AN ULTRAMINIATURE 5-10 GHz, 2-W TRANSMIT MODULE FOR ACTIVE APERTURE APPLICATION

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ABSTRACT

An ultraminiature 5-10 GHz, 2-w transmit module with integral 3-bit phase shifter has been developed for active aperture applications. The module provides nearly 35 dB of gain and occupies a volume of only 0.25 cubic inch! This high degree of miniaturization has been achieved by using a blend of lumped-element and distributed thin film circuits in combination with advanced packaging techniques. The MTTF of the amplifier was an overriding concern and was enhanced by constraining the FET channel temperature rise to 65°C maximum by optimizing the thermal and circuit designs.

INTRODUCTION

In the 1990's, advanced airborne ECM equipment with significantly improved performance and reliability will be required to allow tactical and strategic aircraft to penetrate and survive the anticipated EW threat environments. Present ECM jamming equipment, which depends almost exclusively on mechanically or electronically steered antennas driven by TWT transmitters, have numerous limitations, including low steering rate, large RCS, size, weight, power, and reliability problems. Such equipment will not satisfactorily respond to the projected future threats that are characterized by high PRF as well as spectral and spatial diversity.

The active aperture, which is an electronically steered array of closely spaced antenna elements, each driven by its own integral transmit module, can overcome many of the limitations of present equipment and offer up to a factor of 10 improvement in size, weight, reliability, and significant improvements in electrical performance.

The active aperture, however, poses major challenges to the designer because the transmit module must fit in an inordinately small volume which is constrained by the antenna element size and interelement spacing ($\lambda/4$) and because the enormous amount of heat that is generated in the very small volume must be efficiently removed in order to achieve the desired reliability.

The reliability of the transmit module is a strong function of FET channel temperature that can be minimized by using transistors with high power-added efficiency and low thermal resistance. The module packaging and the thermal interfacing of the package to the aperture's chillplate also are major factors in an optimum thermal design.

The transmit module illustrated in Figure 1 addressed the aforementioned requirements plus those listed in Table 1. Note the size requirement of 0.375 in. (H) x 0.156 in. (W) x 4.5 in. (L) which was one of the major design drivers. This equates to a volume of 0.25 in^3!

To the authors' knowledge, this work is the first to address an octave bandwidth requirement at the 2 w power level for active aperture ECM applications. Previous work (1 and 2) has been primarily aimed at radar applications that generally are narrowband.

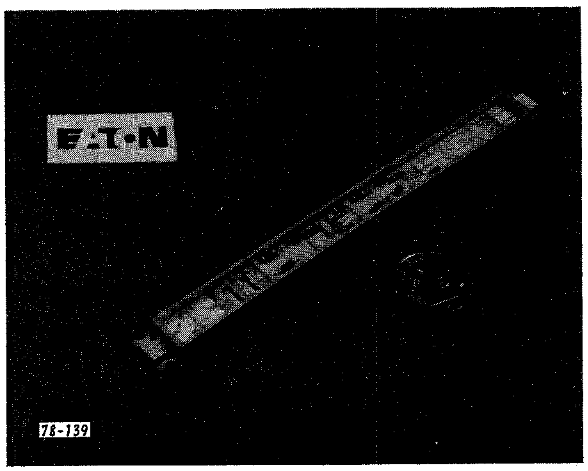

Figure 1. Transmit Module

* Each major subassembly in the transmit module is also referred to as a module.

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Table 1. Transmit Module Requirements

Parameter	Design Goal
Frequency Range, GHz	5-10
Small-Signal Gain, dB	40
Output Power at a Gain Compression of up to 3 dB, dBm	+33
Gain Variation at a Gain Compression of up to 3 dB, dB	± 2
Input VSWR	2:1
Output Impedance, Ω	100, balanced
Output VSWR	3:1
Phase Shifter Increment	3 bit
Size (Excluding Mounting Connectors and Feedthru's)	The volume must not exceed 0.375 in. (H) x 0.156 in. (W) x 4.5 in. (L)
Output Stage Operating Class	Class A
Output Stage Transistor Junction Temperature Rise, °C	65
Output Stage Power-Added Efficiency, %	35

DESIGN APPROACH

Electrical

The electrical design was steered by the need to minimize the FET channel temperature rise and to reduce the circuit sizes to an absolute minimum. A lumped element/thin film on alumina implementation using discrete devices was chosen because of the suitably low thermal resistance of commercially available, discrete, plated heat sink devices, the potential for broad bandwidths because of the high upper limit on characteristic impedance, and low conductor losses. The option to use electrically short transmission lines suspended above the substrate to serve as broadband, lumped, high Q, inductors was regarded as an advantage that this implementation could offer.

To minimize circuit size, lumped elements were used wherever possible and a single-ended configuration was used in all modules* with the exception of the output module which was designed to be push-pull to be compatible with the balanced antenna elements. A block diagram of the transmit module which lists gain and output power allocations is presented in Figure 2. To maintain acceptably low input VSWR on all modules, lossy input matching was used.

Thermal

The thermal aspects dominated the transmit module design since it was of crucial importance to minimize the output module FET channel temperature rise to 65°C for reliability reasons. To achieve this end, a novel low thermal resistance package was developed which was fabricated by Kovar and Elkonite. (The latter is a tradename for a Tungsten-copper composite that has thermal conductivity properties that approximate those of copper and thermal expansion properties that resemble those of Kovar.) The housing consisted of two pieces: a Kovar ring that readily accepted the necessary fired-in RF and dc feedthru glass seals and an Elkonite base that was soldered to the Kovar ring. The modules, on their own Elkonite carriers, were attached to the housing base with a 0.002-in. thick film of conductive epoxy. Size restraints did not permit conventional screw attachment of the carriers. By seam sealing the cover, one obtains a fully hermetic package that has a significantly lower thermal resistance than one made entirely of Kovar. A cross section of the transmit module housing, interfaced to the aperture chillplate is shown in Figure 3. A Chomerics conductive RTV rubber is applied between the housing baseplate and the aperture chillplate to fill voids and reduce thermal resistance.

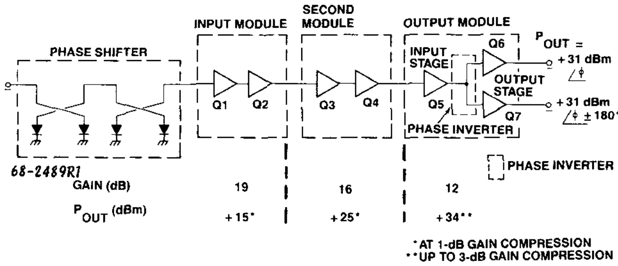

Figure 2. Transmit Module Block Diagram

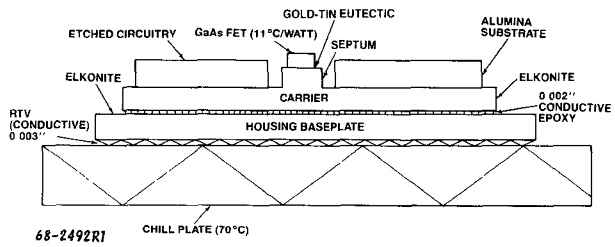

Figure 3. Thermal Design Concept

CIRCUIT DESIGN AND MEASURED RESULTS

This section provides a brief description of the circuit design and a discussion of measured results. Although the objective was 5-10 GHz, the useful bandwidth of the transmit module fell slightly short of this and was limited to 5-9.5 GHz because of difficulties encountered in the alignment of the interstage matching network of second module. The other modules met the bandwidth objective and the data to be presented for them will be for the full frequency range.

Phase Shifter

The phase shifter employs two tandem 90-degree couplers whose arms are terminated by varactor diodes. The couplers were designed to have a 75 Ω impedance to obtain more constant phase shift over the frequency range. Multi-section 50-75 Ω and 75-50 Ω impedance transformers were placed at the input and output, respectively, for impedance matching. The varactors selected for this circuit are silicon types with a capacitance ratio of approximately 11:1.

The measured phase shifter characteristics are tabulated below:

Bit, degrees	Insertion Loss, dB	Phase Shift, degrees
Reference	3.8 to ± 0.3	
45	4.5 ± 0.5	45 ± 8
90	5.1 ± 0.6	90 ± 8
180	6.2 ± 0.5	180 ± 20

The insertion loss was higher than expected because of the poor varactor Q at low bias voltages. The GaAs diodes would have provided lower loss.

Input Module

The input module is a single-ended low power two-stage design employing MELCO MGFC 1403 GaAs FET's. The input and interstage networks employ frequency dependent lossy elements to compensate for the 6 dB/octave gain rolloff of each transistor. The measured small-signal gain of the module was 17 ± 1 dB from 5 - 10 GHz.

Second Module

The second module uses the Harris HMF 0600, 600-μ gate width device in the first stage and the HMF 1200, 1200-μ device in the second stage. Lossy matching circuits are also used in the input and interstage networks to offset the transistor gain rolloff. The measured gain was 13 ± 3 dB from 5 - 9.5 GHz and the measured output power at gain compressions of up to 2 dB varied from +17 dBm to +26.5 dBm and was lowest at 9.5 GHz.

Output Module

The output module consists of an input stage, a passive 180-degree phase inverter, and a two channel output stage to provide balanced outputs. All three FET's are identical and use the same matching networks. A schematic of the input stage (and one channel of the two-channel output stage) is shown in Figure 4. The GaAs FET chosen for this module is the NEC 900400G that has a total gate width of 3000 μ. Four 750 μ cells comprise the 0.5-μ gate-length FET. It was selected for its relatively low thermal resistance of 11°C/w, excellent available gain, and power-added efficiency. Separate gate bonding pads are provided that allow prematching to be performed at the cell level before parallel combining. The NEC 900400G FET has an output power rating of +31 dBm at a 1 dB compressed gain of 6 dB. The input network of each stage in the module provides amplitude tapering to compensate for gain versus frequency rolloff in addition to impedance matching.

The phase inverter consists of a 90-degree coupler with a Schiffman 90-degree phase shifter in one arm to provide the additional 90 degrees of phase shift. The measured phase balance was 180 degrees ± 8 degrees.

The input stage and both channels of the output stage achieved nearly identical performance. The typical output power for compression levels of up to two dB is presented in Figure 5. For 2 dB of gain compression the output power is typically greater than +30 dBm. The typical measured gain is presented in Figure 6. The power added efficiency of the output stages varied from 16% to 35% and typically was 25%.

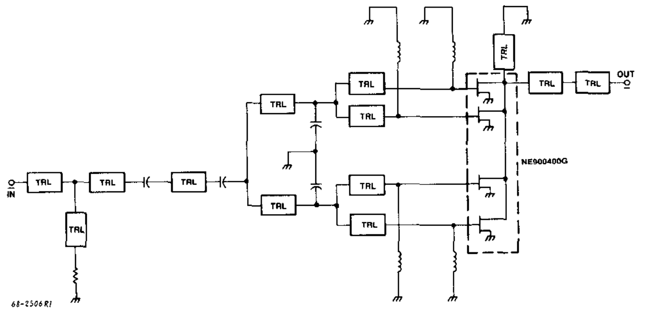

Figure 4. Schematic - Output Module (Input Stage) and Two-Channel Output Stage (One Channel)

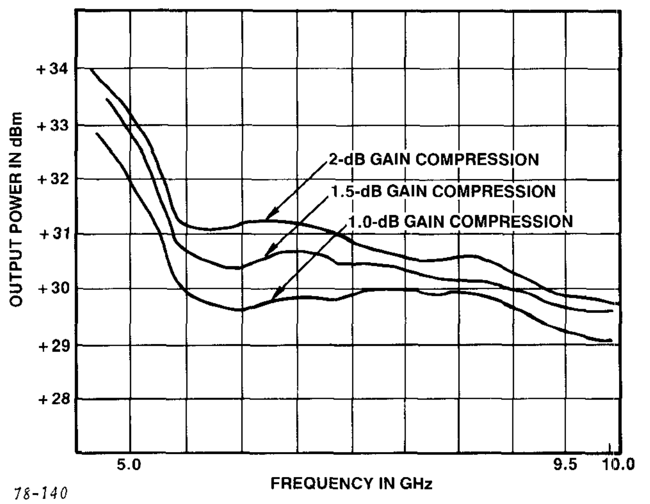

Figure 5. Output Module (Input Stage) Output Power

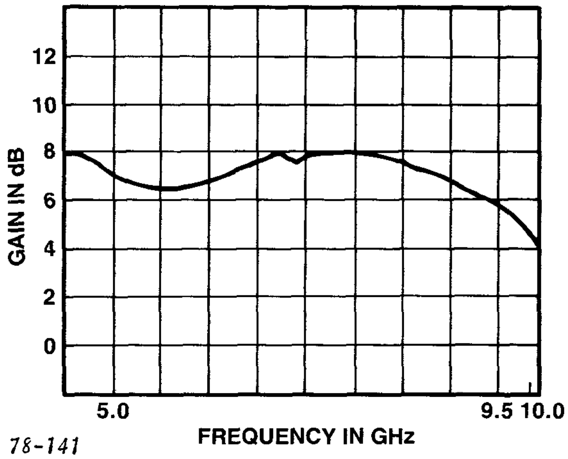

Figure 6. Output Module (Input Stage) Gain

Transmit Module

The measured performance of the transmit module is discussed now. The output power, for a gain compression of up to 3 dB and assuming lossless combining, is plotted in Figure 7. An output power of 30 ± 2.5 dBm was measured that was less than the predicted 33 ± 2 dBm based on the measured performance of the output stages. It was determined that the second module's gain and compression characteristics were responsible for the premature compression of the amplifier. The small signal gain is plotted in Figure 8.

CONCLUSIONS

Using hybrid techniques, an ultraminiature 2-w high performance transmit module was developed for active aperture application. The design emphasized broad bandwidth, power, efficiency, high reliability, and, above all, ultrasmall size.

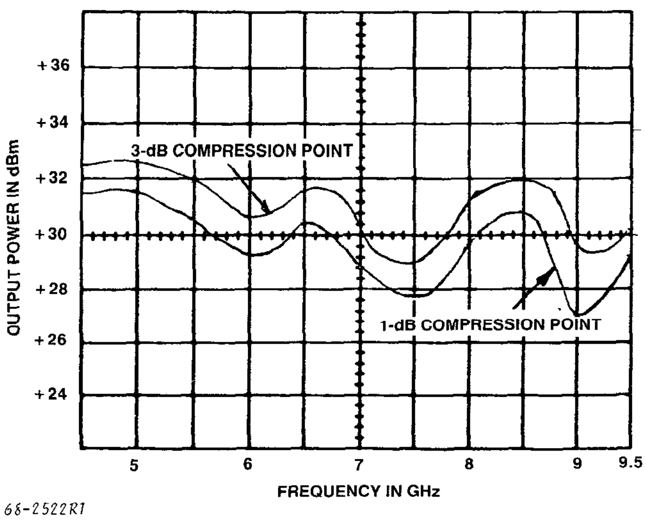

Figure 7. Transmit Module Output Power

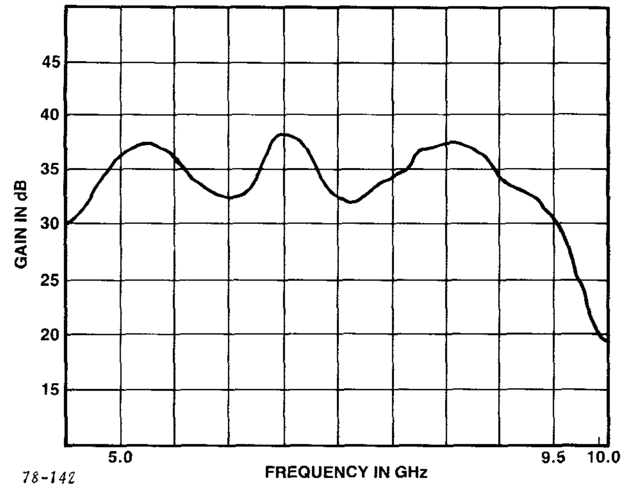

Figure 8. Transmit Module Small-Signal Gain

The authors believe that a MMIC implementation of the transmit module would certainly have advantages with regard to reliability, because of the absence of bonds, and size, but the question of fabricating power devices in MMIC with a thermal resistance of less than 10°C/w without excessive substrate thinning or complex selective plating is a concern. State-of-the-art discrete devices emerging from the laboratory have achieved thermal resistance as low as 2°C/w.

Furthermore, for radar applications where thousands of modules are required, it is clear that MMIC is a cost-effective way to go. However, for ECM applications where hundreds, not thousands, of modules are required, and the demand for systems is less, a hybrid approach may have a cost advantage. This issue is being investigated.

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