A Varactor-Tuned Patch Oscillator for Active Arrays

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***Abstract*—The design and construction of a relatively wideband quasi-optical voltage-controlled oscillator (VCO) is described. This VCO uses a varactor-tuned microstrip patch antenna and may be used as an element in quasi-optical power combining oscillator arrays. Measurements of this VCO indicate that over 1.3 GHz of tuning was achieved, with less than ±1.5 dB of amplitude variation over that range.**

I. Introduction

QUASI-OPTICAL oscillator arrays have been demonstrated to coherently combine power from an ensemble of semiconductor devices [1]–[5]. The design of the individual oscillators in the array presents unique design difficulties, primarily due to the resonant nature of the load (the antenna). If external frequency selective components are used, such as dielectric resonators or resonant matching sections, it becomes necessary to accurately tune the circuit elements to the antennae resonance. In addition, the antenna can exhibit several resonances, as with a patch antenna, and thus mode-hopping can be a problem. A nice solution to the problem has been reported [6], [7], using a feedback oscillator topology where the patch antenna, placed in the feedback path of an amplifier circuit, acts as the sole frequency-selective structure. The amplifier bandwidth is selected to eliminate the possibility of multi-moding.

The feedback oscillator topology proposed in [7] is appealing because of its compact design. However, it is difficult to fabricate a well-matched set of such oscillators, due to small differences in devices, the unavoidably low Q-factor of the antennas, and processing nonuniformities. As a result, post-production frequency adjustments are required to insure mutual locking with the desired phase relationship [10]. Such tuning has previously been accomplished through bias tuning [3], [11], [12], but this approach has limited tuning range and results in an undesirable variation in output power. There are other good reasons for developing an active antenna with a wide tuning range: in newly developed beam scanning methods [11]–[13], voltage-controlled oscillators (VCO's) are used to control the phase distribution in the array and must be capable of tuning with minimal power variation over the collective locking range of the oscillators, which can be significant for strong inter-element coupling [10]. A wideband oscillator is also desirable for frequency modulation of the array. Ordinarily, the narrow bandwidth of the patch antenna would severely limit the maximum tuning range of the oscillator. Wideband quasi-optical VCO's have been developed using a variety of designs [8], [9]. In this paper, we report a modification of the active patch oscillator in [7], using a varactor-tuned patch antenna [14], [15] to control the oscillation frequency.

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II. VCO Design

The feedback oscillator configuration described in [7] requires an amplifier circuit and a resonant feedback/load circuit based on the patch antenna. For frequency tuning, the feedback resonator (patch) is loaded with a varactor diode. The amplifier must then be designed for a wide passband. It is also critical for the array operation that the output power variation be minimized over the tuning range.

A broadband amplifier was designed using the NE32184A low-noise GaAs FET. The amplifier design procedure followed the broadband matching approach described in [16], using a series R-L-C circuit model for the device input impedance. The S-parameters provided by the manufacturer were used to compute the input impedances, giving a 25-Ω resistance in series with a 0.5-nH inductance, and a 0.5-pF capacitance. The E-Syn program [17] was used to design a lumped element 6–10 GHz bandpass filter structure that matched the input impedance of the FET to 50 Ω. Short-circuited stubs and high impedance lengths of transmission line were used to implement the lumped inductances required by this design. The output impedance of the device was similarly determined and matched to 50 Ω using a section of high impedance transmission line.

The microstrip implementation of this circuit is shown in Fig. 1, following closely the layout described in [7]. The primary goal of the feedback circuit design was to provide flat tuning in the range of 7 to 9 GHz. The patch was modelled as a long section of low impedance transmission line loaded with shunt radiation resistances and fringing capacitances at its radiating edges. The radiation resistance of these patch antennas is a function of the patch width and the relative dielectric constant of the substrate, and it was determined from a simple model [18]. For easier matching to the amplifier, a substrate dielectric constant of $\epsilon_r = 2.2$ (Rogers Duroid 5880) and a rather large width of 15 mm was chosen. This results in a single-edge radiation resistance of 400 Ω. Both the length of the patch and the position of the diode within the patch were adjusted so that the tuning range of the resonant frequency

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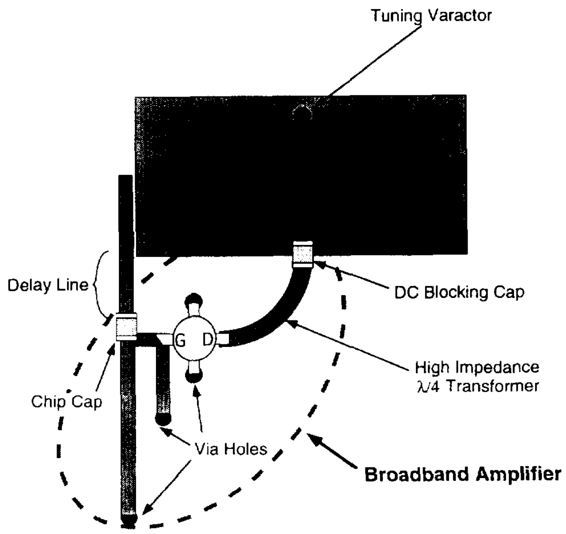

Fig. 1. Illustration of the varactor-tuned patch VCO. (DC circuitry not shown.) The broadband amplifier section of this feedback oscillator circuit is circled. Feedback is provided through the coupled line section, located on one nonradiating edge of the patch antenna.

of the patch was maximized, with a minimal variation in amplitude. The VCO's of this design used the M/A 46605-120 varactor diode, which features a maximum-to-minimum capacitance ratio of about 3.4 (1.7 to 0.5 pF).

One radiating edge of the patch antenna was fed from the output of the amplifier. A DC blocking capacitor was placed in between the amplifier's output and the patch antenna to isolate the drain bias of the device from the varactor bias. A portion of the energy was fed back to the input of the transistor amplifier using a coupled line section, which was placed parallel to the nonradiating edge of the patch antenna. The coupling gap was adjusted to obtain maximum and uniform broadband coupling. In future implementations of this feedback circuit, the coupling gap should be adjusted to provide optimum feedback power as prescribed by [20]. The transmission from the feed point of the patch to the output of the coupled line section at various varactor biases was simulated on Libra [17], using the asymmetric coupled line model. The simulation indicated that under zero varactor bias the patch resonance was 6.8 GHz, while under the maximum reverse varactor bias of 30 V, the patch resonance was shifted to 9.4 GHz. A measurement of this feedback circuit using the HP-8720 Network Analyzer verified that the feedback amplitude across this band was relatively flat. Fig. 2 illustrates a plot of the measured transmission through this tunable feedback circuit. The observed differences between the simulation and the measured transmission are due to the large patch width and the physical size of the varactor diode used. The ratio of the width of the patch to the height of the substrate exceeded the maximum aspect ratio as defined by the asymmetric coupled line model of Libra. It was also observed that the position of the varactor within the patch determined both the tuning range of the circuit and the in band ripple. The appreciable size of the varactor diode (55

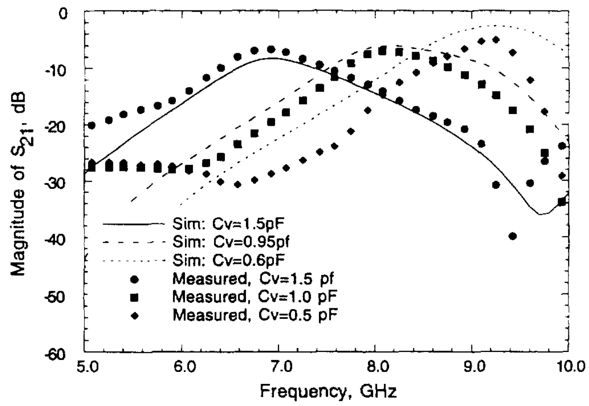

Fig. 2. Measurements and simulations of various varactor biases for varactor-loaded, coupled-line feedback circuit.

mil diameter) may have altered the tuning curves of the circuit from its simulated characteristics.

Prior to construction of the VCO, a linear simulation of the open loop gain of the oscillator was performed using Libra. This simulation indicated that the possibility of multi-moding was present due to zero-crossings of the round trip phase in the region where the loop gain was greater than one. A short length of high impedance line was then placed between the coupled-line section and the the input of the amplifier to shift the undesired zero crossings away from the gain region. Oscillation will occur at the frequencies where the loop gain is greater than one and the loop phase is zero degrees. The linear simulation indicated that when the varactor capacitance is varied from 1.5 to 0.5 pF, the VCO should be tunable from 7.0 to 8.4 GHz.

III. Measurements

Measured H-Plane co-polarization and cross-polarization patterns at a representative frequency in the tuning band are shown in Fig. 3. The received cross-polarization is approximately 10 dB below the maximum of the co-polarized radiation. The cross-polarization is primarily due to currents that run parallel to the radiating edge of the patch antenna. These currents are induced by the coupled line section that was placed off the nonradiating edges of the patch. It has been noted [7] that the cross-polarization of such feedback coupled patch antennas can be dramatically reduced by the addition of another coupled line section located on the other nonradiating edge of the patch antenna.

The VCO was observed to tune from 6.8 to 8.1 GHz with approximately 3 dB of amplitude variation, as illustrated in Fig. 4. This tuning range is very close to the range predicted by computer simulations. The tuning range of the VCO was decreased significantly from the tuning range of the feedback element (7.0 to 9.0 GHz) because of the high impedance transmission line section that was used to prevent multi-moding. The amplitude variations across the band are attributable to variations in the broadband amplifier. Varying the drain bias was observed to produce small changes in the oscillation frequency. The tuning range achieved by adjusting the drain

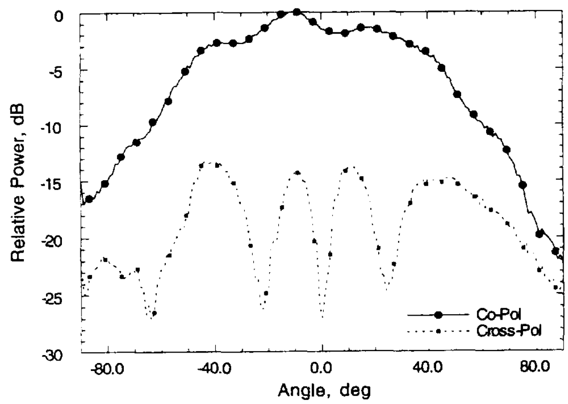

Fig. 3. The H-Plane co-polarization and cross-polarization patterns of a single active patch antenna.

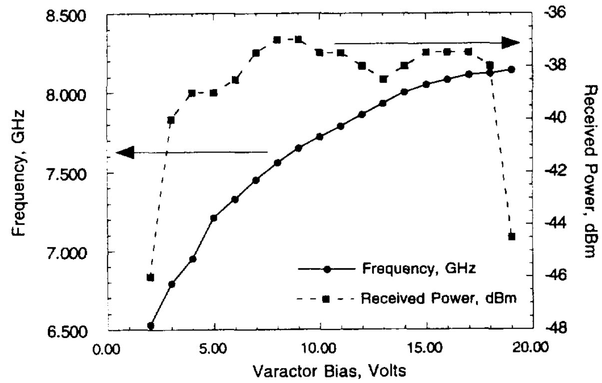

Fig. 4. The tuning curve of the VCO. The VCO was observed to tune from 6.8 to 8.1 GHz.

bias was negligibly small compared to the tuning obtained from varactor biasing. The measured DC-to-RF conversion efficiency of the VCO was 11%. The effective radiated power, (ERP) of this VCO was measured to be 29.5 mW, from which we estimate a total radiated power of approximately 9 mW, based on a typical patch antenna gain of 5 dB; this power is consistent with other oscillators built using the same device. A phase noise of −63 dB/Hz at 100 kHz was measured using an HP8563 spectrum analyzer. This is 10–15 dB worse than other narrowband oscillators we have made with the same device, and therefore is most likely a result of the larger circuit bandwidth.

IV. Conclusions

A tuning bandwidth of 1.3 GHz was obtained through the use of both a wideband amplifier and a wideband tuning element in a feedback VCO. Potential multi-moding prevented the VCO from achieving the full tuning range afforded by the varactor diode. However, the bandwidth of this VCO greatly exceeds what could be obtained from a conventional VCO feeding a fixed-frequency microstrip patch antenna. This oscillator design will be instrumental in future power-combining work. A prototype 10-element array at X-band using this topology was recently constructed using medium power FET's, producing over 1 W of radiated power with a 45-degree scanning range [19].

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