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Research Article

A High Gain Omnidirectional Antenna Using Negative Permeability Metamaterial

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A high gain omnidirectional antenna with low profile is proposed and is investigated numerically and experimentally. Based on the conventional center-fed circular epsilon-negative (ENG) zeroth-order resonator (ZOR) antenna, dendritic structure negative permeability metamaterial (NPM) is used as the substrate to enhance the gain of the omnidirectional antenna. The experimental results show that the gain of a center-fed circular ENG ZOR antenna with NPM substrate is enhanced about 2.2 dB, and the efficiency is enhanced about 38%, in the whole broad operating bandwidth as compared to that of the antenna without NPM substrate, which can be used to improve the reliability of wireless communications.

1. Introduction

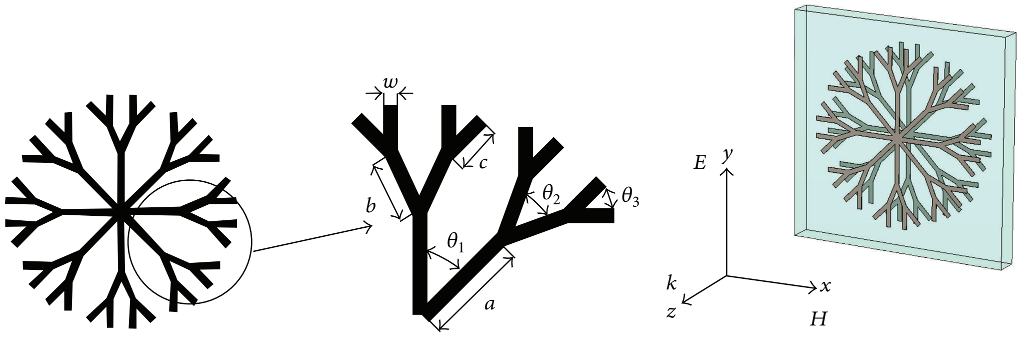
In the past few years, left-handed metamaterials (LHMs) have attracted a lot of attention because of their unique electromagnetic properties. LHMs possess negative permittivity and negative permeability, which have many potential applications in microwave and communication systems [1–4]. Particularly, the application of LHMs to improve the performance of antennas is a hot topic in the area of antenna research in recent years [5–9]. Based on the concept of LHMs and the transmission line theory, Eleftheriades et al. [10], Oliner [11], and Caloz and Itoh [12] realized composite right/left-handed transmission line (CRLH-TL) and epsilon-negative transmission line (ENG-TL), which can be used to design much more compact and more efficient antennas [10–14].

Omnidirectional antennas are often required in wireless communication systems. Based on the infinite wavelength property ($\beta = 0, \omega \neq 0$) of the ENG-TL, a rectangular ENG zeroth-order resonator (ZOR) antenna with an omnidirectional radiation pattern is implemented [15, 16]. One advantage of this antenna is that the antenna size is independent of the resonant frequency. To improve the symmetry of the radiation pattern, our group proposed a center-fed circular ENG ZOR antenna which realized a highly symmetric radiation pattern [17]. Although these antennas are compact, the gains are very low, from 1.5 dBi to 3.5 dBi.

To accommodate the complicated electromagnetic circumstances, high gain omnidirectional antennas are required which can increase the range of wireless network, the signal strength, and sensitivity and hence improve the reliability of communications. One solution to enhance the gain of antenna is to use photonic bandgap (PBG) materials or electromagnetic bandgap (EBG) materials as substrate [18, 19]. These materials have a bandgap within which electromagnetic wave cannot propagate. When the operating frequency of antenna falls into the bandgap, the materials will suppress the surface wave and hence reduce the loss resulting from the surface wave and enhance the efficiency of antenna. However, these structures have some disadvantages, such as large volume and thick substrate.

Similar to the PBG or EBG materials, negative permeability metamaterials (NPMs) have also a bandgap in which magnetic resonance occurs when the NPMs are irradiated by electromagnetic waves [20]. Compared with PBG or EBG structures, NPMs have much compacter structures, and they are more easily to be fabricated. So the NPMs should be able to enhance the antenna gains like PBG or EBG materials.

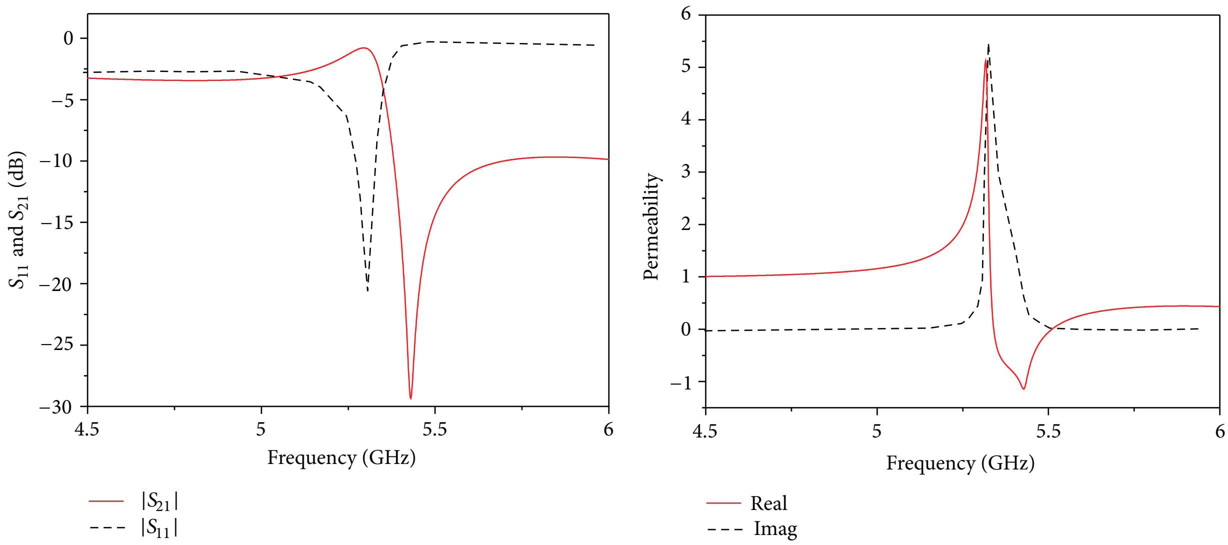
In this paper, combining the concepts of ENG-TL and NPM, we demonstrate an ENG ZOR omnidirectional



(a)

(b)

Figure 1: (a) Unit cell of dendritic structure; (b) schematic for S-parameter simulation.



(a)

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Figure 2: (a) The S-parameters of NPM, (b) permeability of NPM.

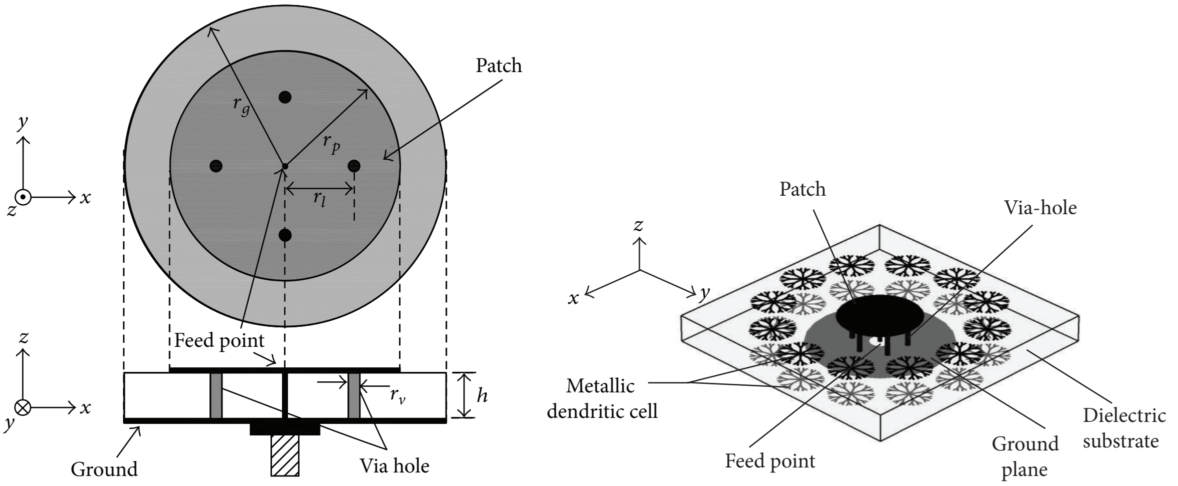
antenna with dendritic structure NPM as substrate. The performance of the antenna is studied numerically and experimentally. The proposed antenna can realize the symmetric omnidirectional radiation pattern with high gain and low profile. Employing the resonance bandgap of NPM, the gain of antenna can be enhanced effectively in the whole operating frequencies.

2. Dendritic Structure NPM

A dendritic cell defined by parameters a, b, c, θ_1, θ_2, θ_3, and w is shown in Figure 1(a). The dendritic structure NPM can be realized by etching metallic dendritic cells on both sides of the dielectric substrate symmetrically. When the electromagnetic wave incident normally to the dendritic structure NPM, the magnetic resonance occurs within a band in which the electromagnetic wave cannot propagate. Consequently, a negative permeability can be obtained in this band. The resonant frequency is determined by the parameters of the metallic dendritic structure, especially by the length of branch in the dendritic structure. Hence, we can design dendritic structure NPMs resonating at different frequencies by adjusting the parameters of the metallic cells. The detailed demonstration has been depicted in [3, 21].

A dendritic structure NPM which resonates at 5.43 GHz is designed. The structure parameters are optimized by using Ansoft HFSS software. The dielectric substrate is 1.5 mm thick Teflon circuit board material ($\varepsilon_r = 2.55$, $\tan\delta = 0.001$). The metallic dendritic structure is made of copper with the thickness of 0.035 mm and the parameters as follows: $a = 3.30$ mm, $b = 1.70$ mm, $c = 1.65$ mm, $w = 0.80$ mm, and $\theta_1 = \theta_2 = \theta_3 = 45^\circ$.

The S-parameters of the unit cell are simulated also by Ansoft HFSS software. Two ports are placed in front and behind the unit cell separately. The electromagnetic wave incidents on the surface of the unit cell normally and then the S_{11} and S_{22} can be calculated. The simulated S-parameters of the designed dendritic structure NPM are shown in Figure 2(a). The permeability of the dendritic structure NPM



(a)

(b)

FIGURE 3: Antenna configurations. (a) Top view and side view of center-fed circular ENG ZOR antenna, (b) 3D view of center-fed circular ENG ZOR antenna with NPM. The center point of antenna is defined as the origin of coordinates.

calculated by S-parameters retrieval method [22] is shown in Figure 2(b), which shows a negative permeability region around 5.43 GHz. These results indicate that the dendritic structure NPM has a forbidden band with the negative permeability at the frequency around 5.43 GHz.

3. Design of ENG ZOR Antenna with NPM Substrate

To verify the concept that NPM substrate can enhance gains of omnidirectional antennas, an omnidirectional antenna with dendritic structure NPM substrate is designed, and a center-fed circular ENG ZOR antenna with monopole like radiation pattern is chosen as the original antenna for comparison [17].

The structure of the original antenna is shown in Figure 3(a). Through the parameter optimization process, a center-fed circular ENG ZOR antenna A-1 is designed. The antenna is designed to work at 5.43 GHz which is the same frequency of the resonance of NPM designed in Section 2. The antenna is realized on Teflon circuit board material ($\varepsilon_r = 2.55$, $\tan\delta = 0.001$). The substrate measures 84 mm × 84 mm with thickness $h = 1.5$ mm. Other parameters of antenna A-1 are as follows: the radius of circular patch $r_p = 17.5$ mm, the radius of circular ground plane $r_g = 26.5$ mm, the distance from the via-holes to the center of the antenna $r_l = 12.075$ mm, and the radius of the via-hole $r_v = 0.45$ mm. For a good symmetry of radiation pattern, the number of the via-hole N is set to be 12. The antenna is fed by 50 ohms coaxial probe and situated at the center of the circular patch.

Based on this original antenna, the proposed center-fed circular ENG ZOR antenna with NPM substrate (A-2) can be realized by placing a circular array of dendritic structure unit cells surrounding the circular metallic patch and ground plane of the ENG ZOR antenna, as shown in Figure 3(b). For each antenna, the center point of antenna is defined as the origin of coordinates.

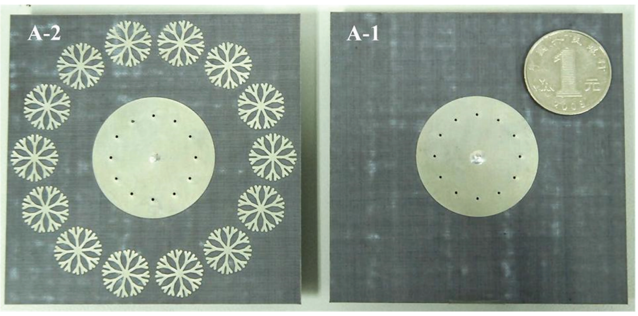


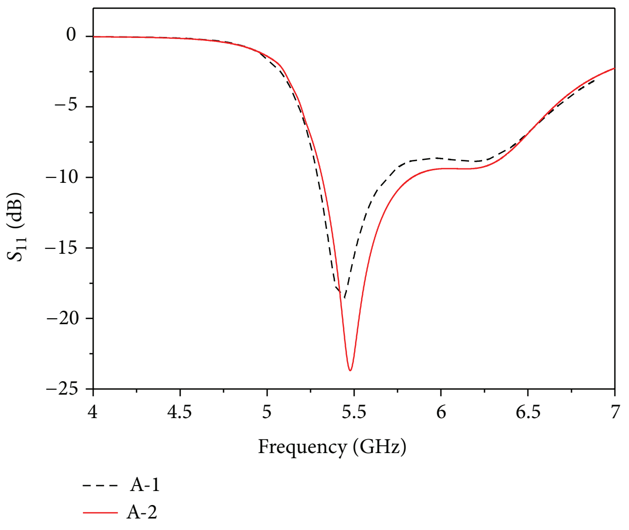
FIGURE 4: Photographs of the fabricated antennas.

The parameters of dendritic structure are described in Section 2. Fourteen dendritic structure NPM unit cells are placed around the antenna, and the distance from the center of the unit cells to the center of the antenna is 34 mm. Figure 4 shows the photographs of the fabricated antennas.

To study the effect of NPM substrate on the performances of antenna, S_{11} parameters, radiation patterns, and peak gains of both antennas are measured. The S_{11} parameters of the antennas are measured by an AV3618 Vector Network Analyzer. The gains and the radiation patterns are measured in an anechoic chamber with a well-defined horn antenna.

4. Results

The simulated S_{11} parameters of A-1 and A-2 are shown in Figure 5(a). The simulated operating frequency is from 5.29 GHz to 5.69 GHz ($S_{11} < -10$ dB) for antenna A-1, and it is from 5.32 GHz to 5.83 GHz ($S_{11} < -10$ dB) for antenna A-2. Figure 5(b) gives the measured results, which show that



(a)

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FIGURE 5: S_{11} parameters of A-1 and A-2 (a) simulation and (b) measurement.

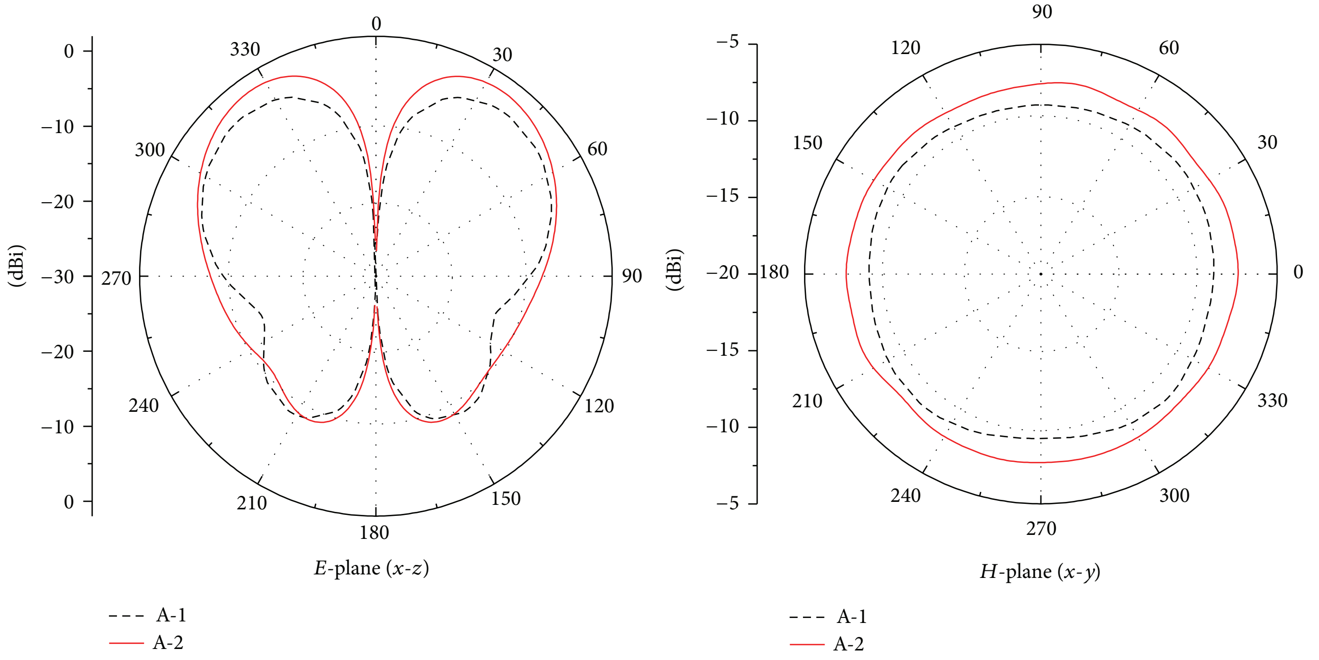
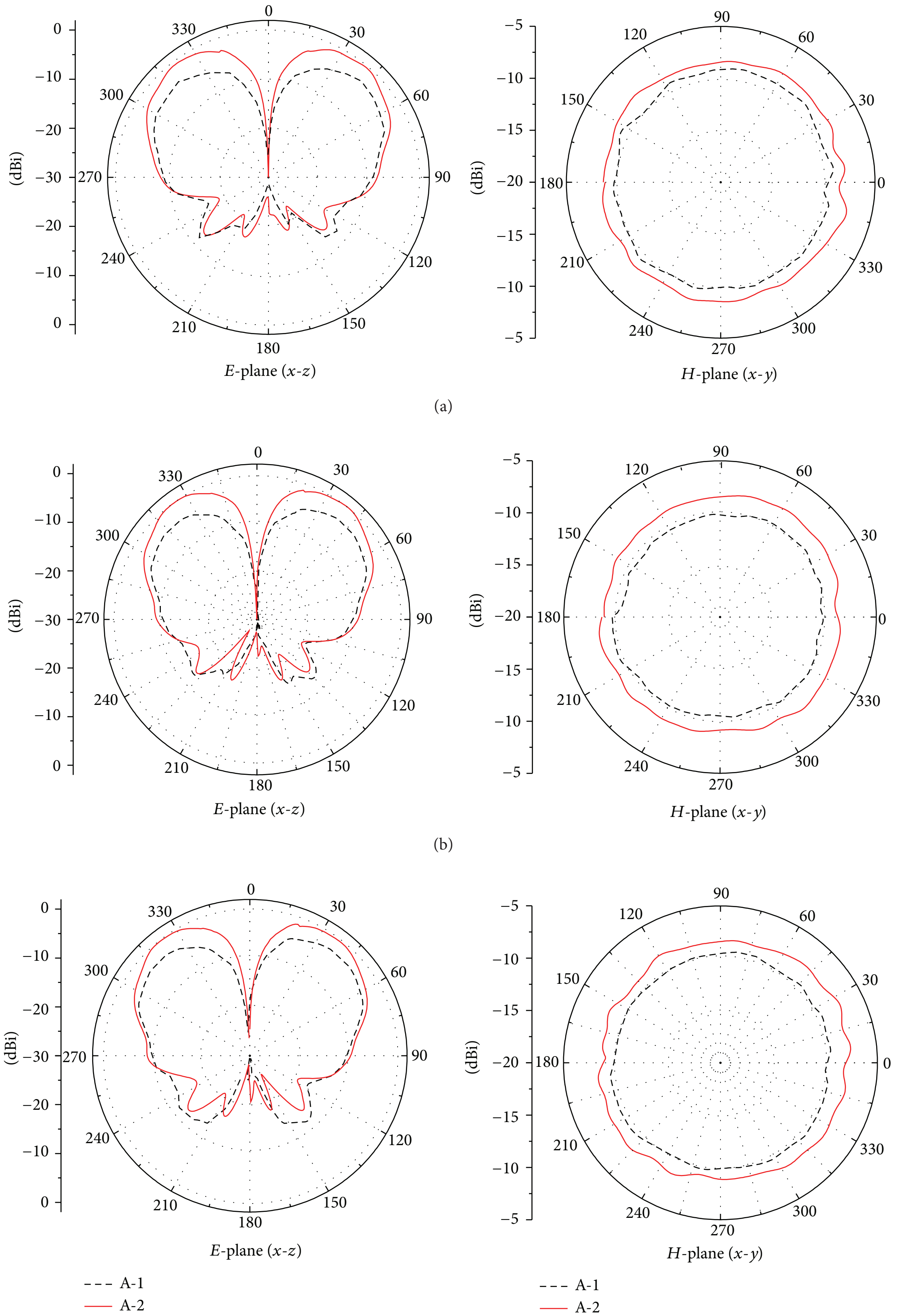


FIGURE 6: Simulated radiation patterns of A-1 and A-2 at 5.45 GHz.

the bandwidth of A-1 is from 5.34 GHz to 5.74 GHz, and it is from 5.38 GHz to 5.79 GHz for A-2. The experimental results are in good agreement with the simulated results. The center frequency of A-2 is almost the same to that of A-1, which means that the NPM substrate does not change the working frequencies of antennas. Moreover, we observed that the operating bandwidth of the antenna lies in the negative permeability frequency of dendritic structure NPM.

The comparative simulated radiation patterns of A-1 and A-2 at 5.45 GHz (where A-1 and A-2 have the same S_{11} parameter) are shown in Figure 6. To reveal the radiation characteristic of the A-1 and A-2 in the whole broad operating bandwidth, the radiation patterns of A-1 and A-2 at 5.35 GHz, 5.55 GHz, and 5.65 GHz are also measured and shown in Figure 7. We observed that A-1 and A-2 have almost the same radiation patterns, which indicates that the center-fed circular ENG ZOR antenna with NPM substrate preserves well the advantage of the conventional center-fed circular ENG ZOR antenna that the omnidirectional radiation is highly symmetrical in the whole operating bandwidth. On



(a)

(b)

(c)

FIGURE 7: Measured radiation patterns of A-1 and A-2: (a) 5.35 GHz, (b) 5.55 GHz, and (c) 5.65 GHz. The coordinate system here is defined in Figure 3.

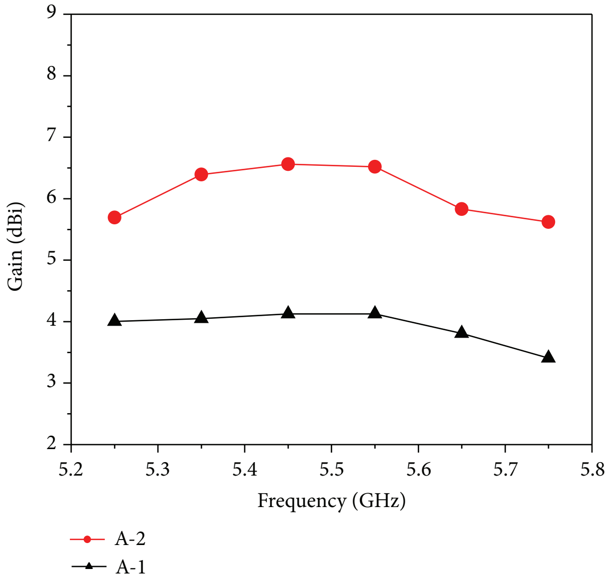


Figure 8: Measured peak gain versus frequency of the fabricated antennas.

the other hand, the energy radiated by A-2 is higher than that from A-1, which means that the NPM enhances the gain of the antenna.

To further study the effect of NPM, the gains of the two antennas are simulated and measured. The simulated peak gains of antennas A-1 and A-2 at 5.45 GHz are 3.9 dBi and 6.4 dBi, respectively. A 2.5 dB improvement in the gain has been obtained. The peak gains as a function of frequency for antennas A-1 and A-2 are measured, and the results are shown in Figure 8. We observed that the gains of A-2 are higher than those in A-1 about 2.2 dB in average at all operating frequencies. So, the dendritic structure NPM can enhance the gain of the center-fed circular ENG ZOR antenna effectively.

In our designed antenna, the angles of the dendritic structures are arranged symmetrically along the circle. The simulation and the measurement results show that this arrangement maintains the symmetry of the omnidirectional radiation pattern. Compared with A-1 antenna, both simulation and measurement results give the 0.8 dB increase of directivity for A-2 antenna. The peak gain of A-2 antenna is about 2.2 dB greater than that of A-1 antenna, so we can deduce that there is a 38% increase of efficiency for A-2 antenna. This increase of efficiency is due to the suppression of surface wave by the dendritic structure NPM. Because of the negative permeability of substrate covered by dendritic structures, the surface wave cannot transmit the area and is confined. Consequently, the loss by surface wave reduces, and the efficiency of antenna increases.

5. Conclusions

A compact and high gain omnidirectional antenna is proposed by using the dendritic structure NPM as the substrate of a center-fed circular ENG ZOR antenna. Using the forbidden band of the dendritic structure NPM, an enhancement of 2.2 dB in average in the whole operating bandwidth is realized for the center-fed circular ENG ZOR antenna. Meanwhile, the advantage of the conventional center-fed circular ENG ZOR antenna, that the omnidirectional radiation is highly symmetrical, is preserved well in the whole operating bandwidth. In addition, the proposed antenna with NPM substrate is low profile, lightweight, easily fabricated, and integrated conveniently with the system, which can be widely used in wireless communication system.

Acknowledgments

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