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NRL Memorandum Report 5167

Considerations for Choosing Microwave Transistors in High Power Shipboard Search Radars

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Search Radar Branch
Radar Division

September 30, 1983

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Washington, D.C.

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Critical technical considerations for choosing microwave transistors for search radar transmitters are addressed along with review of some basic design and purchasing problems. Some guidelines for achieving reliable designs are given along with a procedure called Thermal Rieke diagrams for presenting impedance, power and temperature dependencies. AN/TPS-59 experience is outlined along with observations concerning expected transistor costs as a fraction of total transmitter costs.

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CONTENTS

CONSIDERATIONS FOR CHOOSING MICROWAVE TRANSISTORS IN HIGH POWER SHIPBOARD SEARCH RADARS

INTRODUCTION

In building a solid state Naval shipboard search radar transmitter, complete engineering design control must be maintained over integrating high-power microwave transistors into the transmitter. This means that a systems approach to transmitter design must be used which integrates the internal design of the transistor, along with the input and output matching of the transistor, into the design of the amplifier. Today there is available some control for the specifying and buying of these transistors; but the main concern, that of quality in quantity production, will be overcome by the results of economic competition rather than technical control by contract specifications.

Typically Navy search radars have 50 to 400 kW of peak output-power with average powers ranging from 1 to 20 kW. Since this RF energy is converted from dc, a sophisticated electron device (ED) is needed. When the instantaneous bandwidth and frequency requirements are added to the power requirement, the nature of the electron device can be defined in terms of size, weight, and type of device. For instance, Raytheon's QKW/1671A ring-and-bar traveling wave tube (TWT) has 16A peak pulse current with a voltage of 40 kV and satisfies the search radar power requirement. For an instantaneous bandwidth of 200 MHz at 1300 MHz, this results in a tube 2 m to 3 m (6' to 9') long and 46 cm (18") in diameter with an interaction length for the slow wave structure of about 1.3 m (4'). The device weighs 200 lbs with integral solenoid without modulator and power supply. Typical cost ratios of tube vs total transmitter costs are 1:10. Tube costs range from $50 to $100K.

When transistors are to be used it is not a simple engineering problem to identify all the design parameters for the electronic device and the transmitter. For example, RF output power transistors have emitter characteristics that produce 1.3 W per mm of periphery length. This means that 303m (1000') of emitter periphery is required for a 200 kW peak radar. The contribution of the transmitter designer becomes critical since the electron device is now extended over the entire transmitter cabinet. To package 303 m (1000') of emitter periphery in the transmitter the system designer must share in designing the transistor or he will lose control of critical design parameters. Along with design and performance parameters, cost and availability of transistors are major concerns since present cost of typical devices runs $100 in large volume production with no anticipated breakthrough. The cost of transistors is expected to range from 30 to 70% of the total transmitter cost.

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FUNDAMENTAL DESIGN PROBLEM

High-power microwave electronic devices used in radar transmitters have unique requirements which introduce crucial design problems. In the case of transistors, one crucial problem is the matching of the power output from the interaction zone at the emitter periphery to the antenna with high d.c. conversion efficiency and low transistor cell temperature. A necessary condition for a successful overall transmitter design is the solution of the internal matching problem in the basic transistor design. This must come before the external problems of combining the modular transistor amplifiers are addressed.

Internal Impedance Matching

The ED manufacturer who supplies devices for radar trasmitters must determine the length of emitter periphery per cell needed and the manner this periphery is laid out in each cell for a given device specification. Once the cell design is fixed, (this is sometimes called a discrete device), the problem is that of matching the input and output impedances. The cell layout generally determines the processing technique required, i.e., fishbone, matrix, overlay, etc.

High power transistors are formed by paralleling many cells or chips called dies. A single cell has an equivalent input and output circuit biased in a common base configuration as shown in Fig. 1.

Where

L_e, L_c, L_b, are the inductances of the bonding wires from the cell to the carrier.

R_e is the impedance of the emitter which is almost entirely resistive.

R_c is the collector source resistor.

I is the current generator.

C_c is the collector to base capacitance.

Typical values per cell are:

$$R_e = 1\ \Omega$$

$$R_c = 500\ \Omega$$

$$C_c = 1\ \text{pF}$$

$$L_e,\ L_c,\ L_b = 1 \text{ to } 2\ \text{nH}.$$

As the cells are paralleled the resistance, capacitance, and inductance vary with the number of cells, so that for a 20 cell transistor

$$R'_e = 0.05\ \text{ohm}$$

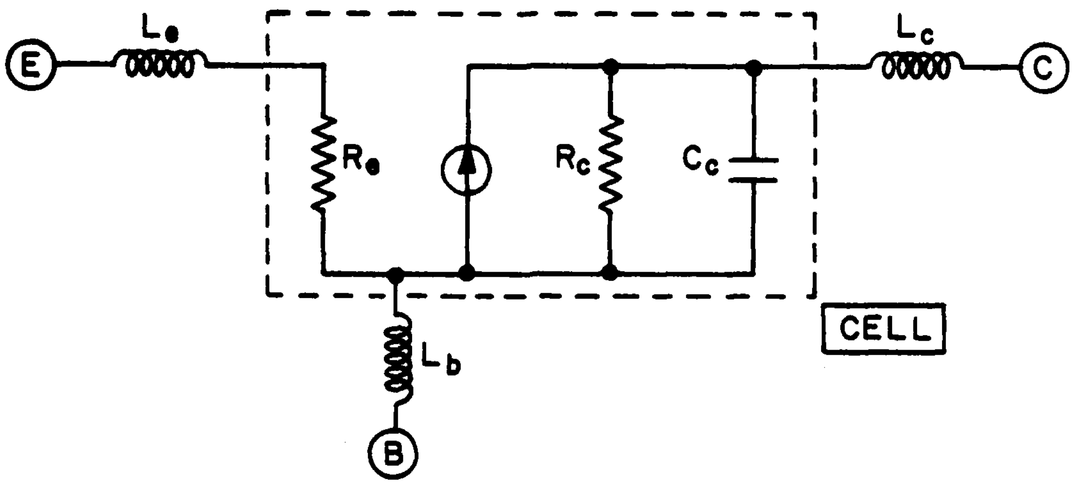

Fig. 1 — Equivalent circuit for a single cell or discrete device

$R'_c = 25$ ohms

$C'_c = 20$ pF

$L'_e, L'_c, L'_b = .05$ nH

Given the above transistor parameters the design of the amplifier gain-bandwidth product must take into account the following design problems;

- the input 50 ohm line must be matched into .05 ohms,
- the output capacitance must be matched to the output 50 ohm line,
- and the instability problems associated with the inductance L'_b of the common base configuration.

Since this is a microwave circuit, the dimensions of the circuits in the matching structures are critical. Since standard stripline construction techniques do not allow much below 1 to 2 ohms because of their large size, the final transistor package must increase the .05 ohm input impedance level to at least 1 to 2 ohms. This requires that some of the matching circuits be inside the transistor and the remaining outside as shown in Fig. 2, which shows the internal input portion labeled "input lead". Similar considerations apply for matching to the output collector capacitance C_c. In Fig. 2 this matching circuit is labeled "output lead".

Figs. 3 and 4 show a breakdown of a typical four section input structure of a 12 cell device featuring a metalized cell pair. A similar circuit can be shown for the output circuit.

The next requirement in the design procedure is to match the transistor carrier to 50 ohms. This is done using familiar microwave strip line techniques.

Total reliability is dependent on individual cell temperatures which are determined by the complex loading. It follows that the match to each cell is critical, but maximum output power is what is usually demanded and so the designs are usually pushed to the maximum with little regard to the cell temperatures generated.

Fig. 5 shows the typical set up used to measure high power transistor characteristics, i.e., output power and cell-temperature profile. Emphasis in this test setup is on total output power and on maximum individual-cell temperatures for complex loads. These plots of cell temperature and output power vs load impedance are similar to Rieke diagrams and the author refers to them as thermal Rieke diagrams.

External Impedance Matching

Figs. 6, 7 and 8 are Thermal Rieke diagrams showing contour plots of constant output power and cell temperature superimposed on output load impedance at 1.3 GHz. Note that each transistor has a different contour plot and slightly different relationship between the cell temperatures and power output contours. These pulling factors, output powers, and cell temperatures for load conditions are critical for making design tradeoffs for

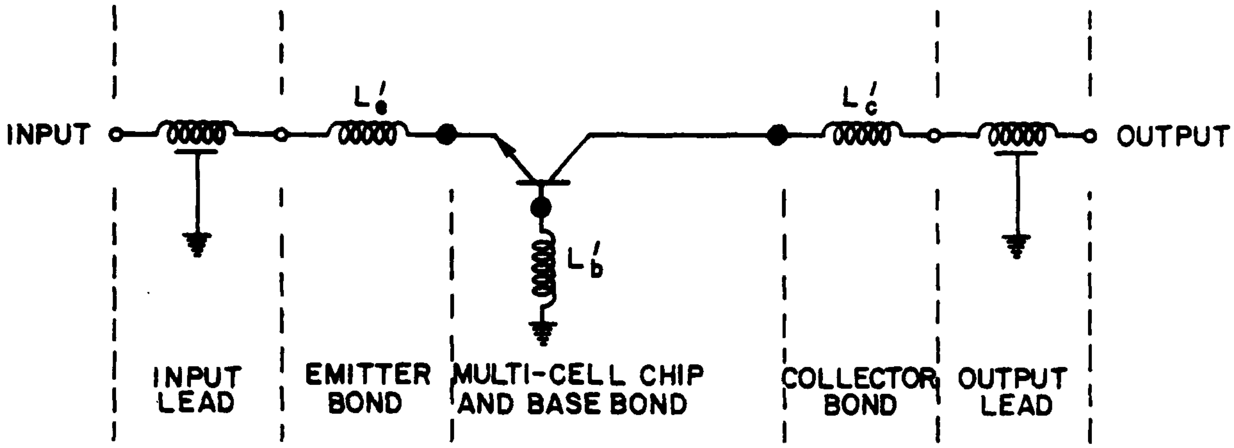

Fig. 2 — Transistor carrier model for multicell chip unit

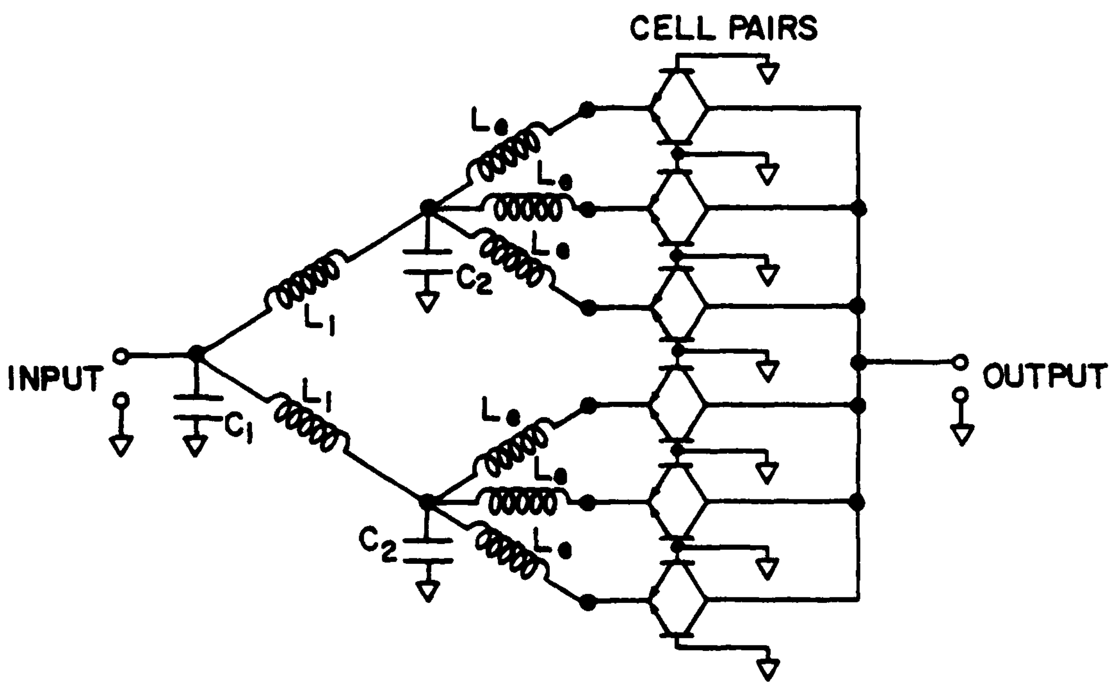

Fig. 3 — Internal input matching for a six (6) cell pair transistor

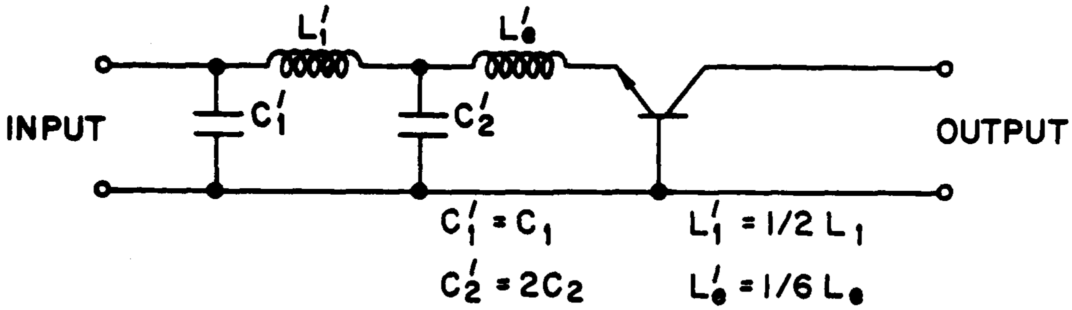

Fig. 4 — Equivalent circuit for the internal input matching for a six (6) cell pair transistor

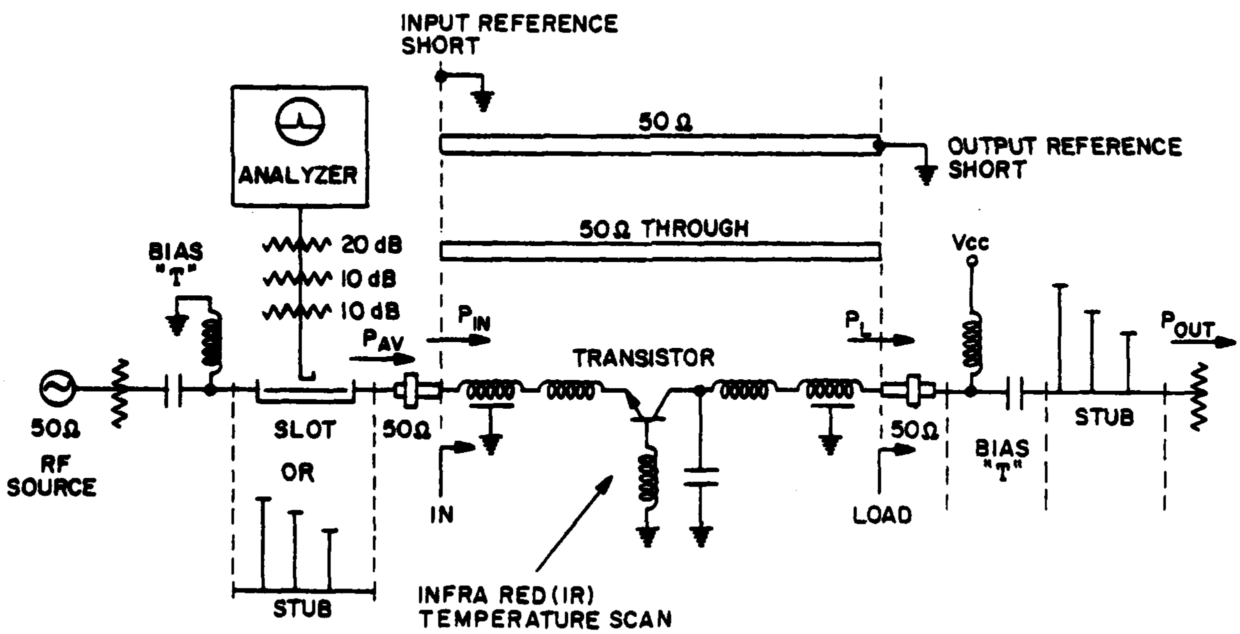

Fig. 5 — Single frequency characterization setup and IR scan

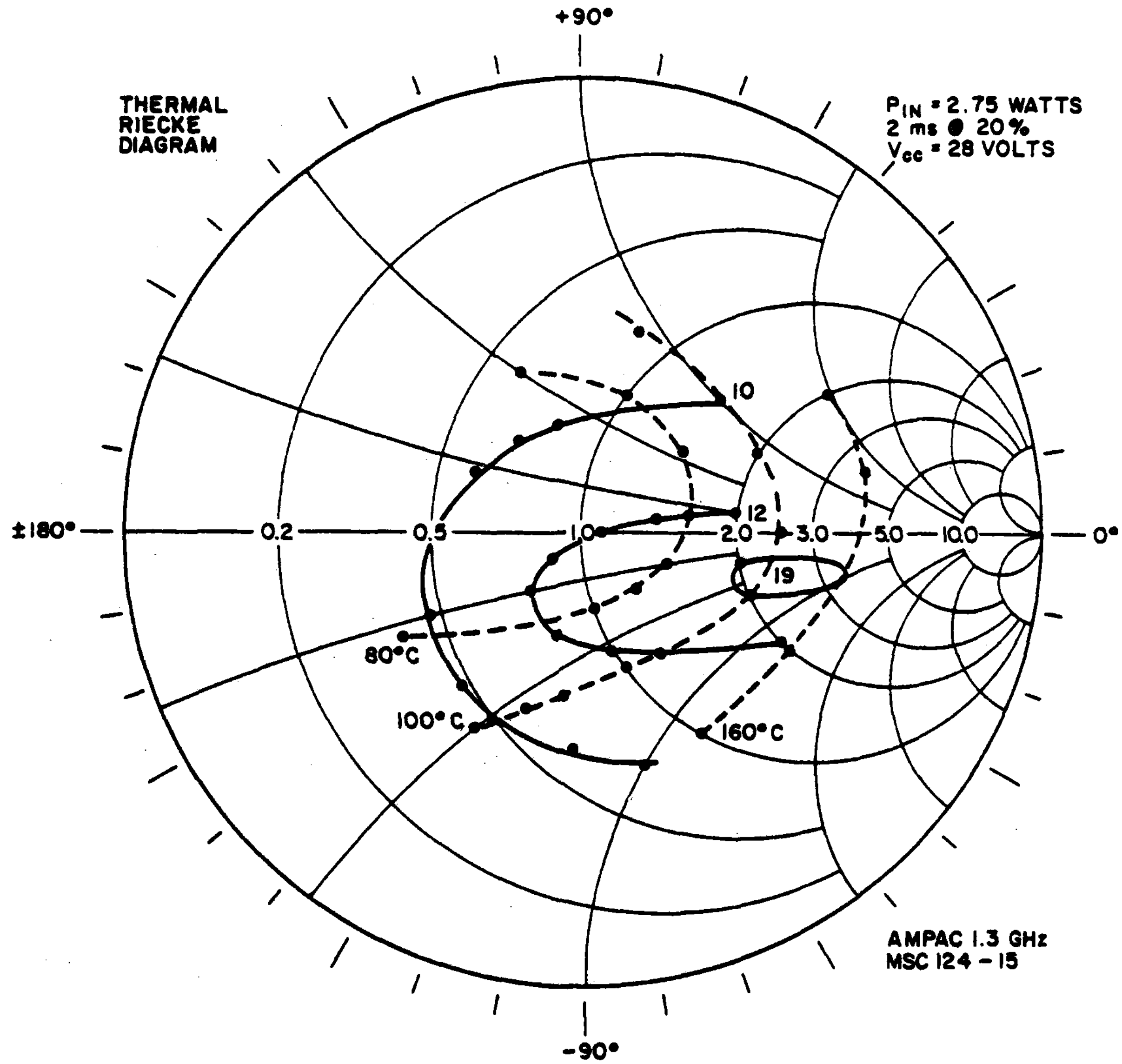

Fig. 6 — Constant power and temperature contours for the MSC 1214-15 AMPAC transistor

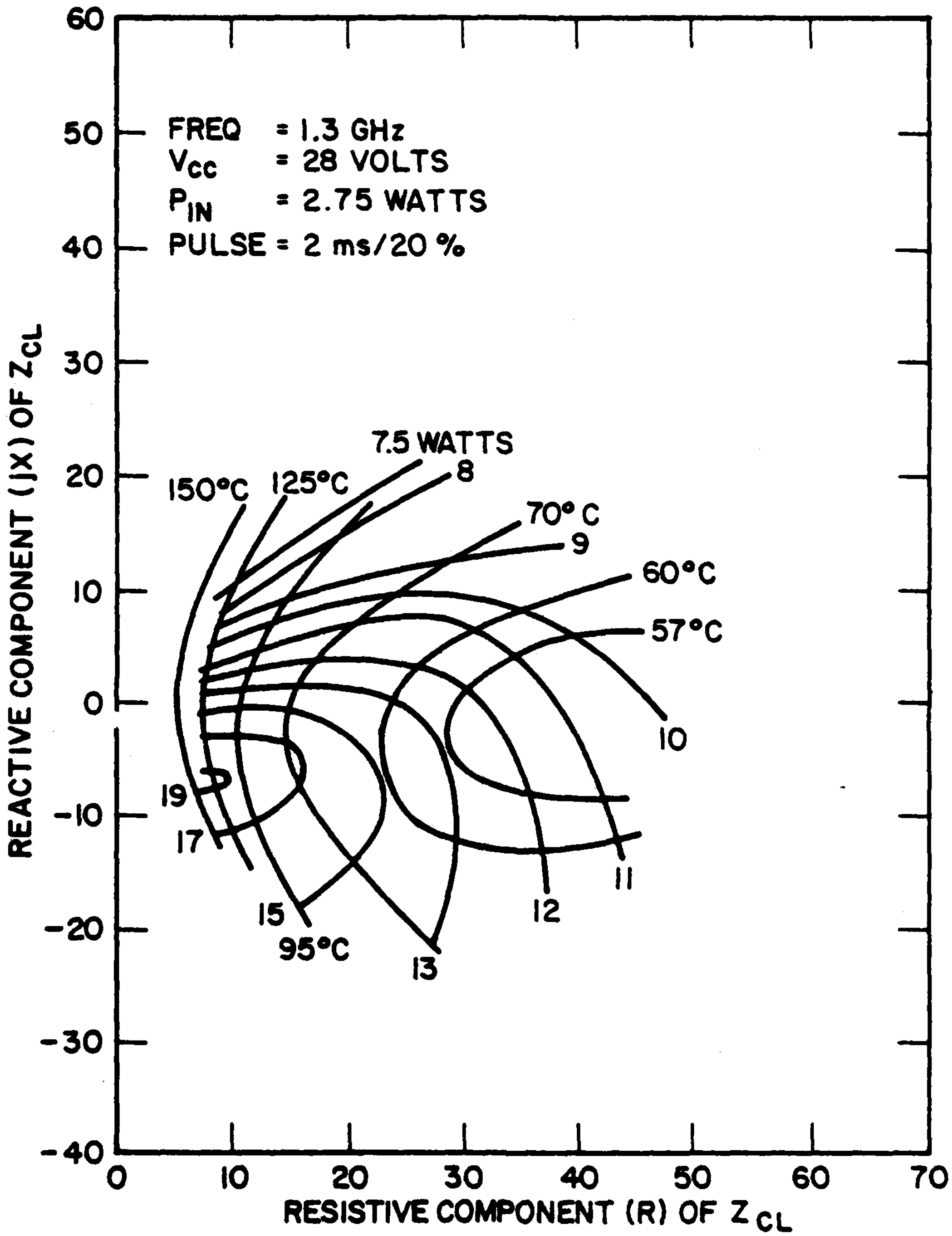

Fig. 7 — Constant power output and temperature contours for the MSC 1214-15

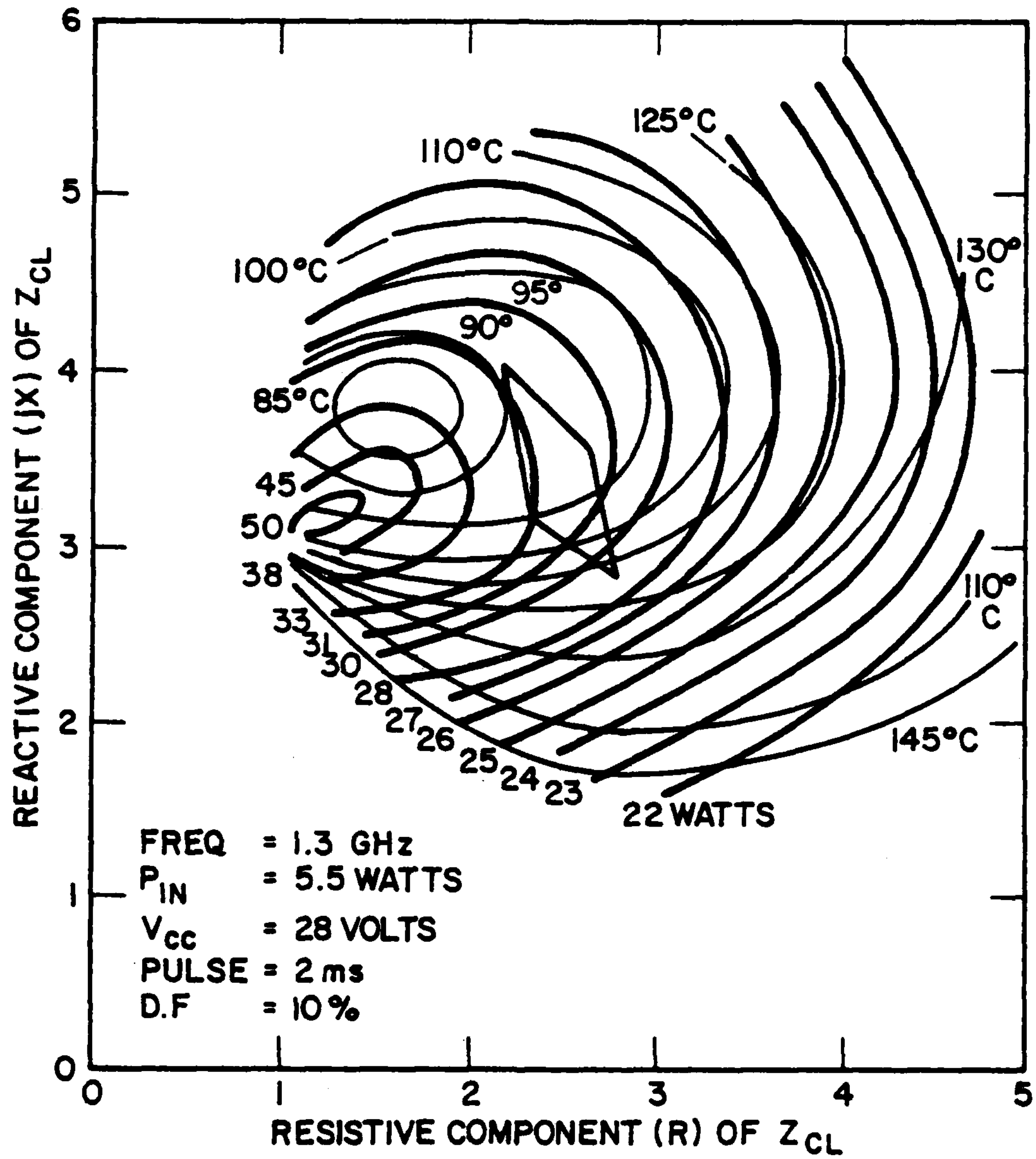

Fig. 8 — Constant power contours superimposed on constant temperature contours for the CTC LM-25-28

long-life goals. Ideally the rate of change of these pulling factors should be small.

The AMPAC MSC-1214-15 power and temperature contours in Fig. 6 are almost orthogonal for load VSWR's less than 2:1. This AMPAC model is used directly in 50 ohm stripline circuits without any impedance matching. The MSC 1214-15 in Fig. 7 which needs external matching, has an orthogonal relationship except on a capacitance reactance line of approximately $jx = -5\Omega$ where the power and temperature contours are parallel. The CTC LM-25-28 of Fig. 8 has large areas of orthogonality and parallelism and needs further external impedance matching.

Little commonality exists in the characteristics of these three transistors which is probably typical of transistors used in power microwave amplifiers today. As a result the selection of the load impedance for each amplifier design is a matter of judgement when using these load diagrams. If the amplifier design is attempted without the help of a Thermal Rieke diagram, the designer would have little guidance and the best and final design would result only after a long development time, much experimentation and high cost. Use of the Rieke diagram is standard design practice in the ED industry for microwave oscillators. For amplifier tubes the phase and magnitude of the load VSWR are always well defined and Rieke type diagrams are not necessary.

Amplifier designers like both rates of change of slope of power and temperature with impedance to be small. In the case of the MSC AMPAC 1214-15, because of orthogonality, the rate of change of one pulling parameter is maximum, while the other is minimum, so a compromise must be made. The MSC-1214-15 has a narrow area where both power and temperature slopes change at minimum rate and the operating point should be along that line. Finally, the CTC LM-25-28 has a parallelogram area marked by an X which should contain the load. All of the above information can be found in reference [1].

In trying to find the right load impedance, the designer encounters conflicting requirements between the case of transistor load impedance and the final output combining techniques chosen [2]. Unless Thermal Rieke diagrams are specified for each transistor the system/amplifier designer can only guess at the optimum configuration or approach the optimum by costly experimentation.

RELIABILITY ASPECTS

Not only because of their direct relation to system performance but also because of their cost, the reliability of ED's is extremely critical. Traditionally, these have been the dominant items in the cost of spares for logistic support. Reliability requires a comprehensive RF design approach using conservative limits and careful control of operating temperatures throughout the system. Traditionally high temperatures are considered the reason for short life, but in amplitude and velocity modulated electron beam devices, the average temperature also determines life since it determines standoff ability, rate of chemical activity, and stability of vacuum, all of which can lead to eventual hot spot failure. This kind of thing is also true of transistors, but since, in the transistor, the active element is much more extended, the hot spot which is caused by electromigration can only be located and measured in the transistor cells and thus can be controlled as a design parameter. In the transistor cell the local peak temperature determines life since any cell failure usually results in a catastrophic failure of the entire transistor. As seen above, cell temperature variation with VSWR and phase is not a simple relationship. In addition, any unequal cell drive inside the transistors, caused by dimensional problems in the internal matching structure, further complicates the prediction of peak cell temperatures.

Transmitter R.F. design can be divided into four parts as follows:

1. cell, chip, and carrier designs used in the transistor,
2. internal matching of transistor input and output impedances,
3. external matching of the transistor to 50 ohms,
4. high power combining techniques.

Note that three out of the four parts are intimately tied to the transsistor. The first is strictly an ED problem but 2. and 3. involve microwave matching disciplines. Historically, it is hard to know where the responsibility for internal matching ends and external begins. There is no standard interface between electronic devices and the system. Transistor manufacturers have not been microwave oriented and transistor design for maximum power out from the device has lagged. Teamwork between manufacturer and user is critical and is going on. Available internally matched transistors have been well designed so that the diffusion process and test screening procedures are mature and well controlled. Those devices which are now shipped are fairly dependable, but generally not the most efficient devices possible. Further work on microwave matching is needed, and efficiency needs to be improved. One reason for the present low efficiency is that these devices are very sensitive to VSWR and phase of the load, which ultimately determines cell temperature, efficiency, and output power. These three parameters are dependent on each other so that the selection of the transistor load must always be carefully evaluated and controlled [1]. The dependence on the internal matching is just as sensitive since it transforms the output load back to the cells. Until recently no overall output design procedures that take the R.F. power from emitter base sites to the output 50 ohm load were known. A comprehensive design approach should result in more efficient microwave networks and lead to improved transistor packaging.

Since both peak and average cell temperatures determine long life, further study must be centered on these parameters. Information and procedures needed to understand and control the design process include:

1. Thermal Rieke diagrams - power and temperature profiles vs output microwave impedance.
2. Judgement factors for using the Thermal Rieke diagram.
3. Means for reduction of package parasitics (specifically the common impedance in the common base and common emitter bias configurations).
4. Procedures for smooth internal matching to control skin currents ensuring uniform drive to each cell.
5. Reduction in the complexity of internal matching procedures required.

6. Design tradeoff criteria for power out, efficiency, and cell temperature for load impedance is required.
7. The transistor device requires more thermal management in design, including control of metallization and site ballasting to insure uniform drive to each area in the cell.
8. Figures of merit to compare one transistor with another are required which are accepted by Industry are required. Possible figures of merit for transistors are:

   a. milliwatts per mm of emitter periphery
   b. size of die
   c. EP/BA - ratios of emitter periphery to base area
   d. site ballasting

9. Which transistor diffusion style is best should be determined and results related to design parameters.

Older conventional electron beam devices have the microwave coupling from beam to waveguide designed in, so that it was possible to verify device performance with specifications and easy to design the system to these specifications. Initial performance and longevity was still a problem but at least a specification was obtainable and the test results could be verified in the final system. There are no clear cut handoff specifications today from transistor manufacturer to transmitter designer. Three separate specifications are needed for three different power transistors in the TPS-59 and with good reason. They are all diffused differently and have different internal matching structures. All three can be used in the power module but each must be processed and tuned differently so that modules made from transistors from different manufacturers can be used anywhere in the radar amplifier.

Clearly the radar system designer must concern himself with the electron device development and production to achieve his design. The system designer must take this comprehensive view of the design problem to get the best out of the device. Putting pressure on the device manufacturers can work but does not resolve the present fragmented R.F. design process now used in industry. An important first step can be achieved if the transistor manufacturer will characterize his device with a Temperature Rieke diagram, a contour plot of output power and average cell temperature vs the complex load emittance on a Smith chart. The system designer requires this relationship between cell temperature and output power before he can expect design success. It is not good enough that the transistor works in the circuit, because, for long term transmitter reliability, a thorough understanding of the temperature and stress imposed on the device is essential.

AN/TPS-59 EXPERIENCE

The AN/TPS-59 radar is a Marine Corps transportable ground based 3D radar consisting of a phased array with 54 rows, with a transmitter, a duplexer, and a receiver for each row. Typically each row transmitter emits a 1 kW pulse in L-band. To generate this power each row has a divider/combiner unit consisting of two stripline directional coupler assemblies with a transistor power module between each of the ten couplers. The hermetically sealed power module has 100 watts of output power and a gain of 14 dB. Each module has two 50 watt output power transistors providing 7 dB gain with input from a separate single ended driver. The output is a single-stage Wilkinson combiner with an added 90° phase shift in one leg for better load isolation.

These modules are manufactured under transistor clean room conditions and procedures. The manner and care in which these modules are produced and used are such that they really should be called an "extended transistor electronic device" rather than a module. Three different vendors supply the transistors. Each set of three, one drive and two output transistors, is purchased under three separate specifications peculiar to each vendor. The three transistors in each module are from one vendor since other vendors' devices are not interchangeable in the module circuit. However, modules once made are interchangeable anywhere in the 540 slots in the antenna array.

The transistors are not interchangeable in the module circuit because they are all diffused and constructed differently; i.e., overlay, fishbone and interdigitated. All have internal matching in both input and output circuits and all are common base single ended devices. Surprisingly, tight technical specification control of the transistors is not maintained. What is maintained is tight competition between the three transistor vendors. This appears to be sufficient for the RF module manufacturer to operate and maintain production control in the radar.

SELECTION OF TRANSISTORS FOR RADAR TRANSMITTERS

The transmitter requirements must be given in sufficient detail to allow the choice of microwave transistors to be narrowed to a few types. A short, but sufficient transmitter parameter list is as follows:

- Frequency Range
- Instaneous Bandwidth
- Peak Power
- Average Power
- Max Pulse Width
- Pulse Modes
- Efficiency
- AM to PM Conversion
- Reliability Related Requirements
    - Temperature-max peak
    - Screening test level
    - Flange temperature

The following are the device parameters and performance criteria for transistor selection that should be addressed.

Cell parameters

- Type or style of diffusion

- fishbone
- overlay
- matrix
- interdigitated

- o Emitter periphery/base area ratio (E_p/B_A)
- o RF power per emitter length
- o Watts per cell for the given pulse length
- o Current density - A/cm^2 (J)
- o Thermal time constant from pulse to CW for junction temperature
- o Median time to failure (MTF)

Die or chip construction

- o Metallization

  Δ Scheme - Ta_2N - Mo - Au, N_1 - Cr/N/Au, P_tS_1/T_1/Pt/Au, etc
  Δ Cells per chip and spacing between cells

- o Type ballasting, site or finger, etc.
- o VCBO and VCEO breakdown and protection
- o Size of chip
- o Type of passivication

Carrier style and construction

- o Common base or common emitter biasing
- o Internal matching scheme and wire bonding
- o Number of wired chips per carrier
- o Type of carrier

Transistor package and circuit parameters

- o Number of carriers per transistor package
- o Single, dual, balanced type, etc.
- o Power gain vs input drive
- o Hermetic sealing - leakage rate
- o Temperature rise, thermal impedance, and pulse thermal time constant
- o Max peak cell temperature, and cell variation
- o Flange temperature
- o Inband spurious noise
- o Out of band spurious noise and gain
- o Median time to failure (MTF) prediction
- o Equivalent circuit - showing internal matching
- o Recommended collector voltage

Transistor screening

- o Die attachment assessment
- o Percentile level of screening - 100%, etc.
- o High temperature reverse bias tests
- o Burn in time

- o Functional tests in actual circuits
- o Stress tests
    - Δ Vibration
    - Δ Thermal cycling

The main criteria for amplifier module design are

- o Thermal Rieke diagram - power and cell temperature vs load pull
- o Combiner/divider circuits used
- o Number of gain stages
- o Nominal junction temperature
- o Power supply requirements
- o Collector and power supply efficiencies

CONCLUSIONS

Most high power solid state transmitter manufacturers have had to become, in some manner, involved in the manufacture of electron devices. This was forced on them in the course of system design and transistor selection because electronic and mechanical specifications could not be agreed upon by buyer and seller. The data and parameter specifications supplied by the manufacturer are not presently sufficient to provide the transmitter designer with the information he needs to select devices and integrate them into his system design. In particular, the transmitter designer requires detailed information concerning cell temperature vs power output and sensitivity to load and drive conditions. A significant part of the information can be provided in terms of a Thermal Rieke diagram.

ACKNOWLEDGEMENT

Conversations with R. G. Rothman, PME 154-2 and A. D. Harris, PME 154-21 concerning the AN/TPS-59 radar were helpful in completing this report.

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Needless to say, neither one of the reference lists is complete or extensive but enough material is listed that if read will make one very knowledgeable in the design of Solid State transistor transmitters.

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