Research Article

A Novel Compact Microstrip Antenna with an Embedded $\lambda/4$ Resonator

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Received 16 August 2019; Revised 6 November 2019; Accepted 13 November 2019; Published 21 December 2019

Academic Editor: Hervé Aubert

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In this paper, a novel design of compact microstrip antenna (MA) using an embedded $\lambda/4$ resonator is presented. By utilizing the strong coupling between the $\lambda/4$ resonator and the radiation patch of MA, the resonant frequency of MA can be decreased. Besides, the $\lambda/4$ resonator is embedded in the patch, which does not enlarge the whole size of MA. Therefore, a compact antenna can be realized. In this paper, after the principle is stated, a sample antenna has been manufactured and measured to prove the predicted characteristics of our proposed antenna. The measurement agrees well with the simulation. Hence, the proposed method in this paper is quite suitable for the design of a compact antenna.

1. Introduction

As the key component of a wireless communication system, transmission and reception of radio waves are accomplished by the antenna. In modern satellite communication and radar systems, the antenna and RF front-end are tightly connected or even integrated together [1]. As well known, mobile terminals increasingly require lightweight, small size, and low-power consumption. Therefore, the miniaturization of the RF front-end becomes the focus in recent years and has brought about our main challenges due to the limitations of a small antenna. Because of the peculiarity of lightweight, low profile, and easy integration with systems, microstrip antennas (MA) are widely applied in modern wireless terminals [2]. With the requirement of compact terminals, compact MA is in required indeed [3].

Several technologies of compact MA have been introduced and discussed in [4, 5] such as using a shorting wall [6, 7], shorting pin loading [8], utilizing a high permittivity substrate [9], and using a split-ring resonator (SRR) [10–13] and irregular ground plane [14].

In [15], a substrate having high permittivity or permeability is used to decrease the resonant frequency of the antenna. Nevertheless, the substrate with high permittivity or permeability might cause strong surface wave on the antenna, which will decrease the gain as well as the efficiency of the antenna. In [16, 17], the size of MAs is reduced by loading short-circuit pins. The short-circuit pin close to feeding point introduces a coupling capacitor into the resonant cavity, which realizes the miniaturization of the antenna. However, such compact MAs tend to have a narrower bandwidth, and the cross polarization level on H-plane becomes worse. In [18], the size of the MA is decreased by etching grooves on the antenna. The slotted patch causes the current to meander around the edge of the grooves, which lengthens the current path. The longer the groove, the lower the resonant frequency of the antenna. But, the cross polarization becomes worse because of the distortion of the current distribution caused by the slots.

In this paper, a compact MA is presented, which is composed of a microstrip patch and a $\lambda/4$ resonator
embedded in the patch. The patch is coupled with the λ/4 resonator by the edge. The resonant frequency of MA can be decreased by coupling between the λ/4 resonator and the patch. As the λ/4 resonator is embedded in the microstrip patch, the antenna size is not enlarged. Furthermore, the proposed compact antenna has good performance such as low cross polarization. Finally, the proposed compact antenna is manufactured and measured. The measured results are in good agreement with the predicted consequences, which prove our design method.

2. Analysis of the Antenna

Figure 1 depicts the proposed compact MA. The proposed compact MA is composed of a rectangular patch and a λ/4 resonator embedded in the patch. The width and length of the resonator is \( W_1 \) and \( L_1 \), respectively. One end of the λ/4 resonator is open, while the other end is shorted by a shorting pin. Probe feeding scheme is introduced in our design. The feed pin is fed by a 50Ω SMA connector at a distance \( D \) from the open end of the λ/4 resonator. By the coupling between the λ/4 resonator and the rectangular patch (i.e., gap \( S \)), the radiation patch of MA is driven.

Figure 2 depicts the equivalent circuit represented by a LC-J-LCR network. The radiation patch is equivalent to a lossy parallel resonator composed of \( R_a \), \( L_a \), and \( C_a \). The coupling between the radiation patch and the λ/4 resonator can be supposed to be a J-inverter \( f_{12} \) equivalently, while the λ/4 resonator is equivalent to a lossless shunt resonator composed of \( L_r \) and \( C_r \).

Seen from the equivalent circuits in Figure 2, \( Y_b \) can be obtained as follows:

\[
Y_b = \frac{1}{R_a} + j\omega C_a + \frac{1}{j\omega L_r} \tag{1}
\]

Based on the cavity model theorem, the patch operates under its TM_{01} mode, and the closed-form formulas in [19] can be used to calculate the values of \( R_a \), \( L_a \), and \( C_a \).

By the basic design theory of the filter [20], the admittance \( Y_a \) can be obtained as follows:

\[
Y_a = \frac{f_{12}^2}{Y_b} \tag{2}
\]

The input admittance \( Y_{in} \) of the antenna can be established as follows:

\[
Y_{in} = Y_a + Y_c \tag{3}
\]

where \( Y_c \) can be obtained as follows:

\[
Y_c = j\omega C_r + \frac{1}{j\omega L_r} \tag{4}
\]

The values of \( L_r \) and \( C_r \) can be calculated by the empirical formulas based on the transmission line resonator principle [20].

By substituting (1), (2), and (4) into (3), input admittance \( Y_{in} \) can be obtained as follows:

\[
Y_{in} = \left\{ \frac{(1/R_a)f_{12}^2}{(1/R_a)^2 + (\omega C_a - (1/\omega L_r))^2} + j \left( \frac{(1/R_a)^2(\omega C_r - (1/\omega L_r)) - f_{12}^2(\omega C_a - (1/\omega L_a)) + (\omega C_a - (1/\omega L_a))^2(\omega C_r - (1/\omega L_r))}{(1/R_a)^2 + (\omega C_a - (1/\omega L_a))^2} \right) \right\} \tag{5}
\]

Table 1. Under simulation, the other dimension parameters are set as follows: \( W = 25.0 \text{ mm}, L = 35.0 \text{ mm}, W_1 = 2.0 \text{ mm}, L_1 = 18.0 \text{ mm}, \text{ and } D = 16.7 \text{ mm}. \) The substrate has a dielectric constant of 2.65 and a thickness of 1.5 mm, respectively.

Seen from the simulation in Figure 3 and Table 1, the resonant frequency of the antenna gradually moves toward the lower frequency band with the decrease of \( S \). At the same time, the simulated \( S_{11} \) of a traditional MA without embedded λ/4 resonator is also plotted in Figure 3 and Table 1. Obviously, compared with that of the traditional MA, the resonant frequency of the proposed MA with embedded λ/4 resonator is dramatically reduced.

Meanwhile, the matching between antenna and 50Ω SMA connector is achieved by adjusting the feed position \( D \). As depicted in Figure 4, good matching can be achieved as the feeding probe moves toward the shorting pins. In the case of simulation, the other dimension parameters are set as follows: \( W = 25.0 \text{ mm}, L = 35.0 \text{ mm}, W_1 = 2.0 \text{ mm}, S = 0.2 \text{ mm}, \text{ and } L_1 = 18.0 \text{ mm}. \)
Figure 1: Physical layout of the proposed compact MA: (a) top view and (b) side view.

Figure 2: Equivalent circuit of the proposed compact MA.

Figure 3: The simulated $S_{11}$ varies with $S$. 

Table 1: Resonant frequency varied with $S$. 

<table>
<thead>
<tr>
<th>The gap $S$ (mm)</th>
<th>Resonant frequency (GHz)</th>
<th>$S_{11}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.53</td>
<td>-17.68</td>
</tr>
<tr>
<td>0.4</td>
<td>2.62</td>
<td>-19.22</td>
</tr>
<tr>
<td>0.6</td>
<td>2.68</td>
<td>-19.89</td>
</tr>
<tr>
<td>Traditional MA</td>
<td>3.45</td>
<td>-18.15</td>
</tr>
</tbody>
</table>

Table 2: Geometric parameters of the proposed MA. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>25.0 mm</td>
<td>$L_1$</td>
<td>18.0 mm</td>
</tr>
<tr>
<td>$L$</td>
<td>35.0 mm</td>
<td>$D$</td>
<td>16.7 mm</td>
</tr>
<tr>
<td>$W_1$</td>
<td>2.0 mm</td>
<td>$S$</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>
3. Measured Results

After optimization carried out by electromagnetic simulation software CST STUDIOSUITE, the size parameters of a sample antenna are determined in Table 2. As mentioned above, the substrate has a dielectric constant of 2.65 and a thickness of 1.5 mm, respectively.

The sample MA is manufactured and measured to validate our design. Figure 5 displays the photograph of the proposed MA. The measurement of return loss and radiation pattern has been carried out by the Keysight E5071C vector network analyzer and SATIMO antenna electromagnetic field measurement system, respectively.

The simulated and measured S-parameters and VSWR are illustrated in Figure 6. The center frequency of the proposed antenna is about 2.59 GHz, and the corresponding value of $S_{11}$ and VSWR at 2.59 GHz is about $-16.5 \, \text{dB}$ and 1.40, respectively. The slight difference between the simulation and measurement might be caused by the manufacture tolerance. Obviously, the resonant frequency of the proposed MA with embedded $\lambda/4$ resonator is reduced compared with that of the traditional MA (without embedded resonator and $W = 25.0 \, \text{mm}$ and $L = 35.0 \, \text{mm}$), which can be observed in Figure 6. The phenomena of the preceding principle analysis are proved.

Seen from Figure 7, the measured gain in the band is around 4.0 dBi, which is in good agreement with the simulated result. Figure 8 depicts the simulated and measured radiation pattern at 2.59 GHz. The measurement is also consistent with the simulated results.

The proposed MA is also compared with the other reported compact MA in Table 3.
Figure 7: Simulated and measured radiation gain of the proposed MA.

Figure 8: Simulated and measured radiation patterns of the proposed MA at 2.59 GHz (a) E-plane (b) H-plane.

Table 3: Comparison of various compact MAs.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Methods</th>
<th>Freq. (GHz)</th>
<th>Size</th>
<th>Gain (dB)</th>
<th>Substrate εₖ</th>
<th>FBW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[22]</td>
<td>Defected ground structure</td>
<td>2.45</td>
<td>0.2λₑ₀ × 0.32λₑ₀</td>
<td>2.35</td>
<td>4.4</td>
<td>6.12</td>
</tr>
<tr>
<td>[23]</td>
<td>Magneto-dielectric metasubstrate</td>
<td>2.35</td>
<td>0.13λₑ₀ × 0.17λₑ₀</td>
<td>1.34</td>
<td>3.5</td>
<td>0.89</td>
</tr>
<tr>
<td>[24]</td>
<td>Sierpinski carpet slot</td>
<td>2.45</td>
<td>0.19λₑ₀ × 0.28λₑ₀</td>
<td>2.69</td>
<td>4.7</td>
<td>2.85</td>
</tr>
<tr>
<td>[25]</td>
<td>Loaded split-ring resonators</td>
<td>2.406</td>
<td>0.27λₑ₀ × 0.27λₑ₀</td>
<td>−2.02</td>
<td>4.02</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>The proposed antenna</td>
<td>2.59</td>
<td>0.22λₑ₀ × 0.30λₑ₀</td>
<td>4.0</td>
<td>2.65</td>
<td>1.16</td>
</tr>
</tbody>
</table>

FBW: fractional bandwidth; λₑ₀: guide wavelength.
Compared with the other antennas tabulated in Table 3, our proposed MA provides better performance in terms of gain and size.

4. Conclusion

A novel compact MA with an embedded $\lambda/4$ resonator is proposed in this paper. By using the coupling between the $\lambda/4$ resonator and the patch, the resonant frequency of the MA can be decreased. Since the resonator is implanted in the MA, the whole size of the antenna does not increase. Furthermore, the proposed compact antenna also has good performance, such as loss cross polarization and easy input matching. Finally, a prototype MA is designed, manufactured, and measured. The simulation agrees with the measurement, which further proves the design method proposed in this paper.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under project no. U1636108, the Key University Science Research Project of Jiangsu Province under project no. 17KJA470005, and SATIMO near-field antenna measurement system supplied by Nanjing University of Posts and Telecommunications.

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