A Slotted-Waveguide Power Amplifier for Spatial Power-Combining Applications

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***Abstract*—A power-amplifier array based on a slotted-waveguide power divider is presented for quasi-optical applications. The advantages of this structure are its low profile and ease of fabrication. Furthermore, efficient heat sinking of power devices is achieved. An X-band version of the power amplifier using eight MESFET's was designed and fabricated. An output power of 14 W was obtained. At 10 GHz, the amplifier gain and power-combining efficiency were 6.7 dB and 88%, respectively. The 3-dB bandwidth for the circuit was approximately 5%. This technique has the potential to meet the increasing demand for solid-state power amplifiers used in millimeter-wave communications and radar systems.**

***Index Terms*—Amplifier, quasi-optical, slotted waveguide.**

I. Introduction

OVER THE LAST decade, there has been significant advances in monolithic integrated-circuit technology, allowing the mass production of solid-state microwave and millimeter-wave systems. These developments have spawned a wide array of military and commercial applications such as anticollision radars, adaptive phased arrays, satellite communications, and local multipoint distribution systems (LMDS's). Despite these advances, most millimeter-wave systems are limited by the modest output power of solid-state devices. A possible way to remedy this fundamental limitation is to combine power from many solid-state devices using quasi-optical or spatial power combining. Several spatial and quasi-optical power-combining techniques have already been proposed for the design of high-power millimeter-wave solid-state amplifiers [1]–[8].

A power-combining technique is presented in this paper, which uses a slotted-waveguide distribution circuit to achieve power dividing, as shown in Fig. 1. The circuit consists of a feed waveguide that divides the input power to the slotted waveguides placed along the feed. By appropriate placement of slots in the slotted waveguides, equal power dividing can be achieved. Power is coupled to a microstrip feeding circuitry containing solid-state power amplifiers. The amplified power can then be radiated using planar antenna elements such as patch antennas. This topology allows for a low profile, good heat sinking capability, and ease of fabrication, and has the potential to meet the increasing demand of millimeter-wave communications and radar systems for solid-state power amplifiers.

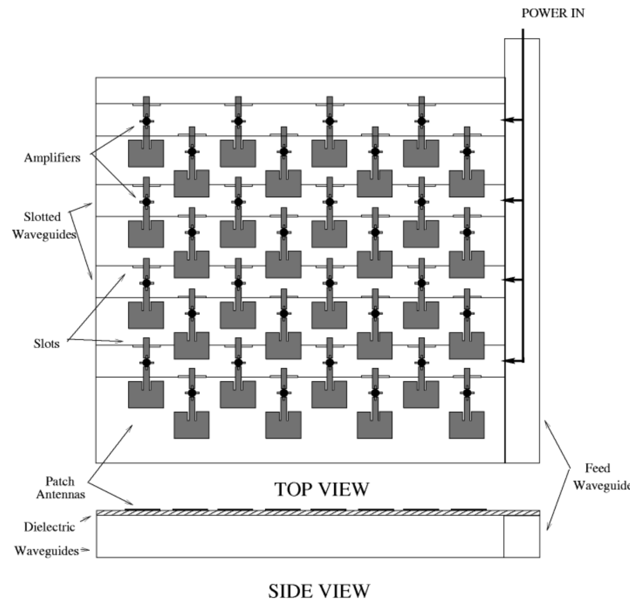

Fig. 1. Millimeter-wave slotted-waveguide amplifier array.

Based on our knowledge, most of the work on slotted-waveguide structures are related to antenna arrays [9]–[12], and little attention has been given to multiaperture waveguide to microstrip couplers [13], [14]. In this paper, rather than radiating energy into free space, the slotted waveguides are coupled to microstrip lines for use in a power distribution system (Fig. 1). To evaluate the performance of this new power amplifier, an X-band power amplifier that implements this dividing technique was designed and fabricated, as shown in Fig. 2. In this design, the amplified signal is recombined through an identical slotted waveguide placed adjacent to the feed waveguide. Efficient heat sinking of the power amplifiers is achieved by mounting the active devices on the thick metal joining the slotted waveguides.

In the following sections, the operation and characteristics of the slotted-waveguide power divider are presented. The analysis developed here uses equivalent-circuit models to simplify the design approach for an N-way slotted-waveguide divider. Analysis of the power and phase deviation at the output ports are also discussed. In addition, simulated and experimental results for a passive eight-way power divider/combiner and an eight-device slotted-waveguide power amplifier are presented.

Manuscript received July 8, 1999. This work was supported by the Army Research Office under a Multidisciplinary Research Initiative on Quasi-Optical Power Combining.

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Publisher Item Identifier S 0018-9480(00)05471-5.

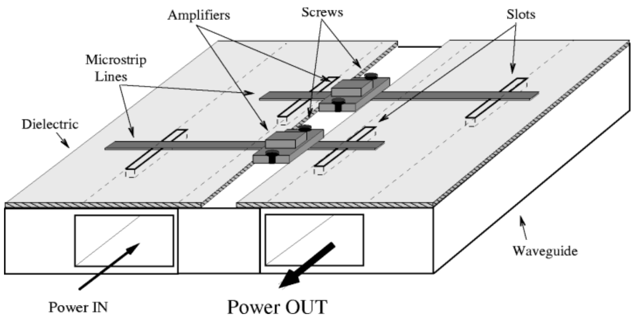

Fig. 2. Topology of the slotted-waveguide power divider/combiner

II. Design Approach

A. Theory

Typical circuit-level divider/combiners can be classified as resonant and nonresonant. The resonant divider/combiner circuits include rectangular and cylindrical waveguide resonant-cavity combiners. The nonresonant type includes the radial-line, hybrid-coupled, and Wilkinson-type combiners [15]. Resonant type combiners, in general, are suitable for high combining efficiency because the output power of the devices combine directly with minimum path loss. However, they have a narrower bandwidth (typically in the 4%–5% range) compared to nonresonant circuits [16].

The power-combining technique proposed herein is based on a resonant slotted-waveguide configuration. As shown in Fig. 2, the power divider/combiner consists of two symmetrical slotted waveguides that couple power to open-circuited microstrip lines placed directly above each slot. The open microstrip lines are extended a quarter-wavelength beyond each slot. The coupling coefficient is determined by the slot offset, slot width, and microstrip-line characteristic impedance. The resonant frequency of the divider/combiner is dictated by the slot length, as well as the periodicity of the slots.

Fig. 3 shows an equivalent-circuit model of the slotted-waveguide divider. In the following analysis, the waveguide losses are assumed to be negligible. The slotted waveguide can be represented with N identical cascaded dividing units, each of which consists of a section of waveguide with a broadwall longitudinal slot and a microstrip line, as shown in Fig. 3(a). The longitudinal slots are represented by shunt elements due to the symmetric forward and backward scattering of the waves near the slot discontinuity [17], [18]. This holds true regardless of whether energy is being radiated into free space or coupled to microstrip lines. Thus, the equivalent-circuit model consists of N dividing units with slots represented by its respective conductance and susceptance, and sections of waveguides represented by transmission lines. Since the distance between slots in adjacent dividing units is one-half guide wavelength, the length of each transmission line in the equivalent-circuit model is also $\lambda_g/2$, where λ_g is the guide wavelength.

As shown in Fig. 3(b), a short circuit placed $3\lambda_g/4$ beyond the last slot presents an open circuit to the last slot. This creates a standing wave with the voltage maxima occurring at the center of each slot. Since all other neighboring slots are separated by transmission lines of $\lambda_g/2$, the equivalent input admittance to the array is simply the sum of all the individual slot admittances.

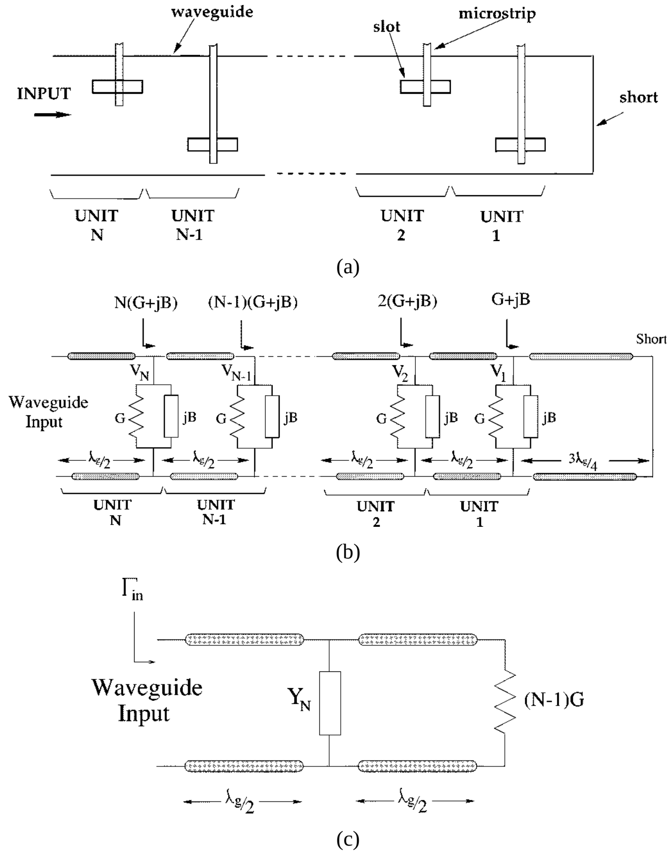

Fig. 3. An N-way slotted-waveguide power divider. (a) Power divider. (b) Equivalent-circuit model. (c) Simplified circuit model.

The power coupled to the ith slot is $(1/2)V_i^2 g_i$, where g_i is the normalized slot conductance and V_i is the equivalent voltage that appears across the ith slot. In order to divide power equally across all slots, two conditions must be met: 1) the voltage amplitudes across the slots must be equal and 2) the addition of the powers delivered to each slot $\sum_{i=1}^{N}(1/2)G_i V_i^2$ should be equal to the power available from the input source.

Fig. 3(c) shows a simplified model used to design the N-way power divider in terms of a single dividing unit. In this model, $Y_N(\omega) = G(\omega) + jB(\omega)$ represents the complex admittance of the N_{th} slot, and $(N-1)G$ constitutes the total conductance looking to the right-hand side of the N_{th} slot. It is assumed that slots $N-1$ through one are essentially identical and are resonant at the center frequency of operation. The susceptance $(jB(\omega))$ of the slot remains to predict the frequency response of this circuit. Using this equivalent model, the input reflection coefficient is given by

$$\Gamma_{\text{in}}(\omega) = \frac{Y_o(\omega) - NG(\omega) - jB(\omega)}{Y_o(\omega) + NG(\omega) + jB(\omega)} \quad (1)$$

where $Y_o(\omega)$ is the characteristic wave admittance of the waveguide. Using (1), the necessary resonant slot admittance to obtain perfect input match is given by $Y_N(\omega) = Y_o(\omega)/N$. Conversely, when values of $\Gamma_{\text{in}}(\omega)$ are specified, the slot admittance can be determined using

$$Y_N(\omega) = Y_o(\omega)\left(\frac{1-\Gamma_{\text{in}}(\omega)}{1+\Gamma_{\text{in}}(\omega)}\right) - (N-1)G(\omega). \quad (2)$$

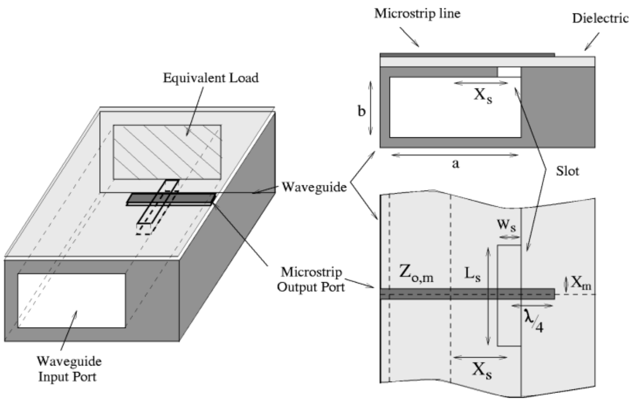

Fig. 4. Single waveguide-to-microstrip transition. Final dimensions used are: $L_s = 1.61$ cm, $W_s = 0.1$ cm, $X_s = 1.143$ cm, $Z_{o,m} = 75\ \Omega$, and $X_m = 0$ cm.

By treating an N-way slotted-waveguide power divider, in terms of the simplified model, the design is reduced to solving a single waveguide to microstrip transition. This design approach becomes important when using full-wave analysis techniques such as the finite-element method (FEM) and the method of moments (MoM) to solve electrically large three-dimensional (3-D) problems. Analyzing a full slotted-waveguide array becomes computationally inefficient due to the stringent requirements placed on the computer resources. Therefore, simplifying the problem allows for a significant reduction in design time.

B. Design of an Eight-Way Slotted-Waveguide Power

A single waveguide-to-microstrip transition is shown in Fig. 4. By properly terminating the waveguide with the equivalent load, the design is reduced to solving for input match at the waveguide port and a slot-microstrip coupling coefficient of $1/N$, where N is the number of slots. The single transition can then be expanded into an N-way power divider/combiner. The transition was simulated in HP-HFSS. The terminating load at the end of the waveguide was realized by introducing a two-dimensional (2-D) resistor boundary, i.e., the equivalent resistive load for an eight-way power divider at 10 GHz is 571.43 Ω.

The slot length L_s, slot width W_s, and characteristic impedance of the microstrip line $Z_{o,m}$ were varied to obtain the desired level of coupling between the waveguide and microstrip line. In order to characterize the slot, the scattering matrix for the geometry shown in Fig. 4 was calculated at several slot lengths (L_s) and slot widths (W_s) for the desired frequency band. 75-Ω microstrip lines were used instead of 50-Ω lines in order to obtain proper match between the slot and microstrip. At 10 GHz, the resonant slot length was determined to be approximately $0.4\lambda_g$ due to the effective air-dielectric constant at the slot.

An eight-way slotted-waveguide power divider was designed by expanding the single waveguide to microstrip transition. The power-dividing structure was simulated in HP-HFSS. Dielectric and conductor losses were included in the simulation. The input return loss is shown in Fig. 5. At the design frequency, the return loss is 22 dB. The −10-dB bandwidth is approximately 400 MHz.

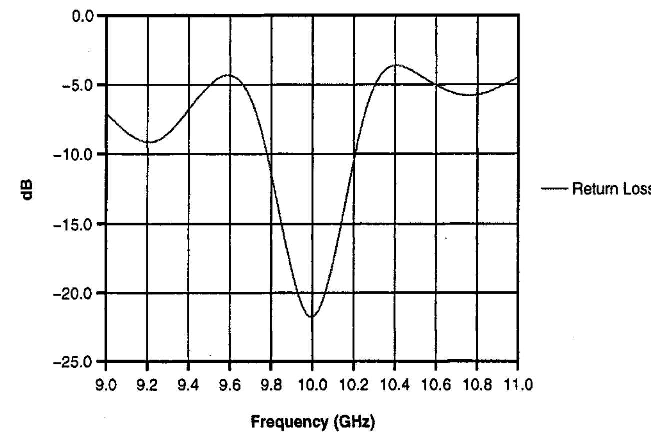

Fig. 5. Input return loss for half the slotted-waveguide divider.

TABLE I
OUTPUT POWER DIVISION AT 10 GHz

S_{21}	S_{31}	S_{41}	S_{51}
-9.2 dB	-9.3 dB	-9.58 dB	-9.92 dB
S_{61}	S_{71}	S_{81}	S_{91}
-9.22 dB	-9.4 dB	-9.31 dB	-9.2 dB

Table I shows the power dividing performance of the slotted waveguide at 10 GHz. The power division at the output ports shows close agreement with the ideal −9 dB required of an eight-way divider. In addition, the voltage and phase variation was determined to be within ±5%.

In order to evaluate the performance of the overall power divider/combiner, the output power of the slotted waveguide is recombined through an identical slotted-waveguide structure. The simulated frequency response of the passive power dividing/combining structure is shown in Fig. 6. At 10 GHz, the predicted insertion loss is 0.3 dB with a 3-dB bandwidth of approximately 650 MHz.

III. EXPERIMENTAL RESULTS

A. Fabrication

Slotted-waveguide array antennas are usually fabricated by making grooves into the base metal plate and placing the etched slot plate on top. A brazing technique is required to provide good electrical contact between the slot plate and the narrow walls grooved in the base [12]. However, in the design presented here, the slotted waveguide was divided into three sections, as shown in Fig. 7. The cuts were made longitudinally along the waveguide center lines to minimize power leakage from the contacts. Pressure contacts were used to avoid brazing and welding of the waveguide contacts. Also, it is possible to feed coolant through the center metallic structure to further improve the thermal dissipation of the power devices.

B. Passive Divider/Combiner Measurement

A passive eight-way divider/combiner was designed, fabricated, and measured. The microstrip circuit placed above the

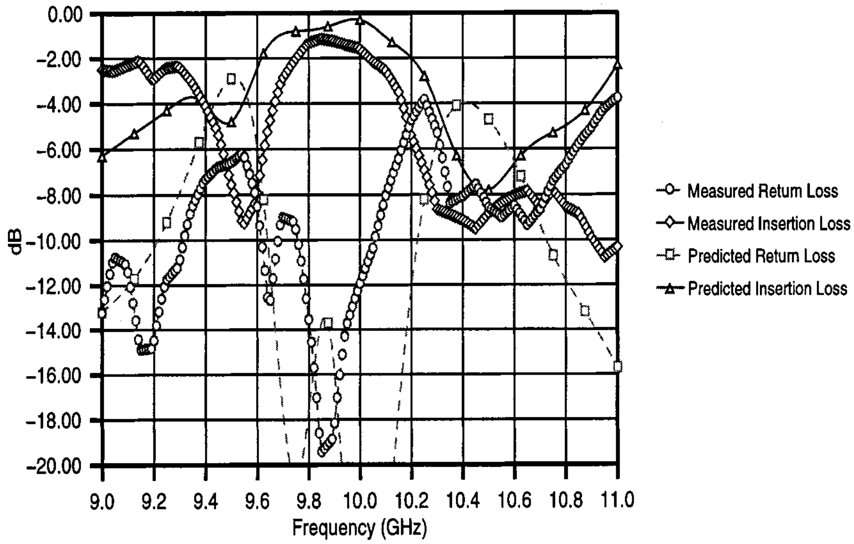

Fig. 6. Predicted and measured return and insertion losses of the slotted-waveguide power dividing/combining structure.

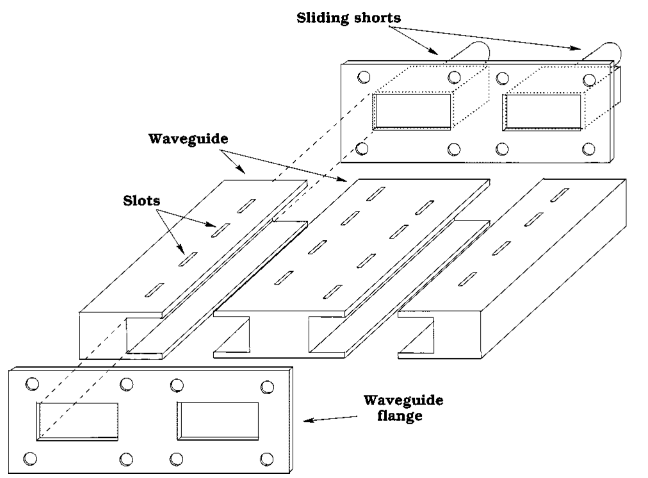

Fig. 7. Assembly of the slotted waveguide to provide good electrical contact.

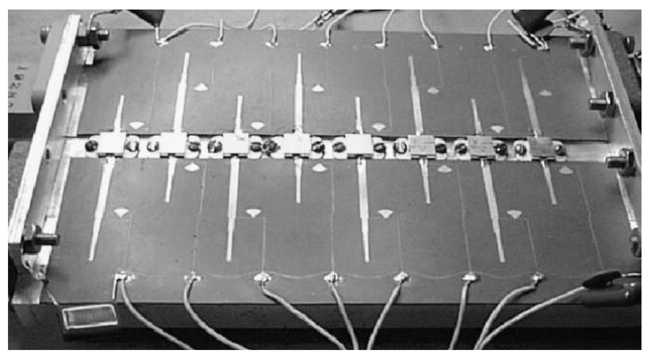

Fig. 8. Slotted-waveguide power amplifier.

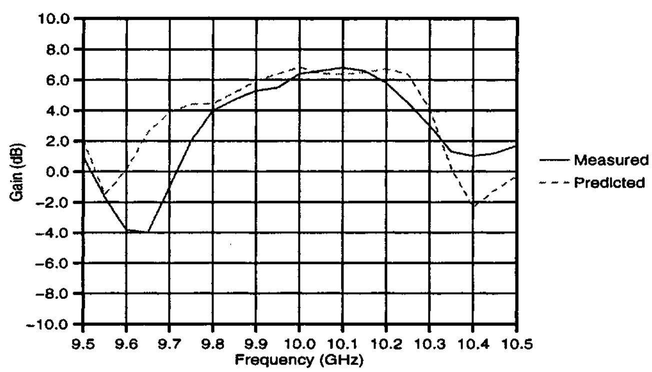

Fig. 9. Predicted and measured gain for the slotted-waveguide power amplifier.

slotted waveguides was fabricated on a 31-mil thick Roger's 5870 RT/Duroid substrate with a dielectric constant of 2.33. In Fig. 6, the measured return and insertion losses for the passive array is shown. The 3-dB bandwidth is approximately 500 MHz and the minimum insertion loss is 1.15 dB at 9.85 GHz. The higher insertion loss in the measured response was due to an imprecision in slot periodicity, which is caused by variation in guide phase velocity near the slots. The shift in frequency was due to inaccuracies in the machining of the slots. Nevertheless, the overall measured response shows good agreement with the predicted results.

C. Active-Array Measurement

An eight-device power-combining amplifier using Fujitsu FLM0910 2-W internally matched GaAs MESFET power amplifiers was designed and fabricated. The 9.7 mm $\times$ 16.5 mm devices were mounted on the thick center plate of the slotted waveguide. Efficient heat sinking of the power amplifiers was achieved by mounting the devices at the center of the metallic structure, as shown in Fig. 8. Each device was biased at 10 V with a drain current of 600 mA. The total input dc power was 48 W. Adjustable shorts were placed at the end of each slotted waveguide. Radial stubs were used for the amplifier input and output bias lines to suppress leakage of RF power. Quarter-wave transformers were used to transform the 75-Ω lines to 50 Ω at the gate and drain of each device. Furthermore, 100-Ω chip resistors in series with 1.9-nH inductors were placed in shunt with the gates of the devices to ensure amplifier stability.

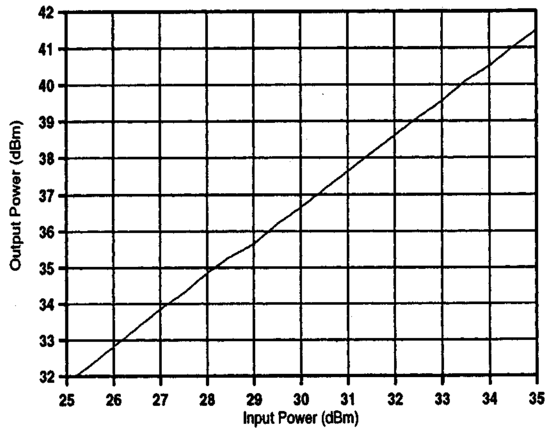

Fig. 10. Measured output power versus input power for the eight-device power amplifier.

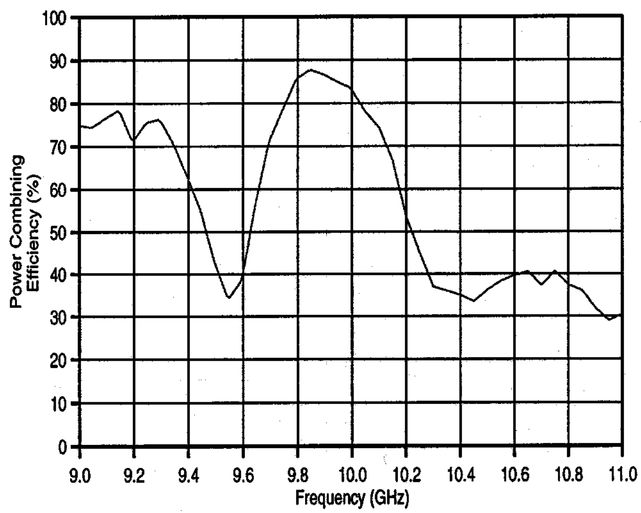

Fig. 11. Frequency dependence of power-combining efficiency for the eight-way power divider/combiner.

Fig. 9 shows the predicted and measured gains of the power amplifier. Lossy microstrip lines and discontinuity models were used in the simulation. The bias lines, stabilizing resistors, and bond wires were also included in the simulation. At 10 GHz, the maximum predicted and measured gain were approximately 6.8 and 6.7 dB, respectively. The measured 3-dB bandwidth for the active array was 500 MHz. Improved bandwidth can be achieved if nonresonant distributed slotted-waveguide topologies are used [10]. Furthermore, the typical bandwidth of microstrip patch antennas is approximately 4%–5%, which will ultimately determine the overall bandwidth in a quasi-optical power-amplifier array.

The output power versus input power is shown in Fig. 10. The power amplifier was not driven into 1-dB compression due to a lack of input power. The maximum output power was 14 W at 9.88 GHz.

The power-combining efficiency of the eight-device amplifier was calculated directly from the measured insertion loss (S_{21}) of the passive divider/combiner [19]. This provides a figure-of-merit for power combining, and is independent of the devices. Fig. 11 shows the power-combining efficiency of the eight-way divider/combiner as a function of frequency. The maximum power-combining efficiency was approximately 88% at 9.85 GHz.

IV. Conclusion

A power amplifier based on a slotted-waveguide power-dividing system has been proposed for the construction of millimeter-wave spatial power-amplifier arrays. An eight-device slotted-waveguide array amplifier was designed and tested to validate the power-dividing/combining mechanism using this technique. The active-array 3-dB bandwidth and power-combining efficiency were approximately 500 MHz and 88%, respectively. An output power of 14 W was achieved without driving the amplifier into 1-dB compression. Furthermore, a general outline of the design procedure has been presented using commercially available computer-aided design (CAD) tools.

Acknowledgment

The authors would like to acknowledge Fujitsu Compound Semiconductor Inc., San Jose, CA, for the donation of the GaAs MESFET power amplifiers.

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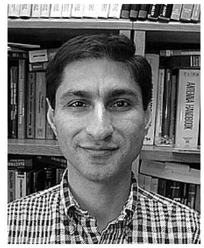

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