A W-Band Spatial Power-Combining Amplifier using GaN MMICs

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***Abstract* — In this paper, we describe a miniature power-combiner for monolithic millimetre-wave integrated circuit (MMIC) chips using spatial power-combining with cavity modes. We have designed GaN MMIC power amplifier chips for 94 GHz, and illustrate the concept of the W-Band Spatial Power Combining Amplifier (WSPCA). Using 1 Watt, 94 GHz MMIC chips in a two-way cavity mode combiner, we were able to achieve 2 Watts of output power with 9 dB gain and 15 % PAE. This technique could be extended to high power MMICs and larger numbers of chips to achieve higher output power in a compact size. The applications include earth science radar, but may be extended to other applications requiring wider bandwidth.**

***Keywords* — MMIC, GaN power amplifiers, cavity mode, TM110**

I. Introduction

In this work, we have developed a new type of miniature power-combiner suitable for combining MMIC amplifier chips. The compact design makes use of spatial power-combining using cavity modes. We demonstrate the power combiner technique using 1 Watt MMIC Gallium Nitride (GaN) power amplifier chips, to produce 2 Watts of output power at 94 GHz.

The use of high power solid state sources is important for earth science radar applications, as power combining large arrays of MMICs reduces the risk of single-point failures with high power vacuum tube technology in radar instruments. Some prior examples of W-band GaN MMICs and arrays are discussed in [1-4]. Our new spatially power-combined amplifier, or SPCA in this work, demonstrates a new technique for compact power-combining of MMICs at high frequency including W-band, and has applications to cloud radar for small satellites, planetary landing radar and altimetry, and local oscillators for terahertz receivers in astrophysics telescopes. This power combining scheme using cavity modes has the potential to enable a new generation of compact W-band power amplifiers for radar instruments. Prior work on spatial power combiners using cavity modes is described in [5,6].

II. Power Combining Concept

A. Cavity Mode for Cylindrical Cavity

We designed our power combiner using a cylindrical cavity of approximately 1.05 λ in diameter, for λ at 94 GHz, or 3.3 mm. When low power W-Band microwaves are fed into the cavity, a transverse magnetic TM_{110} mode is excited within the cavity, shown in Fig. 1. The areas of strongest *E* fields are shown in red, and the mode forms two central lobes of enhanced field strength. By tapping into these lobes of maximum field intensity in the cavity using a cavity probe, we can couple the field energy into a microstrip mode, which can then be wire-bonded to a MMIC chip in a coplanar waveguide or microstrip configuration. The cavity probe consists of a dielectric material with a metal antenna element, similar to a waveguide *E*-plane probe [7]. To transform the TM_{110} cavity mode to a rectangular waveguide for testing, a rectangular iris of suitable dimension is used.

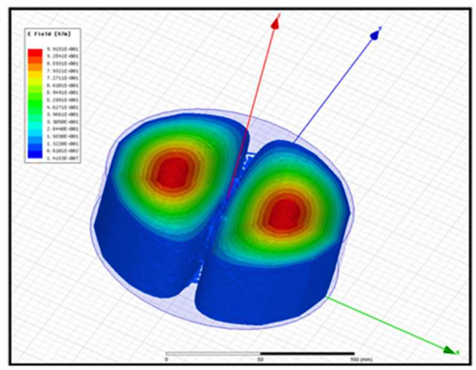

Fig. 1. TM_{110} cavity mode, shown in a cylindrical cavity. Red areas in the centers of the two lobes indicate maximum field intensity.

The W-Band SPCA (WSPCA) is illustrated in Fig. 2. At left in Fig. 2 is the input WR10 waveguide, followed by a rectangular aperture or iris. The iris is then followed by the input cylindrical cavity. Two cavity probes, of metallized dielectric, are inserted into the cavity at the positions of maximum electric fields. The probes then enter a MMIC channel, where either a thru-microstrip line (for evaluation), or a MMIC power amplifier chip, is situated. A pair of output cavity probes follow the MMICs, and couple to the output cylindrical cavity, which is then (by means of the output iris) fed into the output WR10 waveguide. The MMIC amplifiers, via the cavity probes, pick up input power from the TM_{110} input mode, amplify it, and radiate the amplified power via their output cavity probes into the output cavity. Both MMIC amplifiers perform this process in synchrony and inject the amplified power into the output cavity for this dual-chip cell. When implemented in WR10 waveguide, using MMIC chips and printed circuit boards for bias circuitry, the module design is shown in Fig. 3. We chose a split-waveguide block

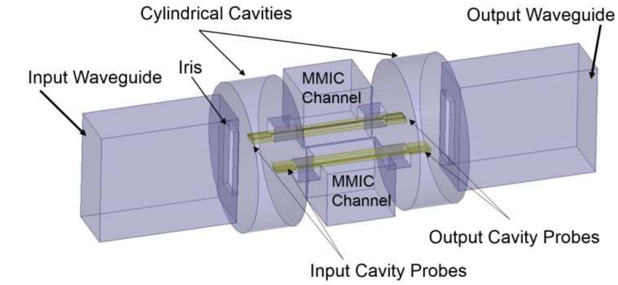

Fig. 2. Illustration of spatial power combined amplifier using cavity modes.

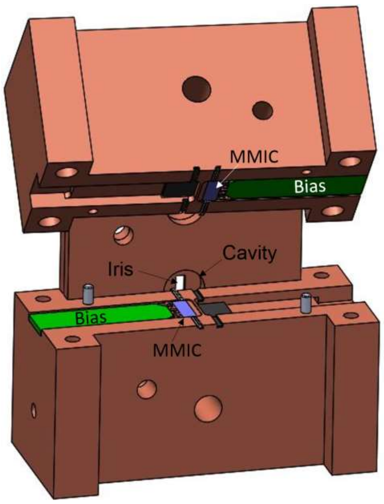

Fig. 3. Split block design showing the bottom block with bottom MMIC, and top block with top MMIC. At center are the cylindrical cavity and iris plate.

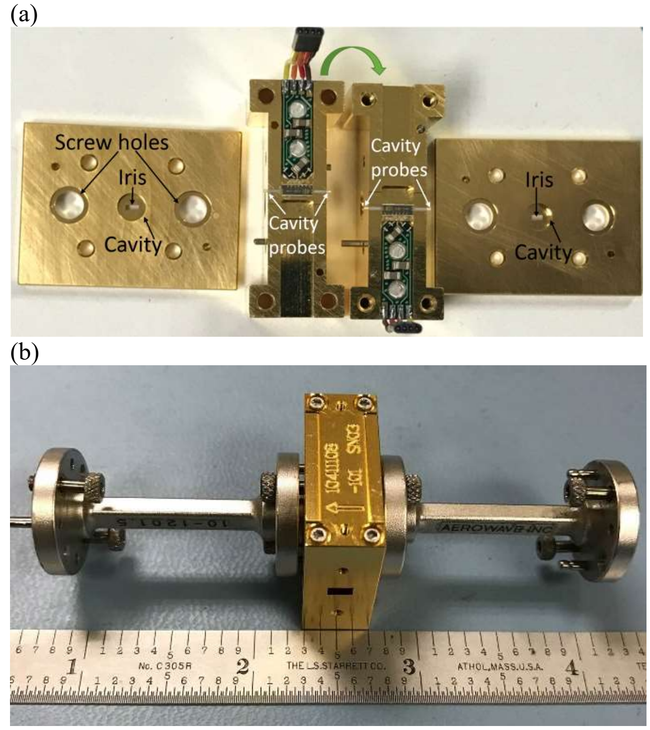

Fig. 4. Assembled split-block WSPCA. a) From left to right: Input cavity and iris plate, top and bottom MMIC block halves with bias circuitry, and output cavity and iris plate; b) complete amplifier block with cavity and iris plates attached, measuring 0.4" long.

configuration for ease of assembly of the MMIC chips, with one MMIC in the top half and the other MMIC in the bottom half of the module. The cylindrical cavity and iris are machined as a separate plate (Fig. 4a), and the plates are aligned with the split-block containing the MMIC channels and cavity probes, using alignment pins.

In the top half of Fig. 4, we show the assembled split block containing the MMIC channels and printed circuit boards for bias circuitry. The two block halves, shown side-by-side, are placed one on top of the other, so that the MMICs and cavity probes appear as in Figs. 2 and 3. The iris and cavity plate, which is machined as a separate plate, is then placed, by means of alignment pins, so the cylindrical cavity encompasses the cavity probes as in Fig 2. Rectangular WR10 waveguides at input and output are then attached with alignment pins and screws to the iris plate. The final power-combined block is shown in the bottom half of Fig. 4, and measures 400 mil long.

III. GaN MMIC Power Amplifiers

A. Design

The GaN MMIC amplifiers that we designed were fabricated in Raytheon's 0.15 μm GaN process, on 50 μm thick SiC substrates, as described in [2]. Thin-film resistors, metal-insulator-metal capacitors, and thru-substrate vias were implemented in the circuits. The design consisted of multiple stages of common- source HEMT amplifiers, utilizing HEMTs with 4 finger transistors, each having a gate width of 35 μm. The first stage used a single HEMT device, followed by two power-combined HEMT devices, followed by a third stage which has four power-combined HEMT devices. Source vias were used for grounding. Each stage was separated by a DC blocking capacitor. DC bias was provided through bias networks utilizing shunt capacitors and resistors. Microstrip elements such as the microstrip power combiners, vias, and capacitors were simulated using Sonnet. A chip photograph of the three stage MMIC amplifier is shown in Fig. 5. Wirebonds were used to connect the MMICs to the cavity probes.

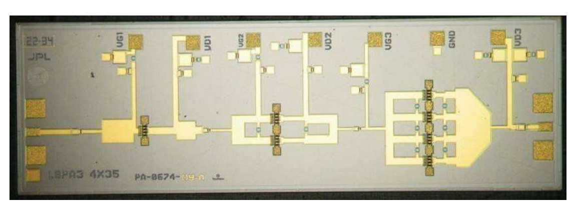

Fig. 5. Micrograph of the GaN MMIC power amplifier chip used to demonstrate the WSPCA.

B. Simulated and Measured MMIC S-Parameters

In order to test the MMIC chips for *S*-parameters, we packaged them in brass WR10 waveguide housings. The GaN amplifiers required between 10 and 14V of drain voltage with a total drain current of about 400 mA for the three stages. The MMICs were mounted in a brass housing with alumina E-plane probe transitions to WR10 waveguide. A photograph of the single-chip MMIC PA module is shown in the inset of Fig. 6.

Small signal *S*-parameters were obtained using WR10 OML vector network analyser extension modules from 75-110 GHz. Simulated *S*-parameters were obtained using Raytheon measured device models with Keysight's ADS and Sonnet models for simulation of the MMIC circuit elements. Simulated *S21* gain agrees well with the measured results. The simulated *S11* and *S22* also show good agreement, though additional features are present. These may be due to differences in the bias conditions of the device model, and also from packaging components such as wire bonds which were not simulated.

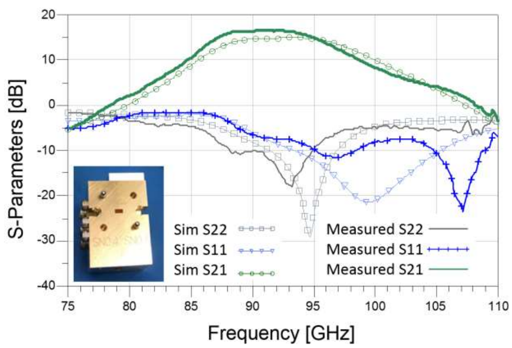

Fig. 6. Measured and simulated *S*-parameters of the GaN MMIC, packaged in the waveguide module shown in the inset, and biased at *Vd* =10V.

C. Packaged and Measured Output Power

The MMIC module was tested for output power, gain, and power added efficiency vs. frequency. Using a drain voltage, V_d of 14V and 440 mA of drain current, we obtained the plots in Fig. 7 for output power vs. frequency. The single-chip MMIC module had 10 dB of gain, Pout of 1 Watt (30 dBm), and 15% power-added efficiency (PAE) at 94 GHz.

IV. Cavity Mode Power Combiner

A. S-Parameters of WSPCA using Thru-Lines

We tested the WSPCA first with microstrip thru-lines wire-bonded to microstrip cavity probes, which were all fabricated in 3 mil alumina at ATP technologies. The Thru-line substrates were mounted into the spatial power combined module in the top half and the bottom half of the block, and were measured for *S*-parameters. A photograph of the module showing the two Thru-lines to be power-combined, is shown in Fig. 8.

In Fig. 9, we show the measured *S*-parameters of the power-combined unit using the Thru-lines. Electromagnetic simulations, performed with HFSS, show the spatial power-combiner bandwidth to be between 86-105 GHz wide. The simulated return loss was centered near 95 GHz. Measured

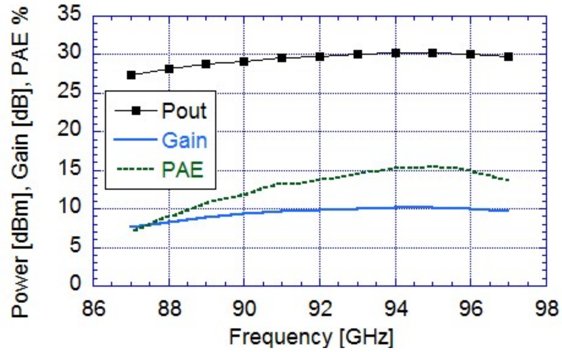

Fig. 7. Measured output power, gain, and PAE of a single-chip GaN MMIC module, biased at *Vd* =14V.

return loss is better than 10 dB from 94-97 GHz, and tuned slightly higher by 2 GHz compared the simulations. Simulations indicate that slight misalignment of the cavity probe into the cavity, as could occur during fabrication and assembly, could cause the minor differences between the predictions and the measurements. Insertion loss as a function of frequency agrees quite well with the measured data, with *S21* of -1.5 dB at 94 GHz including the Thru-line itself. In the following section, we describe the implementation of the WSPCA using two, 1 Watt GaN MMICs.

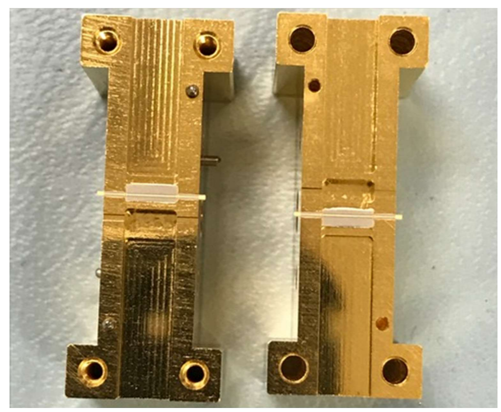

Fig. 8. Two microstrip thru-lines with cavity probes mounted in the top and bottom halves of the WSPCA module.

B. S-Parameters of WSPCA using MMICs

Two GaN MMIC power amplifier chips (as shown in Fig. 5) were inserted into the cavity mode power combiner, as in the assembly of Fig 4a. Cavity probes were wire-bonded to the MMICs. The measured *S*-parameters of the power-combined unit under small signal RF power are shown in Fig. 10. The MMIC chips were biased at the same 14V drain voltage as in the power measurements for the single-chip module of Fig. 7. We measured the power-combined unit for *S*-parameters and obtained 15 dB of gain at 94 GHz. The input and output return losses were approximately 10 dB from 94-105 GHz.

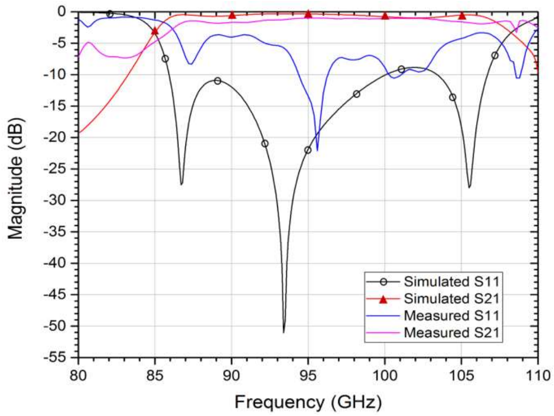

Fig. 9. Measured and simulated results of the WSPCA module containing alumina thru-lines, as shown in the configuration of Fig. 2.

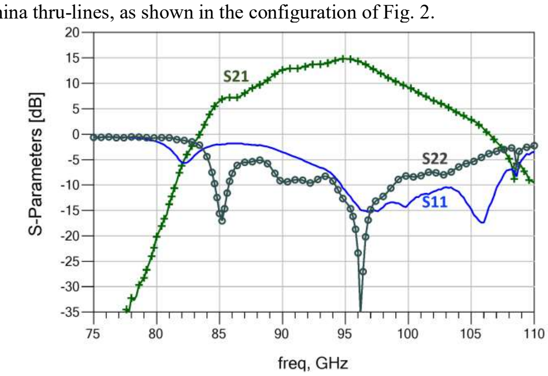

Fig. 10. S-parameters of the WSPCA using two GaN MMICs of Fig. 5.

C. Power Measurements of the Cavity Mode Combiner

We measured the power-combined WSPCA unit for output power, gain, and power-added efficiency. In Fig. 11, we show the *Pout*, Gain and PAE, under the same bias conditions as the single-chip module. We obtained 2 Watts of output power, with 15% PAE and over 9 dB of gain for 23.5 dBm of input power. Fig. 12 shows the output power as a function of frequency, with 25 dBm of input power, where we obtained 33 dBm or 2 Watts of output power from 94-97 GHz.

V. Conclusion

We present a concept for ultra-compact power combining of MMICs in W-band utilizing cavity modes. The W-Band Spatial Power Combined Amplifier (WSPCA) has a bandwidth for the power combiner itself nearly 20 GHz wide, centered at 94 GHz. We tested the power combiner for *S*-parameter measurements using thru-lines, and inserted two, 1 Watt, 94 GHz, GaN MMIC power amplifiers into the cavities. The resultant power-combined WSPCA unit gave 2 Watts of output power from 94-97 GHz. This technique, which implements spatial power combining of MMIC amplifiers in a compact package, can be extended to combining higher power, or wider bandwidth MMICs, combining additional MMICs using higher order cavity modes, or to higher, or lower frequencies. Further improvements could be explored with new low-loss MMIC transitions (in place of the cavity probes) described in [8, 9].

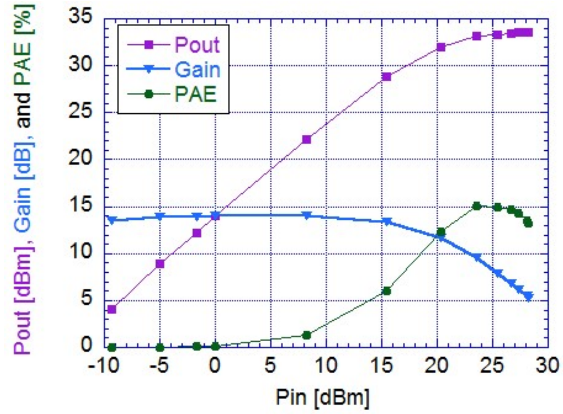

Fig. 11. Pout, Gain and PAE of the WSPCA as a function of input power, at 94 GHz and *Vd* of 14V.

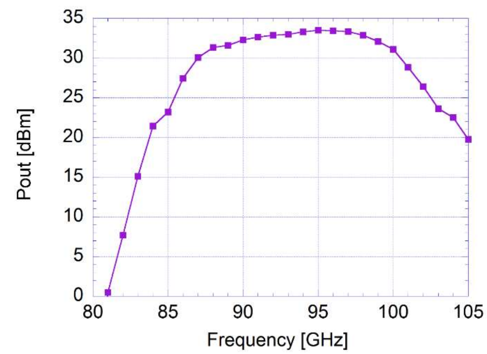

Fig. 12. Output power vs. frequency of the WSPCA unit.

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