Proceedings of the 42nd European Microwave Conference

T/R Module for CASA Phase-Tilt Radar Antenna Array

Rafael H. Medina, Eric J. Knapp, Jorge L. Salazar, David J. McLaughlin
Department of Electrical and Computer Engineering, University of Massachusetts
Amherst, Massachusetts, USA
rmedinas@engin.umass.edu, knapp@ecs.umass.edu, jlsalazar@engin.umass.edu, mclaughlin@ecs.umass.edu

Abstract—**This paper describes the transmit/receive module for the X-band Phase-Tilt array antenna being developed at the Engineering Research Center for the Collaborative Adaptive Sensing of the Atmosphere (CASA). Architecture, fabrication and electrical performance are described. The RF subsystem is designed with commercial-off-the-shelf GaAS MMICs. The design includes a custom PIN diode based diversity switch that provides polarization diversity to the array elements in both transmit and receive channels. The module operates at 9.36 GHz and has a bandwidth of 1.0 GHz. Gain and phase are controlled by a 6-bit digital attenuator and 6-bit digital phase shifter respectively. Commands and RF switching signals are controlled with a FPGA. The T/R modules were fully tested using a measurement station developed specifically for this purpose.**

Keywords- T/R module; Microwave Shicthes; PIN diodes; Phased Array; Radar; CASA

I. INTRODUCTION

During the last five years (2007-2011), the NSF Engineering Research Center (ERC) for Collaborative Adaptive Sensing of the Atmosphere (CASA) has been involved in the development of a low cost active phased array antenna for X-band weather radars. One of the center's goals is to implement a phased array radar (PAR) system in a dense network of short-range Doppler radars to improve the scanning of the lowest level of the atmosphere. Dense networks of short-range radars can overcome the blockage due to the curvature of the earth and complex terrain, which limits today's long-range radar networks from viewing weather hazards and aircrafts at the earth's surface. They also enable high spatial and temporal resolution observations [1].

The phased array radar system being developed by CASA is based on a low-cost, low-power, one dimensional dual-polarization active phased array antenna [2]. The antenna is mounted on a tilt positioner, allowing the radar to perform electronic scanning in azimuth and mechanical scanning in elevation direction. In the active phased array, the transmitter and receiver functions are distributed in 64 transmit and receive (T/R) modules, which provide amplitude, phase and polarization diversity to the radiating elements (vertical subarrays). T/R modules are key components in the antenna functionality because they control the beam-steering and the aperture amplitude distribution function. The requirements that the modules should meet for this application are: transmit peak power equal or greater than 1 Watt, noise figure lower than 5dB, high isolation between antenna polarization ports (greater than 40dB), and high-resolution control on phase and gain. The major goal of this project is to develop the T/R module using commercial-off-the-shelf (COTS) devices and conventional PBC fabrication and assembly process at a cost of less than \$500US [1], including the packaging. This paper describes the design, implementation and measurement of the X-band T/R module developed by CASA for the Phase-Tilt Radar Antenna Array [3].

II. T/R MODULE DESCRIPTION

A. T/R Module Architecture

A block diagram of the T/R module is given in Fig. 1. The T/R module architecture uses a shared control circuitry in both the transmit (Tx) and receive (Rx) channels [4]. This configuration reduces the number of control components per channel and provides a better dynamic range compared other architectures. The shared control circuitry includes a digital attenuator, digital phase shifter, and fixed gain block. This last component is necessary to compensate the losses introduced by the control components. Two separated T/R switches connect the shared control circuitry to the transmitter and receiver blocks. The Tx block consists of a high power amplifier (PA) and medium power amplifier (MPA), while the Rx block consists of a low noise amplifier (LNA) and gain block (GB1). The design is completed with a PIN diode based high power diversity switch that provides transmit/receive and polarization diversity to the radiating elements. An important aspect to be noted is that the diversity switch limits the radar operation to alternating polarization mode.

The transmit channel is designed to have a net gain of about 30dB at room temperature and provide a maximum peak output power of 1.25W when the module is operating in compression. The duty cycle is limited to 30% to protect the power amplifier from excessive heat. On the other hand, the receive channel is designed to have a net gain of approximately 29dB and noise figure of 4.3dB. Both channels use a 6-bit 32dB digital attenuator with attenuation steps of 0.5 dB, and a 6-bit digital phase shifter that provide 360° phase coverage with phase shift step of 5.625°.

The custom designed diversity switch uses a star configuration of 4 Single-Pole Single-Throw (SPST) switches [5]. Each pole is independently controlled by a bipolar control

---

This work is supported primarily by the Engineering Research Centers Program of the National Science foundation under NSF award number 0313747. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation

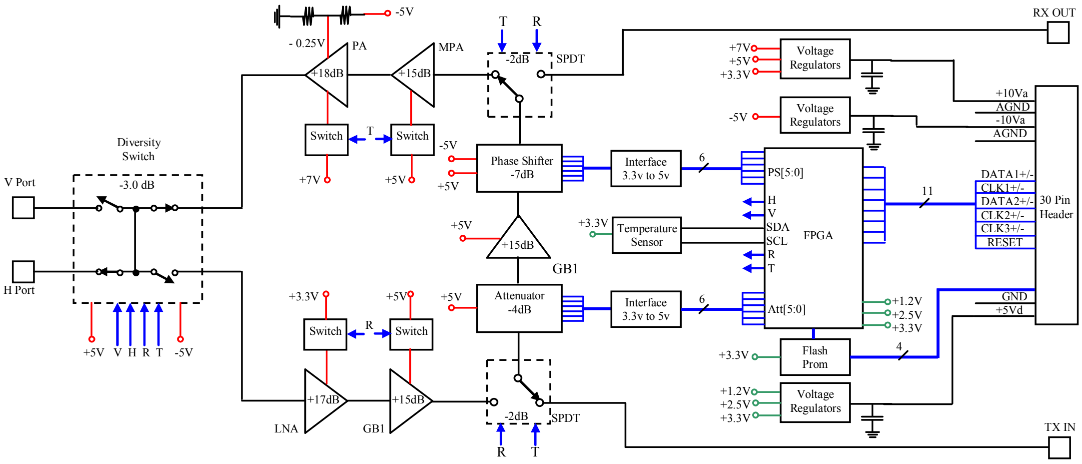

Figure 1. Block diagram of the T/R module components

signal, as illustrated in Fig. 2. The 4 SPST switches incorporate a total of 10 GaAs (Gallium Arsenide) PIN diodes, two diodes at each arm to increase the isolation between ports, and an additional diode in the polarization switches to terminate the ports in a load of 50 Ohms when they are switched OFF. Matched loads are needed in the ports to terminate the radiating array element at its characteristic impedance during the antenna calibration. Tests made in an isolated switch show that the insertion loss and isolation are better than 3 dB and 45 dB, respectively, in the frequency band 9 to 9.6 GHz. An important aspect of the switch design is that its implementation differs from the conventional approaches because the diode cathodes are not directly connected to grounded vias. When diodes are directly grounded with vias, the insertion loss of the switch tends to increase by the impedance of the vias, especially at high frequencies. To avoid this problem, the diode cathodes are directly connected to microstrip lines that are previously grounded to zero potential. To keep a low insertion loss, the reactance of equivalent impedance seen from diode anodes is cancelled out by using radial stubs, which are also part of the bias networks.

Since the T/R module is integrated with analog and digital components, it requires separate power supplies to avoid mixing analog and digital signals. The T/R modules are primarily powered by +10V, +5V and -10V power supplies that are provided from very low-impedance power planes in the backplane board. These voltages are regulated to appropriate DC levels on the T/R module according the specifications of the components. Separate ground and power planes for analog and digital signals distribute the voltages across the module, avoiding in this way the coupling and noise interference among these signals. Fig. 1 shows in detail the voltage levels used by each component. All components are directly connected to the power planes, except the amplifiers used in the transmitter and receiver blocks. The drain bias voltages for these amplifiers are driven by load switches, which in turns are controlled by the T/R signal generated by a digital controller.

B. Control Electronic and Interfacing

The T/R module's control logic is implemented in a Field Programmable Gate Array (FPGA). This component generates the control signals for the attenuator, phase shifter, T/R switches, and amplifier's load switches from commands that are sent from the array controller. In addition, the module is equipped with an I2C temperature sensor, which output register can be read from the FPGA through dedicated lines. The on-board FPGA, a Xilinx Spartan-3E XC3S100E FPGA, is locally programmable with an external flash PROM (Programmable Read-Only Memory). As a part of the control logic, the FPGA's internal memory is configured as a look-up table, where calibrated settings for the attenuator and phase shifter are stored.

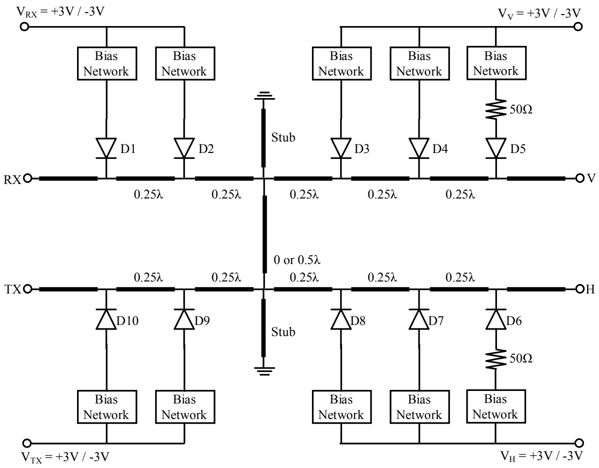

Figure 2. High power diversity switch.

The memory, registers and I/O ports of the FPGA are remotely controlled by a FPGA-based Array Formatter, which translates the user commands from the host computer to control and timing signals for the radar system. The communication (25 Mbps data transfer) between the Array Formatter and the T/R module is realized through five differential transmission lines, which include CLK1, DATA1 and CLK3 as differential inputs to the module, CLK2 and DATA2 as differential outputs from the module. CLK3 is a trigger/synchronization signal that controls the T/R switching.

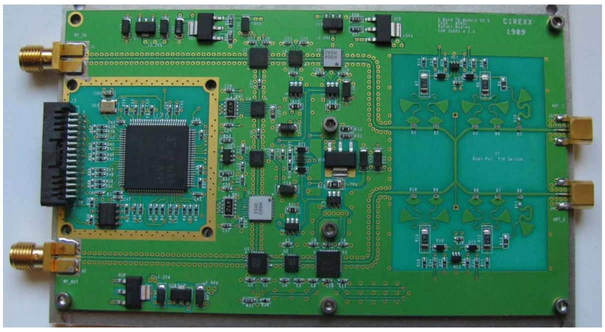

Figure 3. Photograph of the implemented T/R Module

C. *Module Implementation and Fabrication*

A picture of a fully populated T/R module is shown in Fig. 3. The printed circuit board (PCB) comprises 6 circuit layers fabricated on a hybrid construction of Rogers 4350 and FR4. A laminate of 10 mil Rogers 4350 in the TOP layer is used to implement the RF and digital sections. The remaining layers, four FR4 laminates including the bonding adhesives, are used to implement the analog and digital ground/power planes, and to distribute the control signals. The PCB is designed to have low thermal impedance from the power amplifier footprint through the board mounting plate, which works as a heat spreader. A thermal patch isolates the PCB from the baseplate avoiding that vias and transmission lines be short circuited.

The RF components are COTS plastic-packeged GaAs microwave monolithic integrated circuits (MMICs). The large square containing microstrip lines and radial stubs to the right of the module is the high power diversity switch. The area inside the gold square to the left of the module corresponds to the digital components and interfacing section. The two ports at the right side of the module are SMP subminiature connectors that connect to the radiating element via short coaxial cables. The two ports at the left side are SMA connectors that connect the TR module to two separate RF manifolds. All components except the connectors were placed on the board using pick and place machine. The module with enclosure weights 140 g and has a dimension of 6.6 cm x 11.2 cm.

D. *Module Characterization*

One of the challenges of producing phased-array antennas is the large number of T/R modules that must be tested during the development phase or prototype production. In addition, the testing of a single module is a labor intensive that generally involves hundreds or thousands of measurements under different conditions. The use of automated equipments is a requirement to keep a standardized process and reduce cost and time. Based on this need, an automated test station was specifically designed for this project. The test station is based on a PNA series Network Analyzer from Agilent that is remotely controlled via LAN from a host computer. The entire characterization process is controlled with a Graphical User Interface that was developed in the C programming language. Currently, the system only allows measurements of pulsed S-parameters and power at only one temperature. However, measurements can be repeated at other temperatures after manually controlling the module temperature with a cold plate. The process starts by first heating up the module with a pulse of 30% of duty cycle, once the steady-state temperature is reached, the module parameters are measured at several frequencies.

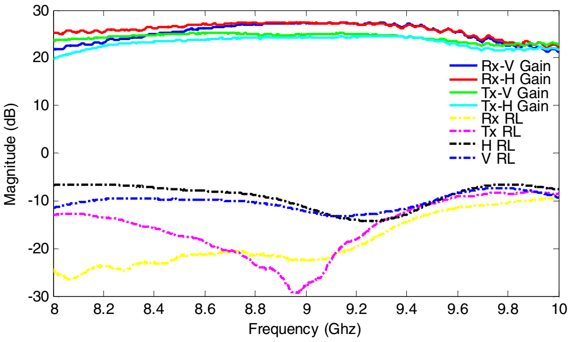

Figure 4. Average gain and return losses for 64 modules

III. TEST RESULTS

Table 1 summarizes the module performance at the operating temperature. The values were obtained from a group of 64 T/R modules at the frequency of 9.36 GHz. Measurements were made with zero insertion attenuation and phase. According the results, the modules present a transmit peak output power of 30.9 dBm, noise figure of 5.5 dB, and isolation between H and V ports of 45 dB. Although the noise figure exceeded in 0.5dB the desired value, the key parameters meet the module design requirements. On the other hand, gains and return losses (RL) were obtains from small signal measurements. The average performance for these parameters is shown in the Fig. 4. From the gain measurements, it can be estimated that the modules have a bandwidth of about 1GHz.

Fig. 5 shows the typical transmit output power and power efficiency of one module as a function of the input power. The maximum transmit output peak power and maximum module efficiency are 31 dBm and 12% respectively. The low efficiency is a consequence of using a commercial linear power amplifier having an efficiency of 20% and the insertion loss produced by the diversity switch.

TABLE I. T/R MODULE PERFORMANCE SUMMARY AT 9.36GHZ

Parameter	**H-Pol**	**V–Pol**
Transmit gain (dB)	24.5	24.7
Transmit input return loss (dB)	15.5	-15.6
Transmit output return loss (dB)	-14	-14
Transmit peak output power (dBm)	30.9	30.8
Tx gain variation over temperature (dB/°C)	0.09	0.09
Receive gain (dB)	27.3	27.1
Receive input return loss (dB)	-12.7	-11.8
Receive output return loss (dB)	-12.9	-13. 0
Receive input power for P1dB (dBm)	-15.7	-15.2
Minimum noise floor (dB)	5.4	5.6
Rx gain variation over temperature (dB/°C)	0.016	0.016
Isolation between TX and RX (dB)	78	78
Isolation between V and H (dB)	-47.4	-46

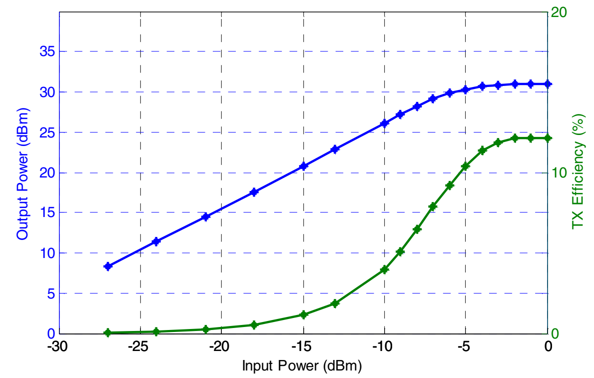

Figure 5. Transmit peak output power/efficiency versus input power

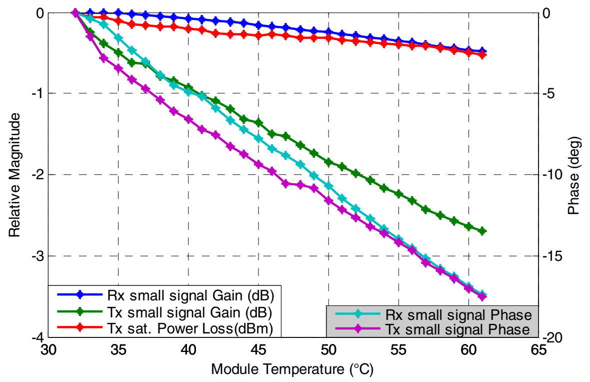

Figure 6. Relative gain/phase performance and saturation power loss versus module temperature

The small signal gain/phase and Tx saturation power performance are shown in Fig. 6 as a function of temperature. Measurements are normalized to the operating temperature of 32 °C. The gain and phase of the Rx channel decay at a rate of 0.016 dB/°C and 0.6 deg/°C respectively. The results show that these variations can be compensated with one attenuation step and 3 phase shifting steps in the temperature range. In contracts, the gain in the TX channel decay a faster rate, 0.09 dB/°C, with a similar phase variation, 0.6 deg/°C. For large signal excitation, the relative saturation power (loss) increases at a rate of 0.018 dB/°C.

The typical gain and phase performance versus the attenuator and phase shifter states of one receive module at 9.36 GHz are shown in Fig. 7 and Fig. 8. The plots comprise of a set of 64 curves, each representing the response at a specific attenuation state. The results show that the gain is affected by the insertion loss of each phase shifter state. Similar effect is observed in the phase, but its value is only affected by the insertion phase of the attenuator. For example, at zero phase state the module phase varies from 0 to -50 degree, when the attenuator is adjusted from the zero to maximum attenuation. Both effects can be corrected by processing techniques and storing the corrected settings in the module memory. Ultimate the calibration should be done at different temperatures. The results could be used, for instance, to compensate the gain/phase variation with temperature that is shown in Fig. 6.

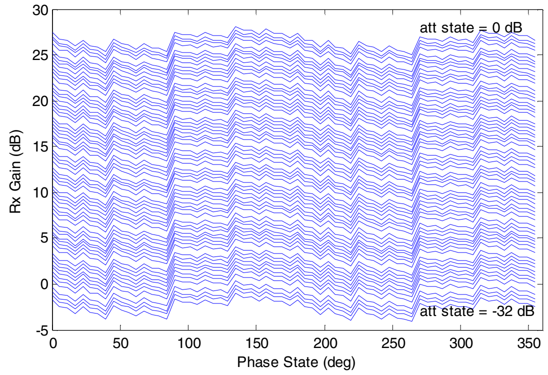

Figure 7. Gain performance versus attenuation and phase shifter state

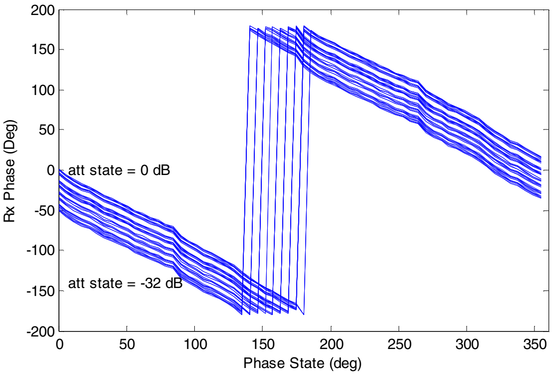

Figure 8. Phase performance versus attenuation and phase shifter state

IV. SUMMARY

This paper has describes the hardware architecture, implementation, fabrication and performance of a T/R module for the CASA Phase-Tilt Radar Antenna Array. Sixty four modules were built and successfully tested. Rapid and accurate measurements were obtained from a computer controlled test station. In general terms, the modules presented a good electrical performance over the required frequency band. The key parameters, the transmit peak power, noise figure and the isolation between antenna polarization ports met the design requirements.

REFERENCES

[1] D. McLaughlin, et al, “Short-Wavelength Technology and the Potential For Distributed Networks of Small Radar Systems”. Bulletin American Meteorological Society, 90, 1797–1817, Dec 2009.

[2] J.L. Salazar, R. Medina, E.J. Knapp, and D. J, McLaughlin, ”Phase-tilt array antennas design for distributed radar network for weather sensing”, in Int’l. Geosci. & Remote Sensing Symposium., Boston, MA, 2008.

[3] E. Knapp, J. Salazar, R. Medina, A. Krishnamurthy and R. Tessier, “Phase-Tilt Radar Antenna Array”, European Microwave Week Conference, Manchester, UK, October 2011.

[4] D. McQuiddy, R. Gassner, P. Hull, J. Mason, and J. Bedinger, "Transmit/receive module technology for X-band active array radar", Proc. IEEE, vol. 79, pp.308 -341 1991.

[5] W.E. Doherty and R. Joos, "PIN Diode Circuit Designers Handbook", Microsemi Corporation, 1999, Chapters 2.