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A PCB Planar Ground Radiation Antenna with Small Resonant Hole

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Abstract—Nowadays, compact terminal is one of the general requirements of modern wireless communication systems. The size of antenna limits further reduction of the structure size. To reduce size, a compact planar antenna based on Printed Circuit Board (PCB) is presented in this paper. This antenna has a new small-scale radiation coupling structure with a small hole and a matching element. This structure makes the ground structure of the circuit become an effective radiator through resonant coupling. This compact design avoids an independent big size radiator and the coupling structure over one quarter wavelength. Meanwhile, it can make the circuit have a good antenna matching effect at specific frequency by adjusting the lumped capacitance. Through the simulation and experiment, the design of antenna in 2.4 GHz ISM band is verified. The measurement results show that the antenna has 1.82 dBi gain and 151° beamwidth. It can be used in the compact wireless communication devices with advantages of low profile, adjustable frequency, and compact size.

1. INTRODUCTION

With the advancement and widespread application of portable electronic devices, communication systems are inclined to be compact. In the meantime, the limitation on antenna size has become more stringent by the requirement of higher performance. Various techniques have been used for antenna miniaturization (e.g., fractal structures, etched trenches, folding structures, high dielectric constant, and magnetic dielectric substrates). However, all the radiators in these structures require at least one quarter of the working wavelengths to radiate and receive electromagnetic waves, thereby limiting the size of the antenna.

Despite numerous challenges, antenna miniaturization technology has been researched due to application requirements. Meandered technologies to achieve compact antenna design have been presented [1–4]. In [4], the meta-material technique was used to design a 2.4 GHz PIFA antenna with the size of 30 mm × 26 mm × 10 mm and 5.29 dB gain. [5] presented an optimization of antenna radiation efficiency and size through metal and non-metallic regions. The miniature 10 mm × 10 mm antenna area develops 1.25 dBi peak gain for WLAN 2.4 GHz tablet computer [5]. In [6], a combination of concentric square rings and micro-strip antenna designs was introduced based on Koch curve fractal geometry for ultra-wideband (UWB) applications with the area of 44 mm × 43 mm at 3.1 GHz–10.6 GHz. [7] presented the design of a grooved meander line structure in the ground plane and the introduction of meta-material to miniaturize the antenna and enhance performance with the 35 mm × 35 mm ground plane at 5.6 GHz.

The technical method mentioned in these references either failed to achieve an antenna size smaller than 10 mm × 10 mm or weakened the radiation performance to reduce the size. In this paper, a compact PCB planar antenna using the resonance excitation edge current for radiation is proposed, in which specific resonant part size is 4 mm × 8 mm. The radiation current in the antenna design completely acts on the PCB ground structure, and it is different from a traditional slot antenna [8, 9]. When the

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traditional slot antenna needs a resonant slot with the size more than one quarter wavelength to radiate, the size of hole in this design is far less than the wavelength. Moreover, the edge current can be excited at any position near the edge of the PCB, so that it can be better adapted to the structure of the circuit system. Meanwhile, this antenna design is different from the antenna with a separate radiator isolated from the ground, such as micro-strip antenna [10, 11] or PIFA antenna [4]. There is no need for a separate radiator, and the size of the antenna can be further reduced. Such a design can be applied to various applications that require micro and portable wireless communication devices e.g., the Internet of Things (IoT).

The present study on communication is organized as follows. In Section 2, the principles and design of this compact antenna are introduced. In Section 3, the simulation results of the model as well as the actual experimental ones are described. Finally, in Section 4, a brief conclusion is drawn.

2. THEORY AND DESIGN

The ground structure in a PCB circuit is usually large enough to produce radiation effect, so it can be considered as an antenna. This method, to make the entire ground plane effective for radiation, often excites the chassis resonance mode by coupling [12, 13]. For instance, the traditional quarter-wavelength slot PCB antenna cut at the edge of the circuit ground plane induces radiated edge current, e.g., in [14–16]. In these traditional designs, the antennas which induce the radiated edge current still play a part of the radiation, so the excitation part cannot be too small to meet the limitations of the antenna design. To achieve effective ground plane radiation operation while avoiding excessive size, a compact resonant structure is proposed to excite the radiated current and receive signal effectively. In this antenna design, the signal feeds through resonance by the small hole with the matching capacitor and radiates along the edge of the PCB metal plate. Therefore, the area of the antenna can be saved, and the thickness of the antenna is the same as that of the circuit board to achieve a sufficiently compact effect.

To describe the basic implementation method, the circuit ground plane is equivalent to a piece of metal structure with a circular hole in the middle and connected with the edge through the notch, as shown in Fig. 1(a). When a high frequency AC signal was applied to both sides of the notch, current I_1 passed through the inner edge of the circular hole. In the meantime, the metal edge inside the circular hole showed inductance as L_1 for AC access [17]. The current I_1 flowed through the outer edge of the metal plate, also showing inductance as L_2. If the resistive loss was not considered, an equivalent AC access circuit model in which L_1 and L_2 would be connected in parallel can be formed, as shown in Fig. 1(b).

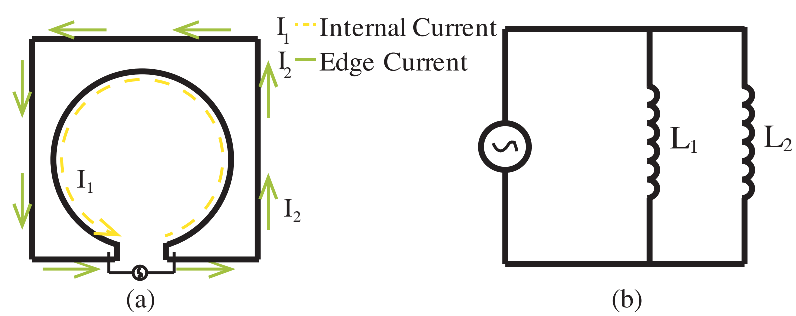

Figure 1. (a) Ground metal model with high frequency excitation. (b) Equivalent AC access circuit.

The total inductance of this equivalent circuit is:

$$L = \frac{1}{{}^{1}\!/\!_{L_1} + {}^{1}\!/\!_{L_2}} \tag{1}$$

When the radius of the circular hole was much smaller than the edge perimeter of the metal plate, the equivalent inductance L_1 would be significantly smaller than the edge inductance L_2, and the total circuit inductance was close to L_1. The radiation generated by the hole would be little when its size was also much smaller than the antenna wavelength. Furthermore, the current flowing out both sides of the notch could induce effective radiation on the metal plate outer edge, so that the metal plate had the function of antenna.

In general, due to the small impedance value and improper matching structure, it is always difficult to connect the metal plate edge to the circuit port with 50 Ω-characteristic impedance. In this paper, the capacitive lumped element and the small hole with equivalent inductance L_1 were employed to get resonant matching effect. As shown in Fig. 2, the π-type capacitance matching circuit composed of C_{p1}, C_{p2}, and C_{p3} formed a resonance matching circuit with the inductor L_1, thereby obtaining high-frequency resonant current on the outer edge of the circuit board to induce radiation.

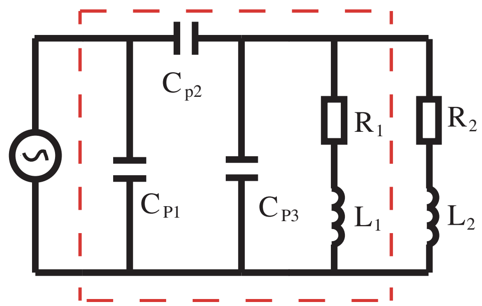

Figure 2. Equivalent AC access circuit with the capacitance matching circuit.

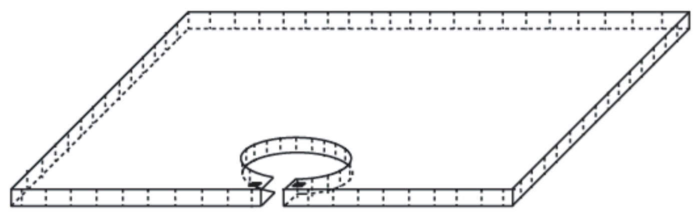

Figure 3. PCB antenna structure with circular hole and dense edge vias.

Such a ground metal model could be implemented by double-sided copper clad laminate and capacitive matching circuit through compatible PCB circuit process. The copper clad laminate refers to a structure in which thin layers of copper metal covered both sides of the dielectric layer, and the top and bottom metal layers could be connected at the edges through closely arranged metal vias. Fig. 3, similar to the structure of Fig. 1(a), shows the PCB antenna structure with circular holes on both metal layers of the copper clad laminate board, and metal vias were added to the edge of PCB. The hole and the spacing of vias were much smaller than the equivalent wavelength. In such a way, PCB acted as a monolithic metal structure for the high frequency current flowing at the edge. The hole on the board corresponded to the inductance L_1 in the equivalent LC resonance models. The inductance value could be estimated by the following formula [21]:

$$\mathrm{L}\,(\mathrm{nH}) = 1.257 \cdot \left[\ln\left(\frac{a}{W+t}\right) + 0.078\right] \cdot K_g \tag{2}$$

where a denotes the average radius of the circular hole; W is the line width; t is the line thickness; K_g is the correlation coefficient. Taking the values of $a = 3$ mm, $W = 0.5$ mm, and $t = 1.2$ mm into the formula, the equivalent inductance of the circular hole structure near 2.4 GHz is approximately 2.44 nH.

When the π-type capacitance matching circuit was introduced, the PCB antenna structure could be connected to a signal source with a 50 Ω-characteristic impedance feeder at the edge notch place. The resonance on the hole-structure and matching capacitors caused the signal current to flow along the edge of the PCB copper plate and induced an antenna radiation. As shown in Fig. 4, the simulation model with the matching excitation structure was constructed outside the FR4 PCB circuit (42 mm × 42 mm × 1.2 mm), consisting of three sets of series-parallel capacitors (C_{p1}: 0.68 pF, C_{p2}: 0.05 pF, C_{p3}: 0.165 pF); the coaxial interface and two sides of hole notch edge were connected by 2 mm width parallel lines with 2 mm spacing. The feeder also introduced a parasitic capacitor with a value around 1.7 pF. It can be found by the parameter simulation S_{11} at 1 GHz–6 GHz (Fig. 5(a)) that the antenna would work at 2.4 GHz. The parameter at 2.4 GHz S_{11} could reach −11.5 dB, of which the Y-Z plane radiation pattern is shown in Fig. 5(b).

To make this type of antenna design usable in the integrated design of the PCB RF transceiver circuit, the external circuit connection structure of Fig. 4 should be transformed into the PCB internal circuit connection structure. Accordingly, the antenna structure design shown in Fig. 6 was proposed.

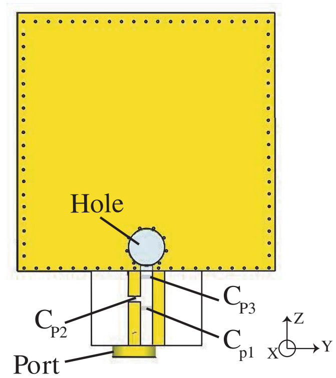

Figure 4. PCB antenna structure with external port excitation.

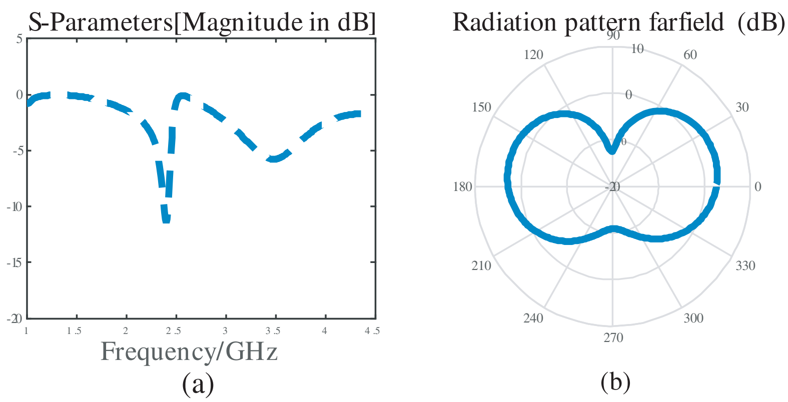

Figure 5. (a) S_{11} curve and (b) Y-Z plane radiation pattern of PCB antenna structure with external port excitation radiation at 2.4 GHz.

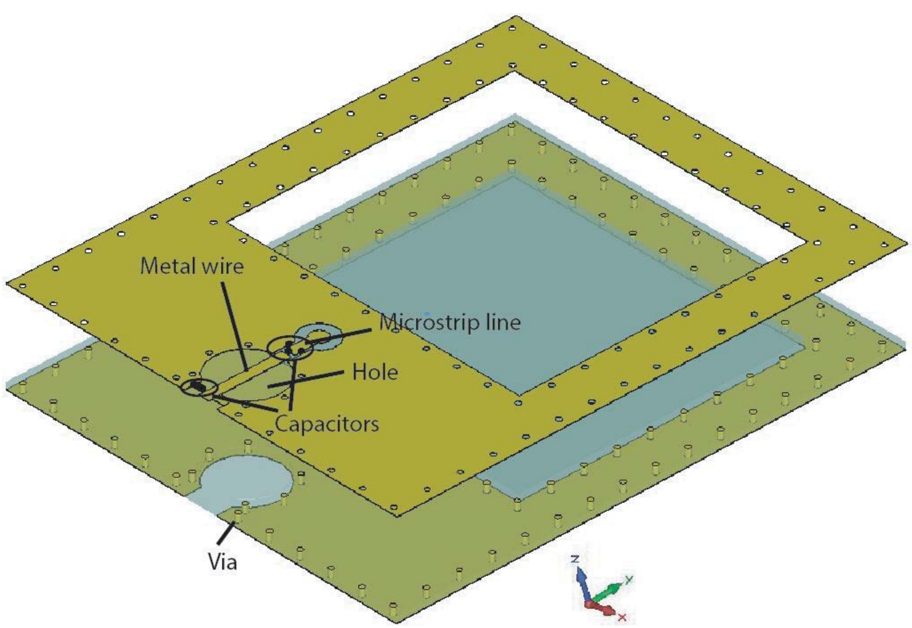

Figure 6. Compact PCB antenna structure.

In this design, the PCB also exhibited a circular metal hole structure near one edge of the board, and intensive vias were placed around all edges to connect the top and bottom metal layers. The internal circuit was connected with this structure via a metal wire. This wire passed through the middle of the hole on one side of the PCB, and it was connected to the metal plate at the notch place on the edge. Several capacitors were placed on the micro-strip line as matching circuit components. The metal wire was short-circuited to one side of metal plate at notch place of the edge of the hole and connected to the other side by a capacitor.

The comparison with the model of Fig. 4 suggests that the metal wire acted as the connection between the micro-strip and the ground of PCB with the hole. This antenna structure could be equivalent to the circuit model as shown in Fig. 7. Resonance was generated by four series-parallel matching capacitors C_{p1}–C_{p4} and equivalent inductance at the edge of the hole-structure L_1 and L_2, so the signal current flowed out along the edge of the board to induce radiation. The losses of the matching capacitor circuit and PCB are equivalent to R_1 and R_2, respectively. Through simulation of the surface current (as shown in Fig. 8 at 2.4 GHz with the size value of Table 1), it can be seen that the inner edge of the hole structure had high density current, and the current flowing through the notch flowed along the left and right portions of the ground plane in the "transmission line mode" [18, 19] and induced antenna radiation [14].

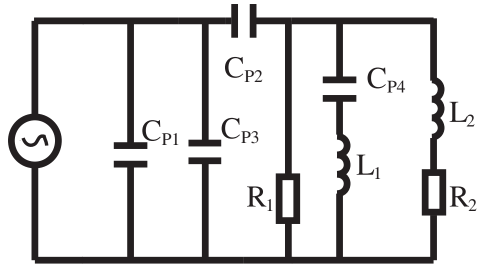

Figure 7. Equivalent AC access circuit of antenna in Fig. 6.

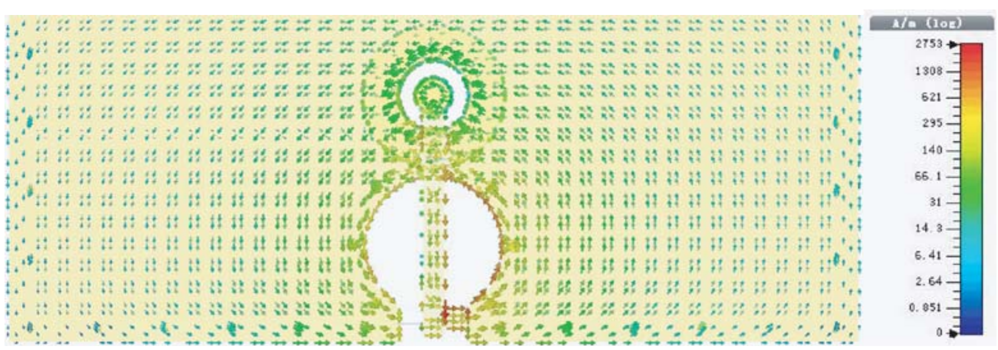

Figure 8. Simulated resonant current distribution results.

This antenna worked on the radiation of current flowing along the edge of the PCB excited by the resonance around the hole. Unlike other design methods using ground current radiation (e.g., the reference [11]), the antenna proposed in this paper could use a smaller hole structure to excite current and radiate without separate radiator, making the antenna design more adaptable and effectively reduce the circuit system size.

3. SIMULATION AND EXPERIMENT

To verify the method, the antenna structure was designed to work on the WiFi band around 2.4 GHz, and it was connected with a WiFi RF circuit for testing. The simulation model and actual antenna structure are illustrated in Fig. 9. It can be seen that the antenna primarily consisted of a PCB structure

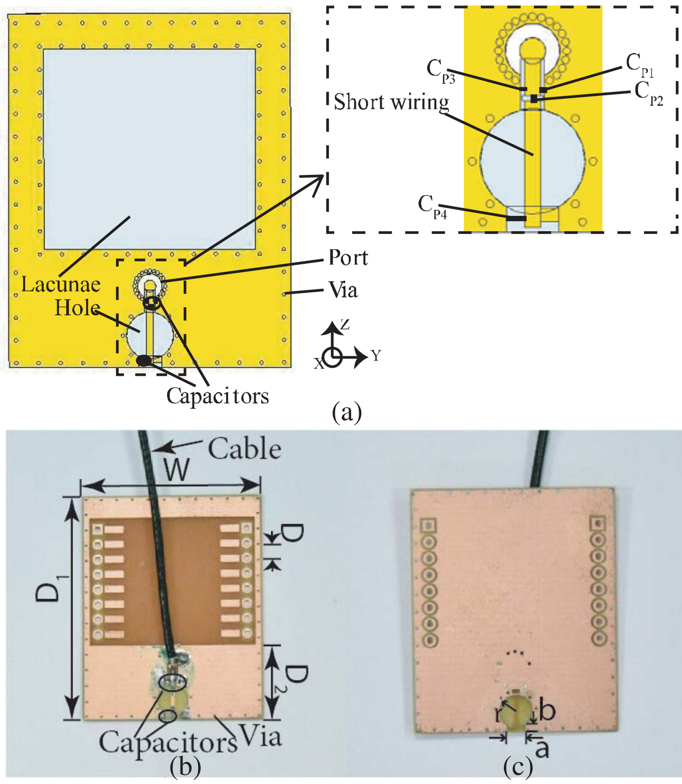

Figure 9. (a) Simulation model and details of feed area. (b) Top side of actual antenna. (c) Bottom side of the antenna.

and lumped capacitors. Fig. 9(a) shows a simulation model of the antenna, in which a circular hole structure connected a 50 Ω signal feeder through port. The top rectangular hollow space would be used to place a test RF module. The intensive vias connecting the top and bottom metal layers were arranged on the edge of the PCB, around the hole structure and signal feed point. The top and bottom sides of the PCB actually processed are shown in Fig. 9(b) and Fig. 9(c). The antenna structure parameters are listed in Table 1.

Table 1. Antenna structure parameters.

Parameter	Length (mm)
Board Length D_1	30
Board Width W	25
Distance D_2	10
Distance of Vias D	2
Hole Radius r	2
Length of notch b	1
Width of notch a	2

For the implementation of the 2.4 GHz antenna, the simulated capacitance parameters were adopted, and the selected appropriate capacitance was used (C_{p1}: 3 pF, C_{p2}: 0.5 pF, C_{p3}: 3 pF, C_{p4}: 0.49 pF), considering the error of the lumped capacitance. As shown in Fig. 10, the comparison between the S_{11} parameters of the simulation and the experiment measurement suggests that the actual antenna and the simulated resonance are at the same frequency point. The experimental S_{11} measurement value

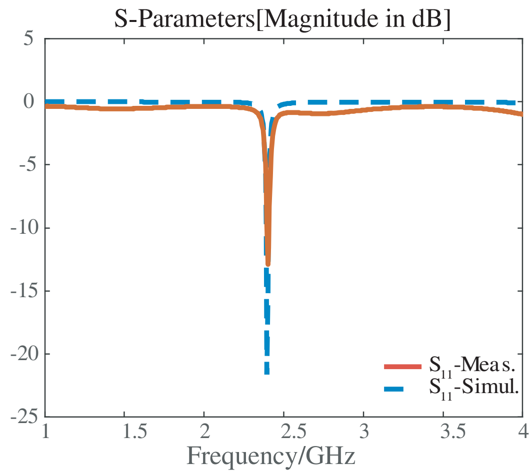

Figure 10. S_{11} parameters of simulation and experimental measurement of 2.4 GHz antenna.

was also below −14 dB. The bandwidth at 2.4 GHz is 15 MHz when S_{11} is less than −10 dB. This is appropriate matching for specific signal channels.

The simulation and experiment measurement of the antenna's X-Y plane and Y-Z plane patterns are shown in Fig. 11. The results suggest that the experimentally measured pattern matched the simulation pattern. The simulation gain of the antenna was 0.81 dBi with the 161° beamwidth, and the experiment measurement was 1.82 dBi with the 151° beamwidth. Since the measurement of the small antenna depended highly on the experimental environment and the effect of the excitation patch cord on the antenna radiation [20], a certain degree of measurement error occurred.

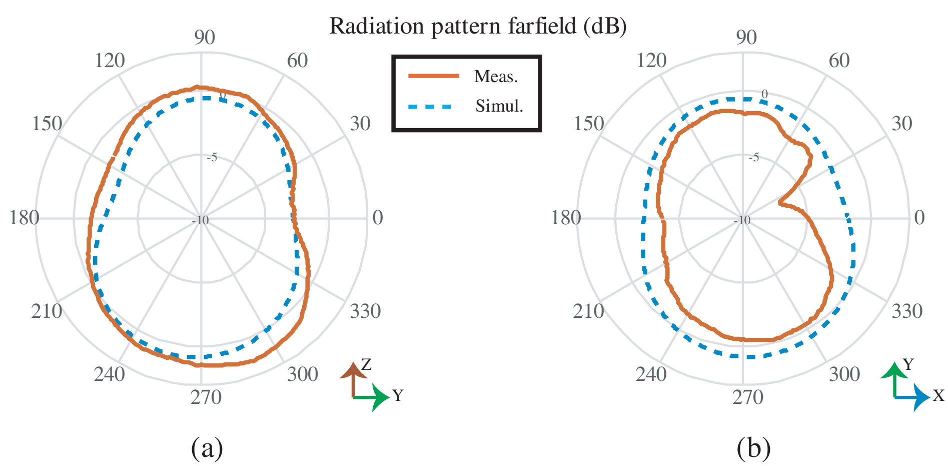

Figure 11. Simulated and experimental antenna radiation patterns in the (a) Y-Z plane and (b) X-Y plane.

The bandwidth of the antenna at 2.4 GHz is sufficient for WiFi, Bluetooth, and zigbee to work. In order to verify the effect of actual condition, this antenna was connected with 2.4 GHz WiFi module ESP-07S connection for performance evaluation. The test circuit is illustrated in Fig. 12. The ESP-07S module was installed in the rectangular cutout area of the antenna PCB, connecting the power supply and serial port with dupont lines.

In Fig. 12, the WiFi module and the antenna were connected via an IPX structure coaxial short cable. The WiFi signal strength was measured by the Received Signal Strength Indication (RSSI) value through Broadcom BCM4355 WiFi chip at different distances in a test location. The test location was

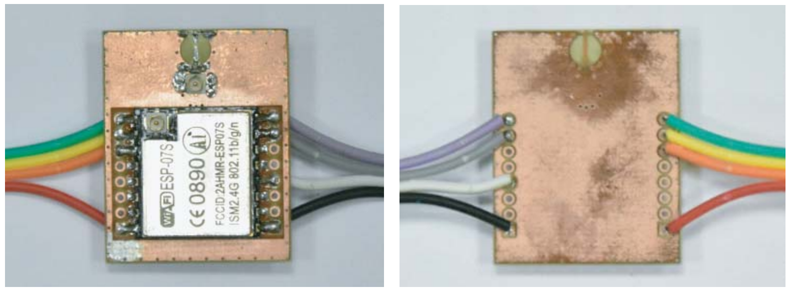

Figure 12. Compact PCB antenna structure with WiFi RF module installed. (a) Top side. (b) Bottom side.

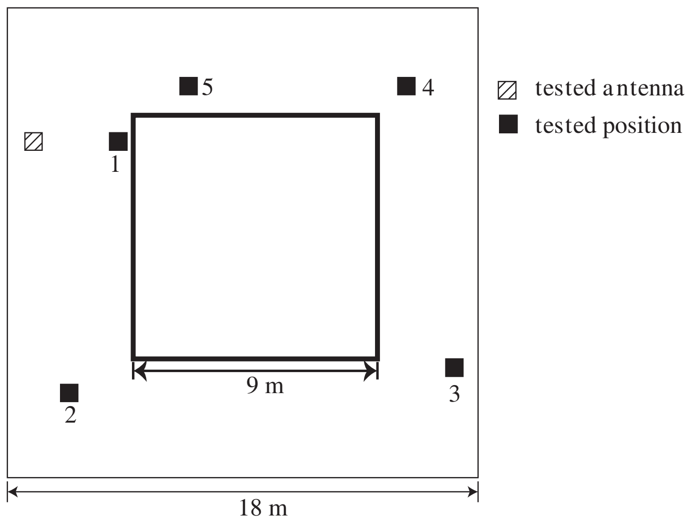

Figure 13. Antenna performance test location map around square metal wall in a square room.

in an 18 m-width square room with 9 m-width square metal wall at the middle place as shown in Fig. 13. The rod antenna in the experiment was used to compare, which was 1-dBi omnidirectional antenna with 11 cm length. The RSSI of compact PCB antenna was more than 2 dB stronger than the rod antenna at each position. This suggests that the antenna performance designed in this paper can achieve a better performance than the rod antenna for 2.4 GHz WiFi module. Whereby, the compact PCB antenna can be applied to work.

4. CONCLUSION

In this paper, a design method of compact plane antenna was developed, using the lumped capacitance and circular hole structure to excite the edge current of the PCB and induce radiation. The design showed a small size of radiation excitation structure and high radiation gain. It exhibited good adaptability and application value in IoT and portable wireless devices. The feasibility of the method was verified through the 2.4 GHz antenna design and measurement of the WiFi band wireless module with a maximum gain of 1.82 dBi with 151° beamwidth. The subsequent study will focus on enhancing radiation efficiency and up-regulating omnidirectional radiation effects.

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