A Broadband Omnidirectional Circularly Polarized Antenna

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***Abstract*—A broadband circularly polarized (CP) antenna is developed with an omnidirectional radiation pattern in the horizontal plane. Four broadband CP rectangular loop elements are employed for broadband omnidirectional CP radiation. The four rectangular loop elements are first printed on a flexible thin dielectric substrate and then rolled into a hollow cylinder. A conducting cylinder is introduced inside the hollow cylinder for achieving desired omnidirectional CP performance. A feeding network consisting of four broadband baluns and an impedance matching circuit is designed to feed the four rectangular loop elements. The omnidirectional CP antenna has a circular cross section with diameter of $0.38\lambda_0$. Experimental results show that the omnidirectional CP antenna has bandwidths of 41% (1.65–2.5 GHz) for axial ratio < 3 dB and 45% (1.58–2.5 GHz) for return loss > 10 dB. The gain variation in the omnidirectional plane is less than 1 dB for the frequency range from 1.65 to 2.5 GHz. Good agreement is obtained between simulated and measured results.**

***Index Terms*—Broadband antenna, circularly polarized (CP) antenna, mobile communications, omnidirectional antenna.**

I. Introduction

OMNIDIRECTIONAL linearly polarized (LP) antennas have been widely used in base stations of mobile communications because they can reduce the number of cell sectors and the effects of small sector variations. Circularly polarized (CP) antennas have an advantage over traditional LP antennas in that CP antennas can enhance the stability of signal reception by receiving arbitrarily LP signals. The use of circular polarization can also suppress the effect of multi-path reflection of waves caused by building walls and the ground surface. It was demonstrated that an omnidirectional CP antenna can enhance signal reception in land mobile systems [1]. Several measurement campaigns have demonstrated that CP antenna always outperform LP antennas in mobile communication environments [2]–[4]. "While the use of a CP antenna is probably not feasible in a small hand held device due to size constraints, the use of CP antennas at the base station could be beneficial." [3] The main reason for wide use of LP antennas nowadays instead of CP antennas is probably that it is much easier to implement a LP antenna than a CP antenna, especially for a broadband operation. We hope our work could help improve this situation and re-inspire the interest in CP antennas for mobile communications. Omnidirectional CP antennas may also find applications in television broadcasts, mobile satellites, and space vehicles such as airplanes, missiles, rockets, and spacecraft [5]–[10]. For *modern* mobile communications, base station antennas must have a wide bandwidth. For example, the 2G/3G systems require covering the frequency range from 1.71 to 2.17 GHz. Therefore, a bandwidth of at least 25% is needed for 2G/3G base station antennas. The purpose of this paper is to demonstrate a new broadband omnidirectional CP antenna configuration.

In recent years, a number of topologies for omnidirectional CP antennas have been investigated. A CP omnidirectional antenna consisting of a vertical sleeve dipole and three pairs of tilted parasitic elements was reported in [11], which has a bandwidth of 6.9% for axial ratio (AR) <3 dB. A small helical CP omnidirectional antenna was proposed in [12]. It has a wide bandwidth for AR, but a narrow bandwidth for return loss (RL) (~3% for $\mathrm{RL} > 10$ dB). A dipole antenna in the form of DNA strands was developed in [13] to give an omnidirectional pattern in circular polarization. But its bandwidth is less than 3%. A three-element polarization-adjustable (including CP) dipole array is presented in [14], but the maximum AR is approximately 9 dB in the operating frequency band (1850–1990 MHz) and the dipole array leads to a bigger antenna size than one wavelength in diameter (λ_0, where λ_0 is the free-space wavelength at the center frequency of an operating frequency band). Several low-profile topologies have been reported in [15]–[17]. A patch antenna produces a vertically polarized wave while four horizontal arms attached around the patch generate a horizontally polarized wave; hence an omnidirectional CP wave can be excited by adjusting the length of the arms. However, the patch antenna usually has a narrow bandwidth, leading to a narrowband omnidirectional CP antenna (bandwidth <5%). In [18] and [19], two strip/slot cylindrical omnidirectional CP antennas were developed for mm-wave applications, but the antennas have a quite large electrical size (~$4.7\lambda_0$ in diameter [18]) and a narrow bandwidth (0.8%), not suitable for base station antennas. A back-to-back patch configuration was proposed for an omnidirectional CP antenna in [20], which has the advantage of low-profile and simple structure, but the topology leads to a poor omnidirectivity and a narrow bandwidth (1.3% for $\mathrm{RL} > 10$ dB). In [21], an eight-element CP patch array was used to construct an omnidirectional CP antenna by wrapping

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around a dielectric cylinder. The wraparound omnidirectional CP antenna has a diameter of $\sim 2\lambda_0$ and a narrow bandwidth ($\sim$2%). Therefore, this paper proposes to develop a broadband omnidirectional CP antenna with a low cross section.

The broadband omnidirectional CP antenna developed consists of four printed broadband CP rectangular loop elements and a feeding network. The rectangular loop elements have an aspect ratio of $\sim$10/3, leading to a low cross section with a more compact and cylindrically conformal configuration when such four printed rectangular loop elements are rolled into a hollow cylinder. The broadband CP rectangular loop element was developed in [22]. A bandwidth of $\sim$50% for circular polarization has been achieved. Therefore, it should be possible to realize a broadband omnidirectional CP antenna if the rectangular loop element is employed as a radiating element for omnidirectional CP antenna. A conducting cylinder is introduced inside the hollow cylinder formed by the four rectangular loop elements to improve the CP performance. A feeding network is designed to excite the four CP rectangular loop elements. The antenna structure and its performance will be described in Section II. The effect of the conducting cylinder and the operating principle of the feeding network will be investigated in Section III. An experimental verification will be presented in Section IV.

II. Antenna Structure and Performance

Fig. 1 shows the configuration proposed for a broadband omnidirectional CP antenna. The configuration includes four broadband CP rectangular loop elements and a feeding network. The four rectangular loop elements are first printed on a thin flexible dielectric substrate and then rolled into a hollow cylinder [Fig. 1(a)]. The omnidirectional CP antenna was designed at the frequency band centered at 2 GHz for 2G/3G mobile systems. The diameter (D1) of the hollow cylinder is 57.2 mm ($0.38\lambda_0$ at 2 GHz), much smaller than most of traditional omnidirectional CP antennas. The geometry of each CP element is displayed in Fig. 1(b). There is a pair of small gaps on the primary loop for the excitation of a traveling-wave current which is required for the generation of a CP wave. A pair of parasitic loops (with a gap for each loop) is introduced inside the primary loop to enhance the bandwidth of the CP element. More details for the broadband CP element can be found in [22] and [23].

The CP rectangular loop element alone is a bidirectional element which radiates a left-handed (LH) CP wave, for example, in one direction and a right-handed (RH) CP wave in the opposite direction. Usually a conducting reflector (or a ground plane) is placed below or above the loop plane to realize a unidirectional radiation pattern. For an omnidirectional CP radiation pattern, we introduce a conducting cylinder inside the hollow cylinder. The conducting cylinder acts as a cylindrical reflector. A gap is introduced at the middle of the conducting cylinder to leave a space for the feeding network. The sizes of the conducting cylinder have significant effects on the CP performance, which will be discussed in the next section. The technique of placing four antenna elements around a tower (which is a reflector itself, or reflectors are placed between the antennas and

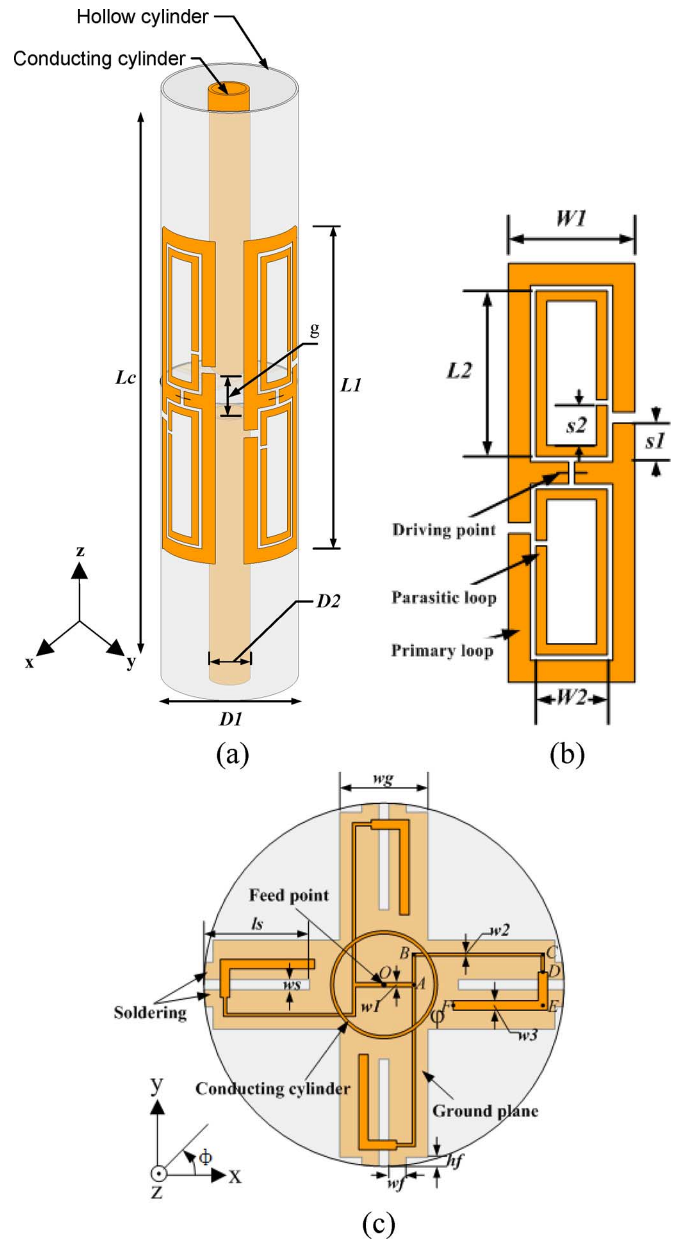


Fig. 1. Configuration of a broadband omnidirectional circularly polarized (CP) antenna: (a) perspective view; (b) broadband cp element; (c) feeding network.

the tower) has been used for a long time in FM radio and TV broadcast [5].

The feeding network designed to excite the broadband omnidirectional CP antenna comprises four broadband baluns and an impedance matching circuit, as illustrated in Fig. 1(c). The broadband balun converts an unbalanced microstrip line to a balanced feed at the "Driving point" of the CP loop element. The matching circuit connects four broadband baluns to a 50-Ω coaxial line at the "feed point" [see Fig. 1(c)]. The operating principle of the feeding network will be described in Section III.

The broadband omnidirectional CP antenna with feeding network was simulated and optimized using *HFSS* v11. The optimized geometric parameters are summarized in Table I. The simulated return loss (RL) is plotted in Fig. 2. The bandwidth for RL>10 dB is about 40% (1.63–2.43 GHz). The gain patterns in the horizontal plane (i.e., the xy plane) simulated at 1.7, 2.0,

TABLE I
OPTIMIZED GEOMETRIC PARAMETERS FOR THE BROADBAND OMNIDIRECTIONAL CP ANTENNA

Lc	235 mm	*CD*	2.75 mm
D1	57.2 mm	*DE*	3.75 mm
D2	16 mm	*EF*	14.25 mm
L1	115 mm	*wg*	14 mm
L2	45.5 mm	*w1*	0.7 mm
W1	35 mm	*w2*	0.5 mm
W2	20 mm	*w3*	1.5 mm
s1	9.2 mm	*ws*	1.6 mm
s2	10.7 mm	*ls*	16.8 mm
OA	4.75 mm	*g*	10 mm
AB	4.75 mm	*hf*	1.5 mm
BC	20.5 mm	*wf*	2.7 mm

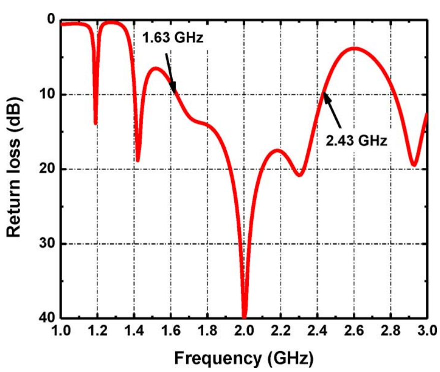


Fig. 2. Simulated return loss for the omnidirectional CP antenna.

and 2.4 GHz are depicted in Fig. 3 for the LHCP component (the copolarization) and for the RHCP component (the cross-polarization). It is seen that the gain variation for the copolarization in the horizontal plane is less than 1 dB; therefore, we also call the horizontal plane an omnidirectional plane. It was observed from simulation that the gain variation in the omnidirectional plane is less than 1 dB over the frequency range of 1.65–2.5 GHz. The cross- polarization in the omnidirectional plane is more than 17 dB lower than the copolarization. The gain patterns in the elevation plane (i.e., the xz plane) simulated at 1.7, 2.0, and 2.4 GHz are also depicted in Fig. 3 for the LHCP component. The beamwidth in the vertical plane decreases as the frequency increases. The reason for the decreased beamwidth is that the electrical length of the omnidirectional antenna increases with increasing frequency. The narrowed beamwidth in the vertical plane leads to an increased gain due to the omnidirectional pattern in the horizontal plane. The axial ratio (AR) averaged in the omnidirectional plane plotted as a function of frequency is shown in Fig. 4. It is found that the bandwidth for $\mathrm{AR} < 3$ dB is about 39% (1.67–2.47 GHz), wide enough to cover the frequency bands for 2G/3G systems of mobile communications. The omnidirectional gain (averaged in the horizontal plane) is also plotted in Fig. 4. The gain increases from 1.5 to 4.5 dBi as the frequency increases from 1.7 to 2.4 GHz.

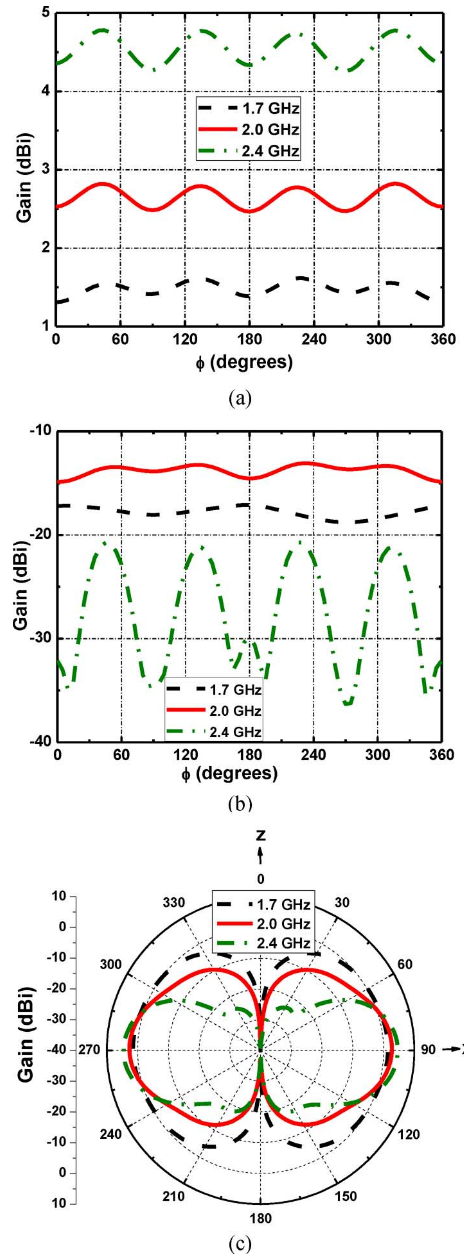


Fig. 3. Simulated gain patterns for the omnidirectional CP antenna: (a) LHCP in the horizontal plane (i.e., the xy plane); (b) RHCP in the horizontal plane (i.e., the xy plane); (c) LHCP in the elevation plane (i.e., the xz plane).

III. PARAMETRIC STUDY AND ANALYSIS

A. Conducting Cylinder

As mentioned in the previous section, the purpose for the introduction of the conducting cylinder is to improve the CP performance of the omnidirectional antenna. In this section, we first investigate how the geometric parameters of the conducting cylinder affect the antenna performance. Fig. 5(a) shows the dependence of the axial ratio (AR, averaged over the omnidirectional plane) on the diameter (D2) of the conducting cylinder. It is seen that if without the conducting cylinder (i.e., $\mathrm{D2} = 0$), the AR at the center frequency (2 GHz) is larger than 12 dB. When the conducting cylinder is introduced, the AR performance is improved. As the diameter D2 increases from 8 to 16 mm, the AR decreases from $\sim$6 dB to less than 3 dB at 2 GHz. And

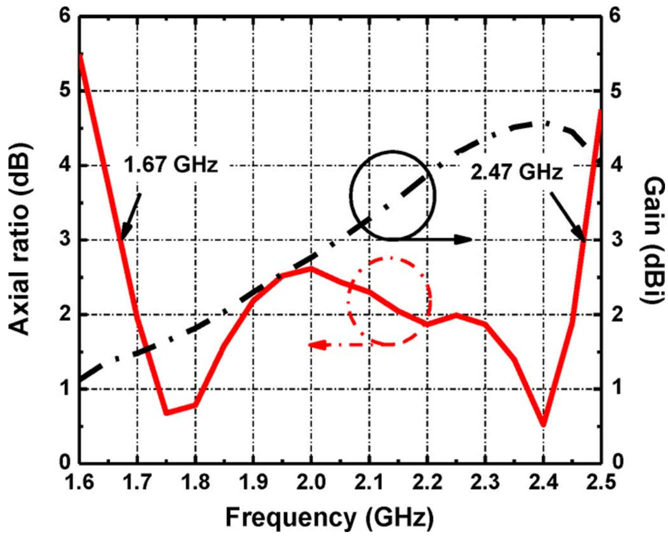
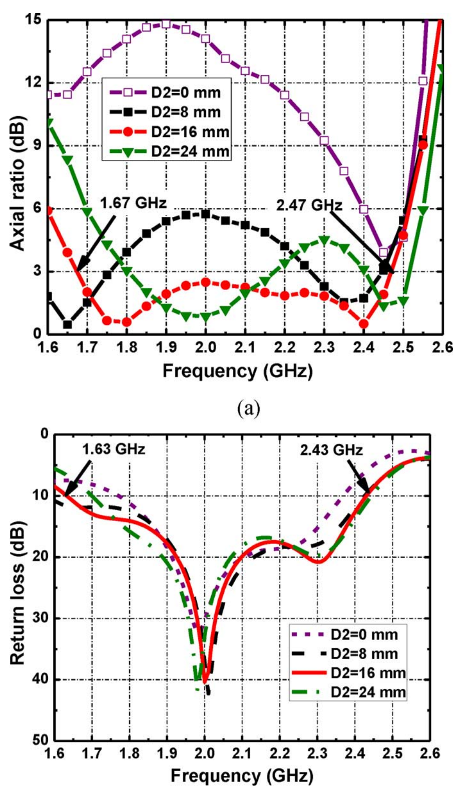


Fig. 4. Simulated axial ratio and gain averaged in the omnidirectional plane for the omnidirectional CP antenna.



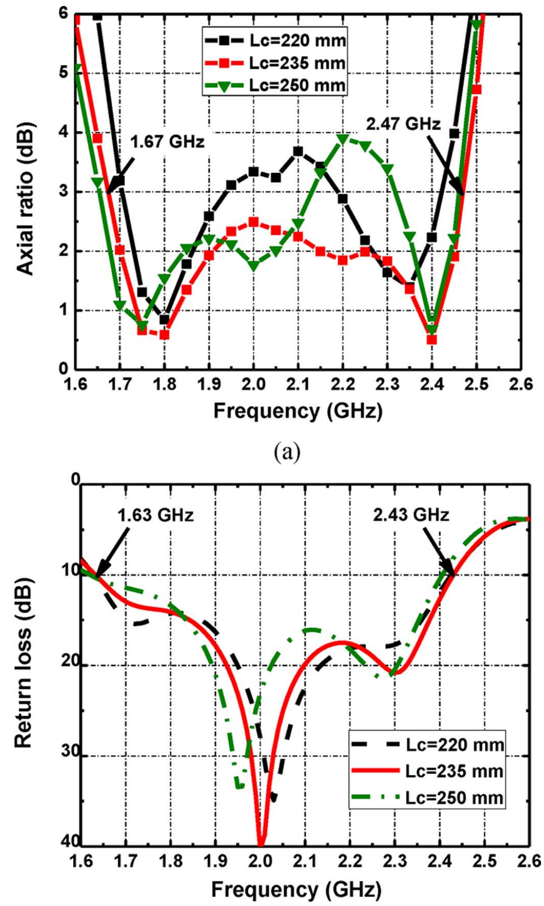
(a)

(b)

Fig. 5. Dependences of (a) axial ratio and (b) return loss of the omnidirectional CP antenna on the diameter of the conducting cylinder.

there is a bandwidth of 39% (1.67–2.47 GHz) for $\mathrm{AR} < 3$ dB at $\mathrm{D2} = 16$ mm $(\sim 0.1\lambda_0)$. However, as D2 further increases to $\mathrm{D2} = 24$ mm, the AR at 2.3 GHz increases to more than 3 dB. Therefore, we choose $\mathrm{D2} = 16$ mm as the optimal value for the diameter of the conducting cylinder. The diameter of the conducting cylinder has no significant effect on the return loss of the omnidirectional CP antenna as demonstrated in Fig. 5(b).

The dependence of the CP performance on the diameter of the conducting cylinder can be understood by considering the cylinder as a cylindrical reflector. For a planar CP loop antenna,



(a)

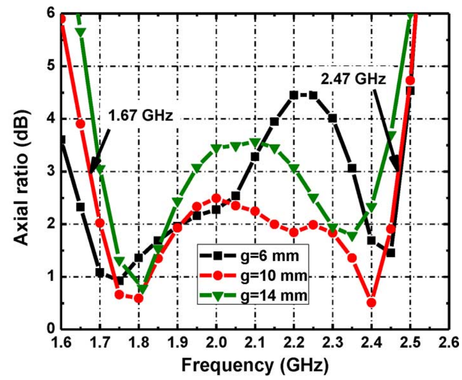
(b)

Fig. 6. Dependences of (a) axial ratio and (b) return loss of the omnidirectional CP antenna on the length of the conducting cylinder.

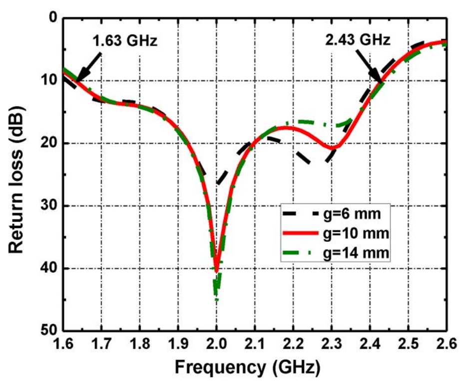
a conducting planar reflector can be introduced for a unidirectional CP radiation pattern. By analogy, for a cylindrical CP loop antenna, a conducting cylindrical reflector is introduced for an omnidirectional CP radiation pattern. If the diameter of the cylindrical reflector is too small, it cannot play the role of a reflector; thus, the desired CP performance cannot be achieved. If the diameter of the cylindrical reflector increases, the distance between the reflector and the cylindrical CP loop elements decreases. It has been demonstrated that the CP performance of a planar CP loop antenna becomes worse as the distance between the CP loop and its reflector decreases [23]. Therefore it is understandable that the CP performance of the omnidirectional CP antenna also becomes worse as the diameter of the conducting cylinder increases.

The length (Lc) of the conducting cylinder has to be longer than the length (L1) of the CP rectangular loop elements. There is an optimal value for the length Lc where the AR is less than 3 dB over the frequency range of 1.67–2.47 GHz. As indicated in Fig. 6(a), the optimal value for Lc is found to be $\mathrm{Lc} = 235$ mm $(\sim 1.6\lambda_0)$. Fig. 6(b) shows that the return loss of omnidirectional CP antenna is not sensitive to the length Lc.

The CP performance of the omnidirectional antenna is also dependent on the length (g) of the gap at the middle of the conducting cylinder, as illustrated in Fig. 7(a). The optimal value for the gap length is found to be $\mathrm{g} = 10$ mm $(\sim 0.068\lambda_0)$. Fig. 7(b)



(a)



(b)

Fig. 7. Dependences of (a) axial ratio and (b) return loss of the omnidirectional CP antenna on the gap length of the conducting cylinder.

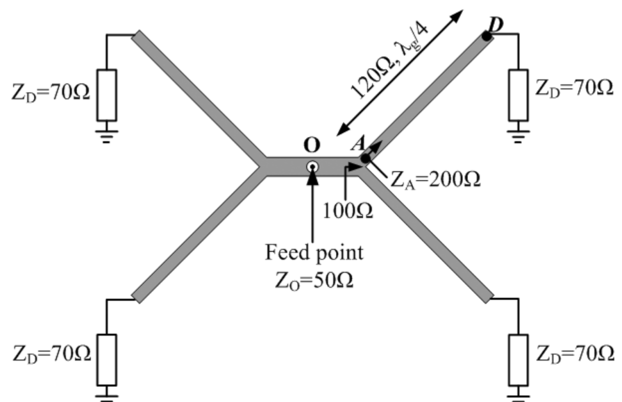


Fig. 8. Equivalent circuit for the feeding network of the omnidirectional CP antenna.

demonstrates that the gap length has no significant effect on the return loss of the omnidirectional CP antenna.

B. Feeding Network

To understand the operating principle of the feeding network for the omnidirectional CP antenna, a simple equivalent circuit for the feeding network is depicted in Fig. 8. The broadband balun for a rectangular loop element is simplified as a 70-Ω lumped impedance since the input impedance [looking at Point D from the unbalanced microstrip line, see Fig. 1(c)] of the broadband balun was designed to be 70 Ω. The theoretical analysis of the broadband balun can be found in [24], [25]. Here we focus on the analysis of the matching circuit which connects four 70-Ω lumped impedances to a 50-Ω coaxial line. First the 70-Ω impedance ($Z_D \approx 70\ \Omega$) at Point D is transformed into a 200-Ω impedance ($Z_A \approx 200\ \Omega$) Point A by a 120-Ω quarter-wave transformer ($\sqrt{Z_D \times Z_A} \approx 120\ \Omega$). Then two 200-Ω impedances Point A are connected in parallel, resulting in a 100-Ω impedance. The 100-Ω impedance is connected to the 50-Ω coaxial line through a 100-Ω impedance microstrip line. Finally two 100-Ω impedances at the "Feed point" (see Fig. 8) are connected in parallel, leading to a total impedance of 50 Ω and matching to the 50-Ω coaxial line.

Fig. 9. Prototype of the broadband omnidirectional CP antenna with front and back views of the feeding network.

IV. Experimental Verification

The broadband omnidirectional CP antenna was fabricated and measured. Fig. 9 shows the picture of a prototype of the antenna with front and back views of the feeding network. Four rectangular loop elements were first printed on a Panasonic R-F775 flexible dielectric substrate ($\varepsilon_r = 3.2$, loss tangent $= 0.0015$, thickness $= 0.05$ mm) and then rolled into a hollow cylinder. The feeding network was printed on a Taconic TLY-5 dielectric substrate ($\varepsilon_r = 2.2$, loss tangent $= 0.0009$, thickness $= 0.8$ mm). The conducting cylinder was made of a piece of copper foil. A flexible coaxial line (Johnson/Emerson RG178) with an SMA connector is connected to the feeding network through the inside of the conducting cylinder. Two pairs of Styrofoam flat washers (thickness $= 5$ mm) are inserted into the space between the hollow cylinder and the conducting cylinder to fix the conducting cylinder at the center of the hollow cylinder.

The measured result for return loss (RL) is compared with simulation result in Fig. 10. Good agreement is observed. The measured bandwidth for RL > 10 dB is 45% (1.58–2.5 GHz). The measured axial ratio (AR) averaged in the omnidirectional plane is compared with simulation result in Fig. 11. Agreement

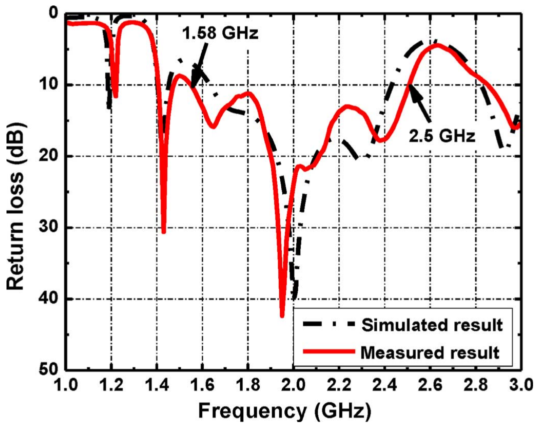


Fig. 10. Measured return loss for the omnidirectional CP antenna compared with simulation result.

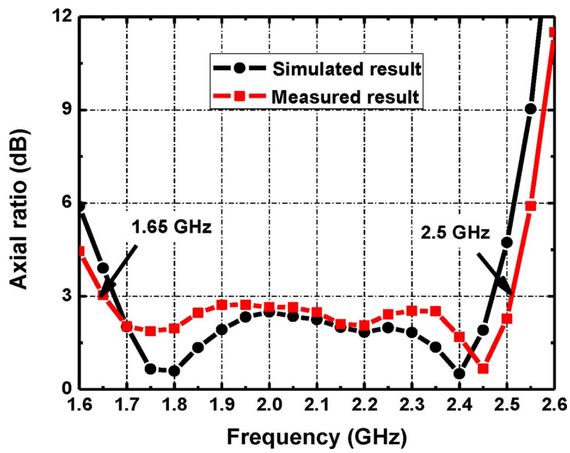


Fig. 11. Measured axial ratio for the omnidirectional CP antenna compared with simulation result.

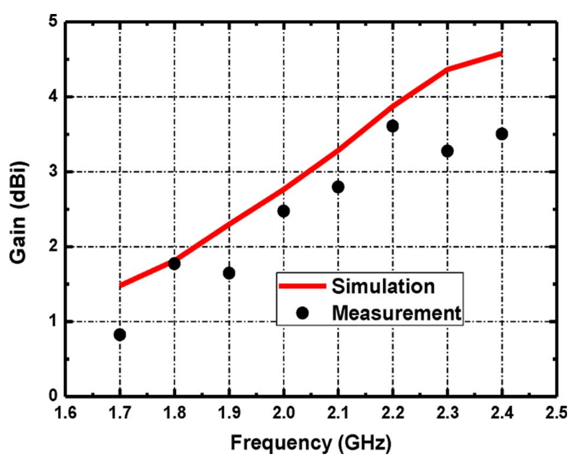
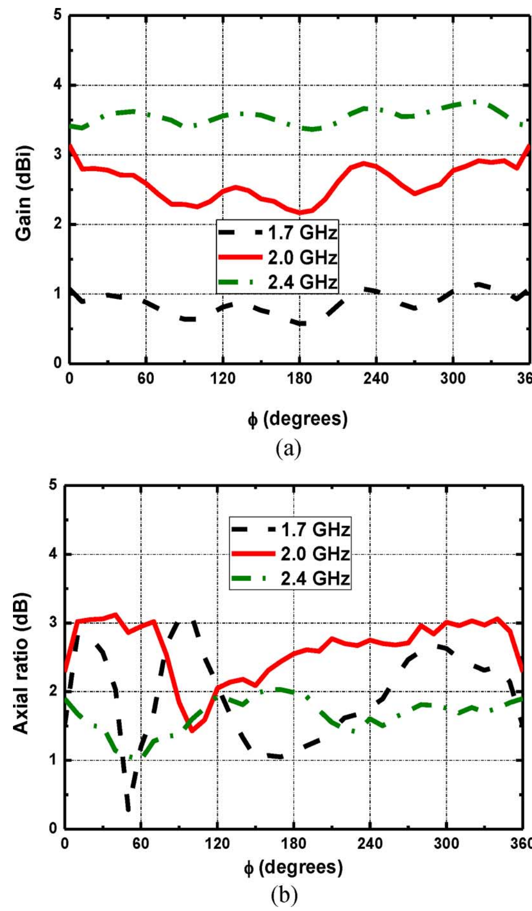


Fig. 12. Measured gain for the omnidirectional CP antenna compared with simulation result.

is obtained. The measured bandwidth for AR < 3 dB is 41% (1.65 GHz–2.5 GHz), which is overlapped with the bandwidth for RL. Fig. 12 shows the measured gain compared with simulated result, which confirms that the gain increases with increasing frequency. The simulated and measured results agree well with each other except at higher frequency band (2.3–2.4 GHz) where the coaxial line has a larger attenuation. Fig. 13 shows the measured gain and AR patterns in the omnidirectional plane (i.e., the xy plane) at 1.7, 2.0, and 2.4 GHz. We can see



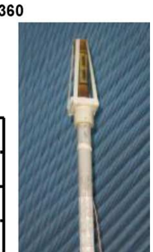


Fig. 13. Measured gain and axial ratio patterns for the omnidirectional CP antenna in the omnidirectional plane (i.e., xy plane): (a) gain pattern; (b) axial ratio pattern.

that the gain variation is less than 1 dB and the AR is less than 3 dB. For mobile communication base station applications, an antenna array is required, similar for an FM or TV transmitting array. This will be our future work.

V. Conclusion

A broadband omnidirectional CP antenna is developed using four broadband CP rectangular loop elements. The rectangular loop elements are first printed on a flexible thin dielectric substrate and then rolled into a hollow cylinder, which has a diameter of $0.38\lambda_0$, corresponding to a more compact configuration than most of traditional omnidirectional CP antennas. A conducting cylinder is introduced inside the hollow cylinder to improve the CP performance. A broadband feeding network is designed to feed the four broadband CP rectangular loop elements. The omnidirectional CP antenna achieves a bandwidth of 45% (1.58–2.5 GHz) for return loss >10 dB and a bandwidth of 41% (1.65–2.5 GHz) for axial ratio <3 dB. The gain variation in the omnidirectional plane is less than 1 dB. Experimental results validate the development of the broadband omnidirectional CP antenna, which allows the antenna element be arrayed for base stations of 2G/3G mobile communication systems.

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