Published in IET Microwaves, Antennas & Propagation
Received on 4th September 2008
Revised on 16th November 2008
doi: 10.1049/iet-map.2008.0299

ISSN 1751-8725

Broadband radial waveguide power amplifier using a spatial power combining technique

K. Song[1,2] *Y. Fan*[1] *X. Zhou*[2]

[1]*EHF Key Lab of Fundamental Science, School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, 610054, People's Republic of China*
[2]*Department of Geophysical Engineering, Montana Tech of the University of Montana, Butte, MT 59701, USA*
E-mail: kjsong@ee.uestc.edu.cn

Abstract: A broadband radial waveguide power amplifier has been designed and fabricated using a spatial power dividing/combining technique. A simple electromagnetic model of this power-dividing/combining structure has been developed. Analysis based on equivalent circuits gives the design formula for perfect power-dividing/combining circuits. The measured small-signal gain of the eight-device power amplifier is 12–16.5 dB over a broadband from 7 to 15 GHz. The measured maximum output power at 1-dB compression is 28.6 dBm at 10 GHz, with a power-combining efficiency of about 91%. Furthermore, the performance degradation of this power amplifier because of device failures has also been measured.

1 Introduction

Recent years have seen a worldwide effort to develop high-power solid-state power amplifiers with high efficiency and wide bandwidth because of the rapid advancements of military and commercial communications systems [1–6]. As the output power from an individual solid-state device is rather modest at microwave, especially millimetre-wave frequencies, the need for power combining at microwave and millimetre-wave frequencies becomes evident. This has motivated considerable research activities to develop broadband and efficient power-dividing/combining circuits at these frequencies [7-11]. Conventional hybrid-type power-combining circuits, such as the Wilkinson power divider, Lange coupler and branch-line coupler, suffer from low power-combining efficiency at microwave and millimetre frequencies [12]. To meet the requirements, various techniques, such as quasi-optical and waveguide-based spatial power-combining approaches, have been proposed for these frequencies [13–18].

A power-combining technique, which uses a radial waveguide distribution circuit to achieve power dividing/combining, is analysed in this paper. The circuit consists of a radial waveguide feed network, a coaxial feed probe connected to its centre and an array of probe-fed elements. The array is made up of N identical elements arranged in M concentric circles. By appropriate placement of the probes in the radial waveguides, equal power dividing can be achieved, and the power can then be coupled from the free space of the radial waveguide. This topology has low loss because of its metal waveguide configuration compared with other transmission lines, such as the microstrip line power divider and the strip line power divider. Furthermore, the radial waveguide power divider has a good heat-sinking capability and is ease of fabrication.

As far as we know, most of the work on radial waveguide structures is related to antenna arrays [19–23]. Although the radial divider/combiner was thoroughly investigated in [24–26], little attention has been paid to its application in a real system that could include active components. In this paper, a power amplifier that implements this dividing technique is designed and fabricated, as shown in Fig. 1. The power-dividing/combining system includes a radial divider and a radial combiner. An input signal is provided to a transmission antenna (the central probe) that radiates the input signal inside the divider. Within the divider, there is an antenna array (peripheral probe array) that receives the signal and feeds it to respective amplifiers. The amplifiers amplify the respective individual signals by a desired amplification gain. The amplified individual signals

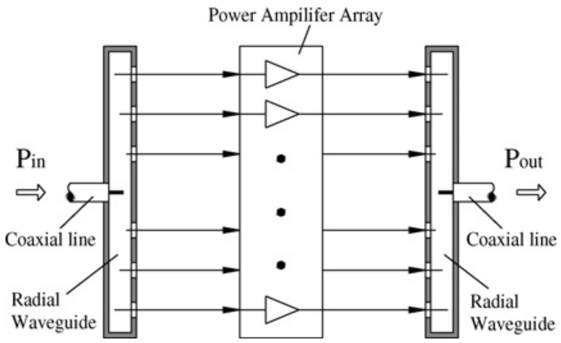

Figure 1 *A schematic of the radial waveguide power combiner*

are fed to a plurality of probe antennas within the combiner. Inside the combiner, the amplified individual signals are combined to form an output signal that is received by a receiving antenna (the central probe) in the combiner.

In the following sections, the operation and characteristics of the radial waveguide power divider are presented. The analysis performed is based on equivalent-circuit models to simplify the design approach for an N-way radial waveguide divider. The design procedure and simulation for the passive power-dividing/combining circuit is also discussed. Fabrication and test results of the eight-way power divider and the active eight-device power amplifier are presented. In addition, the amplifier's tolerance to active device failures has also been measured under different device failure mechanisms.

2 Design approach

An eight-way radial waveguide power divider is shown in Fig. 2. The central probe and the peripheral probes are on the opposite sides of the radial waveguide. The peripheral probes are assumed to be identical in shape and size. For an N-way radial waveguide power divider, its structure is similar to the eight-way power divider and its N peripheral probes are symmetrically located on one sides of the radial waveguide. According to the symmetry of the power divider, we can obtain a simple electromagnetic model for an N-way radial waveguide power divider, as shown in Fig. 3.

A reference plane (the circle of radius R_0) divides the entire power divider into two volumes: a central cylindrical volume of radius R_0 (comprising the central probe) and a cavity region (comprising the peripheral probes) outside the central cylindrical volume. This N-way power divider can be viewed as a structure composed of N identical sectoral waveguides that are separated by magnetic side walls, as shown in Fig. 3. When the N-way power divider consists of a large number of peripheral probes (for example $N > 6$), the section of each sectoral waveguide comprising a peripheral probe can be approximated by a rectangular waveguide comprising a peripheral probe. Thus, the N-way power divider can be viewed as a structure composed of N

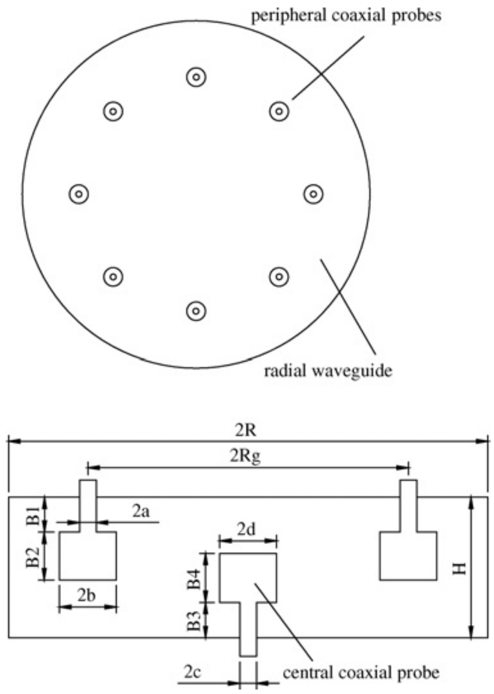

Figure 2 *Topology of a radial waveguide power divider*

identical rectangular waveguides separated by magnetic side walls. Thus, an equivalent-circuit approach can be introduced to analyse this sample model. The input admittance seen from the rectangular waveguide (comprising a peripheral probe) and normalised to the waveguide admittance is

$$Y_w = G_w + jB_w = \frac{1 - \mathrm{Cot}(\Phi_1)\mathrm{Cot}(\Phi_2) - jY_p\mathrm{Cot}(\Phi_1)}{Y_p - j(\mathrm{Cot}(\Phi_1) + \mathrm{Cot}(\Phi_2))} \quad (1)$$

where $Y_p = G + jB$ is the admittance of a peripheral probe, Φ_1 is the electrical length between the waveguide input port and the peripheral probe, and Φ_2 is the electrical length between the waveguide short wall and the peripheral probe.

The central cylindrical volume of radius R_0 comprising the central probe can be viewed as a two-port device, as shown in Fig. 4. Fig. 4*b* shows its equivalent circuit. $Y_c = G_c + jB_c$ is the admittance of the central probe. The radial line from reference plane BB' to AA' is viewed as an $ABCD$ matrix, which can be obtained from its equivalent circuit [27].

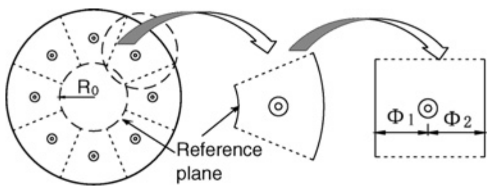

Figure 3 *A schematic of the simple electromagnetic model*

IET Microw. Antennas Propag., 2009, Vol. 3, Iss. 8, pp. 1179–1185
doi: 10.1049/iet-map.2008.0299

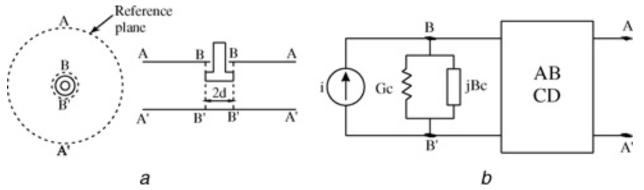

Figure 4 *Central cylindrical circuits*

a A schematic of the central cylindrical volume
b Its equivalent circuit

Based on the analysis above, the equivalent circuit of the N-way radial waveguide power divider can be determined, as shown in Fig. 5. $Y_1 = G_L + jB_L$ is the admittance looking from reference plane AA' to the central probe, and can be obtained from Y_c. The $Y_2 = G_S + jB_S$ is the admittance looking from reference plane AA' to the peripheral probes, and can be given as

$$Y_2 = nY_w = nG_w + jnB_w = \frac{n[1 - \mathrm{Cot}(\Phi_1)\mathrm{Cot}(\Phi_2) - jY_p\mathrm{Cot}(\Phi_1)]}{Y_p - j(\mathrm{Cot}(\Phi_1) + \mathrm{Cot}(\Phi_2))} \quad (2)$$

For perfect impedance match at reference plane AA', the following conditions must be satisfied

$$G_L = nG_W \quad (3)$$

$$B_L = -nB_W \quad (4)$$

The design procedure for an N-way radial waveguide power divider is as follows:

(a) The radial waveguide perimeter and height (H) of the N-way radial waveguide power divider is chosen to be approximately N times the width and height of a rectangular waveguide, respectively, when $N > 6$. The dimensions of the rectangular waveguide can be chosen according to the design frequency. So, the radius of the radial waveguide is

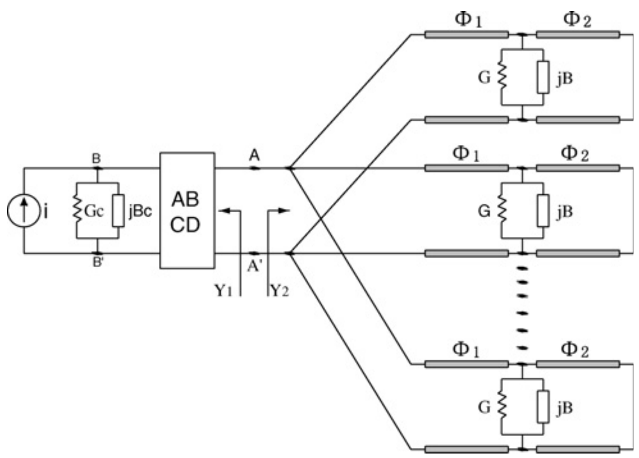

Figure 5 *An equivalent circuit of the N-way radial waveguide power divider*

$$R \simeq \frac{NW}{2\pi} \quad (5)$$

where W is the width of the rectangular waveguide.

(b) The distance of the peripheral probes from the cavity centre is

$$R_g \simeq R - \lambda_g/4 \quad (6)$$

(c) According to the dimensions of the SMA connector, the initial inner conductor radii (a and c) of the coaxial probes can be obtained.

(d) According to [28], the input reflection of the central cylindrical volume can be calculated using field matching method, and the dimensions (d, $B3$ and $B4$) of the central probe can also be optimised. The central probe admittance Y_c can be obtained.

(e) After choosing the reference plane (the circle of radius R_0), the $ABCD$ matrix can be determined, and the admittance Y_1 can also be obtained. Using (1)–(4), the admittance of a peripheral probe, Y_p, can be calculated, and the dimensions (b, $B1$ and $B2$) of the peripheral probe can be determined [28].

(f) According to (a)–(e), all of the dimensions about the power divider are determined. Thus, the whole power-dividing structure can be optimised for a minimum insertion loss and a good input match over the design band by using Ansoft-HFSS.

3 Experimental results

3.1 *Design of an eight-way radial power divider*

Based on the design procedure given above, an eight-way radial waveguide power divider is designed. The power-dividing structure is then simulated and optimised using Ansoft-HFSS. The dielectric and conductor losses are included in the simulation. The initial and optimised dimensions of the radial waveguide, central coaxial probe and peripheral coaxial probe are listed in Table 1. The radial waveguide power-dividing structure has been fabricated through machining of a waveguide cavity in the copper blocks. The power divider is terminated by the type-SMA connectors available commercially. The coaxial probes are inserted inside the waveguide at the designed locations. Fig. 6 shows a picture of the eight-way radial waveguide power divider.

Table 1 Dimensions of the radial waveguide power divider (unit: mm)

Dimensions	*a*	*b*	*c*	*d*	*R*	R_g
initial values	0.65	1.5	0.65	2.5	29.1	22.3
optimised values	0.65	1.55	0.65	2	29	22.6
dimensions	B1	B2	B3	B4	H	
initial values	2	3.5	1.9	3.2	10.1	
optimised values	1.6	2.8	1.7	2.6	7.8	

The simulated and measured *S* parameters (Fig. 7) of the eight-way power divider show an equal power division over a wide bandwidth while maintaining a relatively low return loss. In Fig. 7, only the insertion loss S21 is displayed. The insertion losses S31, S41, S51, S61, S71 and S81 are the same as S21 and thus not shown. The measured and simulated bandwidths of 15-dB return loss of the broadband multiple-port structure are both about 7 GHz. The bandwidth around which the minimum insertion loss increases by 1 dB is found to be 8 GHz experimentally. The predicted value by simulation is about 9 GHz. Compared with the simulation results, the increased insertion loss is most likely attributed to the fabrication errors such as inaccuracies in assembling the coaxial probes and SMA connectors. Nevertheless, the overall measured response shows a good agreement with the simulated results.

3.2 Active-array measurement

Based on the eight-way power divider above, an eight-device power amplifier using Hittite HMC441LM1 internally matched GaAs PHEMT medium power amplifiers is designed and fabricated. A picture of this power amplifier is shown in Fig. 8. The physical dimensions of the finished amplifier are 46.6 mm (length) × 70 mm (width) × 70 mm (height) and its overall weight is about 968 g. Efficient heat sinking of the power amplifiers is achieved by mounting the device on the ground plane between two radial

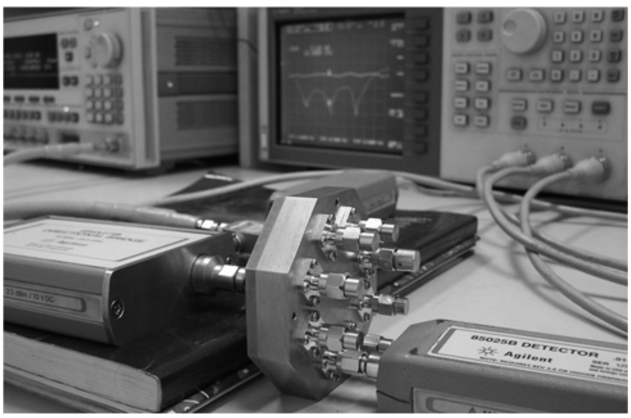

Figure 6 *A picture of the eight-way radial waveguide power divider manufactured*

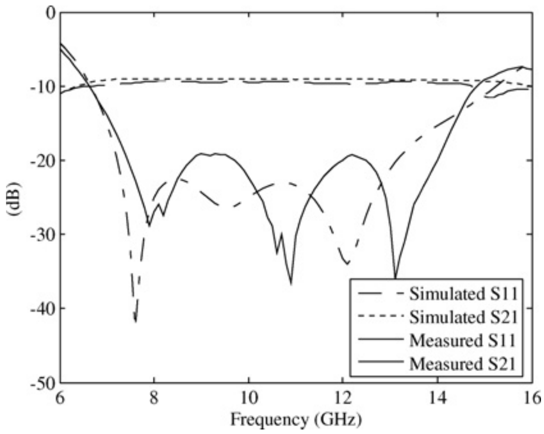

Figure 7 *Simulated and measured S-parameters of the power divider*

waveguides, as shown in Fig. 8. To improve the heat-sinking capability of the power amplifier, the divider, the combiner and the ground block between the two radial waveguides can be fabricated as an integral block using brass, which can efficiently reduce the heat resistance between the ground block and the radial waveguide. In this paper, the divider, the combiner and the ground block have been fabricated separately, in order that the *S* parameters of the divider can be measured and the design procedure described above can be validated. Moreover, to improve the heat-sinking capability of the power amplifiers, the cooling fins can be fabricated under the surface of the radial waveguide. According to (5), the diameter of the power divider/combiner increases with the increasing number of ways, which is good for efficient heat removal, but the operation bandwidth decreases when the number of ways increases.

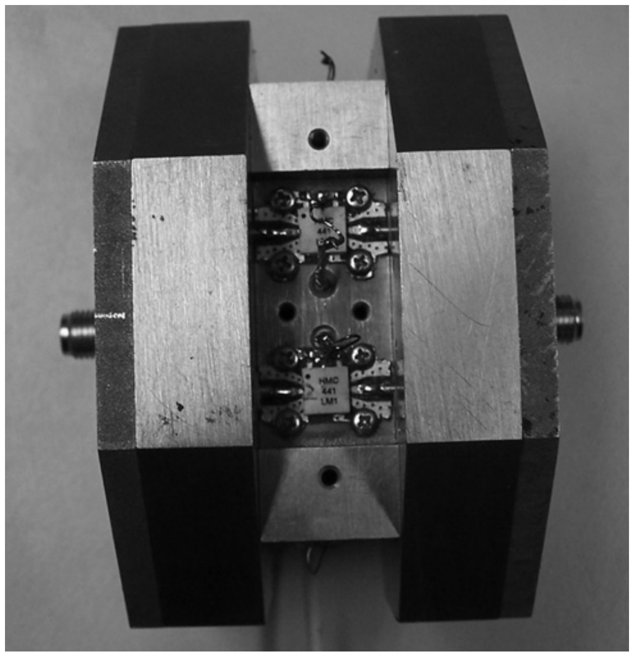

Figure 8 *A picture of the radial waveguide power amplifier fabricated*

doi: 10.1049/iet-map.2008.0299

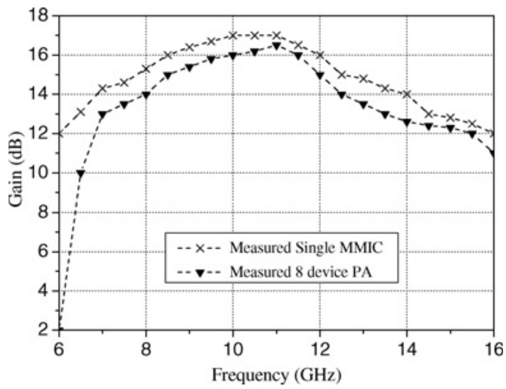

Figure 9 *Measured small-signal gain*

In order to determine the power-combining performance of the eight-device amplifier, a single MMIC amplifier has also been fabricated to characterise its small- and large-signal response. The HMC441LM1 is a broadband (7–15.5 GHz) internally matched GaAs PHEMT MMIC medium power amplifier in a SMT leadless chip carrier package. Typical input return loss of a HMC441LM1 is less than −10 dB and output return loss is less than −15 dB over the frequency range from 8 to 16 GHz. The amplifier provides 15 dB of gain, 21.5 dBm of saturated power at 27% power-added efficiency (PAE) from a +5.0 V supply voltage. An optional gate bias is provided to allow adjustment of gain, RF output power and DC power dissipation. This 50 Ω matched amplifier does not require any external components, making it an ideal linear gain block or driver for HMC SMT mixers. The fabricated single HMC441LM1 power amplifier shows a 14–17 dB small-signal gain over a broadband from 7 to 14 GHz. The measured maximum small-signal gain for the single MMIC amplifier is 17 dB (see Fig. 9) with a 1 dB compression output power of 20 dBm at 10.5 GHz.

The measured small-signal gain of the eight-device power amplifier is also shown in Fig. 9. The radial waveguide power amplifier has 12–16.5-dB gain over a bandwidth from 7 to 15 GHz. The upper and lower ends of the bandwidth of the eight-device power amplifier are limited by the single

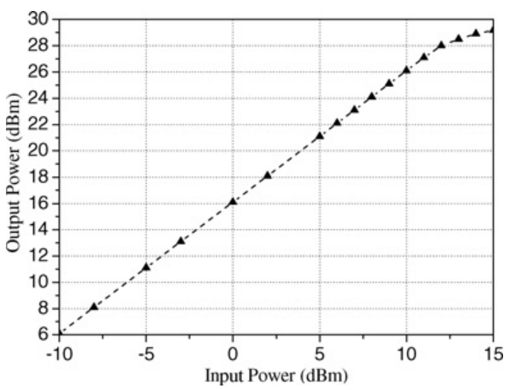

Figure 10 *Output power against input power of the eight-device power amplifier at 10 GHz*

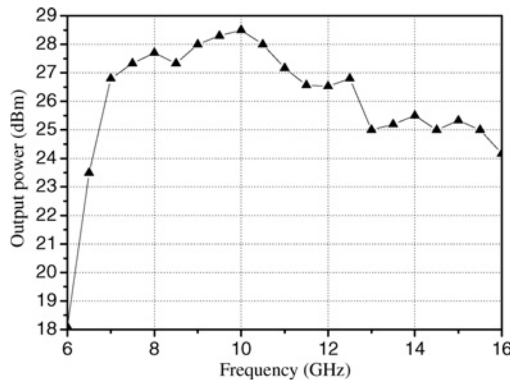

Figure 11 *Measured Pout@1 dB of the eight-device power amplifier*

MMIC of HMC441LM1. It should also be noticed that the variation with frequency of the single MMIC amplifier's gain affects the overall power amplifier's gain flatness (Fig. 9). In addition, the power compression for the eight-device power amplifier has been measured. The maximum output power of 28.6 dBm at 1-dB gain compression has been achieved at 10 GHz (see Fig. 10), with a power-combining efficiency of 91%. The eight-device power amplifier was biased at 5 V with a total DC current of 0.82 A. The overall PAE of the eight-device power amplifier is approximately 17.7% at 10 GHz. The output power at 1-dB gain compression as a function of frequency is also shown in Fig. 11. A 27–28.6-dBm output power at 1-dB gain compression is reached over a broadband from 7 to 11 GHz.

Fig. 12 shows the measured output power compressions of the radial waveguide power amplifier for various numbers of failed devices. In our experiments, multiple active devices are turned off to model the device's failure mechanism, and the device failed can be viewed as a matched load. When a single device fails, the reduction in output power can be calculated by [29]

$$|b\prime_0/b_0|^2 = (1-f)^2 \tag{7}$$

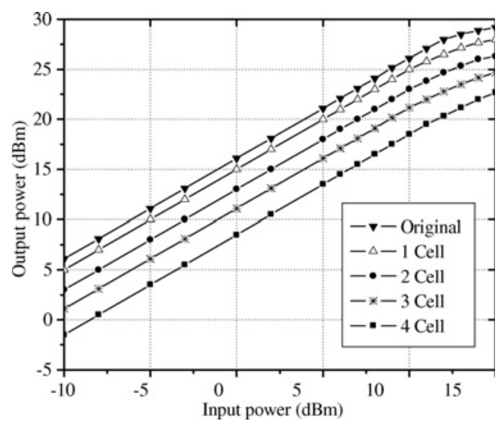

Figure 12 *Measured output power drops as various numbers of device failures*

Table 2 Comparison of the output reductions measured with those calculated by (7)

numbers of device failures	1	2	3	4
output reductions calculated (dB)	1.16	2.5	4.08	6
output reductions measured (dB)	1.2	2.6	4.4	5.9

where $f = 1/N$. Equation (7) can be iterated for multiple failures. The output reductions measured and calculated by (7) are listed in Table 2. It can be seen that both of them are compatible. The measured results further demonstrate the potential utility of the radial waveguide power amplifier for low loss and reliable millimetre-wave power combining.

4 Conclusions

A power amplifier based on a radial waveguide power-dividing/combining system has been developed for the construction of broadband spatial power-amplifier arrays. An eight-device radial waveguide power amplifier is designed and tested to validate the power-dividing/combining mechanism using this technique. The eight-way power-dividing circuit shows a 15-dB return loss bandwidth of 7 GHz. The active circuit demonstrates a maximum small-signal gain of 16.5 dB at 11 GHz with a 3-dB bandwidth of 5.5 GHz. A maximum output power of 28.6 dBm at 1-dB gain compression has been achieved at 10 GHz, corresponding to a power-combining efficiency of 91%. In addition, the measured results demonstrate smooth performance degradation as multiple devices fail. In conclusion, this power-amplifier design demonstrates the advantages of wide bandwidth, low loss, high power-combining efficiency, and sufficient heat sinking for microwave and millimetre-wave power applications.

5 Acknowledgments

This work was supported by Youth Science & Technology Foundation of the University of Electronic Science and Technology of China (JX0711), by NASA through Montana Space Grant Consortium (G316-06-W0381), and by Montana Tech faculty seed grant.

6 References

[1] BELAID M., MARTINEZ R., WU K.: 'A mode transformer using fin-line array for spatial power-combiner applications', *IEEE Trans. Microw. Theory Tech.*, 2004, **52**, (4), pp. 1191–1198

[2] JIANG X., ORTIZ S.C., MORTAZAWI A.: 'A Ka-band power amplifier based on the traveling-wave power-dividing/combining slotted-waveguide circuit', *IEEE Trans. Microw. Theory Tech.*, 2004, **52**, (2), pp. 633–639

[3] JEONG J., KWON Y., LEE S., CHEON C., SOVERO E.A.: '1.6- and 3.3-W power-amplifier modules at 24 GHz using waveguide-based power-combining structures', *IEEE Trans. Microw. Theory Tech.*, 2000, **48**, pp. 2700–2708

[4] YONGSHIK L., EAST J.R., KATEHI L.P.B.: 'Micromachined millimeter-wave module for power combining'. IEEE MTT-S Int. Microwave Symp. Digest, June 2004, vol. 1, pp. 349–352

[5] AOKI I., KEE S.D., RUTLEDGE D.B., HAJIMIRI A.: 'Distributed active transformer – a new power-combining and impedance-transformation technique', *IEEE Trans. Microw. Theory Tech.*, 2002, **50**, (2), pp. 316–330

[6] DE VILLIERS D.I.L., VAN DER WALT P.W., MEYER P.: 'Design of a ten-way conical transmission line power combiner', *IEEE Trans. Microw. Theory Tech.*, 2007, **55**, (2), pp. 302–308

[7] FATHY A.E., LEE S.-W., KALOKITIS D.: 'A simplified design approach for radial power combiners', *IEEE Trans. Microw. Theory Tech.*, 2006, **54**, (1), pp. 247–255

[8] SONG K., FAN Y., ZHANG Y.: 'Eight-way substrate integrated waveguide power divider with low insertion loss', *IEEE Trans. Microw. Theory Tech.*, 2008, **56**, (6), pp. 1473–1477

[9] SONG K., FAN Y., ZHANG Y.: 'Radial cavity power divider based on substrate integrated waveguide technology', *Electron. Lett.*, 2006, **42**, (19), pp. 1100–1101

[10] JIA P.C., CHEN L.-Y., ALEXANIAN A., YORK R.A.: 'Multioctave spatial power combining in oversized coaxial waveguide', *IEEE Trans. Microw. Theory Tech.*, 2002, **50**, (5), pp. 1355–1360

[11] ALEXANIAN A., YORK A.: 'Broadband waveguide-based spatial combiner'. IEEE MTT-S Int. Microwave Symp. Digest, June 1997, vol. 3, pp. 1139–1142

[12] CHANG K., SUN C.: 'Millimeter-wave power-combining techniques', *IEEE Trans. Microw. Theory Tech.*, 1983, **MTT-31**, pp. 91–107

[13] ORTIZ S., HUBERT J., MIRTH L., *ET AL.*: 'A high-power Ka-band quasi-optical amplifier array', *IEEE Trans. Microw. Theory Tech.*, 2002, **50**, pp. 487–494

[14] DELISIO M.P., YORK R.A.: 'Quasi-optical and spatial power combining', *IEEE Trans. Microw. Theory Tech.*, 2002, **50**, (3), pp. 929–936

[15] JIA P.C., CHEN L.-Y., ALEXANIAN A.: 'Broad-band high-power amplifier using spatial power-combining technique', *IEEE Trans. Microw. Theory Tech.*, 2003, **51**, (12), pp. 2469–2475

[16] BECKER J.P., OUDGHIRI A.M.: 'A planar probe double ladder waveguide power divider', *IEEE Microw. Wirel. Compon.*, 2005, **15**, (3), pp. 168–170

doi: 10.1049/iet-map.2008.0299

[17] SANADA A., FUKUI K., NOGI S.: 'A waveguide type power divider/combiner of double-ladder multi-port structure', *IEEE Trans. Microw. Theory Tech.*, 1994, **42**, (7), pp. 1154–1161

[18] SECHI F., BUJATTI M., KNUDSON R., BUGOS R.: 'Radially combined 30 W, 14–16 GHz amplifier'. IEEE MTT-S Int. Microwave Symp. Digest, 1994, vol. 3, pp. 1737–1740

[19] PAZIN L., LEVIATAN Y.: 'Design of a radial waveguide feed network for a pin-fed array antenna', *IEE Proc. Microw. Antennas Propag.*, 2006, **153**, (1), pp. 38–42

[20] VORONIN E.N., EMEL'CHENKOV F.I., KOTOV YU.V., LUK'YANOV A.S.: 'Phased array antenna on a radial waveguide'. IVth Int. Conf. Antenna Theory and Techniques, 2003, vol. 1, pp. 296–299

[21] CHEN S.G.: 'A radial waveguide power divider for Ka band phased array antennas'. Proc. 3rd Int. Conf. on Microwave and Millimeter Wave Technology, ICMMT'02, 2002, pp. 948–951

[22] NAKANO H., TAKEDA H., KITAMURA Y., MIMAKI H., YAMAUCHI J.: 'Low-profile helical array antenna fed from a radial waveguide', *IEEE Trans. Antennas Propag.*, 1992, **40**, (3), pp. 279–284

[23] BIALKOWSKI M.E., KABACIK P.: 'An electromagnetic-field method modeling of a radial line planar antenna with coupling probes', *IEEE Trans. Antennas Propag.*, 2003, **51**, (5), pp. 1114–1120

[24] BIALKOWSKI M.E., WARIS V.P.: 'A systematic approach to the design of radial-waveguide dividers/combiners'. Asia-Pacific Microwave Conf. APMC'92, 1992, vol. 2, pp. 881–884

[25] KUMAR M., HANCZOR M., VOIGT H., CAMBIGIANIS G., SACHS R., BONILLA C.: '22-kW next generation low cost S-band solid state transmitter for surveillance and air traffic control radars'. IEEE MTT-S Int. Microwave Symp. Dig., 1995, vol. 3, pp. 1601–1604

[26] SONG K., FAN Y., HE Z.: 'Broadband radial waveguide spatial combiner', *IEEE Microw. Wirel. Compon.*, 2008, **18**, (2), pp. 73–75

[27] MARCUVITZ N.: 'Waveguide handbook' (McGraw-Hill, New York, 1951)

[28] BIALKOWSKI M.E.: 'Analysis of a coaxial-to-waveguide adaptor including a disc ended probe and a tuning post', *IEEE Trans. Microw. Theory Tech.*, 1995, **43**, (2), pp. 344–349

[29] RUTLEDGE D.B., WEIKLE II R.M.: 'Failures in power-combining arrays', *IEEE Trans. Microw. Theory Tech.*, 1999, **47**, (7), pp. 1077–1082

doi: 10.1049/iet-map.2008.0299