A Six-Element Beam-Scanning Array

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***Abstract*—A six-element beam-scanning coupled MESFET oscillator array was designed and constructed. Resistively loaded transmission line networks were used to strongly couple each oscillator to its two nearest neighbors. Measured H-Plane radiation patterns indicate continuous scanning from -30 to $+40$ degrees (from broadside).**

I. INTRODUCTION

QUASI-OPTICAL coupled oscillator arrays have been used for millimeter wave power combining [1–5], modelocking for pulse generation [11], and electronic beam scanning [4], [6]. The more recent beam-scanning method [6] synthesizes the required inter-element phase shifts by controlling the free-running frequencies of the oscillators in the array. Since this technique permits electronic beam control without using phase shifters, it clearly allows for more compact implementation of beam-scanning systems.

The beam-scanning method applies when the oscillators are mutually synchronized, which is only possible when all the free-running frequencies of the oscillators in the array lie within some collective-locking bandwidth. Naturally, strong inter-element coupling between the oscillators relaxes the frequency restrictions necessary for mutual synchronization. Some techniques which strongly couple the elements in these arrays have been proposed [3], [5], [10]. This paper presents the design and measurement of a strongly coupled, six-element beam-scanning oscillator array. The oscillators used in this array were designed to provide maximum output power using the gain saturation approximation [7], and optimum embedding networks of [8].

II. BEAM-SCANNING TECHNIQUE

The scanning technique has previously been reported [6], so only a brief outline is given here. The technique was first predicted using a theory of coupled Van der Pol oscillators [9]. The phase dynamics of N coupled oscillators with nearest neighbor coupling are given by

$$\frac{d\theta_i}{dt} = \omega_i - \frac{\varepsilon\omega_i}{2Q}\sum_{\substack{j=i-1\\ j\neq i}}^{i+1}\frac{A_j}{A_i}\sin(\Phi+\theta_i-\theta_j), \qquad i = 1,2,\cdots,N \tag{1}$$

where ω_i, θ_i, A_i, and Q are free-running frequency, instantaneous phase, instantaneous amplitude, and quality factor of the ith oscillator, while ε and Φ are the magnitude and phase of the coupling.

If all of the oscillators are mutually synchronized, then the derivatives of their instantaneous phases will be equal to their synchronized frequency, ω_f: $d\theta_i/dt = \omega_f$. Beam-scanned arrays require an equal, progressive phase shift between oscillators, $\theta_i - \theta_{i-1} = \Delta\theta$. Substituting into (1) and defining $\varepsilon' = \varepsilon/2Q$, we find [6] that the constant phase progression is obtained when the free-running frequencies are:

$$\omega_i = \begin{cases} \omega_f[1-\varepsilon'\sin(\Phi+\Delta\theta)]^{-1}, & \text{if } i = 1\\ \omega_f[1-2\varepsilon'\sin\Phi\cos\Delta\theta]^{-1}, & \text{if } 1 < i < N\\ \omega_f[1-\varepsilon'\sin(\Phi-\Delta\theta)]^{-1}, & \text{if } i = N. \end{cases} \tag{2}$$

This requires that all of the innermost oscillators share the same free-running frequency, and the end elements are slightly detuned. The amount of detuning determines the progressive phase shift.

A stability analysis [6] shows that the phase shift $\Delta\theta$ can be tuned over a 180°range. For the case of $\Phi = 0°$, this phase shift will lie in the range $-90° \leq \Delta\theta \leq +90°$. It is likely that the range of allowed phase shifts will be somewhat smaller in practice, since the phase noise of the array output will increase toward the end of the locking range. The scan angle from broadside, Ψ, is related to the progressive phase shift, $\Delta\theta$, via:

$$\Delta\theta = \frac{2\pi d}{\lambda}\sin\Psi. \tag{3}$$

It is possible to increase the scan range by decreasing the element separation in the array. This will cause a broadening of the beam width which can then be reduced by increasing the number of array elements. Note that the progressive phase shift, $\Delta\theta$, is independent of the array size; hence, the scan range will *not* be affected by an increase in the number of array elements.

III. OSCILLATOR AND ARRAY DESIGN

The oscillators in the array were designed to provide maximum power at the design frequency of 4 GHz. The oscillator design employed a simple approach, which combined elements of the techniques described by Johnson [7], and Kotzebue [8]. Johnson observed that $|S_{21}|$ was the only large signal S-Parameter that varied significantly from its small signal value. For the oscillator design, the remaining S-Parameters are left at their small signal values. Large signal values of $|S_{21}|$ were determined from a plot of input power versus output power at the point of maximum power added efficiency.

Optimum oscillator embedding network design equations provided by Kotzebue and Parrish [8] were used to compute

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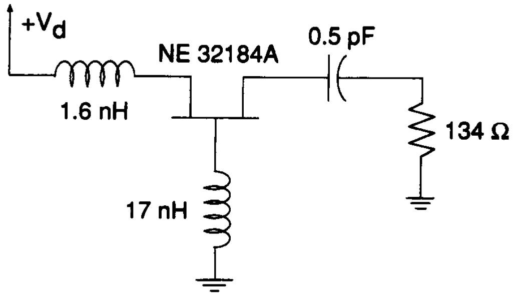

Fig. 1. Optimum 4 GHz Oscillator Circuit. These lumped element values were obtained using the design approach of Johnson [7] and Kotzebue [8].

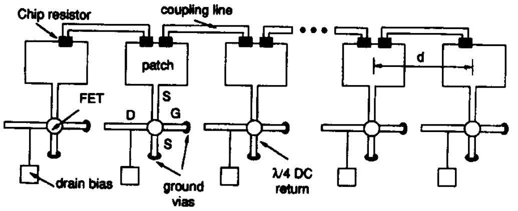

Fig. 2. Illustration of six-element beam-scanning array. Individual oscillators realized the lumped element circuit of Fig. 1. The coupling network is described in [10].

lumped element component values which would provide maximum oscillator power at 4 GHz. The circuit topology and lumped element values are illustrated in Fig. 1. Microstrip equivalents of these lumped elements were then realized. To provide a DC return for each FET, a quarter wavelength short-circuited stub was connected to one of the two source leads. This initial design used an NE32184A GaAs MESFET and was constructed using 31-mil thick Rogers Duroid 5880 microwave substrate, which has a relative dielectric constant of 2.2. The output power from this oscillator was measured to be 12.6 mW at 3.9 GHz in a 50 Ω environment. The obtained output power of 12.6 mW is very close to the maximum of the $P_{out} - P_{in}$ curve. The measured DC to RF conversion efficiency of this design was 43%. It was possible to slightly tune the frequency of the oscillator by varying the applied drain bias.

An illustration of the beam-scanning array is shown in Fig. 2. A six-element array with $\lambda_0/4$ spacing was desired; however, the physical dimensions of the initial microstrip oscillator design were prohibitively large. The array was subsequently fabricated on 31-mil thick Rogers Duroid 6010, which has a relative dielectric constant of 10.8. A microstrip patch antenna was used as a load for each oscillator. A high-impedance transmission line was used to transform the patch antenna impedance to the optimum load impedance prescribed. The antennas were designed to be one-half wavelength long at 4.0 GHz. Each patch antenna was 10.8 mm long by 16.2 mm wide, which provides a load impedance of $\approx 400\,\Omega$ at resonance.

The array was designed to have $\Phi = 0°$, at 4 GHz, for scanning around broadside. Following the coupling method described in [10], each oscillator was then coupled to its two nearest neighbors via a resistively loaded, one wavelength long 50 Ω transmission line at 4 GHz. The series resistors were also 50 Ω, which should provide a coupling strength of: $\varepsilon \approx 4$. The one wavelength-long coupling lines were arranged with an element separation of 19.6 mm or, $0.26\lambda_0$ at 4 GHz.

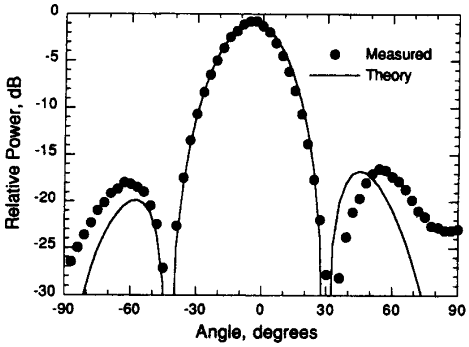

Fig. 3. Measured broadside pattern obtained with the free-running frequencies of all elements nearly identical.

IV. MEASUREMENTS

The oscillation frequency when the oscillators were coupled together via the transmission line networks was 4.24 GHz. This change in oscillation frequency changed the coupling phase, Φ, from its intended value of 0° to about 27°. This increase in oscillation frequency similarly caused an increase in the electrical length of the element separation from the desired $d = 0.26\lambda_0$ to $d = 0.29\lambda_0$. Using [3], the maximum scan range for an array with this element separation is ±59°. Measured radiation patterns obtained from the array are illustrated in Figs. 3 and 4. In practice, it is difficult to measure the true free-running frequencies of the oscillators, because each oscillator is connected to its two nearest neighbors through resistively loaded transmission lines. The initial frequency distribution of the array was set by adjusting the drain bias of each element while every other element was unpowered. Fig. 3 illustrates a broadside pattern which was obtained when the initial frequencies of the oscillators were identically set to 4.24 GHz. The oscillation frequency of the array was then 4.235 GHz and the radiation pattern was slightly shifted from broadside to about −5°. This shift is due to measureable differences in the radiated power from each oscillator in the array and a small degree of randomness in their free-running frequencies. Note that there is good agreement between the broadside measurement and the theoretical pattern, which was obtained by multiplying an array factor with an 8° progressive phase shift by the theoretical H-Plane radiation pattern of a patch antenna with the indicated dimensions.

Several beam-scanned patterns, illustrated in Fig. 4, were measured when the free-running frequencies of the end elements were bias tuned, as prescribed by [2]. The full scan range was measured to be −30° to 40° off broadside. This scan range is smaller than the theoretically achievable scan range for this array, −59° to 59°, mainly because the frequency tuning range of the end oscillators was smaller than the locking bandwidth for the oscillators in this array. Also, the oscillator

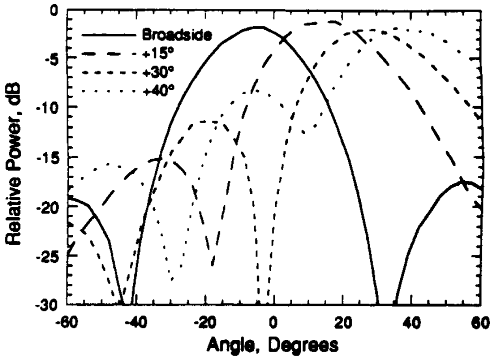

Fig. 4. Sample measurements which illustrate continuous scanning from broadside to the scan limit of +40°.

amplitudes were observed to change significantly over the tuning range. Therefore, the largest progressive phase shift produced between the elements, $\Delta\theta$, was smaller than the one required for maximum beam scan angle. Another factor which conspired against achieving the full scan range was the non-zero coupling phase which was obtained. In the future, wideband VCOs will be used as the end elements.

V. CONCLUSIONS

A beam-scanning array was developed which achieved continuous scanning from −30° to 40°. The bias tuning range of the oscillators in the array limited the obtainable scan range to below the theoretical limit of ±59°. Strong coupling of oscillators was demonstrated using the technique presented in [10]. Future efforts will concentrate on the fabrication of an oscillator that is tunable over a wide bandwidth.

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