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A 1×4 Element Active Phase Array Using Injection-locking Oscillators

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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 achieved 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. Typically coherence is maintained between array elements using a single source distributed to every array elements through a corporate feed network. Separate phase shifters are required at each element, each of which requires biasing and multiple control wires. It is 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.

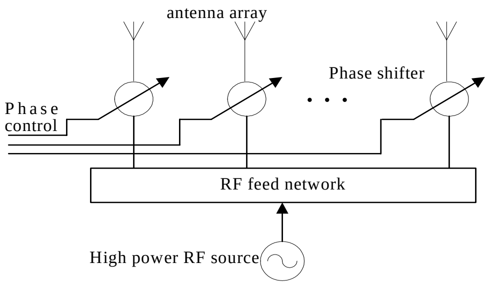

Figure 1. Conventional phase antenna array.

2. Injection-locking oscillator theory

2.1 Injection-locking oscillator

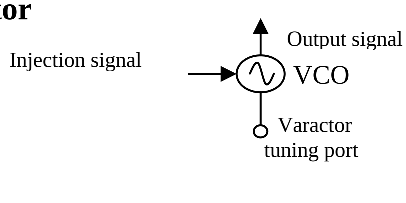

Figure 2. Injection locking oscillator.

Injection locking oscillator was firstly examined by Van der Pol, and later by Kaneyuki Kurokawa. The main principle is based on the fact that any oscillator will be synchronized to an

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externally applied injected signal, if the free-running frequency is close to the signal's frequency. The frequency of output signal is $w = w_{inj}$,The phase of output signal is

$$\phi' = \omega_0 + \left(\frac{\omega_0}{2Q} \frac{V_{inj}}{V_0} \right) \sin\left(\phi_{inj} - \phi\right) \quad (1)$$

(1) is also called Adler equation. where ϕ is the phase of output signal, ω_0 is the instantaneous free-running frequency. Q is the quality factor of the tuning network, V_{inj} is the amplitude of the injected signal, V_0 is the amplitude of the free-running signal. As a steady-state solution can be found for the phase such that ϕ' =0, this indicates that the oscillator is synchronized to the injection signal. Solving for the steady-state phase difference $\Delta\phi = \phi_{inj} - \phi$ between the oscillator and the injection signal gives

$$\Delta\phi = \sin^{-1}\left(\frac{w_{inj} - w_0}{\Delta w_m}\right) \quad (2)$$

(2) indicates that an injection-locked is possible only the injected signal frequency lies within the locking range of the oscillator $w_0 \pm \Delta w_m$. As the injected signal frequency is tuned over the locking range, the phase will vary with $-90^\circ < \Delta\phi < 90^\circ$. Therefore, one can acquire a phase-shifting operation by properly tuning the VCO control voltage as shown in Fig.2.

2.2 Phase array based on injection-locking oscillator

Fig.3 shows a phase array using VCOs and injection-locked technique. Each array element is a self-contain 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 devices the oscillation frequency of each VCO may be different. However, according to the theory of injection-locking oscillator, all the VCOs are locked and have the same frequency. We can change the phase of each oscillator by properly adjusting the oscillator tuning voltage, according to (2), to achieve required phase array operation.

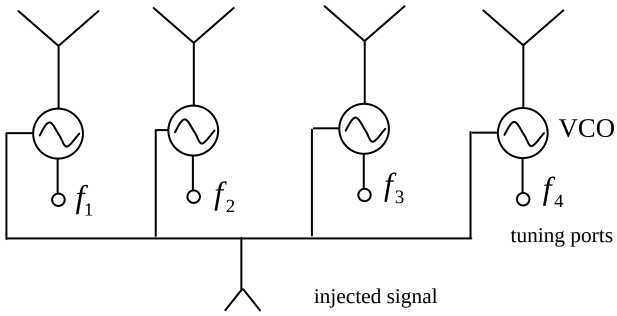


Figure 3. Phase array based on 1×4 element injection-locking oscillators.

3. Active antenna element design

The antenna elements are designed using PM2503 which is an integrated oscillator and its operating frequency is 2-3GHz, Fig.4 shows the schematic diagram of the oscillator unit. Fig.5 is the photograph of a 1×4 element active antenna array. In Fig.4, the output of VCO is connected with microstrip line whose characteristic impedance is 50Ω .The material of PCB is 4350i which is made by Rogers company. The frequency tuning can be completed through L1. D1 is a varactor. C1,C2,C3,C4 are the capacitors which are used to remove the coupling.

Table 1: COMPONENT LISTS

Reference	Description	Specifications	Value
C1	Capacitor	Commercial grade,0603	33pF
C2, C4	Capacitor	Commercial grade,0603	1000pF
C3	Capacitor	Commercial grade,0603	0.1μF
D1	Varactor	Alpha SMV1400-08	4pF
L1	Inductor	Toko LL1608-2N7S	2.7nH
R1	Resistor	Commercial grade,0603	1KΩ

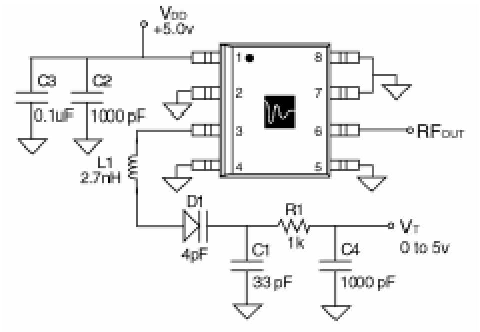


Figure 4. Schematic diagram of the oscillator element.

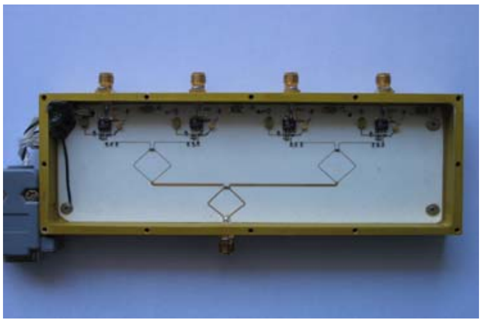


Figure 5. Photograph of 1×4 element injection-locking oscillators.

4. Experiment result

The theoretical predictions were tested using a 1×4 element injection-locking oscillators. The array used 0.762mm thick Rogers Ro4350B as substrate with ξ_r =3.48. The width and the length of each patch antenna were is 15.5mm and 20mm, respectively. The operating frequency is at 5GHz.

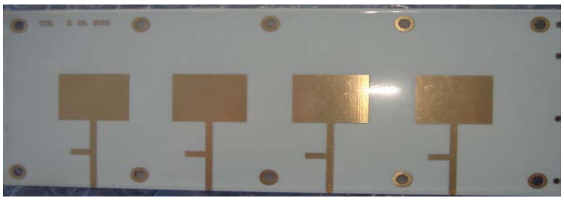


Figure 6. 1×4 element rectangular microstrip patch antenna array

Fig.7 shows the experiment arrangement of this system. Signal generator generates a 4.99GHz signal. for each element, the 4.99GHz signal and oscillator output signal are connected to a mixer (HMC218). 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. 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 two element can be designed, and the direction of main beam can be acquired.

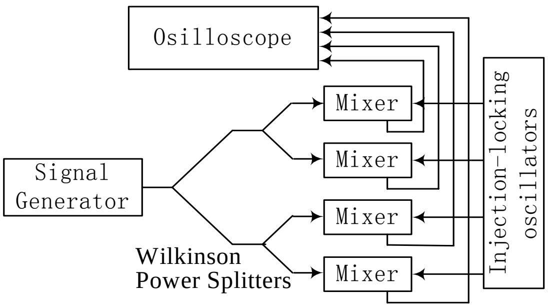
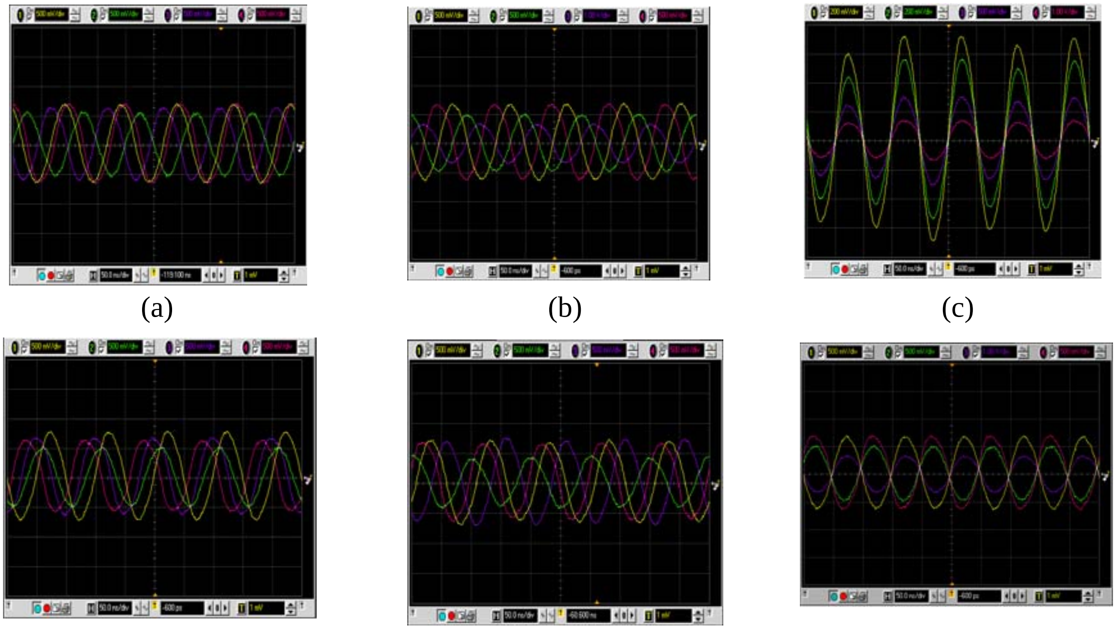


Figure 7. Experiment arrangement of a 1×4 element active phase array

Adjusting the tuning ports to change each VCO's free-running frequency, we can get the output waveform of each element. From the waveform, it is easily to watch the phase difference among the array. Fig.8(a)-(f) shows the typical measured phase difference among the 4 elements. (a) is -90° (b) is -45° (c) is 0° (d) is 45° (e) is 135° (f) is 180° .

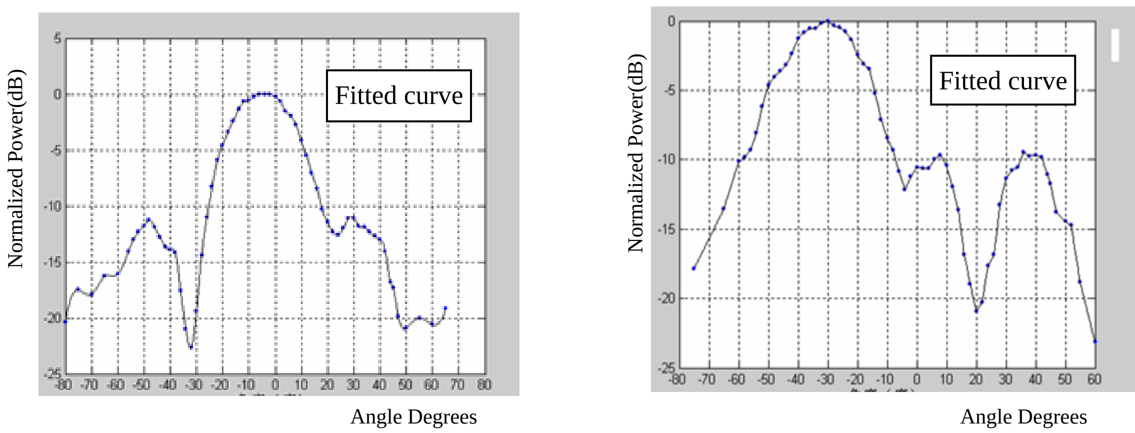
The measured scanning range is from -30.1° to 28.7° , Fig.9 shows the measured radiation pattern of the 1×4 element phase array. (a) is the main beam at 0° and (b) is the main beam at -30° .



(a) (b) (c)

(d) (e) (f)

Figure 8.waveform of phase difference of the 1×4 element phase array



(a) (b)

Figure 9. Radiation pattern of the 1×4 element phase array.

5. Conclusion

An active phase array is designed with its beam-scanning capability not using conventional phase shifter. The frequency synchronization and phase control are achieved by injection-locking technique. This kind of active phase array using injection-locking oscillators has many merits such as low cost high integration and high efficiency and It also can be applied to two-dimensional array.

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