HIGH-POWER HYBRID QUASI-OPTICAL Ka-BAND AMPLIFIER DESIGN

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Abstract **-- We report the first demonstration of a quasi-optical millimeter-wave amplifier. The amplifier unit cell consists of a MMIC driver amplifier chip followed by a two-stage high power amplifier chip. Input as well as output antennas are anti-resonant slots fabricated on a GaAs monolithic antenna array. A 6x6 array is designed for an output power in excess of 8 Watts. The array allows a variety of MMIC amplifier chips to populate any number of cells up to the full array size. An absolute power gain of 6 dB was achieved at 29 GHz. A liquid-cooled test fixture was designed to remove excess heat from the amplifiers. Amplifiers of this type could be used in communication or radar systems to produce high power with reduced size, weight, and lower system cost.**

1 Amplifier Design

Grid amplifiers [1] and antenna array amplifiers [2] have been demonstrated as quasi-optical power combiners up to X-band. We present a high-power quasi-optical Ka-band hybrid amplifier design shown in Figure 1. This amplifier consists of MMIC chips thinned to 100 μm and mounted on a GaAs monolithic antenna array. GaAs was chosen as the antenna array substrate to address issues related to high-power amplifier design of a monolithic high power amplifier currently in fabrication. The hybrid amplifier is a uniformly-spaced square 6x6 array. Each of the unit cells is designed for an output power level of 300 mW, a small signal gain of 16 dB, and a saturated gain of 10 dB. Figure 2 shows a photograph of the unit cell.

The unit cell consists of a driver first-stage amplifier chip followed by a two-stage high-power chip. The driver consists of a self-biased, single-stage power MESFET amplifier that produces 100 mW of output power with 6 dB of small-signal gain, 4.5 dB of large-signal gain, 10 % power-added efficiency at a bias point of V_{DS} = 5 V, and 140 mA drain current. The high-power MMIC amplifier chip consists of four combined 400 μm power MESFETs which produce 400 mW output power with 12 dB of small-signal gain, 6 dB large-signal gain, and 11.8 % power-added efficiency at a bias point of V_{GS} = -1 V and V_{DS} = 5 V with 500 mA total drain current. Small-signal and large-signal measurements on the MMIC chips are shown in Figures 3 and 4. The small-signal 2-dB bandwidth of the MMIC amplifiers in cascade is 5 GHz, centered at 32.5 GHz. The small-signal gain of the cascaded MMIC chips is shown in Figure 5. The chips were individually probed before being mounted onto the hybrid antenna array.

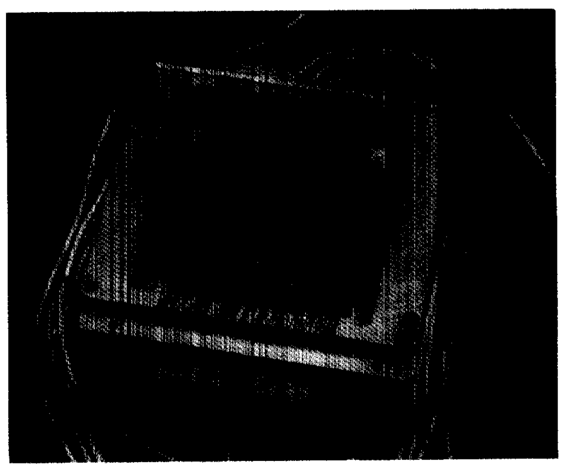

Figure 1. 6x6 hybrid amplifier array.

Each unit cell has a pair of anti-resonant slot antennas. The input and output slots are orthogonally polarized, which facilitates free-space measurements and is necessary for amplifier stability. The anti-resonant slots operate in the second resonant mode and offer broader bandwidth and a convenient input impedance compared to resonant slots. The slot dimensions (4220 X 471 μm) are designed to provide a 25-ohm impedance on the 100 μm-thick GaAs substrate at 33 GHz. The slot length is shorter than a half-wave, free-space wavelength, which is convenient for array design. We used an antenna CAD program, WireZeus, based on an approximate full-wave analysis described in [3]. The slot antennas are matched to the 50-ohm amplifier port impedances with quarter-wave transformers. Low-loss CPW-to-microstrip transitions

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are used at the interface between the CPW-antenna feeds and the microstrip MMICs. Additional hybrid decoupling capacitors are added along the bias lines for stability.

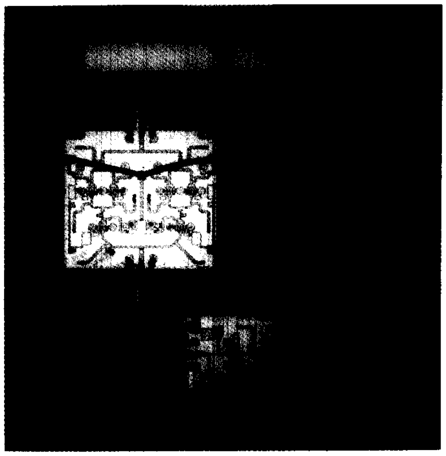

Figure 2. Unit cell of hybrid array.

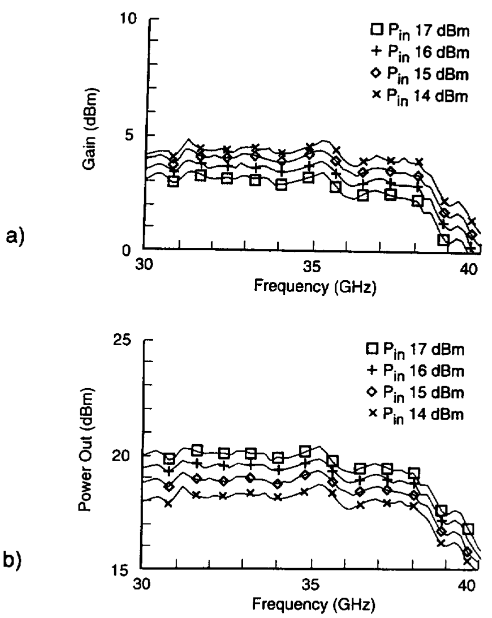

Figure 3 a) Large-signal gain of MMIC driver chip.
b) Power output of MMIC driver chip.

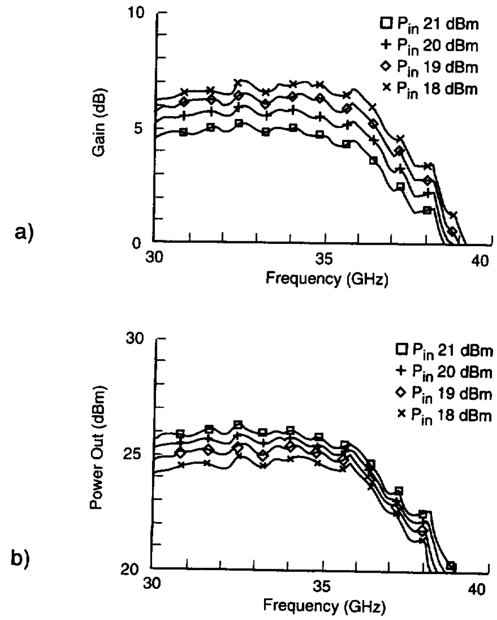

Figure 4 a) Large-signal gain of MMIC power chip.
b) Power output of MMIC power chip.

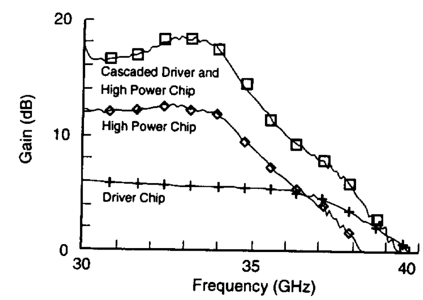

Figure 5 Cascaded small-signal gain of MMIC chips.

The hybrid array's substrate is a 3.8-cm square GaAs monolithic wafer. The substrate is thinned to 100 μm which is substantially less than 90 electrical degrees at 30 GHz and therefore is unlikely to support substrate modes. The thin substrate also allows better heat transfer from the amplifier chips to the backside of the substrate. Input and output polarizers are used to reduce input feed loss and increase transmitted output power. In the array, the gate and drain bias lines are laid out in a square mesh with air bridges at the intersections, allowing testing of each individual cell. The biasing voltage is applied at both ends of each bias line in order to equalize bias conditions across the array.

2 Measurements and Results

A test fixture was designed capable of removing 30 Watts of power dissipated from the array amplifier was designed. The test fixture assembly is shown in Figure 6. Fluorinert FC-43 was chosen as the coolant liquid because it has a low loss tangent of 0.0036 and a reasonable dielectric constant of 1.90 (measured at 8 GHz). The liquid directly cools the backside of the array and flows through a plastic channel that covers the entire backside of the array and is 540 electrical degrees thick at 33 GHz. The plastic and the liquid coolant have the same permittivity of 1.9 and represent a second dielectric layer to the transmitted amplified wave. The transistors are 64° C higher in temperature then the coolant because the heat generated by the transistors has to propagate through 200 μm of GaAs. The material of the GaAs chip carrier is Thermcon, which has the same thermal coefficient of expansion as GaAs.

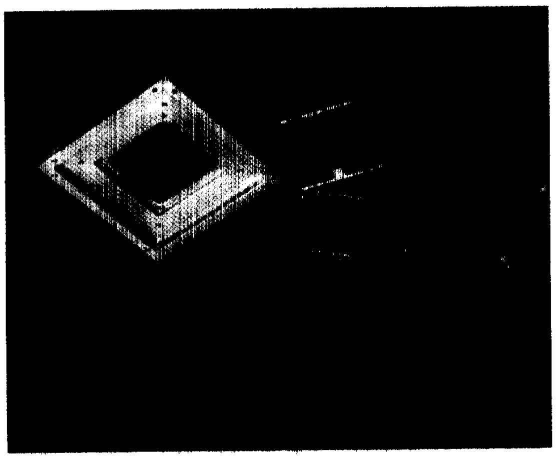

Figure 6. Expanded view of test fixture.

Near field measurements were made with a scalar network analyzer with round corrugated horns. The test setup is shown in Figure 7. The horns produce a Gaussian transverse field profile that focuses 63 % of the power on a 2.5 cm spot size midway between the horns (the power density at the spot edge is $1/e^2$ lower than at the center). Passive array measurements were conducted before the MMIC amplifiers were mounted, and without the coolant present. The passive array had a peak in its transmission frequency response at 34.5 GHz with a 10 % bandwidth. The insertion loss of the passive array is 10 dB. The measured passive array response is shown in Figure 8. Simulated CPW line loss within the unit cell contributes 1 dB of the loss, indicating that there is 4.5 dB of loss on both the input and output sides of the array. Approximately 3.7 dB of the 4.5 dB loss is due to the field patterns spilling over the perimeter of the array.

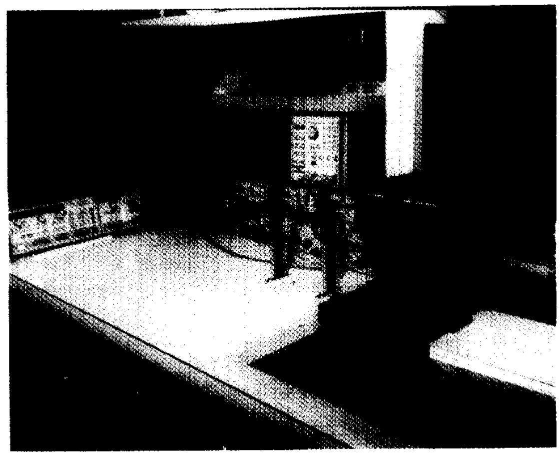

Figure 7. Small-signal quasi-optical test setup.

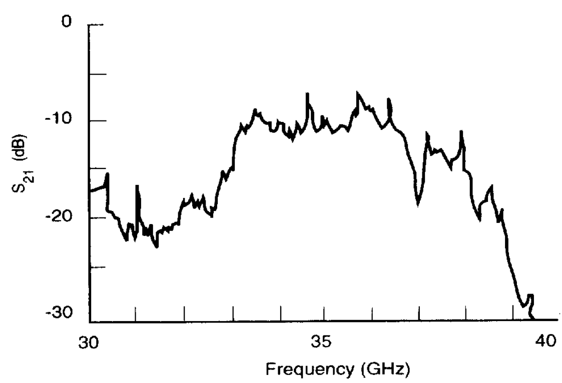

Figure 8. Measured response of passive array.

A 3x3 subsection was populated with MMIC amplifiers, and the substrate was mounted in the liquid cooled test fixture. Small signal measurements yielded the transmission frequency response of the subarray shown in Figure 9. The peak absolute power gain is 6 dB, measured at 29 GHz. The measured frequency is shifted towards lower frequencies as compared to the passive array because the antenna frequency response is changed when it is dielectrically loaded by the cooling structure. This shift has been confirmed on amplifier tests without cooling fluid present. The measured 6 dB gain agrees well with the expected gain when the aforementioned losses are taken into account and the expected cascaded MMIC amplifier small-signal gain is 16 dB less 1.5 dB of circuit losses on the hybrid substrate. If the array were illuminated without spillover, then the gain would have been approximately 12 dB.

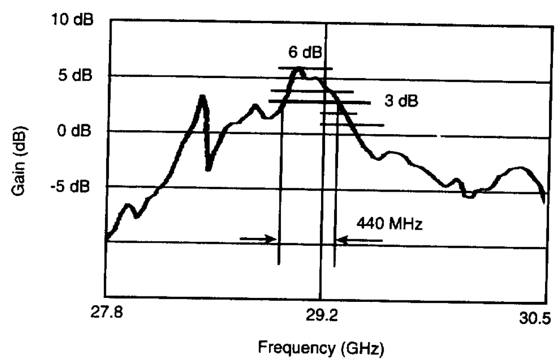

Figure 9. Small-signal gain of amplifier array.

The amplifier has been tested under CW and pulsed conditions, and to date a saturated output power of 1 Watt has been measured. This is in close agreement with the expected output power level of the array when considering the combined unit cell output power level along with the aforementioned feed loss of 4.5 dB. However, complete and accurate measurement of the full capability of the amplifier requires improvements in the feed and collection horns. This work is currently underway. Approaches to improving the feed and collection efficiency include far-field measurements as well as modified feed horn designs. Far-field measurements are standard methods for measuring quasi-optical amplifier gain. Our approach is, however, to collect most, if not all, of the incident power. Our ultimate objective is to totally enclose the amplifier in a miniature, hermetically sealed package suitable for use in small missiles and spacecraft.

3 Conclusion

This paper demonstrates the first quasi-optical millimeter-wave amplifier. This hybrid amplifier is built on a monolithic GaAs substrate with CPW passive lines and anti-resonant slot antennas, and microstrip MMIC amplifiers. An absolute power small-signal gain of 6 dB and a saturated power of 1 Watt were measured at millimeter-wave frequencies. These results are significant and should play an important role in this emerging technology. Further work is underway to improve test methods.

4 Acknowledgments.

We would like to thank the people at Martin Marietta who helped make this work possible, including Terry Duffield for managerial as well as technical input, Steve Gray and Jack Hart for their technical input, Jerry Norton for painstakingly assembling the array, Frank Sims for technical mechanical design input and Al Pergande for his technical input. We would also like to thank GAMMA Monolithics for providing the MMIC chips.

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