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Design of a wideband horizontally polarized omnidirectional antenna with mutual coupling method

ZeDong Wang, YingZeng Yin, Xi Yang and JianJun Wu

***Abstract*—A wideband horizontally polarized (HP) omnidirectional antenna is proposed in this communication, which consists of 12 printed arc dipole units, a wideband 1to12 feed network, two rows of parasitic arc strips and a row of director elements. Based on the tightly coupled dipole array design, twelve printed arc dipoles (about 0.2λ_L, λ_L: effective wavelength at low frequency) are formed as a ring with their edge overlap for strong mutual coupling. Meanwhile, the two rows of parasitic arc strips are radially placed around these arc dipoles as an impedance matching layer. Owing to the strong mutual coupling and impedance matching layer, the proposed HP omnidirectional antenna has a wideband operating band. Additionally, a row of director elements is utilized to enhance the radiation in horizontal plane. The printed arc dipoles are fed by a wideband 1to12 power divider with identical magnitude and phase. Experimental results show that this antenna has a wide 10-dB return loss operating bandwidth of 70.2% (1.7~3.54GHz) and good omnidirectionality performance with gain variation in horizontal plane being less than 1.2dB among 1.7~3.2GHz.**

***Index Terms*—Horizontal polarization, omnidirectional antenna, wideband, mutual coupling.**

I. Introduction

Omnidirectional antenna has been greatly applied in wireless communications systems for 360°coverage. In most indoor and urban environment, the vertically polarized omnidirectional antenna is always used. For increasing the capacity of system, the horizontally polarized (HP) omnidirectional antenna is an essential complement. Owing to development of modern wireless communication system, it induces the requirement of broadband antenna for covering multiple communication bands such as second generation (2G) systems, third generation (3G) system and long term evolution (LTE) system. In order to simultaneously operate in 2G/3G/LTE applications, the omnidirectional antenna must have a wide operating bandwidth of 45.5 %(1.7~2.7GHz). The wideband vertically polarized omnidirectional antenna can be easily obtained by suitable design of monopole [1], [2]. However, it is more challenging to design a wideband HP omnidirectional antenna.

Many literatures have been published in [3]-[9] to obtain an HP omnidirectional antenna. Based on the rotating field method, the turnstile antennas [3], [4] consist of cross dipoles in horizontal plane, which are fed in phase quadrature to achieve omnidirectional horizontal polarization. But these two turnstile antennas have a narrow operating bandwidth about 12.2 % (2.3~2.6GHz). According to the theory of magnetic dipole, the common method to design an HP omnidirectional antenna is to construct a small loop antenna with uniform current distribution. As we all know, the small loop antenna has small radiation resistance and high reactance, which make it difficult to be matched [10]. The loop antenna with large diameter has a reasonable impedance performance. However, it is difficult to ensure the uniform current distribution on the large loop to have a small gain variation in horizontal plane. Meanwhile, the large diameter of loop antenna would make its main radiating direction being off the horizontal plane. Alford loop antennas [5], [6] are proposed to obtain a HP omnidirectional radiation. Four arc dipoles with length about $\lambda/2$ (λ: wavelength in free space at center frequency) construct as a loop antenna. A 1to4 power divider is used to feed these four arc dipole. The Alford loop antenna [5] has a 10-dB return loss (RL) operating bandwidth of 27.1% (1.69~2.22GHz) with a gain variation of 1.5dB in the horizontal plane. A large operating bandwidth of 41 %(1.76~2.68GHz) for RL>10dB is obtained in [6]. But undesirable radiation performance in horizontal plane occurs at high operating frequency because the current is non-uniformly distributed on each arc dipole. In [7], [8], the artificial mu-negative transmission line is utilized in loop antenna to maintain the current on loop in phase for HP omnidirectional radiation. The loop antenna [7] has a narrow operating band 2.32~2.58GHz, while a wider operating band 2.17~2.97GHz is obtained in the antenna [8] with its performance of gain variation becoming worse at high operating frequency. A broadband four magneto-electric antenna array [9] is arranged as a ring to obtain an HP omnidirectional radiation. This antenna has a 38% impedance bandwidth. But its maximum radiating direction is not in horizontal plane. Through the discussion of the previous HP omnidirectional antenna designs, it can be found that it is difficult to design an HP omnidirectional antenna which simultaneously owns a large operating bandwidth over 40% and good gain variation performance among whole operating band.

In recent years, many wideband dipole array designs based on tight coupling mechanism [11]-[16] have been published. The wide bandwidth of tightly coupled phased arrays is attributed to the strong inter-element coupling. The current distribution on elements effectively emulates a sheet of uniform current [17] proposed by wheeler. Through strong inter-element capacitive coupling, these phased dipole arrays can own a very broad operating bandwidth over 100%.

In this communication, a wideband HP omnidirectional antenna is presented. Inspired by the design of tightly coupled dipole array, twelve printed arc dipoles (0.2λ_L, λ_L: effective wavelength at low frequency) are designed with edge overlap for strong inter-element capacitive coupling. They are formed as a loop and fed by a 1to12 wideband power divider with equal magnitude and identical phase to create a good HP omnidirectional radiation. Moreover, two rows of arc parasitic

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strips are radially placed around the printed arc dipoles as impedance matching layer for wide operating band. One row of arc strips is employed as director to enhance the radiation in horizontal plane.

This communication is organized as follows. In section II, designing process of wideband HP omnidirectional antenna is discussed. The section III shows the measured and simulated results. Finally, a conclusion is summarized in section IV.

II. HP OMNIDIRECTIONAL ANTENNA DESIGN

A. *Proposed loop antenna design*

In [11]-[16], some ultra-wideband tightly coupled dipole arrays are presented in 2-D form. The tightly coupled dipole unit cell [11] with periodic boundary is depicted in Fig. 1(a). Two pairs of master and slave boundary are set along x and y axis, respectively, while the radiation boundary is set along +z axis. Fig.1 (b) and (c) show the side and top view of tightly coupled dipole unit. The each arm of dipole unit is printed on the opposite side of substrate. The mutual couplings between dipole units are determined by the overlap section with length s. The mutual coupling between dipole units can greatly improve the impedance bandwidth. In the design of finite tightly coupled dipole array, their operating bandwidths are always deteriorated by their edge effect. Also a complicated feed network must be built for feeding the dipole units. So the fabrication and design of a finite tightly coupled dipole array is a task with technical challenge and high cost.

Though many problems exist in the design of finite tightly coupled dipole array, it comes to know that the operating band of antenna array can be broadened by its strong inter-element coupling. In Fig.2, we can create a loop antenna with some dipole units in [11] being formed as a ring to imitate one-dimension (1-D) infinite tightly coupled dipole array in Fig.1(d). This design method can perfectly solve finite dipole array edge effect on the impedance bandwidth. By these dipole units being fed by equal magnitude and identical phase, a wideband HP omnidirectional antenna can be obtained. Owing to the small electric length of dipole unit in tightly coupled dipole array, the uniform current distribution on loop antenna can be obtained for good gain variation performance in horizontal plane.

In this communication, a wideband HP omnidirectional antenna covering 2G/3G/LTE band (1.7~2.7GHz) is presented for verify the reliability and superiority of mutual coupling method. The first step to design HP omnidirectional antenna in 1.7~2.7GHz is to determine dimension of dipole unit in 1-D infinite tightly coupled dipole array, which can be obtained by its simulated model in Fig.1 (e). All the simulations in this work are conducted by Ansoft HFSS v15. In Fig.1 (e), one pair of master and slave boundary is perpendicular to y axis, while the other four faces parallel to y axis are set as radiation boundary. For simplicity, the superstrate in Fig.1 (a) is replaced by two parasitic strips as impedance matching layer, which is similar to the impedance matching layer design in [16]. The parasitic strips and dipole unit are printed on 1mm-thickness F4B substrate (ε_γ=2.2, tanδ=0.02). With dimensional values of

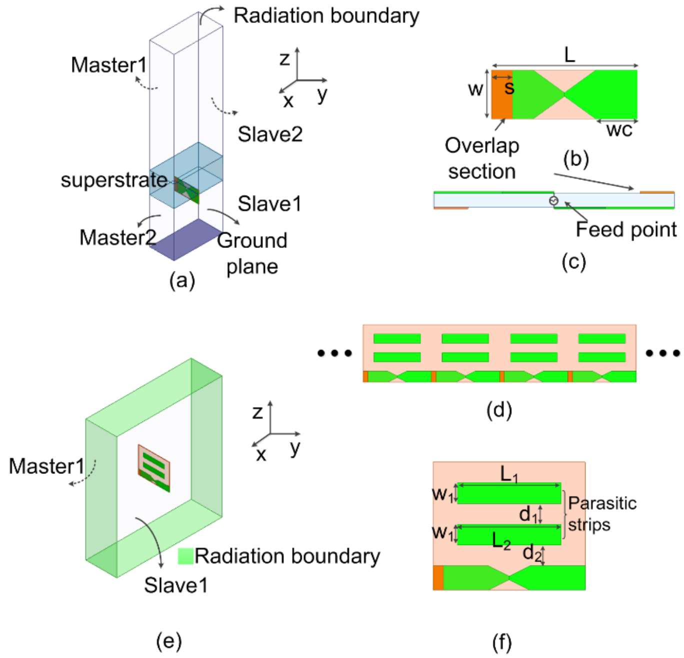

Fig. 1. (a) Simulated model of tightly coupled dipole unit in [11], (b) side view of dipole unit, (c) top view of dipole unit,(d) 1-D infinite tightly coupled dipole array (e) simulated model of unit cell in 1-D infinite tightly coupled dipole array, (f) side view of dipole unit.

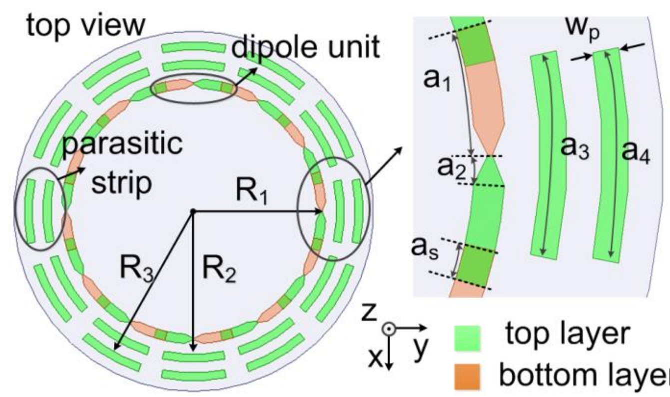

Fig. 2. Loop antenna with twelve dipole units and parasitic arc strips .

s=2mm, w=3.5mm, L=21mm, wc=9.3mm, w_1=3.5mm, L_1=L_2=18mm, d1=d2=3.5mm, the impedance matching performance (referenced to 150Ω) of the dipole unit with parasitic strips is shown in Fig.3 with a large operating bandwidth of 96.1 %(1.6~4.56GHz) for RL>10dB. Fig.3 indicates that the dipole unit without parasitic strips has an operating bandwidth of 79.4 %(1.9~4.4GHz). Moreover, the impedance matching performance of dipole unit with parasitic strips is better than that of dipole unit without parasitic strips among the whole operating band. Thus the parasitic strips can truly enhance the impedance matching performance of dipole unit.

After the determination of dipole unit size, next step is to choose the loop antenna diameter value R_1. In this design, diameter value R_1 of loop antenna can be determined by the

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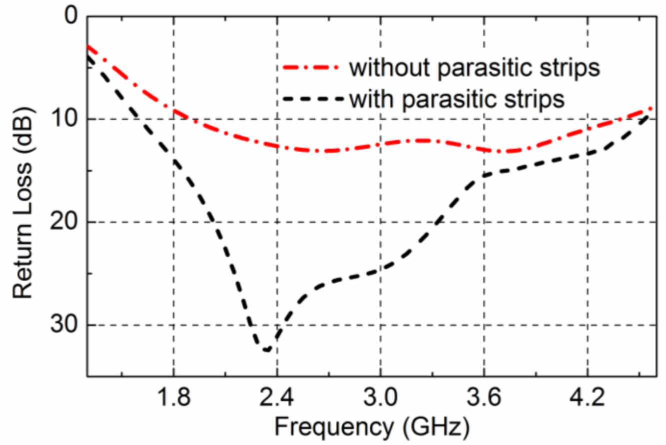

Fig. 3 Simulated RL of dipole unit with and without parasitic strips.

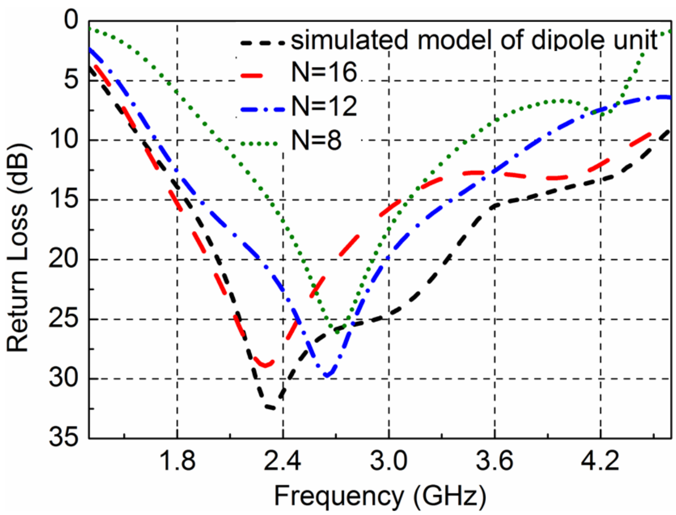

Fig.4. Simulated RL of three loop antenna designs and simulated model of dipole unit.

equation of $R_1= (N\times L)/2\pi$. N is the number of dipole units in loop antenna design, while L is the length of dipole unit. The simulated RL of loop antenna with different dipole unit number (N=8, 12 and16) are compared in Fig.4. It can found the impedance matching performance of loop antenna are closer to that of simulated model of dipole unit with number N of dipole unit increasing. However, the maximum radiating direction of loop antenna is off the horizontal plane with the increase of diameter value R_1. Therefore, it is more appropriate to choose a small loop antenna for good radiation performance. In consideration of the radiation and impedance matching performance of loop antenna with different numbers of dipole unit, the number of dipole units in loop antenna is chosen as 12, which makes this loop antenna having a diameter value of 86mm. With the optimal structural values of a_1=17.5°, a_2 =4°, a_s=5°, a_3=12.3°, a_4=10.5°, w_p=3mm, R_1=43mm, R_2=49mm, R_3=56mm, the operating band 1.65~3.9GHz for RL>10dB can be obtained. The length L_{total} of dipole unit and overlap section can be calculated as 26.27mm by the expression of $L_{total}=2\times a_1\times\pi\times R_1/180$, which respectively be equal to $0.2\lambda_L$ (λ_L: effective wave length at 1.65GHz) and $0.5\lambda_H$ (λ_H: effective wave length at 3.9GHz). The current distributions on loop antenna at 1.65GHz and 3.9GHz are shown in Fig.5. It can be found that the in-phase current with uniform magnitude flows on the loop. The normalized radiation patterns in horizontal plane at 1.65GHz and 3.9GHz are illustrated in Fig.6 to confirm the current distribution. The gain variation in horizontal plane at 1.65GHz is about 0.35dB, while 0.7dB at3.9GHz. It can be concluded that the loop antenna has a good omnidirectional radiation performance among 1.65~3.9GHz.

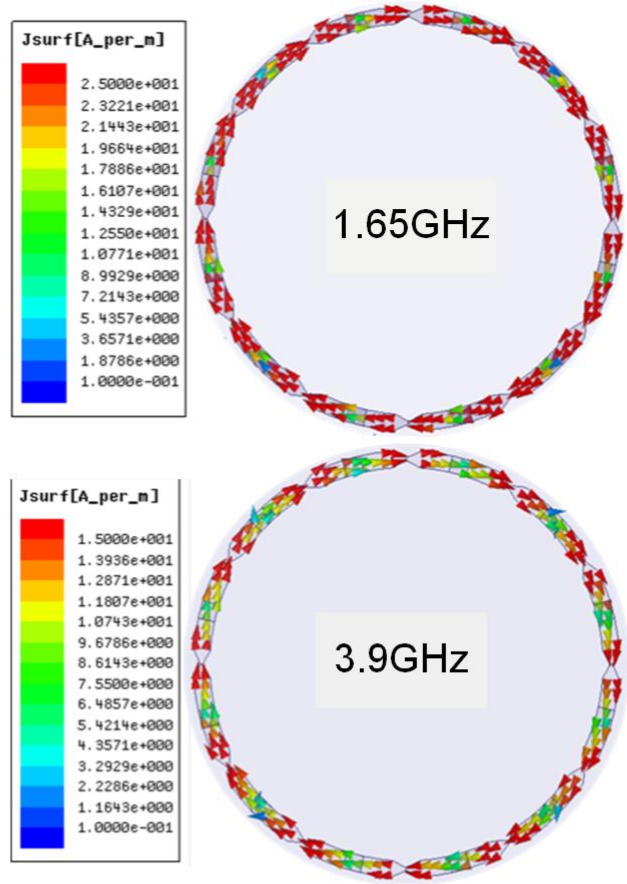

Fig. 5. Current distribution on loop at 1.65GHz and 3.9GHz

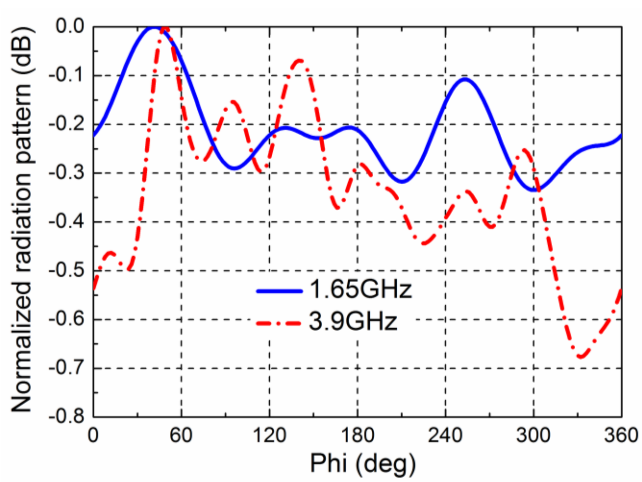

Fig .6. Normalized radiation pattern in horizontal plane at 1.65 and 3.9GHz.

As pointed out above, the maximum radiating direction of loop antenna would not be in horizontal plane with its diameter value increasing. It means that the loop antenna does not radiate

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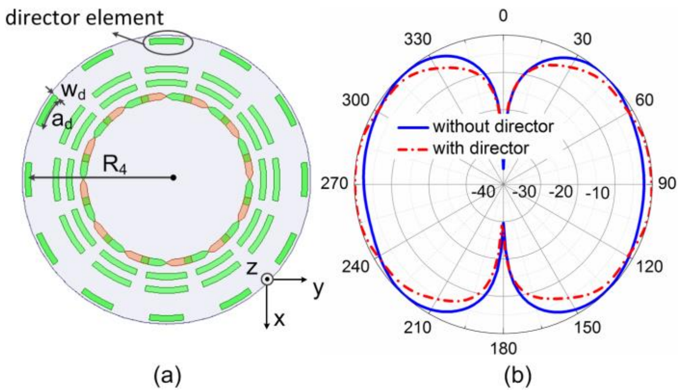

Fig.7 (a) loop antenna with director, (b) normalized radiation pattern in elevation plane of loop antenna with and without director at 2.7GHz.

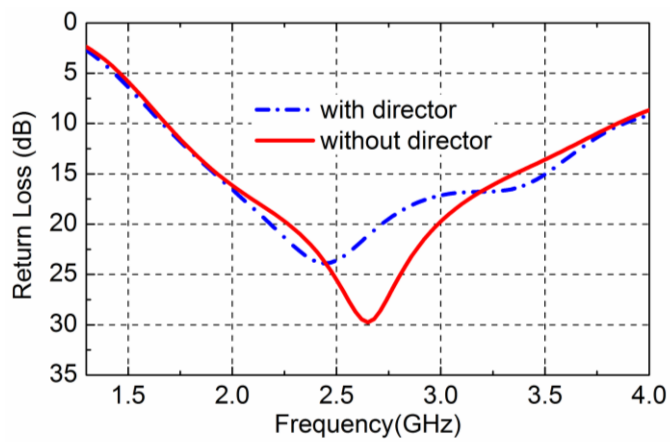

Fig.8. simulated RL of the proposed loop antenna with and without director.

maximally in horizontal plane at high operating frequency. The normalized radiation pattern in elevation plane (i.e., x-z plane) at 2.7GHz of loop antenna without director is shown in Fig.7, which proves that the loop antenna cannot radiate maximally in horizontal plane. To mitigate this problem, twelve arc strips are utilized as director in Fig.7 (a) to guide electromagnetic wave in horizontal plane. The arc director element has an angle a_d of 12 °, width w_d of 3mm and radius R_4 of 70.5mm. As shown in Fig.7 (b), the maximum radiation direction becomes in horizontal plane with the help of director. The simulated RL performances of the proposed loop antenna with and without director have been shown in Fig.8, which demonstrates that the addition of director nearly does not affect the impedance matching performance of loop antenna.

B. *Feed network design*

In order to feed the loop antenna with twelve dipole units, a wideband 1to12 power divider is designed in Fig.9. The power divider is printed on the 1mm-thickness F4B substrate (ε_γ=2.2, tanδ=0.02) with the optimal values as depicted in Fig.9(c) and (d). The equivalent circuit of feed network is drawn in Fig.10.Due to that the input impedance of dipole unit in loop antenna being referenced to 150Ω, the impedance of output load of the designed power divider is set as 150Ω. The dipole units are feed by 150Ω broadside parallel strip (BPS). By two

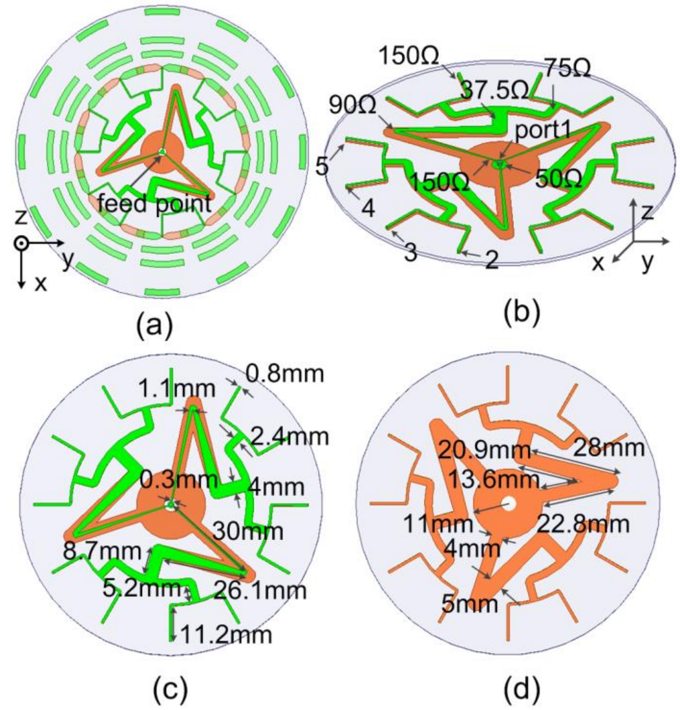

Fig.9 .(a) the loop antenna with 1to12 power divider,(b)3D view of 1to12 power divider, (c) top view, (c)back view.

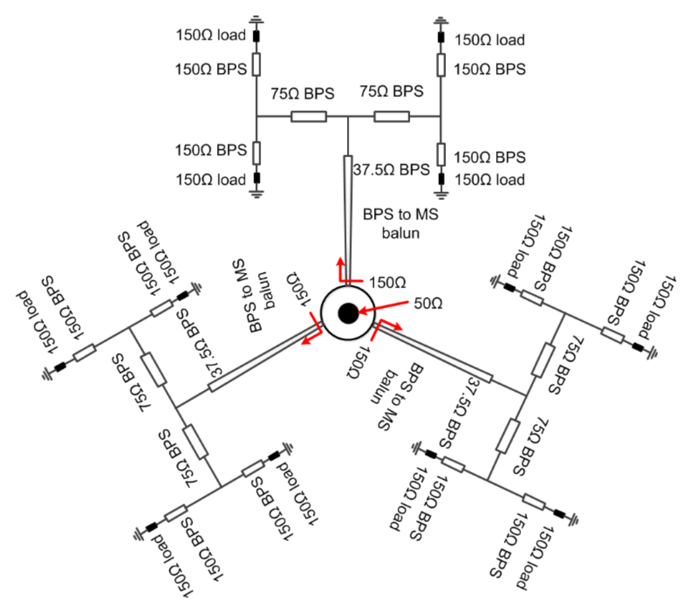

Fig. 10. Circuit diagram of feed network.

150Ω BPSs are connected in parallel, a 75Ω BPS can be used to provide power with equal magnitude in wide operating band. In the same way, a 37.5Ω BPS can be employed to equally provide power to two 75Ω BPSs being connected in parallel. Then, a BPS-to-microstrip(MS) balun (tapered line balun) is used to transform 37.5Ω BPS into 150Ω MS in center point of feed network. Three 150Ω impedances in center point are connected in parallel to match to the 50Ω SMA connector. Owing to the symmetry of feed network structure, the port 1, 2, 3, 4 and 5 in Fig.9 (b) are chosen to show the wideband performance of this feed network. In Fig.11, the simulated reflection coefficient (S11) and transmission coefficient (S21, S31, S41 and S51) are

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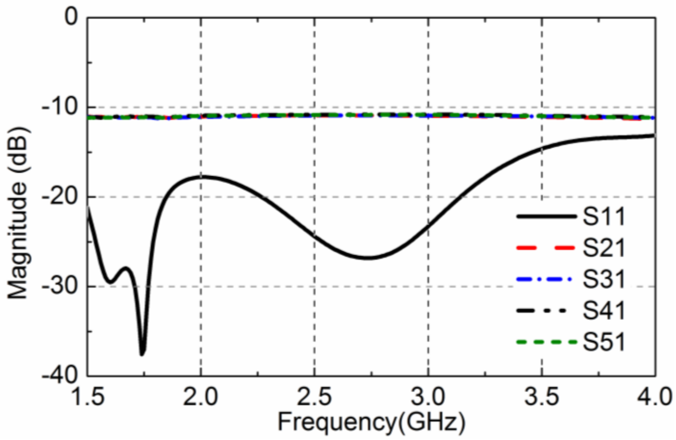

Fig. 11. The performance of proposed 1to12 power divider

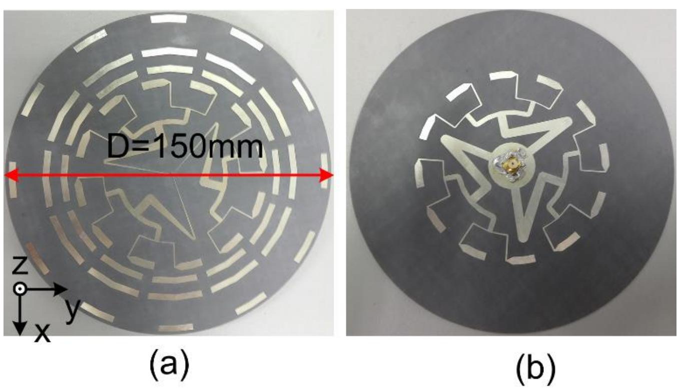

Fig. 12. Photograph of the proposed antenna. (a) Front view, (b) back view.

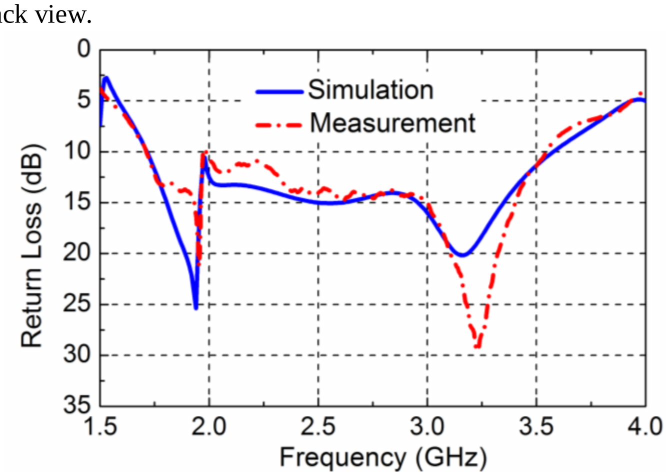

Fig. 13. Simulated and measured RL of proposed antenna.

illustrated. The simulated reflection coefficient (S11) is less than -15dB among 1.5~3.5GHz, while less than -13dB in1.5~4GHz. The transmission coefficients (S21, S31, S41 and S51) have a magnitude of -11 dB with a variation of 0.3dB in 1.5~4GHz. The simulated results confirm that this 1to12 power divider can be suitable to feed the proposed loop antenna with 12 elements

III. Simulation and Experimental Results

The proposed HP omnidirectional antenna has been fabricated and measured. Fig.12 shows the front and back view of the antenna prototype. The proposed antenna has a diameter D of 150mm. The measured operating bandwidth of 70.2 %(1.7~3.54GHz) for RL>10dB can be obtained in Fig. 13, which agrees well with simulated operating band 1.7~3.58GHz. In Fig. 14, the measured radiation patterns in horizontal plane(x-y plane) and elevation plane (x-z plane) are compared with simulated results at four separate frequencies of 1.7GHz, 2.2GHz, 2.7GHz, and 3.2GHz. It can be observed that the

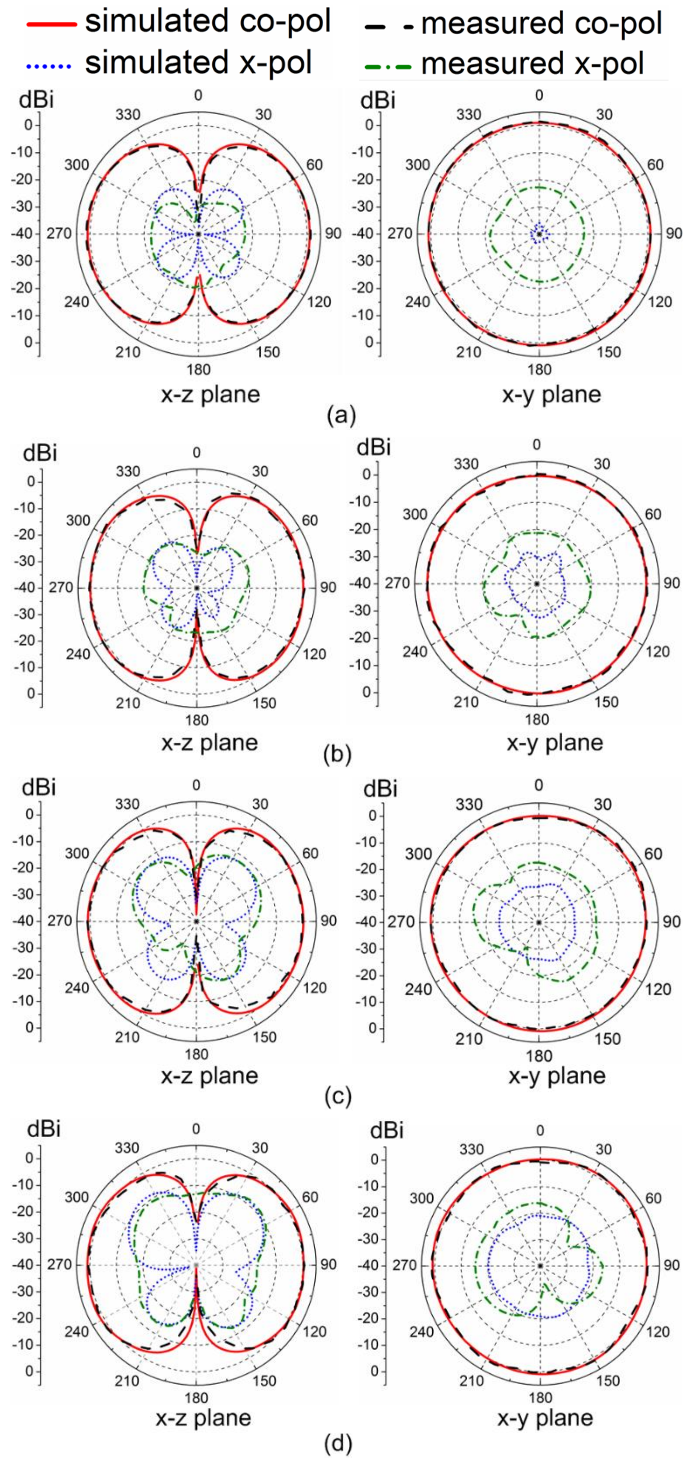

Fig. 14. Simulated and measured radiation patterns at (a) 1.7GHz, (b) 2.2GHz, (c) 2.7GHz, (d) 3.2GHz.

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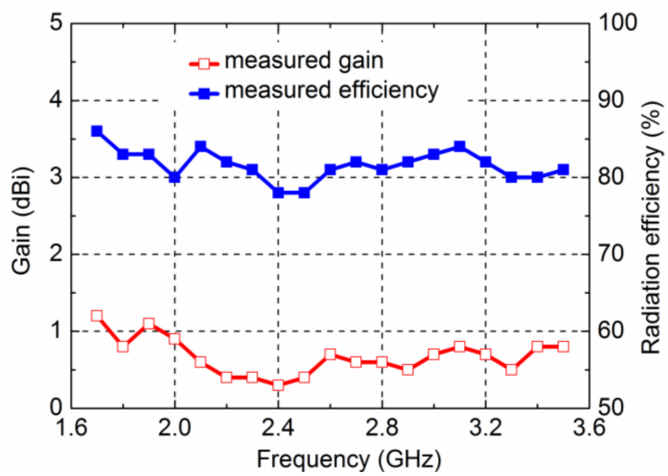

Fig. 15. Measured gain and radiation efficiency of proposed HP omnidirectional antenna.

measured gain variation in horizontal plane (i.e., x-y plane) is less than 1.2dB among 1.7~3.2GHz, which confirms the good omnidirectionality performance as illustrated in Fig.6. The cross-polarization level is -15dB below the co-polarization in horizontal plane. It should be noted that simulated gain variation becomes larger than 1.5dB at high operating frequency over 3.3GHz, which mainly be caused by the feed structure of loop antenna. The measured gain and radiation efficiency are presented in Fig. 15. The measured gain varies from 0.4 to 1.2dBi in the operating band 1.7~3.5GHz. The gain of proposed HP omnidirectional antenna is lower than the gain about 1.7dBi of a small loop antenna with a diameter of λ/10, which is caused by its large diameter value in electric length at high operating frequency. The measured radiation efficiency 78%~84% is obtained over the operating band 1.7~3.5GHz.

IV. Conclusion

A wideband HP omnidirectional antenna is presented in this communication. Based on the design of ultra-wideband tightly coupled dipole array, a loop antenna is divided into twelve dipole units. With tightly mutual coupling between dipole units, parasitic arc strips and a wideband feed network, a wideband HP omnidirectional antenna is obtained. The twelve arc director elements are further utilized to enhance the gain performance in horizontal plane. A wideband measured operating bandwidth of 70.2 %(1.7~3.54GHz) for RL>10dB is achieved, as well as small gain variation in horizontal plane less than 1.2dB among 1.7~3.2GHz. Measured results also show that a measured gain 0.4 ~1.2dBi and radiation efficiency 78%~84% can be obtained. With the good performance of impedance match and gain variation in horizontal plane, several proposed HP omnidirectional antennas can be stacked as a vertical array for high gain in 2G/3G/LTE base-station application. For increasing the capacity of wireless system, HP omnidirectional antenna can be treated as an essential complement for vertically polarized omnidirectional monopole in 2G/3G/LTE application. The HP omnidirectional antenna can also have an application in indoor wireless communication by being mounted under a metallic plate to reduce the effect of ceiling on it and create a conical beam.

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