A NOVEL POWER COMBINER FOR MIC AND MMIC AMPLIFIERS*

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Abstract

A new power-combining technique using a dual-ridged structure in rectangular waveguide is described. The compactness of this combiner makes it especially suitable for high-power MIC or MMIC amplifier applications. Four-way combiner/dividers fabricated at X- and K_u-bands exhibited an insertion loss of less than 0.1 dB (combining efficiency of 98 percent) and return loss of better than 20 dB. An MIC power amplifier was designed for the 14- to 14.5-GHz communications band to demonstrate a potential application for this new combiner.

INTRODUCTION

Solid-state power amplifiers have a significant advantage over traveling wave tube amplifiers in both life-cycle cost and reliability. For satellite ground and space applications, the output power requirements for the transmitters can range from a few watts to 100 W, depending on the frequency band and device availability. Since solid-state power devices usually have limited output power, a power combiner with high combining efficiency is essential.

Various combiners using planar circuits such as Wilkinson, Lange coupler, and branchline have been reported in the literature (1)-(4). These microstrip structures are lossy. Also, waveguide combiners (5)-(7) using structures such as magic tee, rat-race network, and resonant cavity, though less lossy, are relatively bulky in physical dimensions.

This paper describes a new dual-ridged waveguide four-way combiner that has two unique features: extremely low RF insertion loss and compact size. This novel combining concept is particularly suitable for applications that require waveguide interface and high power-combining efficiency. The results to be presented represent the first reported data on power combiners that employ a dual-ridged waveguide structure.

POWER COMBINER/DIVIDER DESIGN

Single-ridged waveguides have been used in the past in the design of waveguide-to-microstrip transitions (8)-(11). Because the distribution of the electromagnetic field below the ridge inside a rectangular waveguide resembles that of microstrip lines, the ridge can be used to transform the waveguide mode into a microstrip mode. Similarly, several ridges in a waveguide can be used to form an interface between a single waveguide and several microstrips, as shown in Figure 1. The two-ridged structure is of particular interest since the power split between the ridges is symmetrical. Each ridge should have a characteristic impedance equal to that of the microstrip line(s) to which it connects.

In the present case, each ridge is designed to match to a 25-Ω load and is connected to two 50-Ω microstrip lines located symmetrically with respect to the ridge center. The resulting structure functions as a two-way power combiner or divider. Based on the geometrical symmetry around the center of the waveguide and around each ridge center, with two ridges inside the waveguide, the complete structure can perform as a four-way power combiner/divider. It should be noted that the symmetry around the ridge center is not perfect except when the ridge height is very close to the ground, and even then a very small imbalance exists between the two edges of the ridge.

As in the case of a waveguide-to-microstrip transition, impedance-matching between the waveguide and the four microstrip lines is achieved by using quarter-wavelength sections of ridges with gradually decreasing impedances. The design of these transformers was optimized by an in-house computer program that has been applied to various waveguide bands from K_u to V-band for MIC/MMIC amplifier applications (11)-(14).

MEASURED RESULTS

Two combiner/dividers for X- and K_u-band applications were designed using WR-75

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waveguide. Two combiners connected back-to-back through a 400-mil section of four 50-Ω microstrip lines on a 10-mil fused-silica substrate are shown in Figure 2. Figure 3 shows the measured insertion loss and return loss of two X-band back-to-back combiners. In the 8.7- to 11-GHz band, the effective return loss of each combiner is greater than 20 dB, and after removing the circuit losses associated with the 400-mil microstrip sections, the insertion loss is less than 0.1 dB.

A higher frequency, K_u-band combiner was also designed for the 14- to 14.5-GHz satellite up-link band. Figure 4 shows the measured data for two combiners connected through 400-mil, 50-Ω microstrip lines. The insertion loss of a single combiner/divider is again less than 0.1 dB, and its return loss is better than 23 dB. For the communications satellite down-link band of 10.95 to 11.7 GHz, the same design provides acceptable performance (see Figure 5).

Figure 6 shows the broadband performance of the K_u-band combiner. The resonant absorptions around 12.4 and 13.0 GHz are caused by the asymmetry between the ridge edges and were easily simulated, as shown in Figure 7, by modeling the four microstrip lines with slightly different lengths. The asymmetry between the lines connected to the same ridge causes a small imbalance between the lines that may not be desirable for efficient power combining. Two approaches can minimize this imbalance:

- Employ small isolation resistors to restore the balance between the lines, as in Wilkinson combiners, at the expense of slightly higher loss.
- Using trial and error, move the ribbons that are close to the waveguide walls in Figure 1 nearer to the center of the ridge to equalize the coupling from the ridge to all four microstrip lines.

Figure 8 shows the performance of a very broadband design from 10 to 15 GHz. Isolation resistors were used between the 400-mil, 50-Ω microstrip lines connecting the divider and the combiner ridges. The loss of the combiner/divider structure is less than 0.3 dB over most of the band, and the return loss is better than 17 dB. Excluding the circuit loss of the 400-mil microstrip lines, the combiner RF loss is less than 0.1 dB. Note that, by incorporating the isolation resistors, the resonance around 13 GHz (as shown in Figure 6) is significantly reduced, indicating much better balance among all four ports. This resonance will not occur in actual combiner/divider applications that employ amplifiers because the resonance circuit would not exist in the presence of the amplifiers, resulting in a very broadband combiner circuit.

POWER AMPLIFIER DESIGN

The four-way combiner described above was used in a power amplifier (Figure 9) for the 14- to 14.5-GHz satellite up-link communications band by combining four MIC hybrid modules. The active devices used are GaAs metal semiconductor field effect transistors (MESFETs) with 0.5-µm gate length. The power amplifier consists of four parallel carrier modules, each delivering close to 1.0 W of output power at saturation. The modules include a three-stage design with interstage matching networks to achieve 15-dB gain. The power stage on each carrier consists of two amplifiers that are assembled using direct combining on microstrip structures. The outputs of the four carriers are connected to the ports of the double-ridged waveguide combiner. Isolation resistors are added between each pair of carriers to improve the isolation between the lines connected to each ridge.

A special effort was made to design all microstrip lines with equal lengths on both the input and output. This arrangement is essential for proper operation of the combiner. The microstrip lines have approximately 0.3 dB of loss. For MMIC power applications, these lines could be greatly shortened (thus reducing their loss), since the circuits are small and can easily be aligned with the waveguide ridges and placed inside the nominal WR-75 waveguide cavity.

AMPLIFIER MEASUREMENTS

Four hybrid amplifier modules were assembled for insertion into the power amplifier. Figure 10 shows the small signal gain of all four modules from 14.0 to 14.5 GHz and the output power of each circuit at 1-dB gain compression. Since the characteristics of the MESFETs are not identical, the performance of the carrier circuits can vary, which can adversely affect the efficiency of the combiner circuit. (MMIC amplifier modules would have a better advantage in terms of performance uniformity than hybrid MIC modules in that respect.) The small signal gain and input and output return losses of the power amplifier are shown in Figure 11. The input return loss measured at the waveguide flange is greater than 13 dB from 14 to 14.5 GHz, and the gain is greater than 17 dB. Figure 12 shows the output power vs input power at 14.0, 14.25, and 14.5 GHz. Note that the output power has very soft compression characteristics compared to the individual amplifiers, which indicates nonuniformity in performance among the combined circuits.

At 1-dB gain compression, the output power is close to 33 dBm (2 W). Since the individual amplifiers all have 1-dB compression around 28 dBm (0.63 W), the output of the combined power amplifier is not exactly the sum of output power of the four modules due to variation among the units, resulting in a combining efficiency of 79 percent. Near saturation, the output power is close to 34 dBm (2.5 W) for the amplifier and 28.5 dBm (0.7 W) for each of the carrier modules, and therefore the combining efficiency is close to 89 percent.

CONCLUSIONS

A novel dual-ridged waveguide combiner has been designed and tested that exhibits extremely high combining efficiency. Two designs with operating frequencies at X- and K_u-bands resulted in low RF insertion loss, good return loss, and extremely compact size. A very broadband combiner was also designed and tested, providing similar performance from 10 to 15 GHz.

The K_u-band combiner was used to build a power amplifier by directly combining the power of four small MIC modules. The measurements of the power amplifier demonstrate the need to achieve reasonable balance between the combined amplifier modules to reach the maximum theoretical efficiency of the combiner. The new combiner is potentially very useful for solid-state, high-power ground and space applications, and especially for MMIC-type module combining. In this case, all amplifier circuits can fit within a very small area that is comparable to the waveguide dimensions, and the uniformity of MMIC amplifiers can be exploited to achieve high combining efficiency.

ACKNOWLEDGMENTS

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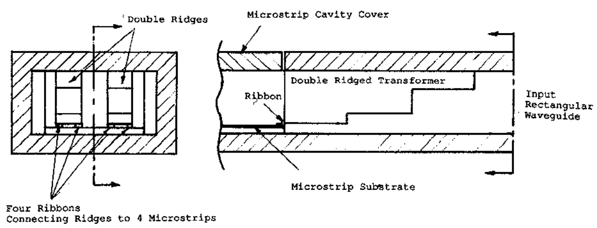

Figure 1. Sketch of Dual-Ridged Waveguide Transformer Connected to Four Microstrip Lines

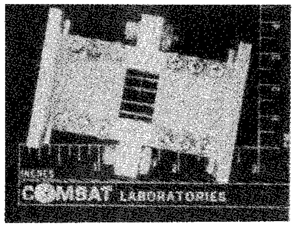

Figure 2. A 4-Way Divider and Combiner Connected Using 400-mil Microstrip

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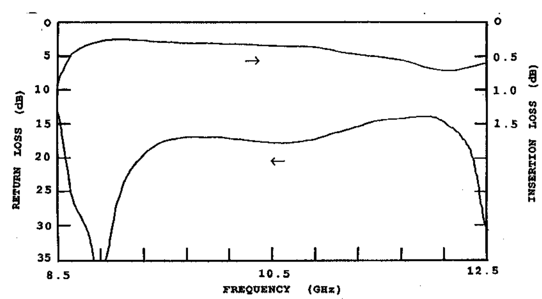

Figure 3. Insertion Loss and Return Loss of Two Combiners Back-to-Back at X-Band

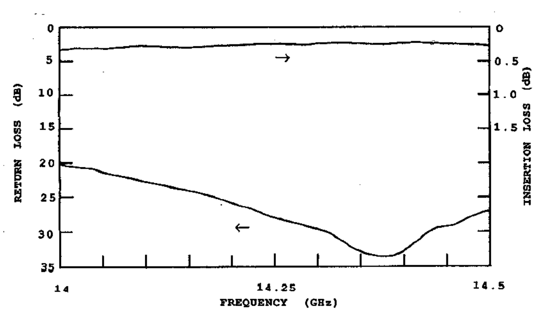

Figure 4. Insertion Loss and Return Loss of Two Combiners Back-to-Back at K_u-Band

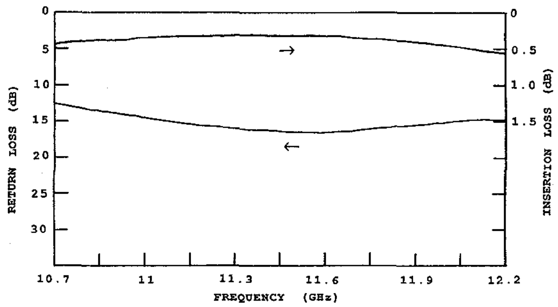

Figure 5. Insertion Loss and Return Loss of Two Combiners Back-to-Back at X-Band

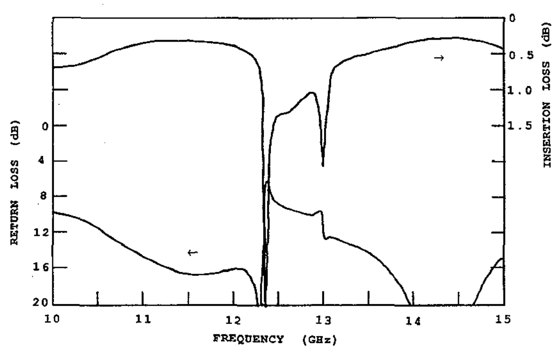

Figure 6. Insertion Loss and Return Loss of K_u-Band Combiners Connected Back-to-Back

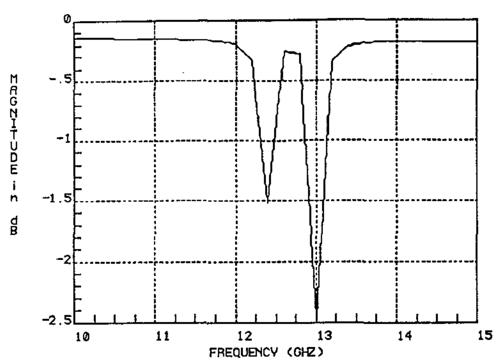

Figure 7. Simulated Transmission of Four Parallel Microstrips With Unequal Length

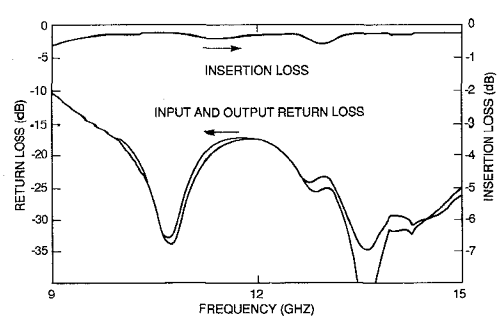

Figure 8. Insertion Loss and Input and Output Return Loss of a Broadband Combiner/Divider Design

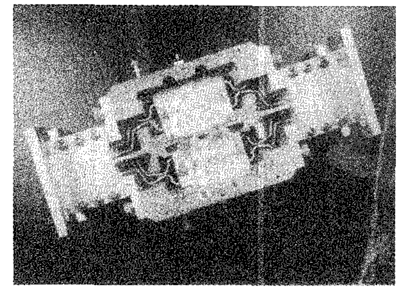

Figure 9. An MIC Power Amplifier Using the 4-Way Double-Ridge Power Combiner

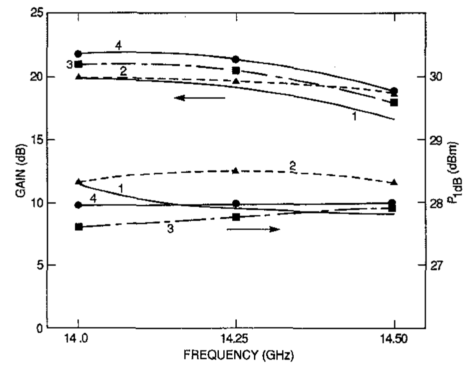

Figure 10. Small Signal Gain and Output Power at 1-dB Gain Compression for All Four Modules

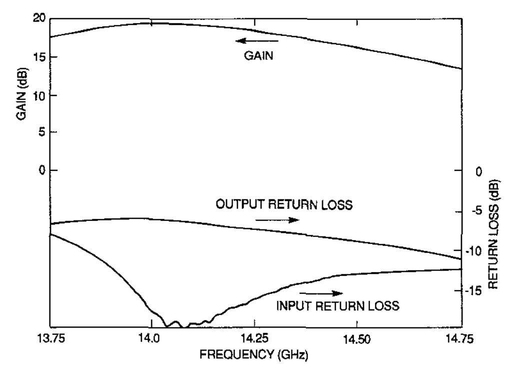

Figure 11. Gain and Input/Output Return Losses of the Power Amplifier

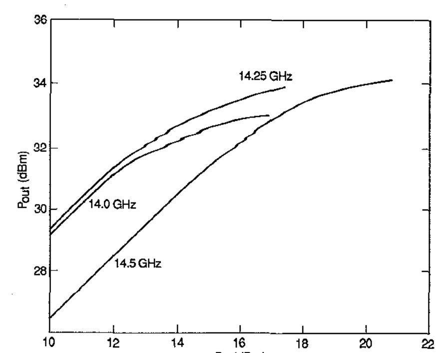

Figure 12. Power Output vs Input of the Power Amplifier