Two-dimensional beam-scanning linear active leaky-wave antenna array using coupled VCOs

C.-C. Hu, C.F. Jou and J.-J. Wu

Abstract: An active phased-array design for electronic two-dimensional beam scanning using a phase-shifterless linear one-dimensional active leaky-wave antenna array is demonstrated. The varactor-tuned voltage-controlled oscillators (VCOs) and coupling network are implemented in this array. Three coupling networks are designed and compared for optimum coupling strength between each VCO element. The measured pattern of a 4 × 1 active leaky-wave antenna array shows that the main beam can be continuously scanned from 68° to 40° in elevation, as the frequency varies from 8.24GHz to 9.15GHz. This is equivalent to over 10% electronic tuning bandwidth. By tuning the free-running frequencies of the end elements, the main beam can be continuously scanned from −26° to +10° from broadside with azimuth symmetry in a conical scan manner.

1 Introduction

Quasi-optical power combining and beam scanning using arrays of coupled oscillators have recently been under investigation by many groups [1–5]. In their approaches, a set of planar antenna-loaded active microwave oscillator circuits are fabricated in a periodic arrangement. The oscillators in the array interact with each other via free space, transmission-line circuits, or external cavities, permitting them to synchronise to a common frequency through mutual injection locking.

This paper proposes an active phased-array design that integrates the antenna systems employing planar microstrip leaky-wave antenna technologies [6–10] and the phase-shifterless beam-scanning technique [11, 12] (see Fig. 1).

In 1979, Menzel proposed a successful method for the excitation of the microstrip line first higher-order mode [6]. In 1990, Oliner [8] proposed a new approach, the two-dimensional beam-scanning array. A pencil beam, which is a narrow beam, can be scanned in both elevation and azimuth (two-dimensional scanning) by employing a linear one-dimensional phased array of leaky-wave line-source antennas. However, phase shifters are required in that design.

In 1993, Liao and York [11, 12] proposed a new phase-shifterless one-dimensional beam-scanning technique, using a patch antenna array with weakly coupled oscillators. A constant phase progression is achieved by controlling the free-running frequencies of the end elements of the array in the locking bandwidth limits. Therefore the main beam can be scanned in azimuth. Furthermore, the phase progression is independent of the number of oscillators.

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Here, we demonstrate a linear active phased-antenna array (see Fig. 1) with two-dimensional beam-scanning capability, (Fig. 2) without using phase shifters. The coupling transmission line enhances the mutual synchronisation of the active antenna array. The controlling of the free-running frequency is achieved by tuning the varactor's DC bias, which also gives the additional advantage of fine tuning the scanning angle of the array.

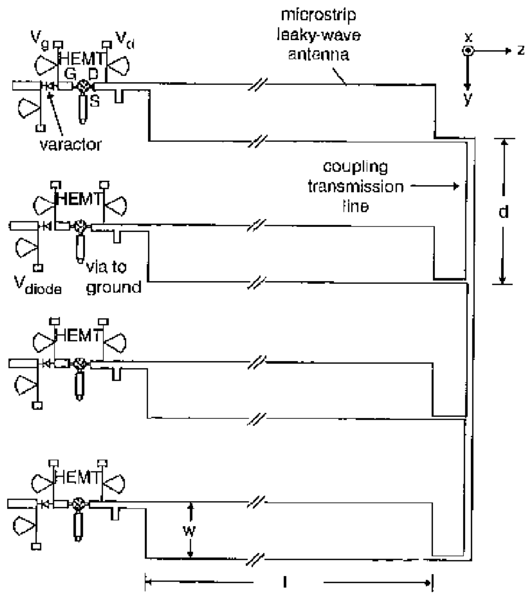

Fig. 1 *Configuration of 4 × 1 active microstrip leaky-wave antenna array*
w = 12mm; l = 100mm; $d = \lambda_g$ at 8.8GHz

2 Design and measurement

2.1 VCO design and measurement

The schematic diagram of our two-dimensional beam-scanning active leaky-wave antenna array design is shown in Fig. 1. The circuit consists of a linear microstrip leaky-wave antenna array integrated with voltage controlled oscillators (VCOs). The VCO (see Fig. 3) is designed using a small-

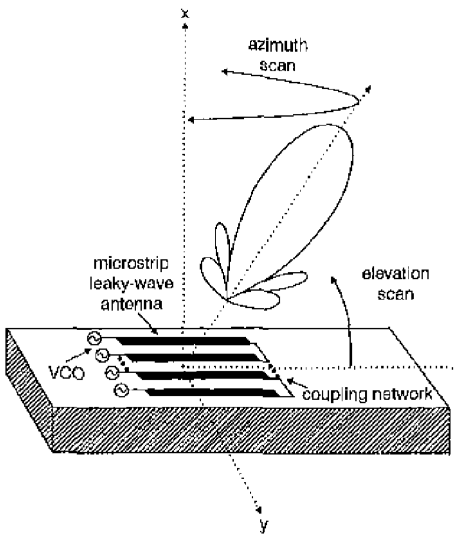

Fig. 2 *Schematic diagram of two-dimensional scanning using linear active phased array of leaky-wave line sources*

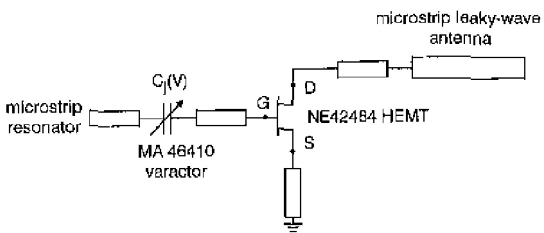

Fig. 3 *Schematic diagram for varactor tuned VCO*

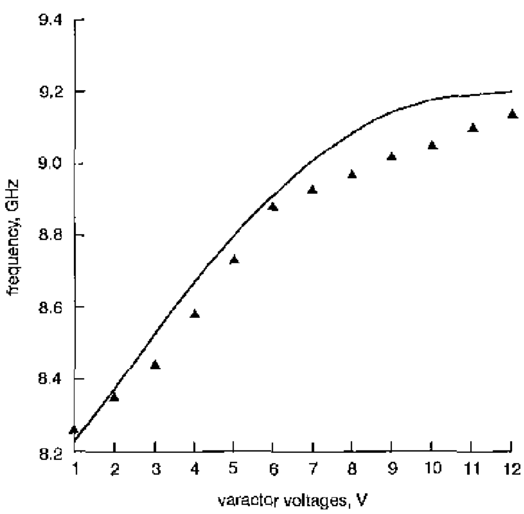

Fig. 4 *Active varactor-tunable leaky-wave antenna array results: simulated and measured varactor tuning frequency against voltage*
- Simulation ▲ Measured

signal iterative procedure utilising a commercially available CAD tool (HP-EEs of 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 = 10cm and w = 1.2cm) is connected to the drain to compensate the negative resistance under steady-state operation. The circuit is designed and fabricated on RT/Duroid substrate, with a dielectric constant of 2.2 and thickness of 20mm. NEC NE42484 low noise HEMT is used as the active device, and the drain is biased at 2.0V with a drain current of 10mA. A GaAs varactor (M/A-COM MA46410) is used as the frequency-tuning element; it has a capacitance ratio of 10:1 and a capacitance of 0.5pF at 4V. For a tuning voltage of 1.0–12V, the active leaky-wave antenna exhibits a measured tuning bandwidth of 8.24–9.15GHz. This is equivalent to over 10% tuning bandwidth. Fig. 4 shows the comparison of the simulated and the measured tuning ranges obtained by varying the varactor diode bias voltages. The output spectrum of a 4 × 1 active antenna array measured under farfield condition at 8.93GHz is shown in Fig. 5, which indicates in-phase mode operation and full synchronisation. A maximum received power of −13.83dBm was measured at 8.93GHz. This measurement result was obtained at a distance of 1.1m from the array, using a 15dB pyramidal horn. The above data correspond to an ERP of 667mW.

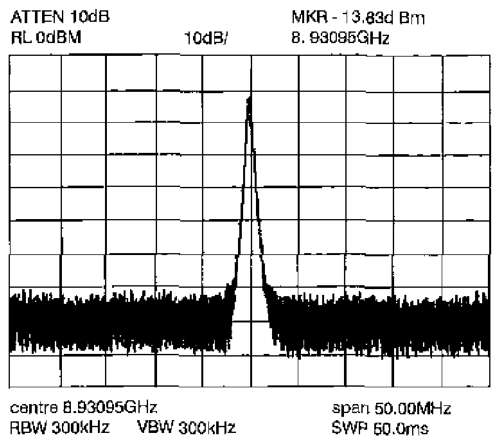

Fig. 5 *Spectrum of 4 × 1 active antenna array measured at 8.93GHz*

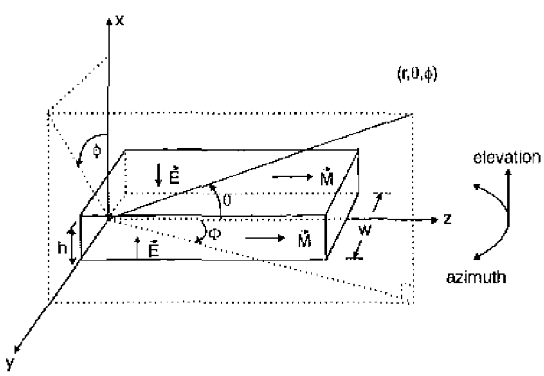

Fig. 6 *Geometry and co-ordinate system for microstrip leaky-wave antenna*

2.2 Elevation scan

The geometry and co-ordinate system of the microstrip leaky-wave antenna structure are shown in Fig. 6. This microstrip leaky-wave antenna is operated in its first higher-order mode and is characterised by a phase constant β and attenuation constant α. Fig. 7 shows the variations of phase constant β and attenuation α as a function of frequency. The complex constants are obtained by employing the rigorous (Wiener–Hopf) solution mentioned in [9]. Such complex propagation constants represent a forward leaky wave radiating into the space at an angle $\theta_m = \cos^{-1}(\beta/k_0)$, 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].

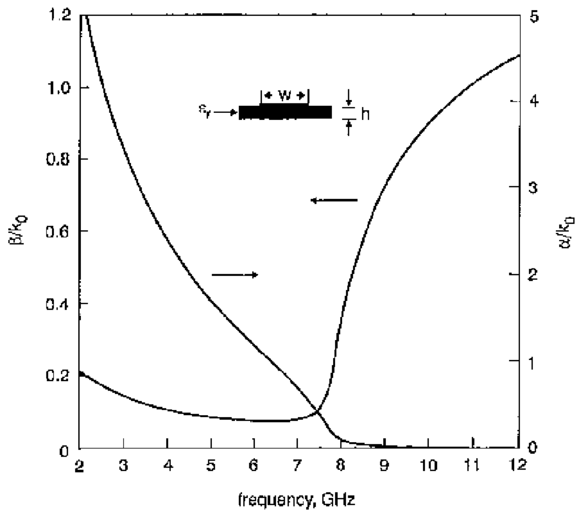

Fig. 7 *Normalised propagation constant of first higher-order mode for particular microstrip leaky-wave antenna*
$h = 0.508$mm; $w = 12$mm; $\varepsilon_r = 2.2$. k_0 is free-space number

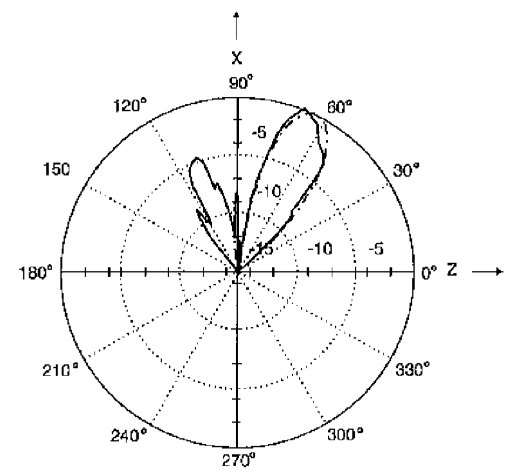

Fig. 8 *H-plane (x-z-plane) radiation patterns of 4 × 1 active microstrip leaky-wave antenna array, for f = 8.24 GHz*
····· Measured ------ Theory

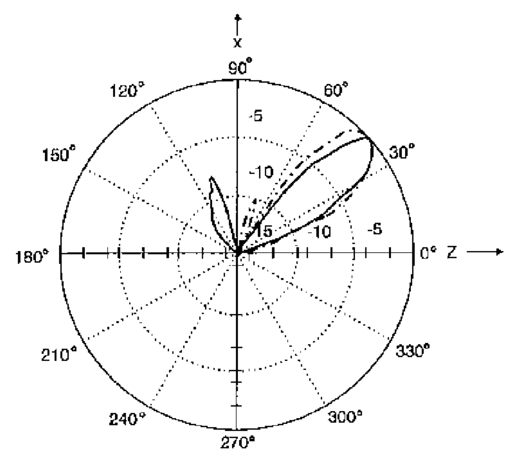

Fig. 9 *H-plane (x-z-plane) radiation patterns of 4 × 1 active microstrip leaky-wave antenna array, for f = 8.95 GHz*
——— Measured — — — Theory

The radiated pattern was measured under the farfield condition. By tuning the DC bias of each varactor simultaneously, the main beam can be scanned in elevation (*H*-plane). Figs. 8 and 9 show the comparison of the measurement results and the theoretical predictions of the *H*-plane pattern for operating frequency at 8.24GHz and 8.95GHz, respectively. The measured *H*-plane main beam can be continuously scanned from 68° to 40° from the *z*-axis.

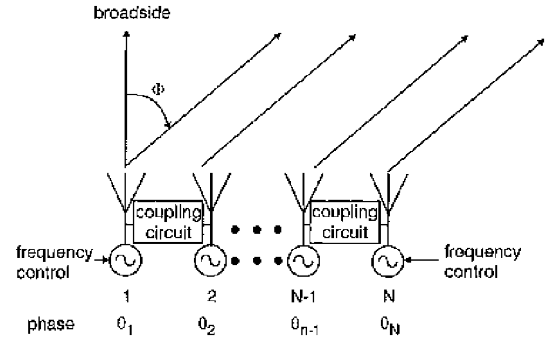

Fig. 10 *Block diagram of N coupled-VCO phased-array system for beam scanning*

2.3 Azimuth scan

A scanning-array diagram is shown in Fig. 10; it comprises N coupled-VCOs, and each of them is coupled to its two nearest neighbours. When a constant phase progression $\Delta\varphi = \theta_i - \theta_{i+1}$ a long the array is established, the radiation main beam is scanned to an angle

$$\Phi = -\sin^{-1}\left(\frac{\Delta\varphi\lambda_0}{2\pi d}\right) \quad (1)$$

In [11, 12], the inter-element phase progression $\Delta\varphi$ is controlled only by tuning the free-running frequency of the end element. For a simplest case, we assume all of the oscillators are identical, such that a constant phase progression $\Delta\varphi$ can be synthesised at a frequency ω_f by the following distribution of free-running frequencies [11]:

$$\omega_i = \begin{cases} \omega_f + \Delta\omega_m \sin\Delta\varphi & \text{if } i = 1 \\ \omega_f & \text{if } 1 < i < N \\ \omega_f - \Delta\omega_m \sin\Delta\varphi & \text{if } i = N \end{cases} \quad (2)$$

where $\Delta\omega_m = \varepsilon\omega_f/2Q$ is the locking bandwidth, ε is the coupling strength of the coupling circuit, and Q is the quality factor of the oscillator embedding circuits. In steady state, all the oscillators run at a common frequency given by the average of the free-running frequencies

$$\omega_f = \frac{1}{N}\sum_{i=1}^{N}\omega_i \quad (3)$$

Using eqn. 2 and slightly adjusting the free-running frequencies of the end elements in opposite directions by an amount $\Delta\omega_m \sin\Delta\varphi$, we can obtain a constant phase progression $\Delta\varphi$, and the radiation pattern can be scanned with azimuthal symmetry in a conical scan manner.

The radiation pattern of our 4 × 1 active phased array was measured on a conical surface corresponding to an angle of 45° from the x-axis. Each varactor was biased individually (see Table 1). When the varactors were simultaneously biased at 5V, a common output frequency of 8.731GHz was observed. The free-running frequency tuning of the end element was achieved by adjusting the outermost varactor's DC bias voltage; this varactor bias tuning range is limited to the maximum locking bandwidth of this array (≃ 120MHz at 8.73GHz). The results obtained from tuning the DC bias of each varactor are given in Table 1.

Table 1: Measurement results for three different DC bias conditions

Bias condition	DC bias, V				Output frequency ω_f, GHz	Main beam angle from broadside
	varactor 1	varactor 2	varactor 3	varactor 4		
1	5.5	5	5	4.5	8.739	−26°
2	5	5	5	5	8.731	0°
3	4.5	5	5	5.5	8.723	+10°

Based on eqns. 2 and 3, the output frequency ω_f should be the same for the three different bias conditions. However, there are frequency shifts of ω_f during the azimuthal scanning measurement. This frequency shift is probably due to the device-parameter variation and the non-linear varactor tuning range across the array. The radiation patterns measured in azimuth are shown in Figs. 11–13. These measured results illustrate that the main beam can scan in azimuth from −26° to +10° off broadside as the varactor DC bias voltage varies from condition 1 to condition 3. This scanning range indicates that it is possible to obtain 120° of phase shift between each element in the array, which corresponds to a phase difference of 360° between the first and last elements in the array.

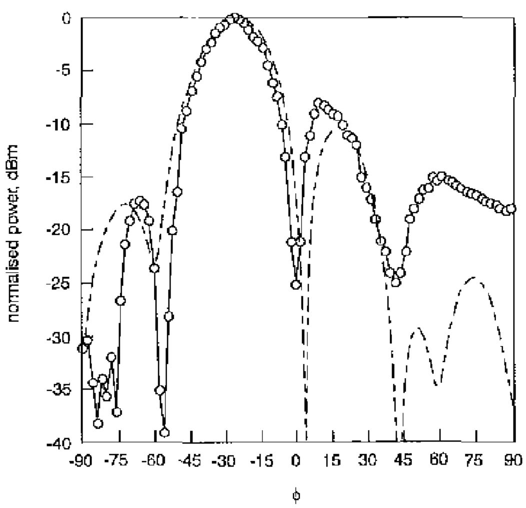

Fig. 11 *Measured and theoretical patterns for* $\Delta\varphi = 80°$, $f = 8.739GHz$
-○- Measured - - - Theory

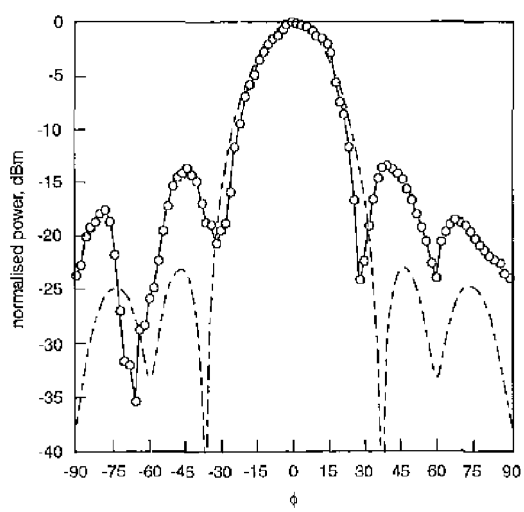

Fig. 12 *Measured and theoretical patterns for* $\Delta\varphi = 0°$, $f = 8.731GHz$
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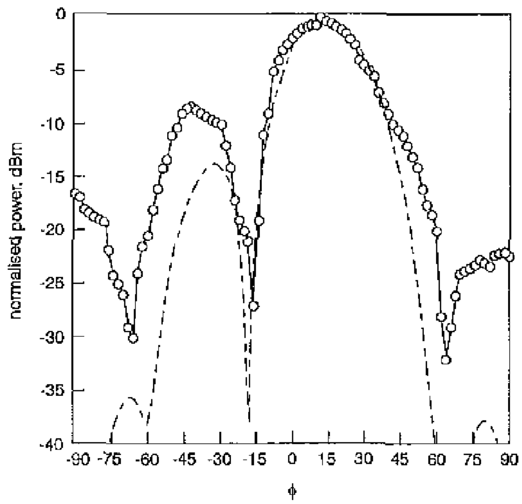

Fig. 13 *Measured and theoretical patterns for* $\Delta\varphi = 40°$, $f = 8.723GHz$
○ Measured - - - Theory

3 Conclusions

A new active phased-array design for electronic two-dimensional beam scanning using a linear active leaky-wave antenna array has been demonstrated without using phase-shifters. A constant phase progression that is independent of the number of oscillators is accomplished by tuning the VCO DC bias voltage, so that the beam can be scanned in both azimuth and elevation in a conical scan manner. The coupling network is designed to create a proper coupling strength between each oscillator. The radiation patterns for the 4 × 1 active microstrip leaky-wave antenna array in both elevation and azimuth were measured and compared with theoretical predictions. The initial results show the potential of using the circuit for low-cost transmitters, active arrays, spatial power combiners and radar applications.

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