

## RADIAL POWER COMBINES FOR SOLID-STATE POWER AMPLIFIERS

Development of solid-state RF power amplifiers has reached the point where it is now common to replace vacuum-tube power devices with solid state amplifiers in the VHF, UHF and Microwave Frequency ranges. However, transistors generally cannot come close to matching the kilowatt levels that tube amplifiers can provide for many radar and communication systems. Fortunately, RF transistors are relatively inexpensive, so high levels of RF power can be realized by summing the outputs of a large number of solid-state amplifier stages.

This approach to high power amplification has some potential advantages over vacuum-tube designs, two of which are 1) failure tolerance (one transistor failure should not degrade performance appreciably) and 2) hot replacement (changing one module while all others are operating). A critical component in the assembly of solid state power amplifiers is the power combiner, because it must dissipate very little power internally and ensure that the extremely high power incident from multiple solid state amplifiers translates to the output port, rather than back into one or more of the input amplifiers.

The subject of this paper is the design and measured performance of a power combining device. It is based on a radial waveguide transmission line and achieves all the desired characteristics of a power combiner, namely, symmetric configuration, low loss, high power handling ability, failure tolerance, and provision for hot replacement. In addition to functioning as a combiner, this device works equally well as a multi-output power divider for many applications, because it maintains excellent phase and amplitude balance at all the output ports.

The most important guideline in the design of these devices is not isolation, but failure tolerance. A good example of a well-isolated power combiner/divider is a simple N-way tee, whose port-to-port isolation when driven by N identical sources is  $20 \log N$ . Hence, a 100-way tee theoretically has 40 dB isolation between ports.

If, however, any one source fails as a short circuit, it presents a short to all other sources, and the only way to determine the behavior of a combiner under all input amplifier failure conditions is to gain knowledge of its entire S-matrix; this is the key to the design of the power combiner presented here.

In formulating the equations that govern the S-parameters, we used the following physical and mathematical properties of radial waveguide combiners.

- Circular symmetry
- Reciprocity
- Unitary property of a lossless N-port device
- Modified ray-tracing between ports

We incorporated these into a computer program, solved the nonlinear equation for the S-parameters with a search algorithm, and used them with output impedance data (under operating and failed conditions) furnished by the amplifier vendor to predict the combiner behavior when different combinations of amplifier modules fail.

Based on this design, we fabricated a 60-way power combiner capable of providing 60 kW of output power over a 2.3 to 3.1 GHz frequency range with an insertion loss of 0.3 dB. Figure 1 and 2 show that the predicted and measure values of the S-parameters are in close agreement, and that the measured values change more smoothly with port position than do the predicted values. This is because the recursive algorithm used to compute them had not converged completely, but the variation is in the low-magnitude elements, and therefore this variation has no significant effect on overall performance. The failure tolerance of this device depends on the device structure itself, contained in the S-parameters, and on the reflection coefficient of the failed transistor amplifier module. A combiner that has good failure tolerance maintains a lower VSWR to all other working ports when one or more input amplifiers fail.

One of the most significant findings of the design relates to the failed module's reflection coefficient, and that high VSWR levels at working ports (representing the potential for another failure) occur over a very narrow region of this electrical phase. Figure 3 illustrates this point by showing the worst (highest) VSWR presented at any of the 59 remaining ports as a function of the phase angle of the failed module's reflection coefficient. Each of the multiple plots corresponds to a different reflection coefficient magnitude.

In summary, we have shown through a design concept, computer program and test data, that a low loss, high power radial waveguide combiner can be built to achieve failure tolerance and hot replacement capability. This is a significant step in developing solid state amplifier systems that can provide tens, even hundreds, of kilowatts of RF power with high reliability. A photo of a typical model is shown in Figure 4.

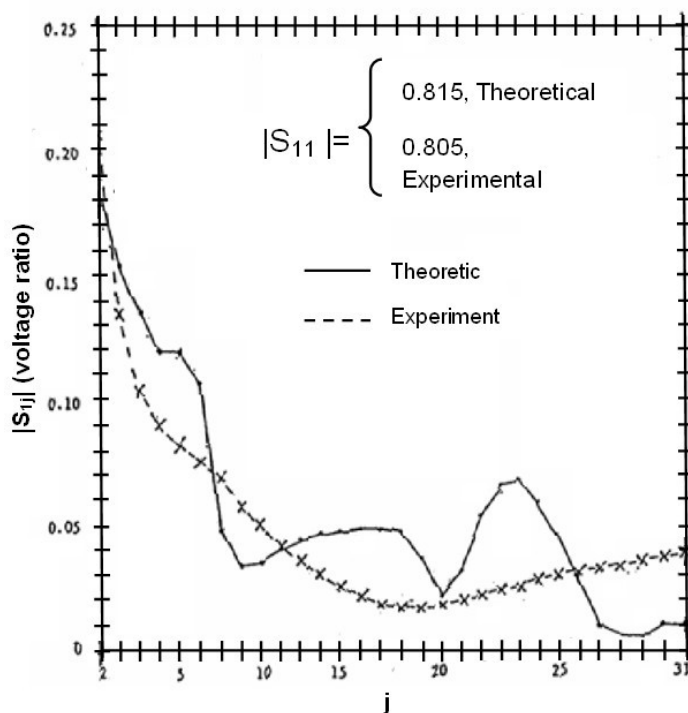


Figure 1. Comparison of Theoretical and Experimental Magnitude of S-Parameters (Center Frequency)

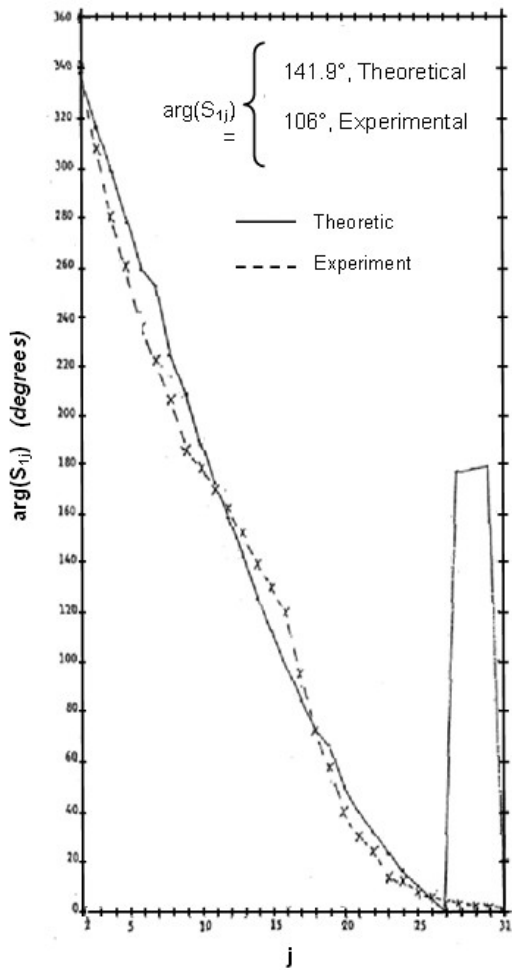


Figure 2. Comparison of Theoretical and Experimental Phase S-Parameters (Center Frequency)

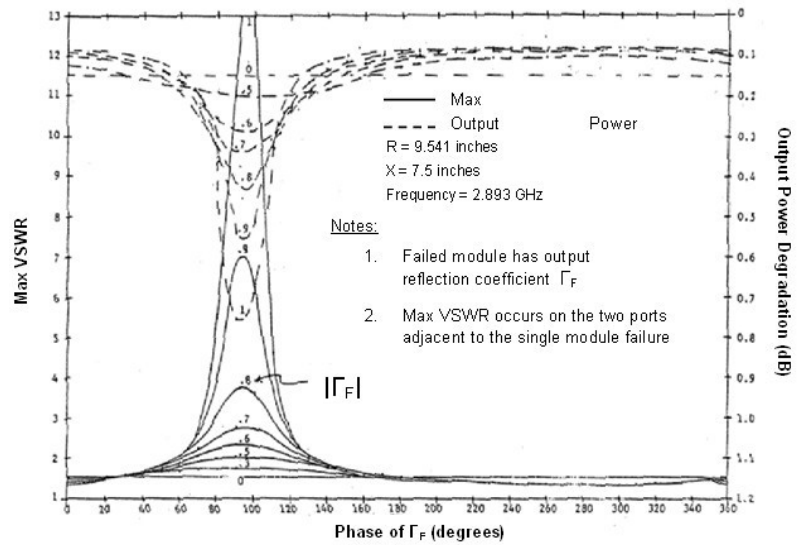


Figure 3. Single Module Failure with Arbitrary Impedance (Centre Frequency)



Figure 4. Combined Radial Power Divider/Combiner Assembly