MILLIMETER WAVE, SOLID-STATE AMPLIFIERS IN RADAR AND COMMUNICATION SYSTEMS

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Abstract

Two different designs of millimeter wave, high-power, solid-state amplifiers are presented here, one each for use in missile radar and satellite communication applications. Details of each design will be given along with the tradeoffs which led to the specific solid-state designs over other alternative solid-state and tube amplifier designs.

Introduction

High power microwave transmitters made up of solid-state amplifiers possess several key advantages over a tube transmitters, primarily "graceful degradation". Multiple solid-state devices combined in parallel can allow for several failures while still maintaining a large percentage of the transmitter output signal, while a single failure in the tube is often catastrophic. Solid-state devices operate at considerably lower voltages than the tube requirements of 15 to 20 kilovolts. The solid-state devices are integrated in a combiner circuit that allows for considerable packaging flexibility, while the tube itself often dictates the form-factor necessary for the entire transmitter. The parts within the solid-state amplifier are made with common machining practices and tolerances, while the slow wave structure and vacuum circuit manufacturing must be extraordinarily precise at millimeter-wave frequencies. Due to the multiplicity of devices, the heat load of the solid-state approach is distributed uniformly throughout the amplifier and not concentrated in a single area. Finally, the active devices within the solid-state amplifier are individually hermetically sealed and storage times of greater than 10 years are not unreasonable, while outgassing of the tube's internal structures into the vacuum require periodic maintenance checks. A transmitter built around a tube amplifier however, will always have an advantage in efficiency over a solid-state transmitter due to the fact that losses in the crucial combiner circuit of the solid-state will subtract output power(and therefore efficiency) from the total transmitter design.

Amplifier Design

Solid-state amplifier design depends on understanding and trading off three key requirements: 1) the desired operating frequency and bandwidth, 2) the performance of the individual solid-state devices to be used, and 3) the efficiency of the power combining technique and circuitry. The particular type of device and power combining circuitry used further depends on the operating frequency, output power level and operating mode, either CW or pulsed. Figure 1 shows the output power and typical operating frequency of a variety of solid-state devices available today in the millimeter wave frequency range.

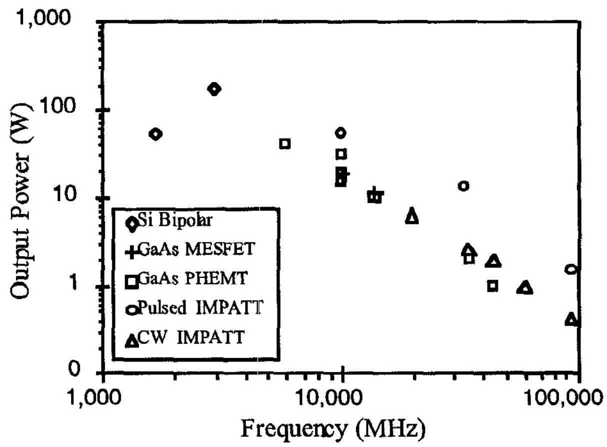

Figure 1 - Solid-State Device Performance

Power devices are generally available in either two terminal (IMPATT, GUNN diodes) or three terminal (MESFET, HBT, PHEMT) topologies. Two terminal, IMPATT diodes are the highest power device available at millimeter wave frequencies, but are typically low-impedance, which requires complex, narrow-band matching structures to use them. Because of their two terminal topology, circulators and isolators are also required to separate the input and output signals. Three terminal PHEMT transistors are the highest efficiency device available, but an order of magnitude less in output power capability.

Power Combining

In order to efficiently combine power generating devices of any type, the combining structure has to possess several important characteristics. Primarily, it must be low loss to minimize any attenuation of the desired signal. It must also have high isolation between any of

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the input/output ports so that none of the power generating devices are influenced by any other device, either during normal operation or when one of the devices has failed. Third, it must be well matched so that the power transfer from all the devices is maximized and no load pulling occurs.

Other factors that relate to the selection of a power combining approach include size and weight, ease and cost of fabrication, design maturity and the amplifier's end use, whether in a distributed array or a single port output. Waveguide, microstrip and quasi-optical techniques are several potential power combining options at millimeter wave frequencies. Microstrip is convenient for small numbers of devices, but its loss and power handling ability becomes a problem for large numbers of devices. Quasi-optical power combining techniques have shown potential for specific applications, however many systems issues remain unresolved with this approach(i.e. beam steering, receive channel isolation). The use of a waveguide combining approach meets many of the above requirements in a mature and cost effective manner, and can best be implemented by the use of high isolation, magic tees or short-slot hybrids for the power splitters and combiners. For amplifiers that must be limited in thickness to a planar, single layer configuration, short-slot hybrids may be the best circuit element. Both types of hybrid circuit elements provide high isolation between output ports and a fourth port for termination of out of phase energy.

Solid-state devices can be combined either in series for gain or in parallel for power. When combining for gain, care must be taken to insure that the devices in each successive stage of the amplifier are capable of providing the output power at the necessary gain level. When combining for power, the reverse is true. In addition, as the number of devices being combined within a stage increases, care must be taken to prevent the loss of the divider/combiner circuit from becoming a significant portion of the stage gain.

Module Design

Individual millimeter wave solid-state devices are small and difficult to handle, and it proves advantageous to combine a small number of devices within a relatively simple circuit as the first step of power combining. These modules can then be individually characterized at a moderate power level prior to combining for high power in the final combiner circuit. The combining approach used within the module can be similar to or completely different from the combining circuitry used in the final combiner circuit; however, the interface between the two must allow for a low loss transition, rapid replacement in the event of failure, and a good thermal path for heat transfer. Repair and troubleshooting is also simplified if the problems can be traced to individual modules for quick replacement.

Missile Radar Amplifier Design

The first power amplifier design to be discussed is a Ka-band, high peak power, 40 dB gain amplifier developed for a missile application that is based on combining pulsed, GaAs IMPATT diodes.[1] This design is capable of over 1000 watts peak while operating at high duty cycles. A key requirement for this system's RF seeker was high sub-clutter visibility, which flowed down to a requirement for the transmitter of low additive phase noise. IMPATT devices were chosen for this application primarily because they provide the highest level of pulsed power of any solid-state device at Ka-band, but in addition, the solid-state design was selected over a tube transmitter because of the demonstrated lower phase noise performance of the IMPATT devices at Ka-band, which is a significant improvement over their noise performance at X-band.

The 40 dB power gain requirement was divided up between a total of eleven stages. The number of stages is determined by the total amount of gain required to boost the input signal to the specified output power level. High power, multiple module stages run at approximately 3 dB power gain, while low power, single module stages run approximately 5 dB gain. The gain of each of the eleven reflection amplifier stages within the power amplifier is provided by a total of 68 modules within which is contained a total of 258 devices. The modules, which contain either one, two, or four devices, are power combined by a low-loss waveguide combiner network machined into a single block of metal containing the waveguide circuit and cooling channels for laboratory testing. Figure 2 is a simplified block diagram of the amplifier showing the eleven stages isolated from each other by ferrite

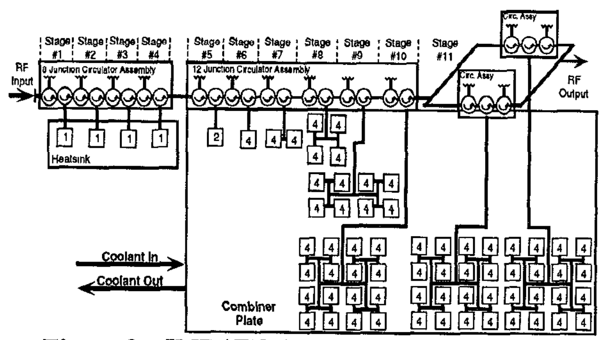

Figure 2 - IMPATT Amplifier Block Diagram

isolator/circulator assemblies, the 68 modules and the distribution of the 258 IMPATTs within the modules and stages. The modules are represented by squares attached to the ferrite assemblies and the numbers within each square identify the quantity of devices within that module.

IMPATT Module Design

In order to easily make use of the output power capability of the IMPATT diode, the devices are assembled into a module that incorporates ease of replacement, low loss, easily matched circuit topology, rugged heatsinking, a convenient mounting surface for the bias current driver, and a low inductance path from the driver to the IMPATT diode. All of these features have been integrated into the single, dual and four diode IMPATT module designs.

The modules themselves consist of a rectangular waveguide cavity with the IMPATT diodes mounted in coaxial lines positioned on the cavity sidewalls. The RF energy from the diodes is magnetically coupled from the coaxial lines to the waveguide and exits through an aperture into the combining plate. Mounted to the side of each module is a hybrid microcircuit that contains the driver circuitry needed to provide the constant current bias to each of the IMPATT diodes.

IMPATT Amplifier

The amplifier is assembled by integrating one stage at a time onto the combiner circuit. Figure 3 shows the assembled power amplifier with the combiner plate visible in the center of the assembly. Visible on the top surface is half of the modules, the second half are located on the bottom surface of the combiner plate.

Figure 3 - IMPATT Power Amplifier

Figure 4 shows a comparison of the measured additive phase noise performance between the IMPATT, PHEMT and a TWT transmitter. Both the TWT and IMPATT transmitter were operating pulsed and measured at the same Ka-band frequency on the same test equipment. The PHEMT was measured separately at 44.5 Ghz.

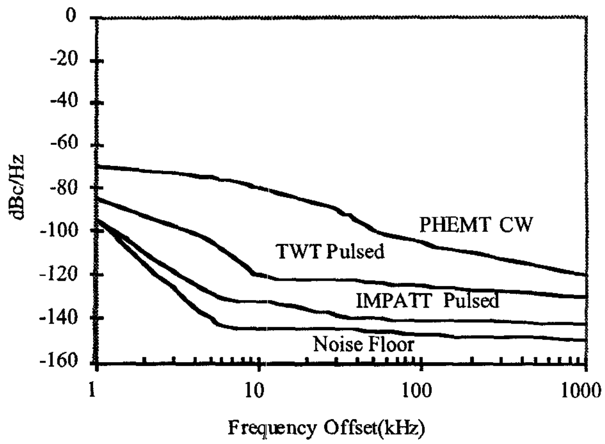

Figure 4 - Transmitter Additive Phase Noise

Satellite Communications Amplifier

The second amplifier design, shown in Figure 5, is a Q-band, CW power amplifier based on the use of 0.15 micron gate length PHEMT MMICs that are power

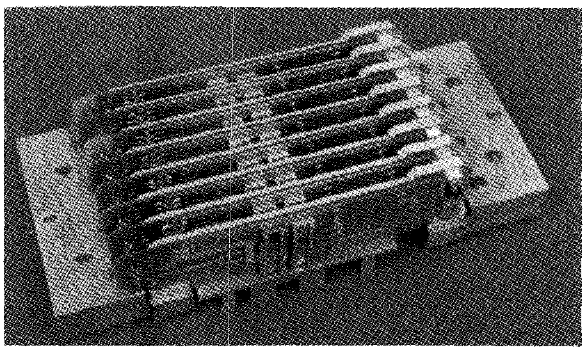

Figure 5 - PHEMT Solid-State Amplifier

combined to achieve high levels of CW power across the 43.5 - 45.5 GHz satellite communications band.[2] A key requirement for this system was to maximize the system's on time when operating on a specified self-contained diesel generator and fuel supply. This requirement flowed down to a specification for the transmitter of maximum DC to RF efficiency. PHEMT devices were chosen for this application primarily because they provide the highest efficiency level of CW power of any solid-state device at Q-band. Their higher impedance also helped the device matching to achieve the 5% bandwidth requirement.

The PHEMT solid-state amplifier consists of an eight way, waveguide power divider and eight PHEMT amplifier modules whose output power is also power combined by an eight way, waveguide combiner network consisting of cascaded waveguide magic tees.

Each PHEMT amplifier module contains one driver and four power MMIC chips, themselves combined using a low-loss, waveguide divider and combiner circuit built up of short-slot hybrids. MMIC assemblies within the amplifier module contain an E-plane probe version of a waveguide to microstrip transition on a quartz substrate at the input and output to transition from the waveguide divider/combiner to the MMIC chip. This is done to minimize the length of microstrip transmission line used and remain within the low-loss waveguide medium as much as possible.

PHEMT Amplifier Module

A photograph of the PHEMT Amplifier Module is shown in Figure 6. The PHEMT Amplifier Module uses a single MMIC driver amplifier assembly to drive four MMIC power amplifier assemblies in parallel. The amplifier topology uses a waveguide short-slot hybrid to form the divider and combiner. Three of the hybrids are used in a one feeding two configuration to form the four way divider and combiner. The amplifier also includes a step twist at the input and output to orient the waveguide opening with that of the 8 to 1 combining network

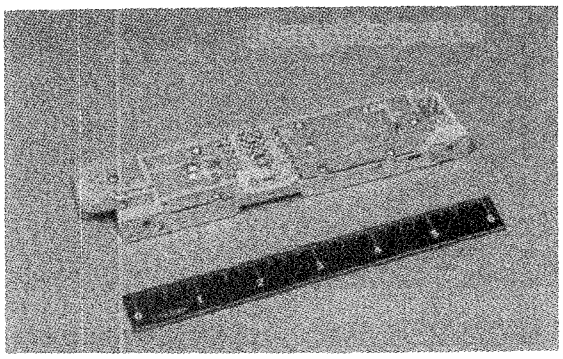

Figure 6 - PHEMT Amplifier Module

The MMIC assemblies are mounted to the waveguide network which contains the 4 to 1 power divider and combiner constructed from waveguide short-slot hybrids. Each of the MMIC assemblies includes a waveguide to microstrip transition at the input and output which transforms the signal between the waveguide and the microstrip medium of the amplifier assemblies. The waveguide to microstrip transition is accomplished with an E-plane probe, as shown in Figure 7. Both MMIC chips use 0.15 μm PHEMT devices, measure 3.9 mm by 2.6 mm and are three stage amplifiers. Each Power MMIC provides 650 mW of output power at the 1 dB compression point with 17 dB of gain at 17% power added efficiency. The Driver MMIC provides 500 mW of output with 12 dB gain at 15% power added efficiency.

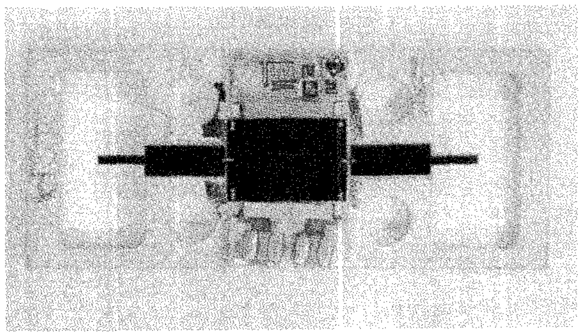

Figure 7 - MMIC Amplifier Module

PHEMT Power Amplifier Performance

Figure 8 shows the output power curve of the completed PHEMT amplifier measured across the operating band at room temperature conditions.

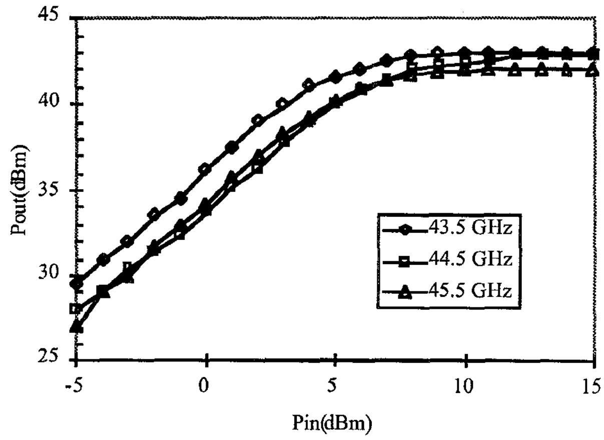

Figure 8 - PHEMT Amplifier Performance

Conclusion

Present devices, characterization techniques, manufacturing technology and screening all lead to the conclusion that medium to high power, solid-state amplifiers are a flexible, cost-effective, highly reliable alternative to tube transmitters.

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