QUARTER WAVELENGTH COMBINER FOR AN 8.5kW SOLID-STATE AMPLIFIER AND CONCEPTUAL STUDIES OF HYBRID COMBINERS

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Abstract

Experimental results to combine ten 900W solid-state amplifier modules based on typical quarter wavelength 10-way combiners are described for a total of 8.5kW RF power output at 500 MHz. The power gain and phase distribution among the ten modules are measured and calculated to sense the combination efficiency. The combination efficiency of 100 modules differing in power gain and phase distribution is theoretically analysed. Groups of 5, 10, 25, 50 and 100 units are used in 4, 3, 2, and 1-stage power combination for total 100 units and the characteristics are calculated and investigated, including bandwidth, efficiency and even redundancy under various output VSWR levels. To simplify combining complexity and to eliminate the drawbacks of single stage combiners, a multi-way 2-stage coaxial to waveguide combiner is thus proposed as an expandable power combiner.

INTRODUCTION

A project for a home-made 60 kW solid-state power amplifier (SSPA) system is in progress at NSRRC. Numerous efforts have been made on the module design including planar balun with better heat dissipation, integrated water cooling plate [1], a temperature measurement circuit and a high directivity PCB directional coupler. After production of some modules, they were used for power combination. These handmade SSPAs were not very identical in gain and phase distribution, but the power combination efficiency still performed satisfactory. To find a relationship between gain and phase distribution on one side and their combination efficiency, circuit models with adjustable power gain and phase distribution on a RF circuit simulator were done based on the measurement data. The range of power and gain distribution among modules seems not to be very narrow at +/- 0.2dB and +/-5deg, respectively [2]. A Gaussian distribution is applied to groups within +/-0.5 dB &+/-10deg and +/- 1dB & +/-20deg to estimate the efficiency of a 100-unit power combination. In addition to the combination efficiency, combination methodology also affects the system performance as does insertion loss and bandwidth. In general, the SSPAs will be combined first in a basic group as a medium power unit, then basic groups are combined until the required power and quantity is reached. Varying the module numbers in a basic group for 1-stage to 4- stage combinations of 100 units and complete combiner systems are analysed to obtain system bandwidth and redundancy capability under different output VSWR. To reduce the number of combination stages, a multi-port coaxial to waveguide combiner is proposed as an expandable two-stage power combiner.

COMBINATION EFFICIENCY ANALYSIS FOR AN 8.5 kW 10-WAY SSPA

The maximum power combination efficiency can be obtained when all SSPA units are identical. However, the actual modules cannot be identical due to the dispersion of errors from different chips, passive components, to misaligned soldering etc. Each one contributes some error leading to big differences between modules which can be controlled by trim capacitors, but some errors still remain. How these errors affect the overall power combination efficiency is an interesting and practical point of study. We start from an experimental 8.5kW, 10-way combiner to a theoretical 100-way power combination for different error distribution ranges in this article.

The measured power gain and phase as a function of output power for each handmade module is shown in Fig. 1 for a power gain and phase distribution within +/- 0.5dB and +/- 18 degrees of experimental values. According to measured power gain and phase distributions at the saturation point, the estimated and measured combination results are shown in Table 1. The measurement results are close to calculation while the combination efficiency is the ratio of combined output power to the total power of 10 modules. From the result, the combination efficiency seems not to be very sensitive to the range of error distribution.
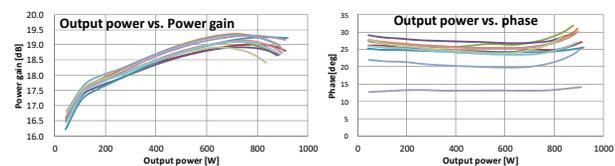

Figure 1: Power gain and phase distribution among the 10 handmade SSPA modules.

Table 1: Calculated and Measured Combined Power Measurements of the 10 handmade SSPA Modules

	Calculated	Measured
Combined output power [kW]	8.87kW	8.68kW
Combination efficiency [%]	99.37%	97.24%

Combining Efficiency Under Various Dispersion

The available overall SSPA efficiency derives from a combination of a few factors: the AC-DC conversion efficiency (Eff_{AC-DC}), the insertion loss/mismatch loss of passive transmission line components including combin-

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ers (IL), the combination efficiency resulting from errors among modules (Eff_combi) as well as divider/combiner errors and finally, the DC-RF conversion efficiency of the SSPA module itself (Eff_{DC-RF}). Thus the overall AC to RF conversion efficiency is given by

$$Eff_{total} = Eff_{AC-DC} \times (1 - IL) \times Eff_{combi} \times Eff_{DC-RF} \quad (1)$$

To find the combination efficiency corresponding to specified power gain and phase errors among the modules, 100 SSPA units have been selected randomly in a circuit simulator and assigned to three Gaussian distributions +/- 0.2dB&+/-5∘, +/-0.5dB&+/-10∘ and +/-1dB&+/-20∘ as shown in Fig.2. A few modules seem not to quite fit within their Gaussian distributions, but the resulting combination efficiency is still satisfactory as shown in Table 2. Assuming 90% in Eff_{AC-DC}, 62% in Eff_{DC-RF} and 2% in IL, the corresponding overall AC to RF conversion efficiency will be affected by less than one percent even under a wide range of errors as in group #3.
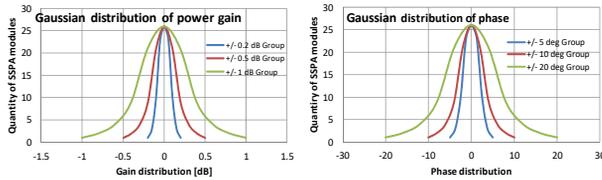

Figure 2: power gain and phase of 100 SSPA units in three Gaussian distribution ranges.

Table 2: Power Combination Efficiency Among Three Gaussian Distribution Ranges

	Combination efficiency
+/- 0.2dB & +/- 5∘(#1)	99.79%
+/-0.5dB & +/-10∘(#2)	99.49%
+/-1dB & +/-20∘(#3)	98.29%

Table 3: The Impact of Combination Efficiency

	Eff_{AC-DC}	Eff_{DC-RF}	IL	Eff_{combi}	Eff_{total}
#1	90%	62%	2%	99.79%	54.58%
#2	90%	62%	2%	99.49%	54.41%
#3	90%	62%	2%	98.29%	53.76%

THE CHARACTERISTICS OF COMBINING TREES

There are various ways to combine SSPA units to the required power level. Usually, the SSPA will be combined first in a basic group, then, these basic groups will be further combined once or twice or even triple to generate the final output power [3-4]. Examples of a combination tree with a three stage combination of 5x2x2 or a one stage combination like 20x1 for 20 SSPA units are shown in Fig. 3. Since combining SSPAs in 1-stage is becoming

popular to simplify system complexity [5], some of its properties will be discussed as well.
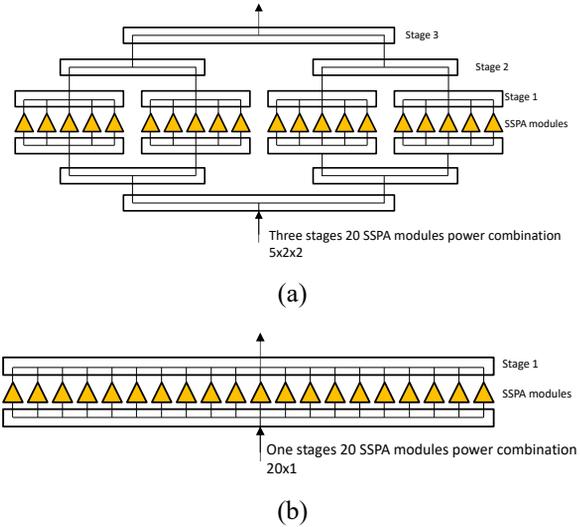

(a)

(b)

Figure 3: (a) SSPAs are grouped in sets of five and combined twice in three stages 5x2x2 (b) SSPAs are combined only once as a 20x1 combination.

Bandwidth

Since the RF frequency used in NSRRC is 499.65MHz, the combining trees would be designed accordingly for convenience. The bandwidth of the combination tree can be presented as an S-parameter from the output port to any input port or vice versa. The single stage combination of various quantities is shown in Fig. 4 (a) and a multi-stage combination of a 100 ways input is shown in Fig. 4 (b). Obviously, larger combinations in a single stage would let the bandwidth become narrower while multi-stages benefit a wider bandwidth which is strongly determined by the quantity in the first stage. Since the SSPA module itself usually is a wideband active component, the required bandwidth of the combination tree may dependent on select specifications.

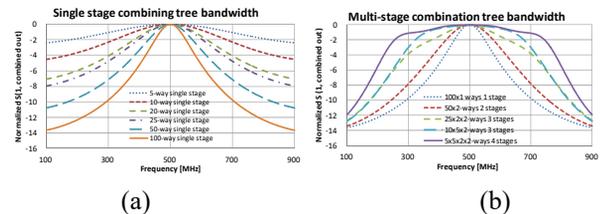

(a)   (b)

Figure 4: (a) different 1-stage combinations and (b) different 100 ways combinations.

Redundancy

Besides the property of low DC voltage operation and energy savings, the most attracting feature of the SSPAs is their redundancy. The SSPA can absorb a certain number of module failures without interrupting system operation. Since a high power RF system usually does not operate at its maximum power rating, the power drop caused by a failed module can be compensated immediately by other active unit through the LLRF control system. The availa-

ble power during some SSPA module failures can be simplified like in Eq. (2), where P_{out} is the output power of the final stage, P_n is the nominal power of each module, N_{total} is the total quantity of SSPA modules and N_{fail} is the number of the failed SSPAs. One failing module can reduce the output power by twice its nominal power since other active modules would react by reflecting power approximately equal to P_n. Note, that this equation holds only for $N_{total} > 10 \cdot N_{fail}$, otherwise, the calculated P_{out} will be lower than the actual output power. For example, if we assume five failing modules, we still have at least 90% of the maximum output power as long as the minimum number of total modules is more than 100.

$$P_{out} = P_n \times N_{total} - 2 \times P_n \times N_{fail} \qquad (2)$$

Risk Behind the Redundancy: Reflected Power

The SSPA module is usually equipped with a circulator and a load to absorb the reflected power and protect the power transistors as well as keeping matching conditions. The power handling capacity of the circulator and load is usually just a little higher than the maximum saturation power of the module such as 1.2 times P_{sat}. For example, when the combined output is connected to a dummy load (VSWR=1) and some modules in the same group have failed, the reflected power of the basic combination group within a 10x5x2 100 units SSPA is shown in Fig. 5. From Fig. 5 the reflected power contributed from other active units will not be equally distributed to all ports and the active modules may see higher reflected power than OFF modules when the number of OFF modules is getting larger. For a single failing module, one would see a higher Pr than for two failed units. Therefore, the reflection power of a single failed module should be taken care of since the chance of one module failing is much higher than that of two modules failing at the same time in normal operation.
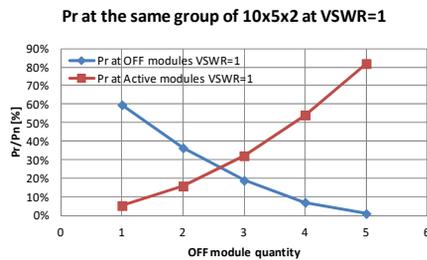
Figure 5: Ratio of reflection power (Pr) to nominal power (Pn) for OFF/active modules in the same group of 10x5x2 SSPA when the output VSWR=1.

The highest Pr of SSPAs will appear at the single failing module with output load VSWR=2 and 100 in 5x1, 10x1, 20x1, 25x1, 50x1 and 100x1 1-stage SSPA, which both are analysed in Fig. 6. The reflected power on the failing module dramatically increases with output VSWR as well as the number of the SSPA modules in the basic group and is highly dependent on the load phase. The highest Pr is observed at 100x1 1-stage SSPA under

VSWR=100 which is almost four times Pn. Even at VSWR=2, the Pr can reach 1.74 times Pn at a 100x1 1-stage SSPA. As the number of SSPA modules get larger within a single stage, the single failed module would have a chance to receive a high reflection power at certain phases. From the analysis, the reflected power could be a risk for the circulator and load of the failed module in a multi-way or single stage combiner when the load VSWR is high. The high reflection power could induce RF arcing propagating through the transmission branch. To provide a four to five times power handling capacity for circulator and load at each SSPA module is not feasible, while adding a high power circulator between SSPAs and final output load or fine adjusting the line length/phase between RF output and the actual load could be a solution.
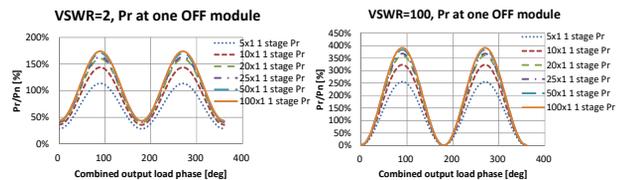

Figure 6: Ratio of reflected power to nominal power for a single OFF module under two VSWRs load conditions and different numbers of 1-stage SSPA units.

2-STAGE EXPANDABLE COMBINER

From the analysis discussed above, multi-stage combination may have higher insertion losses while single stage combination has a narrower bandwidth and a risk of high reflection under some extreme conditions, for which a trade-off solution is proposed as a multi-port 2-stage waveguide combiner with expansion capability as shown in Fig. 7.
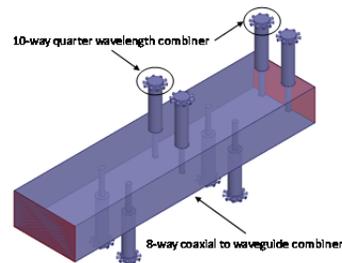

Figure 7: Expandable 2-stage coaxial-to-waveguide power combiner.

CONCLUSION

The experimental results of a 10-way SSPA power combiner for 8.5kW have shown acceptable efficiencies with experimental and calculated results matching well. One hundred SSPA random units, in three Gaussian distribution groups, are used for power combination on a RF circuit simulator showing a satisfactory 98% combination efficiency even when gain and phase errors are distributed as wide as +/- 1 dB and +/- 20 °. The bandwidth of different power combination trees is also discussed. The available output power for a certain number of failing SSPA modules are described as well while the risk behind the redundancy is simply explained by graphs. As a trade-off

between compactness and redundancy, a 2-stage coaxial to waveguide power combiner is proposed as an expandable multi-ports power combiner.

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