III-2. MICROWAVE TRANSISTOR AMPLIFIER DESIGN

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The high frequency transistor equivalent circuit applicable for our consideration is shown in Figure 1. Typical values of the parameters for a state-of-the-art silicon npn microwave transistor are given below:

r_b' = base spreading resistance $\simeq$ 10Ω

C_c = collector to base capacitance $\simeq$ 0.7 pf

r_e = emitter resistance $\simeq \frac{26}{I_E}$ (ma)Ω $\simeq$ 1.3Ω at 20 ma

C_{se} = emitter storage capacitance $\simeq \frac{1}{2\pi f_T r_e} \simeq$ 60 pf typ.,

where f_T is the frequency at which the common emitter current gain is unity.

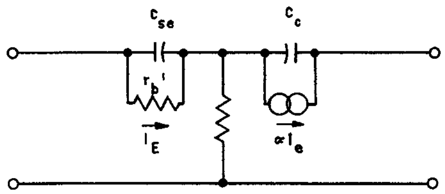

Figure 1. Typical High Frequency Equivalent Circuit of Bipolar Transistor

A summary of performance factors of high frequency bipolar transistors has been given by Cooke (Reference 1), and only the pertinent relationships will be repeated.

The neutralized power gain obtainable from a single transistor can be determined by:

$$PG = \left(\frac{f_{max}}{f}\right)^2 \tag{1}$$

where f_{max} is the maximum frequency of oscillation, i.e., the frequency at which the theoretical power gain is unity, and f is the operating frequency. f_{max} can be determined by:

$$f_{max_{mc}} = 200 \sqrt{\frac{\alpha_o f_{T(mc)}}{r_b C_{c(pf)}}} \tag{2}$$

where α_o is the low frequency alpha of the transistor.

From Equations (1) and (2) one obtains:

$$PG \simeq \frac{2 \times 10^4 \alpha_o f_T}{f^2 r_b' C_c} . \tag{3}$$

Note again that this is the neutralized or unilateral power gain and that it is quite possible to obtain gains less than, or greater than (approaching oscillation), this value in an actual amplifier circuit.

An expression for noise figure (References 2 and 3) which checks closely with measured values in the L-band region is:

$$F = 1 + \frac{r_b'}{R_G} + \frac{r_e}{2R_g} + \frac{(r_b' + r_e + R_G)^2}{2\alpha_o R_g r_e} \left[\frac{1}{h_{FE}} + \left(\frac{f}{f\alpha} \right)^2 + \frac{I_{co}}{I_E} \right] . \tag{4}$$

Circuit Configuration. The choice of whether the basic circuit configuration should be common emitter or common base or, in some cases, common collector, depends upon a detailed analysis involving a number of factors such as the operating frequency, circuit function to be realized, transistor parameters, impedance levels, and the like. However, for high frequency amplifier designs the following general comments can be made.

The common base, (C.B.), configuration is characterized by a low input and high output impedance and positive internal feedback due to the collector capacitance, C_c, which makes possible circuit instabilities if the input and output loading is not correct. As the current gain, α, is less than unity, the power gain is obtained purely by impedance transformation.

The common emitter, (C.E.), configuration has a somewhat higher input impedance and a lower output impedance than the common base. The internal feedback due to C_c is negative which tends to reduce the gain below that given by Equation (1) unless C_c is neutralized or compensated for. When the transistor has an f_T suitably higher than the operating frequency (in the order of two times or more) it is generally preferable to operate in the C.E. configuration because of the inherent stability of this mode of operation.

At the higher frequencies ($f > \frac{f_T}{2}$ typically) the C.B. configuration becomes more attractive. The common collector circuit has a number of limitations and is not generally the best choice for high frequency amplifier circuits.

A number of possible resonating and impedance matching circuits are possible with either the C.B. or C.E. configuration. Figure 2 shows two useful circuit arrangements and their transmission line analogs which can give near optimum gain bandwidth and noise figure performance. C. B. is illustrated but C.E. is equally applicable.

Circuit Realization. Circuit design in the microwave frequency range takes on different aspects from low frequency design due primarily to the difficulty in realizing "lumped" inductors and to the necessity of taking into consideration package inductance and capacitance, and other stray reactances which could be ignored at lower frequencies. At frequencies on the order of 2 gc and below, it is possible to fabricate reasonably lumped inductors of moderate Q. Above this frequency range it is generally preferable to utilize transmission line techniques for achieving circuit resonance and impedance transformation. The transmission line medium used can be coaxial, stripline, etc., or of course, a combination of these mediums. Single-sided stripline, or microstrip geometry, has proved to be particularly versatile for transistor amplifier design. Copper-clad board on a number of high quality dielectric substrates has been commercially available for some time, and provides a convenient medium which has the advantage of being adaptable to photographic processing of stripline boards. High dielectric constant substrates such as some of the ceramics can also be used, resulting in a reduced dimension of the lines.

Experimental Results. Single stage amplifiers in both the C.B. and C.E. configurations have been designed up to approximately 2 gc. Above this range, the C.B. configuration has been used exclusively. Cascaded amplifiers of up to 8 stages in the L-band range and 3 stages in the S-band range have been

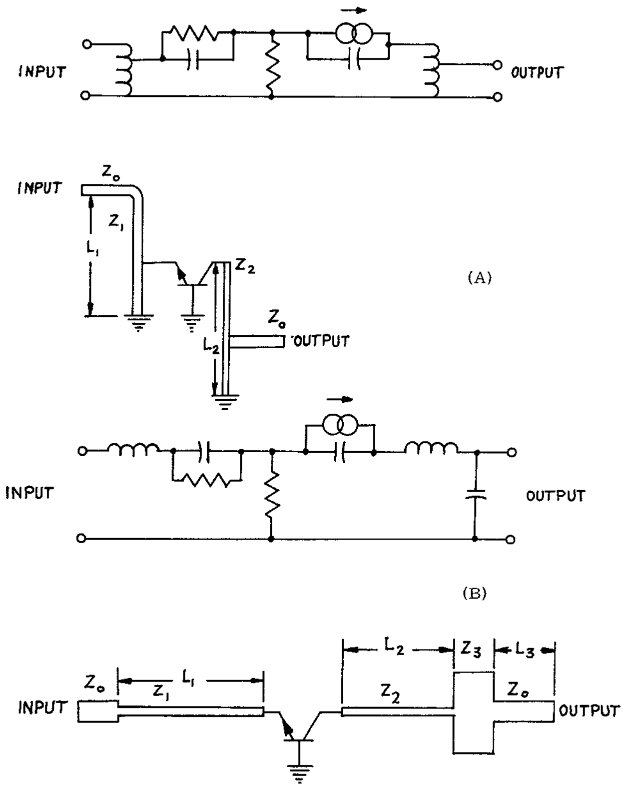

Figure 2. Typical Amplifier Equivalent Circuits and Transmission Line Analog

constructed and evaluated. Figure 3 shows the bandpass and noise figure curves for a wideband L-band amplifier using a circuit design similar to that in Figure 2A and germanium transistors of the 2N2999 type. The same circuit arrangement was used with silicon transistors type TIX 3016 with a similar bandpass characteristic and a slightly higher noise figure.

Figure 4 shows a typical microstrip circuit breadboard used to evaluate circuit designs. This circuit is a three stage C.B. amplifier using specially selected silicon transistors of the TI L-49 type. The gain-bandwidth performance obtained is shown in Figure 5, and Figure 6 gives a plot of the gain and output power versus input power for this amplifier. It should be noted that while fairly respectable output power can be obtained where the amplifier is driven in the saturation region, the maximum power output with any reasonable gain will be appreciably less than obtainable with the same transistor in an optimized oscillator circuit. The power handling capability of the transistors can be increased by paralleling several units and some work has been conducted in this area. The amplifier noise figure was 14 db at 2.25 gc; this could be reduced considerably by optimizing the first stage.

The highest frequency amplifier constructed to date using the microstrip type circuitry described has been at 3 gc. This was a single stage C.B. amplifier which gave 8 db gain and 100 mc bandwidth using a special silicon transistor of the L-49 type. Gain at considerably higher frequencies has been obtained in coaxial circuits, but no attempt has been made to date for maximum gain bandwidth performance.

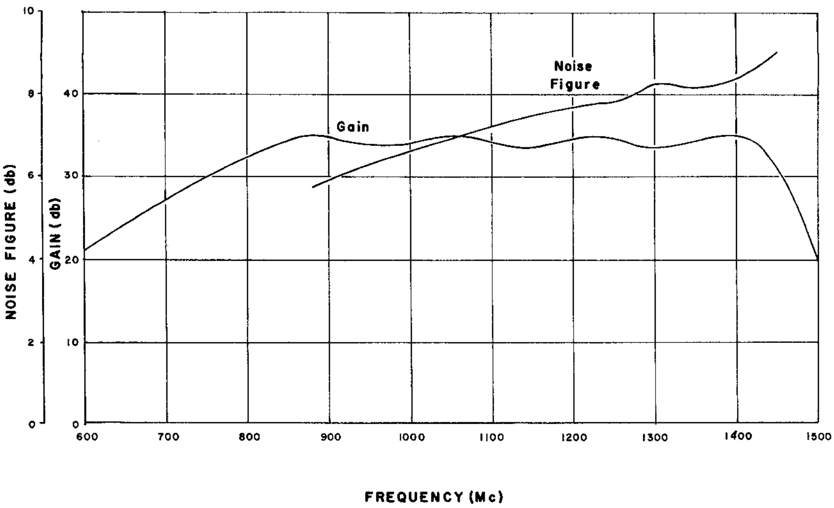

Figure 3. Gain and Noise Figure versus Frequency for 8-Stage Germanium Transistor Amplifier

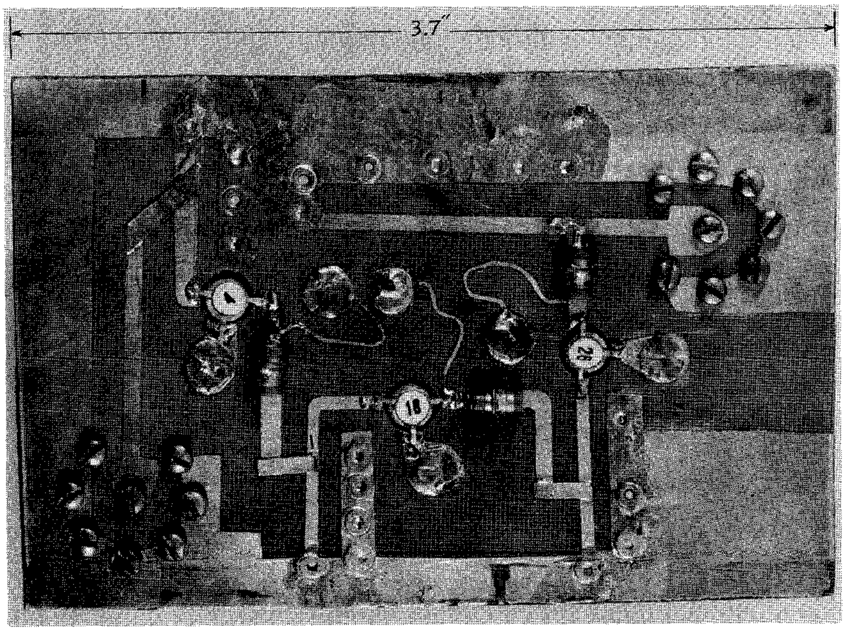

Figure 4. Microstrip Breadboard of S-Band Transistor Amplifier

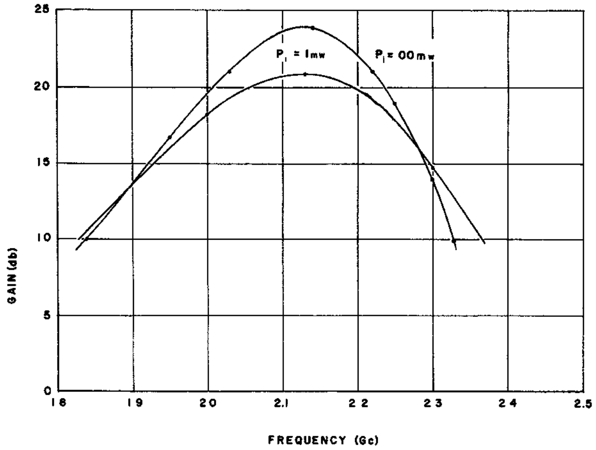

Figure 5. Gain versus Frequency Curve for 3-Stage Silicon Transistor Amplifier

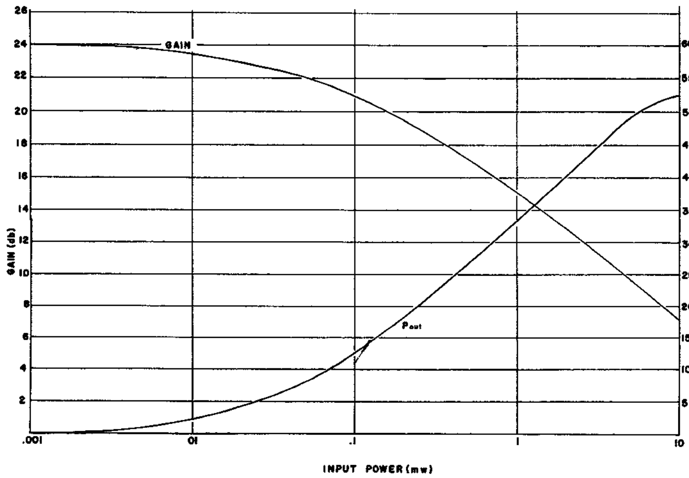

Figure 6. Gain and Output Power versus Input Power for 2.5 gc 3-Stage Transistor Amplifier

REFERENCES

1. Cooke, H. F., "Microwave Transistor Circuits," Microwaves, Vol. 3, No. 8, p. 28, August, 1964.

2. Neilson, E. G., "Behavior of Noise Figure in Junction Transistors," Proceedings of IRE, Vol. 45, No. 7, p. 957, June 1959.

3. Cooke, H. F., "Transistor Noise Figure," Solid State Design, Vol. 4, No. 2, February 1963.