Design of High Gain and Improved Front-to-Back Ratio Multilayer Microstrip Patch Antenna using Modified Feed Line

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ABSTRACT A novel high gain miniaturized rectangular microstrip patch antenna is proposed with a high front-to-back ratio (FBR) using a modified feed line and two single-sided substrate layers to operate at 2.4 GHz frequency. The feed line is modified using a step impedance technique to achieve resonance at the operating frequency. The matched impedance of the feed line helps achieve enhanced bandwidth and antenna miniaturization. The substrate layers are introduced to achieve an enhanced gain and FBR of 6.329 dBi and 27.64 dB, respectively. The impedance bandwidths of 106.9 and 94.1 MHz are achieved for the two separate designs. These proposed designs have a total circuit area occupancy of 0.4λ0 × 0.304λ0. The antenna has been designed and fabricated using FR4 substrate material. The measured results are in good agreement with the simulated results.

1. INTRODUCTION

An antenna plays a key role as the backbone of a wireless communication system. It involves various applications starting from mobile phones to the Internet of Things and from space to underwater communication. These applications demand reliable, secure, and economic infrastructure. A high gain antenna is most preferable for all applications. A compact unidirectional antenna has also gained much attraction due to the rapid advances in wireless systems, such as borehole radar (Srivastava et al. 2020), indoor communication (Liang et al. 2013), remote sensing (Kajiwara 1994), ground-penetrating radar (Zhu et al. 2015), medical examination (Lestari et al. 2005; Zhu et al. 2015), and WLAN and WIMAX applications (Alam and Abbosh 2016). A microstrip patch antenna (MPA) is the most suitable for modern-day wireless communication. MPA consists of a conducting radiating patch and a ground plane, which are separated by a dielectric material (dielectric substrate), as shown in Figure 1. The dielectric constant of the substrate (εr) is typically in the range of 2.2–12 (Balanis 2016). The patch can be of any uniform or non-uniform shape because a perfect electric conductor is used. The most suitable shape is any uniform one, such as rectangle, square, circle, and hexagon, which is etched on the dielectric material. In these antennas, fringing fields between the patch and the ground plane play a critical role in radiation, as illustrated in Figure 1 (Balanis 2016). It has the advantages of small size, ease of fabrication, and cost-effectiveness but suffers from major drawbacks, such as low gain, narrow bandwidth, and high return loss. To enhance MPA performance, many studies have been conducted to develop different methodologies. High gain is one of the major requirements for long-distance communication. Basically, the gain of an antenna is the amount of radiation in a particular direction (Balanis 2016). Achieving high gain from an antenna is possible in different ways, such as using a hexagonal patch and six triangular slots in the ground (Mandal and Sarkar 2013), L-shaped slot (Kelothu et al. 2012), mushroom-type array (Cao et al. 2019), split-ring resonator-based metamaterial superstrate (Gangwar et al. 2017), and slotted array technique.

In this work, a novel inset feed RMPA is designed to enhance gain using a modified feed line and a simple substrate layer at the top of the microstrip patch at a height of 3 mm and at the bottom of the ground plane at a height of 2.5 mm to enhance front-to-back ratio (FBR), as displayed in Figure 2. The antenna is designed at 2.4 GHz operating frequency. The parasitic substrate layers are a single-sided FR4 substrate that is modified to obtain the best result. The simulation is carried out in the HFSS 15.0 simulator.

2. MATERIALS AND METHODS

The FR4 substrate material (substrate height is 1.59 mm, relative permittivity is 4.4, and loss tangent is 0.02) is used for...
the antenna design and fabrication. The design methodology is described in the following sections.

2.1 Design of MPA

According to the transmission line model of RMPA analysis, the following equations must be considered to determine all the design parameters (Balanis 2016).

**Patch width:**

\[
W = \frac{c}{2f_r \sqrt{\frac{\varepsilon_r + 1}{2}}}
\]  

(1)

**Effective patch length:**

\[
L_{eff} = \frac{c}{2f_r \sqrt{\varepsilon_{eff}}}
\]  

(2)

**Length extension due to fringing fields:**

\[
\Delta L = \varepsilon_{eff} + 0.3 \times \frac{N}{5} + 0.258 \times \frac{W}{\lambda_0} + 0.8
\]  

(3)

**Patch length:**

\[
L = L_{eff} - 2\Delta L
\]  

(4)

**Inset gap:**

\[
g = \frac{c}{\sqrt{\varepsilon_{eff}}} \times 4.65 \times 10^{-12}/f_0
\]  

(5)

**Feed width:**

\[
W_f = h\left(\frac{377}{50\sqrt{\varepsilon_{eff}}} - 2\right)
\]  

(6)

**Inset distance:**

\[
Y_0 = \frac{L}{\pi} \cos^{-1}\sqrt{\frac{R_{in}(Y = 0)}{R_{in}(Y = Y_0)}}
\]  

(7)

where:

- \(R_{in}(Y = 0) = \frac{1}{G_r} = \) resonant input resistance when the patch is fed at the radiating edge, \(G_r = \frac{1}{2\pi} \) = Self-conductance of the radiating patch.
- \(R_{in}(Y = Y_0) = \frac{1}{G_r} = \) resonant input resistance when the patch is fed inside the radiating edge using a microstrip line (as in inset feed MPA).

The above equations form the basis to design a typical RMPA. For a particular design requirement when the design frequency and substrate material are decided, these equations give the numerical values of all design parameters, such as patch length and width, inset gap and distance, and feed width. The resonant input resistance plays a critical role in inset distance whose variation leads to a change in input resistance, which has a direct impact on antenna performance. In general, \(R_{in} = \) chosen as 50 \(\Omega\) (same as RF connector impedance) and accordingly, inset distance is decided. In Section 2.2, a conventional antenna is designed using all the design equations mentioned above to operate at 2.4 GHz using FR4 substrate material. However, the antenna performance (e.g., gain, FBR, bandwidth) is not up.
to the level that can serve any practical purpose. To overcome these demerits, the antenna structure is modified, as shown in subsections 2.3 and 2.4.

2.2 Design of conventional RMPA (Antenna-A)

Figure 3 illustrates a conventional MPA designed using FR4 substrate material based on the design equation stated in Equations 1–7. These parameters are found to have the following numerical values: L = 29.45 mm, W = 38.04 mm, g = 1.52 mm, Y₀ = 9.777 mm, and Wᵢ = 3.04 mm. The resonant input resistance, Rᵢ(r = 0) = 197.16 Ω when the patch is fed at the radiating edge and the desired resonant input resistance, Rᵢ(Y = Y₀) = 50 Ω due to inset feeding because the feeding element is a 50 Ω microstrip line. The length (Lg) and width (Wg) of the ground plane are 66.6 and 78.9 mm, respectively.

2.3 Design of RMPA with enhanced return loss (Antenna-B)

The return loss is improved by optimizing the feed line length, feed distance, and a square-shaped ground plane, as displayed in Figure 4. The design parameters are as follows: L = 38.04 mm, W = 28.8 mm, g = 1.64 mm, Y₀ = 7.452 mm, feed line length = 18.052 mm, Wᵢ = 2.94 mm, and the length (Lg) and width (Wg) of the ground plane are both 50 mm.

2.4 Design of RMPA with Enhanced Gain (Antenna-C)

The enhanced gain RMPA is designed using a modified feed line and a substrate layer above the patch, as shown in Figures 2a and 2b. The main reason for the feed line modification is to match the antenna impedance with the port impedance to achieve minimal return loss and miniaturized antenna structure. The feed line modification is carried out using the step impedance technique where a low impedance line is cascaded with a high impedance line or vice versa. The final modified feed line structure is obtained after the fifth iteration of arbitrary high and low transmission lines, as illustrated in Figures 5a and 6a, respectively. The shape of the substrate layer is modified and kept almost the same as the radiating patch to have a good coupling with it. Finally, the optimized shape is obtained using the trial-and-error method, which enhances the gain along the direction normal to the antenna. The design parameters are as follows: Wg = 50 mm, Lg = 38 mm, W = 25 mm, L = 29 mm, g = 0.85 mm, Y₀ = 5.552 mm, feed line length = 21.025 mm, and Wᵢ = 4.6 mm. The length and width of the ground plane is 38 and 50 mm, respectively. A single-layer FR4 substrate is kept at a height of 3 mm from the patch using four nonconducting posts at the four corners, and the design parameters are Wg = 50 mm, Lg = 38 mm, W = 38 mm, and L = 37 mm.

2.5 Design of RMPA with Enhanced Gain and FBR (Antenna-D)

The FBR of an antenna is the ratio of power radiated in the main radiation lobe and the power radiated in the back lobe. It gives information about the extent of backward radiation, which is expressed in decibels. FBR is improved using another substrate layer under the ground plane of Antenna-C at a height of 2.5 mm, as shown in Figures 2c and 2d. The final designed antenna is displayed in Figure 6 where the size and shape of this substrate layer are kept the same as the ground plane of the patch antenna to avoid alignment difficulty while locating below the patch.

3. RESULTS AND DISCUSSION

The simulated return loss plot and the 2D radiation pattern plot are shown in Figures 7 and 8, respectively for all the four different antennas operating at 2.4 GHz. The co- and cross-polarized components of the radiation patterns of all the four antennas are presented in Figure 9. The S-parameter measurement has been carried out using the Ro-
hde and Schwarz ZNB20 vector network analyzer. The measured return loss curves of Antennas C and D are shown in Figures 7b and 7c, respectively. The detailed simulated results are presented in Table 1 and a comparison between the simulated and measured results is provided in Table 2.

Figures 7a and 8a reveal that the return loss and gain of conventional antenna (Antenna-A) are −12.4 dB and 3.132 dBi, respectively. These values are very small to serve any practical purpose, such as Wi-Fi, Bluetooth, and mobile communication. The main reason behind this poor performance is the impedance mismatch between the antenna and feeding port. To improve the performance, i.e., to match the impedance, the feed line is modified using the step impedance technique, as shown in Figure 5a. This technique leads to better performance than the conventional antenna. The achieved return loss and gain are −33.65 dB and 3.87 dBi, respectively, as illustrated in Figs. 7b and 8b. Although the return loss has improved, the gain improvement is unsatisfactory. To increase the gain further, a substrate layer is incorporated above the patch at a distance of 3 mm, as displayed in Figures 2a and 2b. The shape of this parasitic layer is shown in Figure 5b, which is optimized to resonate at the operating frequency of 2.4 GHz. It results in the enhanced coupling between the patch and the layer itself, which increases the gain in the broadside direction. The enhanced gain is 6.329 dBi (Figure 8c), but the impedance mismatch between the antenna and port comes into the picture. This mismatch results in the return loss of −29.43 dB (Figure 7c), which is −33.65 dB without the parasitic layer. This gain enhancement along the broadside direction also leads to the back lobe (back radiation) enhancement, as shown in Figure 8c. This unwanted

| Antenna | Return loss (dB) | Maximum gain (dB) | FBR (dB) | IBW (MHz) | Antenna size (L × W) (λ/2) |
|---------|-----------------|-------------------|--------|-----------|---------------------------|
| A       | −12.4           | 3.135             | 19.95  | 45.1      | 0.53 × 0.631              |
| B       | −33.65          | 3.87              | 9.52   | 70.3      | 0.4 × 0.4                 |
| C       | −29.43          | 6.329             | 10.96  | 106.9     | 0.304 × 0.4               |
| D       | −20.32          | 6.327             | 27.64  | 94.1      | 0.304 × 0.4               |

| Antenna | Simulated value (dB) | Measured value (dB) |
|---------|----------------------|---------------------|
| C       | −29.43               | −20.7               |
| D       | −20.32               | −17.64              |

Figures 7. (a) Simulated return loss comparisons among Antenna-A, Antenna-B, Antenna-C, and Antenna-D; (b) return loss comparisons between the simulated and measured results of Antenna-C and Antenna-D.
back radiation decreases FBR, which degrades the antenna performance. To improve FBR, another parasitic layer is added below the ground plane at a distance of 2.5 mm (a total of two parasitic layers—one above the patch and another below the ground plane), as illustrated in Figures 2c and 2d. From the 2D polar plot that is shown in Figure 8d, the back radiation has been evidently minimized without altering the gain. The improved FBR is 27.64 dB compared with 10.96 dB, which is achieved with one parasitic layer above the patch. However, this layer further increases the impedance mismatch, which leads to a low return loss of −20.32 dB (Figure 7c). Figure 9 shows the polar plot of the co- and cross-polarized components of the E- and H-fields for all four antennas. In general, co-polar means when the polarization of the transmitting (test antenna) and receiving antenna (reference horn antenna) is the same; cross-polarization means when the polarization of both antennas is different. For a good transmitter, the co-polarized component of the E- and H-fields should have a higher magnitude than the cross-polarized component. This characteristic is well evident from the plots that are shown in Figure 9. For each of the designed antennas, the magnitude of the co-polarized component is higher than that of the cross-polarized component. 

In Antenna-C, the feed line is modified and a substrate layer is introduced. The feed line is modified to have impedance matching, which is required to miniaturize the antenna. The substrate layer helps achieve high gain, and its design is optimized to have the best result. This proposed technique of enhancing gain is quite simple and involves few design steps. This layer, at a height of 3 mm from the patch, acts as a resonant circuit to enhance the coupling between the patch and the layer. The resonating frequency of this layer is fixed by changing the separation (capacitance) and the layout of the copper plane (inductance). As a result, the surface current is induced in the layer, which, in turn, produces radiation. An in-phase addition of the radiation from the patch occurs and boosts up the cumulative radiation from the antenna. Given that these kinds of printed planar antennas support quasi-Transverse Electromagnetic wave, their gain therefore depends upon the material property. An antenna designed with a material having a low value of relative permittivity ($\epsilon_r$) has high gain, whereas an antenna designed with a thick substrate has high bandwidth (Balanis 2016). For the desired result, these two parameters are compromised. The proposed design is based on a low-cost FR4 substrate with $\epsilon_r = 4.4$ and substrate thickness = 1.6 mm. With this substrate material specification, achieving high gain with a cost-effective design is quite difficult. Although the gain is improved (6.329 dB) with the introduction of the substrate layer, it also introduces backward radiation with an FBR of 10.96 dB, as shown in Figure 7c. The back lobe is minimized with the help of another substrate layer at a height of 2.5 mm below the ground plane. This layer introduces a cross-polarization effect due to the out-of-phase addition of radiation from the substrate layer and the patch. As a result, FBR is improved to 27.64 dB, but the bandwidth has decreased from 106.9 MHz to 94.1 MHz because EM waves are restricted toward the broadside direction with the introduction of these substrate layers. Here the substrate layers comprise a thin copper sheet, i.e., it is a single-layer PCB. In place of the single-layer PCB, only a copper sheet (conductor layer) can be used, but it becomes tough to maintain the
proper shape of the isolated copper sheet above and below the antenna structure.

Figure 10 shows the fabricated prototype of the proposed antenna etched on FR4 substrate material using the MITS Electronics 21T Precision fabricating machine.

3.1 Performance comparison

The proposed work is compared with other existing studies and presented in Table 3. A microstrip Yagi array was proposed in DeJean and Tentzeris (2007) operated at 5.2 GHz. The design comprised seven patch elements, which acted as a reflector, driven element, and feeding structure. The feeding structure of the array consisted of a 50 Ω feed line that was transformed into a high impedance line through the use of a quarter-wave transformer. To ensure no disruption of the antenna radiation occurred due to the feed line radiation near the driven element, a high impedance line was employed in the feeding structure, and it increased FBR. The achieved impedance bandwidth and gain were higher than the proposed design, but FBR was lower and
antenna size was higher. In Guo et al. (2017), another microstrip Yagi array was proposed to have the operation at 5.14 GHz. The mode superposition technique was applied to achieve high FBR that consisted of an electromagnetic band gap (EBG) structure as a reflector and a quarter-wavelength patch antenna as a director. The EBG structure helped achieve high FBR that had also increased the array size. However, the increased FBR was still lower in the proposed work. In Hu et al. (2016), a microstrip fed planer slot antenna was proposed for MIMO array applications. To enhance FBR, a two-element array structure was proposed. The separation among the array elements was a quarter free-space wavelength. The proposed slotted two-element array antenna enhanced FBR but was lower than in the proposed work. In Wang and Dai (2012), a pair of symmetrical notched slits of uniform width was etched in the upper and lower edges of the ground plane of the monopole slot antenna to achieve a unidirectional radiation pattern and to achieve high FBR. The operating frequency was 2.4 GHz. However, the FBR value was less than the proposed antenna.

4. CONCLUSIONS

In this study, two inset feed RMPAs are designed. The antenna feed line is modified using the step impedance technique that helps miniaturize the antenna (antenna size is 0.304 λ₀ × 0.4 λ₀) and to achieve high return loss of 20.32 dB. Two parasitic single-layer substrate layers are incorporated to enhance the gain to 6.32 dBi and FBR to 27.64 dB in the operating frequency of 2.4 GHz. The size and shape of the layers are optimized using the trial-and-error method to obtain the best result. The FR4 substrate material is used to fabricate the antenna. For validation, the simulated results are compared with the measured results. Good agreements between them are reported.

AUTHORS’ CONTRIBUTIONS

PKD designed the study and carried out laboratory work. PKD, TM, and BKD analyzed the data. PKD and TM wrote the manuscript. All authors read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing of interests.

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