Wearable Inset-Fed FR4 Microstrip Patch Antenna Design

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Abstract. This project proposes the design of a wireless body area network (WBAN) microstrip patch antenna covered by the jeans fabric as the outer layer operating at the center frequency, $f_c$ of 2.40 GHz. Precisely, the microstrip patch antenna with the inset-fed edge technique is designed and simulated systematically by using the Keysight Advanced Design System (ADS) software where the FR4 board with the dielectric constant, $\varepsilon_r$ of 4.70, dissipation factor or loss tangent, $\tan \delta$ of 0.02 and height, $h$ of 1.60 mm is the chosen dielectric substrate. The wearable microstrip patch antenna design is then fabricated using the FR4 printed circuit board (PCB) material, hidden inside the jeans fabric, and attached to clothing, such as a jacket accordingly. Simulation and fabrication measurement results show that the designed microstrip patch antenna characteristics can be applied significantly within the industrial, scientific, and medical (ISM) radio band, which is at $f_c = 2.40$ GHz.

1. Introduction

In a communications system, antenna is the most important part, which operates as a transducer for sending and receiving the electromagnetic waves. In this case, antenna becomes as an electrical device or conductive element, which helps convert the radio frequency (RF) or microwave to electrical power and vice versa. Recently, there is a rapid growth of wearable antenna development. Wearable antennas are becoming more and more lightweight that can be integrated into or hidden inside clothing to improve communication links and support a so-called wireless body area network (WBAN) application [1-2].

The WBAN antenna can be used as clothing used for communication purposes, which includes tracking and navigation, mobile computing, public safety and wireless communication [3]. Moreover, the wearable WBAN antennas need to be integrated within everyday clothing, be low profile, light weight, small size and be hidden as much as possible [4]. Several frequency bands have been assigned for WBAN systems, which are the Medical Implant Communication System band (MICS: 400 MHz), the Industrial Scientific Medical band (ISM: 2.40 GHz and 5.80 GHz), and the Ultra-wideband (UWB: 3.00-10.00 GHz), respectively [5].

This project aims to design a wearable microstrip patch antenna design. The main requirement is to design and fabricate the microstrip patch antenna using the FR4 substrate material covered by the jeans fabric as the outer layer. The FR4 microstrip patch antenna is hidden inside the jeans because of its small size and lightweight.
In order to design a microstrip patch antenna, some of the basic requirements need to be considered, such as radiation, bandwidth and also the parameter of patch antenna [6]. There are two major problems of the microstrip patch antenna, which are narrow bandwidth and low efficiency [7]. Narrow bandwidth means having limited bandwidth and difficulties to capture the signals whereas low efficiency means that the designed antenna cannot operate properly. Antenna size and ground partial location is related to the operating bandwidth and antenna efficiency. The larger antenna and ground partial on substrate will help to improve higher operating bandwidth and higher antenna efficiency.

To overcome the narrow bandwidth constraint, the antenna is designed with the inset-fed edge technique at the operating bandwidth greater than 200 megahertz (MHz). The inset-fed microstrip patch antenna can capture more signals with the improved accuracy. In order to solve for the low efficiency limitation, the antenna is designed and fabricated with the aim of producing both simulated and measured return loss, $S_{11}$ lower than -10.000 decibel (dB) ideally to obtain a good performance [2].

2. Antenna Structure and Design
In this project, a microstrip patch antenna is chosen because it has some advantages compared to other microwave antennas, which includes lightweight, thin profile configuration, cheap cost of fabrication, and can operate at a broad range of 100 MHz to 100 GHz frequency. Normally, the microstrip antenna consists of a conductive material, which radiates and absorbs electromagnetic wave, dielectric substrate, and ground plane. The conductive material and ground plane are basically made up of a thin copper, which is a good material to conduct electrical energy. The conductive material is embedded on the intermediate layer to be exposed to free air. The performance of the conductive material in converting electromagnetic wave to electrical energy and vice versa depends directly on feeding method, shape and dimension (e.g. width, $w$ and length, $l$) applied [8]. Figure 1 shows the methodology applied in designing and fabricating the wearable microstrip patch antenna in this study.

![Figure 1. Methodology Flow Chart](image-url)
2.1 Patch Antenna Design

2.1.1 Calculation of Microstrip Patch Antenna

Figure 2 shows the rectangular microstrip patch antenna structure consists of conductive, substrate and ground planes. The microstrip patch antenna with the inset-fed design depends upon three critical parameters, which are the center frequency, $f_c$ or resonant frequency, $f_r$, dielectric constant, $\varepsilon_r$, and height of dielectric substrate, $h$, respectively [9]. The $f_r$ selected for this design is 2.40 GHz, which is in the ISM band. The dielectric material used is the FR4 board with the $\varepsilon_r$ of 4.70, dissipation factor or loss tangent, $\tan \delta$ of 0.02 and $h$ of 1.60 mm, respectively. The width of the patch, $W$ is calculated using (1):

$$W = \frac{c}{2f_r\left(\frac{\varepsilon_r + 1}{2}\right)}$$

(1)

According to (1), $c$ is the speed of light where the increment of $\varepsilon_r$ will decrease the size of the antenna patch. The actual length of the patch is computed as in (2):

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L$$

(2)

Based on (2), the effective dielectric constant, $\varepsilon_{reff}$ is defined as in (3):

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r + 1}{2}\right) + \left(\frac{\varepsilon_r - 1}{2}\right) + \left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}}$$

(3)

Moreover, the length extension, $\Delta L$ is calculated as shown in (4) below:

$$\Delta L = 0.412h \left[ \frac{\varepsilon_{reff} + 0.3}{\varepsilon_{reff} - 0.258} \right] \left[ \frac{W}{h} + 0.264 \right]$$

(4)

2.1.2 Calculation of Microstrip Line Feed

Then, the microstrip synthesis, $H$ with characteristic impedance, $Z_0$ equals to 50 $\Omega$ is generated using (5):
\[ H = \left( \frac{Z_0 \sqrt{2(\varepsilon_r + 1)}}{119.9} \right) + \frac{1}{2} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \left[ \ln \left( \frac{\pi}{2} \right) + \frac{1}{\varepsilon_r} \ln \left( \frac{4}{\varepsilon_r} \right) \right] \]  

Based on (5), the width of microstrip line feed, \( W_f \) is computed as in the following (6):

\[ W_f = \left[ \left( \frac{e^H}{8} - \frac{1}{4e^H} \right)^{-1} \right] \times 1.60 \text{ mm} \]

Moreover, the length of microstrip line feed, \( L_f \) is obtained through (7) below:

\[ L_f = \theta \times \frac{\lambda_g}{360^\circ} \]

where,

\[ \lambda_g = \frac{c}{f \sqrt{\varepsilon_{ref}}} \]

2.1.3 Calculation of the Antenna Ground Dimension

The length of the ground plane is calculated using the following (9):

\[ L_g = L + 6h \]

Moreover, the width of the ground plane is computed as shown below (10):

\[ W_g = W + 6h \]

After finding the microstrip patch antenna, line feed and ground dimension values through calculations using (1) - (10), the design of the wearable microstrip patch antenna schematic and layout is designed and modeled using the Keysight Advanced Design System (ADS) software. Deploying the ADS built-in controllers, optimization of some key parameters are also performed to obtain the optimum simulated antenna performance measurements.

2.1.4 Calculation of the Inset-Fed Line

This is the last step of design process, which is to calculate the parameter of inset-fed line. It assumes that the input impedance is 50.000 \( \Omega \), the width of microstrip feed line, \( W_f \), the length of inset, \( F_i \) and the gap between the patch and the inset-fed line, \( G_{pf} \), respectively. Figure 3 shows the designed inset-fed microstrip patch antenna parameters, which are recalculated after some troubleshooting processes using the ADS software to achieve the resonant at \( f_r = 2.40 \text{ GHz} \) and simulated return loss, \( S_{11} \) less than -10.000 decibel (dB), respectively. Figure 4 displays the layout of the wearable microstrip patch antenna using the inset-fed edge technique.
In this project, the wearable microstrip patch is inset-fed at an edge. Edge inset-feeding technique on a microstrip patch has few advantages compared to other direct contact and non-contact microstrip feeding technique. One of the advantages is power distribution scheme, which is easy to be fabricated. In this design, the inset-fed network and radiating patches will be etched on the same board. Table 1 shows the list of microstrip patch antenna parameters before and after undergoing optimization using the ADS software. Fig. 5 shows the schematic of the microstrip patch antenna with the optimal parameters of microstrip line (MLIN), microstrip line open-circuited stub (MLOC), and microstrip asymmetric coupled line (MACLIN), respectively. The MACLIN is added in the design to create the inset-fed line. In this case, width 1, $W_1$ and width 3, $W_3$ are equal and calculated based on the width of the substrate, $W$ as in (11):

$$W_1 = W_3 = \frac{W - 9}{2}$$

On the other hand, the width 2, $W_2$ is equal to the width of microstrip line feed, $W_f$ as in (6). Moreover, $S_1$ and $S_2$ are the gaps of the inset-fed where both are equal to $W_f$. 

**Figure 3.** Inset-Fed Line Parameters

**Figure 4.** Edge Inset-Feeding Technique Layout
Table 1. Optimal Antenna Parameter

| Parameter                        | Non-Optimal Value | Optimal Value |
|---------------------------------|-------------------|---------------|
| Length of Patch Antenna, $L$    | 30.00 mm          | 21.00 mm      |
| Width of Patch Antenna, $W$     | 37.00 mm          | 37.00 mm      |
| Length of Line Feed, $L_f$      | 18.00 mm          | 18.21 mm      |
| Width of Line Feed, $W_f$       | 3.00 mm           | 3.00 mm       |

Figure 5. Microstrip Patch Antenna Design in Schematic

Figure 6. Fabricated Inset-Fed Microstrip Patch Antenna

Figure 6 shows the fabricated microstrip patch antenna after being soldered with a 50.000 Ω-impedance subminiature version A (SMA) probe connector. The purpose is to connect the antenna with a vector network analyzer (VNA) via a radio frequency (RF) coaxial cable for performance measurements. Figure 7 (a) and (b) below display the fabricated microstrip patch antenna is covered by the jeans fabric and then is attached to the clothing, such as a jacket. In this case, the inset-fed microstrip patch antenna design is considered as the wearable antenna that can support various WBAN applications operating at $f_c = 2.40$ GHz.

Figure 7. (a) FR4 Covered with the Jeans Fabric  (b) Microstrip Antenna Attached on Clothing
3. Result and Discussion
In this section, both simulation and actual measurements of the inset-fed microstrip patch antenna performance in the free space is discussed. The simulation is performed by using the Keysight ADS software whereas the measurement is prepared using the Agilent E5071C Vector Network Analyzer (VNA). The antenna performance is simulated and measured precisely in terms of return loss ($S_{11}$), impedance matching, three-dimensional (3D) radiation pattern, and gain.

$S_{11}$ in an antenna is a parameter that states the total of power that is lost to the load and does not return as a reflection. The designed antenna should ideally achieve the return loss, $S_{11}$ lower than -10 dB to be considered as a good performance [2]. Figure 8 depicts the simulated $S_{11}$ magnitude in dB of the designed inset-fed microstrip FR4 patch antenna. It is clearly shows that the microstrip patch antenna located on the free space has the $S_{11}$ parameter of -15.284 dB at the $f_c = 2.40$ GHz.

![Figure 8. Simulated Return Loss, $S_{11}$](image1)

Figure 9 below shows the $S_{11}$ measurement on the fabricated FR4 microstrip patch antenna, which is equal to -30.601 dB at the shifted $f_r$ of 2.33 GHz.

![Figure 9. Measured Return Loss, $S_{11}$](image2)

Impedance matching is important in antenna design where the input impedance, $Z_{in}$ of an antenna should be practically near to the characteristic impedance, $Z_0$ of 50.000 $\Omega$ in this study. If $Z_{in}$ does not match with $Z_0$, the signal will be reflected back to the amplifier, hence, will not be radiated by the antenna. By using a marker function, the normalized impedance simulation using the ADS software
is equal to 1.000 - j0.349 Ω as shown in Figure 10. So, multiply by 50 the impedance simulation magnitude is equal to 52.958 Ω. Figure 11 shows the Smith chart where the measured impedance matching using the Agilent E5071C VNA is equal to 49.815 Ω at the frequency of 2.33 GHz. In general, the magnitude impedance matching measurement is also acceptable and almost equal to the simulation, respectively.

Figure 10. Simulated Impedance Matching

Figure 11. Measured Impedance Matching

Gain, directivity and radiated power are also antenna performance indicators. Figure 11 shows the gain, directivity, efficiency, and power radiated simulated measurements versus frequency. Precisely, the designed FR4 microstrip antenna has the simulated gain of 5.20905 deci-bel isotropic (dBi), directivity of 6.28795 dBi, input power of 2.42596 milliwatt (mW), and radiated power of 1.89231 mW at $f_c = 2.40$ GHz, respectively. In this case, the directivity of the designed microstrip antenna is theoretically in the normal range, which is between 5.00000 dBi and 8.00000 dBi. The expression dBi basically defines the gain of an antenna system relative to an isotropic radiator at the ISM radio band. Moreover, the antenna has acceptable radiation efficiency. The radiation efficiency is based the percentage of the radiated power-to-input power ratio, which is 78%. In summary, all the simulated and actual measurements indicate that the microstrip patch antenna has a good and adequate performance.

Figure 12. Antenna Performance Parameter vs. Frequency
4. Conclusions

In sum, the designed FR4 microstrip patch antenna covered with the jeans fabric as the outer layer and then attached to clothing, such as a jacket proven can have a satisfactory performance operating at the ISM band, which is $f_c = 2.40$ GHz. However, there is a deviation between simulated and actual $S_{11}$ measurements where the $f_c$ shifts from the desired 2.40 GHz to 2.33 GHz. This might be due to the manual antenna fabrication process deficiency, SMA connector intermittent, coaxial cable loss, and radiated power loss to surrounding, respectively. However, the actual $S_{11}$ measurement, which is -30.601 dB is far below than -10.000 dB threshold. Similarly, the actual impedance matching magnitude deviates from the simulated impedance matching magnitude from 52.958 Ω to 49.815 Ω. The result for actual impedance matching magnitude is still acceptable, which is near to the predefined characteristic impedance, $Z_0$ of 50.000 Ω. Furthermore, substrate relative permittivity, substrate thickness, and conductive conductivity are critical in affecting the dimension values of microstrip patch and inset-fed line.

For future work, different substrates as the dielectric materials and fabrics as the outer layers can be possibly deployed and compared in terms of antenna radiation performance. Furthermore, this design can also be extended where many microstrip patch antennas will be positioned in certain geometry configuration of array. Besides, the design can also be applied with sensor to construct a portable Internet of Things (IoT) sensing device or rectifier circuit to develop a rectenna, which can convert harvested radio frequency (RF) energy into the direct current (DC).

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