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Two Ka-Band Quasi-Optical Amplifier Arrays

Michael Forman, Todd Marshall, and Zoya Popović

Department of Electrical and Computer Engineering
University of Colorado
Boulder, CO 80309-0425

Abstract—
Performance repeatability, thermal properties, and effects of biasing are studied on two Ka-band quasi-optical slot amplifier arrays fabricated with commercial MMICs on 254-μm aluminum-nitride substrates. The unit cells are arranged in a 6x6 triangular lattice to suppress sidelobes. The amplifier arrays have peak small-signal gains of 2.1 dB at 31.02 GHz and 6.5 dB at 31.40 GHz, respectively.

I. Introduction

The motivation for quasi-optical amplifier power combining is to obtain watt power levels from solid-state amplifiers at millimeter-wave frequencies while taking advantage of high combining efficiency [1] and graceful degradation [2]. Several researchers have demonstrated Ka-band quasi-optical amplifier arrays: in [3], MMIC amplifiers were combined using slot antennas with up to 2.4 W of output power and 6 dB of small-signal gain; in [4] and [5], monolithic grid amplifiers using HBTs and PHEMTs respectively showed gain up to 60 GHz; and in [6], 1 W of power was obtained in an array mounted in a waveguide.

All of the arrays have raised issues related to stability and heat dissipation. In [3], a GaAs substrate was used, and even with liquid coolant flowing on the backside of the array, the 20 W of heat that was produced caused the array to crack. A solution to thermal management is pursued with high-efficiency switched-mode amplifiers [7]. An alternative was to use a diamond substrate with edge cooling [8], but in this array, there were problems with the metalization of the substrate, as well as bias-line oscillations. In [4] and [5], stabilization resistors in the emitters and sources, respectively, caused substantial losses. The monolithic array in [6] consists of 112 amplifiers with 90% yield and the bias network contains resistors and capacitors designed to stabilize the array.

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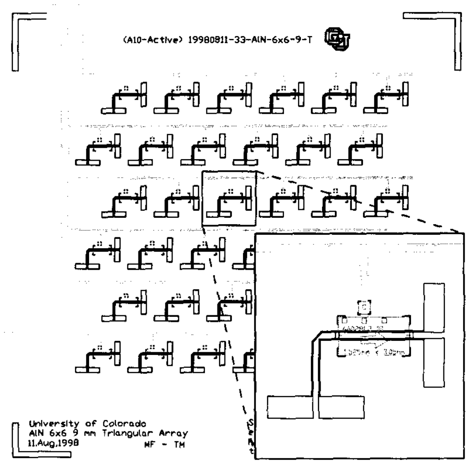

Fig. 1. Schematic of a unit cell within the amplifier array. The unit cells are arranged in a triangular lattice. The slot antennas are orthogonally polarized and are connected to the MMIC by CPW transmission lines. The DC-bias line and blocking capacitor are also shown.

In this work, we present some fundamental studies related to repeatability of array performance, thermal properties and choice of substrate, importance of proper biasing, and sensitivity to fabrication tolerances. The studies are performed on two experimental Ka-band arrays (refered to as A and B) of nearly identical RF architectures. The differences between the two are in the biasing network and type of substrate metalization. Based on the power available from a single MMIC (16 dBm at 1 dBc), the predicted output power of each array is 1.4 W. The power measurements, however, could not be completed due to unavailablity of commercial Ka-band sources. This problem demonstrates a need for developing alternative watt-level Ka-band sources.

II. Array Amplifier Design

The quasi-optical amplifier schematic is shown in Fig. 1. Each input slot antenna receives power from an

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incident vertically-polarized plane wave. The received power is coupled onto the 50-Ω CPW transmission line and is then amplified by a commercial *Alpha* AA028P3-00 MMIC amplifier. The amplified power is re-radiated with a horizontal polarization by the output slot antenna. Isolation and stability is provided by orthogonal input and output antennas.

The choice of substrate is determined by the approximate 125°C maximum operating temperature of the MMIC. Thermal gradients on substrates during operation can be approximated with a simple analytical model of heat conduction. The model assumes a uniform heat flux under the MMIC and a uniform temperature of 25°C along the edges of the substrate. The substrate dimension is fixed to 7.62 cm-by-7.62 cm-by-h. h varies between 254 μm to 406 μm, depending on the commercial availability of various substrates. There are 36 unit cells spaced 9 mm apart in each amplifier array. The 36 *Alpha* AA028P3-00 MMICs can produce at most $P_h = 33$ W of heat assuming a worst-case efficiency. The results of the conduction model for diamond, aluminum nitride (AlN), and *Rogers* TMM6 substrates are given in Table I.

TABLE I
THE THEORETICAL MAXIMUM TEMPERATURE BASED ON CONDUCTION ONLY.

Substrate	h (μm)	k (W/mK)	P_h (W)	T_{max} (°C)
Diamond	406.4	2000	33	30.3
AlN	254	170	33	124
TMM6	381	0.7	33	15000

The diamond substrate has the best thermal properties. The AlN substrate has a T_{max} close to 125°C. The unrealistic maximum temperature calculated for the TMM6 substrate demonstrates the limitation of any model based solely on heat conduction. However, at higher temperatures, cooling is dominated by convection and radiation which only decreases the maximum temperature.

The AlN substrate is 254 μm thick with a relative permittivity of 8.6. *HP Momentum* is used to design the 50-Ω slot antenna and CPW feed lines. The second-resonance slot is 4.150 mm long and 0.900 mm wide, and has a modeled return loss of 50 dB at 33 GHz with a 13% 2:1 VSWR bandwidth.

HP Momentum simulations were performed to study coupling between slot antennas and bias lines to determine the size of the unit cell. A unit-cell size of 0.9λ is required to guarantee that coupling between orthogonally polarized input and output antennas is below −20 dB. The DC bias line is perpendicular to the output antenna to minimize RF coupling.

A bias-voltage variation across the array is expected due to ohmic losses in the thin bias line. The biasing network can be modeled by a resistive ladder network consisting of series (R_{bias}) and shunt (R_{MMIC}) resistors. R_{bias} represents the bias-line resistance between unit cells and R_{MMIC} represents the resistance of the internal MMIC biasing circuity. The bias voltage along a row at the $(k+1)$ unit cell is given by:

$$V_{k+1} = \frac{R_{N-k-1}}{R_{\text{bias}} + R_{N-k-1}} V_k \quad \text{, where} \qquad (1)$$

$$R_j = \left[\frac{1}{R_{\text{MMIC}}} + \frac{1}{R_{\text{bias}} + R_{j-1}}\right]^{-1}. \qquad (2)$$

The number of unit cells in a row is N=6, j=1 to N-1, and k=0 to N-1. k=0 corresponds to the supply voltage V_0 and $R_0 \equiv R_{\text{MMIC}}$. Eqs. (1) and (2), expressed as a function of the ratio $R_{\text{MMIC}}/R_{\text{bias}}$, show that the bias voltage variation over an array may be substantial (Fig. 2).

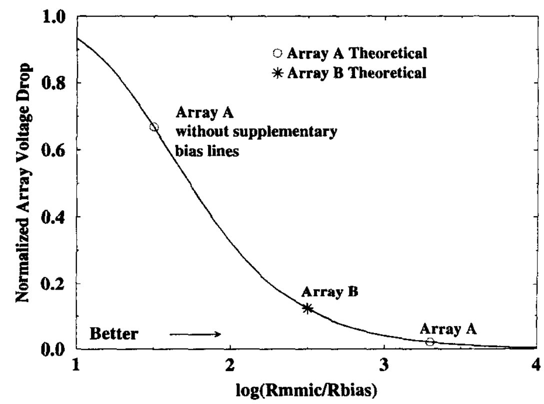

Fig. 2. Normalized array voltage drop as a function of $R_{\text{MMIC}}/R_{\text{bias}}$.

III. Fabrication

Array A and B, shown in Fig. 3, were fabricated using photolithography with the same mask on identical substrates. The MMICs and capacitors were bonded with silver epoxy. Each of the unit cells in both arrays have 25 gold bond wires in identical configurations. The bond wires provide connections between the MMIC pads, capacitor pads, and array metalization, as well as airbridges along the CPW lines to prevent slot modes.

The differences between Arrays A and B are in the metal thickness and bias line configuration. Array A

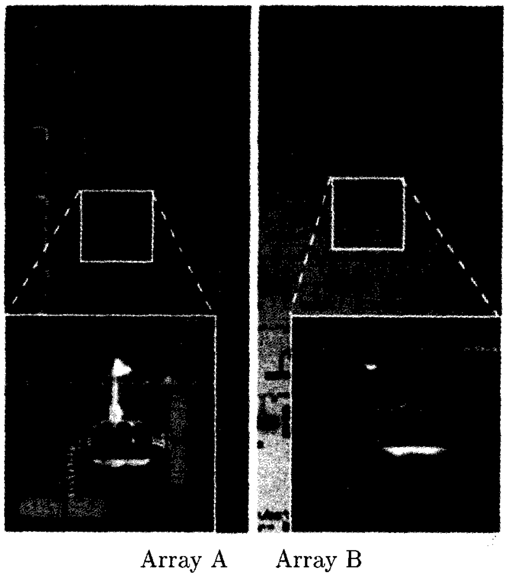

Fig. 3. Arrays A and B with corresponding unit cells enlarged.

has $4\,\mu$m of gold. Due to a low $R_{\text{MMIC}}/R_{\text{bias}}$ ratio, a supplementary bias line network consisting of insulating adhesive mylar and copper tape was added. The substrate for Array B has $4.3\,\mu$m of copper with a $2\,\mu$m layer of electroplated gold. The thicker metal increases $R_{\text{MMIC}}/R_{\text{bias}}$, thus decreasing the DC-bias network voltage variation. Array B has additional airbridges and a capacitor along the bias line.

IV. Experimental Results

TABLE II

Measured results using standard horns (a) and hard horns (b). BW indicates the range over which the arrays have gain. G_a is with respect to a passive array.

(a) Standard-horn small-signal gain measurements.

Array	freq (GHz)	Gain (dB)	BW (GHz)	On/Off Ratio (dB)	G_a (dB)
A	31.02	2.1	0.34	34	10
B	31.40	6.5	0.50	38	14

(b) Hard-horn small-signal gain measurements.

Array	freq (GHz)	Gain (dB)	BW (GHz)	On/Off Ratio (dB)	G_a (dB)
A	30.32	2.0	0.22	25	10
B	31.30	4.7	0.70	35	12

Two cross-polarized standard horn antennas are placed 60λ from either side of the array for small-signal far-field gain measurements. Polarizers are used to increase the gain and enforce unidirectional radiation of the slots. A passive array with through-lines in the place of the devices is used to measure the gain contributed by the MMICs. The measured gain of the passive array and the active arrays are plotted in Fig. 4(a) and summarized in Table II(a). A "through" calibration is used in all measurements.

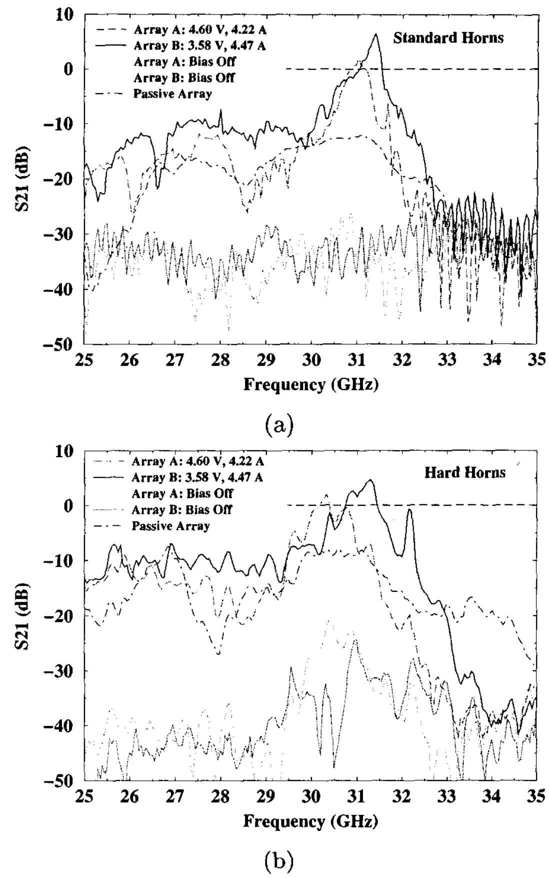

Fig. 4. Small-signal gain measurements with standard horns (a) and hard horns (b). Measurements are with respect to a "through" calibration.

Near-field small-signal gain measurements are repeated using two cross-polarized hard-horn antennas. The hard-horn antennas provide a uniform field distribution with amplitude and phase variations of only ± 1 dB and 80° over 98% of the horn aperature[9]. The small-signal hard-horn gain measurements are shown in Fig. 4(b) and summarized in Table II(b).

With the arrays mounted vertically, natural heat convection leads to measured steady-state temperatures of 69° C and 62° C for Array A and B, respectively. Employing forced-convective cooling using two fans with a flow of 1 m^3/minute, the maximum steady-state temperatures for Array A and B dropped to 39° C and 38° C. Natural convection is sufficient to keep the MMICs below their maximum operating temperature in small-signal operation.

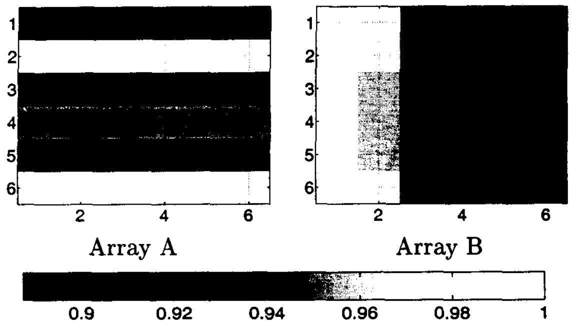

Fig. 5. Measured normalized voltage levels for Array A and B.

Voltage variations are measured across the bias network. Fig. 5 shows the normalized measured voltage deviation along the bias network at each MMIC due to the bias ladder network. Voltage variations for Array B match the expected values within 5% relative error based on Eqs. (1) and (2). Array A's vertical voltage uniformity differs from theory due to resistive bus-bar connections (see Fig. 3(a)).

Pattern measurements are performed using a near-field hard-horn feed 7λ from the array and a far-field standard receiving horn 60λ from the array at 30.8 GHz. The theoretical and measured E- and H-plane patterns are shown in Fig. 6.

In conclusion, the different voltage distributions between the two arrays result in differing radiation patterns, which also differ from the theoretical uniform array patterns. The different values of peak gain (2.1 dB and 6.5 dB) are also partially due to nonuniform MMIC gains. We believe that the 1% shift in frequency at which the peak gain occurs results from 2 factors: variation in MMIC frequency response determined by biasing; and slight differences in slot and CPW dimensions due to different metallizations and associated processing.

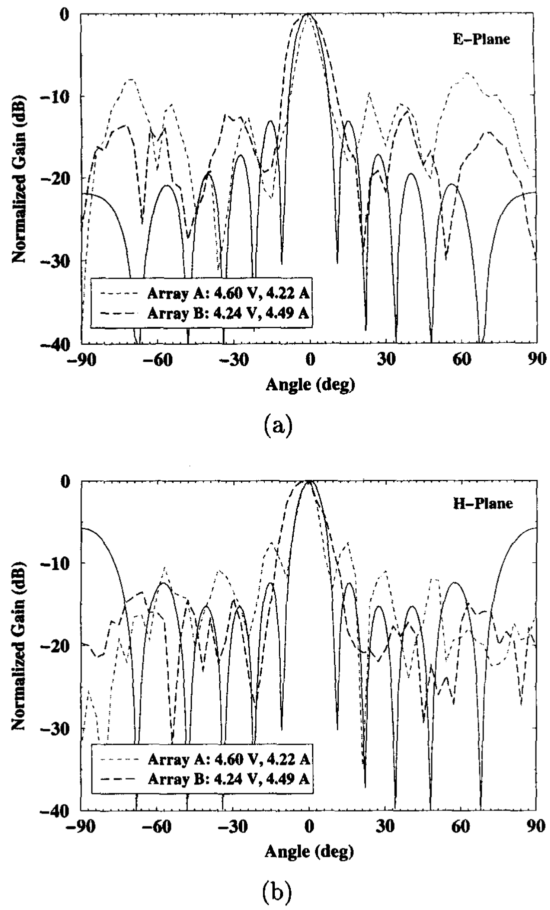

Fig. 6. E-plane pattern measurement (a) and H-plane pattern measurement (b). The measurement frequency is 30.8 GHz. The theoretical plot assumes a uniform array.

References

[1] Robert A. York, "Quasi-optical power combining," in *Active and Quasi-optical arrays for solid-state power combining*, Robert A. York and Zoya B. Popović, Eds., chapter 1. John Wiley, New York, 1997.

[2] Zoya Popović and Amir Mortazawi, "Quasi-optical tranmit/receive front ends," *IEEE Trans. Microwave Theory Tech.*, vol. 46, no. 11, pp. 1964–1975, Nov. 1998.

[3] J. Hubert, J. Schoenberg, and Z. Popović, "High-power hybrid quasi-optical Ka-band amplifier design," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 585–588, May 1995.

[4] C. M. Liu, E. A. Sovero, W. J. Ho, J. A. Higgins, M. P. De Lisio, and D. B. Rutledge, "Monolithic 40-GHz 670-mW HBT grid amplifier," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1123–1126, June 1996.

[5] M. P. De Lisio, S. W. Duncan, D. W. Tu, S. Weinreb, C. M. Liu, and D. B. Rutledge, "A 44-60 GHz monolithic pHEMT grid amplifier," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1127–1130, June 1996.

[6] E. A. Sovero, J. B. Hacker, J. A. Higgins, D. S. Deakin, and A. L. Sailer, "A Ka-band monolithic quasi-optic amplifier," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1453–1456, June 1998.

[7] Eric W. Bryerton, Manoja D. Weiss, and Zoya Popović, "A 10-GHz high-efficiency lens amplifier array," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1461–1464, June 1998.

[8] Lee Mirth and John Hubert, *Personal Communication*, Lockheed Martin, Electronics and Missiles, Orlando, Florida.

[9] Maha A. Ali, Sean Ortiz, Toni Ivanov, and Amir Mortazawi, "Analysis and measurement of hard horn feeds for the excitation of quasi-optical amplifiers," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1469–1472, June 1998.