A COMPREHENSIVE DESIGN TECHNIQUE FOR THE RADIAL WAVE POWER COMBINER

Gerald W. Swift and David Ian Stones

TRW Electronic Systems Group
Redondo Beach, CA 90278

ABSTRACT

A novel structure based upon the radial wave power combiner has been developed, incorporating a radially periodic internal structure which permits its design to be accomplished using techniques similar to those used for distributed element filter design. This paper discusses the development of a radial combiner structure providing less than 0.3 dB insertion loss and operating over greater than one octave bandwidth.

INTRODUCTION

Solid State high power amplifiers have and will find numerous application in space and ground based communications equipment, radar, and partical accelerators for research, medical, and military applications. To achieve the very high powers required for these applications, it is necessary to coherently combine the output power of very many lower power solid state devices. At the device level, this is accomplished by incorporation of more cells within the die, and combining multiple die on the same header within the device. This approach reaches theoretical as well as economic limits as the resulting device becomes more and more difficult to efficiently match and device yield becomes unacceptably low. To a limited extent, binary and serial power combiners may be utilized to increase amplifier output power, however, circuit losses impose an upper bound on the number of amplifiers that may be efficiently combined in this manner.

Losses following the outputs of combined amplifier devices have a significant impact upon overall power amplifier efficiency. When efficiency is a major concern, particularly in spaced based applications, these losses must be minimized as a decrease in efficiency requires additional power, which requires a larger power source, a larger power supply for the amplifier, and additional radiator area to discharge waste heat, all translating to additional payload size and weight.

Several factors contribute to power combining losses. These are losses due to isolating elements, transmission losses due to the overall electrical length of the combining structure manifested in conduction and dielectric losses, radiation and moding losses, and amplitude and phase imbalance. The radial wave power combiner, by nature of its geometry, tends to minimize these losses.

A variety of radial power combining structures have appeared in the literature including microstrip by Schellenberg, et.al.[1], waveguide/microstrip by Stones, et.al.[2], a TEO1 cavity type by Chen [3], a double ridged structure by Oz [4], as well as a twin cavity structure by Okubo [5].

Empirical techniques have been successfully employed in the design of radial combiners [6], however, because the radial power combiner offers a superior approach to high order, high power combining, it has become neccessary to develop a design technique which permits the combiner design to be optimized for the specific application.

THEORETICAL CONSIDERATIONS

The design of an N-way in-phase power combiner, in the general case, may be simplified to a very basic real-to-real impedence matching problem whereby an equivalent source impedence of Zo/N must be matched to to the common port impedence, typically Zo, as shown in figure 1.

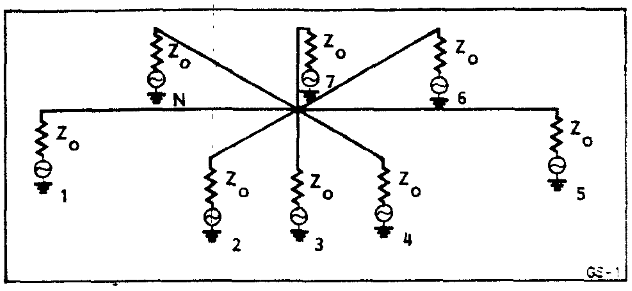

Figure 1. N-way in phase combiner.

In the case of a sixteen-way combiner, in a 50 Ohm system, an equivalent source of 3.125 Ohms must be matched to 50 Ohms. The design of a lumped element filter network between the above unequal terminations is relatively straightforward. In terms of a distributed radial line realization, however, the problem is significantly complicated by the existence of complex characteristic impedences with spatial dependence, as well as Bessel function arguments associated with the radial line quantities. Never-the-less, the marked similarity between the behavior of the uniform TEM transmission line and the radial transmission line in terms of cascaded impedences, i.e.;

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$$Z_i = Z_o \left[\frac{Z_L \cos\beta l + jZ_o \sin\beta l}{Z_o \cos\beta l + jZ_L \sin\beta l} \right] \quad \text{for the uniform TEM line,} \quad (1)$$

verses

$$Z_i = Z_{oi} \left[\frac{Z_L \cos(\theta_i - \Psi_L) + jZ_{oL} \sin(\theta_i - \theta_L)}{Z_{oL} \cos(\Psi_i - \theta_L) + jZ_L \sin(\Psi_i - \Psi_L)} \right] \quad \text{for the radial transmission line} \quad (2)$$

suggests that a radial wave distributed matching network can be developed with techniques similar to those using TEM transmission lines.

In the radial structure however, since the sources are actually discrete, rather than distributed uniformly at the periphery, lumped element parasitics must be absorbed by the equivalent network. A radial network realization may therefore contain lumped, semi-lumped, as well as distributed elements. Additional considerations are that since a radial backshort will necessarily be present at the periphery of the combiner, resulting in a complex equivalent source impedence, a periodic internal structure should be anticipated for broadband operation.
Series capacitive coupling in a radial line topology is not only difficult to realize but may also present voltage breakdown problems in high power applications. For these reasons, inductive transitions should be used for the central and peripheral ports.

The desired modes within the combining structure are the fundamental mode, with no circumferential variations, and those evanescent modes which have integral multiples of the number of ports in the combiner, required for the field matches at the input ports to the fundamental mode. Fields not periodic with the number of input ports contribute to transmission among the ports and ultimately, with no internal mode suppression, the amount of reactive isolation. In the axial direction, dimensions are chosen such that higher order modes are not supported.

Because, in the non-isolated combiner, isolation is manifested purely as inter-port reactances, the amplifiers driving the input ports, must present well behaved output impedences. Hybrid combined output stages (90°) are adequate to satisfy this requirement, or isolators may be employed.

DESIGN

Were it desired to realize the combiner in terms of lumped elements, the design would be simply be a filter, with elements sub-divided among the peripheral ports, and matching between the appropriate unequal terminations over the prescribed operating bandwidth. Such a filter covering 800 to 1600 MHz is shown in Figure 2.

This network, chosen to be very nearly compatible with a distributed network realization, is a sixth degree 0.1 dB Chebychev response incorporating a single Norton transformation. The series input capacitor, however, is undesireable for the reasons previously discussed.

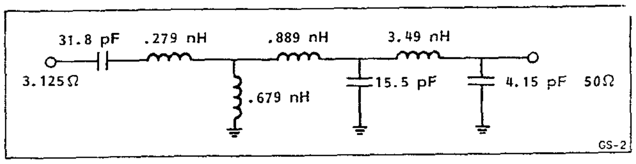

Figure 2. Lumped element prototype.

Two rather drastic approximations may be employed to convert the lumped element network to one suitable for distributed network realizations. The series input capacitor, although essential to the exact response, does not significantly contribute to the impedence transforming properties of the network and is eliminated. The responses of the inductors are then approximated by 1/8 wavelength sections of TEM transmission line with characteristic impedences equal to each inductors reactance at the geometric mean passband frequency. Although these approximations have been made, passband ripple degrades by less than 0.5 dB and computer optimization of the network restores the 0.1 dB passband response as shown in figure 3.

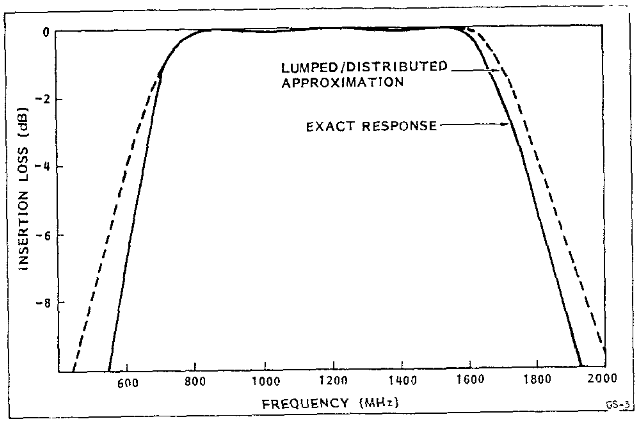

Figure 3. Lumped/distributed matching network response.

The filter skirts of course degrade with this process but maintaining a rejection bandwidth is not a design objective.

A similar procedure could be applied to the shunt capacitances such that the network could then be realized very nearly as a distributed network, highly compatible with microstrip, stripline, and with appropriate transformations as coupled line structures.

The previous network, however, is particularly advantageous for radial line realization as the first series transmission line on the input serves to absorb input launch inductive parasitics. The single shunt transmission line provides similarity to the radial backshort, and the remaining lowpass network suggests a stepped periodic internal structure of radial transmission line with semi-lumped element capacitors. Indeed, this network could be realized in a cascade of conical (TEM) sections. Such a structure, however, would be difficult and costly to manufacture. An additional approximation is employed to further simplify the network which is to replace the theoretical conical sections with radial transmission line of equivalent capacitance as shown in figure 4.

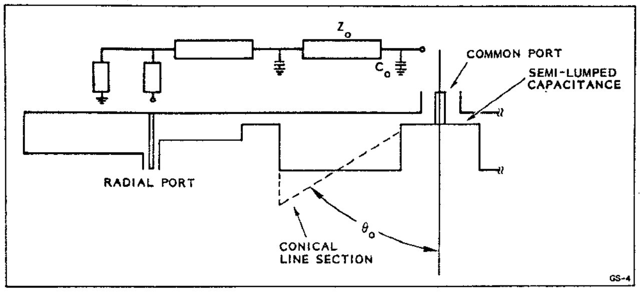

Figure 4. Radial transmission line approximation.

The resulting approximate dimensions result in very close to optimum starting values for a smiple gradient search optimization routine. The combiner is analyzed as a series of cascaded radial transmission lines with variable length (radii) and impedence (spacing) and includes the parasitic effects of probe inductances and fringing capacitances. The additional degrees of freedom introduced by allowing the impedences and lengths to vary permit additional constraints to be imposed to reduce size, meet complicated packaging requirements, meet breakdown voltage requirements, or reduce internal complexity.

A sixteen-way prototype combiner designed by these techniques exhibits a very flat response, as shown in figure 5.

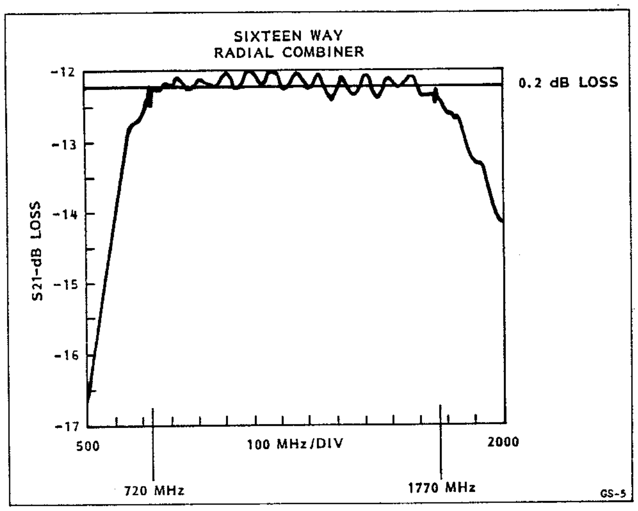

Figure 5. Response of prototype combiner.

The measurement was made from the central port to each of the sixteen ports with the remaining fifteen terminated. Imbalance was negligible with the loss above the power split measured at less than 0.3 dB over greater than one octave bandwidth. Because the design technique allows for very accurate theoretical analysis, no special launch port hardware was required; standard type-N and SMA bulkhead connectors were employed. The combiner measures 16 inches in diameter and the simplicity of the internal structure is shown in figure 6.

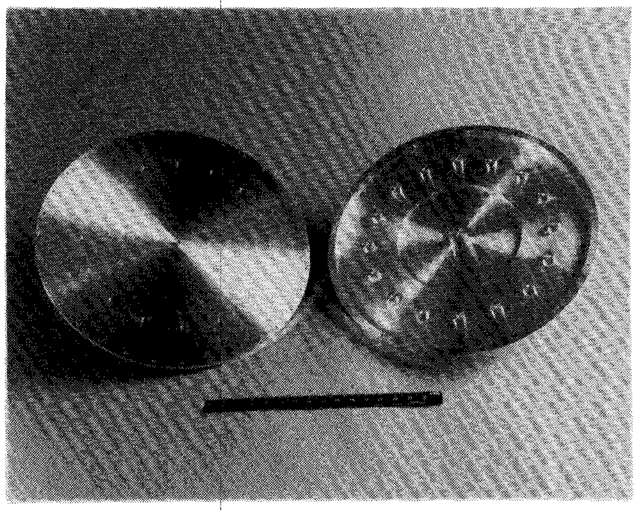

Figure 6. Opened combiner showing internal structure.

Because the design techniques are very versatile, structures which includes dielectric loading in critical areas have been designed, resulting in further reduction in physical size and weight over the conventional approach.

CONCLUSION

A comprehensive design technique has been demonstrated for the design of a radial wave combining structure which achieves highly predictable performance, and is sufficiently general such that it may be applied to combiners of any order, operating bandwidth, and operating frequency.

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