

MINIATURE POWER AMPLIFIER FOR TELEMETRY TRANSMITTERS

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Summary There is continuing emphasis to reduce the size and weight of telemetry transmitters and to increase the frequency at which the power is generated. An approach to achieve this goal is discussed.

A power amplifier stage designed specifically for a telemetry transmitter is described. It produces 1 watt output at 500 MHz with 7-10 db of gain. Typically it is midpoint in a series of similar amplifier stages. An extraordinarily small size is achieved by using microstrip transmission lines on an alumina substrate. The dielectric constant of alumina is relatively high; which makes the transmission lines relatively short. Furthermore, the judicious use of lumped capacitors results in a further foreshortening of the transmission lines. The transistor die is attached directly to the microstrip transmission line. This minimizes any stray inductances and makes the circuit reproducible and broadband. This amplifier is composed of three basic component types: 1) a transistor 2) four microstrip transmission lines, and 3) three lumped capacitors.

Of special importance is the fact that the entire amplifier, that is, the transistor plus the matching network, is enclosed inside a hermetic envelope. The terminals are 50 ohm microstrip input and output. The hermetic envelope is less than 1.100" x .830" x .085". Complete with a heat sink the unit is no higher than .150".

Useful design information for this type of amplifier is presented.

Introduction It has been commonplace in telemetry transmitters to amplify an r.f. signal from a stable frequency source at a frequency many times lower than transmitted signal. This high power r.f. signal is then multiplied in a varactor chain to arrive at the transmitted frequency.

The semiconductor industry has made steady progress in pushing the useful frequency of operation power transistors upward. This has allowed the amplification process to be performed at frequencies closer and closer to the transmitted signal. This paper will describe an amplifier stage which is suitable for use in this application.

There has been increasing use of microstrip transmission lines in microwave systems. For some time it was impractical to use microstrip lines at the low frequencies typical of older power transistors because a circuit using them would have been larger than its discrete counterpart. Useful power gain is now available above 400 MHz so that microstrip techniques offer substantial size reductions over discrete components. A 500 MHz amplifier will be described which is four times smaller than its discrete counterpart. Furthermore, as will be disclosed, microstrip offers some performance advantages. This approach is even more valid above 1000 MHz where good transistors are becoming available.

A third key building block to this approach is the availability of relatively large hermetic envelopes using alumina substrates. Packages having an alumina substrate bottom have been developed for integrated circuit arrays in computers. Because they are used by the thousands per week, the technology is well developed and can be applied to the smaller volume VHF and microwave needs.

The 500 MHz Amplifier Four important electrical characteristics of an amplifier are: 1) R.F. Power Output vs. R.F. Power Input, 2) Bandwidth, 3) Change in output power due to mismatched load, and 4) Input match.

This amplifier, useful as it is in telemetry transmitters, also is suitable to illustrate techniques which are applicable to oscillators, multipliers, etc. at other frequencies and power levels. It is capable of delivering 1 watt of r.f. output from signals which are smaller by 7 to 10 db. Although the specification tests are performed at 28 volts, the performance is not greatly different at 20 volts. These characteristics are shown in Figure 1. This size transistor requires about 20 mw to turn on, therefore, it is appropriate to use this amplifier as a driver for itself but a smaller transistor should be used for lower power signals or a small amount of forward bias should be applied.

The bandwidth is of particular interest in telemetry applications wherein the modulated signal is amplified in the power amplifier chain. The bandwidth is approximately 10% or more to the -1 db points. This is very close to the value one would obtain by matching the low input impedance to 50 ohms with a series L and shunt C and by matching the high output impedance to 50 ohms in a similar network. This indicates that the bandwidth has not been deteriorated by spurious effects. This bandwidth of 50-90 MHz is more than sufficient for telemetry applications wherein 10-20 MHz would suffice.

Ideally, the amplifier would operate into a matched load. Unfortunately, this often is not the case. The "change in incident power for various VSWR loads" indicates the capability of the amplifier to supply a mismatched load. If the following stage has a VSWR of 1.5, then the power incident from the amplifier will be changed by only 5% at the worst possible phase condition. Generally, of course, the phase will be more

favorable and even less change can be expected. in terms of decibels of gain, this is only 0.2 db loss for a load with 1.5 VSWR.

Since this amplifier is generally driven by another amplifier, it is desirable to know the VSWR it presents to the driver. Typically it is less than 1.5 within the normal operating range. This is shown in Figure 2.

Amplifier Design

Electrical The electrical design can be separated into two distinct problems, the input and the output:

The input circuit must:

- 1) Provide an impedance matching network between the 10 ohm base resistance and the 50 ohm input termination.
- 2) Provide a d c return path for the base current.

The output circuit must:

- 1) Provide an impedance matching network between the 250 ohm output conductance and the 50 ohm output termination.
- 2) Provide a d c path for the collector current.
- 3) Filter the supply lead to avoid r.f. leakage, and
- 4) Isolate the output terminal from the d c bias on the transistor.

The input matching is accomplished with two 50 ohm microstrip lines. This network is visible in the photograph, Figure 3. one transmission line is shunted between the transistor base and ground. A second extends from the base to the input terminal. A lumped capacitor is placed directly between the input terminal and ground.

The output matching is accomplished with only two microstrip lines. one extends from the collector to the output terminal. It has 32 ohms of characteristic impedance. A second line of 50 ohms extends from the output termination to ground. This second line also provides the d.c. current to the collector so that a bypass capacitor is required to provide the r.f. ground. A second capacitor is used to isolate the output terminal from the d.c. collector voltage.

Terminals Microstrip transmission lines permit the interconnection of many circuit elements without bulky coaxial or waveguide fittings. Furthermore, many circuit

functions can be made with microstrip lines. Therefore this type of terminal was chosen for the amplifier.

Inside the package where the alumina substrate is .026" thick, a 50 ohm transmission line is .026" wide. In a 1/16" teflon circuit board, a 50 ohm line is .3" wide. The terminals of the amplifier provide a strip .175" wide. The signal passes through four adjacent holes in the ceramic which are sealed for hermeticity.

The resistive loss of this terminal system is equivalent to about one ohm of series resistance.

The leads extend from either side of the package so that matching to 50 ohm microstrip circuit boards is facilitated. The power supply lead can also be etched on the circuit board. These amplifiers can be placed approximately 3/8" apart in series with one another giving a center to center spacing of less than 1 1/4".

A single unit mounted on a test fixture is shown in Figure 4. The cover is removed in this photograph. There is 3/16" between the inside of the cover of the test fixture and the ground plane. There are six leads at the top of the package. The four center ones are the r.f. output terminals. They are all connected in parallel to provide a low loss matched feedthrough. They are soldered or clamped to the conductor of a 50 ohm microstrip transmission line. An OSM fitting is mounted directly beneath the microstrip line in this test fixture but in most applications, the microstrip line conveys the signal to the next component. The terminal at the top right hand corner of the package is for the supply voltage. The two terminals at either side of the r.f. output are connected to the heat sink and package envelope. They are used only to provide a ground lead on the top surface of the circuit board for those who desire to provide the power supply interconnections by etching the circuit board.

Mechanical The electrical design requires a transistor, four microstrip transmission lines, two bypass capacitors, and one matching capacitor.

The microstrip lines are gold plated metalizing which are formed by photoetching techniques. This metalizing is also used for brazing the leads and flange and for soldering the various components into the circuit.

Through long experience in this field, it has been determined to be advisable to pretest the discrete components before assembly. The transistors, capacitors, and resistors, when required, are mounted on rectangular tabs of gold plated molybdenum and wirebonded to a temporary carrier header for test. Subsequently, they are removed from the carrier header and soldered into the circuit.

Hermetic Package The hermetic package used for this amplifier is, similar to one used in quantities of thousands for digital airborne computers. Making quality hermetic packages is not one of the most interesting problems to the electronic engineer, but it can represent the biggest stumbling block between having a laboratory curiosity and a successful production item. The envelope materials are gold plated kovar and alumina ceramic which are metalized and brazed at high temperatures to give a product quality equivalent to the best transistor headers or vacuum tube envelopes available today.

The heat sink has the capability of dissipating 100 watts of power. The backside metalizing and heat sink provide the ground plane for the microstrip transmission lines.

Techniques

Transmission Lines A major goal is to reduce size. Microstrip transmission lines can be made substantially shorter if lumped capacitances are permitted. For instance, the low base resistance of a transistor can be matched to fifty ohms by a quarter wave length long transmission line with a characteristic impedance equal to the square root of the product of 50 ohms and the base resistance. in this case no lumped capacitor is needed.

However, if the transmission line impedance is higher and a capacitor is used at one end, the line can be foreshortened as shown in Figure 5. The higher the characteristic impedance of the connecting line, the shorter it can be. of course, a price is paid for this. The bandwidth is narrowed.

Similarly the high output impedance is transformed to fifty ohms by using a transmission line which is relatively low in impedance and the reactive component is cancelled, not by a capacitor as at the input, but by an inductance.

Even though a quarter wave length is two inches long at 500 MHz on an alumina substrate, only two inches of microstrip were required to perform all the matching functions in the one watt amplifier.

Lead Inductance A special problem which is encountered in using lumped capacitors is the series lead inductance which connects them to the rest of the circuit.

A shorted transmission line has a reactance equal to:

$$X = jZ_0 \tan \frac{2\pi l}{\lambda}$$

where

- X = the reactive input impedance
- Z₀ = the characteristic impedance
- l = the length of transmission line
- λ = the wave length

Due to the high dielectric constant of alumina, the wavelength is only four inches at 1000 MHz.

As long as the reactance of the capacitor is small compared to the characteristic impedance of the connecting transmission line, and if the line itself is short, the effect of the connecting lead is to reduce the capacitive reactance by an amount equal to approximately $\frac{2 \pi l Z_0}{\lambda}$

Just how important this can be is shown in Figure 6. Only .135" of fifty ohm transmission line is sufficient to cancel the capacitive reactance of a 10.6 ohm (15 Pf) capacitor. Therefore, considerable attention should be paid to the detailed way the lumped capacitor is used.

A second and related problem concerns the lead inductance of the emitter connection to the transistor. it is fairly easy to demonstrate the seriousness of this parasitic inductance. Near the frequency for unity current gain the power gain of a common emitter amplifier is inversely proportional to:

$$r_b' + \frac{2 \pi f_t L_e}{2}$$

where: r_b' = base resistance
 f_t = frequency for unity current gain
 L_e = emitter inductance

Using the 2N3375 as a well known example of a transistor designed to operate at 400 MHz, the pertinent parameters are:

$$\begin{aligned} r_b' &= 1.5 \text{ ohms} \\ f_t &= 600 \text{ MHz} \\ L_e &= 2.6 \text{ nh} \end{aligned}$$

where the inductance is only that portion due to the T0-60 header.¹

The transistor, r_b' , contributes 1.5 ohms and the package inductance, L_e , contributes 4.91 ohms. The T0-60 packaging clearly degrades the gain immensely. By attaching the transistor die directly to the microstrip transmission line and wire bonding directly to the circuit, substantial improvement in electrical performance is achieved.

Secondly, there is also an equal inductance in the input base lead. Consequently, the T0-60 header has introduced a larger inductive reactance to the input circuit than the intrinsic resistance of the transistor. Furthermore, the position of the leads connecting to the package effect the tuning. This serves to illustrate that eliminating the header and placing the transistor chip on the microstrip circuit has a distinct electrical performance advantage. Additionally, there are benefits in reproducibility, size and cost.

Heat Sinking The alumina substrate obviously impedes the flow of heat from the transistor. This problem is solved by mounting the die on a metal tab which distributes the heat across a larger surface of the alumina. A large copper heat sink is brazed to the underside of the substrate. For instance, fifty watts is dissipated in one transistor in a circuit made by these techniques. And this is certainly not the limit.

The copper heat sink also provides the ground plane for the microstrip transmission lines. The heat sink can be screwed down from top as shown in Figure 4 or attached from underneath by studs.

Other Circuits This paper has largely been concerned with a particular circuit to provide a concrete example of one design approach. This does not by any means include all the available techniques of which a few are categorized below:

- 1) Microstrip lines
 - a) Thick film molybdenum and gold.
 - b) Thick film pastes.
 - c) Thin film.
 - d) Thin films with plating.

- 2) Capacitors
 - a) Chip capacitors.
 - b) Aluminum films on oxidized silicon.
 - c) Thick film pastes.

- 3) Resistors
 - a) Tantalum thin film resistor arrays.
 - b) Thick film pastes.
 - c) Thin film evaporated on substrate.

- 4) Substrates
 - a) Ground alumina.
 - b) Polished alumina.
 - c) Glazed alumina.
 - d) Sapphire.

Conclusions A particular 1 watt 500 MHz r.f. power amplifier was described in considerable detail. It is only one of a family which extends from 1 mw to 2 watts and from 300 to 800 MHz. It incorporates only a limited number of techniques available. They are:

- 1) Thick film microstrip transmission lines.
- 2) Lumped capacitors.
- 3) Transistor dissipating 3 watts of power.
- 4) Hermetic package completely enclosing the amplifier circuit. The bottom of the hermetic package is also the alumina substrate for the microstrip transmission lines.

The electrical design took advantage of the ability to foreshorten transmission lines by a suitable choice of characteristic impedance and lumped capacitors. Special attention was paid to parasitic inductances.

This method of making microwave circuits offers considerable advantage in size and weight.

References

1. M. Caulton, H. Sobol, R.L. Ernst, "Generation of Microwave Power by Parametric Frequency Multiplication in A single Transistor", R.C.A. Review, Vol. XXVI, No. 2, pp 286-311, June 1965

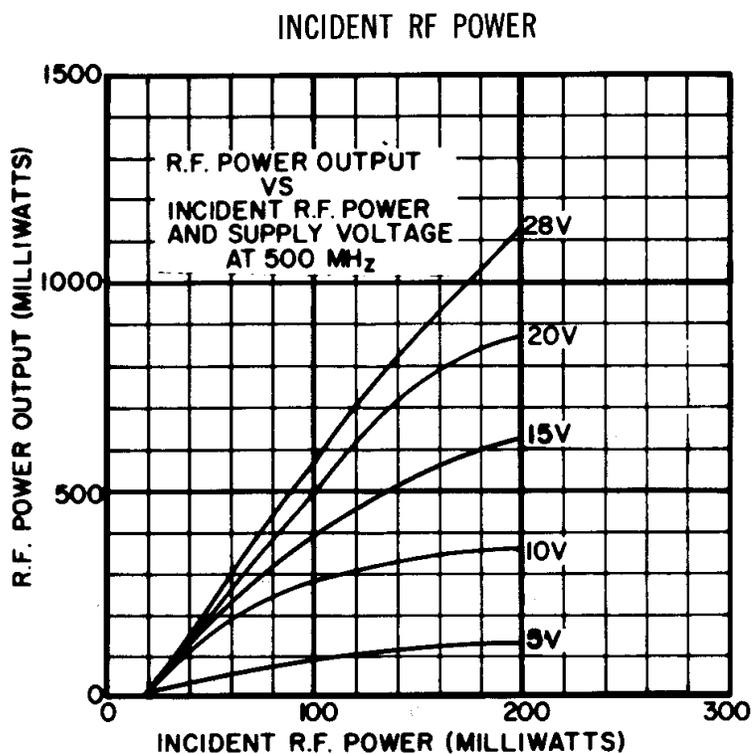


Fig. 1 - R. F. Power output Characteristics

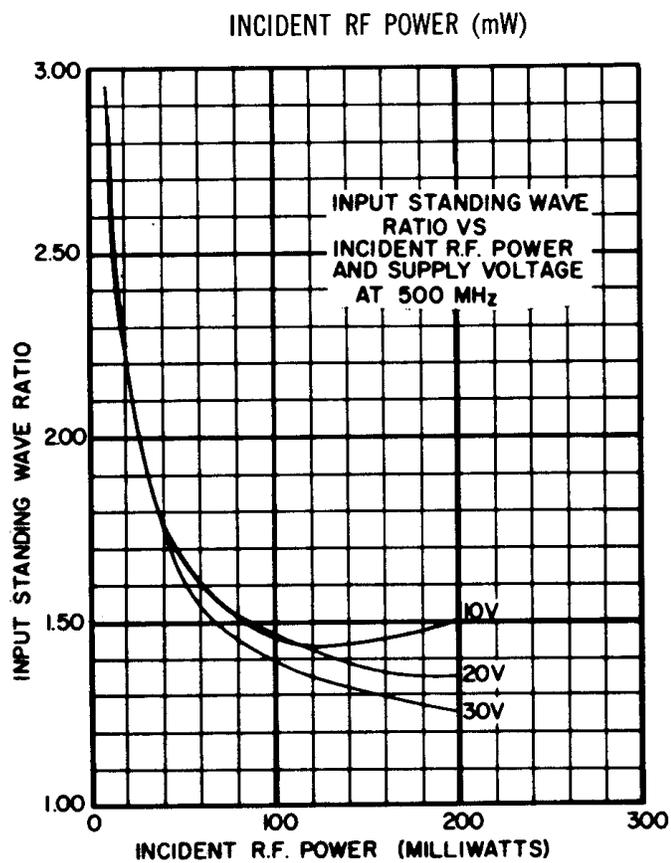


Fig. 2 - Input Match

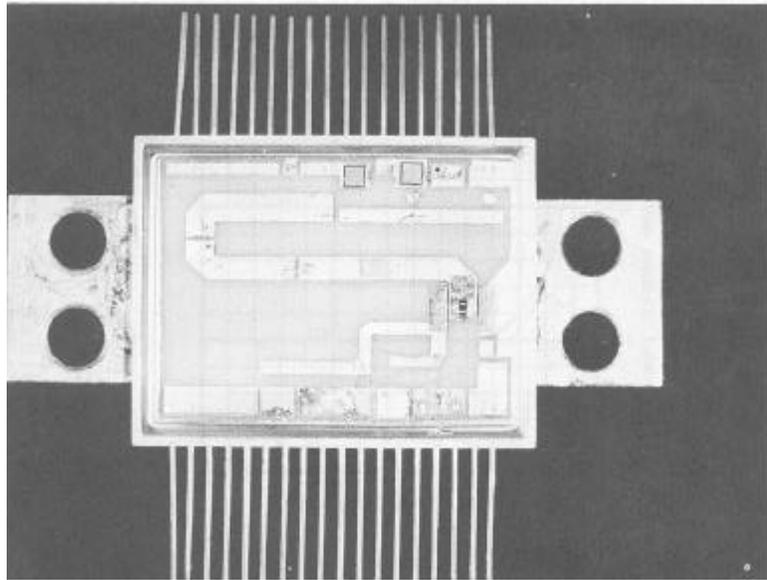


Fig. 3 - Amplifier Before Welding Cover

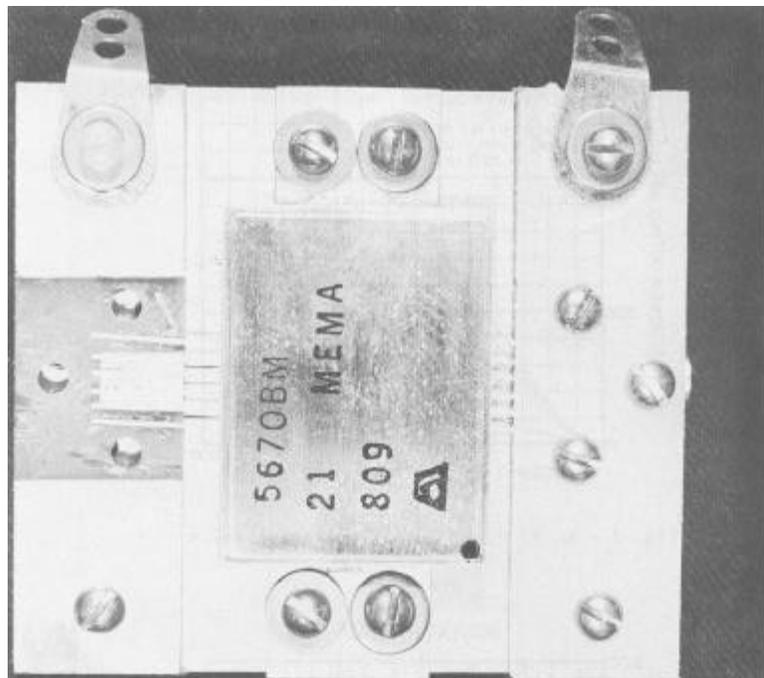


Fig. 4 - Amplifier Mounted in Test Fixture

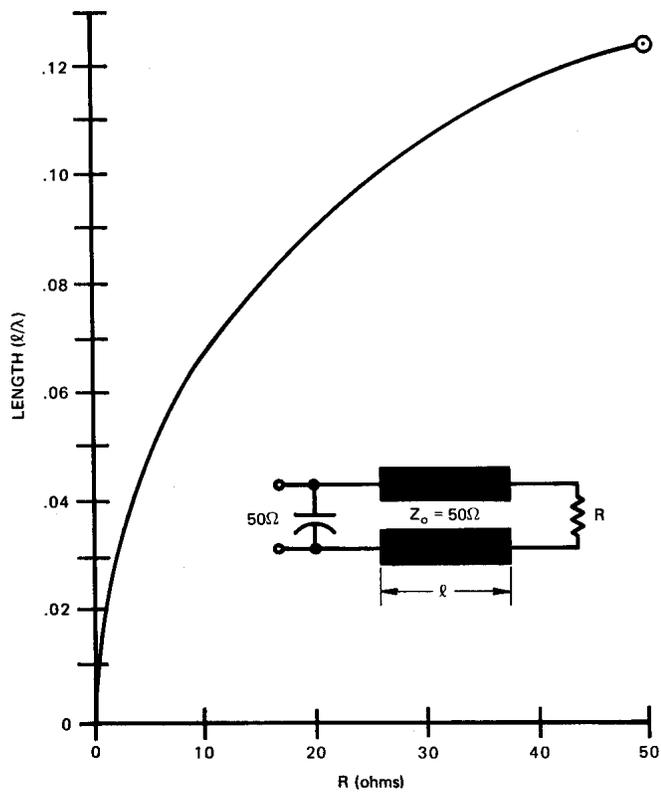


Fig. 5 - Foreshortening of Transmission Line by Capacitive Loading

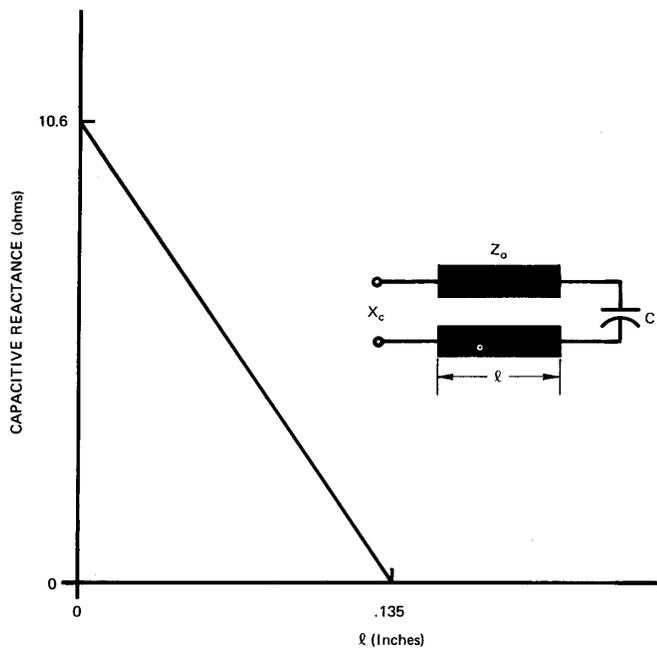


Fig. 6 - Reduction in Effective Capacitive Reactance due to Connecting Line for $C = 15$ pf, $Z_0 = 50$ ohms and $f = 1$ GHz