A V-band Single-Chip MMIC Oscillator Array Using a 4-port Microstrip Patch Antenna

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Abstract — **In this paper, a V-band strongly-coupled single-chip MMIC oscillator array is presented. To reduce the MMIC chip size and increase the output power of the millimeter-wave source module, the output powers of the four oscillators are combined in a single chip using a four-port patch antenna. A parallel combination of the two pairs of the oscillators operating in a push-pull mode was implemented using a single four-port patch antenna. When measured in a closed over-sized waveguide, the circuit showed the output power of 3.8dBm at 60.626GHz. The measured radiation pattern of the active antennas array in free space shows broadside pattern with low cross-polarization level, verifying that the current profile on the antenna closely follows that of the ideal push-pull mode. The proposed active antenna approach is a promising candidate for a low-cost source module at mm-waves.**

I. Introduction

Millimeter-wave source is one of the most important elements of millimeter-wave communication systems. Considering the weight and reliability, the best way to realize a millimeter-wave source is to use solid-state oscillators. However, the output power available from a single oscillator decreases rapidly as the frequency increases. Therefore, to get high output power at millimeter-waves, efficient power combining is required. For this purpose, oscillator arrays with spatial power combining have been developed [1-9]. For large output power, massive spatial power combining is implemented using the coupled oscillator array consisting of multiple unit cells. Each unit cell is composed of a single oscillator integrated with an antenna. This kind of spatial power-combining array has shown watt-level output powers at X-band using FET oscillators [7]. However, due to the large overall size of the array, this approach cannot be easily implemented in monolithic circuits. As an alternative, a unit-cell power combining approach is proposed, where the output powers of multiple oscillators are combined using a single antenna at a unit-cell level [2]-[5]. Push-pull type of operation, where a pair of oscillators operating in out-of-phase modes are attached to the opposite edges of the patch antennas, is generally used for this purpose. The possibility of a four-way push-pull power-combining antenna has also been demonstrated at 6GHz using hybrid circuits [2]. In this work, we have developed a single-chip power-combining oscillator at V-band, where the output powers of the four individual oscillators are combined using a single patch antenna. To our knowledge, this corresponds to the first demonstration of a fully monolithic power-combining active antenna at this frequency range.

II. Design

To maximize the output power for a given chip area, we employed a 4-port antenna that has four input ports as shown in Fig. 1. The antenna is based on a push-pull patch antenna resonator [2]. The push-pull antenna has two input ports and each port is injected by the signals of the same amplitude and anti-phase. Since the patch antenna has a 180-degree of phase difference between the two opposite radiating edges, the anti-phase signals injected from the opposite edges of the antennas make the current profile equal to the case of single-port excitation. In this way, two-way power combining is achieved with minimum perturbation in the current profile.

A four-port antenna shown in Fig. 1 is a parallel combination of two push-pull antennas. In-phase signals are applied to ports 1 and 3, and out-of-phase signals are applied to ports 2 and 4. The current profile in the patch is thus equivalent to that of 2-port push-pull antenna, and efficient four-way power combining is expected.

The design of the multi-oscillator active antenna circuits presents a major challenge due to the difficulty of analysis. Harmonic balance simulation is typically used for frequency-domain oscillator analysis. However, when one tries to simulate the whole structure consisting of an

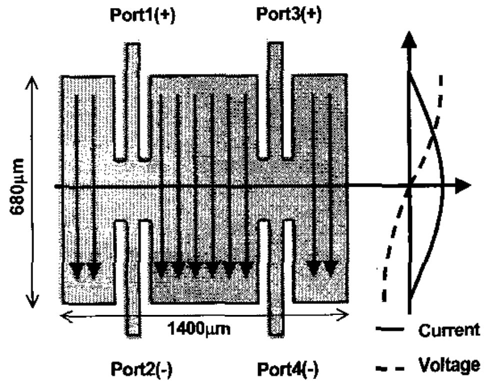
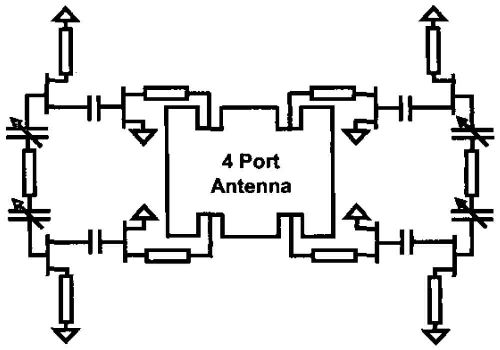
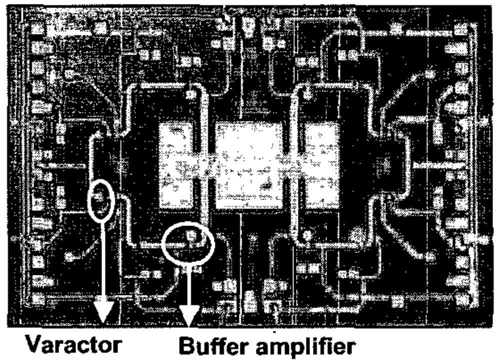


Fig. 1. Layout and current profile of designed 4-port microstrip patch antenna



(a)



(b)

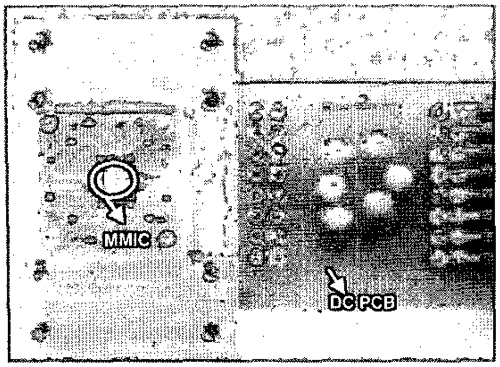
Fig. 2. (a) Schematic of designed circuit (b) Photograph of fabricated circuit (Dimension: 3.8mm x 2.5mm)

antenna and four oscillators simultaneously using the harmonic balance program, unacceptable results may occur due to excessive simulation time and oscillator stability issues. Therefore, we developed a simplified design procedure as follows. First, electromagnetic simulation is performed to find out the four-port S-parameters of the antennas. Then, the simulated 4-port S-parameter was reduced to equivalent 1-port S-parameters at each port of the antenna assuming that the signals applied to the antenna have the appropriate amplitude and phase as described earlier. In this way, the four-oscillator array design could be reduced to a simple single-oscillator design using one FET. As a final step, harmonic balance simulation of the whole circuit is performed to simulate the large-signal properties of the oscillator circuit.

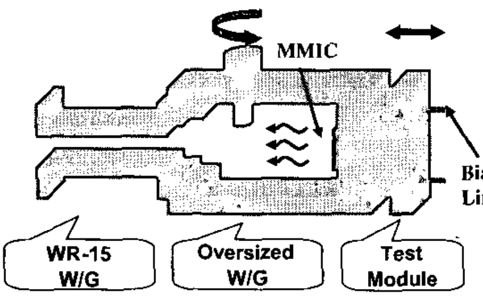
The circuit schematic and photograph of the four-oscillator active antenna chip are shown in Fig. 2. Each oscillator employs an FET with series source feedback for negative resistance, and varactor diode at the gate for frequency tuning. Buffer amplifier is also integrated between the oscillator and the antenna to minimize the pulling effect. The gates of the push-pull FET's are connected via a short-length transmission line, which forces the two oscillators to be in anti-phase. [6] FET's used in the oscillator design were PHEMT's with 0.15µm gate length and 80µm gate periphery. Using the 100µm-thick GaAs substrate(ε_r=12.9, tanδ=0.025), patch antenna simulation using 3-D EM simulator showed 61% radiation efficiency and 5.9dBi directivity. However, the actual efficiency of the patch antenna at 60 GHz can be lower than the simulated value since the simulation was based on the dielectric loss data of the substrate material as estimated from the low-frequency loss tangent. Harmonic balance simulation of the whole circuit confirmed that all the input signals to the antenna showed proper amplitude and phase characteristics for push-pull operation.

III. MEASUREMENT

The fabricated circuit, shown in Fig. 2 (b), was packaged in a 15x15mm^2 oversized square waveguide to measure the operating frequency and the total radiating power. The oversized waveguide guides the radiated wave to WR-15 standard waveguide via multi-section impedance transformer. The schematic of the test jig is shown in Fig. 3. The position of the packaged circuit was tuned to get the highest output power and tuning knobs were inserted for fine tuning. Spectrum analyzer and harmonic mixer were used to evaluate the output spectrum, while the power meter was used to measure the output power level of the module. As a result, the packaged module showed an output of 3.8dBm at 60.626GHz. The measured spectrum is shown in Fig. 4. The measured phase noise of the oscillator is approximately -82dBc/Hz at 1MHz offset. The combining efficiency is estimated to be in excess of 75 %, based on the measured output power of the individual MMIC oscillator and the assumption that the antenna radiation efficiency is on the order of 60 %.



(a)



(b)

Fig. 3. (a) Photograph of circuit mounted on test module (b) Schematic of oversized waveguide package

To verify the current profile of the designed active antenna circuit, the radiation pattern of the circuit was inspected by free-space radiation measurement in an an-echoic chamber. H-plane co- and cross-polarization patterns are shown in Fig. 5. Small fluctuation of the pattern appears to have arisen from parasitic radiation of passive elements inside the oscillator circuit, and minor pattern asymmetry is attributed to the slight difference in the amplitude of the oscillation signals between each pair of oscillators. However, the overall measured pattern and low cross-polarization level confirm that the circuit operates as designed with appropriate amplitude and phase relationship among the individual oscillators.

Since we observed about –31dBm at a distance of 1.3m using standard horn antennas with 25dBi gain, EIRP of the circuit is calculated as 14.3dBm. Considering that typical output powers of the conventional MMIC-only oscillators at this frequency range from 0 to 10 dBm [10-11], the active antenna of this work is a promising solution for an integrated mm-wave source at this frequency range.

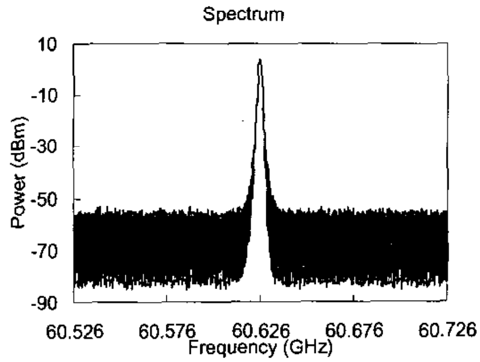


Fig. 4. Measured spectrum, 3.8dBm at 60.626GHz (V_{ds}=2V, I_{ds}=110mA, V_{gs}=-0.3V, V_{tune}=3.7V, Span=200MHz, Res BW=300KHz, VBW=1MHz)

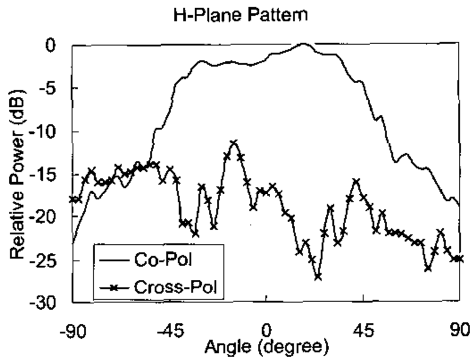


Fig. 5. H-plane radiation patterns

IV. CONCLUSION

A V-band single-chip MMIC coupled oscillators array, where the outputs of the four oscillators are combined using a single patch antenna, has been design and tested. Double push-pull operation has been implemented using a four-port patch antenna. In this way, the output power of the active antenna has been increased to the level appropriate for system use without significant increase in the chip size and cost. The active oscillator showed a total radiating power of 3.8dBm at 60.626GHz in a closed over-sized waveguide, and showed decent free-space radiation pattern. The output power is comparable to that of the MMIC-only oscillators at this frequency band. The proposed circuit can be used as a single-chip transmitter as well as a unit cell of massive spatially-combined millimeter-wave source module.

V. ACKNOWLEDGEMENT

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