Broadband High Power Amplifier using Spatial Power Combining Technique

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Abstract — **High power, broad bandwidth, high linearity and low noise are among the most important features in amplifier design. Broadband spatial power combining technique addresses all these issues by combining the output power of a large quantity of microwave monolithic integrated circuit (MMIC) amplifiers in a broadband coaxial waveguide environment, while maintaining good linearity and improving phase noise of the MMIC amplifiers. Coaxial waveguide was used as the host of the combining circuits for broader bandwidth and better uniformity by equally distributing the input power to each element. A new compact coaxial combiner with much smaller size is investigated. Broadband slotline to microstrip line transition is integrated for better compatibility with commercial mmic amplifiers. Thermal simulations are performed and a new thermal management scheme is employed to improve the heat sinking in high power application. A high power amplifier using the compact combiner design is built and demonstrated to have a bandwidth from 6 to17 GHz with 44-watt maximum output power. Linearity measurement has shown a high IP3 of 52 dBm.**

I. INTRODUCTION

UCSB's microwave group attempted a "tray" scheme inside waveguide to achieve broad bandwidth, better thermal management and more efficient power collection [1-3]. However, the bandwidth of the rectangular waveguide is limited. In addition, the dominant TE_{10} mode inside rectangular waveguide will lead to non-uniform illumination of the loaded antenna trays inside the waveguide. To broaden the bandwidth and to meet the requirement of linearity, we extend the "tray" approach from rectangular waveguide to coaxial waveguide. A multi-octave bandwidth amplifier achieved bandwidth from 3.5 to 14 GHz with good linearity using oversized coaxial waveguide combiner [4]. We also reported an improved compact passive structure for broadband high power amplifier design [5]. A significant reduction in size has been achieved while maintaining a 6-18GHz bandwidth and capacity for 32 MMIC amplifiers. A broadband slotline to microstrip line transition was developed and monolithically integrated with the slot-line antennas, to eliminate a troublesome bond-wire transition in earlier design and provide better compatibility with commercial MMIC amplifiers. The Spectral Domain Method (SDM) is applied to compute the field in the structure, and small reflection theory is applied again to synthesize the waveguide taper and optimize finline taper array. In this paper, we integrated active MMIC amplifier to the compact passive structure. The compact coaxial waveguide combiner has shown 6 to 17 GHz bandwidth with 44-Watt maximum output power while with good linearity and high dynamic range. That enables it a good rival for current dominant TWT amplifiers.

II. ASSEMBLY AND THERMAL ANALYSIS

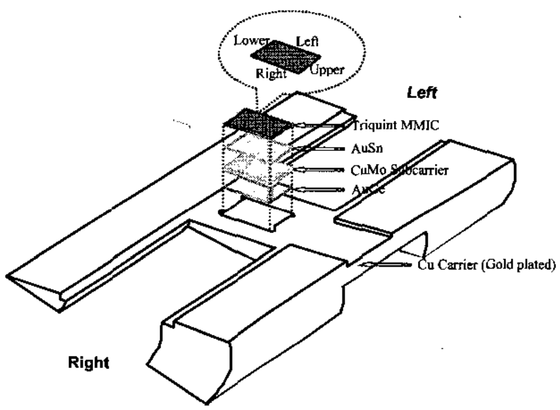


Fig. 1 MMIC assembly process to the metal carrier.

In power amplifiers, the heat generated by the MMIC amplifiers need to be effectively dissipated to the ambient environment. The heat is dissipated into the air by two modes: conduction and convection. Since copper is only inferior to silver in thermal conductivity at room temperature and is 1.6 times better than aluminum, we chose copper as the material for the metal carriers in the high power combiner instead of aluminum that was used in the medium power combiner design. MMIC amplifiers were attached to the Copper/Molybdenum (Cu/Mo) subcarriers first since the GaAs's thermal expansion coefficient is very similar to Cu/Mo but much different from copper. To minimize thermal resistance from MMIC to the outside surface, eutectic solders were used for die bonding instead of epoxy. The assembly scheme is shown in Fig. 1.

The heat is dissipated to the ambient environment by forced air convection. To help dissipate heat, fins were machined into the outside surface. Simulation shows that the temperature is reduced dramatically to be within 84 °C at the hottest spot after 3 fins are added.

The assembled circuit tray is shown in Fig. 2. The 2-channel MMIC amplifier sits on the bridge that connects inner and outer sections. Input and output antennas were epoxyed on both sides. Bonding wires connect the end of microstrip line to the input and output pads of the MMIC amplifier.

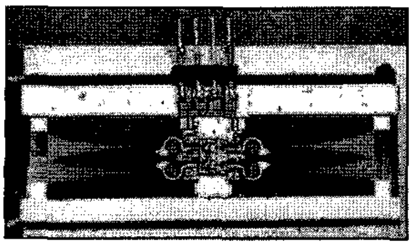


Fig. 2 A circuit tray of the 16-tray combiner.

III. SMALL SIGNAL MEASUREMENT

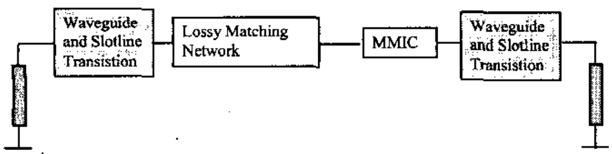


Fig. 3 Small signal modeling of the combiner in ADS.

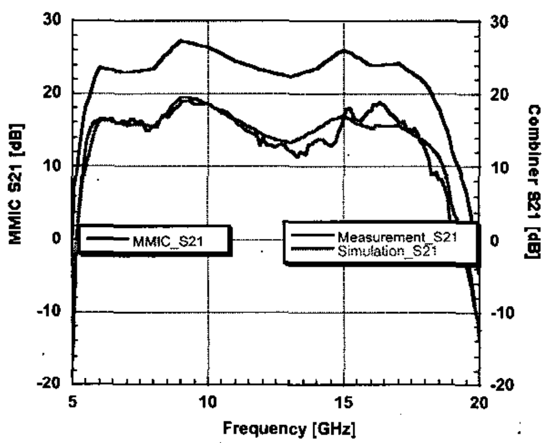


Fig. 4 Comparison of simulation and measurement of the combiner and measurement of the MMIC amplifier.

As explained in [4], the performance of the waveguide structure and finline transition is simulated by HFSS, a 3D FEM simulator. We exported the S parameter results from HFSS to S2p files, and then imported them into Agilent Advance Design System (ADS). The ADS small signal circuit model of the combiner is shown in Fig. 3.

The TGA9092 MMIC amplifier we chose has a gain in excess of 25 dB, which can cause oscillation problems in a packaged waveguide environment. The circuit becomes stable when the overall gain is reduced within the 20 dB range due to the insertion of the lossy matching network. The results from both the measurement and the simulation is shown in Fig. 4. There is around 8-dB difference in the gain between the MMIC amplifier and combiner, which arises from the lossy matching network.

IV. POWER MEASUREMENT

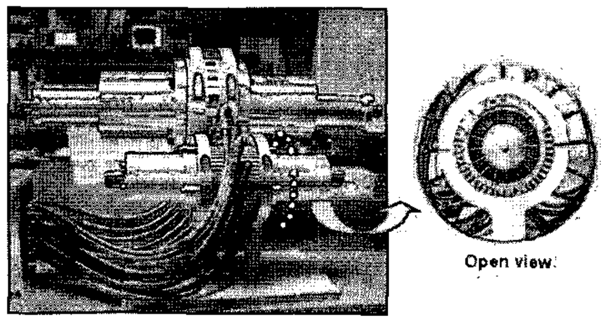


Fig. 5 High power amplifier using the compact combiner, compared with the medium power amplifier

Fig. 5 shows the assembly of the combiner system. Fins on the outside surface can be observed from the open view. The bias lines were connected from a biasing board to the 16 individual circuit trays.

The input power level was chosen to be 30 dBm. A frequency sweep measurement result is shown in Fig. 6. A maximum power of 44 Watts is obtained at 10 GHz. The 3 dB bandwidth is from 6 to 17 GHz. We noted that two MMIC amplifiers of the 32-MMIC combiner were nonfunctional during the measurement. The combiner's output power was measured with 30 working MMIC amplifiers, which is 88% of the 32-MMIC combiner's output power basing on the graceful degradation theory [6].

The PAE is measured and shown in Fig. 7 with the output power and gain sweep over the input power. At 30 dBm input power, the gain is compressed by 1.8 dB. The power added efficiency was about 17% at an output power of 44-Watts.

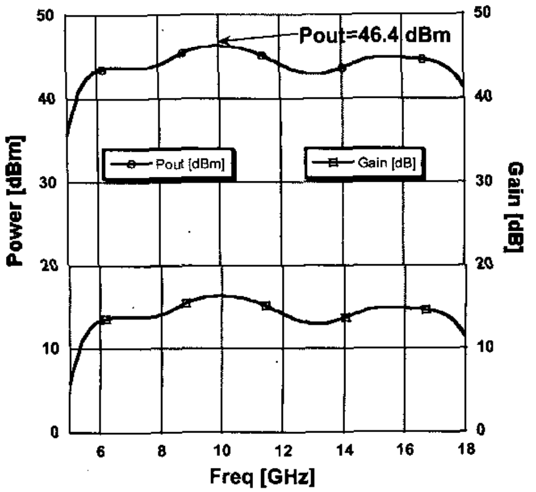


Fig. 6 Frequency sweep at 30 dBm input power.

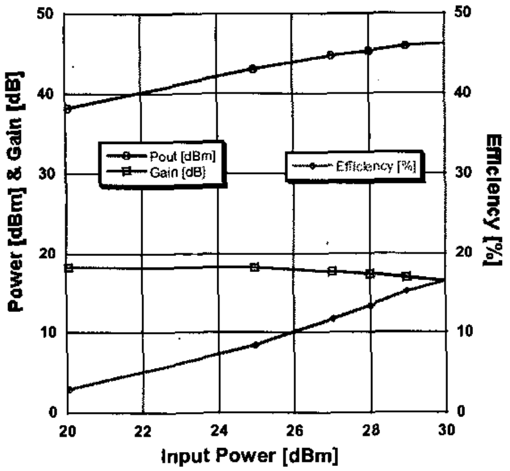


Fig. 7 Power sweep at 10 GHz.

V. LINEARITY ANALYSIS

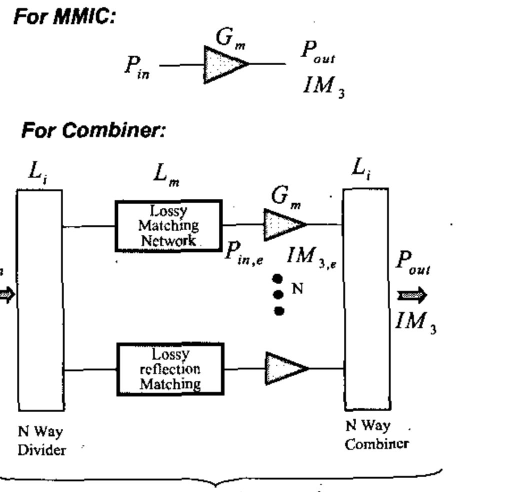
As shown in Fig. 8, we can express the fundamental and IM3 output power of a MMIC amplifier as

$$P_{out} = G_m P_{in}$$
$$IM_3 = A P_{in}^3 \tag{1}$$

where G_m is the gain of a MMIC amplifier, and A is the coefficient for IM_3.

The comparison of IM3 between a single MMIC and the combiner is shown in Fig. 8. The OIP3 is the output power at IP3 point where the linearly extrapolated fundamental output power $P_{out}=IM_3$. The OIP3 of a MMIC amplifier is

$$OIP3_m = \left(\frac{G_m^3}{A}\right)^{\frac{1}{2}}. \tag{2}$$



Overall Gain $G_c = G_m L_i^2 L_m$

**We assume divider and combiner are identical*

Fig. 8 Linearity analysis for the MMIC amplifier and the combiner.

For a combiner, we have

$$G_c = G_m L_i^2 L_m,$$
$$P_{out} = G_c P_{in} = G_m L_i^2 L_m P_{in}, \tag{3}$$

where L_m is the loss of the lossy matching network and we assume the passive N way divider and combiner are identical.

For each MMIC amplifier in the combiner, we have

$$P_{in,e} = \frac{P_{in} L_i L_m}{N}$$
$$IM_{3,e} = A P_{in,e}^3 \tag{4}$$

where N is the number of channels in the combiner.

The $IM_{3,e}$ from each MMIC amplifier are added in the same way as the fundamental signal. The sum of the $IM_{3,e}$ at the output port is expressed in IM_3 as

$$IM_3 = N\, IM_{3,e} L_i = N\, A\, P_{in,e}^3 L_i \tag{5}$$

Then, we have

$$P_{out} = IM_3 = N\,A\,\left(\frac{P_{in}L_iL_m}{n}\right)^3 L_i$$
$$OIP3_c = N\,L_i\left(\frac{G_m^{\,3}}{A}\right)^{\frac{1}{2}} \tag{6}$$

where $OIP3_c$ is the OIP3 of the combiner.

Comparing equations (2) and (6), we conclude that

$$OIP3_c = N\,L_i OIP3_m. \tag{7}$$

For a 32-channel combiner with a L_i of 1dB, the combiner will have a factor of 14 dB improvement in OIP3 over a MMIC amplifier. We note that the OIP3 has no relationship with the lossy matching network. The relationship between the fundamental component and third order component also remains the same for the combiner and a MMIC amplifier.

The intermodulation distortion was measured by two tones at 10 GHz with a separation of 1 MHz in spectrum. The IMD measurement result of the combiner is shown in Fig. 9.

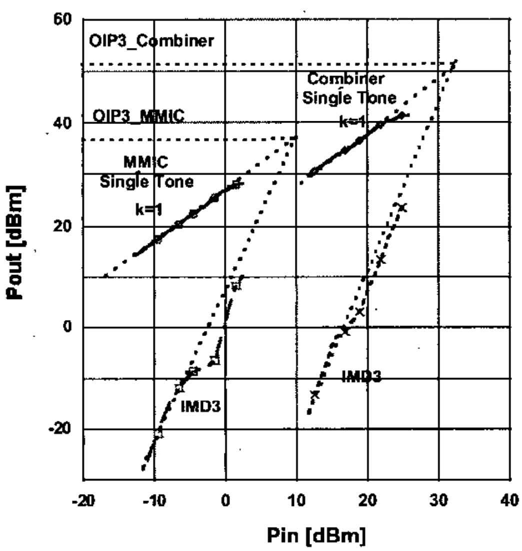


Fig. 9 Comparison of IMD between the MMIC amplifier and the combiner.

At 10 GHz, the output IP3 (OIP3) is 52 dBm compared to around 38 dBm of a single MMIC, which corresponds very close to a 14 dB improvement over a single MMIC amplifier. Fig. 9 consolidates the conclusion from equation (7).

The residual phase noise measurement was also performed and showed a low phase noise of –140 dBc at 10KHz offset from the carrier frequency.

VI. Conclusion

A compact coaxial waveguide combiner structure is presented in this paper. The total size of the new system is reduced dramatically compared to previous ones. In addition, with the monolithic integration of the microstrip to slotline transition, fabrication of the system becomes easier with better performance. The amplifier using the compact coaxial waveguide combiner shows the 3-dB bandwidth from 6 to 17 GHz with a maximum power of 44 Watt. We maintain the combiner's linearity similar to that of a MMIC amplifier, while improving the OIP3 of the combiner to 52 dBm, which is 14 dB higher than that of a single MMIC amplifier used in the combiner. These features enable this amplifier a good candidate for high power amplifiers in wireless and satellite communication base stations.

Acknowledgement

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