Chapter 5

Studies of Suppression of the Reflected Wave And Beam-Scanning features of the Antenna Arrays

This chapter describes a two-directional linear scanned design by integrating a short leaky-wave antenna (LWA) with aperture-coupled patch antenna arrays. This architecture proposes a technique not only having the advantage of suppressing the back-lobe due to the reflected wave in the short LWA but also producing two separate linearly scanned beams, each of them radiating in a different region of space (in both the front side and backside of the LWA). In this design, most of the reflected wave of the short LWA is coupled to the patch antenna arrays on the backside of the substrate. The phase of this coupled signal to each antenna element is adjusted by tuning the individual phase shifter in order to control electronically the patch antenna main beam in the cross plane ($x<0$). Meanwhile, on the front side, the main beam of the short LWA can be simultaneously scanned in the elevation plane ($x>0$) by changing the operating frequency. Hence, the two linear beam-scanning radiation patterns of individual direction can be created independently, including a narrow beam in the elevation plane (xy plane at $x>0$) at the front side and a broadside beam in the cross plane (xz plane at $x<0$) on the backside. The measured results show that the reflected wave of the short LWA in the proposed design is suppressed 8 dB as compared with a traditional short LWA without the aperture-coupled antenna arrays at 10.5 GHz. As a result, this novel architecture provides more flexibility both in the upward elevation plane (H plane) and the downward cross plane (backside-E plane) for possible beam-scanning applications in microwave communications and remote identification.

5-1. Introduction

The conventional microstrip leaky-wave antenna has the characteristics of wide bandwidth, narrow beam, and frequency scanning capability [1]~[4]. Although the leaky-wave antenna has an excellent beam-scanning ability, the serious problem of the leaky-wave antenna lies in structures of long length. Hence, there has been a lot of research devoted to studying this issue with the hope to reduce the LWA length in order to make the use of LWAs more extensively [1]. In [1], it was mentioned that with a strip of 10.0 cm (2.23 λ_0), the leaky-wave antenna could radiate about 65% of the power. The remaining power was reflected from the open end of the antenna and produced a large back lobe from the same angle in the broadside direction. If the antenna strip length is increased to 21.7 cm (4.85 λ_0), 90% of the power could be radiated out. In our previous study, we found that the reflected wave was only 3dB lower than the main beam. According to the recent research, it was understood that the reflected wave could be suppressed by using technologies of longer antenna length [1], array topology [5] and a taper-loaded antenna end [6]. However, all the proposals mentioned above require large circuit size or complicated structure.

In 1979, Menzel proposed an asymmetrical feeding arrangement and an impedance-matching network to excite the leaky-mode of the microstrip line [1]. Also, Lin et al [7] proposed three feeding structures for the microstrip leaky-wave antenna in 1996. These proposed structures (slotline-fed, coupled-slotline-fed, CPS-fed) could enhance the microstrip line antenna to radiate in first higher-order mode. In 1997, Luxey and Laheurte [8] made use of an open-ended CPW slot in the center of the antenna to excite the leaky mode at C band. From the literature described above, we know that the first high order mode is successfully excited by asymmetrical feeding. Furthermore, some attempts of the 2-D beam-scanning LWA especially in the elevation plane (the H plane) and the cross plane (the quasi-E plane) have been made by encompassing the phase control technique of the coupling oscillators or by utilizing the 4×1 aperture-coupled series-fed electronically steerable microstrip LWA array [9]~[10].

In 2001, Wang and Guan [11] made a research to suppress the back lobe of a short leaky-wave antenna by using an aperture-fed patch antenna. In this paper, the research followed this original idea to make advanced array structures to gain more completed results. An alternative structure with two-directional space beam-scanning capability is proposed. This proposed array is made up of two types of antennas feeding in series. One of them is a microstrip short LWA, whose scanning beams are radiated above the ground plane. The other beam-scanning antenna is a linear array of phase-controlled aperture-coupled patch antennas that radiate below the ground plane. This proposed novel short microstrip LWA (2 wavelengths) integrated with the aperture-coupled phase arrays is shown in Fig. 5-1. In this design, the back lobe of the short LWA can be suppressed effectively since the apertures transfer the remaining power from the antenna end to the patch arrays on the backside. In addition, by changing the operating frequency, the LWA has beam-scanning capability in the elevation plane (xy-plane in Fig. 5-1) located on the half space side of leaky-wave line ($x>0$), and the power-combining beam of the patch arrays can scan in the cross plane (xz plane) on the patch half space ($x<0$) by utilizing the electronically tuning varactor-diode phase shifters.

5-2. Circuit Design

5-2.1 Design of short LWA integrated with an aperture coupled antenna

The proposed geometry and coordinate system for the topologies of the designed LWA integrated with the aperture-coupled phase arrays are shown in Fig. 5-1. The topology of the beam-scanning LWA module consists of three parts: a microstrip leaky-wave antenna on the top plane, the apertures, and the patch antenna arrays on the bottom of the substrate plane. The whole circuit was designed and fabricated on RT/Duroid substrate with a dielectric constant of εr =2.2 and a thickness of H = 0.508 mm. The length L_{leaky} and the width W_{leaky} of the microstrip LWA are calculated to be 60 mm and 11 mm in such a way that the leaky mode can be excited in an operating frequency range from 9.0 GHz to 10.5 GHz. And the input feeding line of this LWA is designed to be 50 ohms characteristic impedance. The geometry of the aperture-coupled patch antenna is shown in Fig. 5-2. The length L_{patch} and the width W_{patch} of the patch antenna are designed to be 10 mm and 8 mm in order to have the best power radiation. The overlap length L_s of the feeding line is optimized to be 2.3 mm. Each of the patch antennas is aperture-fed by a microstrip line with a characteristic impedance of 50 ohms and an open stub is added to the feeding line of the arrays to perform the impedance matching to reduce the mismatch due to mutual coupling. The aperture-feeding structure is designed to couple the remaining power of the leaky-wave antenna into the patch antenna [12]. The length L_{ap} and the width W_{ap} of the aperture were optimized to be 3.5 mm and 0.5 mm. The space D between the patch antenna elements is 18.4 mm.

5-2.2 Design of varactor-tuned phase shifter

In order to change the phase difference between the radiating elements, a pair of phase shifters was designed and fabricated to modulate the phase of each input signal. Figure 5-3 shows the simplified schematic diagram of the varactor-tuned phase shifter proposed in [13]. The varactor-tuned phase shifter was designed from 9.0GHz to 10.5GHz by using a commercially available CAD tool. Varactor-diode phase shifters are basically analog devices in which the variable reactance is achieved through voltage-tuned capacitance of the diode under the reverse-bias condition. As the bias voltage of this GaAs varactor (M/A-COM MA46410) is varied from 0 volts to a large negative value close to its breakdown voltage, –15 volts, the capacitance of the diode decreases from a maximum value $C_{\max}$ to a low value $C_{\min}$, with a capacitance ratio of 10:1, thus, and the maximum phase change can be achieved. As expected, the phase progression of the phase shifter varies linearly with bias voltage.

5-3. Results and Discussion

5-3.1 Antenna Characteristics

We employed a rigorous (Wiener-Hopf) solution [14] to find the normalized complex propagation constant $\beta/k_0 - j\alpha/k_0$ of the first higher order mode, where β/k_0 is the normalized phase constant and α/k_0 is the normalized attenuation constant. Moreover, the LWA scanning angle θ between the main-beam direction and the end-fire direction (the Y-axis direction) is calculated using the equation $\theta = Cos^{-1}(\beta/k_0)$. Hence, the angle θ is a function of frequency. After comparing the results of

Fig. 5-4 and [7], it is expected that the asymmetrical feeding would excite the first higher mode. Figure 5-4 shows the simulated and measured return loss of the traditional LWA with the open end. Figure 5-5 shows our simulated and measured return loss of this short LWA integrated with an aperture-coupled patch antenna. A higher frequency 10.5 GHz was chosen because of its high reflection coefficient. However, in this case, it was found that the return loss had improved by over 30 dB at 10.5 GHz when compared with traditional short LWA. This indicates that the proposed antenna configuration indeed had radiated power through the aperture to the backside. In addition, we had also found that the proposed configuration could enhance the LWA radiation efficiency and provide a broader bandwidth. Figure 5-6 illustrates the measured H-plane radiation patterns of the proposed antenna structure in comparison with the traditional LWA at 10.5 GHz. The measured power of the reflected wave of the traditional LWA is only 2 dB lower than the main beam, but the proposed design can suppress the reflected wave by at least 8dB. The measured H-plane beam-scanning radiation patterns of the proposed structure are shown in Fig. 5-7. It shows that as the operating frequency varies, the main beam could be steered towards the endfire electronically in the elevation plane. The main beam scans from 38º to 58º as the operating frequency increases from 9.0 GHz to 10.5 GHz. On the side, the measured power density at the peak of the main beam of the single-element patch antenna at the downward E plane is 4.83 dB lower than the measured power density radiated from the upward LWA. Furthermore, the beamwidth of the patch beam is about 60º. Figure 5-8 shows the simulated and measured return loss of the short LWA integrated with the two-element aperture-coupled patch arrays. The return loss is about 20 dB at 10.5 GHz. Figure 5-9 and Figure 5-10 illustrate the simulated and the measured H-plane beam-scanning radiation patterns between the short LWA integrated with the two-element patch antenna arrays and the traditional LWA. In the following figures we will show that as the patch antenna elements increase, the backside radiation power become more comparable as the front side LWA radiation power. Figure 5-11 shows simulated and measured backside E-plane radiation patterns of 2-element patch antenna arrays. It is found that the maximum power of the two-element patch arrays is 2dB less than the maximum power beam of the LWA, and the beamwidth of the patch beam is 20º. Figure 5-12 shows the comparison of the measured H-plane beam-scanning radiation patterns between the proposed short antenna design with four-element aperture-coupled patch arrays and the traditional LWA. As you can see the maximum power beam of patch antenna arrays at the backside–E plane is only 1.17 dB less than the maximum power beam of the LWA; meanwhile, the beamwidth of the patch arrays is approximately 10º.

5-3.2 Antenna with beam-scanning ability

In our past experience with respect to two-element antenna arrays using delay lines, the beam directly points to the broadside direction when the phase is in phase, and if the phase difference is 45 degrees, the beam will steer 8 degrees at 10.5 GHz. If the phase difference is 90 degrees, the main beam is steered 22 degrees off the broadside. When the bias voltage of the varactor diode is changed, the phase of the output signal of the phase shifter will vary and the phase difference between each input signal of the radiating elements will be modulated. As expected, the phase progression of the phase shifter varies linearly with the bias voltage of the varactor diode. The phase varied 65 degrees with the control voltage of 15 V and the results also proved that the matching is good between each stage. Thus, the proposed phase shifter can achieve the beam-scanning ability. Figure 5-13 shows the measured backside-E plane phase-scanning patterns of the two-element phased arrays with control voltage of (-15V, 0V) and (0V, -15V). The scanning angle of the patch beam is ±10 degrees. The direction of the main beam can be steered from 260º to 280º, respectively. According to the scanning angle of the experimental results, it implies that the phase shifter has almost the phase difference of 65º. It agrees well with our previous results. In addition, a novel push-pull RF MEMS switch and MEMS based true-time delay network was also designed to achieve the phase shifter function. It is planed to replace the varactor phase shifter to make it have small size and better performance. More detailed information can be seen in Chapter 6.

5-4. Conclusions

In this chapter, we have successfully demonstrated a method to effectively suppress the reflected wave of the short leaky-wave antenna and it can also perform two-directional scanning patterns on two different planes. The radiating elements on the backside of the LWA are designed to be flexible. Different types of antennas can be used to replace the open end of the short LWA. This designed array scanning capability is suitable for military application, air traffic control, collision avoidance system, or radiolocation, etc. Thus, there is great potential for application in the future.

5.5 References

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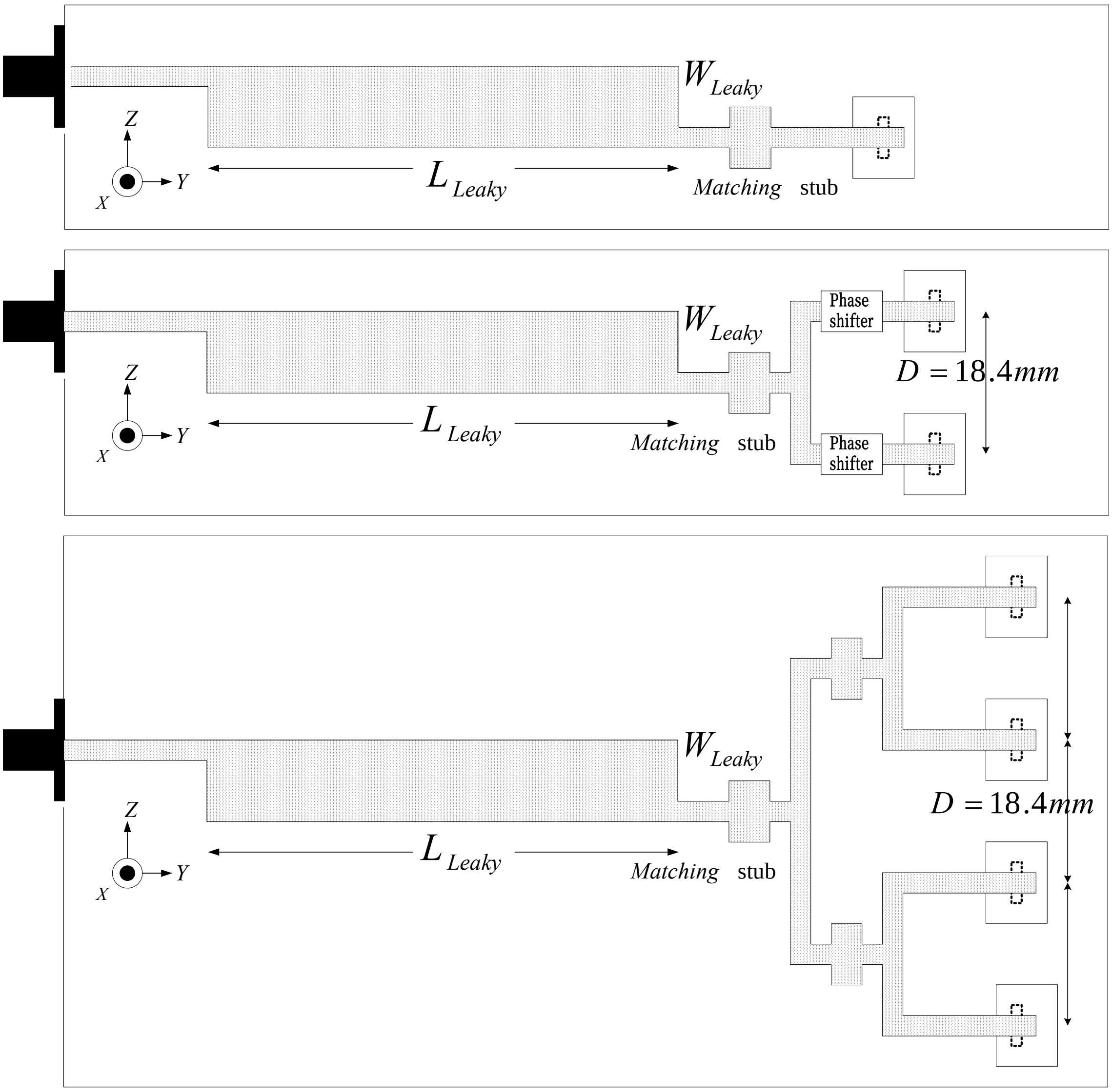
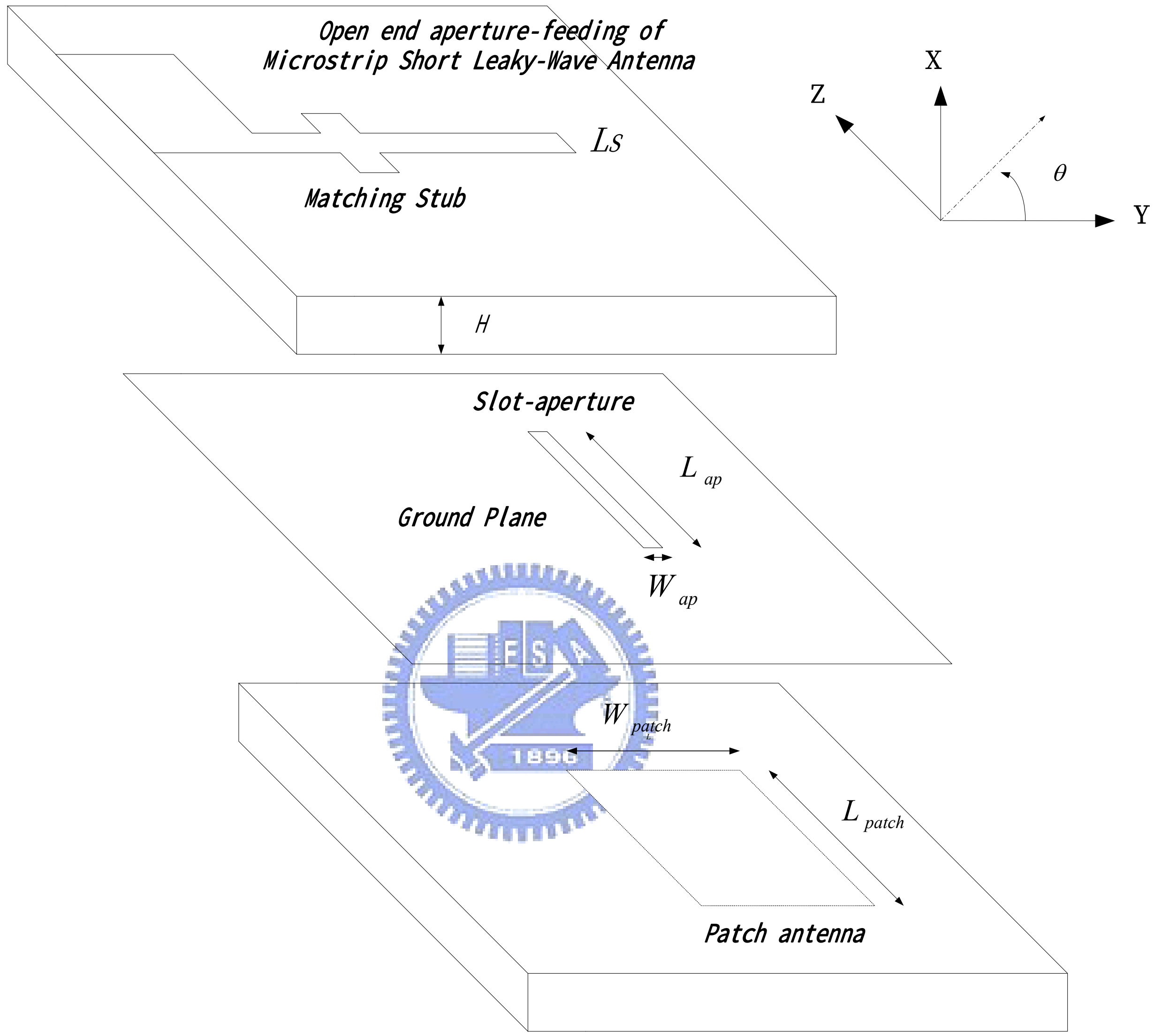


$$L_{leaky} = 60mm, W_{leaky} = 11mm, D = 18.4mm$$

Figure 5-1: The configuration of the short leaky-wave antenna integrated with the 1-, 2- and 4-element aperture-fed patch antenna arrays.



$$L_{patch} = 10mm, W_{patch} = 8mm, L_{ap} = 3.5mm, W_{ap} = 0.5mm, H = 0.508mm, L_s = 2.3mm$$

Figure 5-2: The geometry and coordinate system for the aperture-coupled patch antenna.

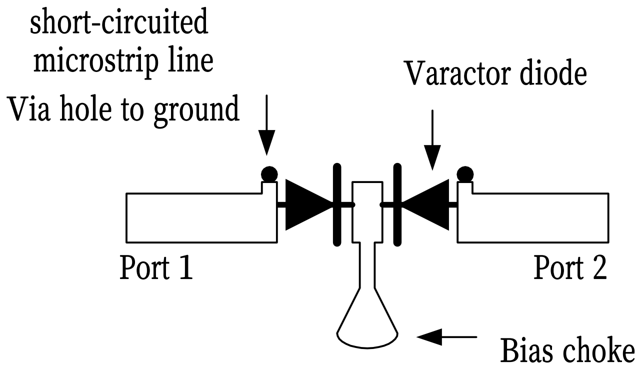


Figure 5-3: The schematic diagram of the varactor-tuned phase shifter.

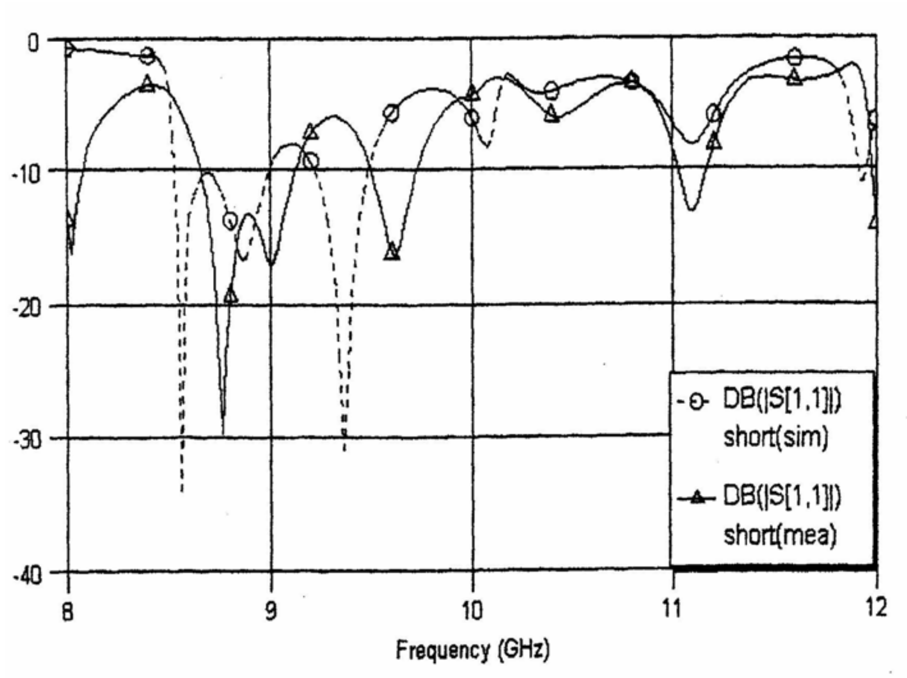


Figure 5-4: The simulated and measured return loss of the short LWA with the open end.

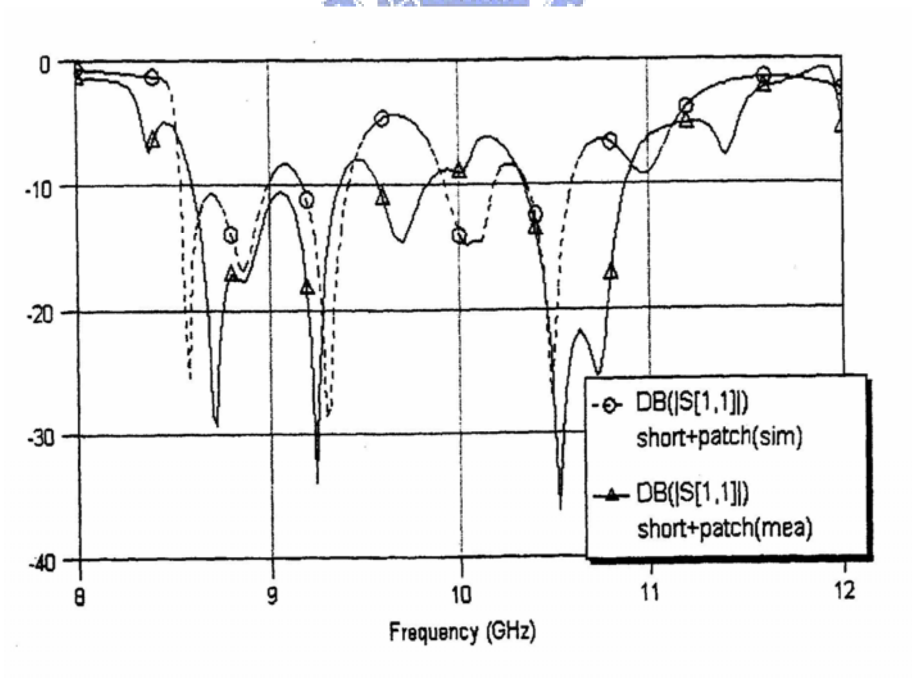


Figure 5-5: The simulated and measured return loss of the short LWA integrated with an aperture-coupled patch antenna.

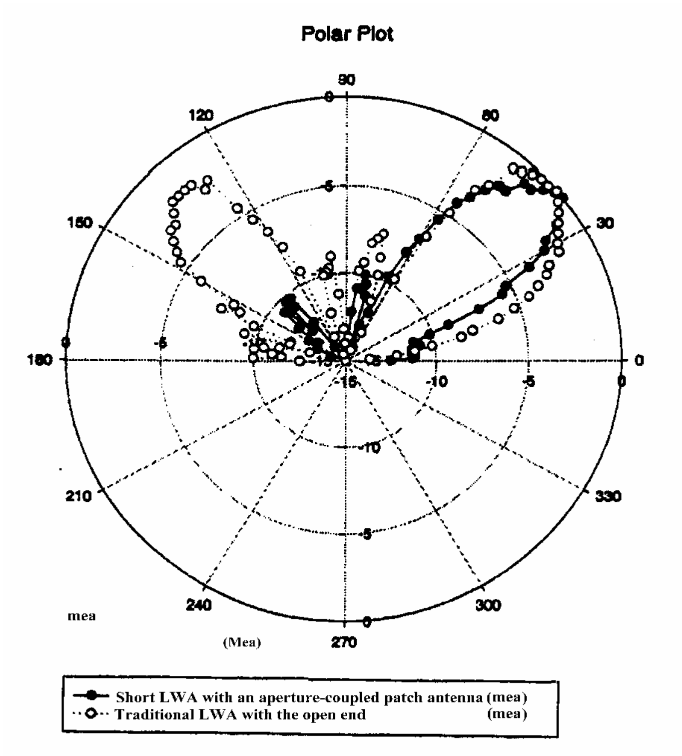


Figure 5-6: The comparison of the measured radiation patterns of the proposed antenna structure comparing to the traditional LWA at 10.5 GHz.

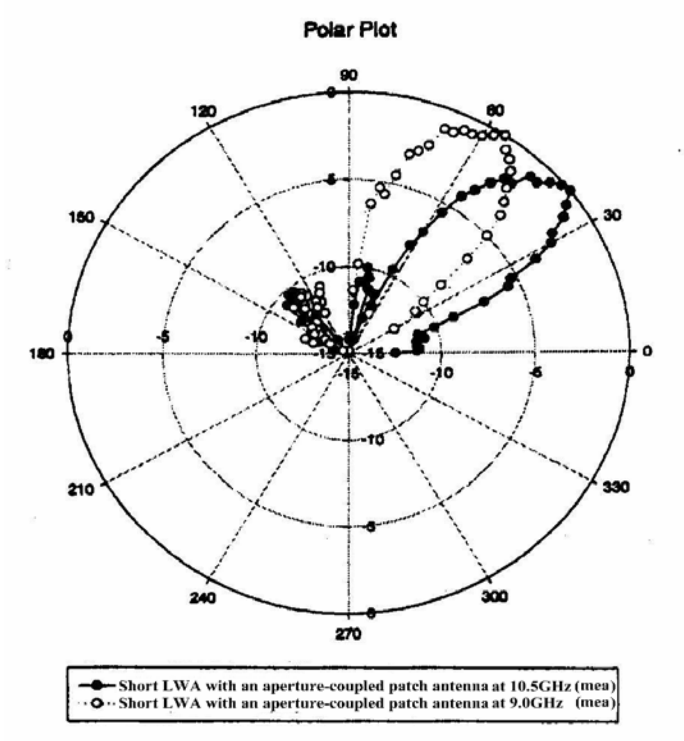


Figure 5-7: The measured radiation patterns of the short LWA integrated with an aperture- coupled patch antenna at 9.0GHz and 10.5GHz.

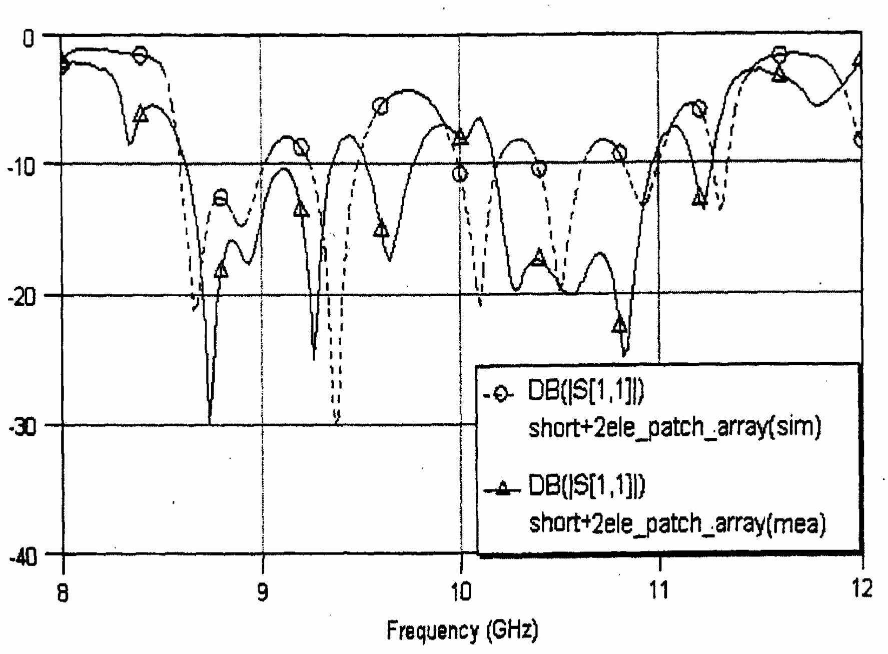


Figure 5-8: The simulated and measured return loss of the short LWA integrated with 2-element aperture-coupled patch antenna arrays.

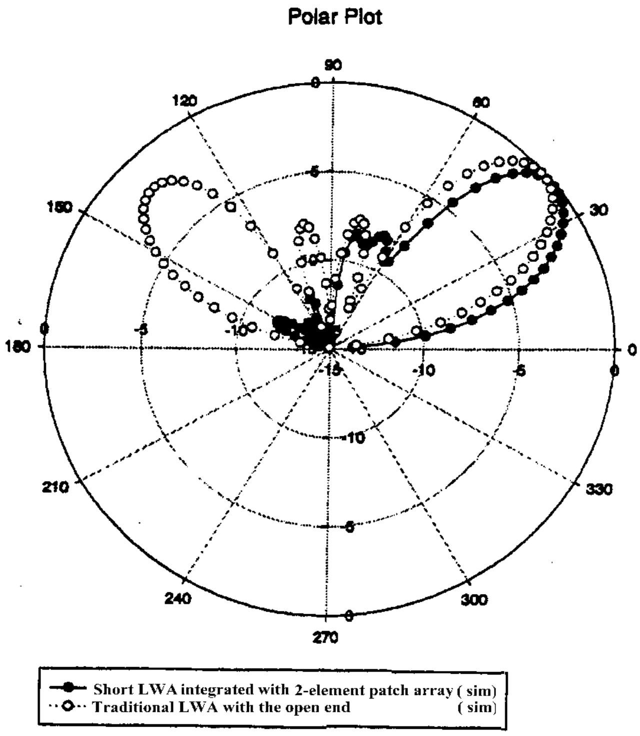


Figure 5-9: The simulated radiation pattern between the short LWA integrated with the 2-element aperture-coupled patch arrays and the traditional LWA.

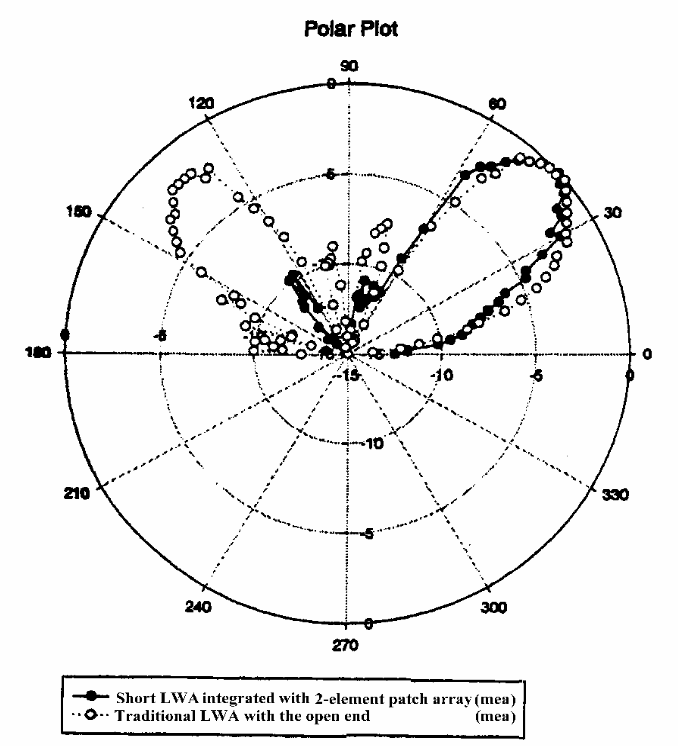


Figure 5-10: The measured radiation pattern between the short LWA integrated with the 2-element aperture-coupled patch arrays and the traditional LWA.

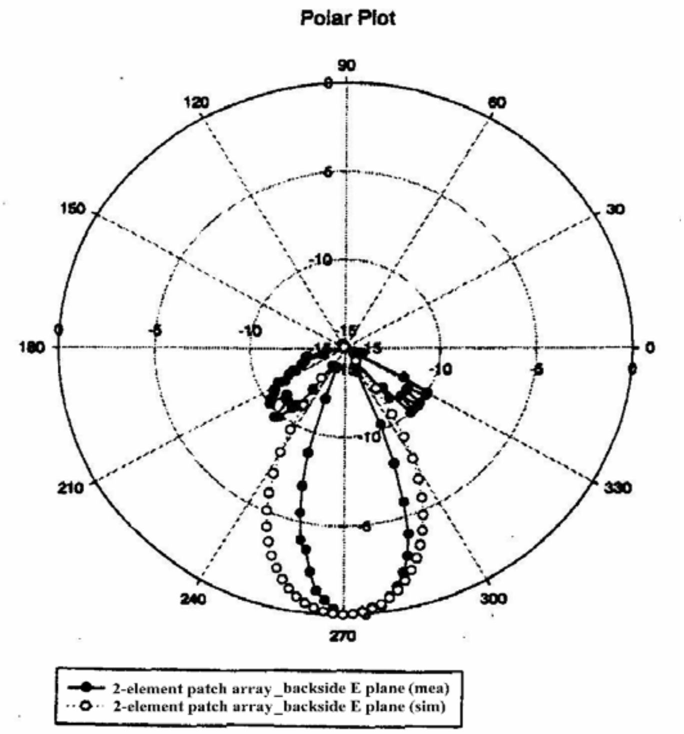


Figure 5-11: The simulated and measured radiation pattern of the 2-element aperture-coupled patch antenna arrays.

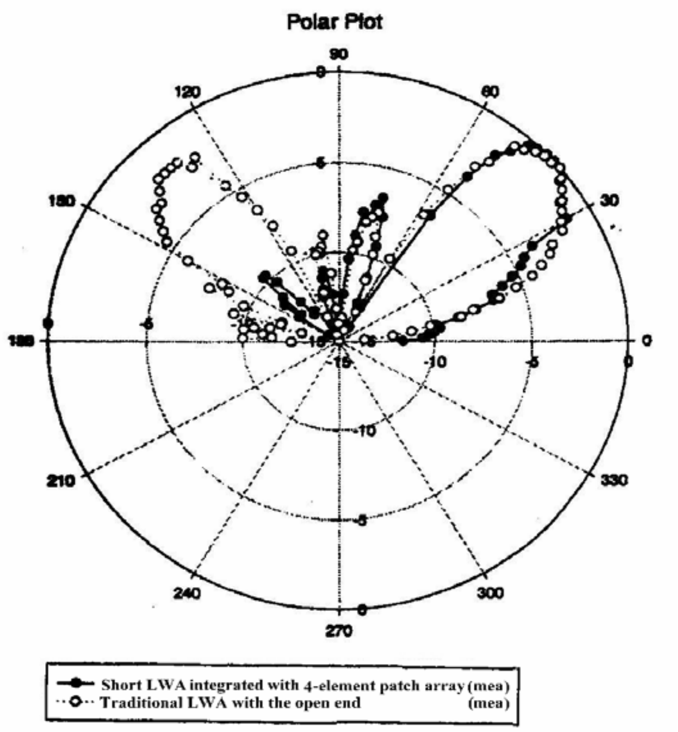


Figure 5-12: The comparison between the short LWA integrated with the 4-element aperture-coupled patch arrays and the traditional LWA.

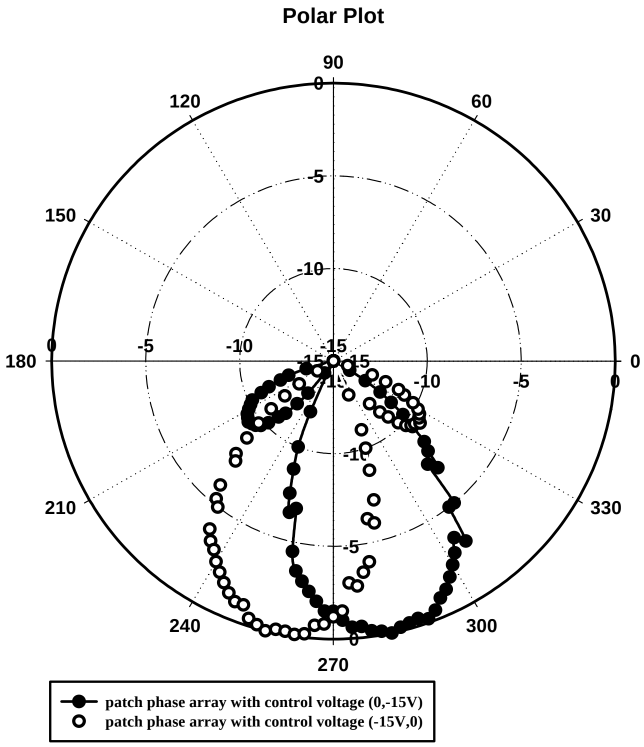


Figure 5-13: The measured radiation pattern of the short LWA integrated with 2-element aperture-coupled patch arrays at the bias of –15V.