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Active Phase Array Using Injection-Locked Oscillators

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This paper presents the design and measurement results of an active phase array using injection-locked oscillators. The required phase relation for each array element is obtained by electronic tuning through injection-locked technique, and the beam-scanning capability is demonstrated.

1 Introduction

Injection-locked technique [1] provides an efficient approach to generate stable high frequency signal source and finds its application in phase array. It can be used to achieve synchronous operation of a number of antenna elements, and allow for the manipulation of the phase distribution without additional phase shifting circuit. Hence, in modern microwave and millimeter-wave radar, imaging, and communication systems, the injection-locked technique is very suitable to be implemented for intelligent scanning antenna design.

In a conventional phase array [2], as shown in Fig.1, coherence is maintained between array elements using a single source and a corporate feed network. Phase shifters are required at each element, and each is equipped with proper biasing and control wires. It is then a challenge to collectively integrate antennas, feed networks, phase shifters, and control signals into a small package. In this arrangement, components such as phase shifters may add considerable expense to the system. In addition, it is difficult to generate the required output power with a solid-state source at millimeter-wave frequencies.

In this paper, an active phase array with beam-scanning capability is designed using injection-locked oscillators. The necessary phase shifts are achieved via injection-locked technique.

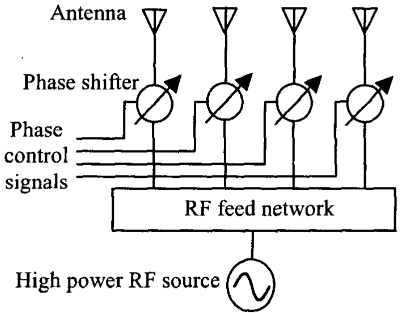


Fig. 1 Conventional phase array.

2 Basic Theory

2.1 Injection-locked oscillator

If a signal with its frequency close to the free-running frequency of an oscillator is injected, the oscillation condition will be changed. As the oscillator is synchronized or locked to this injecting signal, this is called an injection-locked oscillator as shown in Fig.2. The practical use of injection-locked oscillator for phase control is based on Kurokawa's theory [1]. The oscillator output signal phase is given by Adler's equation [3] as

$$\frac{d\phi}{dt} = \omega_0 - \omega_{inj} + \sqrt{\frac{P_i}{P_o}}\frac{\omega_0}{Q_{ext}}\sin(\psi - \phi) \qquad (1)$$

where ω_0 is the free-running frequency, Q_{ext} is the external Q of the resonant circuit, P_i is the injection power, P_o is the output power. As a steady-state solution can be found for the phase such that $d\phi/dt = 0$, this indicates that the oscillator is synchronized to the injection signal. Solving for the steady-state phase difference $\Delta\phi$ between the oscillator and the injection signal gives

$$\Delta\phi = \sin^{-1}(\frac{\omega_{inj} - \omega_0}{\Delta\omega_m}). \qquad (2)$$

(2) indicates that an injection-locked solution is possible only the injected signal frequency lies within the locking range of the oscillator $\omega_0 \pm \Delta\omega_m$. As the injection signal frequency is tuned over the locking range, the phase difference will vary with $-90° < \Delta\phi < 90°$. Therefore, one can acquire a phase-shifting operation by properly tuning the VCO (voltage controlled oscillator) control voltage as shown in Fig.2.

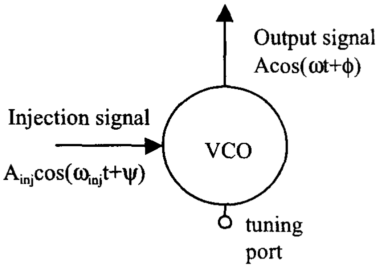


Fig. 2 An injection-locked oscillator.

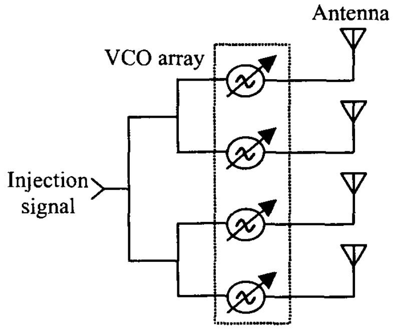


Fig.3 Phase array using injection-locked oscillators.

2.2 Phase array using injection-locked oscillators

Figure 3 shows a phase array using VCOs and injection-locked technique. Each array element is a self-contained VCO to deliver its energy to an antenna. The oscillators are slaved to the injection signal, which can be distributed using a corporate feed network. Due to the non-uniformity of the device, the oscillation frequency of each VCO may be different. However, as an injection signal is applied, all the VCOs are locked and have the same frequency. One can then change the phase of each oscillator by properly adjusting the oscillator tuning voltage, according to (2), to achieve the required phase array operation.

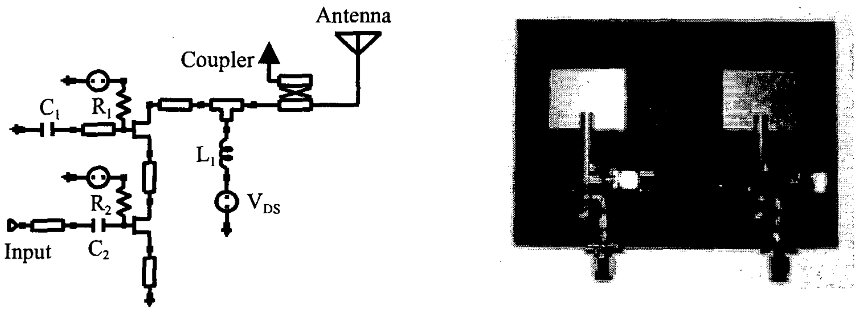
3 Active antenna element design

The antenna elements are designed using NE32684A transistors on a FR4 substrate with dielectric constant 4.3 and thickness 1.6 mm. The oscillator element and rectangular patch antenna are integrated on the same substrate in this design. The oscillator uses a cascode of two transistors, because the cascode configuration has higher power gain and higher negative resistance [4]. In addition, it operated with injecting-locked technique conveniently. The rectangular patch antenna is connected to the drain of the upper transistor, and the antenna input impedance is designed to satisfy the oscillation condition. Fig.4(a) shows the schematic diagram of the active antenna element, and Fig.4(b) is the photograph of a two-element active antenna. In Fig.4(a), C_1 and C_2 are dc blocking capacitors. L_1 is a RF choke. R_1 and R_2 are used to bias the circuit at $I_D = 10mA$ and $V_{DS} = 3V$. In the antenna feed line, a coupler is inserted to provide a phase monitor signal, which will be discussed in the next section.

4 Experimental results

Figure 5 shows the experimental arrangement of a two-element active phase array. The antenna elements are placed 0.716 λ_0 apart, where λ_0 is the free-space wavelength at 3.07 GHz. An isolator is connected after the injection signal source to reduce the mismatch effect which may affect the locking ability. Two 6 dB attenuators are connected after a Wilkinson power divider to reduce the mismatch of oscillator input port and add the isolation of Wilkinson power divider. Four couplers are used to extract signals from the oscillator output and injection source. For each element, the coupled injection signal and oscillator output signal are connected to a mixer (MiniCircuit ZEM-4300). By monitoring the mixer IF port using a digital oscilloscope, the phase of each oscillator output can be measured for the design of antenna array beam direction. In other words, the IF output is a dc voltage which can be read from oscilloscope, and this dc voltage is a function of the phase difference between the injection signal and oscillation signal. Using this dc voltage, the relative phase of these two active antennas can be designed, and the direction of main beam can be anticipated.

Fig. 6(a)-(c) shows the measured and simulated pattern with different relative phase difference between two elements. The measured scanning range is from –28.8° to 31.2°, which is close to the maximum ± 31.8° are in the simulation. The measured array radiation patterns are shown in close agreement with the simulated results. Some small discrepancies may be due to the unequal in oscillator amplitudes and the instability when the free-running frequency is tuned to the locking band edge. Fig. 7(a)-(d) shows the measured and simulated pattern of a four-element active phase array. Similarly, the simulation results are shown in good agreement with the measured results. The measured scanning range is from –12° to 10.8° and the theoretical scanning range is ± 15.6°.



(a) (b)

Fig. 4 (a) Schematic diagram and (b) photograph of active antenna array.

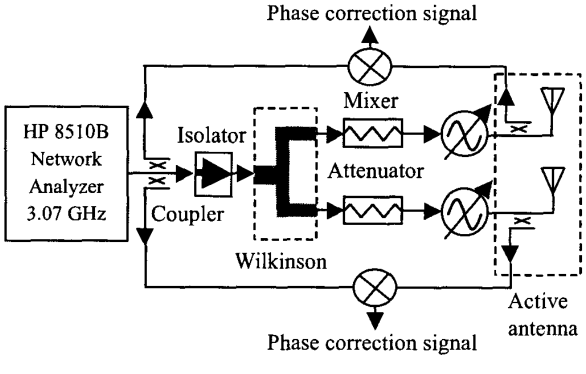
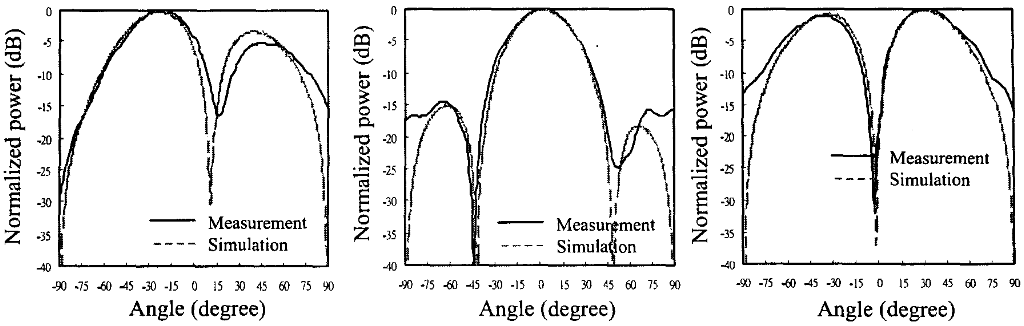
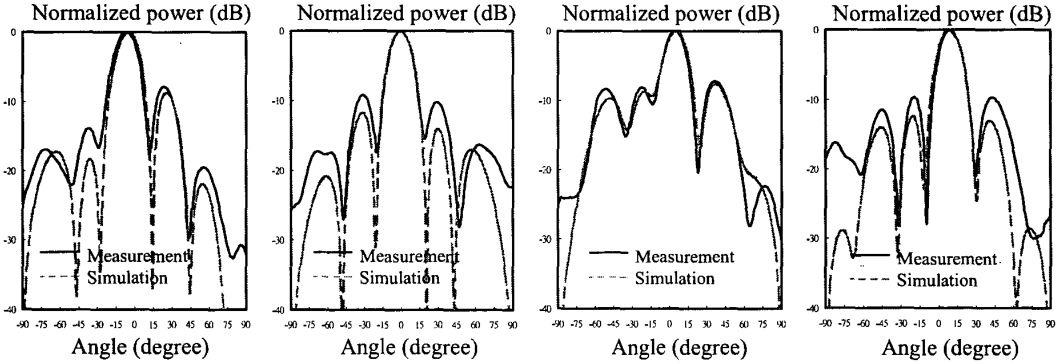


Fig. 5 Experimental arrangement of two-element active phase array.



(a) (b) (c)

Fig. 6 Radiation patterns of a two-element active phase array with their phase difference to be (a) –130.2°, (b) 9° and (c) 170.3°.



(a) (b) (c) (d)

Fig. 7 Radiation patterns of a four-element active phase array. The main beam direction is at (a) –7.2°, (b) –1.2°, (c) 3.6° and (d) 8.4°.

5 Conclusion

An active phase array is designed with its beam-scanning capability not using conventional phase shifting circuits. The frequency synchronization and phase control are achieved by injection-locked technique. The measured patterns are shown in good agreement with simulated results.

Acknowledgement

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