International Journal of Infrared and Millimeter Waves, Vol. 19, No. 2, 1998

ACTIVE FREQUENCY-TUNE BEAM-SCANNING LEAKY-WAVE ANTENNA ARRAYS

Chien Jen Wang,[1] Jin Jei Wu,[2] and Christina F. Jou[1]

[1]*Institute of Communication Engineering*
National Chiao Tung University
Hsinchu, Taiwan
Republic of China
[2]*Department of Electric Engineering*
Kao Yuan College of Technology & Commerce
Luchu, Kaohsiung, Taiwan
Republic of China

Received December 9, 1997

Abstract

X-band active beam-scanning leaky-wave antenna arrays, including 1 × 1, 1 × 2 and 1 × 4 prototypes, have been demonstrated. These antennas integrated one or several microstrip leaky-wave antenna elements with a single varactor-tuned HEMT VCO as an active source. Measured results on experimental antennas indicate that the beam scanning angle of the 1 × 1 antenna close to 40^0 can be achieved and the scanning range of 1 × 2 and 1 × 4 antenna arrays are both close to 32^0. Furthermore, reflected wave due to the open end of each leaky-wave antenna element has been suppressed by the symmetric configuration of this antenna array and the antenna efficiency increases. When comparing with the measured radiation pattern of the single element antenna, we found that the 1 × 2 and 1 × 4 antenna arrays can effectively suppress the reflected power by more than 5.5 dB and 10.5 dB, respectively, at 10.2GHz. The power gain are more than 2 dB and 3.16 dB higher than the single element antenna with a measured EIRP of 18.67 dBm.

Key Words

beam-scanning; the leaky-wave antenna arrays; the reflected wave; the first higher order mode; phase-shifterless

0195-9271/98/0200-0349$15.00/0

I. Introduction

The active integrated antenna is widely used in applications such the automotive radar system, the mobile communication, and the personal communication system (PCS). It indicates more specifically that the active circuit and the passive antenna elements are integrated on the same substrate [1]. Recently, the leaky-wave antenna has become popular and there is a growing interest in the active-integrated leaky-wave antennas (see Fig. 1) using as frequency scanning elements [2],[3]. Due to low profile, easy fabrication, easy matching, simple structure, narrow beam, and frequency scanning, the leaky modes of uniform open waveguides are very suitable for active integrated millimeter-wave antenna applications. Menzel first discovered the phenomenon of a wider bandwidth in the microstrip leaky-wave antenna compared with resonator antennas [4]. The leaky-wave theory had been derived thoroughly by Oliner [5]. Some research of the leaky-wave antenna have also been intensively investigated in [6],[7].

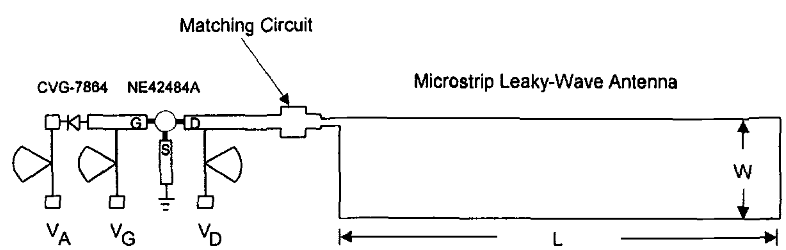

Fig. 1 The configuration of the single asymmetric feeding active microstrip leaky-wave antenna

The propagation region of the microstrip-line first higher order mode in this paper was operated in the radiation region, where the guided mode leaks power into the space wave as well as into the surface wave. Because the leaky-wave antenna is open above, the space wave actually corresponds to radiation at some angle, the value of this angle changing with the frequency. To excite the first higher order mode and leak in the form of the space wave, the leaky-wave antenna is fed asymmetrically.

The leaky-wave antenna, without phase shifters, has excellent beam scanning performance than other antennas, e.g., the patch antenna and the dipole antenna. Here, an active phase-shifterless beam scanning antenna by integrating a varactor-tuned HEMT VCO with microstrip leaky-wave antenna is developed. Operating frequencies tuned by adjusting the varactor DC bias are controlled to vary the beam position. Therefore, we can use it as the frequency-scanning antenna by the characteristic of wide bandwidth and leaky mode. Due to the finite length of the leaky-wave antenna, the reflected wave resulting from the mismatch of the open end of the microstrip antenna may cause the receiving system mistakenly taking the reflected signal for the true signal and the efficiency of the antenna is reduced. Hence, we demonstrated another alternative approach, which using the symmetric configuration of this leaky-wave antenna array not only can effectively reduce the reflected wave, but it also can increase the power gain.

II. Radiation Characteristics of The Leaky-wave Antenna

The nature of the leaky-wave antenna comes from the property of the first higher order mode in microstrip line. In [8], Oliner developed the theory of the leakage and several examples were presented to illustrate the leaky mechanisms, including radiation from waveguide discontinuities into the surface wave, the space wave or leaky below-cutoff higher order modes of the open waveguides themselves. In the bond-mode region or the surface-wave region, the power leaks in the form of the surface wave and the quasi-TEM wave; the space wave dominates the radiating energy in the radiation region. The leaky-wave antenna is operated in the radiation region, the phase constant β less than 1, and the space wave dominates most of the leakage. To obtain the complex propagation constants of the mode of the leaky-wave antenna, the spectrum domain analysis would be used.

The geometry and coordinate system for the microstrip leaky-wave antenna are shown in Fig. 2. Each slot will radiate the same field as the magnetic dipole [7],[9] with the equivalent magnetic current density $\underline{M}_S$ and the equivalent reflected magnetic current density $\underline{M}_{RS}$ due to the mismatch of the load at the end of the leaky-wave antenna. The ratio of $\underline{M}_{RS}/\underline{M}_S$ is the reflected ratio less than 1. We employed rigorous (Wiener-Hopf) solution mentioning by [10], to obtain the normalized complex propagation constant $\beta - j\alpha$ of the first higher order mode in its leak range for the leaky-wave antenna, where β is the phase constant and α is the attenuation constant. The variation of β and α as a function of the frequency are shown in Fig. 3. θ can be calculated using the equation $\theta = Cos^{-1}(\beta / k_0)$, where θ is the elevation angle between the main-beam direction and the end-fire direction, the Z-axis direction. We can use the characteristic of the variation of β as a function of the frequency to change the scanning angle θ.

The radiation pattern of the microstrip leaky-wave antenna can be derived by using the far field equivalence principle. Under the far field condition, we can express the equivalent magnetic current density $\underline{M}_S$ and the equivalent reflected magnetic current density $\underline{M}_{RS}$ as

$$\underline{M}_S = \underline{Z}\ E_0\, e^{-j(\beta - j\alpha)z}$$

$$\underline{M}_{RS} = \underline{Z}\ \Re\, E_0\, e^{j(\beta - j\alpha)z}$$

where E_0 is the arbitrary constant and $\Re$ is the reflected ratio due to the mismatch of the load at the open end of the leaky-wave antenna. For the geometric configuration of the microstrip leaky-wave antenna shown in Fig. 2, the far-zone electric fields are given by the following equations :

$$E_r \cong E_\theta \cong 0$$

$$E_\phi = -jE_0 \frac{kHe^{-jkr}}{\pi r} \left\{ \sin\theta \left[\frac{\sin(X)}{X} \right] \left[\frac{e^{ZL} - 1}{Z} \right] \right\} \cdot \cos\left(\frac{kW \sin\theta \sin\phi}{2} \right)$$

where $X = kH \sin\theta \cos\phi$

$Z = j(k\cos\theta - \beta) - \alpha$

$k = 2\pi/\lambda$ are the wave number

and the width W, the height H and the length L are the dimension of the leaky-wave antenna. This equation of E_ϕ assumes that there is no reflection from the open end of the waveguide and the total radiated power is almost in the form of a space wave.

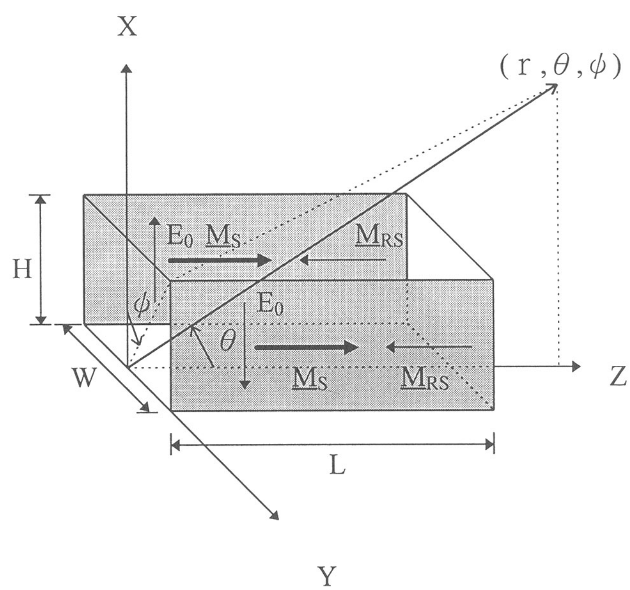

Fig. 2 The geometry and coordinate system for the microstrip leaky-wave antenna. $\underline{M_S}$ was the equivalent magnetic current, and $\underline{M_{RS}}$ was the equivalent reflected magnetic current.

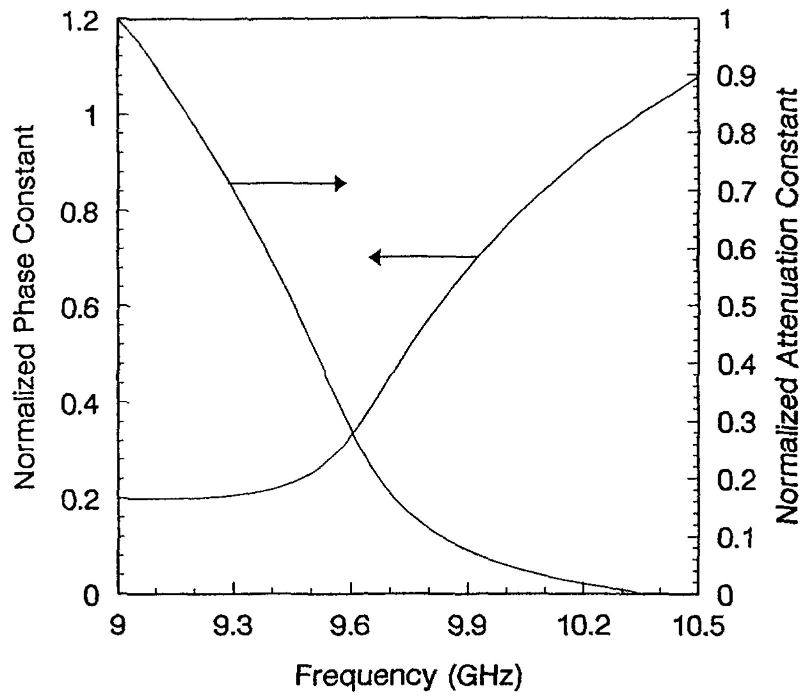

Fig. 3 Normalized phase constant β / k_0 and normalized attenuation constant α / k_0 of the first higher order mode as functions of frequency for the leaky-wave antenna. H=0.635mm, W=4.191 mm, and ϵ_r=10.2.

III. Design of the Active Leaky-Wave Antenna Arrays

In our experiment, three configurations of the active integrated beam-scanning leaky-wave antennas, the 1 × 1 (Fig. 1), 1 × 2 (Fig. 4), and 1 × 4 (Fig. 5) arrays, were fabricated. The basic 1 × 1 configuration shown in Fig. 1 consists of a HEMT VCO as the active source, the matching circuit, and the microstrip leaky-wave antenna. The advantage of one active source, the HEMT VCO, is that the modes of the arrays do not need to be synchronized. The circuits use 0.635 mm thick RT/Duriod substrate with the relative permittivity ϵ_r=10.2, and a NE42484A low-noise GaAs HEMT was used as the oscillator device. The VCO is designed using negative-resistance method utilizing a commercially available CAD tool HP-EEsof Libra. ALPHA CVG 7864 GaAs package varactor is used as a tuning varactor in this experiment and the tunable capacitance for the tuning voltage of 1V to 11V is approximately 11pF to 0.3pF in data sheet. The matching circuit is necessary for the VCO to match the input impedance of the leaky-wave antenna, and the operating frequency can be varied continuously.

To excite the first higher order mode, the microstrip leaky-wave antenna is fed asymmetrically. The width W and the length L of the leaky-wave antenna are 4.2 mm and 6.734 cm, respectively. The dimension is chosen empirically so that the space wave dominates the radiating power, and the first higher order mode can be excited with in the operating frequency. Because the operating frequency is below the cutoff frequency, the normalized phase constant β/k_0 is less than 1, and the space wave dominates the leakage.

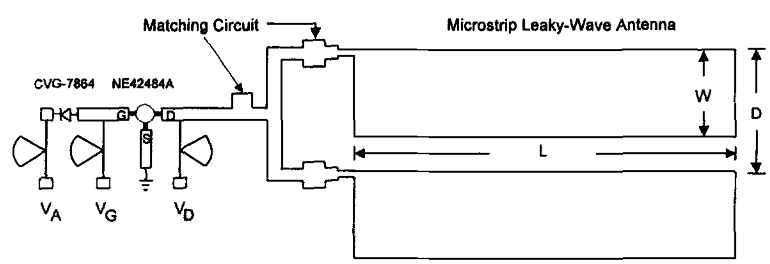

Fig. 4 The configuration of the two-unit active leaky-wave antenna array. D=0.7 λ_0.

Fig. 4 and Fig. 5 show the 1 × 2 and 1 × 4 active leaky-wave antenna arrays. Two passive individual radiating elements are integrated with the single active HEMT VCO by a T-type divider in the 1 × 2 prototype of the antenna array; in the similar configuration, three T-type dividers are used in the 1 × 4 array. The phase of the wave on each of the radiators was set automatically equal. We used the impedance-matching theory to design the inter-element separation D in order to obtain the minimum reflected coefficient and D = 0.7 λ_0 (where λ_0 is the free space wavelength at 10GHz).

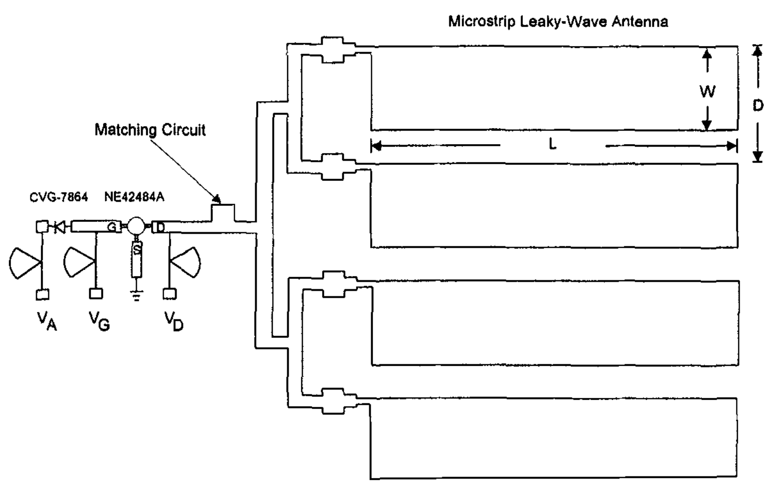

Fig. 5 The configuration of the four-unit active leaky-wave antenna array.

The simple T-type power divider provides the wide bandwidth. The matching circuit is designed to obtain the maximum radiating power and the continuous operating frequency range. By this design procedure, the radiator can have the maximum power input and the portion of the reflected wave also can be reduced. In addition, the loading effect will not affect the oscillator's operation.

IV. Theoretical And Experimental Results

Under the far-field condition, Fig. 6 showed the theoretical and measured radiation patterns of the microstrip leaky-wave antenna for 10.2GHz, in the situation of the finite length, L=6.734cm. The experimental radiation patterns of the prototypes, including the 1×1, 1×2 and 1×4 active integrated leaky-wave antenna arrays, are presented in Fig. 7, Fig. 8 and Fig. 9 for three frequencies, 9.5GHz, 9.9GHz, and 10.2GHz. The measured Effective Isotropic Radiated Power (EIRP) of this 1×1 antenna was approximately 18.67 dBm and the measured power (EIRP) of the 1×2 and 1×4 symmetric antenna arrays were 20.67 dBm and 21.83 dBm at 10.2GHz. The power gain were 2 dB and 3.16 dB higher than the single-element leaky-wave antenna.

The experimental figures displayed that the main beam swings up from the end-fire direction (Z-axis) and the beamwidth becomes wider as the operating frequency is decreased. Noted that the measured scan angles of the 1×1, 1×2 and 1×4 antennas were close to 40^0, 32^0 and 32^0. In other words, the reflected wave due to the open end of the antenna is apparent at the higher frequency, close to the cutoff frequency. We can see from Fig. 7 that the reflected wave (at about angle 150^0) at 10.2GHz which was only 3 dB below the main beam can have an apparently harmful influence on receiving. It is necessary for antenna designers to suppress this reflected wave. Using the configuration of the two-unit and four-unit symmetric antenna arrays, we found that the reflected wave of the measured data were effectively suppressed at 10.2GHz (see Fig. 10). The suppression of the reflected wave for the two-unit and the four-unit arrays were about 5.5 dB and 10.5 dB, respectively when comparing with the measured radiation pattern of the single element antenna.

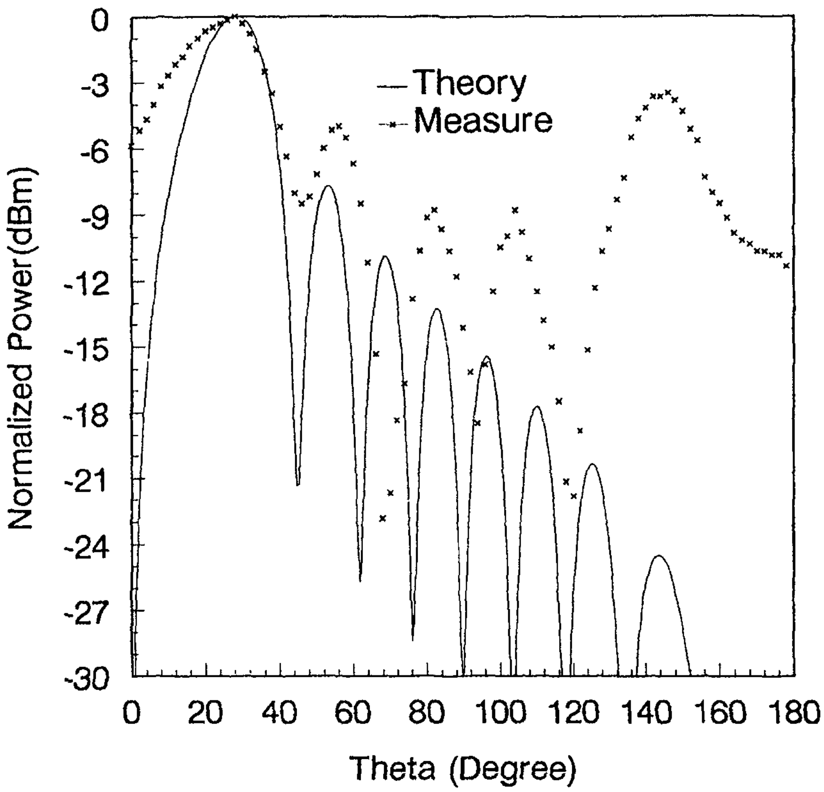

Fig. 6 The theoretical and measured far-field radiation patterns (ϕ=0) of the single active leaky-wave antenna at 10.2GHz.

V. Conclusion

The active integrated beam-scanning leaky-wave antenna arrays have been demonstrated in this paper. The advantage of one active

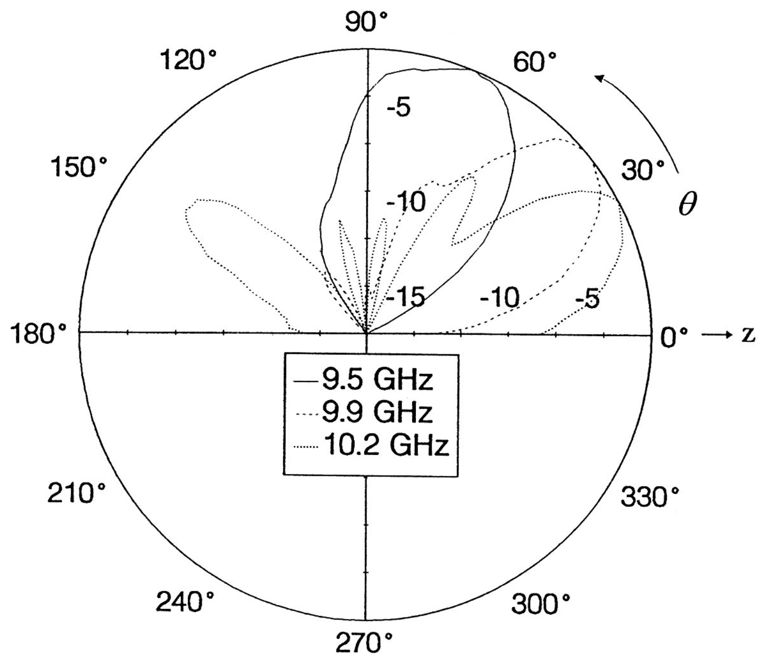

Fig. 7 The measured far-field radiation patterns (ϕ=0) for the scan beam of the 1 × 1 active leaky-wave antenna at 9.5GHz, 9.9GHz, and 10.2GHz.

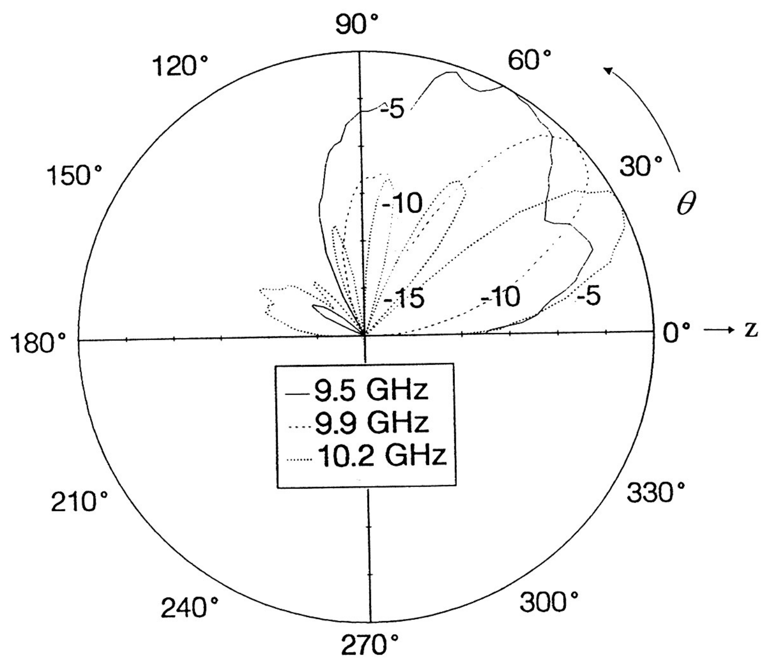

Fig. 8 The measured far-field radiation patterns (ϕ=0) for the scan beam of the 1 × 2 active leaky-wave antenna at 9.5GHz, 9.9GHz, and 10.2GHz.

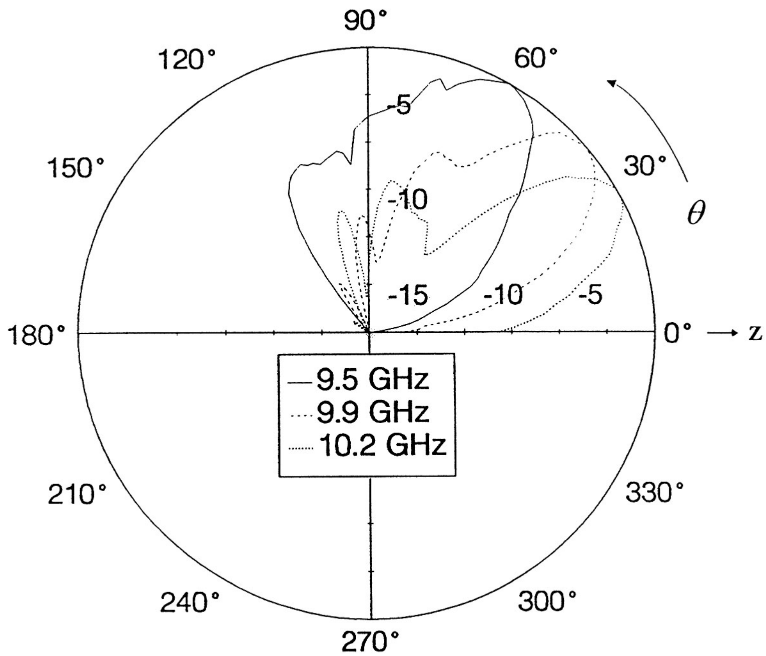

Fig. 9 The measured far-field radiation patterns (ϕ=0) for the scan beam of the 1 × 4 active leaky-wave antenna at 9.5GHz, 9.9GHz, and 10.2GHz.

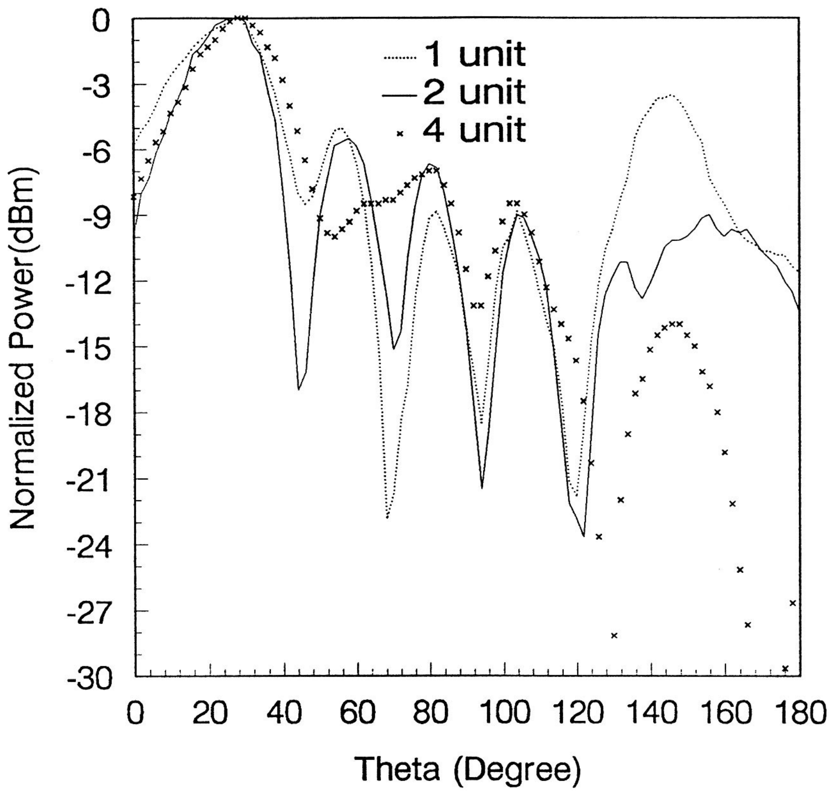

Fig. 10 The measured far-field radiation patterns (ϕ=0) of the 1 × 1, 1 × 2, and 1 × 4 active leaky-wave antenna arrays at 10.2GHz.

source, the HEMT oscillator, is that the arrays do not need to be synchronized. The beam scanning range of the leaky-wave antenna in excess of 30^0 can be achieved by tuning the varactor. It is found that as the number of elements increases in the symmetric configuration of this antenna array, it can not only have more power gain, but also effectively suppress the reflected signal without using longer lines or substrate material of larger height. Hence, the leaky-wave antenna arrays are suitable for frequency scanning and the system can distinguish the true main beam more correctly.

Acknowledgment

This work is supported by the National Science Council under Grants: NSC 86-2215-E009-31

References:

[1] J. Lin and T., Itoh, " Active Integrated Antennas," in *IEEE Trans. Microwave Theory Tech., vol. 42*, pp. 286-2194, 1994.

[2] Arthur A. Oliner, " A new class of scannable millimeter wave antennas," in *Proc. 20th European Microwave Conf.*, pp. 95-104, 1990.

[3] C. C. Hu, J. J. Wu and C. F. Jou, " An Asymmetric Feeding X-Band Active Frequency-Scanning Leaky-Wave Antenna," , in *International Journal of Infrared and Millimeter Wave*, vol. 18, no. 9, Sep., 1997.

[4] W. Menzel, " A new traveling wave antenna," in *Proc. 8th European Microwave Conf*, pp. 302-306, 1978.

[5] Arthur A. Oliner, " Leakage from higher modes on microstrip with application to antennas," in *Radio Science, vol.* 22, no. 6, pp. 907-912, Nov., 1987.

[6] Z. Ma and E. Yamashita, " Space wave leakage from higher order modes on various planar transmission line structure," in IEEE MTT-S Int. Microwave Symp. Dig., San Diego, CA, May 1994, pp. 1033-1036.

[7] G. J. Jou and C. K. Tzuang, " Oscillator-type active-integrated antenna: The leaky-mode approach," *IEEE Trans. Microwave Theory Tech., vol. MTT-44*, pp. 2265-2272, Dec. 1996.

[8] A. A. Oliner, " Leakage from various waveguides in millimeter wave circuits," in *Radio Science, vol.* 22, no. 6, pp. 866-872, Nov., 1987.

[9] C. A. Balanis, " Antenna theory analysis and design," 2nd ed., New York: Wiley, 1997.

[10] D. C. Chang and E. F. Kuester, " Total and partial reflection from the end of a parallel-plate waveguide with an extended dielectric loading," in *Radio Science, vol.* 16, pp. 1-13, Jan.-Feb. 1981.