A 1 WATT X-BAND POWER COMBINING ARRAY USING COUPLED VCOs

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Abstract — The design and construction of a ten element power-combining array using coupled voltage controlled oscillators (VCOs) is described. A varactor-tuned patch and broadband coupling network are used in the array. Preliminary measurements indicate an effective radiated power (ERP) of 10.5 W at 8.4 GHz, with beam-scanning capability via voltage tuning of the end elements.

1. Introduction

Quasi-optical coupled oscillator arrays have emerged as a technology which can offer greater power at higher frequencies than previously available from single solid state devices [1-5]. Quasi-optical arrays achieve power combination through the coherent addition of radiated power from many nearly identical sources. In coupled oscillator arrays, mutual coherence is achieved through the bilateral injection locking of each source to its nearest neighbors. The coupled oscillator dynamics which are used to model these quasi-optical arrays indicate a need for precise control over the oscillation frequency of the elements. This paper discusses the design and construction of an X-Band VCO suitable for an oscillator array. The design goals were tunability over the locking range of the array, as well as a simple and compact design which could be easily fabricated monolithically.

2. VCO Design

A feedback oscillator topology was used in the design of these VCOs. A compact and simple design was required because a half wavelength spacing between elements was desired. An illustration of the VCO array constructed is shown in Figure 1. A photograph of the constructed array is shown in Figure 5. The VCOs in this quasi-optical array used a medium-power NEC900276 GaAs MESFET. This MESFET has a saturated power of about 27 dBm at X-Band. A resonant-matched amplifier centered about the design frequency of 8.45 GHz was first designed. This common source amplifier employed single stub matching networks at the drain and source of the MESFET. A quarter wavelength transformer followed each single stub matching network to transform the input and output impedances to the desired 50 Ω. The transistor was biased at 8 Volts with a drain current of 180 mA. The measured gain of this amplifier was about 10 dB with a 3 dB bandwidth of approximately 750 MHz.

A half wavelength long rectangular microstrip patch antenna served as both a load and frequency selecting network for the feedback oscillator. A shunted varactor diode was embedded in the microstrip patch antenna to tune the resonant frequency of the patch. The position of the varactor diode determined the tuning range, as well as the resonant frequency of the VCO. The VCOs used a M/A 46604 varactor diode, which features a maximum to minimum capacitance ratio of about 3.

The layout of the VCO resembles the design proposed by [11]. RF energy is fed back to the input of the transistor amplifier by coupling energy from the non-radiating edge of the patch antenna, as shown in figure 1. From [9], the amount of feedback energy which is required to obtain maximum oscillator power was found to be:

$$\frac{P_{in}}{P_{out}} = \frac{\ln G_o}{G_o - 1}$$

where P_{in}, P_{out}, and G_o are the input power, output power, and small signal gain of the transistor amplifier. The measured gain of 10 dB indicated that 25% of the output power had to be fed back to obtain maximum oscillator power. This is accomplished by a quarter-wave coupled line section, with a gap spacing of 0.25 mm. A one wavelength long line then connected the coupled line to the input of the amplifier for phase matching. The output of the amplifier was gap coupled to the patch antenna. This gap coupling served to isolate the DC biases of the varactor diode and the drain of the MESFET, while permitting RF transmission.

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An effective radiated power of 700 mW was obtained from a prototype VCO constructed. The observed tuning range from these VCOs was 150 MHz, centered at 8.45 GHz. A constant output power was observed over the tuning range. The second harmonic power was measured to be -10 dBc.

3. Array and Coupling Network Design

The array was comprised of ten VCOs, each of which was coupled to its two nearest neighbors. For broadside beam-forming, relatively strong nearest neighbor coupling with a coupling phase of zero degrees was desired. This coupling was achieved through a resistively loaded, one wavelength long transmission line [10]; the coupling phase is determined by the length of the lines, while the coupling strength is inversely proportional to the coupling resistors used.

Individual varactor bias is supplied through the coupling circuit. Each bias line was placed one quarter wavelength away from the edge of the VCO's patch antenna, where the impedance on the line is quite low. DC blocking capacitors were placed in series at the center of each resistively loaded transmission line to isolate the varactor biases from one another. Since the varactor does not draw any significant current under reverse bias, the coupling resistor has little effect on the varactor bias.

Drain bias was applied to all of the VCOs through a common transmission line. It was not necessary to apply gate bias to these VCO, due to a self biasing effect.

4. Measurements

Figure 2 illustrates a typical spectrum obtained from a single VCO on an HP 8563 spectrum analyzer. Using the noise measurement capability of this analyzer, the phase noise of a single VCO was measured to be approximately -90 dB/Hz @ 100 kHz from the carrier. The effective radiated power (ERP) of the array was measured to be 10.5 W at 8.43 GHz. To determine the actual radiated power, a knowledge of the array directivity is required. Using a simple model for the patch radiation pattern and elementary antenna theory, the gain of the array was estimated to be about 10 dB, giving an total radiated power of over 1 W. Figure 3 illustrates a typical broadside pattern which was obtained when the free-running frequencies of the VCOs in the array are set identically to 8.45 GHz. The asymmetry of the side lobe levels of the pattern indicate a non-uniformity in the amplitude levels of the elements in the array, however the main lobe at broadside clearly indicates that the elements are in phase.

Following the coupled oscillator theory described in [6], beam scanning of the radiation pattern can be achieved by adjusting the free-running frequencies of the VCOs on the ends of the array. Figure 4 illustrates that it was possible to scan the array over from $-10°$ to $20°$ off broadside. This scanning indicates that it was possible to obtain $61°$ of phase shift between each element in the array, which corresponds to a phase difference of $554°$ between the first and last elements in the array. This is an important point: since the total phase shift is greater than $360°$, this clearly indicates that the beam-scanning technique is not limited by the number of array elements.

5. Conclusions

A ten-element linear combining array was built using a novel patch-antenna based VCO design and broadband coupling network. The design has evolved from work on coupled oscillator dynamics, and has demonstrated that phase control between the elements is achieved through control of the free-running frequencies of the end elements of the array. Over $500°$ of phase shift was obtained over the array, which clearly indicates that the beam-scanning technique is not limited by the number of array element. Over 1 Watt of power was produced using medium power FETs; higher power can be achieved by adding more elements and using a larger FET. In the near future, work on a monolithic implementation is planned, which is expected to produce better results by virtue of improved uniformity as compared with the hybrid construction used in this work.

6. Acknowledgments

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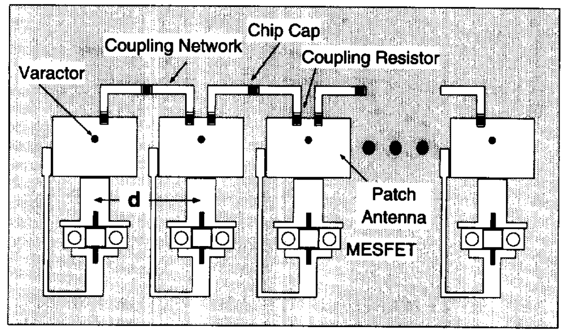

Figure 1 - Illustration of the coupled VCO array. Coupling between oscillators is accomplished with a resistively loaded transmission line. The chip capacitor is included as a DC block. Not shown are the bias lines to the varactors, which are connected via the coupling network.

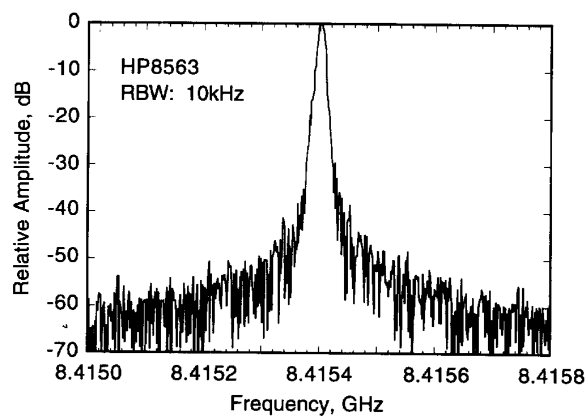

Figure 2 - Measured spectrum of a single VCO element. A rough phase noise measurement gives -90 dB/Hz @ 100 kHz from the carrier.

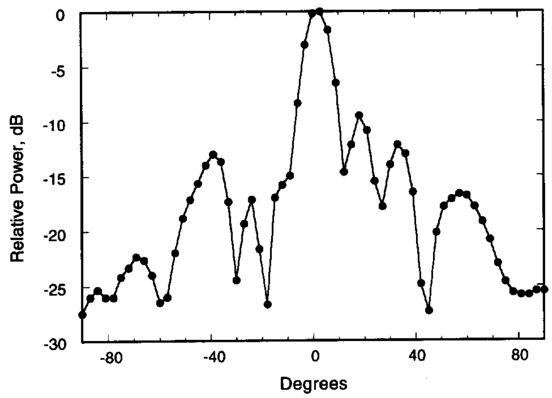

Figure 3 - Measured broadside radiation pattern obtained with all elements operating at nearly the same free-running frequency.

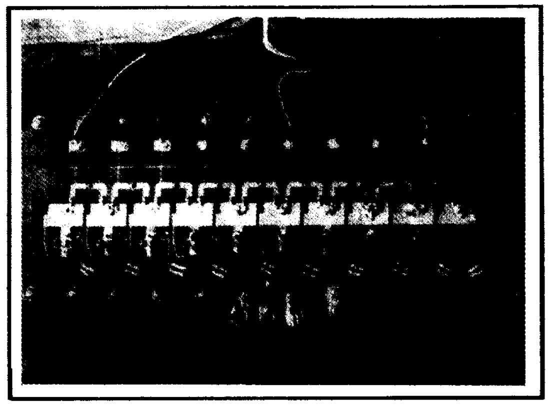

Figure 5 - Photograph of 10 X 1 linear array which produced 1 W @ 8.4 GHz.

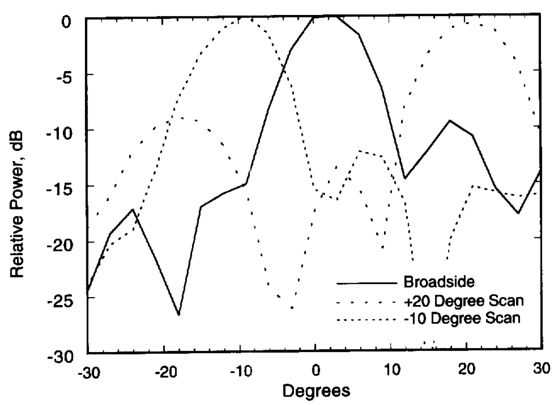

Figure 4 - Three pattern measurements at different scan angles, indicating continuous scanning from -10° to +20°.