Progress In Electromagnetics Research Letters, Vol. 9, 183–192, 2009

A SMALL 3-D MULTI-BAND ANTENNA OF "F" SHAPE FOR PORTABLE PHONES' APPLICATIONS

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Abstract—A small *3-Dimensional* (3-D) multi-band antenna of "F" shape is proposed for portable phones' applications. The designed configuration of the proposed antenna is different from traditional *Planar Inverted-F Antenna* (PIFA) radiators. The proposed antenna has the good characteristics of wide band. The ratio of impedance bandwidth to the central frequencies 2.5 and 5.1 GHz is 28.6% and 9%, respectively. It can be applied to *Bluetooth* (BT) 2.4 GHz and *Unlicensed NII* — 5 GHz, UNII-1 5.1 $\sim$ 5.25 GHz and UNII-2 5.25 $\sim$ 5.35 GHz. The experimental results have fairly good agreement with the simulation data by *High Frequency Structure Simulator* (HFSS).

1. INTRODUCTION

Wireless communication devices are now more extensively used than the last decade. And the radiators used in portable phones are designed compactly. However, the characteristics of antennas such as gain, efficiency, bandwidth, and radiation patterns should be improved in order to be applied to compact portable phones [1–3]. Although wireless communication elements are convenient to everyone, there is a public concern about electromagnetic (EM) energy radiation absorption that may influence human health [4–9]. Therefore, the internal antenna *Planar Inverted-F Antenna* (PIFA) is greatly used due to easily made, low profile, compact configurations, low price and low *Specific Absorption Rate* (SAR) [10–15].

The proposed small antenna is different from traditional PIFA radiators. The configurations of the small antenna are made by using metal conductive single-core wires. The whole structure is similar to

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the radiator of PIFA [16, 17]. It also has the same shape of "Inverted-F". As a matter of fact, metal conductive single-core wires are used to make radiators in which the characteristics of impedance bandwidth are limited. Besides the effect of Q factor of an antenna, the case, battery, and any internal materials with telephone are also important issues. [18] proposed how to enhance the impedance bandwidth of a radiator with conductive single-core wires by using the concept of nonsymmetrical parallel short-circuit. The detailed geometry of the small antenna will be illustrated in Section 2.

The small multi-band antenna is operated at *Bluetooth* (BT) 2.4 GHz, *Unlicensed NII* — 5 GHz, UNII-1 5.1 $\sim$ 5.25 GHz and UNII-2 5.25 $\sim$ 5.35 GHz. The total volume of the small antenna is $30(L) \times 5(H) \times 0.2(W)\,\mathrm{mm}^3$. The ratio of impedance bandwidth to the central frequencies 2.5 and 5.1 GHz is 28.6% and 9%, respectively. Therefore, the good characteristics of the antenna with conductive single-core wires can be conducted. The experimental results completely agree with the simulation data by *High Frequency Structure Simulator* (HFSS).

2. ANTENNA CONFIGURATION

The optimum configuration of the proposed small antenna for BT 2.4 GHz, UNII-1 5.1 $\sim$ 5.25 GHz and UNII-2 5.25 $\sim$ 5.35 GHz applications is shown in Fig. 1. The radiators are made by using metal conductive single-core wires. The diameter of the metal conductive single-core wire is 0.2 mm. In order to improve the impedance bandwidth of the proposed small antenna, the nonsymmetrical parallel coupling line, radiator element 1 (ANT 1), is used close to the radiator element 2 (ANT 2). On the other hand, the ANT 2 element is used to create the low frequency band 2.4 GHz. In order to make the key resonant frequency of the proposed antenna, the calculation in Equation (1) refers to [10]; where c denotes the velocity of light (3×10^8 m/s); L and W denote the length and width of a radiator element; and f_0 denotes the resonant frequency.

BT 2.4 GHz is defined to be the main resonant frequency in the study. The idea of using Equation (1) is from the PIFA. The diameter of the metal conductive single-core wire is to be the width (W). The ANT 2 fulfills Equation (1) other than ANT 1. Therefore, the main resonant frequency can be calculated. As illustrated in the third sentence of the first paragraph of session 2, ANT 1 is just for coupling and modifying.

In order to be applied to commercial products, the proposed small antenna is mounted in a real phone case according to the telephone specifications of Dopod P100 [19]. The size of ground plane (GND) is $100(L) \times 60(W)$ mm. The material *Flame Retardant 4* (FR4) is used in the dielectric substrate of which the thickness is 1.6 mm, and the relative permittivity (ε_r) is 4.4. It is a kind of material that is used to make a *Printed Circuit Board* (PCB) without coating copper layer [20]. The ANT 2 element is worked at low frequency band of 2.4 GHz. The total length of the ANT 2 element is 32 mm by one-quarter wavelength ($\lambda/4$). The interval between GND and the shorter side (x-direction) of ANT 1 is 1 mm. The interval between the right side of GND and the shorter side (x-direction) of ANT 2 is 5 mm. Utilizing the nonsymmetrical line as ANT 1 element is to induce the high frequency band 5 GHz by coupling. The total length of ANT 1 is 33 mm. When the total length of ANT 1 is decided by one-quarter wavelength, the goal of 5 GHz is not achieved. Therefore, the length is a little bit modified by one-half wavelength ($\lambda/2$). Other detailed dimensions of the small antenna are shown in Fig. 1(a).

The 50 Ohm coaxial-SMA is used to connect the small antenna due to transmitting the EM energy from the equipment *Vector Network Analyzer* (VNA) E8362B. ANT 1 and ANT 2 are connected together. They are using the same excitation source. The total volume of the small antenna is $30(L) \times 5(H) \times 0.2(W)\,\text{mm}^3$. It satisfies the compact requirement and has the good characteristics of wideband.

$$f_0 = \frac{c}{4(L+W)} \tag{1}$$

3. EXPERIMENTAL RESULTS

The far-field antenna measurement system, NSI-800F-10 and VNA E8362B, are used for measuring the characteristics of the proposed small antenna. The experimental results are also compared to the numerical simulation data by HFSS. Fig. 2 illustrates the *Return Loss* (RL) only using the ANT 2. The solid-line (measured) shows the RL that is not very good at 2.4 GHz referring to −8 dB. Generally, the conductive single-core wire is used to construct radiators of which the impedance bandwidth is constricted due to the high Q (Quality Factor) referring to Equation (2).

Besides the effect of Q factor, the interactions between internal elements and telephone case are also important. Fig. 3 illustrates the operation bandwidths of a dipole antenna and a monopole antenna by using metal conductive single-core wires, respectively. It can be seen that only one resonant frequency band is got, and the impedance bandwidth is very narrow. It is well-known that radiators are made by metal conductive single-core wires of which the performances are not

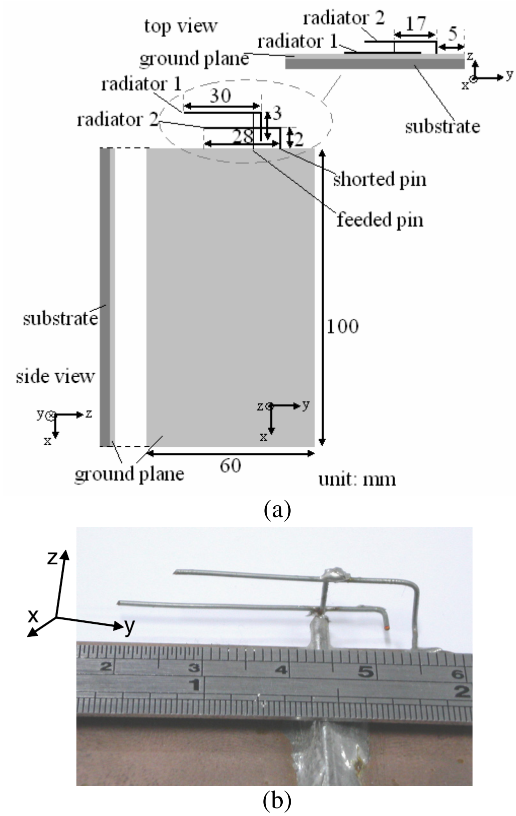

Figure 1. Geometry of the proposed small antenna.

very well due to high Q as described in Equation (2) [20, 21].

$$Q = \frac{f_o}{BW} = \frac{\beta}{2\alpha} \tag{2}$$

where f_o, the resonant frequency [Hz]; BW, the bandwidth [Hz]; β, the propagation constant [rad/s]; α, the attenuation constant [Np/m].

In order to improve the impedance bandwidth of the proposed antenna, the transmission line concept is adopted. As shown in Fig. 1(a), the nonsymmetrical coupling line of ANT 1 is conducted. Besides improving the impedance bandwidth, another frequency band will be induced. Fig. 4 illustrates the RL of using ANT 2 and ANT 1. It can be seen that the characteristics of RL at 2.4 GHz is greatly improved. The RL of 2.4 GHz is deeply down to −22 dB with 14 dB improvement (from −8 dB to −22 dB).

Furthermore, the impedance bandwidth (BW) of 2.1–2.8 GHz is covered as well as the high frequency band of 4.9–5.36 GHz is induced. The impedance bandwidth is improved up to 28.6% and 9% at (2.1 to 2.8 GHz) and (4.9 to 5.36 GHz) according to −10 dB (RL), respectively.

In order to reach the requirement of a small antenna, the design condition of one-quarter wavelength ($\lambda/4$) is used for ANT 2. Furthermore, the ANT 1 is just used to induce the high frequency band by using the concept of coupling. Therefore, the design condition of one-half wavelength ($\lambda/2$) is used. Referring to Equation (3), the input impedance of transmission line can be calculated. The Equation (3) can be rewritten to (3a) when the length of the transmission line is one-half wavelength. Therefore, it can be known that the input impedance is the same as Z_L [20, 21].

$$Z_{in} = Z_o \frac{Z_L \cosh \beta l + Z_o \sinh \beta l}{Z_o \cosh \beta l + Z_L \sinh \beta l} \tag{3}$$

$$Z_{in} = Z_L \tag{3a}$$

where Z_o, the characteristic impedance [Ω]; βl, the electric length of transmission line [rad].

Figure 5 illustrates the simulated RL of the presented antenna when ANT 1 and ANT 2 are mounted on the same plane. When ANT 1 and ANT 2 are put on the same plane, the presented antenna does not have the good performances of RL. As shown in Fig. 5(a), ANT 1 and ANT 2 are put on the x-y plane (horizontal plane) that shows the bad performances of RL at 5 GHz. As shown in Fig. 5(b), ANT 1 and ATN 2 are put on the y-z plane (vertical plane) that shows the

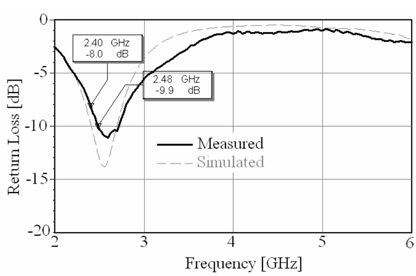

Figure 2. The *return loss* (RL) of only using the ANT 2.

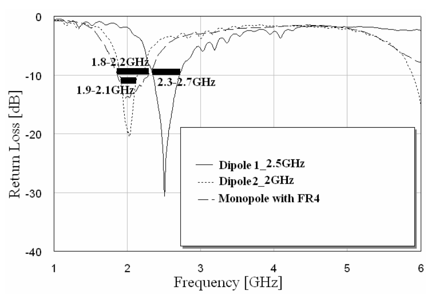

Figure 3. The impedance bandwidth is constricted by using conductive single-core wires.

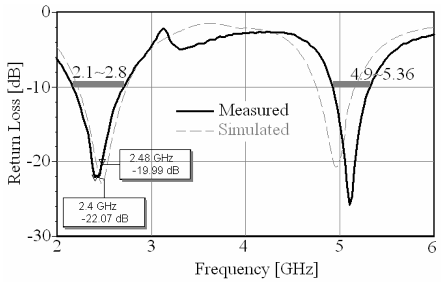

Figure 4. The return loss (RL) of using the ANT 2 and ANT 1.

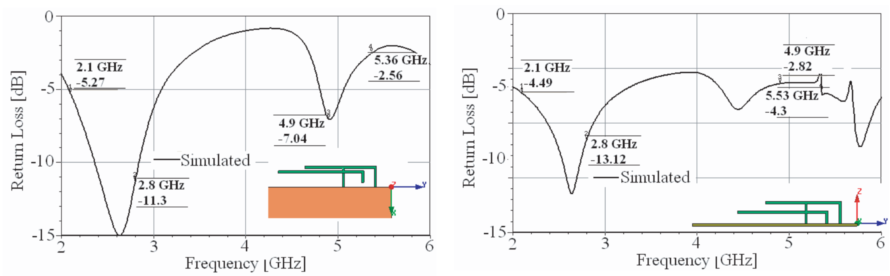

Figure 5. The simulated *return loss* (RL) of the ANT 1 and ANT 2 mounted on the, (a) x-y plane; (b) y-z plane.

bad performances of RL at 5 GHz. For the two cases, the frequency band of 2.4 GHz still keeps the good performances of RL because this resonant frequency is created by the radiator of ANT 2. Therefore, the variation of the performances of RL at 2.4 GHz is not seriously influenced by the relative positioning of ANT 1 and ANT 2.

At this moment, it can be identified again that 2.4 GHz is created by ANT 2, and 5 GHz is created by ANT 1 with EM coupling. From the results in Fig. 5, it can be seen that the two radiators of ANT 1 and ANT 2 must be reciprocal in order to get the maximum coupling of EM energy. Therefore, the good characteristics of RL at 5 GHz can be achieved.

The resonant frequency band of the presented antenna will be lightly shifted if the gap G is modified. It means that the best performance of the presented antenna can be made when the feeding is in the suitable position. Because of the presented antenna made by hands, there will be some differences created at any time and anywhere for the type of antenna. Therefore, the parameter G can be applicably modified in order to get the good performance. As shown in Fig. 6

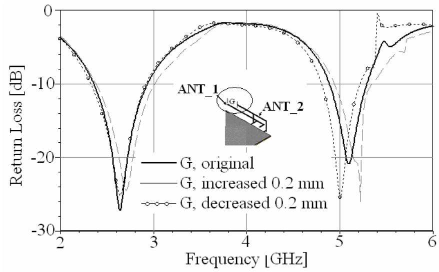

Figure 6. Frequency versus *Return Loss* (RL) by modifying the gap of *G*.

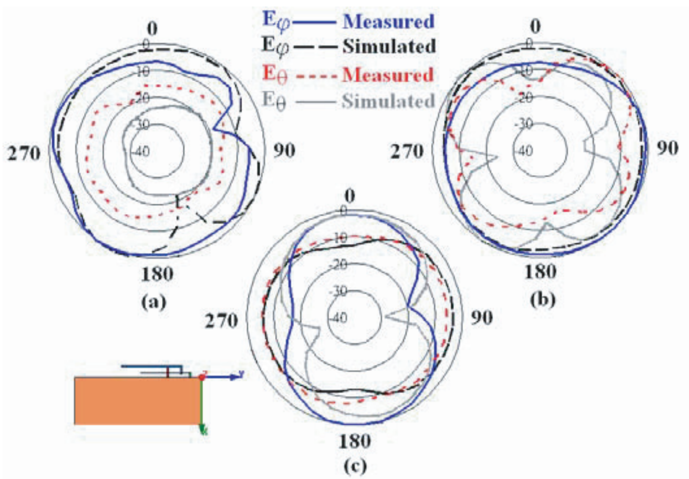

Figure 7. The far-field radiation patterns of the presented antenna at 2.4 GHz on (a) x-y, (b) z-x, (c) y-z plane.

by simulation, it illustrates that the resonant frequency band is lightly shifted when the gap of G between ANT 1 and ANT 2 is modified.

For measuring the radiation patterns of the presented antenna, the far-field antenna measurement system, NSI-800F-10 including VNA E8362B, is used. The far-field radiation patterns of the presented antenna at 2.4 and 5.2 GHz are shown in Figs. 7 to 8. Table 1 illustrates the peak gains of the presented antenna on the three different planes at the resonant frequency bands. Due to the measurement system used, it is a two-dimensional (2D) system. Therefore, the antenna gain of the presented antenna is defined as the average peak gain. It means that the maximum values will be picked up on the three planes, x-y, y-z and z-y, and then do the average calculation. The average peak gains are shown in Table 2.

Table 1. The peak gain of the presented antenna.

Frequency	Plane	Peak Gain (dBi)	Location (degree)
2.4 GHz	x-y plane	0.34	217°
5.2 GHz	x-y plane	1.81	180°
2.4 GHz	z-x plane	−0.68	140°
5.2 GHz	z-x plane	1.18	173°
2.4 GHz	y-z plane	0.94	183°
5.2 GHz	y-z plane	−1.10	193°

Table 2. The average peak gain of the presented antenna.

Frequency	Average Peak Gain (dBi)
2.4 GHz	1.04
5.2 GHz	1.46

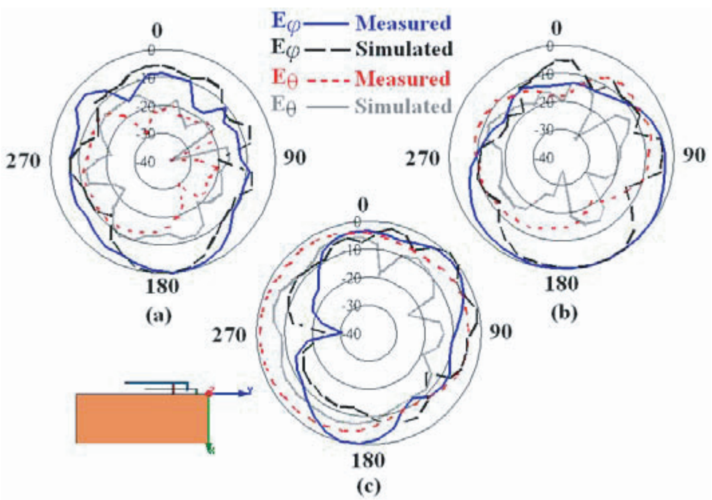

Figure 8. The far-field radiation patterns of the presented antenna at 5.2 GHz on (a) x-y, (b) z-x, (c) y-z plane.

4. CONCLUSION

A small three-dimensional (3D) internal multi-band antenna is presented with the metal conductive single-core wires. The antenna works at ISM band of 2.4 GHz (2.4 $\sim$ 2.48 GHz) and Unlicensed NII — 5 GHz (UNII-1 and UNII-2, 5.1 $\sim$ 5.35 GHz). The ratio of impedance bandwidth to the central frequencies 2.5 and 5.1 GHz is 28.6% and 9%, respectively. The volume of the presented antenna is $30(L) \times 5(H) \times 0.2(W)\,\mathrm{mm}^3$. The experimental results show fairly good agreement with simulated ones. The antenna should have good potential for applications in commercial products.

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