A Ka-Band Power Amplifier Based on a Low-Profile Slotted-Waveguide Power-Combining/Dividing Circuit

Xin Jiang, Li Liu, Sean C. Ortiz, *Student Member, IEEE*, Rizwan Bashirullah, and Amir Mortazawi

***Abstract*—In this paper, a Ka-band power amplifier based on a resonant slotted-waveguide-to-microstrip power-dividing/combining circuit is presented. The advantages of this structure are its low profile, ease of fabrication, as well as its potential for high power-combining efficiency. In addition, efficient heat sinking of monolithic microwave integrated circuit (MMIC) devices is achieved. A slotted-waveguide power amplifier using eight MMIC amplifiers was designed and fabricated. The measured power-combining efficiency at 33 GHz is 72%. In addition, simulation results predicting the performance degradation of the slotted-waveguide power amplifier due to multiple device failure are presented.**

***Index Terms*—Ka-band, power amplifier, power combining, slotted waveguide.**

I. Introduction

CONVENTIONAL hybrid-type power-combining circuits, such as the Wilkson power divider, Lange coupler, and branch-line coupler, suffer from low power efficiency at millimeter frequencies [1]. Several techniques, such as quasi-optical and waveguide-based spatial power-combining approaches, have been proposed to address this issue [2]–[6]. At Ka-band, the waveguide-based 1×2 and 2×2 power-amplifier modules were reported in [6] with a power-combining efficiency of 83%. This paper presents the design and experimental results for a Ka-band slotted-waveguide power amplifier. The waveguide structure used in this design has several advantages, such as high efficiency, low profile, low complexity, and efficient heat sinking for active devices. In our previous design, a waveguide power combiner at X-band was demonstrated with a power-combining efficiency of 88% [7]. In this paper, besides the experimental results for the eight-device Ka-band power amplifier, simulation results that predict the performance degradation of the amplifier due to multiple device failure are also presented.

II. Design

As illustrated in Fig. 1, the circuit consists of input and output slotted waveguides coupled to microstrip lines and Ka-band monolithic microwave integrated circuit (MMIC) amplifiers. The input power is divided into N ways through identical slots on the broadwall of the input waveguide. These slots are separated by half-guide wavelength to achieve an equal power division. The input and output ports of the slotted-waveguide power amplifier can either be on the same or the opposite sides of the slotted waveguides, with the other two waveguide ports terminated with shorts. This offers more flexibility in feeding the circuits without degenerating the performance.

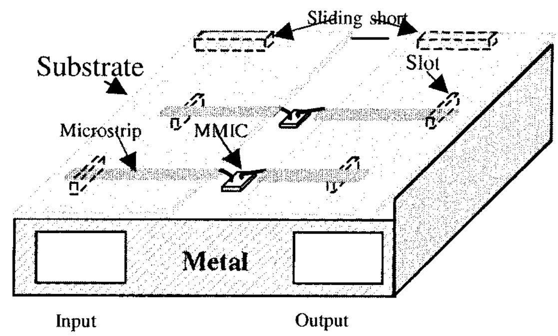

Fig. 1. Topology of the eight-device Ka-band waveguide power amplifier. (Only the last two sections of the dividing/combing structure is shown.)

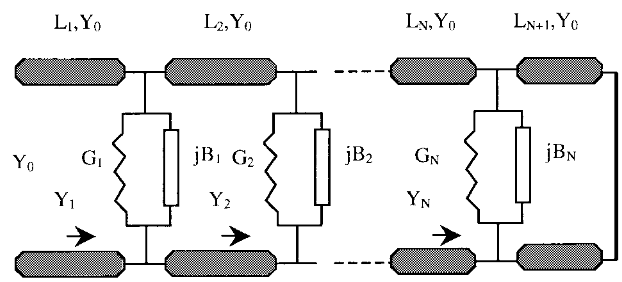

Fig. 2. Equivalent circuit of an N-way resonant power-dividing/combining structure.

Although designing the entire multiple ports' dividing/combining structure at millimeter-wave frequencies is possible through an iterative approach based on full-wave electromagnetic (EM) simulations, such an approach can be very time consuming due to the large size of the whole structure in terms of wavelength. Since all slot-to-microstrip coupling units are identical, a better solution is to use a distributed equivalent circuit for the entire structure based on single waveguide-to-microstrip coupler design with desired equivalent admittance. As shown in Fig. 2, the longitudinal waveguide slot is modeled as a shunt element along a transmission line [8]–[10]. The

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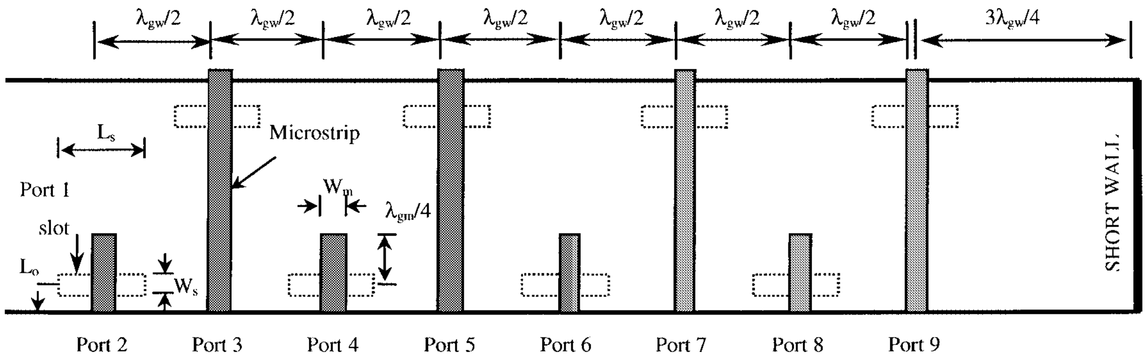


Fig. 3. Geometry of the eight-way dividing/combining structure and its port numbering [W_s: 0.58 mm, L_s: 5.80 mm, L_o: 1.45 mm, W_m: 0.61 mm (50 Ω)].

conductance G_k and susceptance B_k represent the discontinuity due to the kth slot. L_k ($k = 2, 3, \ldots, N$) represents the distance between the center of the kth and $(k+1)$th slot, and Y_0 is the TE_{10}-mode impedance for the waveguide. Assuming that the coupling between the adjacent slots is negligible, the admittance looking into each section of the waveguide is

$$Y_k = (G_k + jB_k) + Y_0 \frac{Y_{k+1} + jY_0 \tan(\beta L_{k+1})}{Y_0 + jY_{k+1} \tan(\beta L_{k+1})},\quad k = 1, 2, \ldots, N. \tag{1}$$

Perfect power dividing/combining requires uniform amplitude and phase between each dividing and combining unit [11], which can be achieved by placement of these identical slots along the waveguide with a spacing of $\lambda_g/2$. For each single slotted-waveguide to microstrip coupler, the design goal is to achieve the proper waveguide to microstrip coupling by adjusting the slot length, width, and its offset from the waveguide edge, as shown in Fig. 3. The entire dividing/combing circuit is then designed by cascading the N slotted-waveguide couplers.

Based on the design procedure discussed, an eight-way Ka-band passive power divider was designed. A sliding short was used to terminate the waveguide end. The signal is coupled to microstrip lines placed directly above the slots, where the top wall of the waveguide serves as the ground plane for the microstrip lines. The open-ended microstrip lines extend a quarter-wavelength beyond the center of the slots to provide a virtual short at the slots. To accommodate the slots in a compact space, they are alternately positioned with respect to waveguide walls. In order to obtain a better impedance match between waveguide and microstrip lines, a reduced height WR-28 waveguide (7.112 mm × 1.778 mm) was used. The thickness of the waveguide's top wall is 1.016 mm (slot thickness). Rogers TMM6 with a dielectric constant of 6.0 and thickness of 0.381 mm was used as the substrate for the microstrip line. Other dimensions are given in Fig. 3.

III. Simulation and Experimental Results

The S-parameters of the eight-way dividing circuit part were simulated using Agilent HFSS. Equal power division (−9.25±0.55 dB) is achieved at approximately 32 GHz [see Fig. 4(a)], which is close to the expected value of −9 dB. Also, the phases of the coupling coefficients are found to be uniform [see Fig. 4(b)]. A passive divider/combiner circuit was built by

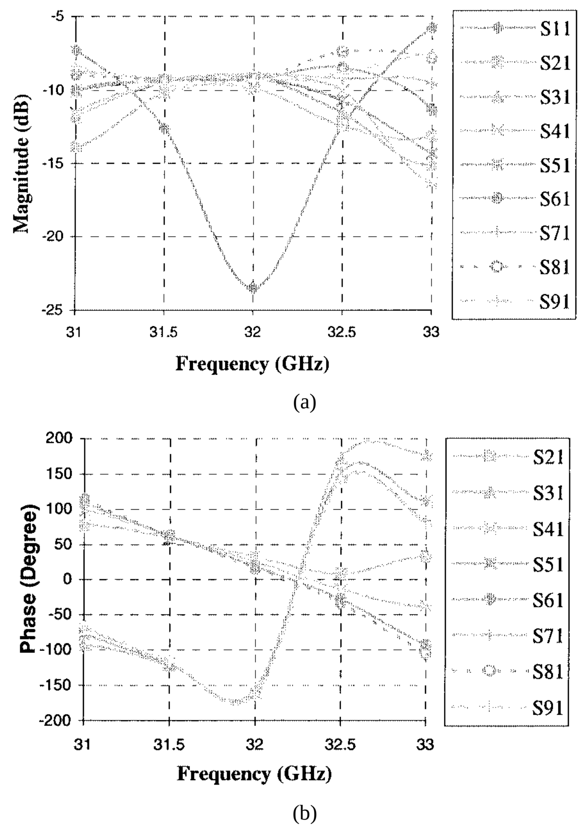


Fig. 4. Simulated results of the eight-way power divider/combiner. (a) Magnitude. (b) Phase.

placing two identical circuits back to back. At 32.5 GHz, the measured insertion loss of 1.8 dB was achieved with a return loss of 13 dB (Fig. 5), which indicates a maximum expected power-combining efficiency of 81% for the combining circuit. At 33 GHz, the measured insertion loss is 2.4 dB, corresponding to a power-combining efficiency of 76%. A slight frequency shift was noted between the measured and HFSS simulation results.

Based on the passive power dividing/combining circuit, the Ka-band slotted-waveguide power amplifier using eight Triquint TGA1073A MMIC chips was fabricated and measured. The amplifier has over 17 dB of small-signal gain and over 10 dB of return loss at 33 GHz [see Fig. 6(a)]. The measured 3-dB bandwidth is 1.25 GHz ($f_L = 32.42$ GHz, $f_H = 33.67$ GHz).

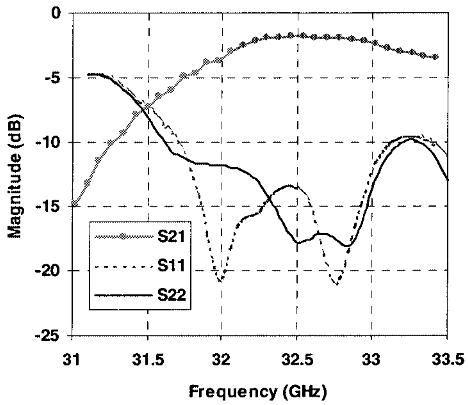
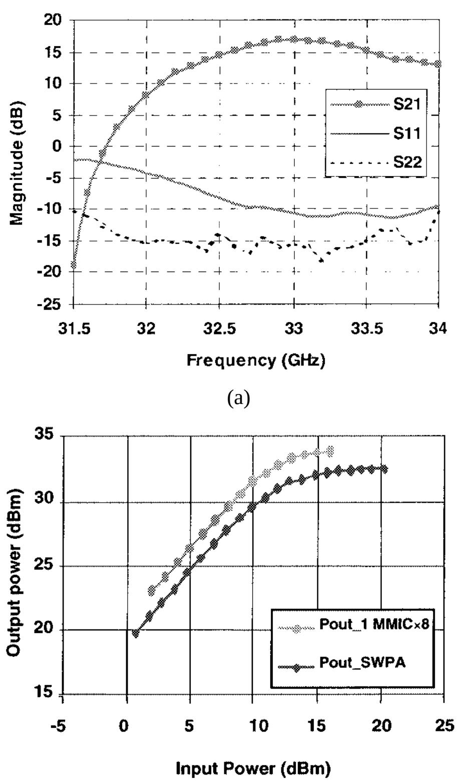


Fig. 5. Measurement results of the passive power divider and combiner placed back to back.



(a)

(b)

Fig. 6. (a) Measured S-parameters of the slotted-waveguide power amplifier. (b) Single MMIC output power $\times 8$ and the measured output power of the eight-device slotted-waveguide power amplifier.

In addition, the power compression for the amplifier has been measured [see Fig. 6(b)]. At 33 GHz, this eight-device slotted-waveguide power amplifier provides an output power of 31.6 dBm at 1-dB compression. Since the measured single MMIC chip output-power level ($P_{\mathrm{out@1\,dB}}$) is 24 dBm, the ideal eight-device power combiner would provide output power of 33 dBm. This translates into the power-combining efficiency of approximately 72%, close to the 76%, the expected value based on the passive divider/combiner measurement at 33 GHz. The MMICs are biased at 6 V with a total dc current of 1.76 A. The overall power-added efficiency (PAE) is approximately 13.7% at 33 GHz. We believe it is possible to achieve a better

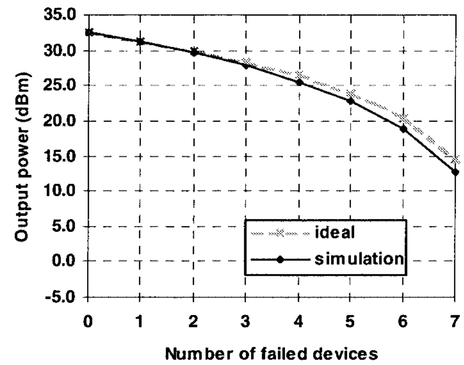


Fig. 7. Simulated output power of the slotted-waveguide power amplifier versus number of failed devices.

power-combing efficiency by reducing the length of the microstrip lines in the existing circuits and through more accurate construction of the waveguide power divider/combiner.

By modeling MMIC failure as the open, short, and matched load for different failure mechanisms [12], the performance degradation of the slotted-waveguide power amplifier as a function of the number of failed devices can be predicted. The power drop is slightly dependent on the location of the faulty device, and the matched case scenario has a more pronounced impact on the slotted-waveguide power-amplifier output-power level. However, as the number of failed devices increases, the output-power drop becomes less sensitive to short, open, and matched conditions representing various failures. Fig. 7 shows the simulated output power of the slotted-waveguide power amplifier as a function of the number of failed devices. (The faulty devices are treated as match and their locations are arbitrarily chosen.) It can be seen as follows that the simulated output power P for the match case is very close to the ideal case predicted in [12]:

$$P = P_0(1-f)^2 \tag{2}$$

where f is the fraction of the failed device, and P_0 is the output power when all devices work. This further demonstrates the potential utility of the slotted-waveguide power amplifier for low loss and reliable millimeter-wave power combining.

IV. Conclusions

An eight-device Ka-band power amplifier has been designed based on a resonant slotted-waveguide power-dividing/combining structure. Low loss and high power-combining efficiency have been achieved at millimeter-wave frequencies using this power-combining method. Meanwhile, this design can provide sufficient heat sinking for high-power solid-state devices. The power amplifier developed in this study provided 17 dB of small-signal gain with return loss greater than 10 dB at 33 GHz. A power-combining efficiency of 72% was achieved from this eight-device power amplifier at 33 GHz.

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