GRID-OSCILLATOR BEAM-STEERING ARRAY

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Abstract—**Recently Liao and York showed that beam-steering can be achieved by detuning the end elements of a coupled-oscillator array. The advantage of this approach is that no phase shifters are required. Liao and York used a single line array of patch antennas. Here we report the results for a pair of 1×4 HEMT line-grid oscillators at 11 GHz. This array can scan from −6.5° to +5° by changing the bias.**

INTRODUCTION

Beam-steering in an array is achieved by establishing a constant phase difference between adjacent elements. Conventionally the phase difference is set by phase shifters. However, the phase shifters are expensive at microwave and millimeter-wave frequencies. York proposed a new method of beam-steering without using any phase shifters [1]. His idea is to establish a constant phase progression by detuning the end elements. Liao and York demonstrated this using a line array of patch antennas [2]. Here we use a line-grid oscillator as the radiating element. The line-grid oscillator is based on the planar grid developed by Weikle *et al* [3]. This radiating element is shown in Figure 1a. In Weikle's grid the drain and source leads are vertical and parallel to the radiated electric field. The gate leads are horizontal, perpendicular to the electric field. Capacitive coupling from the drain lead back to the gate lead sustains the oscillation. A mirror behind the grid helps to lock the devices together and assures that the power radiates in one direction. DC bias is fed from the sides of the grid. Our beam-steering array consists of two line-grid oscillators (Figure 1b). It is fabricated on a 15-mil Duroid substrate with a dielectric constant of 2.33. We chose a line-grid oscillator as the radiating element because this would allow us to have directivity in both the E-plane and the H-plane, although we can only scan in the E-plane.

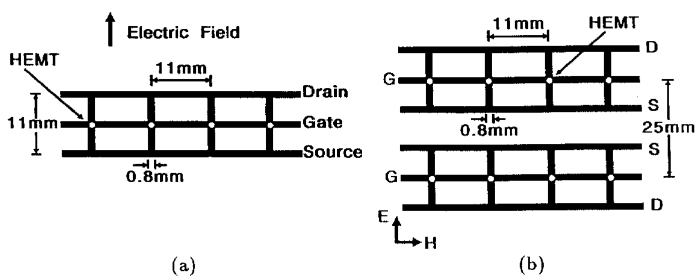

Figure 1. (a) The line-grid oscillator radiating element for 11 GHz. (b) The 2-element 1×4 HEMT grid oscillator beam-steering array.

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York's Beam-Steering Theory

York's theory is based on the van der Pol oscillator equation [4] and the Adler injection-locking theory [5]. York accounts for the interaction between adjacent elements of a system of coupled oscillators by a complex coefficient with magnitude ε and phase ϕ. The oscillator phases satisfy the following equations

$$\frac{d\theta_i}{dt} = \omega_i - \frac{\varepsilon\omega_i}{2Q}\left[\sin(\phi + \theta_i - \theta_{i-1}) + \sin(\phi + \theta_i - \theta_{i+1})\right] \tag{1}$$

where θ_i is the phase of oscillator i, ω_i is the free-running frequency, Q is the Q-factor of the oscillator embedding circuit. When the oscillators synchronize to a common frequency ω, we can write

$$\frac{d\theta_i}{dt} = \omega \tag{2}$$

For beam steering, a constant phase progression $\Delta\theta = \theta_i - \theta_{i+1}$ is required along the array. When the coupling phase ϕ is zero, a constant phase difference $\Delta\theta$ between adjacent elements can be achieved if

$$\omega_i = \begin{cases} \omega\left[1 - \frac{\varepsilon}{2Q}\sin\Delta\theta\right]^{-1} & \text{if } i = 1 \\ \omega & \text{if } 1 < i < N \\ \omega\left[1 + \frac{\varepsilon}{2Q}\sin\Delta\theta\right]^{-1} & \text{if } i = N \end{cases} \tag{3}$$

From equation (3) we get

$$\Delta\theta = \sin^{-1}\left[\frac{Q}{\varepsilon}\left(\frac{\omega_1 - \omega_N}{\omega}\right)\right] \tag{4}$$

This equation has two solutions, but York showed that when the coupling phase ϕ is zero, only the solution between -90° and $+90^\circ$ is stable. The relation between the phase difference and the beam steering angle is

$$\Delta\theta = kd\sin\Psi \tag{5}$$

where Ψ is the scan angle measured from broadside, d is the element separation, k is the free-space propagation constant and $\Delta\theta$ is the phase difference.

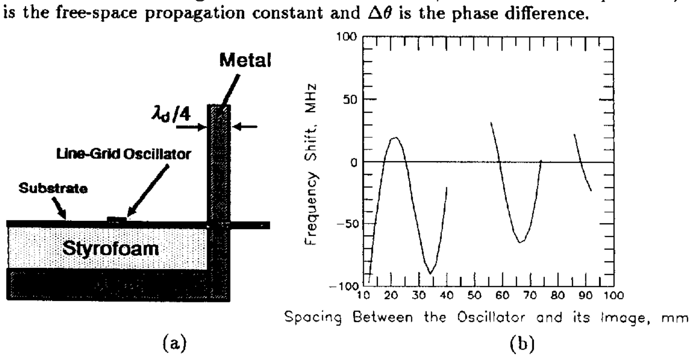


Figure 2. (a) Setup for the coupling coefficient measurement. (b) Measured frequency shift with free-running frequency of 10.87 GHz . There are gaps where the grid did not oscillate. In addition, the frequency shift is not symmetrical about the free-running frequency. We do not know the reason for this.

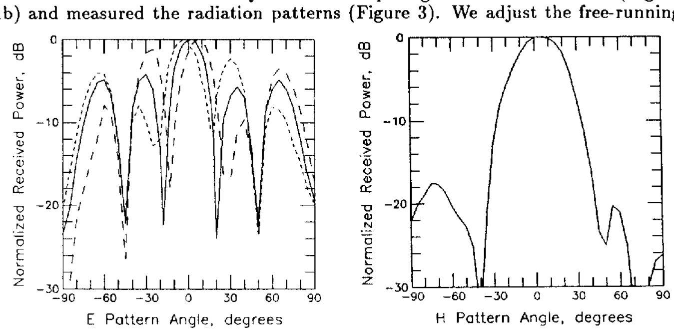
Measurements

The spacing between the radiating elements determines the coupling coefficient. The coupling coefficient was measured to determine the appropriate spacing between the adjacent elements such that the coupling phase angle $\phi = 0°$. We used Shillue and Stephan's approach for measuring the mutual impedance between the oscillators [6]. Figure 2a shows the measurement setup. A 1×4 HEMT line-grid oscillator is fabricated on a 15-mil Duroid substrate with dielectric constant 2.33. The horizontal metal plate is a part of the line-grid oscillator to provide the feedback necessary for oscillation. The oscillator is imaged by the vertical metal plate, thus simulating two coupled identical oscillators. There is a slot on the vertical metal plate so that the substrate can be moved back and forth. The vertical metal plate is $\lambda_d/4$ thick, where λ_d is the wavelength in the dielectric substrate at the free-running frequency of the oscillator. It transforms the high impedance at the right side of the metal plane to a low impedance at the left side of the metal plate. The oscillator and its image are effectively locked oscillators with the same phase. From Equation 1 and 2 we find

$$\frac{f - f_0}{f_0} = -\frac{\varepsilon(x)}{2Q}\sin[\phi(x)] \tag{6}$$

where f is the locked frequency and f_0 is the free-running frequency of the two oscillators. Varying the distance between the oscillator and its image causes a frequency shift. This frequency shift can be used to determine the distance. From Equation 6 we know that the distance corresponding to the zero-crossover with negative derivative is the desired spacing between the adjacent oscillators such that $\phi(x) = 0°$. From Figure 2b, the measured frequency shift shows that when the horizontal metal plate is 18 mm away from the chips, the desired spacing between adjacent elements is 25 mm.

We then built a 2-element array with 25 mm spacing between the elements (Figure 1b) and measured the radiation patterns (Figure 3). We adjust the free-running



(a) (b)

Figure 3. (a) Comparison of measured E-plane radiation patterns at three different scan angles: broadside when $\Delta f = 0$ (solid line), $+5°$ when $\Delta f = 40$ MHz (dashed line), and $-6.5°$ when $\Delta f = -40$ MHz (dotted line), where Δf is the difference of free-running frequencies of the two oscillators. Continuous beam scanning was possible from $-6.5°$ to $+5°$ by adjusting the element frequencies. (b) H-plane radiation pattern for the 2-element beam-steering array.

frequencies of the two line-grid oscillators by varying the drain and gate bias. When the free-running frequencies are identical, we get the broadside E-plane radiation pattern shown in Figure 3a. The radiation pattern can be steered by tuning the free-running frequencies of the elements. The patterns corresponding to the maximum beam-scanning angles achieved in both directions are also plotted in Figure 3a. For comparison, an H-plane pattern is shown in Figure 3b. The peak effective radiated power is about 200 mW.

Conclusions

A 2-element planar grid oscillator beam-steering array without using any phase shifters was presented. Continuous beam steering was possible from -6.5° to $+5^\circ$ by detuning the free-running frequencies of the radiating elements in the array. This is considerably less than the theoretical maximum beam scanning range determined by the spacing between elements. This is calculated from Equation 5 to be between $\pm 16^\circ$.

Substantial improvements would be necessary to make this array practical. The scan angle should be increased, presumably by decreasing the spacing between the elements. This would require a narrower grid element. In addition the sidelobes in the E-plane are poor, and would need to be improved. This could possibly be done by adding more line-grid oscillator elements.

Acknowledgments

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