A Millimeter-Wave Quasi-Optical Amplifier Array Using Inclined-Plane Horn Antennas

C. E. Saavedra, W. Wright, K. Y. Hur, and R. C. Compton

***Abstract*—A novel millimeter-wave quasi-optical amplifier array architecture is presented. The amplifier array consists of a horn antenna that tapers down to a parallel-plate waveguide. Stacked between the parallel-plates is a microstrip power divider circuit which feeds the active elements. At the output there is a similar power-combining circuit and transition to free space. Measurements on the active array show a maximum gain of 7.25 dB at 43.25 GHz and a bandwidth of 5.75 GHz.**

***Index Terms*— Amplifier array, gratings, power combining, quasi-optics.**

I. INTRODUCTION

OBTAINING significant output power and gain from quasi-optical amplifier arrays has been limited due to amplifier chip size limitations, coupling efficiencies, and thermal dissipation [1]–[4]. In this letter, an approach is presented for millimeter-wave power combining that simultaneously addresses these issues. Fig. 1 shows a three-dimensional view of the amplifier array. Incident energy is coupled from free space into a stack of ten parallel-plate waveguides via a tapered grating. From the parallel-plate guide there is a transition to a microstrip-based power amplifier monolithic microwave integrated circuit (MMIC). The output signal is transitioned back to the parallel-plate guide and finally to free space via another grating. In this approach, multistage amplifiers can be used because there are no restrictions on the longitudinal length of the grating. In addition, the structure can house an $n \times n$ array because there are no limits on either the vertical or the horizontal dimensions of the grating. As opposed to other designs that use printed circuit antennas, the design presented here allows for a low loss, broad-band coupling of energy from free space to waveguide, and finally, to microstrip. Furthermore, the mutual and input–output coupling between vertical gain elements is reduced, allowing for graceful degradation of the array and stable oscillation-free operation. Finally, heat is readily removed from the array, thereby allowing for greater mean-time-to-failure.

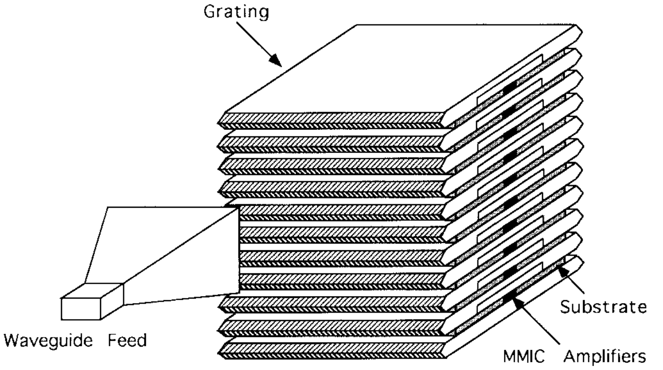

Fig. 1. Millimeter-wave quasi-optical MMIC amplifier array. The amplifiers are approximately spaced $\lambda/2$ apart in both the horizontal and vertical dimension at the operating frequency. Lenses (not shown) are used to focus the beam from the waveguide feed to the grating.

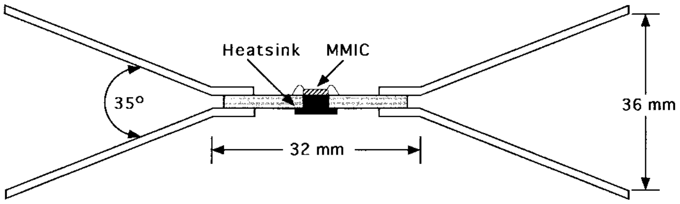

Fig. 2. Cross section of the 1 × n amplifier array. The dielectric material stacked between the parallel plates has an ϵ_r of 3.27 and a thickness of 0.381 mm. The MMIC's are bonded to the substrate using an ultrasonic bonder.

II. AMPLIFIER ARRAY DESIGN

To facilitate the design and optimization of the amplifier array hybrid circuits, a one-dimensional (1-D) version of the array shown in Fig. 1 was developed. The 1-D array consists of two back-to-back inclined-plane horn antennas that taper down to a parallel-plate waveguide. Each horn has a flare angle of 35° and a slant height of 57 mm. The aperture of the horns is 36 mm in the E-plane and over 75 mm in the H-plane. In the parallel-plate region, the separation between the plates is 0.381 mm and the distance between the throats of the input and output horns is 32 mm (Fig. 2). Stacked between the parallel-plate waveguide is the microwave substrate with the waveguide-to-microstrip transitions and the active elements (Fig. 3). Since each transition is spaced 4.24 mm apart and the substrate thickness is 0.381 mm, the impedance of a parallel-plate waveguide with these dimensions is $Z_1 = \eta_o d/(w\sqrt{\epsilon_r})$, where η_o is the free-space wave impedance, d is the substrate thickness, $d = 0.381$ mm, w is the spacing between transitions,

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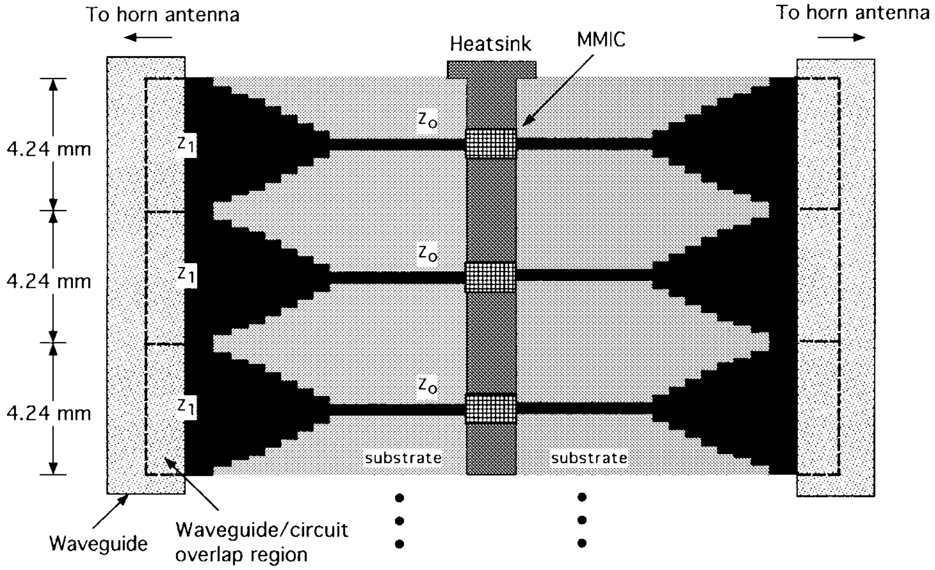

Fig. 3. Top view of the microstrip circuit which is stacked between the parallel plates of Fig. 2. There is an overlap region between the waveguide and the substrate. The black surfaces represent the copper cladding on the substrate.

$w = 4.24$ mm, and $\epsilon_r = 3.27$ (TMM3 from the Rogers Corp), giving $Z_1 = 18.7\ \Omega$. Notice that there is an overlap region between the waveguide and the substrate. The impedance from the overlap region to the beginning of the transitions is Z_1. The impedance matching network from Z_1 to the desired microstrip impedance, Z_o, was accomplished by using seven $\lambda/4$ microstrip lines at the design frequency of 44 GHz.

The GaAs PHEMT MMIC amplifiers used in the array were designed and fabricated at Raytheon Electronics, Advanced Device Center. Each MMIC consists of three class A amplifier stages with a total linear gain of 13 dB and output power of 28 dBm at the 1-dB compression point at 44 GHz. The gate periphery of the discrete PHEMT's in the amplifier is $10 \times 60\ \mu$m. The amplifier uses seven PHEMT's for a total periphery of 4.20 mm. The dimension of each amplifier chip is approximately 3.94×2.66 mm^2. A 2-mil wafer thinning process was implemented to enable individually grounded source finger vias and to enhance the thermal management of the MMIC's. The MMIC amplifiers and the TMM3 substrates were both epoxied onto an aluminum heatsink and the MMIC's bond-wired to the substrate.

III. RESULTS

Gain measurements on the array were performed using a gaussian-beam test setup similar to that of [6]. The reference planes of the measurement system were at the mid-point of the optical setup. After calibration the array was placed in the optical setup and the reference planes were separated by 32 mm (Fig. 2) by physically moving the left-half of the setup. In this manner, the reference planes were at the throat of the input horn antenna (port 1) and the output horn antenna (port 2) of the amplifier array. The array was illuminated by a gaussian beam with a beam radius at the waist of 10 mm. To date, three amplifier arrays have been built and tested. A photograph of an amplifier array is shown in Fig. 4.

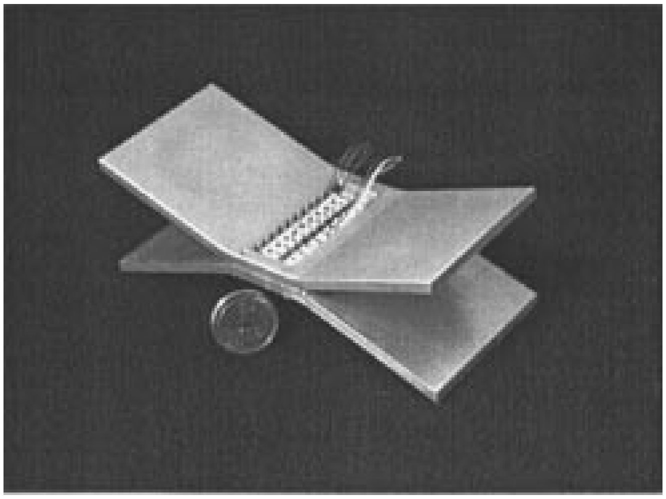

Fig. 4. Photograph of a 1-D amplifier array using the inclined-plane horn antennas.

In Fig. 5, three distinct measurements are shown. A passive measurement of the array structure was done by using microstrip through lines in place of the active elements. This experiment was used to determine the losses in the passive structure, which are about −3 dB on average (approximately 0.5 dB at each transition, 1.4-dB microstrip losses, and 0.3 dB per horn antenna). In addition, the gain of a MMIC like those in the array was measured using coplanar waveguide probes. Finally, Fig. 5 also shows measurements of an amplifier array with two active elements (solid curve). Note that if the passive measurement is subtracted from the chip measurement, the result is a plot that resembles that of the active amplifier array. The maximum gain of the array is 7.25 dB at 43.25 GHz and the 3-dB bandwidth is 5.75 GHz. The drain and gate bias lines of both MMIC's were connected together. The drain–source voltage $V_{\rm ds}$ was 5.0 V, $V_{\rm gs}$ was −0.2 V, and $I_{\rm ds}$ was 0.70

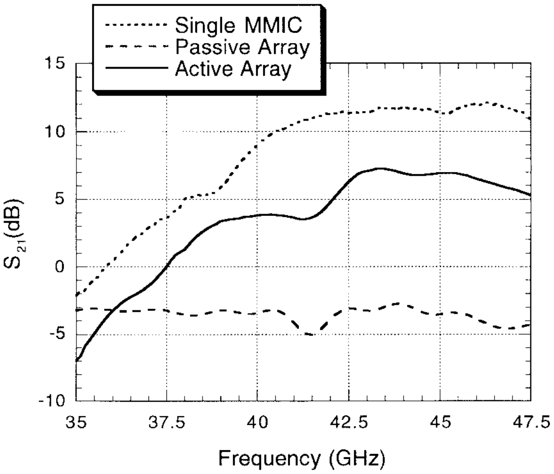

Fig. 5. S_{21} measurement of the active array, the passive array, and a typical MMIC used in the array using CPW probes. For the passive measurement, the active elements were replaced by microstrip through lines.

A. To prevent low-frequency oscillations in the system, large choke inductors were used in the bias lines.

IV. CONCLUSIONS

A *Q*-band amplifier array with a maximum small-signal gain of 7.25 dB and a bandwidth in excess of 5.75 GHz has been demonstrated. The power-combining efficiency of the array is mainly determined by the loss incurred at microstrip to waveguide transition at the output of the array. Since the microstrip transition loss has been estimated at −0.5 dB, it is expected that the power-combining efficiency will be on the order of 90%.

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