# Electronic Beamsteering of Active Arrays With Phase-Locked Loops

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*Abstract*—**A new electronic beamsteering technique for active arrays is presented along with experimental results at 10 GHz. The technique uses a single balanced diode mixer to phase-lock neighboring oscillators in an active array. Each oscillator has its own antenna that radiates energy into free space, so the phase difference between oscillators determines the direction of the main radiating beam. An offset voltage added to the phase-locked loop controls the phase difference and beam direction. Experimental results demonstrate over 100° of adjustable phase difference between neighboring oscillators. Because of its simplicity, this technique has significant advantages over traditional beamsteering arrays.**

## I. INTRODUCTION

IN AN ACTIVE quasi-optical array an ensemble of antennas and active devices are integrated into a planar substrate. Each active device has its own antenna that radiates energy into free space. Most of the research on active arrays has concentrated on obtaining a fixed beam [1]–[3]. These active arrays are similar to antenna arrays in that the phase difference between antennas/devices determines the direction of the main radiated beam. Various techniques based on optics [4], [5] and electronics have demonstrated some control over the phase difference between oscillators. Other techniques [6], [7] use injection-locked oscillators to set a phase between neighboring oscillators.

A phase-locked loop maintains, or locks-on, a fixed phase difference. Phase-locked loops use a feedback system to force one oscillator to track the frequency of another oscillator. When the oscillator is tracking, a phase difference appears between the oscillators. Because this can be controlled by adding a DC offset voltage into the loop [8], phase-locked loops are a natural choice for beamsteering active oscillator arrays.

## II. PHASE-LOCKED LOOP BEAMSTEERING

The terminology and operation of phase-locked loops are well established [9]. Fig. 1 shows a diagram of a phase-locked loop for a 1×2 active oscillator array. Most of the power from each oscillator is delivered to the antennas, and a fraction of the power is used to drive the mixer. The oscillator on the right side is fixed at a reference frequency, and the voltage controlled oscillator on the left tracks this reference frequency. When these oscillators operate at the same frequency, the average voltage of the mixer's IF, $V_{IF}$, depends on the phase difference, $\phi$, between the oscillators:

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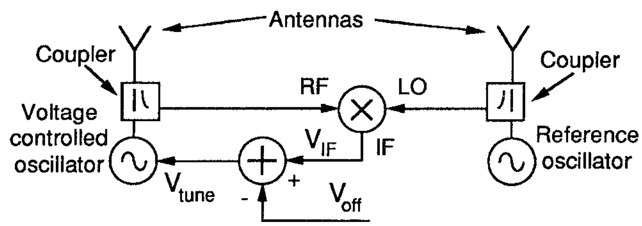


Fig. 1. Phase-locked loop applied to a 1×2 oscillator array. Each oscillator has its own antenna and couplers deliver power to the mixer. Varying $V_{\rm off}$ changes the phase difference between the oscillators, which in turn changes the direction of the radiating beam.

$$V_{IF} = K_\phi \sin\phi \tag{1}$$

where $K_\phi$ is a constant that depends on the mixer and the RF power.

Along with the offset voltage, $V_{\rm off}$, this phase difference can be used to express the tuning voltage, $V_{\rm tune}$, applied to the voltage controlled oscillator:

$$V_{\rm tune} = V_{IF} - V_{\rm off} = K_\phi \sin\phi - V_{\rm off} \tag{2}$$

Equation (2) can be rewritten to explicitly state the phase dependence:

$$\phi = \sin^{-1}\left(\frac{V_{\rm tune} + V_{\rm off}}{K_\phi}\right) \tag{3}$$

When the phase loop remains locked, the frequency of the voltage controlled oscillator matches the reference frequency, so the tuning voltage, $V_{\rm tune}$, is constant. By varying the offset voltage in (3) between its extremes, the phase difference changes:

$$-K_\phi - V_{\rm tune} \le V_{\rm off} \le +K_\phi - V_{\rm tune} \implies -90^\circ \le \phi \le +90^\circ \tag{4}$$

When the offset voltage, $V_{\rm off}$, is outside of the boundaries in (4), the mixer cannot compensate for the large offset voltage and maintain the proper tuning voltage. But within the limits, a phase-locked loop can generate a phase difference between antennas from $-90^\circ$ to $+90^\circ$.

## III. IMPLEMENTATION

The antennas and oscillators in Fig. 1 are already present in an active array of oscillators, so to add a phase-locked loop requires couplers, a mixer, and an adder. Design of the mixer

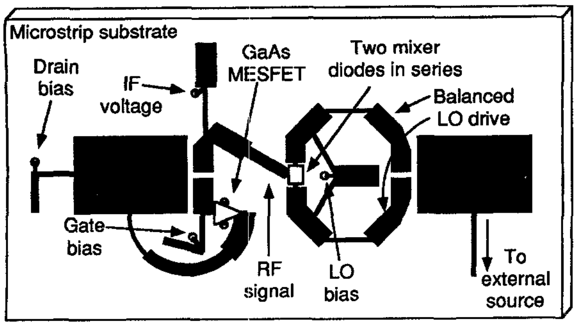


Fig. 2. Microstrip layout of X-band phase-locked loop. The MESFET and patch on the left form a voltage-controlled oscillator, and the patch on the right is driven by an external reference oscillator. Between the patches are circuits for the phase-locked loop.

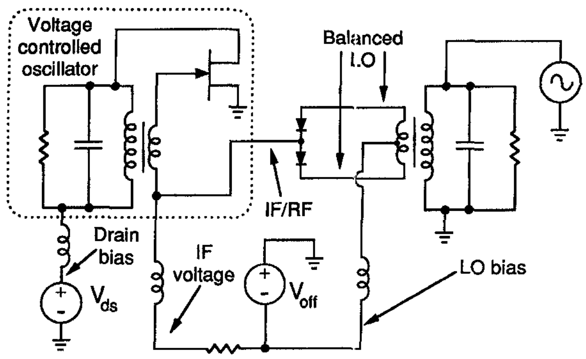


Fig. 3. Equivalent lumped element circuit of phase-locked loop. The offset voltage, $V_{\text{off}}$, adds to the IF voltage and is then applied to the gate bias to control the oscillator frequency.

trades-off simplicity with the need for good isolation [10]. The simplest is a single diode mixer, but it has poor LO-RF isolation. A single diode mixer has no isolation when the LO and RF are the same frequency as in this case. A high LO-RF isolation is critical to prevent the voltage controlled oscillator from injection locking to the reference oscillator [11] because injection locking may inhibit the phase-locked loop from operating properly [12]. A single balanced, two-diode mixer is more complicated, but it provides the necessary isolation. Note that even if the mixer completely isolates its RF and LO ports, the antennas exchange power between the oscillators and provide some RF-LO leakage.

To implement a phase-locked loop for an active array of oscillators, only two diodes and a resistor are necessary for each oscillator. Fig. 2 shows a 1×2 10 GHz active array fabricated on a microstrip substrate, with the phase-locked loop between the microstrip patches. The patch on the right (reference patch) is driven by an external synthesized source, and a GaAs MESFET configured as a voltage controlled oscillator drives the patch on the left [13]. A 90° coupler adjacent to the nonradiating edge of the left patch supplies the RF signal to the mixer diodes. Two 90° couplers near the reference patch provide out-of-phase balanced signals to drive the mixer's LO. Four bias circuits isolate the microwave and DC signals, two are for the voltage-controlled oscillator, and the other two are for the mixer. Jumper wires for all the low frequency signals and DC bias supplies pass under the substrate through via-holes. With this layout, the patch, voltage controlled oscillator, and phase-lock loop circuits can be duplicated to make a larger active array.

The operation of the phase-locked loop system is best explained with the equivalent lumped element schematic in Fig. 3. Two parallel RLC circuits represent the resonance and radiation resistance of the two microstrip patch antennas. The external reference oscillator feeds the parallel RLC on the right, and a MESFET in a feedback oscillator configuration drives the parallel RLC on the left. With this single balanced mixer, the IF and RF are the same node, but a microstrip circuit filter behaves as an RF choke to separate the low frequency IF voltage. The IF voltage that the mixer diodes generate is relative to the LO bias, so the offset voltage at the LO bias is effectively added to the IF voltage. A low-frequency resistor

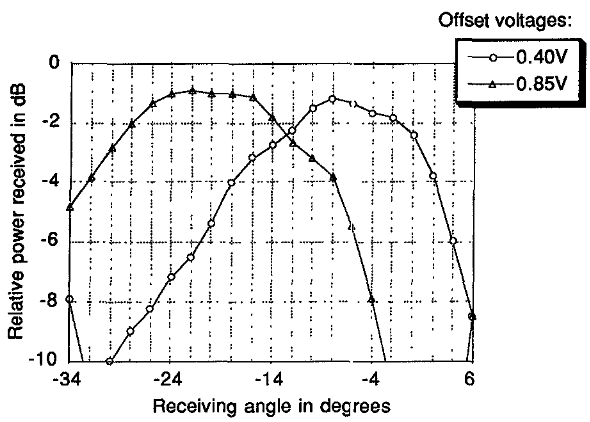


Fig. 4. Received power for main radiating beam versus the receiving angle. As the offset voltage changes, the radiating beam changes direction. By using basic array analysis, the adjustable phase difference between antennas is 122°.

behind the substrate is connected between the offset voltage and the IF voltage to provide a DC path that prevents the RF/IF voltage from floating. On the backside of the substrate, the IF voltage is shorted to the DC gate bias and it controls the oscillator frequency. In this implementation of the phase-locked loop, the mixer's IF voltage is directly attached to the tuning voltage and the offset voltage is added to the LO bias.

## IV. Results

The E-plane measurement of the radiated power for the 1×2 array is similar to that of a single patch oscillator [13]. The H-plane measurement is shown in Fig. 4, and the radiated power is plotted versus receiving angle for two different offset voltages. As the offset voltage changes from 0.85 V to 0.40 V, the angle of the maximum power received moves from −22° to −7°. When the offset voltage exceeds the 0.85 V to 0.40 V range, the mixer's voltage range cannot compensate to keep the oscillators locked. The separation between the patch antennas in Fig. 2 is 484°, referenced to a wavelength in free space at the operating frequency of 10.0 GHz. Using basic array analysis [14], the offset voltages change the phase by 122°. To increase the angle of beamsteering, the separation of the patch antennas can be reduced.

## V. Conclusions

An active array with phase-locked loops is an attractive technique for steering the main radiated beam. With two diodes and a resistor, the adjustable phase difference between antennas was 122°. In addition, the phase-locked loop compensates for a nonuniform array of oscillators: if an oscillator's frequency is different from the design frequency, the phase-locked loop will automatically adjust the tuning voltage to match the desired frequency.

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