6 to 18 GHz Transmit/Receive Modules for Multifunction Phased Arrays

D. E. Meharry, J. L. Bugeau, W. J. Coughlin, and M. A. Priolo

Sanders Associates, Inc. Nashua, NH 03061-2041

Abstract

A full 6 to 18 GHz Transmit/Receive module is demonstrated for multifunction phased array applications utilizing a family of high performance MMICs. Featured are output powers reaching over 1.0 W, a 4:1 bandwidth 5-bit digital phase shifter, a low loss, high isolation switch, and a high dynamic range design incorporating all required system functions.

Most Transmit/Receive (T/R) module development to date has been for radar applications, which require only a relatively narrow bandwidth. Recent requirements for multifunction phased arrays, which combine EW receive and transmit, ESM, direction finding, and radar in the same array, require T/R modules to operate over very broad bandwidths. This paper describes the integration of a state-of-the-art family of 6-18 GHz bandwidth MMIC chips into an ultra-broadband T/R module. No hybrid circuits are used to 'tweak-up' the module performance in any way. Transmit amplifier chips are power combined to yield up to 1.2 watts at the antenna port. Results of key chips, all developed at Sanders Associates, are also presented. The performance of the 4:1 bandwidth digital phase shifter and the DC-20 GHz SPDT switch surpasses all previously presented results.

Broadband T/R Module Design

Figure 1 shows the block diagram of the first prototype 6-18 GHz T/R module. Individual chip functions are shown within the four basic blocks: transmit power amplifier, receive amplifier, phase and amplitude control, and the transmit/receive switch. Receive output and transmit input buffer amplifiers are also included in order to compensate the loss of the phase/amplitude control section. The module features a 4.5-18 GHz 5-bit digital phase shifter and a 250 mW power amplifier chip. The output power of the module is limited to about 100 mW by the 3 dB loss in the T/R switch.

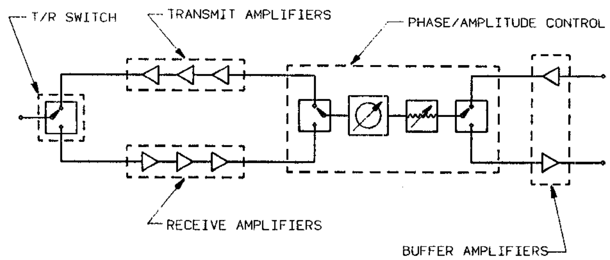

Figure 1. Initial Prototype 6-18 GHz T/R Module Block Diagram

Although the first prototype demonstrated unique capabilities, improvements in performance were required to support multifunction arrays. Output power greater than 1 watt, high spurious free dynamic range, and higher module gain were the main considerations for the improved T/R module configuration shown in figure 2. To meet the power goal, 4-way power combining, an improved power amplifier MMIC, and a different T/R switch were all necessary. Quadrature power combining was selected over in-phase type combiners, to allow the elimination of the lossy T/R switch (see fig. 2). Simple shunt FETs are turned on to reflect power back through the Lange couplers for the receive state. When turned off the FETs have very low loss. Maximum power is thus available to the antenna port, improving overall module efficiency and ultimately reducing module complexity. This approach also provides for antenna polarization selection. Note that the insertion loss of this switch in the receive path is at least as good as that of the original T/R switch. The power amplifier MMIC and other improved chips will be discussed later.

The applications mentioned often have severe requirements for spurious free dynamic range. This is achieved by utilizing amplifiers with high third order intercept, interspersed with lossy components such as the phase shifter and attenuator. High intercept corresponds to high power saturation levels in the amplifiers. The phase/amplitude block of the T/R module in figure 2 utilizes this approach to satisfy dynamic range requirements.

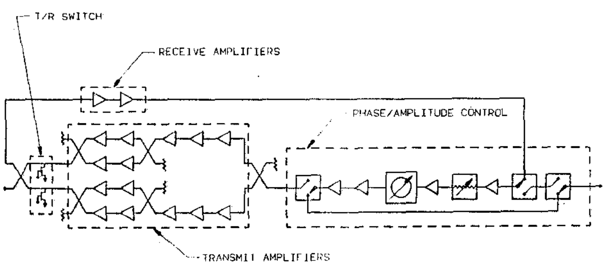

Figure 2. Improved 6-18 GHz T/R Module Block Diagram

MMIC Chips

A breakthrough in MMIC broadband phase shifter technology is the key to high performance 6 to 18 GHz T/R modules. A 4.5 to 18 GHz digital 5-bit phase shifter is shown in figure 3. Further details and performance data of this device are presented in reference 1. RMS phase and amplitude errors for all 5 bits over the entire 4:1 frequency band (accumulated for 46 chips) are respectively 6.4 +/- 0.7 degrees and 0.44 +/- .08 dB. The insertion loss is -11 +/- 2 dB. over the 2 octave band. Worst case input and output VSWR are 2.5:1 with a typical maximum value (per phase state) of 1.7:1. This 4:1 bandwidth phase shifter is accurate enough to accept direct digital drive without the need of calibration and lookup tables.

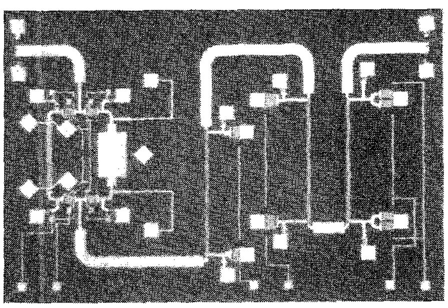

Figure 3. High Performance 4.5-18 GHz 5-Bit Digital Phase Shifter

The DC to 18 GHz MMIC SPDT switch developed for this T/R module has performance superior to any previously reported (see ref. 2-4), and has acceptable performance to 23 GHz. This switch has (figure 4) insertion loss and isolation of 2.0 dB and 43 dB respectively at 18 GHz. Worst case VSWR for the band is 1.5:1 for the common port and 1.7:1 for the switched port. Amplitude control is achieved with the voltage variable attenuator chip. This MMIC has 10 dB of control range with an associated VSWR of a 2:1 or better.

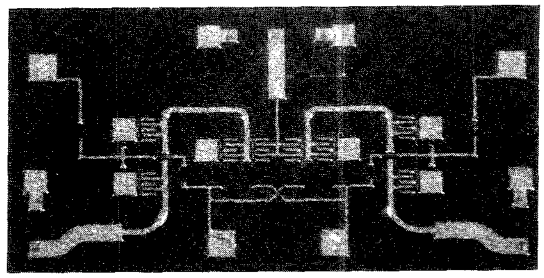

Figure 4. a) DC to 20 GHz MMIC Single-Pole-Double-Throw Switch

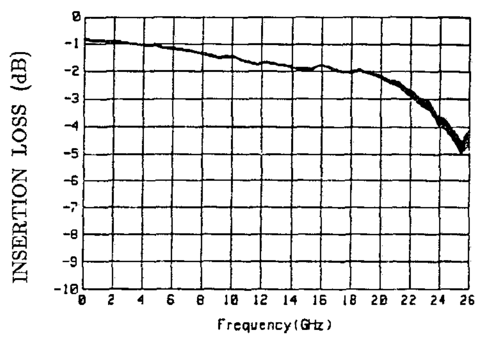

Figure 4. b) Insertion Loss (35 MMIC Switches)

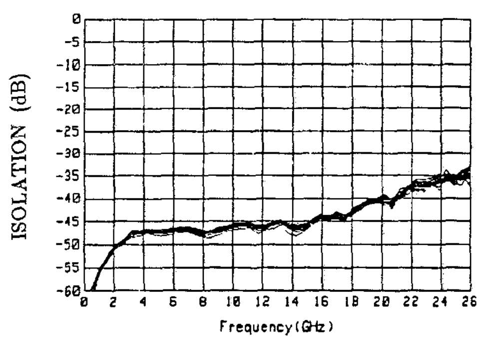

Figure 4. c) Isolation (35 MMIC Switches)

Distributed amplifiers are used thoughout the T/R module for both small signal gain and high power. The 2-18 GHz power MMIC, shown in figure 5 with associated performance data, utilizes 1800 um of total FET periphery and achieves 12% peak power added efficiency. Worst case input and output VSWR over the 4 to 18 GHz band is 1.8:1. The gain plot includes data from 18 wafers having 50% total (wafer start through RF test) yield.

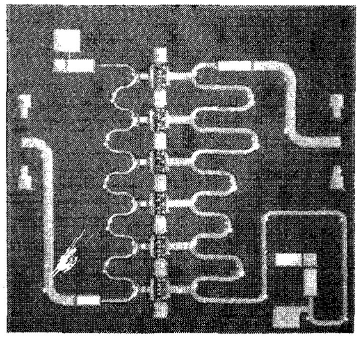

Figure 5. a) 6-18 GHz Distributed Power Amplifier

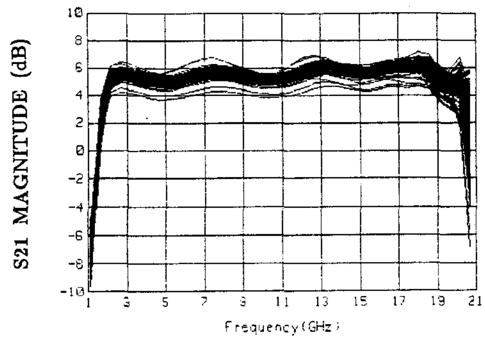

Figure 5. b) Gain Response of 217 Chips

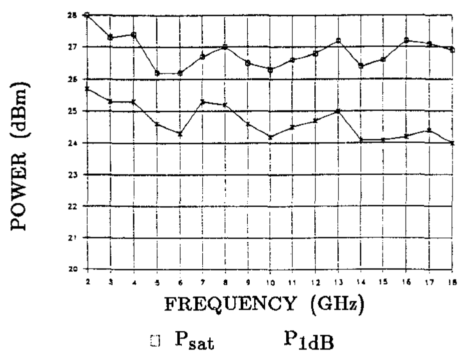

Figure 5. c) Typical P_{SAT} and P_{1dB}

All MMIC chips described above are based on Sanders' MMIC Pilot Line process, which features self aligned, recessed 0.5 micron FET gates on ion implanted substrates. The implant is activated by rapid thermal annealing. Capacitors and passivation are formed from silicon nitride, and plated gold is used for metal interconnect and air bridge structures. Substrates are ground to a thickness of 125 microns, and via holes are formed with a uniform, self limiting plasma etch prior to back side metallization. Design efficiency is enhanced by the high degree of process repeatability and uniformity and by accurate device characterization

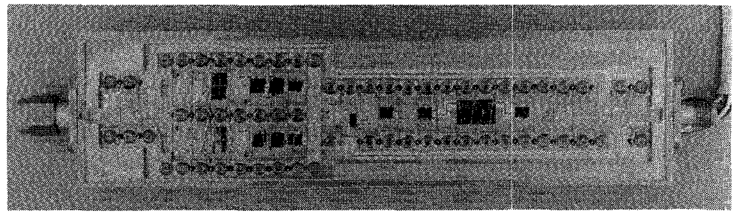

Figure 6. Advanced Prototype 6-18 GHz T/R Module

to 26 GHz. For instance, the switch performance quoted above was achieved on the first design iteration. For power MMICs the self aligned gate recess is modified to enhance the breakdown voltage of the FETs. Finally, all designs are 100% RF and DC tested on wafer, which is important both for design evaluation and production testing of critical performance chips. This MMIC process provides high performance MMICs at an affordable cost for broadband multifunction T/R modules and other applications.

T/R Module Construction and Performance

Figure 6 shows a photo of the advanced prototype 6-18 GHz T/R module. The module dimensions are 0.4 x 1.3 x 5.0 inches. Note the the 4-way power combining section at the antenna port of the module. This module incorporates all of the improved MMIC chips described previously into the block diagram of figure 2. The housing and cover are fabricated from aluminum alloy 6061 for its high strength to weight ratio and plated with gold over nickel for solderability and corrosion resistance. A 4047 aluminum alloy cover can be used when laser welding is required.

The chip carriers are .010 inch thick copper-tungsten which closely matches the thermal expansion of both alumina and GaAs with execellent thermal conductivity for maximum heat dissipation. The chip components are attached to the carriers using a gold-tin eutectic solder. The chip carriers are held in place by individual clips which form a channelized cavity designed to suppress non-TEM modes up to 20 GHz. This carrier approach allows for individual stage testing along with the flexibility of chip interchangeability during module upgrades.

The dc and control lines are routed on a printed circuit board mounted on the back side of the RF cavity. They are brought to the RF side via hermetic feedthrus. All interconnects within the rf cavity utilize thermosonically bonded .003 inch gold ribbon.

Excellent module test results were obtained over the nominal 6-18 GHz band. The transmit and receive gains, shown in figure 7, are 39.8 +/- 3.6 dB and 26.2 +/- 2.8 dB respectively. The match at the T/R electronics port was 2.3:1 worst case (in either transmit or receive mode), while the match at the antenna port was 2.0:1, again for either the transmit or receive states. The match for the two ports is illustrated in figure 7. Figure 8 shows the attenuation (a dynamic range of 13 dB) in the transmit state and the phase response of all 32 states of the module. The saturated power measured without the output T/R switch is greater than 1.0 W from 6 GHz to 10 GHz, though it decreases to 300 mW at 18 GHz. With inclusion of the switch, the power drops by roughly 2 dB. Both of these situations are shown in figure 9.

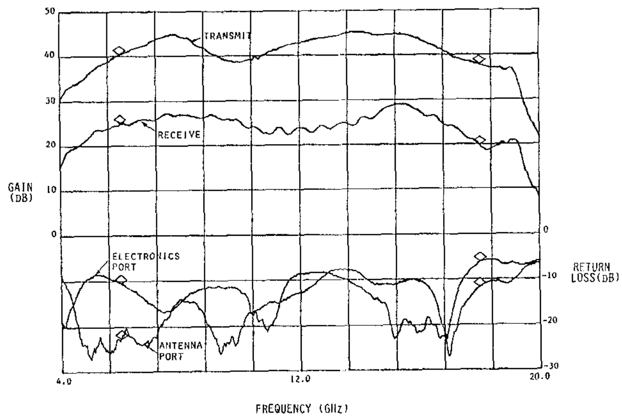

Figure 7. Gain and Match of T/R Module

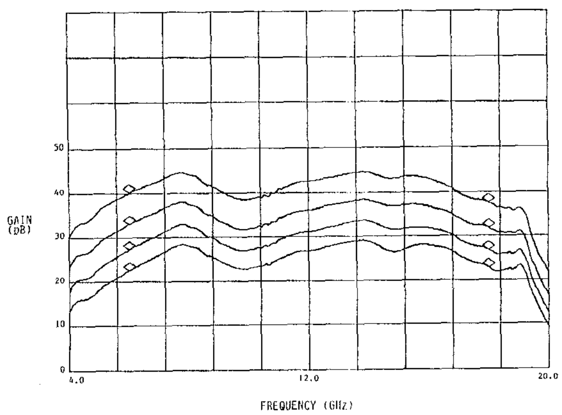

Figure 8. a) Attenuation of Transmit Gain

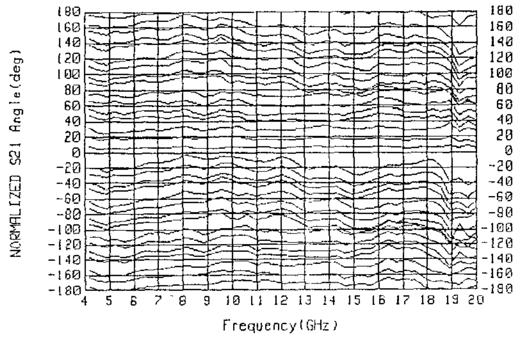

Figure 8. b) 32 Phase States of T/R Module

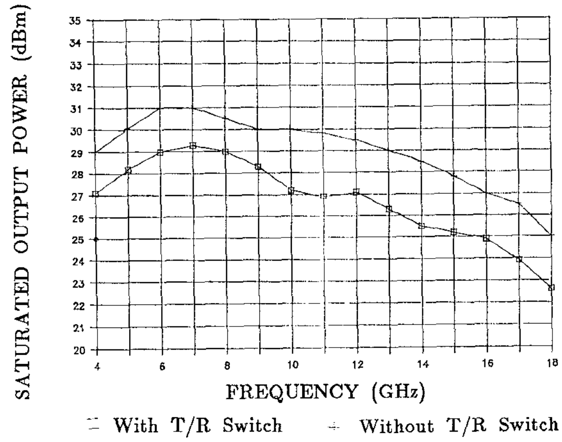

Figure 9. Output Power of T/R Module With and Without Output T/R Switch.

Summary

Multifunction phased arrays over the 6-18 GHz band are becoming a reality, based on state-of-the-art MMIC chips integrated into prototype T/R modules. Accurate digital phase shifters, high power amplifiers power combined to 1.0 watt, and low loss, high isolation switches have all been combined in this demonstration. Further improvements, already under way, in high power MMIC amplifiers will make two watts of power possible in the near future. Additionally, packaging improvements coupled with a reproducible, high yield process will make the modules affordable in large quantities.

Acknowledgements

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References: 1) D. Boire, et. al., 1989 MTT-S Digest. 2) M.J. Schindler, et. al., 1988 MTT-S Digest, pp 1001-2. 3) Tachonics, Inc. Marketing Brochure. 4) Texas Instruments, Inc. Marketing Brochure no. TGS8250.