A Compact Wideband Leaky-Wave Antenna With Etched Slot Elements and Tapered Structure

Jin-Wei Wu, Christina F. Jou, and Chien-Jen Wang, *Senior Member, IEEE*

***Abstract*—A compact wideband leaky-wave antenna (LWA) with etched slot elements and tapered structure is studied. The proposed antenna is composed of an asymmetric-fed multi-section tapered short leaky-wave antenna with two embedded slots and a ground plane with etched slot elements. Base on the concept of LWA, the asymmetric-fed is utilized to excite the first higher order mode. By etching slot elements on the ground plane, the current distribution of this antenna can be influenced to compact the width of conventional LWA. In order to achieve the impedance matching, this multi-section tapered short leaky-wave antenna is embedded with two rectangular slots. This technique not only improves the impedance matching but also suppresses the back lobe. According to the measured results, the impedance bandwidth achieves about 1.30 GHz for 7-dB return loss, which covers the range from 3.30 to 4.60 GHz, and the scanning angle of the measured main beam is about 36°, which covers the range from 17° to 53°. This short LWA is only about 1.14 λ_0 at 3.4 GHz, and the back lobe can be suppressed by 7.5 dB at 4.3 GHz. Due to the etched slot elements on the ground plane, the frequency of the radiation angle is shifted to lower frequency by 750 MHz, which can compact the width of LWA by more than 20%.**

***Index Terms*—Back lobe, cutoff frequency, frequency scanning, leaky-wave antennas (LWAs).**

I. Introduction

MICROSTRIP leaky-wave antennas (LWAs) have been presented nearly thirty years, the structure of which was proposed in 1979 by Menzel [1] and the theory of which was derived in 1986 by Oliner and Lee [2]. LWAs are usually used in the radar system and the satellite communication because they possess the advantages of narrow beam, frequency-scanning capability, wideband bandwidth, and fabrication simplicity [3], [4]. For enhancing the applications of LWA, the frequency-fixed beam-scanning LWAs are proposed [5], [6]. In [5], the structure of microstrip leaky-wave antenna contained many feeding terminals and control switches which achieved the ability of frequency fixed beam-scanning by switching different feeding terminal. In addition to use of the switch, an active microstrip leaky-wave antenna which derived the dual-beam asymmetrically scanning pattern by the active circuit was designed [6].

Although owning many advantages, LWA is faced with a major problem of large size. As well known, the length and the width of LWA are respectively required about four and half wavelengths to radiate effectively. There are two ways to reduce the antenna size: shortening the length and reducing the width. In general, if the length is shortened, the induced back lobes, which are caused by the reflected power, will be increased. For suppressing the back lobes of short LWA, a radiating element was added at the end of short LWA to radiate the remaining power in [7]. Recently, a method of utilizing two patches with short-circuit edges was designed to couple the radiation power, and then suppressed the back lobe [8]. Excluding short LWA, the techniques of compressing the width have been presented in [9], [10]. The electric-magnetic-electric (EME) microstrip was added in the LWA to affect the first higher order mode, and a half width LWA was designed to compact the width of conventional LWA by the image theory [9].

In this paper, see Fig. 1, we propose a novel method to achieve compact size, wide bandwidth, and low back lobes. This antenna is composed of etched slot elements on the ground plane. Although this method can shift the cutoff frequency to lower frequency in order to reduce the width of conventional LWA, these etched slot elements on the ground plane causes the impedance mismatching. Therefore, we embedded two rectangular slots, Slot-A and Slot-B, on the multi-section tapered short LWA. These two slots can achieve the impedance matching and suppress the back lobe. Detail design rules and results of the short LWA antenna (only about 1.14 λ_0 at 3.4 GHz) demonstrate that the impedance bandwidth can be achieved about 33% at the center frequency of 3.95 GHz for 7-dB return loss. The cutoff frequency of this antenna can be shifted about 750 MHz from 4.15 GHz to 3.40 GHz in order to reduce the width of the LWA by more than 20%. The back lobe can be suppressed by 7.5 dB at 4.3 GHz. The design procedure of the proposed antenna, which includes the ground plane with slot elements and the multi-section tapered short LWA with embedded Slot-A and Slot-B, will be discussed in Section II. Section III will illustrate the simulated and experimental results, which includes the radiation patterns and return loss. Finally, a brief conclusion is given in Section IV.

II. Procedure of Leaky-Wave Antenna Design

Fig. 1 shows the proposed configuration of the compact leaky-wave antenna. The antenna is fabricated on FR4 substrate with a dielectric constant (ε_r) of 4.4, loss tangent (tan δ) of 0.024, and thickness (H) of 1.6 mm. The total length L_1 of the multi-section tapered short leaky-wave antenna is chosen to be 10.0 cm (about 1.14 λ_0 at 3.4 GHz). In order to achieve good impedance matching condition, the tapered geometry was derived by changing the antenna shape and observing variations of the return loss. The width and length of each section of the

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J.-W. Wu and C. F. Jou are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

C.-J. Wang is with the Department of Electrical Engineering, National University of Tainan, Tainan, Taiwan, R.O.C. (e-mail: cjwang@mail.nutn.edu.tw).

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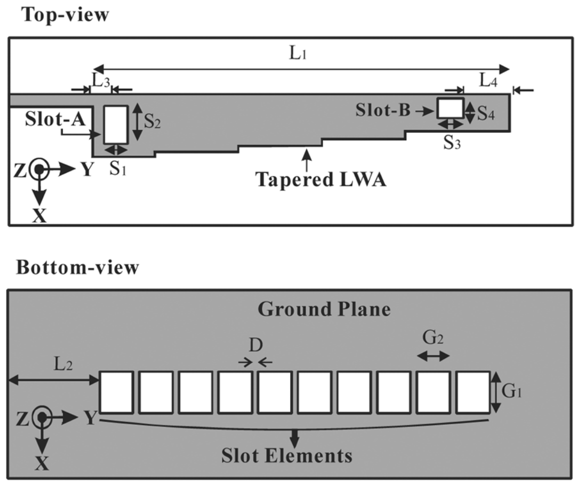


Fig. 1. Configuration of the proposed leaky-wave antenna.

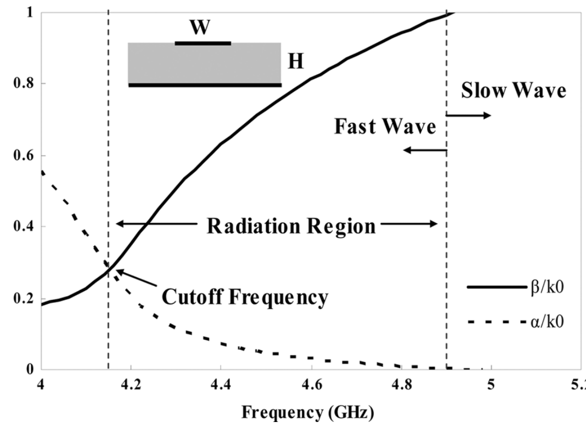


Fig. 2. Normalized complex propagation constants of the conventional microstrip LWA. H = 1.6 mm, W = 15 mm, and $\varepsilon_r = 4.4$. k_0 is the free space wave number.

TABLE I
DIMENSIONS OF THE PROPOSED LEAKY-WAVE ANTENNA

L_1	10.0 cm	S_1	7.0 mm
L_2	22.0 mm	S_2	13.0 mm
L_3	2.20 mm	S_3	8.0 mm
L_4	10.0 mm	S_4	7.0 mm
G_1	10.0 mm	H	1.6 mm
G_2	8.0 mm	D	1.5 mm
Width of Section 1	15.0 mm	Length of Section 1	15.0 mm
Width of Section 2	14.5 mm	Length of Section 2	20.0 mm
Width of Section 3	14.0 mm	Length of Section 3	20.0 mm
Width of Section 4	13.3 mm	Length of Section 4	20.0 mm
Width of Section 5	11.8 mm	Length of Section 5	25.0 mm

tapered LWA are listed in Table I. Here, we embedded two rectangular slots with the sizes of $S_1 \times S_2$ (Slot-A) and $S_3 \times S_4$ (Slot-B) on the leaky-wave antenna. The etched slot elements with the size of $G_1 \times G_2$ are on the ground plane, and the gap between the slots is D. The dimensions of the geometric parameters are also displayed in Table I. In this section, the design procedures of this antenna, which include the etched slot elements on the ground for reducing width of leaky-wave antenna, and the multi-section tapered short leaky-wave antenna with embedded Slot-A and Slot-B for increasing the impedance bandwidth and suppressing the back lobe, are introduced step by step.

A. Compact Leaky-Wave Antenna

Generally, the cutoff frequency of a conventional leaky-wave antenna is controlled by the normalized complex propagation constant which includes the normalized phase constant β/k_0 and the normalized attenuation constant α/k_0, where k_0 is the free space wavenumber. See Fig. 2, as the normalized attenuation constant equals the normalized phase constant ($\alpha/k_0 = \beta/k_0$), the cutoff frequency can be defined. When the normalized phase constant is less than one ($\beta/k_0 < 1$), which is called fast wave ($\beta < k_0$), the radiation region can be found. The β/k_0, α/k_0, cutoff frequency, and radiation region can be determined by the width of leaky-wave antenna, dielectric constant, and substrate thickness. The theoretical β/k_0 and α/k_0 of the conventional microstrip LWA as a function of frequency are plotted in Fig. 2. They are calculated by employing a rigorous (Wiener-Hopf) solution [11] and [12]. The cutoff frequency is about 4.15 GHz, and the radiation region is operated from 4.15 to 4.9 GHz. In [4] and [13], the normalized constant β/k_0 and α/k_0 relate directly to the maximum radiation angle θ_{m} between the broadside direction and the main-beam direction, and the 3-dB radiation beamwidth $\Delta\theta$. These relations are given by

$$\sin\theta_m \cong \beta/k_0 \tag{1}$$

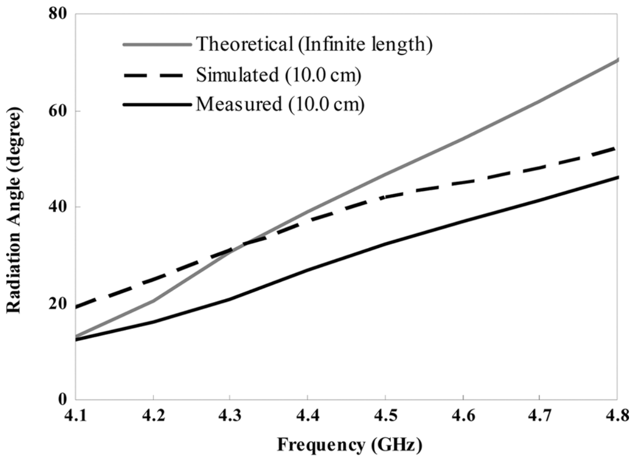
$$\Delta\theta \cong \frac{1}{(L/\lambda_0)\cos\theta_m} \tag{2}$$

and

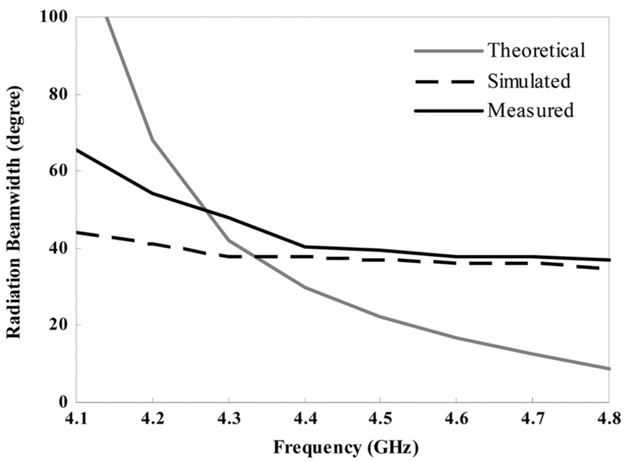
$$L/\lambda_0 \cong \frac{0.183}{\alpha/k_0} \tag{3}$$

In (3), when 90% of the radiated power is achieved, the length of L will be determined.

Fig. 3(a) compares the theoretical θ_{m} of infinite length, and the simulated and measured θ_{m} of finite length (about 1.40 λ_0 at 4.2 GHz) conventional LWA. The characteristics of the finite length conventional LWA were simulated by Ansoft High Frequency Structure Simulator software. Fig. 3(b) illustrates the theoretical $\Delta\theta$ of infinite length, and the simulated and measured $\Delta\theta$ of finite length conventional LWA. The values of theoretical θ_{m} and $\Delta\theta$ are determined in (1)–(3) by the values of theoretical β/k_0 and α/k_0. The theoretical, simulated, and measured radiation angles of convention LWA are respectively about 16°, 22°, and 15° at the cutoff frequency of 4.15 GHz; therefore, it can be seen that the length of LWA does not influence the value of θ_{m} and β/k_0 much [see (1)]. However, from Fig. 3(b) we can see that the 3-dB radiation beamwidth, $\Delta\theta$, of the theoretical calculation of infinite-length LWA, and the simulated and measured results of finite length LWA are respectively about 95°, 43°, and 60° at 4.15 GHz. This result agrees very well with the thesis in [13] that the length of LWA can vary the value of $\Delta\theta$ and α [see (2) and (3)]. Furthermore, since the cutoff frequency



(a)

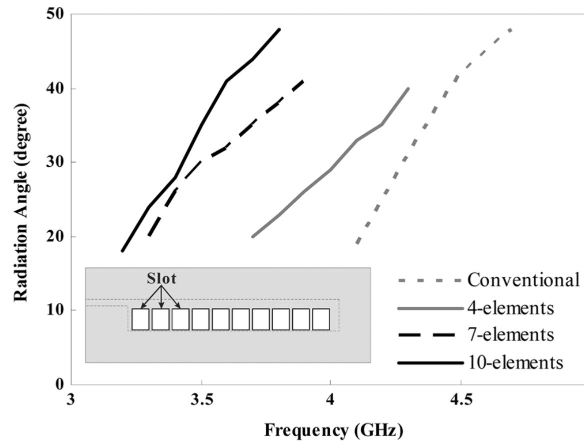


(b)

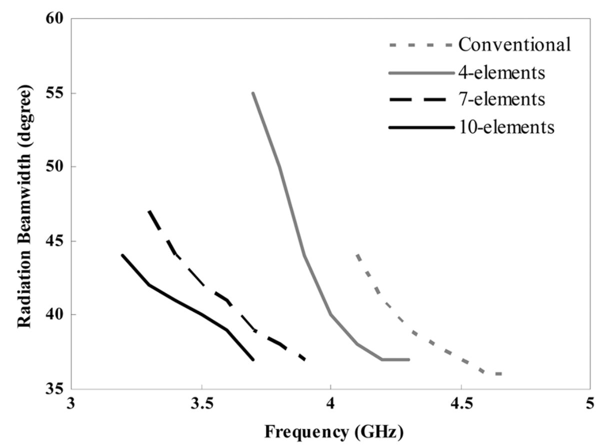
Fig. 3. Comparison of the theoretical, simulated, and measured θ_{m} and $\Delta\theta$ of a conventional LWA: (a) Radiation angle θ_{m}; (b) Radiation beamwidth $\Delta\theta$.

can be controlled by the width of leaky-wave antenna, the width of LWA can be reduced by reducing the value of β/k_0 and α/k_0 or the cutoff frequency.

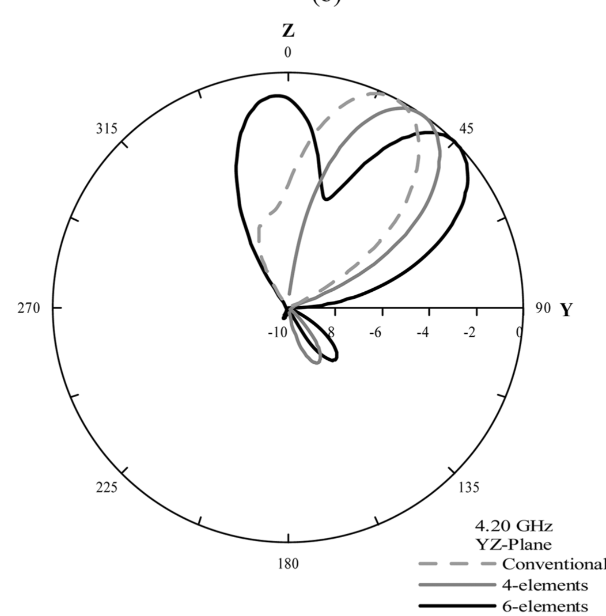
In order to compact the leaky-wave antenna size, the slot elements with the size of $G_1 \times G_2$ are etched on the ground plane of the conventional LWA. This method of etching slot elements on the ground plane can change the current distribution on the ground to reduce the frequency of the first higher order mode. Therefore, the radiation angle θ_{m} and 3-dB radiation beamwidth $\Delta\theta$ are also varied. Fig. 4(a)–(c), shows the simulated results of the radiation angle, 3-dB radiation beamwidth, and radiation pattern at 4.2 GHz with different number of slot elements. The slot elements are 0, 4, 7, and 10 elements, respectively. For the results of Fig. 4(a), we can find that the frequency of θ_{m} is strongly dependent on the number of the slot elements. As they are increased to 7 elements, the frequency of 22° radiation angle is decreased from 4.15 to 3.33 GHz. Furthermore, the frequency of 22° radiation angle is converted from 3.33 to 3.25 GHz when the number of the slot elements is increased from 7 to 10. In Fig. 4(b), the characteristic of shifting to lower frequency of the $\Delta\theta$ is similar to that of the θ_{m}. As the cutoff frequency is shifted to lower frequency, the β/k_0 and α/k_0 has been varied; therefore, the width of LWA is reduced. From Fig. 4(c), due to



(a)



(b)



(c)

Fig. 4. Simulated radiation angle and 3-dB radiation beamwidth of LWA with etched slot elements: (a) Radiation angle θ_{m}; (b) Radiation beamwidth $\Delta\theta$; (c) Radiation pattern at 4.2 GHz.

a change of the propagation constant, the position of the main beam becomes large as the slot elements are increased. The slot lobe appears for the LWAs with the slots. For conventional LWA, if it is operated at lower frequency, obviously, the width

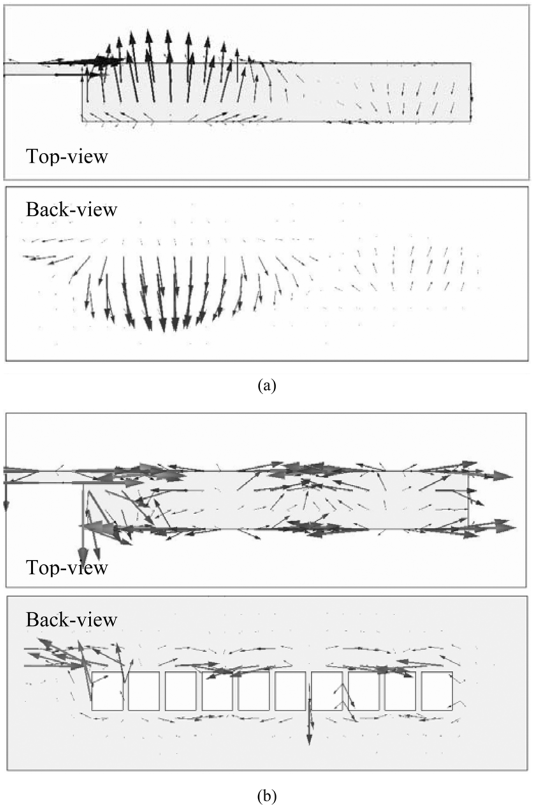


Fig. 5. Simulated surface current distributions: (a) conventional LWA at 4.2 GHz; (b) LWA with 10 slot elements at 3.3 GHz.

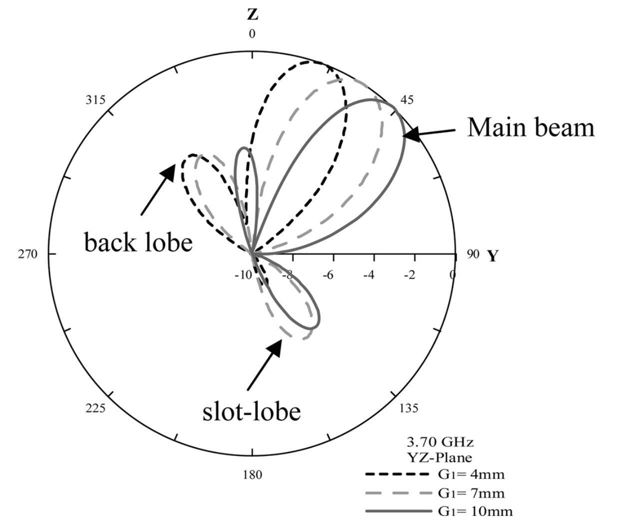


Fig. 6. Simulated radiation patterns of the slot widths, G_1, in the YZ-plane at 3.70 GHz.

of LWA must be increased. However, using this technique of etched slot elements on the ground plane, the LWA can be operated at lower frequency without increasing the width of LWA. From these simulated results, it can clearly be concluded that the cutoff frequency is decreased about 900 MHz from 4.15 to 3.25 GHz. Therefore, by this technique, we can compact the width of conventional LWA by more than 20%.

The $\theta_{\rm m}$ and $\Delta\theta$ are changed because the current distributions are influenced by etching slot elements on the ground plane. The simulated surface current distributions of the conventional LWA at 4.2 GHz and the LWA with 10 etched slot elements on the ground at 3.3 GHz are illustrated in Fig. 5(a) and (b). Comparing the surface current distributions on the LWA of Fig. 5(a) with that of (b), it can be found that the wavelength on the LWA is different. The wavelength of the LWA with 10 etched slot elements on the ground is less than half of that of the conventional LWA. Since the current distributions of ground plane are affected by the slot elements, which are equivalent to the PMCs (perfect magnetic conductor), the wavelength on the LWA is decreased. This phenomenon is explained that the fast wave $(\beta < k_0)$ of the conventional LWA is changed to the slow wave $(\beta > k_0)$ by etching the slot elements on the ground at 4.2 GHz. The cutoff frequency and the radiation region are shifted to the lower frequency; therefore, the width of LWA is reduced.

B. Parameter Study of Etched Slot Elements

Due to the coupling effect between the LWA and the slot elements on the ground plane, this antenna can excite dual-beam radiation pattern, which includes the radiations of LWA above the substrate and radiation below the ground plane with etched slot elements. Fig. 6 exhibits the simulated normalized radiation patterns by adjusting the width of slot elements (G_1) in the YZ-plane at 3.7 GHz as the number and length of the slot elements are respectively 10 and 8 mm. The main beam, the back lobe, and the slot lobe resulted from the injection power, the reflected power at the antenna end, and the power leaked from the slots. Because the slots on the ground plane can be treated as the PMCs, the image equivalent magnetic currents were induced below the plane and excited a side slot lobe in the lower semi-space. It could be observed that the main beam at 45° and the lower slot lobe at 135° are symmetrically radiated. As can be seen from Fig. 6, the radiation angle of the main beam at 3.7 GHz is increased from 20° to 44° as the width is increased from 4 mm to 10 mm. The 3-dB radiation beamwidth of the main lobe and the magnitude of the back lobe above the substrate are slightly affected by the width of slot elements. Nevertheless, this gain of back lobe is almost independent of the width of slot. The slot-lobe below the substrate is radiated because the power of the ground is coupled by the LWA and radiates though the slot; consequently, the size of slot can influence the slot-lobe. In this case, the magnitude oft he slot-lobe is enlarged as the width is increased from 4 mm to 7 mm, and it can be found that the radiation angle is depending on the radiation angle of main lobe. The simulated normalized radiation patterns of 3.7 GHz in the YZ-plane at the different length of slot elements (G_2) are shown in Fig. 7 as other parameters are fixed. As shown in Fig. 7, the 3-dB radiation beamwidth of the main lobe and the magnitude of the back lobe are respectively narrowed and enlarged by increasing the length of the slot, and it can also be seen that the back lobe is mainly varied by the length of the slot. From the results of Figs. 6 and 7, it can be concluded that the large area of the slots is required when the radiation angle of the main beam increases.

The simulated return losses of the conventional LWA and the LWA with 10 slot elements on the ground plane are plotted in Fig. 8. The dimensions of the slot and the distance between the two slot elements are displayed in Table I. The 7-dB impedance

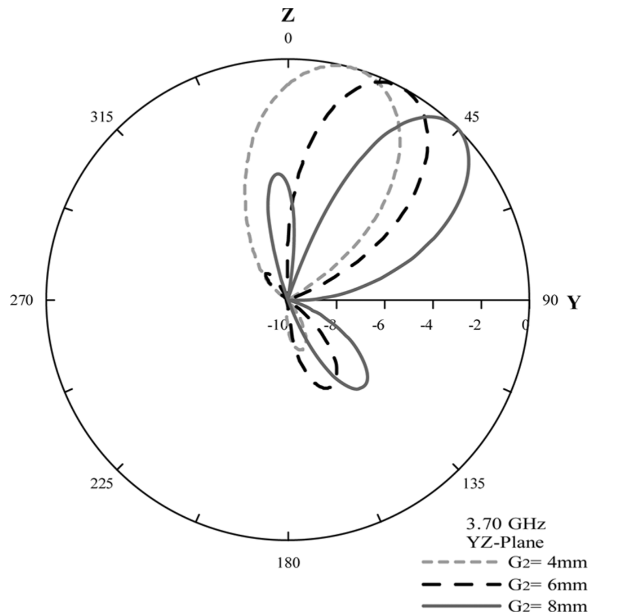


Fig. 7. Simulated radiation patterns of the slot lengths, G_2, in the YZ-plane at 3.70 GHz.

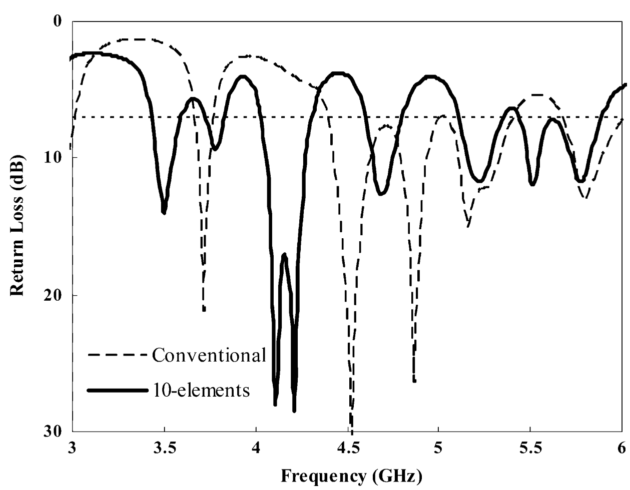


Fig. 8. Comparison the simulated return losses of conventional LWA and LWA with 10 slot elements on the ground plane.

bandwidth of the conventional LWA is about 1.0 GHz from 4.4 to 5.4 GHz. When slot elements are etched on the ground plane, the initially frequency can be decreased from 4.4 to 3.4 GHz; nonetheless, the impedance mismatched from 3.4 to 4.3 GHz is caused by this method.

According to above discussions of etching slot elements on the ground plane, we can conclude that the numbers and the dimensions of these slot elements can reduce the frequency of the radiation angle, control the 3-dB radiation beamwidth, influence the back lobe, and excite the slot-lobe. Although reducing the width of LWA, the slot elements cause the impedance mismatching.

C. Increasing Bandwidth and Suppressing Back Lobe

In order to achieve the impedance matching, the multi-section tapered leaky-wave antenna is utilized. Because the radiated frequency is determined by the width and length of each section

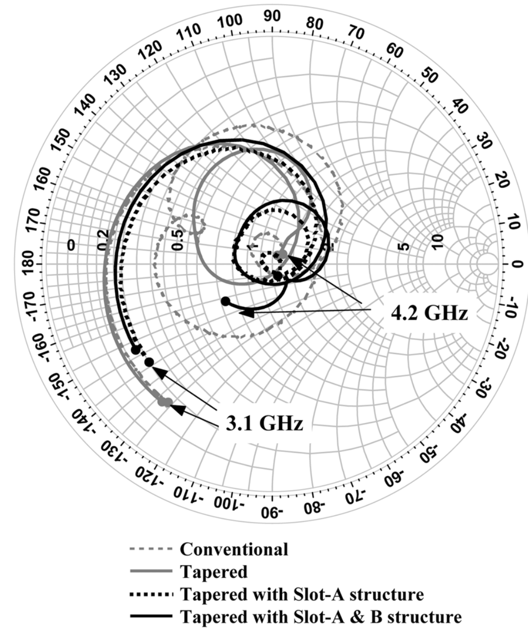


Fig. 9. Comparison the simulated impedance of the LWA of conventional, tapered, and tapered with Slot-A structure.

of the tapered structure, the impedance and the radiation region can be improved [14]. However, this method of the multi-section tapered short leaky-wave antenna results in serious back lobes. To increase the impedance bandwidth further and reduce the serious back lobe, the Slot-A with the sizes of $S_1 \times S_2$ is embedded on this multi-section tapered short LWA to improve the impedance matching, and the Slot-B with the sizes of $S_3 \times S_4$ is utilized to suppress the back lobe. In this analysis here, the parameters of etched slot element on the ground plane are fixed.

Fig. 9 describe the simulated impedance of the conventional, tapered, and tapered with Slot-A structure. The dimensions of the multi-section tapered short LWA and Slot-A are listed in Table I. According Fig. 9, we can see that the real part impedance of the conventional short LWA is very low, and the imaginary part of the impedance tends to be inductive. When the LWA is changed from conventional to tapered, the low impedance is increased in the real part impedance, and the phenomenon of the imaginary part impedance which is inductive is lowered. Even though the real and the imaginary part impedance are improved by tapered structure, the impedance matching is not optimum. In order to achieve wideband impedance matching, the Slot-A is embedded on this multi-section tapered short LWA. It can be seen from Fig. 9, the real part impedance is changed to almost 50 Ω, and the imaginary part of the impedance is decreased to approach 0 Ω. The location of Slot A must be designed at the Section I of tapered LWA. If Slot A is designed at the other sections, the impedance matching cannot be achieved. Consequently, this method of the multi-section tapered short LWA with embedded Slot-A can improve the impedance bandwidth.

The simulated normalized radiation patterns in the YZ-plane of the tapered short LWA with no slot, that with only Slot-A, and that with both Slot-A and Slot-B embedded at 4.3 GHz are compared in Fig. 10. We can see that the magnitude of the back

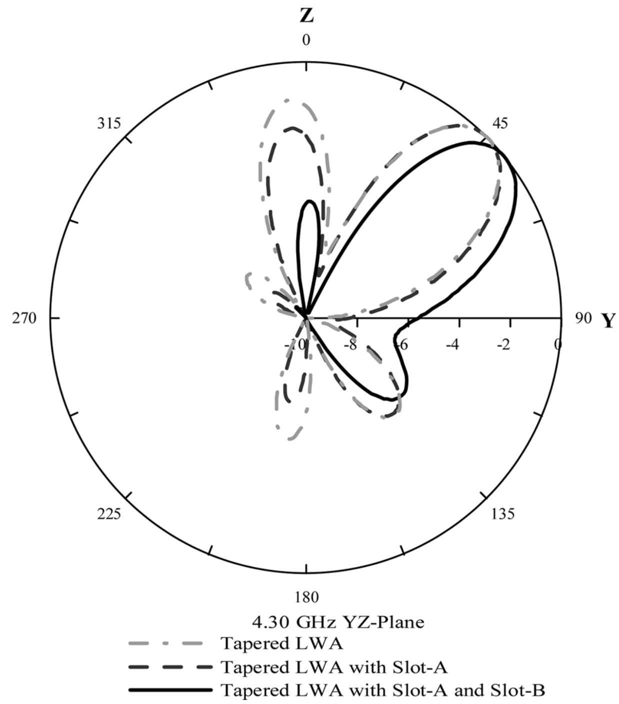


Fig. 10. Comparison the simulated radiation patterns of the multi-section tapered short LWA without slot, that with Slot-A, and that with Slot-A and Slot-B at 4.3 GHz.

lobe of the tapered LWA with no slot embedded is only about 1.4 dB lower than the main beam at 4.3 GHz. It was observed that as the frequency was increased, the magnitude of the back lobe could be even larger than the main beam or even substitute for the main beam. As Slot-A was embedded on this tapered short LWA, the magnitude of back lobe can now be suppressed to about 2.5 dB at 4.3 GHz. Therefore, we can see that although embedding Slot-A can improve the impedance matching, but it still cannot suppress the back lobe effectively. To further suppress the back lobe, Slot-B is embedded on this tapered short LWA (as shown in Fig. 1). The location of Slot B is embedded about one wavelength at 4.3 GHz between Slot A and Slot B to suppress the back lobe. Finally, from the simulated results, we can see the magnitude of the back lobe is successfully suppressed by 5.5 dB.

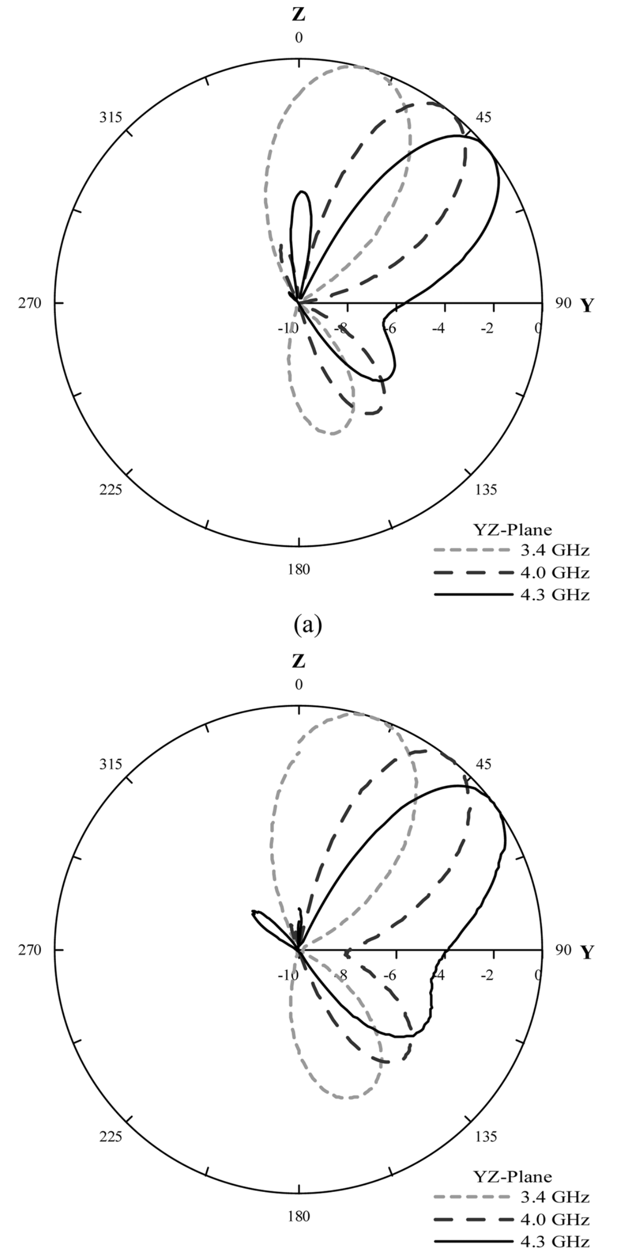


Fig. 11. Simulated and measured radiation patterns of the proposed LWA in the YZ-plane: (a) simulated patterns; (b) measured patterns.

III. RESULTS

From the above discussion of antenna design, etching slot elements on the ground can reduce the frequency of the radiation angle, and the multi-section tapered short leaky-wave antenna with embedded Slot-A and Slot-B can achieve both the impedance matching and suppressing the back lobe. Fig. 11(a) and (b) respectively illustrate the simulated and measured normalized radiation patterns in the YZ-plane of the proposed antenna at 3.4, 4.0, and 4.3 GHz. The measured gain of the back lobe is 7.5 dB lower than the main beam at 4.3 GHz. The measured results of the characteristic of the radiation angle, 3-dB radiation beamwidth, and back lobe, are similar to the simulated results [see Fig. 11(b)]. The scanning angle of the measured main beam is 36° from 17° to 53° as the operating frequency increases from 3.4 to 4.3 GHz. In addition, the measured 3-dB beamwidth of 46° at 4.3 GHz is larger because the main beam and the slot-lobe are combined to increase the 3-dB beamwidth. Comparing the measured results of the conventional short LWA (in Fig. 3) and the proposed LWA [in Fig. 11(b)], it can be inferred that the cutoff frequency of LWA is decreased about 750 MHz from 4.15 to 3.4 GHz; therefore, the width of conventional short LWA can be reduced by more than 20%.

The simulated and measured return losses of the conventional LWA and our proposed LWA are exhibited in Fig. 12. It has good agreement between the simulated and measured results of our proposed LWA. Comparing with the impedance bandwidth of about only 24% for the conventional LWA, the measured 7-dB impedance bandwidth of our proposed LWA reaches about 33% with respect to the center frequency at 3.95 GHz. In addition,

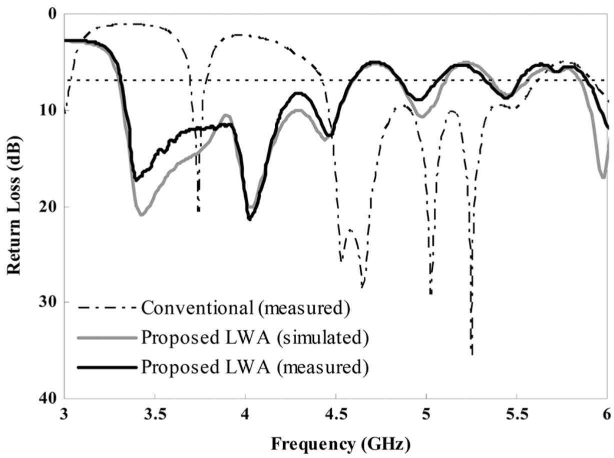


Fig. 12. Comparison the simulated and measured return losses of the conventional LWA and proposed LWA.

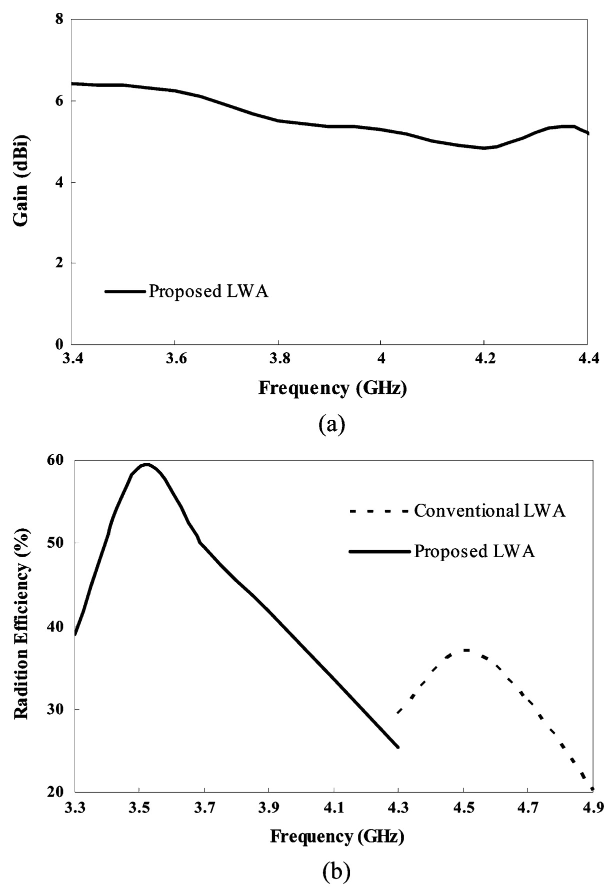


Fig. 13. (a) Measured gain of the proposed LWA; (b) simulated radiation efficiency of the conventional LWA and proposed LWA.

the initially frequency is decreased about 1.12 GHz from 4.42 GHz of the conventional LWA to 3.30 GHz of the proposed LWA. From the measured results, it can be seen that this compact antenna, which is formed by the multi-section tapered short leaky-wave antenna with two slots and a ground plane with ten etched slot elements, not only creates a wideband impedance bandwidth and suppresses the back lobe, but also reduces the width of conventional LWA by 20%. The measured gains and the simulated efficiency of the LWAs are shown in Fig. 13(a) and (b). The gains are larger than 4.8 dBi from 3.4 to 4.4 GHz, and the gain variation is less than 1.6 dB. The maximum efficiency is about 60%, theoretically, and the efficiency of our proposed LWA is higher than that of the conventional LWA. It is shown that utilizing our proposed methods can enhance the efficiency for the short LWA.

IV. Conclusion

In this paper, a novel compact leaky-wave antenna has been presented. The width of LWA was reduced by using the method of etching slot elements on the ground; it thus influenced the current distribution of leaky-wave antenna, reducing the frequency of the radiation angle and influencing the back lobe, and excited the slot-lobe. Furthermore, it causes impedance mismatching. As a result, we tapered this short leaky-wave antenna and embedded Slot-A and Slot-B to achieve both the impedance matching and suppressed the back lobe. With these methods, the 7-dB impedance bandwidth can be achieved from 3.30 to 4.60 GHz. The scanning angle of the measured main beam is 36° from 3.40 to 4.30 GHz. This compact LWA with length of only about 1.14 λ_0 at 3.4 GHz not only successfully reduces the width of a conventional LWA by more than 20%, but also suppresses the back lobe by 7.5 dB at 4.3 GHz. This compact LWA provides a lot of advantages such as compact size, low cost, and easy fabrication. It is suitable for the scanning systems, such as traffic control and collision avoidance system.

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Jin-Wei Wu was born in Tainan, Taiwan, R.O.C., in 1982. He received the B.S. and M.S. degree in electrical engineering from Feng-Chia University, Taichung, Taiwan, in 2004 and 2006, respectively, and the Ph.D. degree in communication engineering from the National Chiao-Tung University, Hsinchu, Taiwan, R.O.C., in 2009.

In 2009, he joined Compal Communications, Inc., Taipei, Taiwan, as a Senior Engineer, where he developed built-in antennas for handsets. His research interests include design of microstrip filters and antennas.

Christina F. Jou was born in Taipei, Taiwan, R.O.C., in 1957. She received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of California, Los Angeles, in 1980, 1982, 1987, respectively. The subject of her doctoral thesis was the millimeter wave monolithic Schottky diode-grid frequency doubler.

From 1987 to 1990, she worked at Hughes Aircraft Company, Torrance, CA, as a Member of the Technical Staff in the Microwave Products Division, where she was responsible for microwave device modeling. In 1990, she joined National Chiao-Tung University, Hsinchu, Taiwan, R.O.C., where she is now an Associate Professor of communication engineering. Her current research is in developing RF and microwave active circuits and MEMS antennas, and filters.

Chien-Jen Wang (M’00–SM’06) was born in Kaohsiung, Taiwan, in 1971. He received the B.S. degree in electrical engineering from the National Sun-Yet-Sen University, Kaohsiung, Taiwan, in 1993 and the Ph.D. degree from the National Chiao-Tung University, Hsinchu, Taiwan, R.O.C., in 2000.

In 2000, he joined the Wireless Communication BU, BenQ Corporation, Taipei, Taiwan, as a Project Researcher, where he developed built-in antennas for handsets. In 2001, he joined the Department of Electrical Engineering, Feng-Chia University, Taichung, Taiwan, as an Assistant Professor and, in 2004, an Associate Professor. In 2006, he joined the Department of Electrical Engineering, National University of Tainan, Tainan, Taiwan, as an Associate Professor where, in 2009, he became a Professor. His research activities involve the design and applications of RF/microwave circuits, antennas, and wireless communication systems.