Phase Noise Reduction in Scanning Oscillator Arrays

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Abstract -- A five element coupled voltage controlled oscillator array using injection locking technique to obtain low phase noise combined power output is described. Spectrum measurement shows that a great improvement on the spectrum purity of the combined output of the array has been achieved. Measured radiation patterns indicate that phase-shifterless beam scanning technique works properly when a single element is phase-locked to a low phase noise source.

1. Introduction

Quasi-optical oscillator arrays have the potential to generate greater power at high frequency than single solid state devices. However, these active arrays have exhibited very poor phase noise behavior so far. A typical free running 10GHz VCO, for example, has single sideband phase noise of -60dB/Hz at 1kHz offset frequency [2]. The phase noise of a transmitter or a receiver local oscillator greatly affects the system overall performance. In the case of CW Doppler radar system [1], if a signal/clutter ratio of 20dB is required, the ground clutter return is 90dB greater than the target return, and for a receiver bandwidth of 100Hz, the maximum permissible transmitter phase noise sideband density at f_m =1kHz must be better than -136dB/Hz.

Obviously we can not use complicated phase noise reduction techniques to each individual element in a quasi-optical array. This paper presents a simple injection locking technique to purify the combined output spectrum of a coupled oscillator array. A key feature is that this noise reduction technique does not hinder the utilization of the new beam scanning technique in a coupled oscillator array [6].

2. Phase Noise Improvement by Injection Locking

If we neglect the random amplitude fluctuation, which is usually much less than the phase fluctuation, the output voltage of a oscillator and injected signal can be written as,

$$v_0(t) = A_0 + Cos(\omega_0 t + \varphi_0(t)) \qquad (1)$$

$$v_{inj}(t) = A_{inj} Cos(\omega_{inj} t + \varphi_{inj}(t)) \qquad (2)$$

Injection locked oscillators can be described by Adler's equation [4]

$$\frac{d\theta}{dt} = \omega_0 + \Delta\omega_m \sin(\theta_{inj} - \theta) \qquad (3)$$

where $\theta = \omega_0 t + \varphi_0(t)$ and $\theta_{inj} = \omega_{inj} t + \varphi_{inj}(t)$, and $\Delta\omega_m$ is the locking range. Using (1)-(3), it can be shown that the oscillator phase variation exactly follows the injected signal variation according to

$$\frac{d\varphi_0(t)}{dt} = (\omega_{inj} - \omega_0) + \frac{d\varphi_{inj}(t)}{dt} \qquad (4)$$

as long as the injected signal is within the locking range. Equation (4) indicates that the frequency instability of the oscillator depends on the frequency instability of the injected signal. So if a low noise signal is injected, the oscillator will assume the noise properties of the signal.

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In a large coupled oscillator array, it would be undesirable to inject a low noise signal into every array element. However, since the oscillators are coupled together, there is no need to do this; only a single oscillator in the array must be slaved to a low noise source. The question is then whether slaving the array to an external source in this way would compromise the phase relationships and beam-scanning capability of the array. Using the theoretical techniques presented in [3,6], it can be shown that the requirements for beam-scanning in the presence of an injected signal become

$$\omega_i = \begin{cases} \omega_{inj} + \Delta\omega_m sin(\Phi + \Delta\phi) & if\ i = 1 \\ \omega_{inj} + 2\Delta\omega_m sin\Phi cos\Delta\phi & if\ 1 < i < N \\ \omega_{inj} + \Delta\omega_m sin(\Phi - \Delta\phi) & if\ i = N \end{cases} \qquad (5)$$

where ω_i is the free-running frequency of oscillator i, Φ is the coupling angle, and $\Delta\phi$ is the desired phase shift for scanning. This is similar to our previous result for beam-scanning, except that now the free-running frequencies of the elements must match the injected signal for best performance. Computer simulations based on equation (5) and our five element array were consistent with our phase measurement by Tektronic CSA803 at each element output port of the array under signal injection.

3. Array Design

The array is comprised of five varactor tuned FET VCOs and works at 8.6GHz. The VCOs are coupled together by a 1λ length microstrip transmission line and two 75Ω chip resistors. Each oscillator delivers its output to a SMA connector in a 50Ω environment. The low phase noise signal is injected to the middle element of the array via a 75Ω chip resistor and a section of microstrip transmission line. Figure 1 is a diagram of the five element array. Figure 2 gives the details of the element and the injection circuit. All elements are identical except that the middle element has an additional input path for an injected signal. In the injection path, L_3 is the equivalent inductor of the transmission line. R_1 is a 75Ω resistor which functions the isolation between the oscillator and injection path in order for the oscillator to work properly. The VCO is common gate configuration which is advantageous for wide bandwidth tuning. L_1 and L_2 are formed by a section of microstrip transmission line. C_1 is the DC block chip capacitor. Each element has approximately 1 GHz tuning range at the center frequency 8.5 - 8.8GHz and around 10dBm power output.

4. Measurement

We have carried out two kinds of measurement on the array: 1) spectrum measurement to demonstrate the phase noise improvement by injection lock technique, and 2) radiation pattern measurement to prove that phase shifterless beam scanning technique is still valid under the external signal injection. The first step was to adjust the varactor bias for frequency uniformity. When the oscillators are synchronization, the output spectrum is measured with HP8563A Spectrum Analyzer. An HP8350B Sweep Oscillator was used to provide injection signal. The injection signal needed to lock the entire array was as small as 0dBm. Figure 3 and figure 4 respectively give the results with and without the low phase noise signal injection, showing obvious improvement.

In order to observe beam scanning function of the coupled oscillator array, we connected a 5 element half wavelength spaced patch antenna array to the coupled oscillator array. This enable us to obtain the radiation patterns. Three patterns were measured corresponding to different end-elements frequencies.

Pattern1: equl frequencies,

$$f_1 = f_2 = f_3 = f_4 = f_5 = f_s$$

Pattern 2:

$$f_1 = f_s - 70MHz \qquad f_5 = f_s + 70MHz$$

$$f_2 = f_3 = f_4$$

Pattern 3:

$$f_1 = f_s + 20MHz \qquad f_5 = f_s - 20MHz$$

$$f_2 = f_3 = f_4$$

We printed the three patterns together and provided it in figure 5. It shows that approximate 26 degree beam scanning angle has been realized which is close to the theoretical scan range predicted by the theory for these frequency detunings and antenna spacing.

5. Conclusions

A five element array was described. With the array it was demonstrated that injection locking technique is a effective way to improve the phase noise behavior of a quasi-optical power combining array. Under the signal injection phase shifterless beam scanning technique can also be exploited in a coupled oscillator array.

6. Acknowledgments

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7. References

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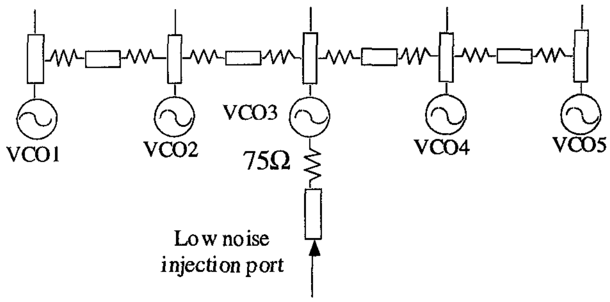

Fig. 1 Diagram of five element array showing injection port

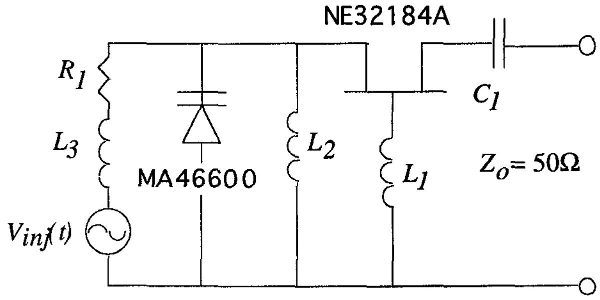

Fig. 2 a diagram of the middle element of the array

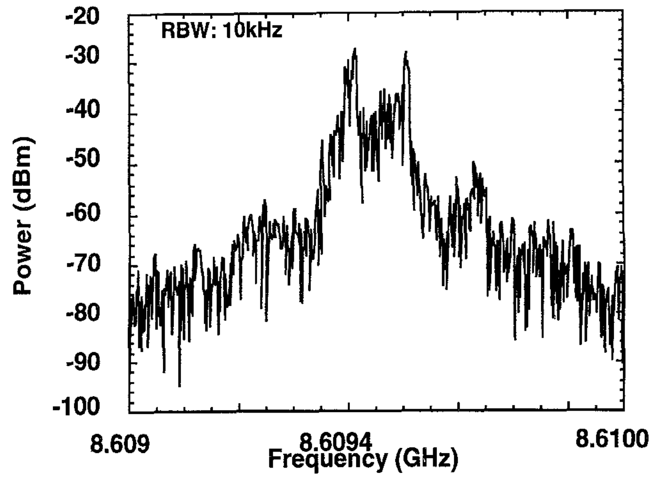

Fig.3 output spectrum of the array without injected low phase noise signal

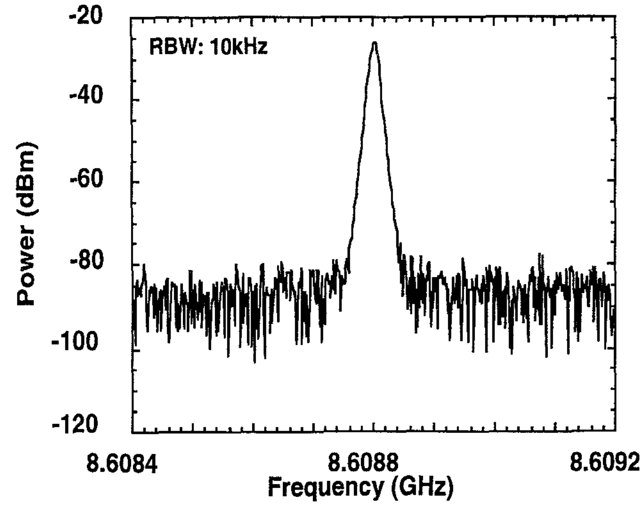

Fig.4 output spectrum of the array when low phase noise signal is injected

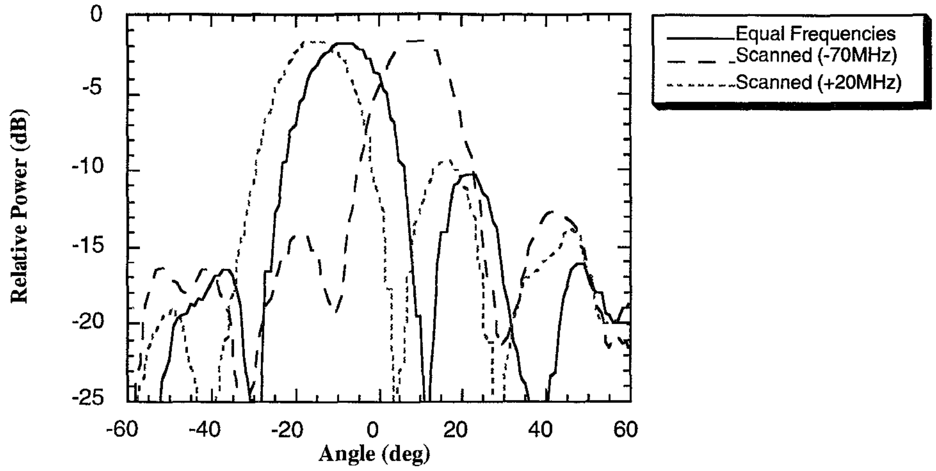

Fig. 5 Beam scanning was realized by adjusting the end-elements free running frequencies