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HYBRID COUPLED MICROSTRIP REFLECTION AMPLIFIERS

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ABSTRACT

A two-stage (four diode) hybrid coupled amplifier has been fabricated on microstrip using Indium Phosphide Gunn diodes. A minimum of 5 dB gain was achieved over 33-38 GHz. The gain of this type of amplifier is very dependent on input and output VSWR. It will be shown analytically that these devices, even when constructed monolithically, will be limited to narrow bandwidths.

Introduction

Because no circulators are required, the quadrature coupled diode amplifier would appear to be an ideal circuit element for millimeter-wave wide bandwidth amplification where such circulators are not readily available. In particular, hybrid coupled amplifiers are the only means available for monolithic amplification at the higher frequencies where FETs are unusable. It seemed reasonable, therefore, to attempt to build a Ka band microstrip amplifier in discrete form as an initial approach. At the 1980 IEEE MTT-S Symposium the author reported on the design and fabrication of a 10 GHz bandwidth microstrip reflection amplifier (measured without hybrid coupling)[1]. Also reported was a coupled stage (2 diodes) which gave 7 dB gain over 1.5 GHz bandwidth.

Computer programs have been developed to model multiple hybrid coupled devices and a two stage amplifier (4 diodes) has been fabricated with limited success, i.e., less bandwidth than predicted. Calculations were made to determine the effect of input and output VSWR on both practical discrete diode circuits and for ideal negative resistance elements in monolithic form.

Analysis

A single stage hybrid coupled amplifier consists of a 3 dB quadrature coupler connected to two reflection amplifier networks terminated by negative resistance stable diodes. Figure 1 shows how these elements, together with connecting transmissions lines, forms a two-port. When the coupler is symmetric and the matching networks and diodes are identical, the gain and return loss can be found by even and odd mode analysis as indicated in Figures 1b and 1c. The reflection coefficient is then

$$\frac{b_1}{a_1} = \frac{1}{2} S_{11}'(1b) + \frac{1}{2} S_{11}'(1c)$$

and the voltage gain

$$\frac{b_4}{a_1} = \frac{1}{2} S_{11}'(1b) - \frac{1}{2} S_{11}'(1c)$$

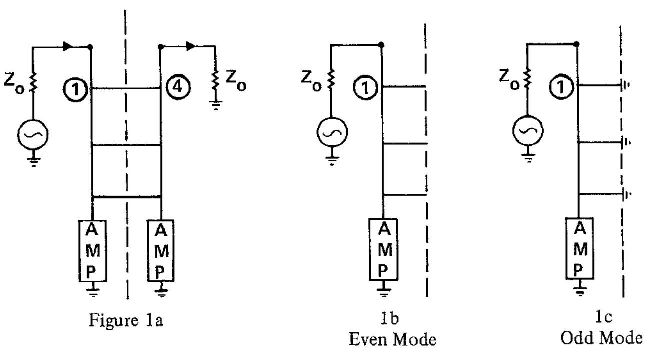

Figure 1. Even and Odd Mode Superposition for Symmetric Hybrid Coupled Amplifier Analysis.

where $S_{11}'(1b)$ and $S_{11}'(1c)$ are the input reflection coefficients calculated from the two-ports of Figures 1b and 1c, respectively.

Non symmetric circuits, such as exists when non identical diodes are used, can also be analyzed using two-port analysis. As shown in Figure 2a the amplifying networks and their diodes give reflection coefficients Γ_2 and Γ_3. The symmetric coupler four-port parameters S_{11}, S_{12}, S_{13}, and S_{14} are determined by even and odd mode analysis. The coupler combined with the amplifiers result in the flow graph of Figure 2b. Mason's loop analysis[2] can be used to solve for the resulting two-port, i.e., $S_{11}' = b_1/a_1$, $S_{41}' = b_4/a_1$, $S_{44}' = b_4/a_4$, and $S_{14}' = b_1/a_4$. The conference attendee will be spared the resulting equations, however it should be noted that for all values of Γ_2 and Γ_3, $S_{41}' = S_{14}'$, whereas $S_{11}' = S_{44}'$ only if $\Gamma_2 = \Gamma_3$. The resultant two port parameters can be converted to ABCD parameters and used in subsequent analysis, i.e., multiple stage amplifiers with input and output VSWRs and interstage coupling.

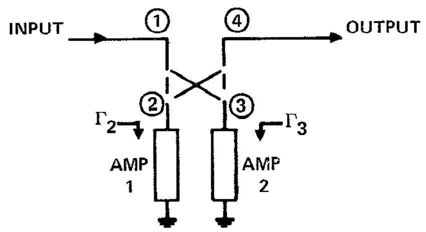

Figure 2a. Hybrid coupled amplifier with different reflection networks or different diodes.

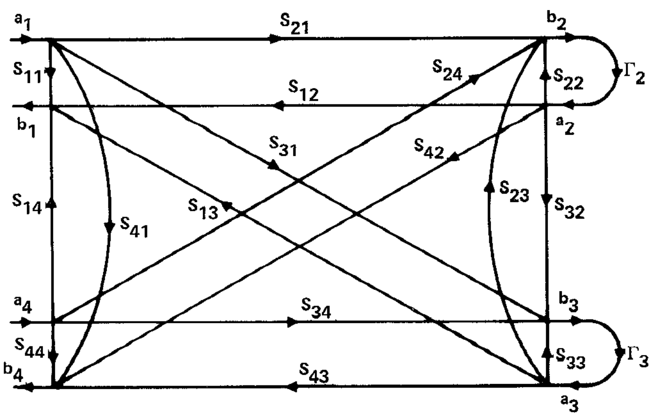

Figure 2b. Flow graph for circuit of 2a.

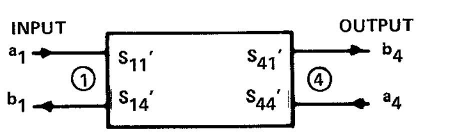

Figure 2c. Resultant two port parameters determined from 2b.

Figure 3 is a computation of a two stage amplifier design using identical packaged Varian Diodes. Figure 4 shows the result of using two slightly different diodes in the same circuit. No transition VSWR was used in these computations. Other results will be presented.

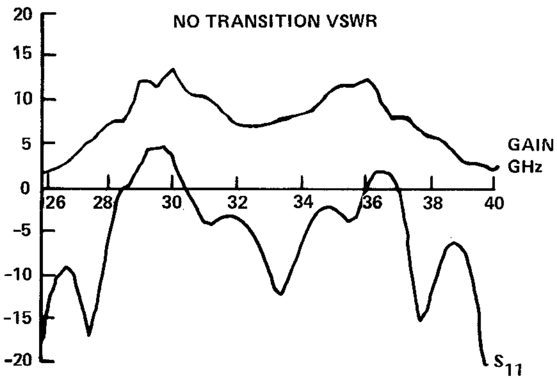

Figure 3. Calculation of gain and return loss for two-stage amplifier with identical diodes.

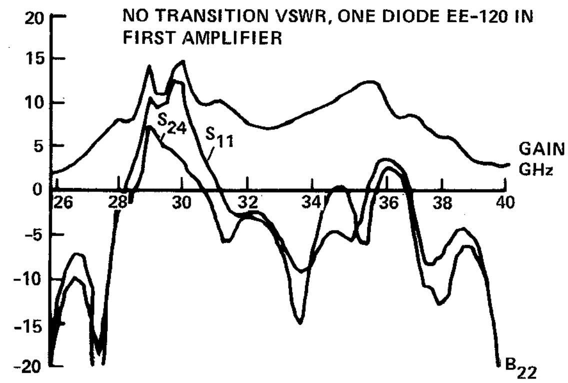

Figure 4. Gain and return loss for the same circuit as Figure 3, except slightly different diodes used.

Experimental Results

The actual device constructed is shown in Figure 5. Duroid 5880, .010" thickness substrates were used. The diodes were mounted parallel to the substrate and a small amount of lateral motion was permitted along the surface of the last transformer section to allow for some tuning. The design of the couplers along with the diode matching networks should have yielded results similar to that of Figure 4, except for losses and transition VSWR. The actual results are shown in Figure 6. More gain could be attained if additional reflection was allowed. The actual circuit design followed somewhat the method previously described[1].

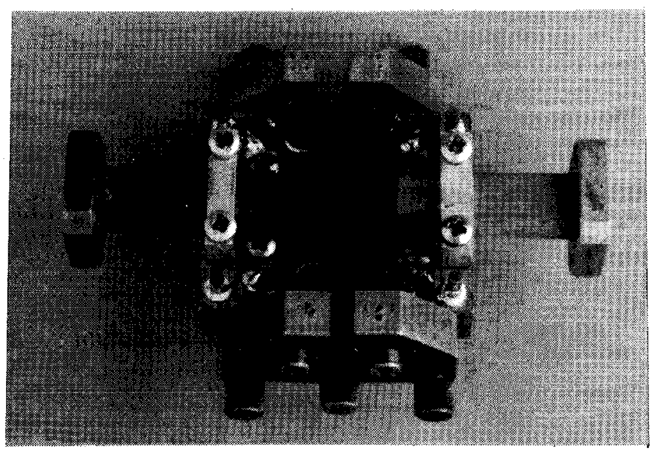

Figure 5. Two-stage hybrid coupled amplifier.

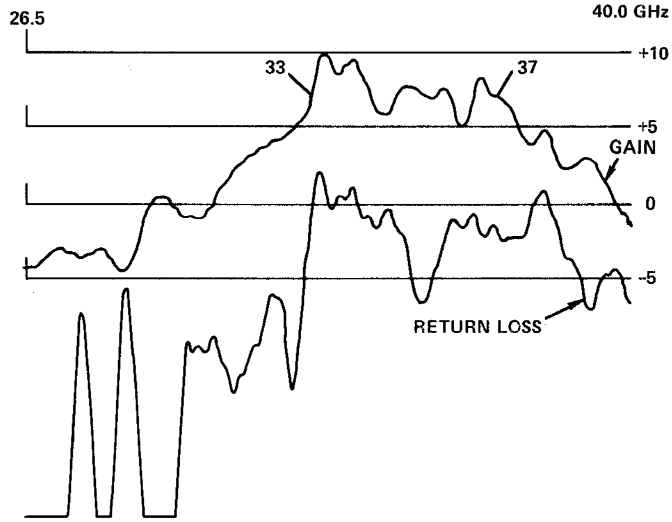

Figure 6. Four diode amplifier tuned for maximum gain-bandwidth.

The VSWR Problem

Any single or multiple stage reflection amplifier can be reduced to a two-port with input and output as shown in Figure 7a. A flow graph comprising both amplifier and input and output reflection coefficients (due to transitions, etc.) is shown in Figure 7b. Denoting the *three* two-port parameters of the total amplifier as S_{11}, S_{22}, and S_{21}, and the input and output reflection coefficients as ρ_1 and ρ_2, the forward and reflected power gains are

$$\left|\frac{b_2}{a_1}\right|^2 = \left|\frac{S_{21}}{1 - (\rho_1 S_{11} + \rho_2 S_{22} + \rho_1 \rho_2 S_{21}^2) + \rho_1 \rho_2 S_{11} S_{22}}\right|^2$$

$$\left|\frac{b_1}{a_1}\right|^2 = \left|\frac{S_{11}(1 - \rho_2 S_{22}) + S_{21}^2 \rho_2}{1 - (\rho_1 S_{11} + \rho_2 S_{22} + \rho_1 \rho_2 S_{21}^2) + \rho_1 \rho_2 S_{11} S_{22}}\right|^2$$

These equations can be maximized and minimized by assigning phases to the various parameters. It is therefore possible to find the worst case effects of the VSWR transitions or terminations as shown in Table 1. This table lists the maximum possible gain variations (total), and worst case return losses for 5 and 10 dB single stage amplifier gains and various input and output external reflection coefficients. As can be seen, for useful amplification:

1. 5 dB amplifiers should have output and input VSWRs corresponding to -20 and -15 dB (or greater), respectively.
2. 10 dB amplifiers require input and output VSWR corresponding to -20 dB return loss or greater.
3. An extension of the table to 15 dB gain amplifiers would show them to have greater than 4 dB ripple and return gain of 8 dB minimum with the lowest VSWRs given in the tables.

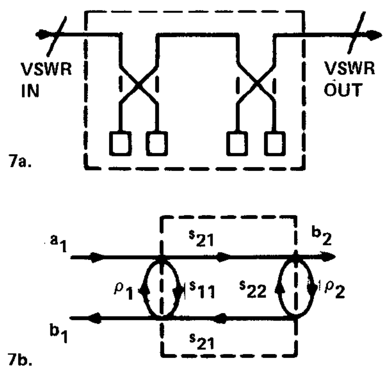

Figure 7. Flow graph for generalized hybrid coupled amplifier with mismatched terminations.

Table 1.

Gain (dB)	Chg (dB)	$S_{11} = S_{22}$ (dB)	New Ret. Loss	ρ_1 (dB)	ρ_2 (dB)
5.00	1.22	-10.00	-5.39	-20.00	-25.00
5.00	1.75	-10.00	-2.92	-20.00	-20.00
5.00	2.70	-10.00	0.50	-20.00	-15.00
5.00	4.43	-10.00	5.00	-20.00	-10.00
5.00	1.94	-10.00	-5.00	-15.00	-25.00
5.00	2.70	-10.00	-2.39	-15.00	-20.00
5.00	4.87	-10.00	1.32	-15.00	-15.00
5.00	6.66	-10.00	6.55	-15.00	-10.00
5.00	3.23	-10.00	-4.26	-10.00	-25.00
5.00	4.43	-10.00	-1.35	-10.00	-20.00
5.00	6.66	-10.00	3.00	-10.00	-15.00
5.00	11.31	-10.00	9.97	-10.00	-10.00
5.00	1.94	-5.00	-1.38	-20.00	-25.00
5.00	2.70	-5.00	0.64	-20.00	-20.00
5.00	4.07	-5.00	3.72	-20.00	-15.00
5.00	6.66	-5.00	8.37	-20.00	-10.00
5.00	3.04	-5.00	-0.75	-15.00	-25.00
5.00	4.07	-5.00	1.46	-15.00	-20.00
5.00	5.99	-5.00	4.94	-15.00	-15.00
5.00	9.82	-5.00	10.64	-15.00	-10.00
5.00	5.06	-5.00	0.49	-10.00	-25.00
5.00	6.66	-5.00	3.14	-10.00	-20.00
5.00	9.82	-5.00	7.67	-10.00	-15.00
5.00	17.81	-5.00	17.25	-10.00	-10.00
10.00	1.94	-10.00	-0.04	-20.00	-25.00
10.00	3.04	-10.00	4.10	-20.00	-20.00
10.00	5.06	-10.00	9.39	-20.00	-15.00
10.00	9.07	-10.00	16.50	-20.00	-10.00
10.00	3.23	-10.00	0.70	-15.00	-25.00
10.00	5.06	-10.00	5.35	-15.00	-20.00
10.00	8.65	-10.00	11.85	-15.00	-15.00
10.00	17.93	-10.00	23.86	-15.00	-10.00
10.00	5.63	-10.00	2.20	-10.00	-25.00
10.00	9.07	-10.00	8.12	-10.00	-20.00
10.00	17.93	-10.00	19.44	-10.00	-15.00
10.00	17.69	-10.00	21.36	-10.00	-10.00
10.00	2.70	-5.00	2.61	-20.00	-25.00
10.00	4.07	-5.00	6.32	-20.00	-20.00
10.00	6.66	-5.00	11.55	-20.00	-15.00
10.00	12.22	-5.00	19.75	-20.00	-10.00
10.00	4.43	-5.00	3.65	-15.00	-25.00
10.00	6.66	-5.00	8.00	-15.00	-20.00
10.00	11.31	-5.00	14.97	-15.00	-15.00
10.00	30.22	-5.00	36.11	-15.00	-10.00
10.00	7.75	-5.00	5.87	-10.00	-25.00
10.00	12.22	-5.00	12.15	-10.00	-20.00
10.00	30.22	-5.00	32.05	-10.00	-15.00
10.00	13.53	-5.00	17.11	-10.00	-10.00

These charts are actually too restrictive, since they allow arbitrary phases corresponding to the worst cases. These are only approached when the distances between circuit elements are on the order of one or more wavelengths. Just how bad the problem actually is, and whether or not the device has any practical use, can be predicted from Figure 8. These are gain and return loss composites of single and dual amplifiers using "ideal" negative resistances and two different practical branch couplers. The four branch synchronous coupler was used in our actual amplifier because of its large bandwidth. The three branch periodic has nearly perfect return loss and directivity over the 32-34 GHz band shown. The ideal negative resistance has been set to zero outside of this band. Figure 7 demonstrates:

1. Even for the most ideal amplifier circuit, input and output VSWR should be less than 1.2 (-20 dB return loss). In general, this may require tuning out transition and load admittances, or the use of external isolators.
2. The limiting criteria for hybrid coupled amplifiers are not the parasitics associated with packaged diodes or low directivity couplers. The problem is due to transition VSWR and source and load mismatches.

Conclusions

It has been shown how two-port analysis can be extended to calculate the r.f. response of single and multiple hybrid coupled amplifiers. Because circulators are not required, it was thought (by the author) that this form of circuit would be the most useful means of achieving wide band amplification at millimeter-waves, particularly using monolithic InP or GaAs. Some reasonable results with two stage discrete amplifiers were obtained. These results, however, were obtained with isolators between the input sweeper and the amplifier; also the output power was sampled through a standard 10 dB coupler. This is an ordinary test set-up for most circuits at these frequencies. As has been shown, the hybrid coupled amplifier is ill-prepared to meet the challenges of an unisolated world. Transitions and input and output load mismatches may be tuned out over a narrow band of frequencies, however a wide bandwidth amplifier, operating into and out of normal mismatched loads, appears to be a physical impossibility.

References

1. D. Rubin, "Millimeter-Wave Microstrip Amplifier Using Indium Phosphide Diodes," 1980 International Microwave Symposium Digest, pp. 67-69.
2. J. K. Hunton, "Analysis of Microwave Measurement Techniques by Means of Signal Flow Graphs," IRE Trans. on Microwave Theory & Techniques, March 1956, pp. 206-212.

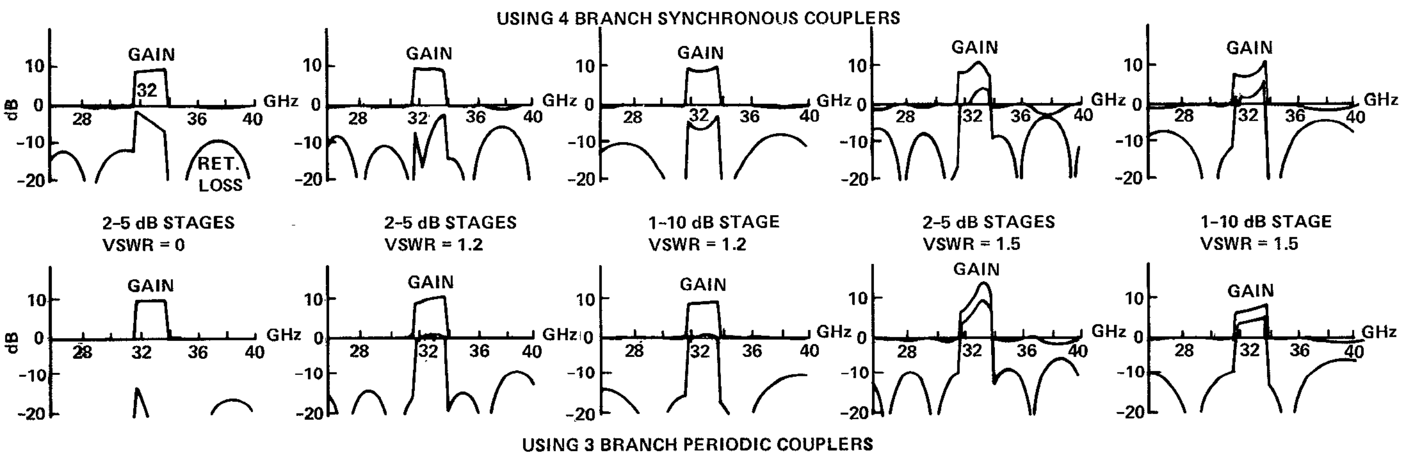

Figure 8. 10 dB Gain Hybrid Coupled Amplifiers (One and Two Stages) Using Ideal Negative Resistance Amplifying Elements Between 32 and 34 GHz. Input and Output VSWRs Have Been Set Equal and are Capacitive.