Design of a Wideband Horizontally Polarized Omnidirectional Printed Loop Antenna

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***Abstract*—This letter presents the design of a novel wideband horizontally polarized omnidirectional printed loop antenna. The proposed antenna consists of a loop with periodical capacitive loading and a parallel stripline as an impedance transformer. Periodical capacitive loading is realized by adding interlaced coupling lines at the end of each section. Similarly to mu-zero resonance (MZR) antennas, the periodical capacitive loaded loop antenna proposed in this letter allows current along the loop to remain in phase and uniform. Therefore, it can achieve a horizontally polarized omnidirectional pattern in the far field, like a magnetic dipole antenna, even though the perimeter of the loop is comparable to the operating wavelength. Furthermore, the periodical capacitive loading is also useful to achieve a wide impedance bandwidth. A prototype of the proposed periodical capacitive loaded loop antenna is fabricated and measured. It can provide a wide impedance bandwidth of about 800 MHz (2170–2970 MHz, 31.2%) and a horizontally polarized omnidirectional pattern in the azimuth plane.**

***Index Terms*—Horizontally omnidirectional radiation patterns, loop antennas, mu-zero resonance (MZR), wideband.**

I. Introduction

OMNIDIRECTIONAL (in the azimuth plane) antennas capable of functioning over a wideband are required in many applications, including electronic countermeasures or as calibration antenna for electromagnetic compatibility testing, and particularly in wireless telecommunications systems [1], [2]. In indoor or urban areas, although many current wireless communication systems are vertically polarized, the polarization of the propagating electromagnetic wave may change significantly after complicated multiple reflections or scattering [3]. Hence, a horizontally polarized antenna with an omnidirectional pattern is preferred to harvest the polarization resource and maximize a system's capacity. However, compared to a vertical polarized omnidirectional antenna, a wideband horizontally polarized omnidirectional antenna is more difficult to design.

To achieve a horizontally polarized radiation pattern, the small loop antenna with a uniform current distribution, which can act as a magnetic dipole, is first taken into account. However, due to very small radiation resistance and high reactance, impedance matching of the small loop antenna is very poor. Although a larger loop antenna has a reasonable radiation resistance, the antenna currents distribution along the loop becomes nonuniform and hence cannot yield the desired horizontally polarized omnidirectional pattern [4]. Several kinds of loop antennas based on the Alford loop principle have been studied and introduced as a useful design for generating magnetic dipole radiation patterns [5], [6]. These designs, however, suffer a problem of narrow bandwidths of about 6%. A zeroth-order resonator antenna with a narrow bandwidth of about 2% based on left-handed loading has been shown in [7] to obtain horizontally polarized omnidirectional patterns. The radiation efficiency is very low, and the gain is about 0.3 dBi.

Recently, Dobkin *et al.* presented a segmented magnetic antenna consisting of a number of segments, where each segment is composed of a metal line and a series lumped capacitor [8], which can provide a strong magnetic field for near-field RFID applications. However, this antenna is not an effective far-field radiator, as the antenna is loaded by a discrete resistor to achieve good matching. Based on the method, several segmented antennas [9], [10] have been presented for UHF near-field RFID reader applications. However, the far-field radiation is not taken into account in these antennas.

In this letter, a wideband horizontally polarized omnidirectional (in the azimuth plane) loop antenna is realized by adding interlaced coupling lines at each section. Similarly with mu-zero resonance (MZR) antennas [11], [12], the periodical capacitive loaded loop antenna in this letter allows current along the loop to remain in phase and uniform. Therefore, it can achieve a horizontally polarized omnidirectional pattern in the far-field like a magnetic dipole antenna. Furthermore, the periodical capacitive loading is also useful to achieve a wide impedance bandwidth. The proposed antenna can provide a wide impedance bandwidth of about 800 MHz (2170–2970 MHz, 31.2%) and a good horizontally polarized omnidirectional pattern in the azimuth plane. Details of the considerations of the proposed designs and the experimental results of the prototype developed are presented and discussed.

II. Antenna Design

The basic geometry of the proposed wideband horizontally polarized omnidirectional loop antenna is shown in Fig. 1. The

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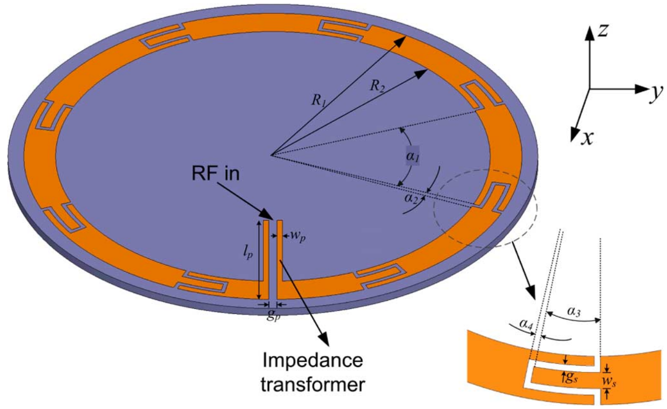

Fig. 1. Geometry of the proposed wideband horizontally polarized omnidirectional loop antenna.

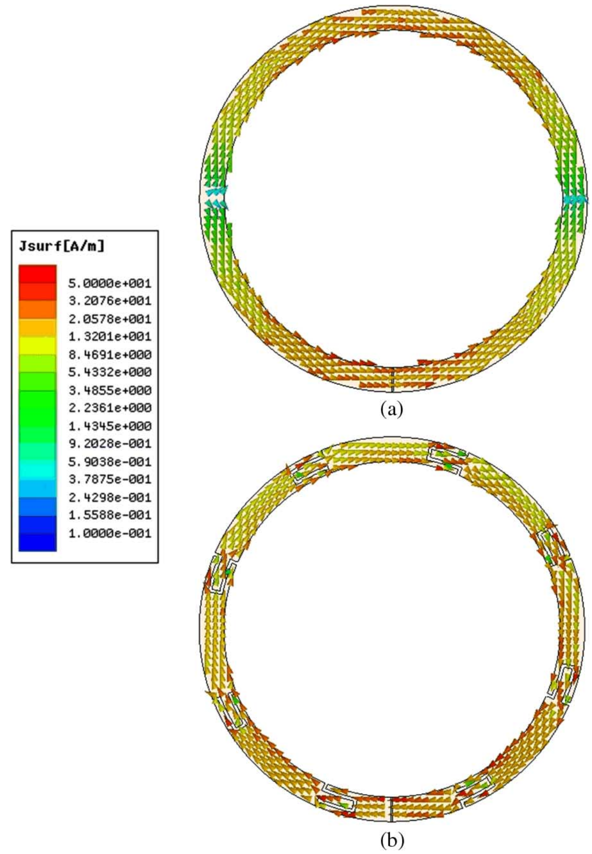

Fig. 2. Simulated surface currents distribution at 2.4 GHz. (a) Conventional loop antenna. (b) Proposed loop antenna.

proposed antenna consists of a loop with periodical capacitive loading and a parallel stripline as an impedance transformer, which were printed on a Teflon substrate ($\varepsilon_r = 2.65$ and $\tan\delta = 0.002$) with a thickness $h = 0.8$ mm. The periodical capacitive loading comprises several arc stripline sections that are symmetrically structured with respect to the origin of the circular substrate. The first section is connected to the parallel feed line. The loop has the following parameters: number N arc stripline sections, outer radius R_1, inner radius R_2, angle α_1 of each arc line section, and spacing angle α_2 between adjacent line sections. The periodic angle α_1 and the spacing angle α_2 are related to the number N by

$$\alpha_1 + \alpha_2 = 360/N. \tag{1}$$

Periodical capacitive loading is realized by adding interlaced coupling lines at the end of each arc stripline section. As shown in Fig. 1, each interlaced coupling line has the following parameters: inner bulgy stub width w_s, separation g_s between the inner bulgy stub and the outer hollow stub, angle α_3 of the inner bulgy stub, and spacing angle α_4 between the inner bulgy stub and the outer hollow stub.

These interlaced coupling lines periodically introduce series capacitance to the loop, which provides a very small phase correction between the adjacent sections so that the current flowing along the loop is kept in phase and uniform even though the perimeter of the loop is comparable to the operating wavelength. Therefore, the proposed loop antenna can obtain a horizontally polarized omnidirectional pattern in the far field. The current distribution of the proposed loop antenna is determined by the length of each arc stripline section and the series capacitance introduced by the interlaced coupling lines. The antenna was designed and simulated using the Ansoft HFSS full-wave simulator. The dimensions of the proposed antenna are finally optimized as follows: $N = 8$, $R_1 = 23.5$ mm, $R_2 = 20.5$ mm, $w_s = 1$ mm, $g_s = 0.4$ mm, $\alpha_1 = 44^0$, $\alpha_2 = 1^0$, $\alpha_3 = 11^0$, $\alpha_4 = 1^0$. The total length of the proposed loop antenna is approximately $1.8\lambda_{\text{eff}}$ at 2.4 GHz. To intuitively investigate the radiation pattern of the proposed loop antenna, the surface currents distribution at 2.4 GHz for both the conventional loop antenna and the proposed loop antenna are shown in Fig. 2. As a reference, the dimensions of the conventional dipole antenna are chosen to be the same as the geometries of the proposed antenna. As revealed in Fig. 2, currents in the case of the conventional loop antenna become nonuniform with the phase shift and have the same direction at both the top and bottom edges along the loop, giving a maximum radiation in the broadside. However, the proposed loop antenna in this letter allows current along the loop to remain in phase and uniform, which is identical to that of a small loop antenna. Therefore, the antenna can be considered close to a magnetic dipole to achieve a horizontally polarized omnidirectional radiation pattern. The unique current distribution of the proposed antenna is induced by periodical loaded series capacitance. The in-phase current distribution of the proposed antenna is similar to that of MZR antennas [12], which is also implemented by the series capacitance of a unit cell.

The other improvement of the proposed antenna is the impedance matching. The simulated input impedance from 1 to 4 GHz on a Smith chart for different angles α_3 of the inner bulgy stub in the proposed loop antenna, without the impedance transformer, is shown in Fig. 3. The angle α_3 affects the coupling between adjacent line sections, so that it determines the value of the series capacitance. Please note that the angle α_3 is not the only parameter to tune the value of the series capacitance. Other parameters such as g_s or w_s can also be used to tune the impedance, but will not be shown here for brevity. In a conventional loop antenna, the resonance frequencies ω_m correspond to frequencies where the perimeter of the loop is a

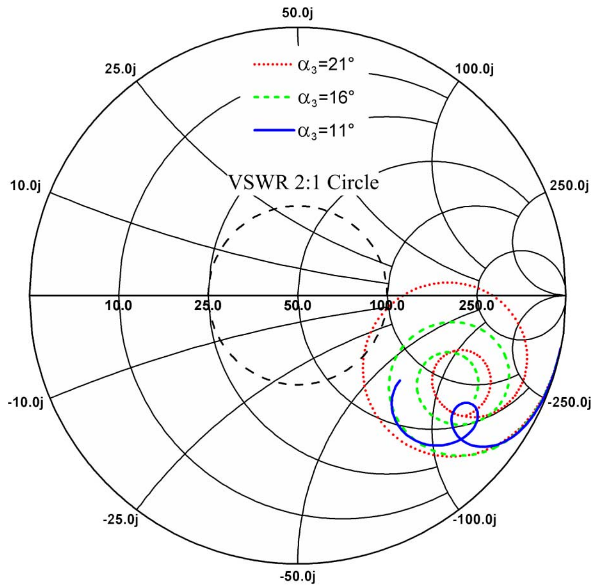

Fig. 3. Simulated input impedance from 1 to 4 GHz for different angle α_3 in the proposed loop antenna without the impedance transformer.

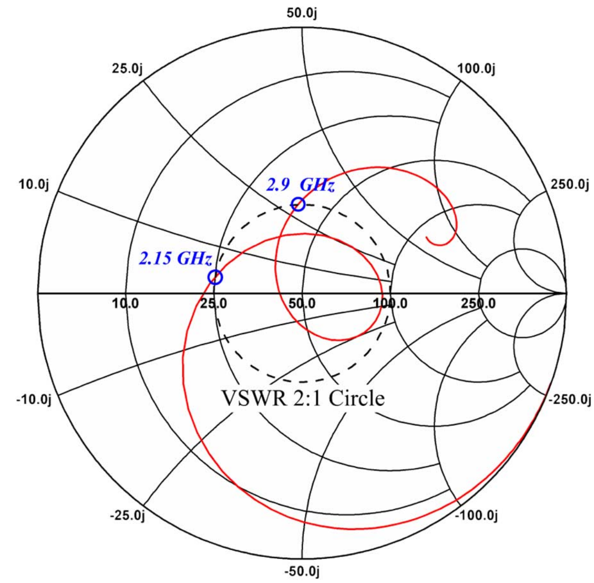

Fig. 4. Simulated input impedance from 1 to 4 GHz for the proposed loop antenna with the impedance transformer when the angle $\alpha_3 = 11^0$.

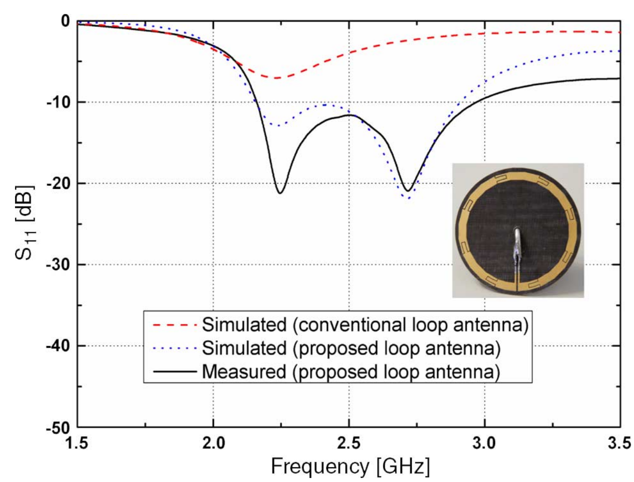

Fig. 5. Measured and simulated S_{11} of the proposed loop antenna and the conventional loop antenna.

multiple of the operating wavelength and the impedance of the conventional loop varies acutely with the change in frequency. However, due to the unique property of the periodically capacitive loaded loop, it is very easy for the proposed antenna to achieve a wide impedance bandwidth. As illustrated in Fig. 3, the curve of the input impedance of the proposed loop antenna shrinks as the angle α_3 of the inner bulgy stub is decreased. This means that the impedance of the proposed loop antenna can maintain a stable value within a wideband, when the angle $\alpha_3 = 11^0$. The proposed antenna can be matched by a simple impedance transformer. As shown in Fig. 1, The antenna is fed by a parallel stripline with a strip length l_p, width w_p, and a separation of g_p. It acts as an impedance transformer to achieve the antenna impedance matching over a wideband range. As the parallel stripline is a balanced structure, it also plays the role of balun to transfer the unbalanced SMA feed to a balanced feed. The parallel stripline has been optimized with the following parameters: $l_\mathrm{p} = 13$ mm, $w_\mathrm{p} = 0.5$ mm, and $g_\mathrm{p} = 0.8$ mm. The input impedance on a Smith chart for the proposed loop antenna with the impedance transformer is presented in Fig. 4. It can be observed that the simulated impedance bandwidth $(\mathrm{VSWR} < 2:1)$ is as large as 750 MHz, or about 29.7%.

III. Measurement Results

According to the parameters given in Section II, a prototype of the proposed loop antenna was fabricated and measured. In Fig. 5, the measured and simulated reflection coefficient of the constructed prototype are presented. For comparison, the simulated S_{11} of the conventional loop antenna with the same geometries is also shown in Fig. 5. It is clear that the impedance bandwidth of the proposed loop antenna is significantly improved. The VSWR 2:1 $(S11 < -10$ dB$)$ impedance bandwidth is measured as large as 800 MHz (2170–2970 GHz, 31.2%).

The radiation characteristics of the fabricated prototype were also studied. Ferrite beads were used to cover part of the test cable except for the cable close to the joint. The length of ferrite bead covering the section of the feed cable is about 50 mm. The measured and simulated normalized radiation patterns of the fabricated prototype are shown in Fig. 6. Only three representative frequencies ($f = 2.20, 2.45, 2.70$ GHz) are presented. Measurements at other operating frequencies across the bandwidth (not shown here for brevity) also present similar radiation patterns as those plotted here. From the results, the copolarization and cross polarization correspond to the radiated electric field in the φ-direction and in the θ-direction, respectively. As can be seen from all the azimuth plane (xy-plane) radiation patterns, it is clear that good omnidirectional radiation with horizontally polarization in the azimuth plane is obtained. The radiation patterns at the elevation plane (xz- or yz-plane) show a quasi-eight shape. Therefore, the radiation patterns of the proposed antenna are very close to that of an ideal magnetic dipole. The measured polarization purity in the azimuth and the elevation plane is around 20 dB. The asymmetric pattern at the

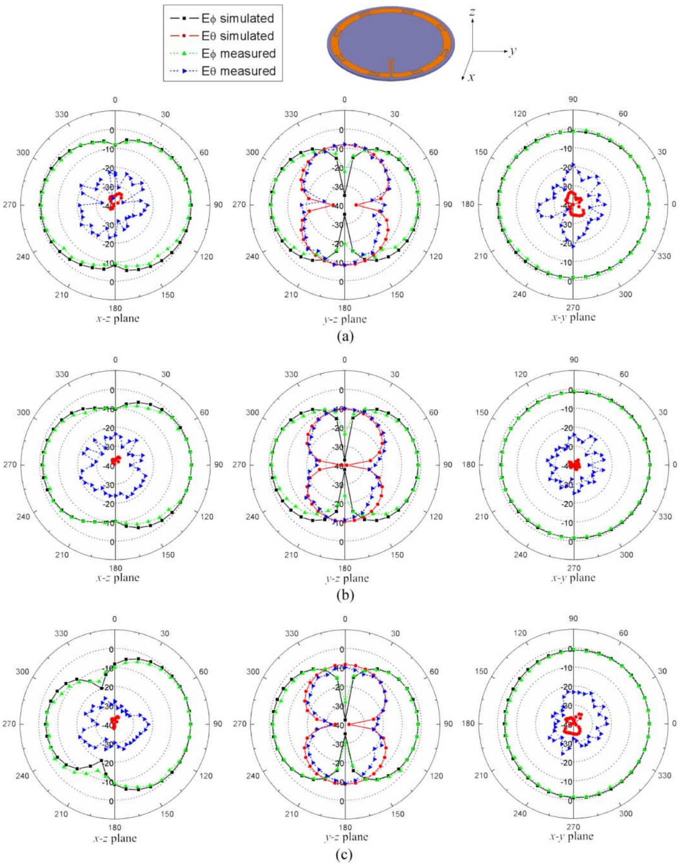

Fig. 6. Measured and simulated normalized radiation patterns of the fabricated prototype. (a) $f = 2.20$ GHz. (b) $f = 2.45$ GHz. (c) $f = 2.70$ GHz.

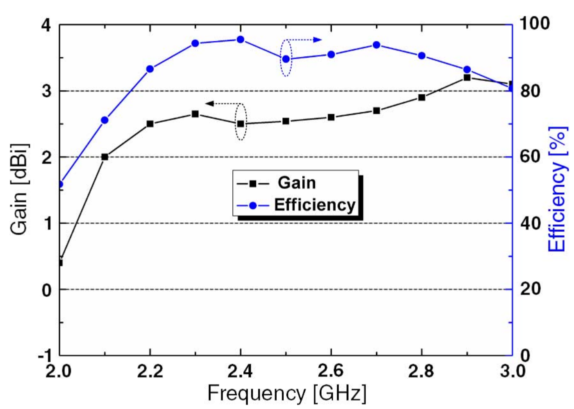

Fig. 7. Measured efficiency and antenna gain of the proposed loop antenna.

xz-plane and the lower value of the polarization purity at the broadside of the yz-plane might be due to the feed line. The feed line along the x-axis may slightly affect the uniform and in-phase current distribution along the loop and shield the radiation of the loop. The omnidirectionality is defined as the gain variation (maximum to minimum) in the azimuth plane. As shown in Fig. 6, the omnidirectionality becomes slightly distorted with an increase in the operating frequency, which might be due to the asymmetry caused by the feed point.

Measured antenna gain and efficiency as a function of the operating frequency are presented in Fig. 7. Across the operating band, the measured gain of the proposed design is in the range of about 2.5 $\sim$ 3.2 dBi. The efficiency is defined as the ratio of radiated power versus the total available power from the power source. Thus, the efficiency value includes all impacts from mismatch loss, dielectric loss, and conductor loss. The efficiency of the proposed loop antenna varies from 82% to 94% within the operating band. Compared to the traditional Alford loop antenna [5], [6] with approximate dimensions, the bandwidth of the proposed antenna shows an improvement in the order of several multiples.

IV. Conclusion

The design of a novel wideband horizontally polarized omnidirectional loop antenna was described in this letter. It allows current along the loop to remain in phase and uniform even though the perimeter of the loop is comparable to the operating wavelength. Similarly to mu-zero resonance antennas, the unique current distribution of the proposed antenna is induced by periodical loaded series capacitance. Furthermore, the periodical capacitive loading is also useful to achieve a wide impedance bandwidth. Therefore, a wideband horizontally polarized loop antenna with good omnidirectional radiation patterns has been achieved. The fabricated prototype can provide a bandwidth of about 800 MHz (2170–2970 MHz) and a horizontally polarized omnidirectional pattern in the azimuth plane. The experimental results show that this design is ideally practical for wideband horizontally polarized omnidirectional antenna.

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