TRAPPED INVERTED MICROSTRIP (TIM) CIRCUITS FOR COMBINING THE OUTPUTS OF HIGH-POWER IMPATT OSCILLATORS

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ABSTRACT

High-power IMPATT oscillators were combined through balanced hybrids realized in trapped inverted microstrip (TIM) line. Combining efficiencies approached 80 percent, with CW power outputs of 42 W at 5 GHz and 22 W at 9.3 GHz from four-oscillator arrays.

Introduction

Power outputs greater than those possible with a single IMPATT diode can be produced using a single-cavity multiple-diode circuit configuration,[1,2] or by combining the outputs of several independent oscillators or amplifiers through an appropriate hybrid circuit.[3] When the latter approach is used with high-power (5-15 W CW) IMPATT devices, the hybrid circuit should have: small losses to obtain good circuit efficiency; good isolation between diode ports, extending over a wide frequency range, to suppress spurious modes of oscillation; and sufficient power-handling capability to withstand the internal power dissipation which results either from unequal diode power outputs or from the failure of a diode. In addition, the hybrid should be physically compact, economical to manufacture, and should require a minimum of adjustments to obtain good performance.

We have recently constructed and tested a series of hybrids which demonstrate one way in which the foregoing requirements can be satisfied. Four-way divider/combiner circuits were realized in C- and X-bands by cascading 3-dB in-phase hybrids of the type described by Gysel.[4] Trapped inverted microstrip (TIM) was used as the transmission line medium for the hybrids.[5] Individual coaxial cavity IMPATT diode oscillators, operated in the injection-locked mode, were combined through the hybrids. The resulting prototype FM power amplifier output stages produced 42 W CW at 5 GHz with 11 dB locking gain, and 22 W CW at 9.3 GHz with 16 dB locking gain. The combining efficiencies achieved were 75 percent at 5 GHz and 79 percent at 9 GHz.

Circuit Configuration

The Wilkinson hybrid[6] has been used quite widely for IMPATT diode power combining.[3] This circuit, shown in a two-diode-port version in Fig. 1, has two principal disadvantages. First, its power handling capability in the presence of an imbalance of the voltages applied at the diode ports is limited by the maximum dissipation allowable in the internal termination Z_T'. Second, the circuit topology of the Wilkinson hybrid is such that versions with more than two diode ports cannot be constructed on a planar substrate while retaining the perfect symmetry desirable in an equiphase power divider/combiner.

Gysel[4] described a modification of the Wilkinson hybrid which has increased power-handling capability. The Gysel circuit, also shown in Fig. 1, divides the termination into two separate resistors, Z_T, which are connected from line to ground. Internal terminations, heat-sunk to the circuit ground plane, or high-power external loads can be used.

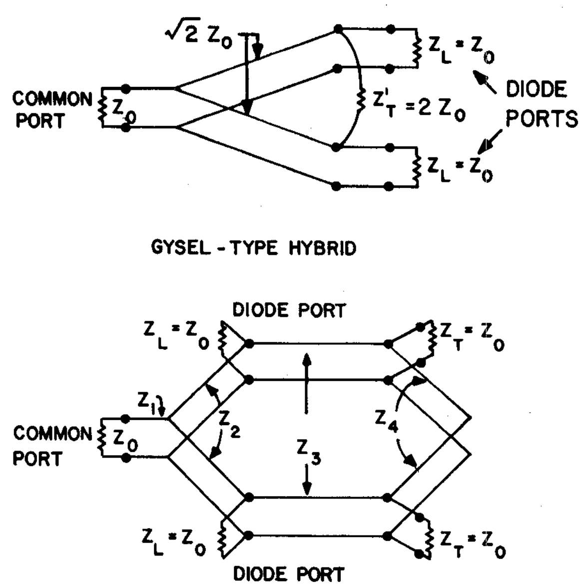

Figure 1. Transmission Line Configurations for Wilkinson and Gysel Hybrids with Two Output Ports. Transmission line segments are λ/4 in length.

The requirement for operation of the combining circuit at high CW power levels led to the selection of the Gysel hybrid for the work reported here. Of the possible choices for line impedances, $Z_1 = Z_3 = Z_4 = Z_0$, $Z_0 = 50\ \Omega$ and $Z_2 = 70.7$ ohms gave the best balance between performance and ease of fabrication. Planar circuits with four diode ports were formed by cascading basic two-port units.

Transmission Line Medium

A transmission line offering smaller losses and better isolation than conventional alumina-substrate microstrip, but having smaller physical size than air-dielectric stripline, was sought for construction of the Gysel hybrids. Trapped inverted microstrip (TIM) line[5] appeared to satisfy these requirements and was selected for the present work.

The TIM-line structure is shown in Fig. 2. It is basically a trough line with a dielectric overlay. The dominant mode of propagation is quasi-TEM, with much of the wave energy concentrated under the printed conductor in the channel. Fringing fields tend to be "trapped" in the dielectric layer and are confined close to the channel. The effective dielectric constant of the line is ~ 3 for typical cases, and the line is slightly dispersive. Computed loss per wavelength is about 70 percent of that in conventional microstrip.

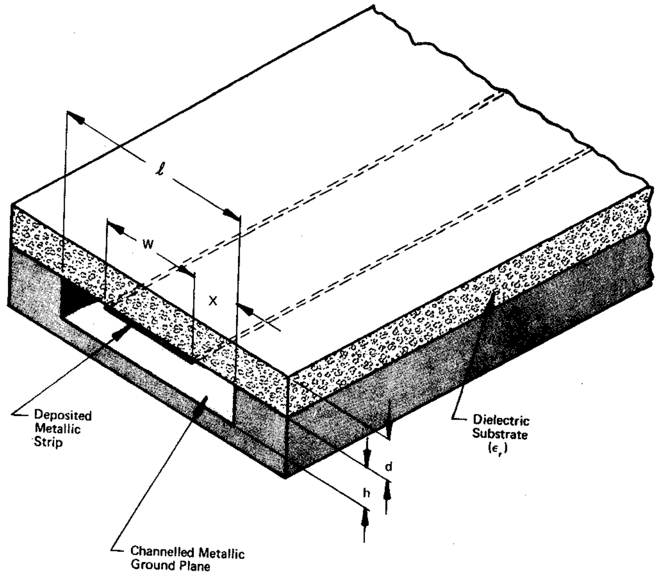

Figure 2. Trapped Inverted Microstrip (TIM) Line Structure.

Figure 3 shows one of the 5 GHz TIM-line Gysel hybrids constructed. The substrate size in this case was 2" × 2". The X-band units were constructed on 1" × 1" substrates.

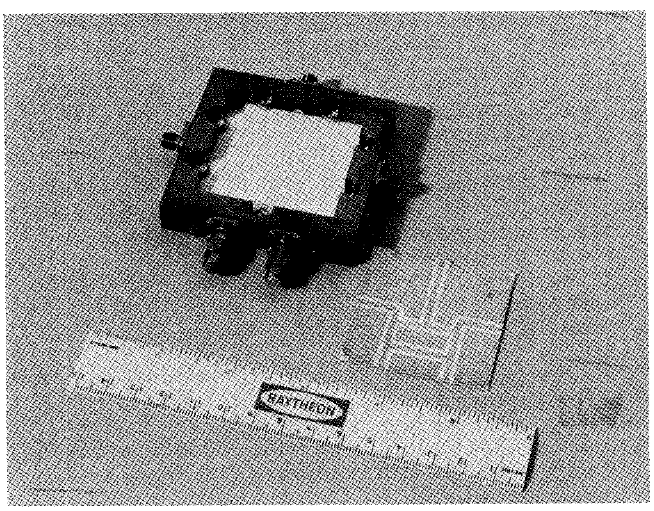

Figure 3. 5 GHz TIM-Line Gysel Hybrid. Low-power terminations are installed in this photo.

Circuit Performance

The TIM-line hybrids were designed, fabricated, and tested without making any circuit adjustments to optimize performance. The C-band units showed operating band centers about 200 MHz above the nominal 5.0 GHz design value. Band centers of the X-band units were scattered around, but within 200 MHz of, the 9.0 GHz design value. Except for this offset, performance was close to that predicted analytically.

Figure 4 compares the computed and measured loss and isolation for the "5 GHz" hybrid as functions of frequency. The frequency scale has been normalized to the band center, and line losses were neglected in the computation. In a 500 MHz band centered on f_o, excess loss between the common port and the two diode ports was only 0.2 - 0.3 dB. The two diode ports

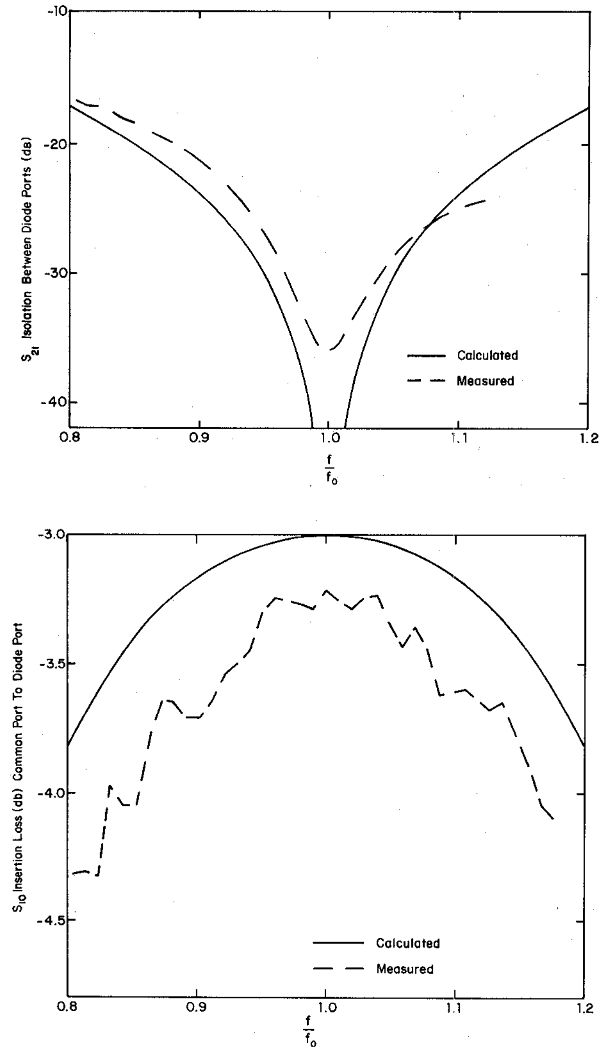

Figure 4. Comparison of Computed and Measured Performance for the 5 GHz TIM-Line Gysel Hybrid. The frequency scale is normalized to the operating band center. Line losses were neglected in the computation.

were balanced within 0.1 dB in amplitude and 3° in phase. Isolation between the two diode ports was at least 30 dB and reached 38 dB at band center. The maximum VSWR at the common port was 1.2, and VSWR at the diode ports was less than 1.1. Band-center VSWR's were less than 1.04 at diode and common ports.

Measured performance of the individual X-band hybrids was comparable to that of the 5 GHz units. All data apply to the 1 GHz band centered on 9 GHz. Within this band, the best unit showed a maximum excess loss of 0.35 dB between the common port and the diode ports. Outputs at the diode ports were typically balanced within 0.1 dB (0.2 dB worst case) in amplitude and 2° (5° worst case) in phase. The isolation between diode ports was at least 29 dB, and reached 37 dB at band center. Maximum VSWR at the diode ports was typically 1.2, and was relatively constant across the band. The VSWR at the common port was typically 1.2 at band center, and decreased from a maximum of 1.4 at the lower band edge to 1.1 at the upper band edge.

Performance of the cascades of hybrids having four diode ports was also satisfactory. For the C-band structure, loss between the common port and the diode ports was typically 1 dB, including the loss of the output circulator. The individual diode ports were balanced within 0.1 dB in amplitude and 2° in phase at 5 GHz. Isolation between diode ports was typically 30 dB. The isolation between diode ports on opposite sides of the cascade was better than that between adjacent diode ports.

Figure 5 summarizes the performance of the cascade of X-band hybrids. The excess loss at 9 GHz was typically 0.6 - 0.7 dB excluding the output circulator. Individual diode ports were balanced within 0.2 dB in amplitude and 5° in phase across the operating band. Isolation at 9 GHz was typically more than 30 dB, with isolation being better between ports on opposite sides of the cascade (S_{31}) than between adjacent ports (S_{21}) located on the same individual hybrid.

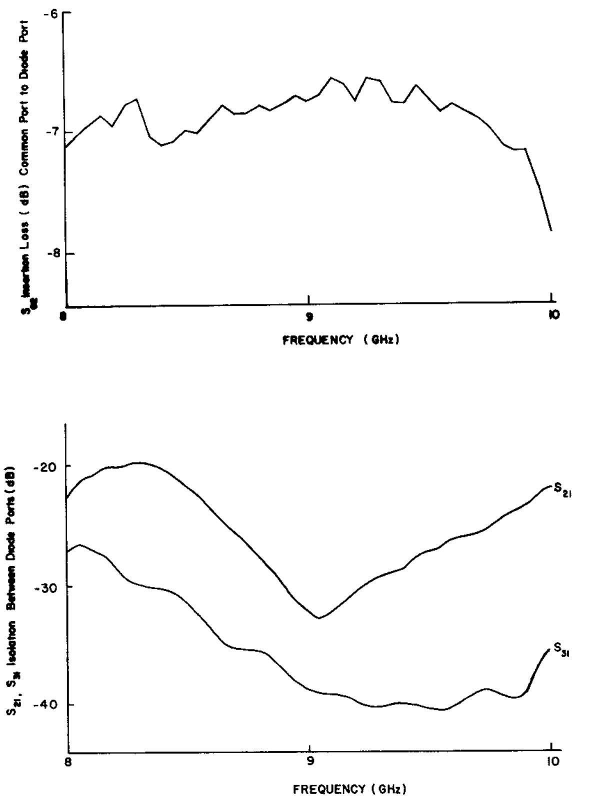

Figure 5. Measured Performance of the Cascade of X-band Gysel Hybrids Forming a Four-Way Divider/Combiner. Loss in excess of the nominal 6 dB division is ~0.7 dB at band center.

Coaxial cavity IMPATT oscillators were combined through the four-way divider/combiner circuits to form prototype FM power amplifier output stages operating in the injection-locked oscillator mode. The individual C-band oscillators were capable of 12 - 13 W CW output with 25 percent dc-to-rf conversion efficiency. The X-band oscillators produced 6 - 7 W CW output with 20 percent efficiency.

Setup of the output stages was simplified by the good isolation and large power-handling capability of the hybrids. Each oscillator was set to the desired band center and tuned for nominal power output singly with bias removed from the other units. The injection signal was then applied and bias brought up on all oscillators simultaneously without further readjustment.

The C-band stage produced a maximum of 42 W CW output with 11 dB locking gain at 5 GHz with 18 percent power-added efficiency. Combining efficiency was 75 percent. The X-band stage produced a maximum of 22 W CW output with 16 dB locking gain at 9.25 GHz with 15.6 percent power added efficiency. This efficiency would be improved with the use of more efficient oscillator modules. Combining efficiency was 79 percent. The locking bandwidths at C- and X-bands were limited to 1-2 percent by the relatively high Q_{ext}'s of the coaxial oscillators used.

Conclusion

Trapped inverted microstrip (TIM) hybrids have been successfully used to combine high-power C-band and X-band IMPATT oscillators. The combining circuits required no adjustment after fabrication, indicating a potential for low-cost manufacture.

Acknowledgement

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References

1. K. Kurokawa, "The Single-Cavity Multiple-Device Oscillator," IEEE Transactions MTT-19, 793 (1971).

2. K. Kurokawa and F. M. Magalhaes, "An X-Band 10-Watt Multiple-IMPATT Oscillator," Proc. IEEE 59, 102 (1971).

3. R. E. Lee, U. H. Gysel, and D. Parker, "High-Power C-Band Multiple-IMPATT-Diode Amplifiers," IEEE Transactions MTT-24, 249 (1976).

4. U. H. Gysel, "A New N-Way Power Divider/Combiner Suitable for High-Power Applications," 1975 IEEE MTT Symposium Digest, p. 116.

5. C. Buntschuh, "A Study of the Transmission Line Properties of Trapped Inverted Microstrip Line," Final Technical Report RADC-TR-74-311, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York 13441, December 1974.

6. E. J. Wilkinson, "An N-Way Hybrid Power Divider," IRE Transactions MTT-8, 116 (January 1960).