High-Efficiency L-band Transmit/Receive Module for Synthetic Aperture Radar

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Abstract -- Space-based radar places significant demands on the spacecraft resources (mass, power, data rate) and is therefore very expensive to implement. These systems typically require active phased-array antennas with hundreds or thousands of Transmit/Receive (T/R) modules distributed on the array. High-efficiency is a vitally important figure of merit for the radar T/R module because it reduces the power consumption and therefore makes best possible use of the limited power available. High efficiency also improves the thermal design and reliability. In this paper, we describe the design and preliminary results of a novel L-band (1250 MHz) T/R module technology to achieve ultra-high efficiencies. We will show that a dramatic improvement in overall T/R module efficiency is possible using the results of current research in high-efficiency Class-E/F amplifiers. The T/R module performance goals are to achieve an overall module efficiency greater than 70% with a minimum of 30-Watts output power at L-band frequencies.

I. INTRODUCTION

Radar remote sensing plays an important role in deriving unique measurements that address fundamental questions in the National Aeronautic and Space Administration (NASA) Earth Science Enterprise (ESE) strategic plan. Synthetic aperture radar (SAR) can provide measurements key to the water cycle (e.g. soil moisture and water level), global ecosystem (biomass estimation, land cover change), and ocean circulation and ice mass (ice motion). L-band radar provides the ability to make these measurements under a variety of topographic and land cover conditions, day or night, with wide coverage at fine resolution and with minimal temporal decorrelation.

L-band repeat-pass interferometric SAR (InSAR) techniques can provide very accurate and systematic measurements of surface deformation and surface strain accumulation due to seismic and volcanic activity. The dynamics of the solid Earth motion are complex and there are vigorous efforts to model, understand and eventually predict earthquakes using InSAR data. L-band InSAR is also useful for natural hazard monitoring, assessment and disaster response.

L-band SAR technologies developed for NASA also have national-security application. For example, these techniques could provide observations that are complementary to the traditional high resolution imagery of the intelligence community. L-band SAR can provide information on vehicle and troop movements, and building damage. Significant contributions are also possible in providing detailed surface characteristics, such as the measurement of surface soil moisture and sub-pixel roughness for trafficability. Furthermore, L-band radar technologies could also have application to future DoD space-based radar (SBR) for airborne moving target indication (AMTI) and ground moving target indication (GMTI).

A. *System Requirements*

Large, lightweight, high power, electronically-steerable L-band phased-arrays are required to enable the next-generation NASA Earth science SAR missions. L-band is the preferred frequency for land-related studies because the wavelength favors long-term correlation, is less sensitive to ionospheric disturbances and has sufficient frequency allocated bandwidth. Electronically-steered phased array antennas are required for beam agility to enable rapid accessibility, global coverage and short revisit times.

Future NASA L-band SAR missions, such as concepts currently being studied from LEO to geosynchronous orbits, require very powerful radar systems [1, 2]. For these systems, dramatic improvements in overall efficiency will help make near-term missions with moderate transmit power requirements (2-10 Kwatts) more reliable and affordable and could enable next-generation missions at MEO or geosynchronous orbits which have much higher transmit power requirements (>20 Kwatts). In the most advanced applications, very high efficiency is paramount.

The T/R module is a key component in electronically-steered antennas (ESA) and the T/R module efficiency has direct implications on the power dissipation and power generation requirements of the system. Significant improvements in the efficiency of the T/R module will make very large, high power, two-dimensionally scanned radar antennas more feasible and affordable. By miniaturizing the high-efficiency T/R modules, they can be used for both conventional rigid panel phased-array antennas as well as in more advanced super lightweight flexible membrane antennas currently being developed for future NASA missions [3]. Significant improvements in efficiency will also simplify the thermal design and increase reliability, particularly for membrane antennas, where heat dissipation is particularly challenging.

B. Technical Challenges

We are developing high-efficiency L-band T/R modules for use in future NASA radar missions. At the heart of the new T/R module architecture is a Class-E/F switching amplifier used as the power amplifier. The potential of switching power amplifiers has been known for many years [4], however most of the research has been limited to the RF frequencies below 500 MHz. A high-efficiency (92%) high power (30W) Class-E power amplifiers was reported at 50MHz frequencies [5]. In this paper we discuss the use of a new Class-E/F power amplifier at L-band frequencies. The design goals were to achieve 30 Watts at L-band (1.25 GHz) with greater than 80 MHz bandwidth and over 80% drain efficiency. By integrating the Class-E/F power amplifier into an L-band T/R module, overall T/R module efficiencies on the order of 70% can be achieved. Current T/R modules can only achieve moderate efficiencies of 30-40%. The highly efficient T/R module also addresses the major concerns of active space antenna arrays dealing with power consumption and temperature control, thermal dissipation and reliability.

II. CLASS-E/F POWER AMPLIFIERS

Switching amplifiers, such as Class-E and Class-E/F amplifiers, use the active devices as switches. That is, the active device is ideally fully-on (short-circuit) or fully-off (open-circuit). These circuits are commonly found in switching power supplies, but only recently have they been exploited as RF amplifiers due to the availability of transistors with substantial gain and power at microwave frequencies. The theoretical efficiency for Class-E and Class-E/F amplifiers is 100%; practical efficiencies of 70-90% have been demonstrated at UHF frequencies [5, 7].

A. Switching-Mode Power Amplifiers

In switching-mode amplifiers, the transition between the on-state and the off-state can be achieved instantaneously. The switching-mode amplifiers differ from the traditional classes of amplifiers, which use the active devices as controlled current sources. Since ideally the device is either fully-on or fully-off, the voltage and the current will never be non-zero simultaneously. Therefore, ideally no power is dissipated, and the efficiency is 100%. This theoretical number is much higher than the traditional amplifiers, such as Class-A and Class B amplifiers. To achieve ultra-high efficiency, there are four primary loss mechanisms to overcome: conduction loss, input power loss, discharge loss, and passive component loss. The first three loss mechanisms are due to the active devices. Active device losses for switch-mode amplifiers occur mainly during transitions from one switch state to another. By using a high-Q resonant output network, Class-E and Class-E/F amplifiers minimize this switching loss. At L-band, the active devices are typically large in size, have large on-resistance, large output capacitance, and very low input impedance; all contributing to the loss. The last loss mechanism is due to the passive networks. The design of a low loss passive network also presents technical challenges. Due to the topology of the push-pull amplifier, a balun is used to convert the single-ended signal to a double-ended signal at the input and vice versa at the output. This balun must be small and planar with a flexible geometry for easy integration into the amplifier circuit. Proper modeling of parasitic capacitance and inductance is also another important challenge to ensure the circuit can be properly designed and reproduced to the given requirements.

B. Push-Pull Class-E/F power amplifiers

S. Kee, in his recent work, has reported a new class of power amplifiers – the Class-E/F amplifier [8]. Figure 1 shows the schematic of a Class-E/F amplifier in push-pull configuration. The amplifier uses a pair of transistors as switches. The transistors are driven at 180-degrees out of phase. Tuning circuit includes a parallel LC circuit with the output capacitance of the transistor. The tuning circuit is slightly inductive to minimize the discharging loss of the capacitance.

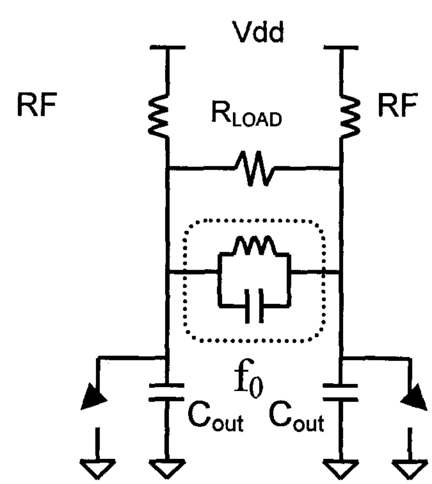


Figure 1. Schematic of Push-Pull Class E/F Power Amplifier

The push-pull class E/F amplifier has several advantages. It combines two transistors to achieve higher power level. It incorporates the transistor output capacitance into the tuning circuit. Since most high power devices have high output capacitance, this feature improves the performance of the tuning circuit and allows high operation frequency. By symmetry of the push-pull configuration, the amplifier suppresses the even harmonics of the operating frequency, thereby achieving higher efficiency. In comparison with Class-E amplifiers, it has lower peak voltage. It also has lower RMS current, which reduces resistive loss of the circuit. It has soft-switching, which keeps the current at a low level while the capacitors discharge. This feature reduces the discharging loss of the amplifier. Compared to the Class-E amplifier, the Class-E/F amplifier also has a less complex circuit and can potentially be used for higher frequency and bandwidth applications.

C. *Low loss L-band microstrip balun*

Due to the topology of push-pull amplifiers, a balun is required at the input and output of the amplifier to convert the single-ended signal to double-ended. There are many different versions of microwave baluns. However, at L-band, the traditional microwave baluns are not practical due to the large size. A microstrip balun has been reported [6] that uses two small sections of magnetically coupled metals as the balun. This balun is smaller than the conventional microwave balun. It is planar, and it has a flexible geometry. However, the drawback of the balun is the low coupling coefficient between the primary and the secondary inductors. Previously reported work uses two microstrip inductors side-by-side (Figure 2). Better coupling can be achieved using interdigital coupled inductors (Figure 3). Using this method, the magnetic field is more confined inside the structure, which increases the magnetic coupling between the primary and the secondary inductors.

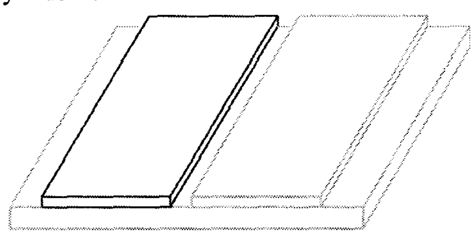


Figure 2. Coupled inductors.

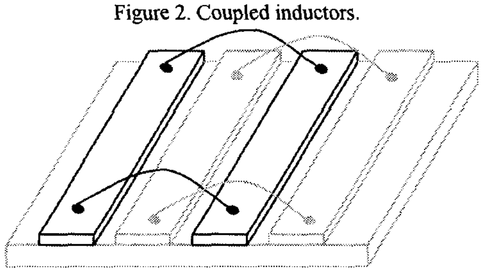


Figure 3. Interdigital coupled inductors.

III. L-BAND HIGH EFFICIENCY T/R MODULE

To demonstrate the utility of Class-E/F amplifiers in a radar system application, a complete L-band T/R module is being designed and built. A key component in the module is the 30W high-efficiency Class-E/F power amplifier. The goal is to achieve the highest possible efficiency in both the transmit and receive modes since low average power consumption is a critical factor in space applications. The module contains a complete 30-Watt transmitter, a low noise amplifier and a common 6-bit programmable attenuator and phase shifter. The performance goals for the final integrated T/R module are given in Table 1.

TABLE I
PERFORMANCE GOALS OF THE INTEGRATED T/R MODULE

Parameter	Value
Frequency	1250 MHz
Bandwidth	80 MHz
Peak Transmit Power	30 Watts
Overall Module Efficiency	70%
Pulsewidth	50 μsec
PRF	2000 Hz
Transmit Gain	48 dB max
Receive Gain	25 dB
Receive Noise Figure	< 2.5 dB
Phase Shifter	6-bit
Third Order Intercept (output)	> +5 dBm
Tx/Rx Programmable Atten	30 dB in 0.5 dB steps
VSWR	<1.5:1
T/R Module Mass	<100 g
T/R Module Size	2.5 in x 1.5 in x 0.25 in

A. *Design Requirements*

The key parameters in the transmitter design are 30 watts peak output power with a minimum transmit efficiency of 73% operating at 1.25 GHz over 80 MHz bandwidth. In the receiver chain, the goals are 25 dB of gain, less than 2.5 dB noise figure, with output 3rd order intercept point of +5 dBm, and less than 100 mW of dc power. The calculated DC power drawn with 10% duty cycle is 4.2 watts which corresponds to 67% overall module efficiency. This includes the receiver low noise amplifiers, attenuators, phase shifter and switches. We believe that with improvements in other components of the module (i.e. receiver, driver amplifier and circulator), an overall efficiency of 70% is achievable.

B. *Architecture*

The block diagram of the T/R module, given in Fig. 4, shows all of the elements of the transmitter, receiver and the control and power switches. A common 6-bit phase shifter and programmable attenuator are used for both receive and transmit chains. The RF circuits use GaAs MMICs except for the high-efficiency power amplifier which currently uses Silicon LD-MOS technology.

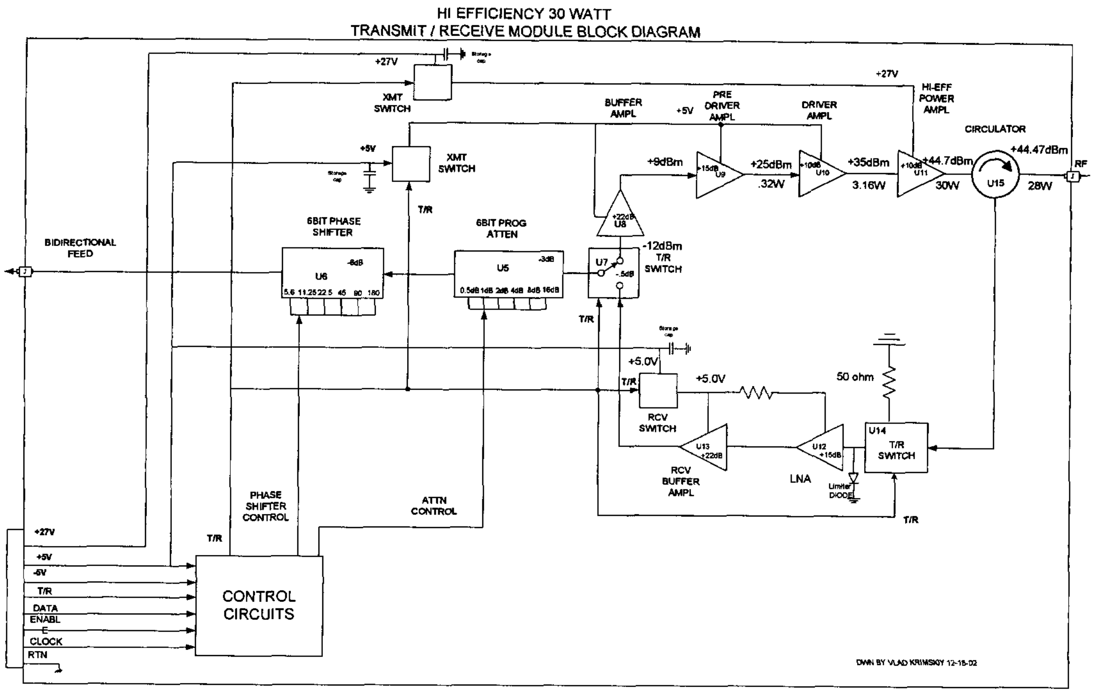
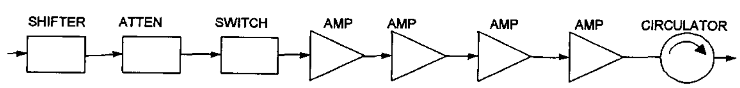


Figure 4. L-band T/R Module block diagram. The 30W Class-E/F power amplifier is the final power amplifier.

Transmit Chain

The transmit chain consists of a buffer amplifier, driver amplifier, medium power amplifier, and the high-efficiency Class-E/F amplifier. The circulator provides isolation for the receiver, as well as VSWR protection for the power amplifier. The total gain of the transmit amplifier chain is 57 dB. The details of the transmit chain analysis are given Table 2. The table shows the gain, power in, power out, and drains efficiency of each element of the transmitter. Also given at each stage is the 1 dB compression point, the operating voltage and currents and power dissipated. We projected the power amplifier will attain 85% efficiency with 10dB gain and 30 watts of output power. It operates in Class E/F mode, as previously described, utilizing Motorola MRF284 MOSFET devices in a push-pull configuration. For high-efficiency these devices are driven above the 1 dB compression point. The medium power amplifier is a GaAs HJ-FET operating at +5v and producing +24.7 dBm of power with 60% drain efficiency and 10 dB of gain. For optimum efficiency this FET is also driven above 1 dB compression, with 24.7 dBm of input drive. The pre-driver and driver amps provide 37 dB of gain with lower efficiencies. The input RF power to the T/R module to is –2.8 dBm. The total transmit efficiency is 73%. Additional losses in the module due to the power MOSFET switches and the control circuits are negligible in the transmit mode.

TABLE II
TRANSMIT CHAIN ANALYSIS



Gain	db	-6.00	-3.00	-0.40	22.000	15.00	10.00	10.00	-0.30	
Cumulative Gain	db	-6.00	-9.00	-9.40	12.600	27.60	37.60	47.60	47.30	
Power In	dbm	-2.83	-8.83	-11.83	-12.228	9.77	24.77	34.77	44.77	
Power In	watts				0.000	0.01	0.30	3.00	30.00	
Power Out	dbm	-8.83	-11.83	-12.23	9.772	24.77	34.77	44.77	44.47	
Power Out	watts			0.00	0.009	0.30	3.00	30.00	28.00	
1 db comp	dbm	20.00	20.00	20.00	12.000	24.00	34.00	45.00		
Eff, drain	%				10.000	45.00	60.00	85.00		
Voltage	v				5.000	5.00	5.00	27.00		
+27v current	amp									
+5v current	amp				0.019	0.13	1.00	1.31		
Dc power	watts				0.095	0.67	5.00	35.30		
Power dissipated	watts				0.085	0.38	2.30	8.29	2.00	
Total +27v current	amp	1.15								
Total +5v current	amp	1.31								
Total power	watts	41.06								
Transmit Eff	%	73.07								
Transmit Eff with circ	%	68.19								
Receive Chain	watts	0.1	(PS, Attn, LNA, sw)							
Total Avg DC Power	watts	4.21								
Overall Module Efficiency		66.57								

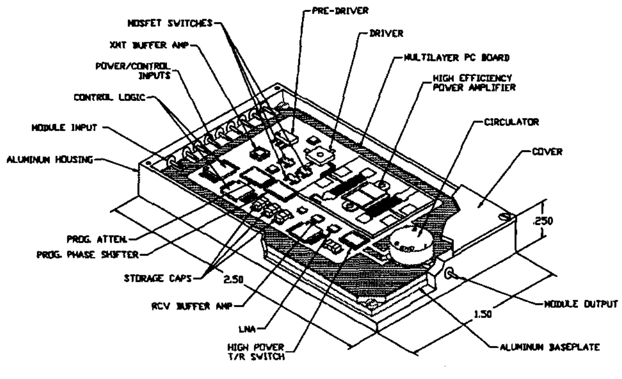
Receive Chain
The receive channel consists of the high power T/R switch, the LNA, and the receive buffer amplifier. The T/R switch in combination with the circulator provides receive protection during the 30 watt transmit cycle. The high power T/R switch gives 35 dB of isolation so that with a worst case 5 dB return loss at the antenna port, 40 dBm or 10 Watts flowing into the receiver would be attenuated to + 5 dBm into the LNA. A limiter diode at the input to the LNA provides additional protection of input signals up to +15 dBm for transmit leakage and jamming signals while in the receive mode. The LNA has 1.5 dB of noise figure 15 dB of gain and draws less than 5 mA at 3 V. The receive buffer amplifier has an additional 22 dB of gain and draws 14 mA. The total receive channel has a noise figure of 2.5 dB and 26 dB of gain. The third order output intercept point is + 5 dBm at maximum gain. The circulator and T/R switch combined losses are about 1 dB.

Attenuator and Phase shifter
The programmable attenuator and phase shifter will be used to set the insertion gain and phase of each T/R element to steer the beam and control the sidelobe levels. The common channel contains the low loss GaAs switch, the 6 bit programmable attenuator and the phase shifter. At minimum attenuation setting the combination has about 9.5 db of loss. Both devices use GaAs-FET switches as control elements to maintain high intercept point operation. The phase shifter has < 3 deg RMS error over all bits with less than 1 dB gain variation. The attenuator has a maximum of 31.5 dB attenuation with 0.5 dB resolution, and 0.5 dB total accuracy.

Control/power
The control circuits interface the module with the external commands, setting the 6-bits of the attenuator and phase shifter, and providing the T/R command to the transmit and receive MOSFET switches to activate the drain voltages of each channel alternately. The input data is serial and clocked in to the control circuits and stored during each update cycle. Well regulated power supplies of +27 v, + 5 v and – 5 v with low ripple and noise content are input to the module, where they are additionally filtered. Storage capacitors supply the peak turn-on currents to the power amplifier stages and maintain the drain voltages with small droop.

C. *Implementation*

A preliminary layout of the T/R module is shown in Figure 5. The hybrid circuit will be packaged using a Low Temperature Co-fired Ceramic (LTCC) substrate for high-density multilayer RF, DC and control interface connections. The phase shifter, attenuator, T/R switches and buffer amplifiers are used in both receive and transmit modes to minimize parts count. There is one RF in/out from the module to the distribution network to simplify interfaces. All the MMICs are enclosed in a hermetically sealed cavity formed by the metal matrix and LTCC. The power amplifier is eutectically attached to the metal matrix carrier directly, through a hole in the LTCC. The overall module size is estimated at 2.5 in x 1.5 in by .25 in.



HIGH EFFICIENCY T/R MODULE
Figure 5. Preliminary layout of integrated T/R module.

IV. Preliminary Results

The efforts described in this paper are part of a three year on-going task sponsored by the NASA Earth Science Technology Office (ESTO) under the Advanced Component Technology (ACT) program. The preliminary results reported here are the results of the first phase of the program to establish overall feasibility of using Class-E/F amplifiers at L-band frequencies and to establish their utility as an integral element of an innovative new T/R module architecture that can achieve very high radar instrument operating efficiencies.

Figure 6 shows a picture of the Class-E/F power amplifier. The output power and drain efficiency are measured and shown in figure 7. The measurement was performed at 800 MHz. At 30 W output power level, 12 dB gain and 64% drain efficiency is achieved. The current operating frequency is less than the target 1215-1300 GHz, which may be due to the parasitic capacitances and inductances. Further improvements need to be made to adjust the operating frequency.

In parallel to the Class-E/F PA development, a breadboard T/R module was built using commercially available components (Fig. 8). The performance of the complete T/R module will be characterized before proceeding to the next phase.

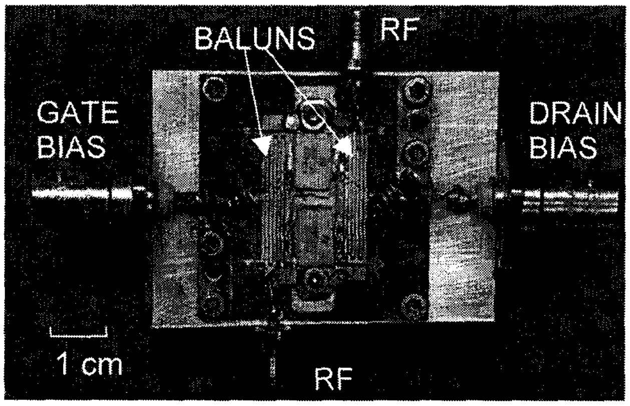


Figure 6. Picture of L-Band Class E/F PA

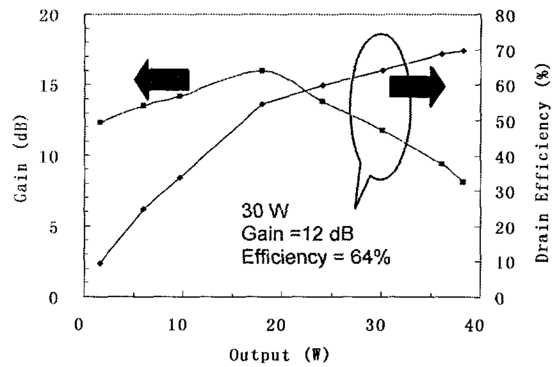


Figure 7. Output power, efficiency and gain of the PA at 800 MHz

V. FUTURE WORK

Improvements to the power amplifier operation and performance are currently being addressed. Currently the amplifier works at 800 MHz, which is different from the target frequency of operation. The first step is to adjust the center frequency of the amplifier to 1.25 GHz. Also, to improve the efficiency of the amplifier, harmonic traps may be used at the output to reduce the harmonics of the fundamental frequency.

Since the active devices are the most critical components of the amplifier, a study is planned to compare different device technologies. GaAs FET is an alternative choice for the amplifier. Also wide bandgap devices, such as SiC and GaN transistors, have both shown promises in high-frequency and high-power applications. The comparison between LDMOS, GaAs, SiC and GaN, will be a part of future studies.

During the next phase the entire T/R module will be integrated on one multilayer circuit board to achieve a compact T/R module package. The components are surface mount devices and will be eutectically attached to the printed circuit board except for the power amplifiers and the circulators. These will be soldered directly to the plated aluminum baseplate for good grounding and heat sinking. A matching network between the driver and the high power amplifier will be incorporated to optimize the VSWR and efficiency.

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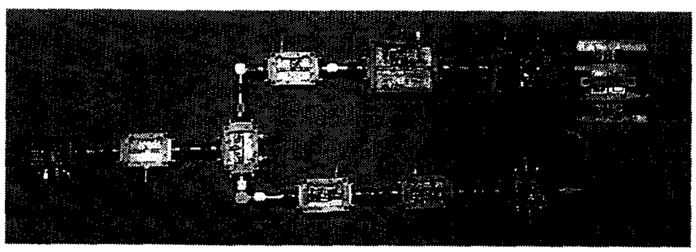

Figure 8. Breadboard of complete L-band T/R module.