Frontiers of Information Technology & Electronic Engineering
www.zju.edu.cn/jzus; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Antenna-in-package system integrated with meander line antenna based on LTCC technology*

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Received May 20, 2015; Revision accepted July 9, 2015; Crosschecked Dec. 8, 2015

Abstract: We present an antenna-in-package system integrated with a meander line antenna based on low temperature co-fired ceramic (LTCC) technology. The proposed system employs a meander line patch antenna, a packaging layer, and a laminated multi-chip module (MCM) for integration of integrated circuit (IC) bare chips. A microstrip feed line is used to reduce the interaction between patch and package. To decrease electromagnetic coupling, a via hole structure is designed and analyzed. The meander line antenna achieved a bandwidth of 220 MHz with the center frequency at 2.4 GHz, a maximum gain of 2.2 dB, and a radiation efficiency about 90% over its operational frequency. The whole system, with a small size of 20.2 mm×6.1 mm×2.6 mm, can be easily realized by a standard LTCC process. This antenna-in-package system integrated with a meander line antenna was fabricated and the experimental results agreed with simulations well.

Key words: Antenna-in-package (AiP), Meander line antenna, Multi-chip module (MCM), Low temperature co-fired ceramic (LTCC)

http://dx.doi.org/10.1631/FITEE.1500167 **CLC number:** TN82

1 Introduction

With the development of production processes, low temperature co-fired ceramic (LTCC) technology is becoming more and more popular for wireless communication systems. Due to its high relative dielectric constant, antennas can be designed at a small size while maintaining high performance. In addition, antennas and integrated circuit (IC) chips can be easily integrated in a compact system by using a standard LTCC process (Brzezina *et al.*, 2011; Beer *et al.*, 2012). This method is called antenna-in-package (AiP). AiP can effectively reduce the volume of systems and improve their reliability.

As a typical patch antenna, an LTCC patch antenna is also facing the problems of small bandwidth and low gain in a small size. To overcome these deficiencies, much work has gone into improving the characteristics of patch antennas (Sharma *et al.*, 2009; Abutarboush *et al.*, 2012; Malekpoor and Jam, 2013). Many studies also showed that meander line structure is a suitable way of realizing small size and wideband antennas (Gong *et al.*, 2010; Pasakawee and Hu, 2012; Liu *et al.*, 2014; Kadam and Kulkarni, 2015).

To make the system lighter, multi-purpose, better in performance, and lower in cost, multi-chip module (MCM) technology has been developed for high density assembly (Li *et al.*, 2006). Using MCM technology, more chips can be stacked along the Z-axis with vertical interconnection. This method obviously reduces the volume and results in lower power consumption and faster speed (Al-Sarawi *et al.*,

* Project supported by the National Natural Science Foundation of China (Nos. 61574106 and 61334003), the National Defense Pre-research Foundation of China (No. 9140A2306 0115DZ01062), and the Key Science and Technology Special Project of Shaanxi Province, China (No. 2015KTCQ01-5)

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1998). In this paper, an AiP system integrated with a meander line antenna based on LTCC technology is designed and fabricated.

2 Antenna mechanism and design

Fig. 1 shows the geometry of the proposed antenna. This antenna is designed for 2.4 GHz applications. The 2.4 GHz band has the advantage of low cost, strong anti-interference, and high transmission efficiency; thus, it is widely used in wireless communication technology including WiFi, Bluetooth, and ZigBee. LTCC (Ferro A6M) is used as its substrate material. The parameters of this material are listed in Table 1. The center frequency (f) of an antenna can be written as

$$f = \frac{1}{2\pi\sqrt{LC} \cdot \sqrt{\varepsilon_{\rm r}}}, \tag{1}$$

where L and C are the inductance and capacitance of the resonant tank, respectively, and $\varepsilon_{\rm r}$ is the relative dielectric constant of the material. When f is constant, choosing a material with high dielectric constant can decrease the required L and C. So, using LTCC is a suitable way to reduce the dimensions.

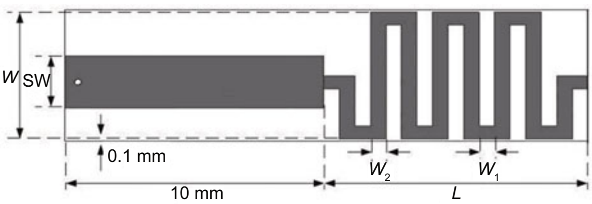

Fig. 1 Design parameters of the meander line antenna

Table 1 Parameters of Ferro A6M

Parameter	Value
Relative dielectric constant	5.9
Loss factor	0.2%
Thickness of each sheet	93 μm
Surface roughness	<0.25 μm
Thermal conductivity	2.0 W/(m·K)

To reduce the impact of environmental changes on the antenna characteristics, the antenna is embedded in the LTCC substrate 0.096 mm from the top surface.

The meander line structure is adopted to decrease the volume of the system and to expand the bandwidth. These characteristics are because of meander line structure's long electrical surface-current length. To determine the characteristics of the meander line antenna, a study of its radiation field distribution is necessary. As shown in Fig. 2, current flows through the meander line from the left side. According to electromagnetic theory, the radiation fields of adjacent lines along the Y-axis are in the opposite direction, so they offset each other. Thus, the radiation field of meander line antenna depends mainly on the electrical paths along the X-axis.

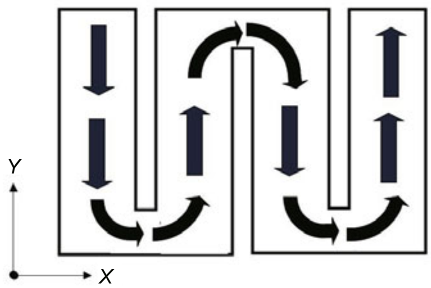

Fig. 2 Direction of current in the meander line antenna

As Nassar and Weller (2011) reported, a ground plane beneath the antenna has a bad effect on the performance of meander line antennas. In addition, it is necessary to decrease the electromagnetic coupling effect between antenna and package by using an internal ground layer. To deal with this, a microstrip line is chosen as the feeding line. It is placed adjacent to the meander line antenna. By adjusting its width, good impedance matching can be obtained. With this method, the internal ground and the package can be placed beneath the microstrip line to prevent the electromagnetic coupling effect.

In this design, the parameters of the meander line antenna are calculated through modeling it as a linear dipole antenna with inductive loading, which is decomposed into two parts: short-terminated lines and a linear circular cylindrical conductor, and the characteristic impedance Z_0 of the short-terminated line is (Endo *et al.*, 2000)

$$Z_0 = \frac{Z_{\rm C}}{\pi}\lg\frac{2(W_1+W_2)}{W_1}, \tag{2}$$

where $Z_{\rm C}$ is the intrinsic impedance, W_1 and W_2 are given in Fig. 1, and the input impedance $Z_{\rm in}$ of the short-terminated line is

$$Z_{\rm in} = {\rm j}X = {\rm j}Z_0\tan\left(\beta\frac{W}{2}\right), \tag{3}$$

where β is the phase constant of the short-terminated line and X is its reactance. The inductance of all short-terminated lines (L_{m}) and the inductance of the linear conductor (L_{l}) are respectively given by Eqs. (4) and (5):

$$L_{\mathrm{m}} = \frac{Z_0}{\pi c} NW \lg \frac{2W_1}{W_2} \cdot \left[1 + \frac{1}{3} \left(\beta \frac{W}{2} \right)^2 \right], \quad (4)$$

$$L_{\mathrm{l}} = \frac{Z_0}{\pi c} L \left(\lg \frac{8L}{W_2} - 1 \right), \quad (5)$$

where N is the number of turns of the meander line antenna, c is the speed of light, and L and W are given in Fig. 1. Endo *et al.* (2000) reported an equation for the relationship among N, L, W, W_1, and free space wavelength (λ):

$$N = \frac{\frac{\lambda}{4} \left(\lg \frac{2\lambda}{W_2} - 1 \right) - L \left(\lg \frac{8L}{W_2} - 1 \right)}{W \cdot \lg \frac{2L}{NW_2} \cdot \left[1 + \frac{1}{3} \left(\beta \frac{W}{2} \right)^2 \right]}. \quad (6)$$

After a rough calculation, it is found that adjustments are still necessary. The electromagnetic simulation software HFSS is used to analyze and adjust the parameters of the meander line antenna. Finally, N=3, L=10.2 mm, W=6.1 mm, W_1=W_2=0.6 mm, and SW=2.6 mm are obtained as the optimal parameters. Fig. 3 shows the simulated return loss of the meander line antenna. It is found that the antenna resonance frequency is 2.4 GHz, and its impedance bandwidth is about 240 MHz. Simulated E- and H-plane radiation patterns are shown in Fig. 4. The antenna is in linear polarization within the entire working frequency. Fig. 5 is the 3D radiation pattern. The peak gain of this antenna is about 2.68 dB. The simulated radiation efficiency of the meander line antenna is approximately 90% over its operational frequency. The simulation results suggest that the proposed antenna can satisfy the requirements of standards such as IEEE 802.11 and IEEE 802.15 at 2.4 GHz.

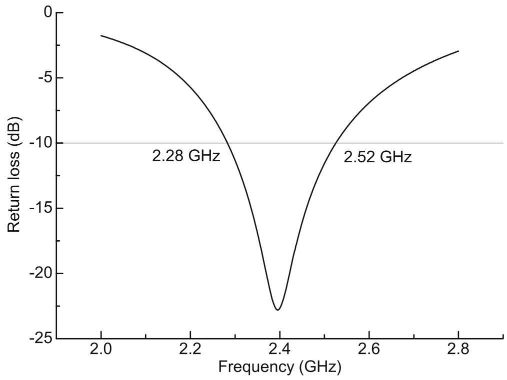

Fig. 3 Simulated return loss characteristics of the proposed antenna

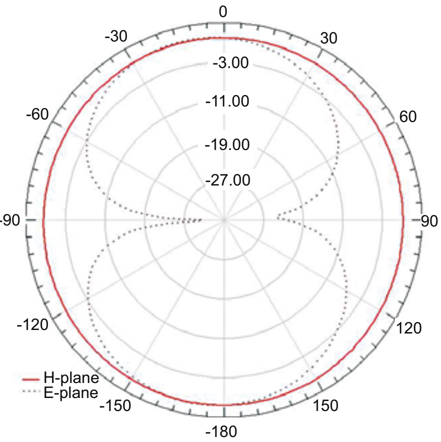

Fig. 4 Simulated E- and H-plane radiation patterns at 2.4 GHz

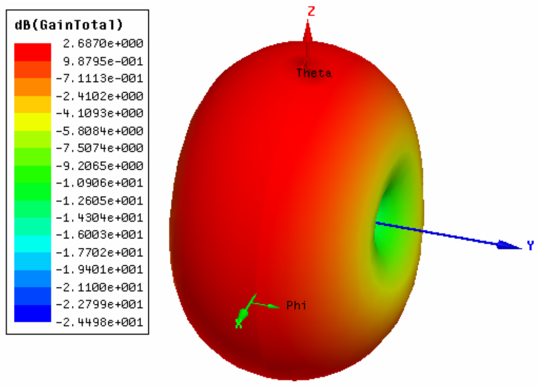

Fig. 5 Simulated 3D radiation pattern at 2.4 GHz. Reference to color refer to the online version of this figure

3 Integrated packaging layer and MCM

The integrated packaging layer plays a significant role in the antenna feed network and integration of IC bare chips. This layer mainly consists of a cavity and four side walls with via holes in them. It can be easily fabricated by the LTCC process. The feed network is realized by a vertical feed via inside the side wall and a microstrip feed line. As mentioned above, the package layer should be placed beneath the microstrip line to prevent the electromagnetic coupling effect.

In this design, metal via holes are used for two reasons. First, the internal conducting ground plane is connected to the bottom ground using these via holes. Second, these via holes constitute shield walls for decreasing the electromagnetic coupling. To verify these effects, two control studies are conducted by HFSS simulation. In the first study, the effects of the internal ground and its connection with via holes are investigated by removing them in turn. As shown in Fig. 6, the return loss characteristic is affected badly when the internal ground is removed. A similar result is obtained by removing its connection with via holes. These results confirm the necessities of having an internal ground and metal via.

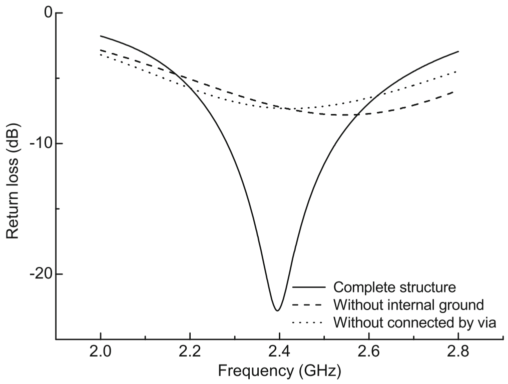

Fig. 6 Return loss characteristic of different internal ground configurations

In the second study, systems with different numbers of via holes are designed and their simulated return loss characteristics are shown in Fig. 7. It can be seen that the return loss characteristic changes slightly when the number of via holes decreases from 21 to 9. But when the number of via holes reduces to 3 or even zero, its center frequency and bandwidth are seriously affected. According to the simulation, although the packaging layer has not been placed under the antenna, a sufficient number of via holes is still necessary for the system.

IC bare chips are integrated in the packaging layer by MCM technology. In this design, a laminated LTCC MCM is applied to realize multi-function in the system as shown in Fig. 8. LTCC is used as the substrate material. This laminated MCM mainly consists of three layers, which are connected to each other by metallization vias. These layers are stacked by solder pads and solder bumps using a reflow soldering process. The solder bumps can also act as input or output ports. A hermetic lid is placed on the top of this MCM for protection.

The designed laminated MCM is integrated in the packaging layer of the system. As mentioned above, the system is designed for 2.4 GHz applications. For example, when the system is used for ZigBee at 2.4 GHz, IC chips such as a location chip or a temperature sensing chip can be integrated in this MCM to achieve multi-purposing. The structure of the laminated MCM can be changed to meet different requirements. In addition, AiP and MCM are realized by a similar LTCC process, which can decrease the complexity of manufacturing.

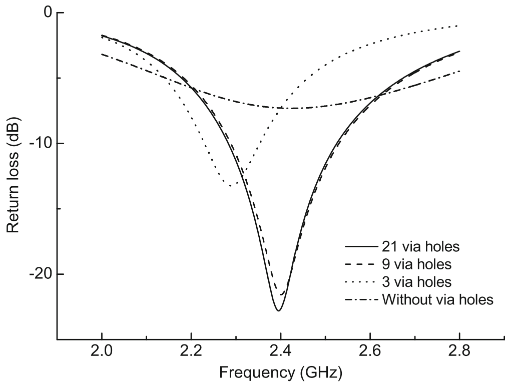

Fig. 7 Return loss characteristic of the various number of via holes

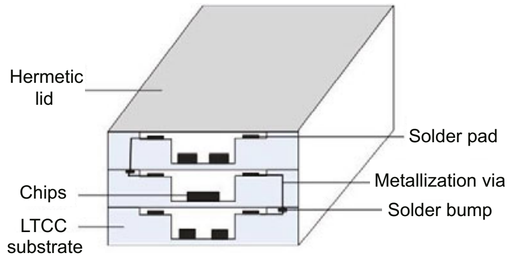

Fig. 8 Illustration of the laminated LTCC MCM

Fig. 9 shows the dimension of the proposed package. The radius of the metal via hole is 0.1 mm. The distance between neighboring via holes is about 0.01λ (λ is the free space wavelength at 2.4 GHz). The cavity dimension is 8.1 mm×4.7 mm×1.2 mm. Based on MCM technology, three layers of IC bare chips are integrated in the cavity and the size of each chip is 3 mm×3 mm×0.3 mm. The whole package layer dimension is 20.2 mm×6.3 mm×1.4 mm.

After the packaging layer is added to the system, the resonant frequency of the antenna will decrease slightly. To solve this problem while keeping the other parameters constant, it is necessary to tune the width of the microstrip feed line. Here, the width of the microstrip line is adjusted to 2.85 mm. Finally, the center frequency returns to 2.4 GHz.

The electric field intensity of the packaging layer

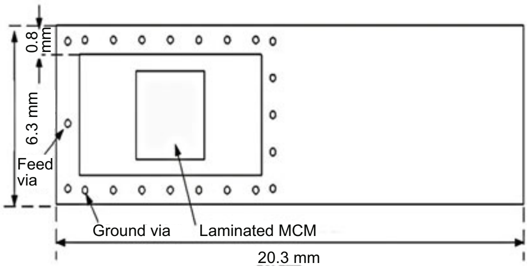

Fig. 9 Design parameters of the packaging layer

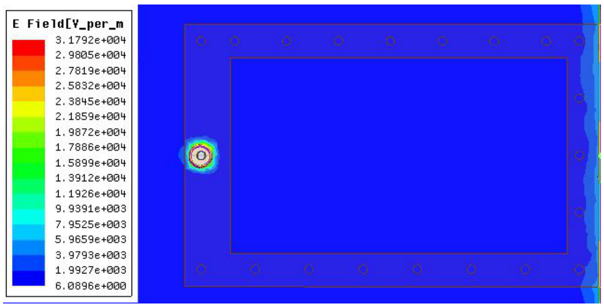

Fig. 10 Electric field intensity of the packaging layer. References to color refer to the online version of this figure

simulated by HFSS is shown in Fig. 10. It can be seen that most of electric fields distribute around the feed via and the edge near the meander line antenna. This result shows that the shield walls can prevent the external electric field from influencing the cavity and confirms that this packaging layer can protect multilayer bare chips from electromagnetic coupling.

4 Measurements and results

In this section, the proposed AiP system integrated with a meander line antenna is fabricated and tested. Fig. 11 shows the expanded view of the proposed system. The thickness of each layer is listed in Table 2. A meander line antenna was designed and placed on the top surface of the system. An internal conducting layer was placed underneath the LTCC substrate. The package layer of the system is composed of four side walls and a laminated MCM which is used for integrating IC bare chips. The ground layer was placed on the bottom of the system.

This AiP system was manufactured by a standard LTCC process. Silver was used as the metal material of the electrode and via hole. After slitting green sheets, via holes were punched in the sheets and filled with metal conductive paste. To ensure accuracy, the meander line antenna was printed on green sheets using a registration camera. The cavity was fabricated by cutting penetrating windows in appointed sheets. Then each printed green sheet was placed in turn, and pressure and heat were applied to laminate them. By co-firing them together, a complete system was formed (Fig. 12a).

In addition, as a sample designed for study and analysis, the fabricated system still needs some modifications for actual use. To optimize the process of actual production, the process would be to put the package layer over the microstrip line and then turn the antenna to the upper side for measurement; this is a suitable way to reduce the difficulty in processing.

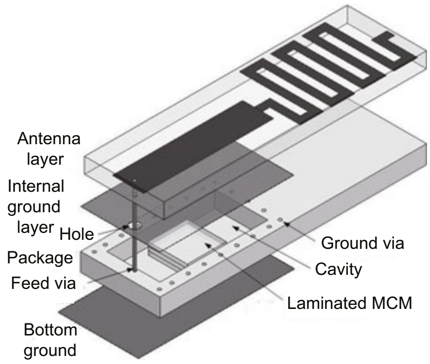

Fig. 11 Expanded view of the proposed system

Table 2 Thickness of each layer

Layer	Thickness (mm)
Antenna	1.20
Internal ground	0.01
Packaging	1.40

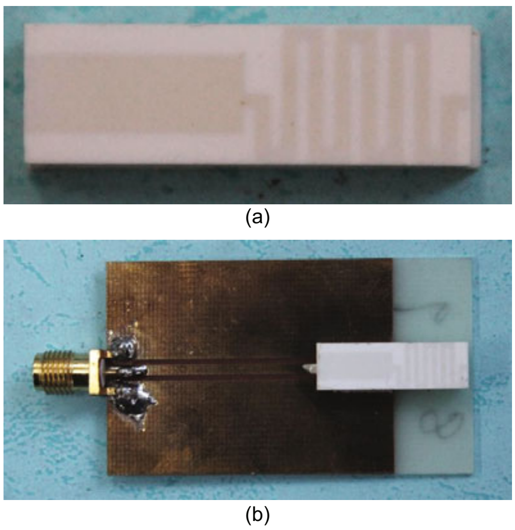

Fig. 12 Fabricated AiP system (a) and testing environment (b)

Fig. 12 shows the fabricated AiP system and its testing environment. The system was placed on a PCB plane and its feed network was connected to the CPW signal line with an SMA connector. The material of this PCB plane is FR4 (dielectric constant = 4) and its size is 50.2 mm×30 mm×0.8 mm. The characteristics of the AiP system were tested by a microwave network analyzer. The system has been mounted on a rotating platform in a microwave anechoic chamber for far-field characteristics test.

Fig. 13 shows the simulated and measured return losses. The measured E- and H-plane radiation patterns are shown in Fig. 14. The measured center frequency and radiation patterns are very similar to the simulation results. It is found that the measured impedance bandwidth is about 220 MHz, which is roughly 20 MHz lower than that of the simulation. The peak gain of the AiP system is about 2.2 dB, which is 0.4 dB lower than the simulation result. The difference between measurement and simulation is due to various losses such as cable loss or interconnect loss. Overall, experimental results agree well with the simulations.

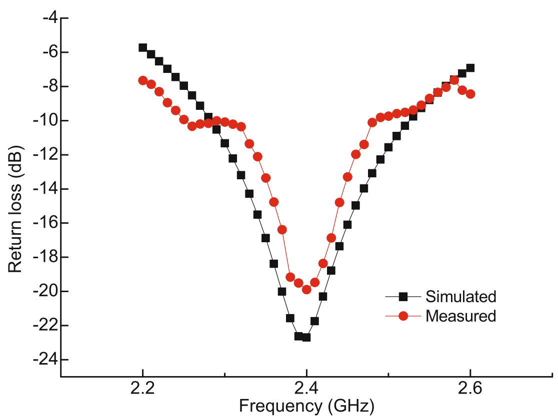

Fig. 13 Measured and simulated return loss characteristics

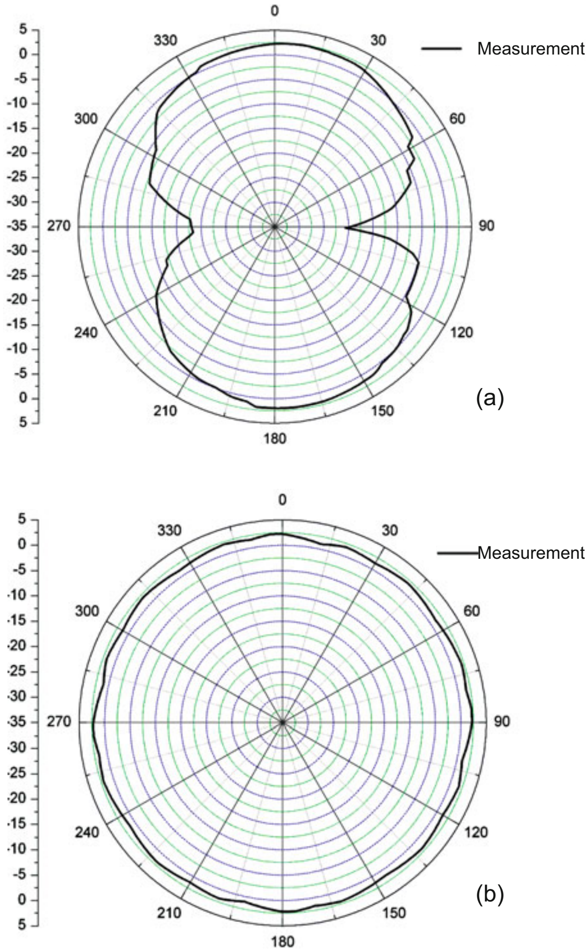

Fig. 14 Measured E-plane radiation pattern (a) and H-plane radiation pattern (b)

5 Conclusions

In this paper, a compact antenna-in-package system integrated with a meander line antenna is designed and fabricated. The IC bare chips are integrated in the system by MCM technology. To realize the miniaturization of the system, a meander line antenna is adopted. To decrease the electromagnetic coupling effect between antenna and packaging layer, a microstrip line is used as the feed line. A laminated LTCC MCM is designed for integration of multilayer IC chips. The structure of the system (such as the position of the packaging layer) and the number of via holes are carefully studied. The results show that a sufficient number of via holes is necessary for the proposed system. These analyses provide guidance for choosing a suitable structure and parameters for this system. Finally, the proposed system has been tested. Its impendence bandwidth is 220 MHz and the center frequency is 2.4 GHz. The maximum gain of the proposed system is 2.2 dB and the radiation efficiency is about 90% across the operational frequency band. The experimental results agree with the simulations, which suggests that this designed AiP system is suitable for 2.4 GHz applications.

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