paper, wireless capsule endoscopy (WCE) has been studied and its components and method of work. This small device is very important because it has a significant role in facilitating the process of imaging the digestive system. Since the capsule is a pictorial device, the most important part of it is the transmitter. It has been suggested to use the microstrip antenna due to its many advantages such as small size and easy design and others. The microstrip antenna was designed with ultra-wideband technology (UWB) by using fractal geometry. The proposed antenna has a return loss of -41.1 at 5.78 GHz. Also, the radiation patterns are Omni-directional radiations over the UWB bandwidth.

1. Introduction
The endoscope is a device used to photograph the digestive system, starting from the esophagus and ending with the outlet. In the normal endoscopy, the patient is under local anesthesia because this process is accompanied by pain. The development of the techniques has been invented by the wireless capsule endoscopy to facilitate the process of gastrointestinal endoscopy and also to get rid of the accompanying pain and release from anesthesia [1] and [2]. Therefore, this capsule is very important, especially for elderly patients who cannot afford the pain associated with the endoscopic tube. Also, anesthesia may cause health problems for them.

Since the capsule travels along with the digestive system with involuntary movement so it does not require any effort from the patients who can carry out their daily activities during the examination process. Therefore, interest in improving the capsule in terms of obtaining clear images, as well as making it cheap price is very important and makes a big difference in the process of medical visualization, which facilitates the process of imaging to the patient and a doctor also [3].

And to improve the wireless capsule endoscopy and make them cheap and also give clear images We chose to improve and develop the antenna used in the capsule for being responsible for the transmission of signals and images to the receiver that worn by patients, so in this thesis we chose the use of the Micro Strip antenna because it has several features, including lightweight and inexpensive and also small size and can Works on Ultra-wideband technology (UWB) [4].

UWB is a technology that transmit information spread over a large bandwidth (>500 MHz), the bandwidth of UWB antennas defined by U.S. (Federal Communications Commission) (FCC) to have a range from 3.1 to 10.6 GHz [5].
The data rate depends on bandwidth and signal to noise ratio according to the Shannon equation 1. [6], [7]:

\[ C = B \log_2 (1 + \text{SNR}) \text{ [b/s]} \]  

(1)

Where \( C \) represented channel capacity, \( B \) is bandwidth, and \( \text{SNR} \) is signal to noise ratio.

So, when the width of the band increases the data transfer speed will increase. Therefore, the use of UWB technology has become important and necessary in communications due to its benefits that exceed other technologies. The UWB technology has several features, including the consumption of a small amount of power, send data quickly, simple hardware arranging and also have the ability to prevent proliferation in many paths as well as inviolability to multipath spread [8].

Several previous studies were studied such as, In 2016, M. A. Tajin et al. [9] designed and measured performance of an UWB antenna for wireless capsule endoscopy which was U-shaped bend microstrip patch antenna, it had over size of \((28\text{mm} \times 24\text{mm} \times 0.707\text{mm})\) and bandwidth of \(2.268\text{GHz}\). In 2017, M. Kaffa et al. [8] designed a microstrip antenna for Wireless Capsule Endoscopy in Wireless Body Area Network which has small circular patch half ground and slit on it, it had over size of \((12 \times 8 \times 1.97\text{mm})\) and it had bandwidth of \(3\text{ GHz}\). In 2018, R. Islam et al. [10] designed In-Body Antenna for Wireless Capsule Endoscopy at MICS Band that worked at \((402-405\text{ MHz})\), it had Bending cylindrical microstrip patch antenna that had overall size of \((20\text{mm} \times 30\text{mm} \times 0.5\text{mm})\), through these researches the most important gaps to be addressed were identified.

In this paper, the main objectives of antenna designing are to obtain high data rate inorder to improve the resolution of image, to minimized the antenna and capsule to be easily swallowed by patients and to improve the efficiency of the antenna when it work inside human body. The microstrip antenna will be designed using the CST program. It should be noted that since the capsule will be swallowed by the patient so it will be in direct contact with the tissues of the body, which consider as absorbed environment, so the calculation of the electrical conduction of the body tissues and their impact on the antenna signal are very important in order to obtain a signal with high efficiency and thus we can get clear pictures.

2. Antenna Structure

This antenna has an elliptical shape with two sizes of circular slots. The antenna designed using an iterative method up to the 2nd iteration for obtaining a wide bandwidth. The substrate material is made of FR4 with a dielectric constant of 4.3, and a thermal conductivity of 0.3. Ground and patch are made from copper material as shown in Figure 1 of simulated design and Figure 2 of fabricated design.

![Figure 1. Proposed antenna structure: (a) front view and, (b) back view](image-url)
Steps of Antenna Design

**Step 1:** Initially, the patch has an elliptical shape (initiator) with an X radius of 4 mm and Y radius of 2.5 mm. Also, the feed line technique has been used in this design with three widths to make the match of 50 \( \Omega \) impedance as shown in Figure 3 (a).

**Step 2:** In the first iteration, three circular slots are inserted in the patch, each one with a radius of 0.75 mm, as shown in Figure 3 (b).

**Step 3:** In the second iteration, the other three circular slots are inserted in a patch with a smaller size with a radius of 0.25 mm, as shown in figure 3 (c).

The partial ground has been used with a length of 2.5 mm that altered to obtain higher bandwidth. After the process of optimization, the parameters of the proposed antenna are listed in Table 1. The antenna operates at UWB frequency from (4.87 to 10.3 GHz) with a bandwidth of 5.43 GHz and resonance.
frequency at 5.78 GHz. The dimensions of the antenna’s details are presented in Table 1. The design methodology was explained during the chart shown below:

**Figure 4.** Antenna design flow chart

| Parameters                          | Dimensions (mm) |
|-------------------------------------|-----------------|
| Width of ground $W_g$ and substrate $W_s$ | 10              |
| Length of substrate $L_S$           | 10              |
| Length of ground $L_g$              | 2.5             |
| Thickness of substrate $h$          | 1.5             |
| Thickness of patch and ground $t$   | 0.036           |
| Width of feed line respectively $W_1, W_2, W_3$ | 0.6, 1.8, 2.8 |
| Length of feed line respectively $L_1, L_2, L_3$ | 1.5           |
| Radius of iterations circles $R_1, R_2$ | 0.75, 0.25     |

3. Simulation Set up
The antenna performance simulation is developed with CST Microwave Studio Test. The proposed antennas was simulated and measured in the human body model which an approximate environment of the stomach that created using predefined tissue materials with CST program.

The antenna designed for the implemented device is based on the study of the materials and the propagation characteristics in the body. There is a difference in the spread of RF waves in the human body and free space because of the difference between these two environments. The human body consists of
many tissues that have different permittivity and conductivity and leads to different dielectric properties.[11]

The permittivity defined as material’s ability to rotate molecular dipoles, and the conductivity defined as material’s ability to transport charges in a material, the energy stored per unit volume can give by equation 2 [12]:

\[ u = \frac{\varepsilon E^2}{2} \]  

(2)

And the power dissipated per unit volume can give by equation 3:

\[ p = \frac{\sigma E^2}{2} \]  

(3)

So, as shown in equations above the permittivity and conductivity of human tissues have an effect on the RF wave. Table 2 shows many values of them of different tissues at 5.78GHz.

| Tissues   | Relative permittivity (\(\varepsilon\)) | Conductivity (\(\sigma\)) S/m |
|-----------|-----------------------------------------|--------------------------------|
| Skin      | 38                                      | 1.46                           |
| Muscle    | 52.7                                    | 1.77                           |
| Fat       | 5.3                                     | 0.11                           |
| Stomach   | 60                                      | 1.9                            |

Therefore, the antenna must be examined within a medium similar to the human body and has a conductivity value and permittivity close to it to obtain the results close to the real values. So, the human body model designed in CST program in way that similar to human body, the tissues of the body surrounded the antenna in the form of sequential layers. The antenna is placed inside the proposed capsule that made of Teflon which considered bio-compatible material as shown in Figure 4 (a), and then surrounded with the tissues which represent the stomach then muscle layer, fat and skin sequentially as shown in Figure 4 (b).

4. Measured Results

Antenna is fabricated and measured by the VNA device that shown in Figure 5. To further examine the sensitivity of proposed antennas in a live multi-tissue environment, it was embedded inside a rabbit stomach. Experiment steps are described below:
1. First, sterilize all the devices that used in the experiment including the antennas, coaxial cable and SMA (Subminiature version A) connectors by Medical sterilizer
2. Cut the hair where the antennas will be implanted
3. Make an incision through the skin, muscles, and stomach
4. Then, the implantable antenna would be implanted inside the rabbit’s stomach as shown in Figure 5.
5. Perform the reflection coefficient measurement using VNA device

![Surgical implantation of the implantable antennas into the rabbit](image)

Figure 6. Surgical implantation of the implantable antennas into the rabbit

Figure 6 presents the simulated and measured reflection coefficient ($S_{11}$) of the proposed antenna in different environments. The simulated $S_{11}$ has resonance frequency at 5.78 with reflection coefficient values of -41.25 dB while the measured has -29.05 at 5.82 GHz.

The simulated impedance bandwidth inside human body model can cover around 4.85-10.42 GHz (72.95%) measured impedance bandwidth in the rabbit can cover around 4.75-9.85 GHz (69.87%)

![Comparison between $S_{11}$ values in three different environments](image)

Figure 7. Comparison between $S_{11}$ values in three different environments
The antenna must have an Omni-directional radiation pattern for detecting the transmitted signal independent of a transmitter position as shown in Figure 7 and 8.

![Simulated 3D radiation pattern at 5.78 GHz](image)

**Figure 8.** Simulated 3D radiation pattern at 5.78 GHz

![Simulated 2D radiation pattern at 5.78 GHz](image)

**Figure 9.** Simulated 2D radiation pattern at 5.78 GHz

In the chart below, we can distinguish the improvement in the value of the bandwidth compared to previous research:
Figure 10. Comparison between the bandwidth of the proposed antenna with previous research antennas

5. Parametric Study of the Proposed Antenna
Feed line width and ground length are considered as major factors affecting bandwidth, so changing them will lead to optimizing the results.

5.1 Effect of Changing Feed Line Width
Feed line width $W_2$ will be optimized to have values of 0.5 mm, 0.7 mm and 0.9 mm. Figure 9. Shows that; higher bandwidth can be obtained at 0.9 mm. The results for different values of $W_2$ are summarized in Table 3.

| Feed Line Width (mm) | $S_{11}$ dB | Resonance Frequency (GHz) | Coverage Bandwidth (%) |
|----------------------|-------------|---------------------------|------------------------|
| 0.5                  | -22.1       | 5.62                      | 58.14%                 |
| 0.7                  | -34.7       | 5.72                      | 65.36%                 |
| 0.9                  | -40.23      | 5.79                      | 72.78%                 |
5.2 Effect of Changing Ground Length

Figure 10 illustrates the effect of changing the length of ground (\( L_g \)) on the return loss \( S_{11} \), where we tested \( S_{11} \) at three values of length 2.25 mm, 2.5 mm and 2.75 mm. This figure shows that the length of 2.5 mm has the highest bandwidth. The results for different values of \( L_g \) are summarized in Table 4.

| \( L_g \) Ground Length (mm) | \( S_{11} \) dB | Resonance Frequency (GHz) | Coverage Bandwidth (%) |
|----------------------------|----------------|--------------------------|------------------------|
| 2.25                       | -37.55         | 6.1                      | 72.6%                  |
| 2.5                        | -40            | 5.75                     | 73.4%                  |
| 2.75                       | -41.25         | 5.5                      | 36.5%                  |

Figure 11. Effect of feed line width

Figure 12. Effect of ground length
6. Specific Absorption Rate (SAR)

It is a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency (RF) electromagnetic field. It is usually averaged either over the whole body or over a small sample volume typically 1 g or 10 g of tissue. The SAR value is measured in terms of watts per kilogram (W/kg).[15] and [16], SAR can be given by equation 4.: 

\[
\text{specific Absorption Rate (SAR)} = \frac{\sigma \times E^2}{m_d}
\]

\[
Incident \ Power \ Density = \frac{E^2}{377}
\]

where \( \sigma \) = conductivity of material, \( E \) = electric field (RMS), \( m_d \) = mass density

Since the proposed antenna is implanted inside human body, so it important to measure SAR value. Table 5 shows the comparison of Proposed Antenna with Previous Works that used inside human body in term of SAR values.

| Ref. | Dimension (mm) | Coverage Bandwidth | Gain (dB) | SAR (W/Kg) 1g | SAR (W/Kg) 10g |
|------|----------------|--------------------|-----------|---------------|---------------|
| 2012/[17] | 16.5x16.5x2.54 | 13%                | -31       | 318            | -             |
| 2014/[18] | 13.4x16x0.835  | 16.5%              | -30.6     | -              | 88.52         |
| 2015/[19] | 10.6x10x1.27   | 29%                | -1.13-4.36 | 770            | -             |
| 2017/[20] | 14.3x14x15     | 5.9%               | -23       | 21.47          | 10.06         |
| Proposed Antenna | 10x10x1.5 | 72.95%             | -2.46     | 0.9            | -             |

7. Conclusions

In this paper, micro strip patch antenna was designed by using fractal geometry. It has dimensions of 10 x 10 mm². I have concluded that use of fractal geometry in the design of the antenna has a significant effect on increasing the bandwidth. The antenna was simulated inside the human stomach model that created using predefined tissue materials with CST program and the results were also enhanced by the antenna implantation within the rabbit stomach under anesthesia. There is little difference between the results due to the different environments as well as the external factors affecting the antenna measurements. It works at a bandwidth of 5.43 GHz, so it has a high data rate with an Omni-directional radiation pattern which important performance for a capsule that has involuntary movement inside the digestive system.

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