UWB Pentagonal Shaped Fractal Patch Antenna for Wireless Capsule Endoscopy

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Abstract. The capsule endoscopy device is one of the most important devices that have been invented recently because of its importance in facilitating the process of imaging the digestive system. The process of developing and improving the transmitter in the capsule is one of the most important things to improve images and accelerate the process of imaging. Microstrip antenna will be used because it has several benefits such as small size, ease of manufacture and low cost. In this paper, the microstrip antenna was designed with ultra-wideband technology (UWB) by using fractal geometry. The proposed antenna has a return loss of -25.1 at 5.45 GHz and VSWR of 1.13. Also, the radiation patterns are Omni-directional radiations over the UWB bandwidth.

Keywords: fractal geometry, microstrip patch, omnidirectional antenna, UWB

1. Introduction
Endoscopy is considered as an important device in medicine because it is responsible for imaging the digestive system and detecting the diseases that accompany it. But besides its importance, it has several disadvantages due to the pain it causes and the need for anesthesia. Therefore, the search for an alternative is important to protect patients from the dangers of anesthesia, especially the elderly and also to rid them of the pain associated with the examination. So they invented the wireless capsule endoscopy, which is characterized by the small size and the possibility of detection and imaging of places cannot be seen by the conventional endoscopy. The capsule consists of a photosensor, a transceiver system, battery, and optical dome [1].

For an excellent scan and clear images that the doctor can detect any disease in the digestive system, the antenna in the capsule must have a high specification such as high data rate, which depends on the bandwidth that used for transmitting the information, according to the Shannon equation [2] and [3]:

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

where \( C \) is channel capacity, \( B \) is bandwidth and \( SNR \) is signal to noise ratio.

So the UWB technology is desired, the UWB is a radio technology that uses a very low energy level for short-range [4] and [5] which defined by Federal Communication Commission (FCC) as this which has bandwidth larger than 500 MZH. Several researchers in the past years designed and used types of antennas in the capsule to reach the ideal type such as spiral, helical and conformal antenna but these types have several limits that make them limiting uses. So using microstrip patch antenna is considered as the desired solution due to its advantage such as small size, low cost, easy to design and fabricate and can work in ultra-wideband detect [6], [7], and [8].
In 2010, Qiong Wang et al. [9] designed a conformal trapezoid strip antenna which has resonance frequency at 3.8 GHz with a reflection loss (S11) of -23 dB and a wide bandwidth of 1.7 GHz from 3.1-4.8 GHz. In 2014, Changrong Liu et al. [10] designed circularly Polarized helical Antenna in ISM Band with bandwidth of 80 MHz from 2.4 to 2.48 GHz. In 2015, Farhadur Arifin and Pran Kanai [11] designed circular patch micro strip antenna with square slot with 81 mm$^3$ volume and operating in a wide bandwidth of 501.8 MHz and in 2016, they improved Bandwidth by using two rings slot and a saw tooth partial ground for circular patch antenna with 110 mm$^3$ volume [12] and it became 1.84 GHz. In 2016, Md. Abu Saleh Tajin et al. [13] improved the bandwidth by enlargement the size of antenna and using folded technique and get 2.268 GHz. In 2017, Mutiara Kaffa et al. [14] also designed a small circular antenna with 189.12 mm$^3$ volume and has a wide bandwidth of 3 GHz. In 2018, Wen Lei and Yong-Xin Guo [15] designed a Dual-Polarized Wideband Conformal Loop antenna with 285.75 mm$^3$ volume and has a wide bandwidth of 293 MHz.

In the proposed antenna using fractal geometry which can be defined as the same object repeats at varying degrees of miniaturization. So it is considered as a self-similar object which was repeated several times with the same shape but with a smaller size. One of the most important applications of fractal geometry is the designing of antennas, by which we can obtain miniature size with wideband antenna due to its distinctive properties of space-filling and self-similarity properties. The space-filling reduces the size that takes by the antenna by increases the effective electrical length of current, while the self-similarity property is repeating the same object with smaller size over the same area so it leads to produce wideband antenna by lapping various resonant frequencies together. [16], [17] and [18].

The antenna was designed by using CST studio 2014. Since the antenna operates inside human body, it simulated inside predefined tissues model that exist in program simulation. The rest of this paper is organized as follows: Section 2 presents the antenna structure. Section 3 produces the simulation method. Section 4 shows the measured results. Section 5 shows Parametric Study of Proposed Antenna, Section 6 shows the discussion of results. Section 7 presents the related work and comparison, and finally, the paper conclusions are presented by Section 8.

2. Antenna Structure
The proposed antenna has star shaped slots inside pentagonal shaped fractal micro strip patch antenna (MPA) which used self-similar property of fractal geometry technique. The substrate is made of FR4 which has dielectric constant of 4.3, and Thermal Conductivity of 0.3. The ground and patch are made of pure copper. The antenna structure is shown in Figure 1.

The overall volume of antenna is 10 * 10 * 1.572 mm$^3$ with substrate thickness h = 1.5mm. The proposed antenna is designed based on an iterative method up to the 4th iteration for obtaining a wide bandwidth. Steps to design antenna are:

![Figure 1. Antenna structure.](image-url)
Step 1: Initially, the patch has a shape of a pentagonal with outer radius $R_1$ of 3.4 $mm$ and inner radius $R_2$ of 2.65 $mm$. Then, two inverse squares are etching inside the pentagonal to form a star slot as shown in Figure 2.

![Figure 2. First iteration shapes.](image)

Step 2: In second iteration, a second pentagon is etched inside the first star slot and second two inverse squares (star) are etched as shown in Figure 3.

![Figure 3. Second iteration shapes.](image)

Step 3: The same procedures were repeated to obtain the third and fourth iterations with smaller sizes as shown in Figure 4 and Figure 5.

![Figure 4. Third iteration shapes.](image)
The partial ground has been used with length of 2.27 mm which is altered to obtain higher bandwidth. After the process of optimization, the parameters of the proposed antenna are listed in Table 1. Microstrip line feed technique has used with three widths for impedance matching which must be 50 Ω [19]. The antenna operates at UWB frequency from (4.7 to 9.18 GHz) with bandwidth of 4.49 GHz and resonance frequency at 5.45 GHz. The dimension size of the proposed antenna details is presented in Table 1.

| Parameters                        | Sizes (mm) |
|-----------------------------------|------------|
| Width of ground and substrate     | 10         |
| Length of substrate               | 10         |
| Length of ground                  | 2.27       |
| Thickness of substrate            | 1.5        |
| Thickness of patch and ground     | 0.036      |
| Width of feed line respectively   | 0.7, 1.1, 2.74 |
| \( W_1, W_2, W_3 \)              |            |
| Length of feed lines respectively | 1, 0.85, 1.15 |
| \( L_1, L_2, L_3 \)              |            |
| Radius of pentagonal Respectively | 3.4, 2.65, 2, 1.35, 0.8 |

3. Simulation set up
CST Microwave Studio program has been used to simulate the antenna performance. The predefined tissue materials with CST program used to create an environment similar to the stomach to get semi-precise results. The antenna is put inside the capsule which built-in program with Teflon material. After that, the capsule is surrounded by four layers of human body tissue which are stomach, muscle, fat, and skin respectively that create the human body model which is shown in Fig.6 (a) and (b).
4. Measured Results

4.1 Free space:
First, the antenna was simulated in free space. The return loss and voltage standing wave ratio (VSWR) have been shown in Figures 7 and 8 respectively. The return loss curve shows that the antenna has good impedance matching in frequency band of 4.74 – 15.5 GHz and the minimum value of return loss is -25.95 dB at 5.88 GHz.
The advantage in this antenna temple is that, it has low gain at resonance frequency so can be used as implantable antenna for biomedical applications [20].

4.2 Inside human body:
In Figure 9 and Figure 10, the antenna return loss and VSWR respectively are shown when placed inside human body model. The antenna has frequency band of 4.7 – 9.81 GHz and return loss of -10 dB bandwidth of 5.11 GHz. The return loss has minimum value at 5.45 GHz with -25.1 dB.

Figure 7. Return loss (in free space).

Figure 8. VSWR (in free space).

Figure 9. Return Loss of the proposed antenna inside human body.
In Figure 11, the 3D radiation pattern of antenna inside human body model is shown. The antenna has Omni-directional pattern which desired in capsule to radiate in all direction regardless of the direction of the capsule inside the body. The polar of 2D radiation pattern is shown in Figure 12 of the proposed antenna as an Omni-directional radiation.

Figure 10. VSWR characteristic inside human body.

Figure 11. 3D radiation pattern at resonance frequency (inside human body)

Figure 12. 2D radiation pattern at 5.45 GHZ.
All results above is summarized in Table 2.

Table 2 results summary.

| Parameters       | values     |
|------------------|------------|
| Bandwidth        | 5.11 GHz   |
| Impedance Bandwidth | 71.1%     |
| Resonance Frequency | 5.45 GHz  |
| Gain             | -3.25 dB   |
| Directivity      | 6.88 dB    |

5. Parametric Study Of Proposed Antenna

Feed line width and ground length are considered major factors affecting band width, so changing of them will lead to optimize the results.

5.1. Effect Of Changing Feed Line Width

Feed line width $W_2$ will optimize. It will have value of 0.35 mm, 0.45 mm and 0.55 mm. Figure 13 shown that; higher bandwidth can obtain at 0.55 mm. The results for different values of $W_2$ are summarized in Table 3

Table 3 Effect of feed line width.

| $W_2$ (Feed line width) | S11 (dB) | Resonance frequency (GHz) | Bandwidth (%) |
|-------------------------|----------|---------------------------|---------------|
| 0.35                    | -19.72   | 5.41                      | 60.5%         |
| 0.45                    | -21.07   | 5.43                      | 61.25%        |
| 0.55                    | -25.11   | 5.46                      | 69.9%         |

Figure 13. Effect of feed line width.
5.2. Effect Of Changing Ground Length

Ground length $L_g$ will optimize. It will have value of 2 mm, 2.27 mm and 2.54 mm. Figure 14 shown that; higher bandwidth can obtain at 2.27 mm. The results for different values of $L_g$ are summarized in Table 4.

Table 4. Effect of ground length

| $L_g$ Ground length | S11 dB | Resonance frequency(GHZ) | Bandwidth (%) |
|---------------------|--------|--------------------------|---------------|
| 2.17                | -23.98 | 5.39                     | 37.55%        |
| 2.27                | -25.11 | 5.46                     | 72.15%        |
| 2.37                | -26.52 | 5.55                     | 65.33%        |

Figure 14. Effect of ground length.

6. Discussion of Results

By looking at the results in the free space and inside the human body, there was a difference in bandwidth and a slight shift in the resonance frequency due to the effect of the body tissues on the antenna performance.

The antenna designed for biomedical telemetry is based on the study of the materials and the propagation characteristics in the body. The human body consists of many tissues with different permittivity and conductivity, which leads to different dielectric properties. Where the dielectric constant of air is 1 while for the stomach is 55, therefore, the antenna is heavily affected. Also, the total power is consumed easily in the human body so the efficiency of the antenna becomes lower than free space.

7. Related work and comparison

Table 5 shows comparison of the proposed antenna based on size and bandwidth with different micro strip patch antennas.
Table 5. Comparison with different micro strip patch antennas

| No | Configuration                                | size                  | Bandwidth    |
|----|----------------------------------------------|-----------------------|--------------|
| 1  | Circularly polarized helical antenna [10]    | height=3.81mm         | 80 MHz       |
| 2  | Dual polarized wide band conformal loop antenna [15] | 15 * 15 * 1.27 mm   | 293 MHz      |
| 3  | Circular patch micro strip antenna [11]      | 10 * 9 * 0.75 mm      | 501.8 MHz    |
| 4  | Conformal trapezoid strip antenna [9]        | N/A                   | 1.7 GHz      |
| 5  | Circular patch antenna with two ring slots [12] | 10 * 10 * 1.1 mm    | 1.84 GHz     |
| 6  | Folded patch antenna [13]                    | 24 * 28 * 0.987 mm    | 2.268 GHz    |
| 7  | Circular patch antenna [14]                  | 12 * 8 * 1.97 mm      | 3 GHz        |
| 8  | The proposed antenna                          | 10 * 10 * 1.572 mm    | 5.1 GHz      |

8. Conclusions
In this paper, the UWB fractal patch antenna was designed which has dimensions of 10 x 10 mm2. The use of fractal geometry in the design of the antenna has a significant effect on increasing the bandwidth. The antenna was simulated in free space and inside the human stomach model that created using predefined tissue materials with CST program, there is a clear difference in results between these two environments due to the great influence of the body tissues on the performance of the antenna. It works at a bandwidth of 5.1 GHz, so it has a high data rate with an Omni-direction radiation pattern which important performance for a capsule that has involuntary movement inside the Digestive system. The simulation results of return loss (S11) are -25.1 at 5.45 GHz and voltage standing wave ratio (VSWR) 1.13.

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