A Two-Dimensional Beam-Scanning Linear Active Leaky-Wave Antenna Array

Cheng-Chi Hu, Christina F. Jou, and Jin-Jei Wu

***Abstract*—This letter presents a new technique for electronic two-dimensional beam scanning using a phase-shifterless linear active leaky-wave antenna array. The varactor-tuned voltage-controlled oscillators (VCO's) and coupling network are implemented in this array. The measured pattern of this 4 $\times$ 1 leaky-wave antenna array shows that the main beam can be continuously scanned from 68° to 40° in elevation as the frequency varied from 8.24 to 9.15 GHz. By tuning the free-running frequencies of the end elements, the main beam can be continuously scanned from $-26°$ to $+10°$ in azimuth. A maximum ERP of 667 mW is measured at 8.9 GHz for this active antenna array.**

***Index Terms*—Beam-scanning, leaky-wave antenna, VCO's.**

I. Introduction

ACTIVE phased antenna arrays with electronically controlled beam-scanning capability are very important in radar systems and quasi-optical communication systems [1]–[4]. Many beam-scanning techniques have been demonstrated in the microwave and millimeter-wave frequency range [5]. Most of these techniques have serious limitations due to size and moding problems. They become impractical at frequency increases and the waveguide dimensions become very small.

This letter proposed some progress being made toward the millimeter-wave integrated antenna systems employing the planar microstrip leaky-wave antenna technologies [6]–[9] and the phase-shifterless beam-scanning technique [10], [11]. The microstrip realization of leaky-wave antenna was successfully implemented by Menzel [6]. In 1990, Oliner [8] proposed a new approach of two-dimensional (2-D) beam-scanning array. A pencil beam which is a narrow beam can be scanned in both elevation and azimuth (2-D scanning) by creating a one-dimensional (1-D) phased array of leaky-wave line-source antennas. However, phase shifters are required in this design. In 1993 and 1994, Liao and York [10], [11] proposed a new phase-shifterless 1-D beam-scanning technique using patch antenna array with coupled oscillators. By controlling the free-running frequencies of the end elements of the array, the main beam can be scanned in azimuth. Furthermore, the phase progression is independent of the number of oscillators. To demonstrate a linear phased antenna array with 2-D scanning capability without using phase shifters, we extend the work to encompass phase control techniques [10], [11] and leaky-wave characteristics [6]–[9], leading to a new active leaky-wave antenna array as shown in Fig. 1, which is a planar microstrip realization. Therefore, it is suitable for monolithic microwave integrated circuit (MMIC) implementation.

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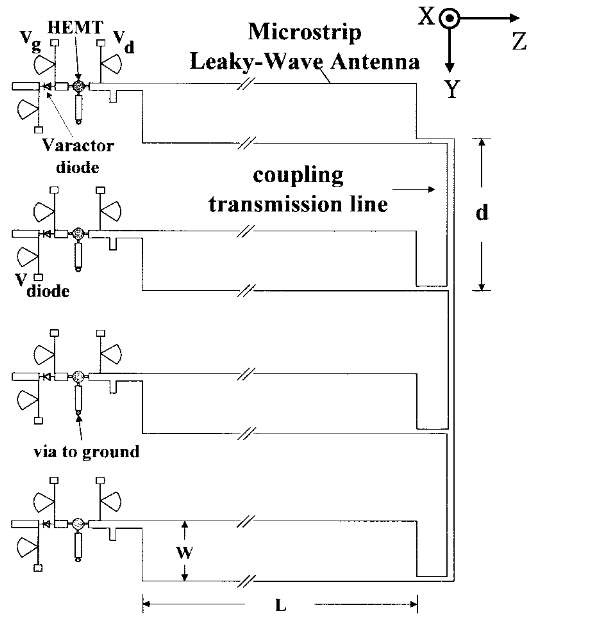


Fig. 1. Configuration of the 4 $\times$ 1 active microstrip leaky-wave antenna array: $w = 12$ mm, $L = 100$ mm, $d = 1\lambda_g$ at 8.8 GHz.

II. Design and Measurement

Fig. 1 shows the structure of the 4 $\times$ 1 active leaky-wave antenna array. The circuit consists of microstrip leaky-wave antennas integrated with high-electron mobility transistor (HEMT) voltage-controlled oscillators (VCO's). The HEMT oscillator is designed using small-signal iterative procedure utilizing a commercially available CAD tool HP-EEsof Libra. A short-circuited microstrip line feedback is used in series with the source to provide the device negative resistance. The leaky-wave antenna (with $L = 10$ cm and $W = 1.2$ cm) is connected to the drain to compensate the negative resistance under the steady-state operation. The circuit is designed and fabricated on RT/Duroid substrate with a dielectric constant of 2.2 and thickness of 20 mil. NEC NE42484 low-noise HEMT is used as the active device, and the Drain is biased at 2.0 V with a drain current of 10 mA. A GaAs varactor (M/A-COM MA46410) is used as the frequency tuning element, which has a capacitance ratio of 10 : 1 and a capacitor of 0.5 pF at 4 V. For a tuning voltage of 1.0–12 V, the active leaky-wave

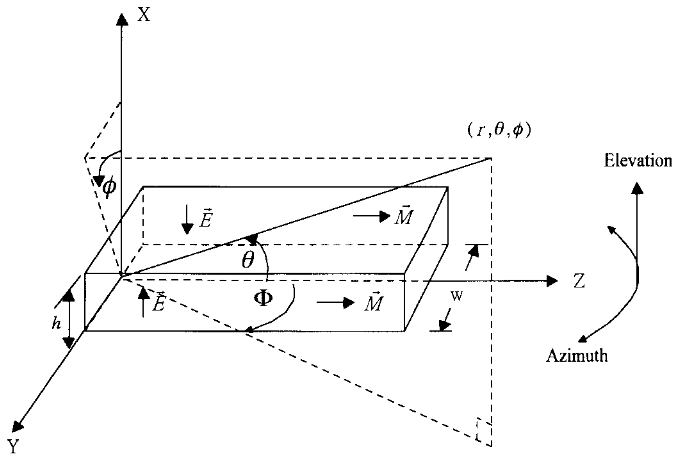


Fig. 2. Geometry and coordinate system for the microstrip leaky-wave antenna.

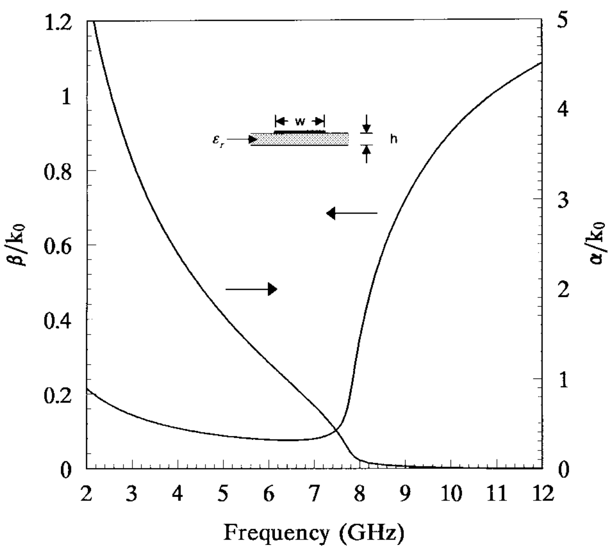
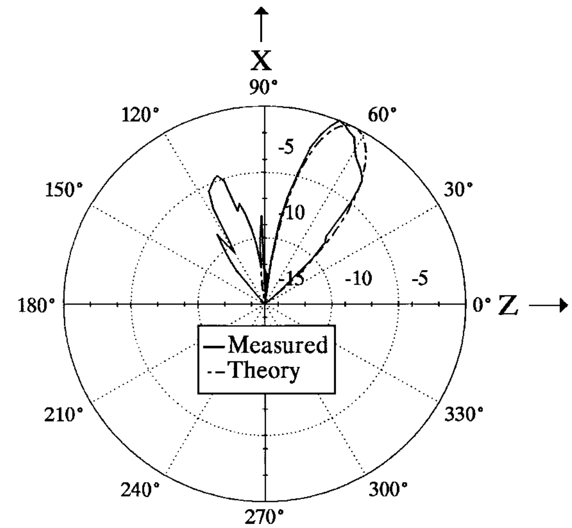
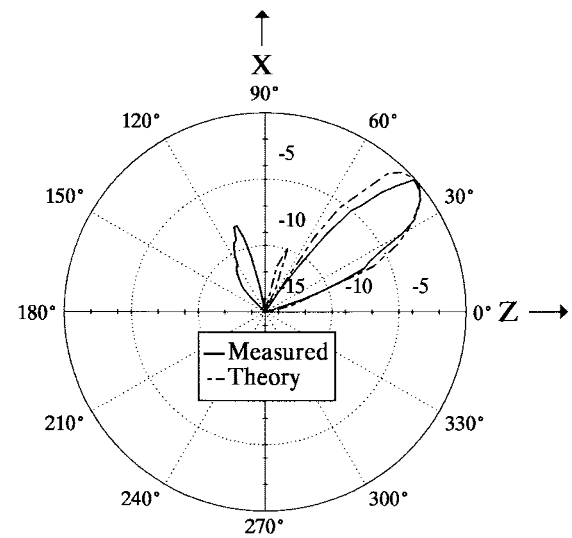


Fig. 3. Normalized propagation constant of the first higher mode for the particular microstrip leaky-wave antenna: $h = 0.508$ mm, $w = 12$ mm, and $\varepsilon_r = 2.2$. k_0 is the free-space number.



(a)



(b)

Fig. 4. H-plane (x–z plane) radiation patterns of the 4 × 1 active microstrip leaky-wave antenna array: (a) $f = 8.24$ and (b) $f = 8.95$ GHz.

antenna exhibits a tuning bandwidth of 8.24–9.15 GHz. This is equivalent to over 10% tuning bandwidth.

The geometry and coordinate system of the microstrip leaky-wave antenna structure is shown in Fig. 2. This microstrip leaky-wave antenna is operated in its first higher order mode and is characterized by a phase constant β and attenuation constant α. Fig. 3 shows the variations of phase constant β and attenuation α as a function of frequency. Such complex propagation constants represent a forward leaky-wave radiating into the space at an angle $\theta_m = \cos^{-1}(\beta/k_o)$, where θ_m is the angle of the beam maximum measured from the z-axis. In addition, the scanning angle θ_m can be varied with frequency. To excite the first higher order mode, the microstrip leaky-wave antenna is fed asymmetrically [6].

This array (see Fig. 1) is comprised of four VCO's, and each of them is coupled to its two nearest neighbors. Electronic beam-scanning in azimuth requires a constant phase progression $\Delta\varphi$ along the array. In [10] and [11], the interelement phase progression $\Delta\varphi$ is controlled only by tuning the free-running frequency of the end element. For a simplest case, which we assume all of the oscillators are identical such that a constant phase progression can be synthesized at a frequency ω_f by the following distribution of free-running frequencies (derived by Liao and York [10]):

$$\omega_i = \begin{cases} \omega_f[1 + \varepsilon' \sin \Delta\varphi], & \text{if } i = 1 \\ \omega_f, & \text{if } 1 < i < N \\ \omega_f[1 - \varepsilon' \sin \Delta\varphi], & \text{if } i = N \end{cases} \quad (1)$$

where

- ε' $= \varepsilon/2Q$;
- ε coupling strength of the coupling circuit;
- Q quality factor of the oscillator embedding circuits;
- $\Delta\varphi$ phase progression.

In steady state, all the oscillators run at a common frequency given by the average of the free-running frequencies:

$$\omega_f = \frac{1}{N} \sum_{i=1}^{N} \omega_i. \quad (2)$$

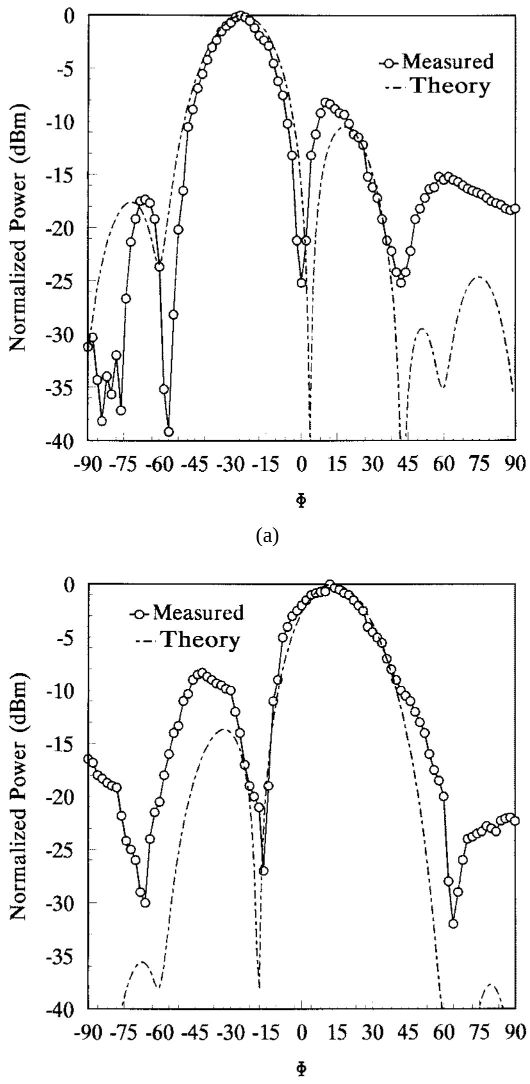


Fig. 5. Comparison of theoretical and experimental results for two different scan angles. By controlling the free-running frequencies of the end elements of the array, main beam can be scanned in azimuth and measured with a conical manner corresponding to an angle $90^\circ - \theta$ ($\theta = 55^\circ$) from x-axis: (a) measured and theoretical patterns for $\Delta\varphi = 80^\circ$, $f = 8.739$ GHz and (b) measured and theoretical patterns for $\Delta\varphi = -40^\circ$, $f = 8.723$ GHz.

By slightly adjusting the free-running frequencies of the end elements in opposite directions by an amount $\varepsilon' \omega_f \sin \Delta\varphi$, a constant phase progression can be achieved and the radiation pattern can be scanned in azimuth. Consequently, the coupled oscillator array cannot lock effectively to a common frequency in a very weakly coupled oscillator array, since the weak coupling strength in the antenna array limits the locking bandwidth. Therefore, a proper coupling circuit is designed to enhance the mutual synchronization. A one-wavelength-long ($1\lambda_g$ at 8.8 GHz) transmission line connected at the end of each leaky-wave antenna (see Fig. 1) helps create the proper coupling strength and in-phase mode oscillation.

The measurement is done under the far field condition. By tuning the dc bias of each varactor simultaneously, the main beam can be scanned in elevation (H-plane). Fig. 4 shows the experimental results of the H-plane pattern for operating frequency at 8.24 and 8.95 GHz, respectively. The measured H-plane main beam can be continuously scanned from 68° to 40° from the z axis.

Following the coupled oscillator theory [10], [11], beam scanning in azimuth can be achieved by adjusting the free running frequencies of the VCO's on the ends of the array. In this experiment, a constant phase progression is achieved simply by controlling the dc bias of the outmost varactors in opposite directions. Fig. 5 illustrates that the main beam can scan in azimuth from -26° to $+10^\circ$ off broadside corresponding to a measured frequency from 8.739 to 8.723 GHz, respectively. However, there is frequency shifts of ω_f during the azimuthal scanning measurement. This frequency shift is probably due to the device parameter variation and the nonlinear varactor tuning range across the array. This scanning indicates that it is possible to obtain 120° of phase shift between each element in the array, which corresponds to a phase differences of 360° between the first and last elements in the array. A maximum ERP of 667 mW is measured at 8.9 GHz for this active antenna array.

III. Conclusion

A new technique for electronic 2-D beam-scanning using a linear active leaky-wave antenna array has been presented without using phase shifters. A constant phase progression which is independent of the number of oscillators is accomplished by tuning the dc bias of varactors, while the beam can be scanned in both azimuth and elevation in a conical scan manner. The measured radiation patterns agree well with the theoretical predictions. A maximum ERP of 667 mW measured at 8.9 GHz for this active antenna array. The initial results show a good potential of using the circuit for low cost transmitters, active arrays, spatial power combiners, and radar applications.

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