T/R Modules for Active Phased Array Radars

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***Abstract*— This paper presents a summary of the three T/R modules developed for weather active phased array radars. Critical factors that influence the system performance are discussed in terms of the technology and tradeoffs that includes cost. Performance is considered for deployable dual-polarized PAR radar systems. The three T/R modules and antenna aperture Line Replacement Units (LRU) have been designed, integrated and tested. Performance and cost are derived from affordability constraints imposed by the latest technology is presented.**

keywords—dual-polarized; T/R modules; active phased array; -e-scanning array; weather phased array antenna.

I. INTRODUCTION

The weather radar community increasingly demands low-profile, lightweight, and relatively inexpensive dual-polarized phased array radar systems. Fast electronically scanning radars are key to improving temporal resolution of a radar observation for an atmospheric event that provides early warning detection [1]. Low profile, low-weight and low mass antennas are required for many applications; for space and airborne radar systems, those elements are essential [2], [3]. Two-dimensional (2-D) electronically scanning (e-scanning) arrays are the most attractive solution for many applications. Removing mechanical parts and distributing a single source power in thousand of elements makes a system more robust, reliable, and cost effective [7], [8]. Linear and dual-polarized capability enables hydrometeor classification and attenuation correction due to the atmospheric and precipitation attenuation in the radar path [4], [5]. One of the biggest limitations of using 2-D e-scanning array antennas for civil applications is cost [7], [8]. For an acceptable spatial resolution, a radar system requires antenna that provides less than 2^o x 2^o beamwidth. Assuming a spacing of a half wavelength between elements, the aperture size requires around 4,000 elements. In the past the cost of a single transmit and receive module (T/R) could vary from \$350 to \$600 per module [8]-[10]. Based on this, the cost incurred by the T/R modules can be around \$1.6M to \$1.8 M. Today the fast evolution of the RF industry enables the use of commercial components for the development of new phased array radar for civilian applications Substantial progress in GaN, SiGe and CMOS technology enables a significant reduction in cost and size of the integrate circuit (IC) [12], [14]-[18].

In this paper we present a snapshot of the evolution of the technology used in T/R module architectures for weather radar over the last 10 years. We present a brief overview of the most fundamental requirements and enabling technology than can be used for active phased array antennas. We present three T/R module architectures (two in X- and two in C-band) developed during the past four years. Factors influencing system performance are discussed in terms of the allowable tradeoffs that must be considered for deployable systems. Size, complexity, power consumption cost, and performance are the main factors that this paper addresses.

II. REQUIREMENTS AND DUAL-POLARIZED T/R MODULE ARCHITECTURES

Most of the polarimetric radar systems used for atmospheric applications require an operation frequency below 10 GHz, considering the atmospheric and precipitation attenuation. S- and C-band radars are preferred for long-range ground-based application, while X-band radar is the most commonly used for short-range, mobile radars and airborne radars due to the size of the aperture array antenna. Weather radars use the advantages of dual-polarization to improve accuracy of precipitation estimation and also to enable hydrometeor classification [4],[5]. To make use of these polarimetric features a minimum integrated cross-polarization below -20 dB and -40 dB is required for simultaneous transmit modes. In addition, a mismatch between co-polar beam antenna patterns (between H and V) below 7% is required [9]-[11]. This requirement is difficult to achieve without a high performance antenna array and the T/R modules.

Dual-polarized radars for weather applications commonly use three polarization modes [4], [5]: simultaneous transmit and simultaneous receive in reception (STSR), alternate polarization in transmit and simultaneous in reception (ATSR), and alternate polarization in transmit and receive (ATAR). A representation of these three T/R modules architectures is

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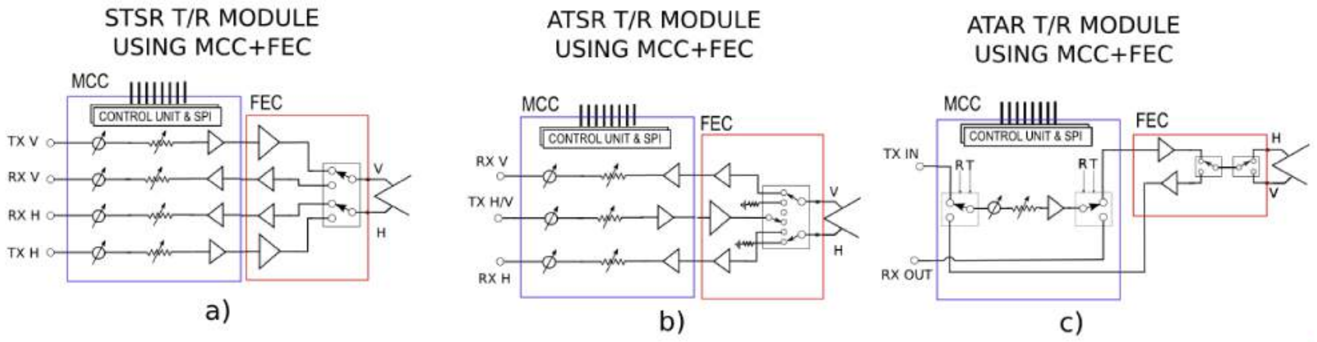

Figure 1. Dual-polarized T/R receive modules for weather phased array radars.

illustrated in Figure 1. In the case of STSR, four independent channels, two for transmission, two for reception and one T/R switch to commute the transmission and reception signals, are required.

In the case of ATSR, one channel is shared for transmitting H and V signals and two independent channels are used for reception. Similar to the previous mode, a T/R switch is required to commute the transmit and receive signals. ATAR on single channel, well known as common leg circuit configuration, is used for both polarization and for transmit and receive. In terms of the number of components, STSR requires 17 components, ATSR 13 components, and ATAR 9 components. ATAR seems to be cost effective (1 channel) and smaller, which is quite convenient for satisfying cross-polarization isolation (<20 dB). ATAR and ATSR provide full polarimetric measurements. However, many radar engineers prefer STSR for the large range of Doppler measurements and higher number of samples it provides.

III. COST AND TECHNOLOGY CONSIDERATIONS

T/R modules are sized to fit within the lattice of a phase array, which it is a function of frequency. Typically the spacing between modules is chosen to be around $0.5\lambda o$ for wide-antenna scanning beam performance (±45°). At X-band (10 GHz), C-band (5.4 GHz), and S-band (3 GHz), the spacing between modules is 1.5 cm, 2.5 cm, and 5 cm, respectively. For S-band the lattice array size can contain modules using COTS components based on the architectures illustrated in Figure 2. For higher frequencies, such as C- and X-band, the limited space requires high integration at the IC level or adopting a brick module architecture. Brick modules are a very common architecture in military radars. They are placed vertically to the antenna aperture, not having any constraint with the antenna unit size. In phased array radars the cost of T/R modules is between 50% and 60% of the overall cost of the antenna array panel. The T/R modules cost can vary as a function of frequency, polarization mode, technology, functionality, and production volume. Short wavelength radars (C- and X-bands for example) require a more compact design that demands high component integration and low power consumption modules with acceptable RF performance level. The cost of CASA X-Band T/R modules based on COTS components is $567 for 100 units, which can be reduced to $341 if large quantities (>1000 units) are produced [11], [13]. Similarly the cost of a C-band ATSR T/R module based on COTS components is $399, which can be reduced to $188 for a production volume of 10,000 units [6].

The fast evolution of technology, especially in CMOS, SiGe, and GaN, has enabled the integration of most of the components of T/R modules (Figure 2) into one or two small chip commonly called core chips (CCs) or multicore chips (MCCs) and front-end chips (FECs). Small chips (<10 mm^2) enable the possibility of integrating the electronics in the back of the antenna and reduce the cost of the phased array antenna system. Currently, ATAR multi-core chip modules in X-band can be found on the market for $70-$100 per unit for a production volume of 10,000 units. Adding the cost for the high power amplifier, LNA, and switches, the overall cost per T/R module can be between $100 to $180 per unit. Polarization and functionality can also increase the cost of the system. Based on current COTS components, a C-band ATSR T/R module is 30% more expensive than an ATAR due to the two additional channels required. In section IV more detailed information about the performance of T/R modules is discussed. Two ATAR brick modules for X- and C- band and one X-band T/R module in tile architecture are presented.

Figure 2a-b illustrates the brick modules developed in CASA for one-dimensional scanning active array and for NCAR Airborne Phased Array Radar (APAR) based on COTS components. Brick modules in general provide excellent RF performance, considering the large area available for distributing the component for high RF and thermal isolation. A drawback of brick modules involves the size, weight, cost, mechanical design complexity, and intensive labor required for integration and testing. Figure 2c shows the high integration

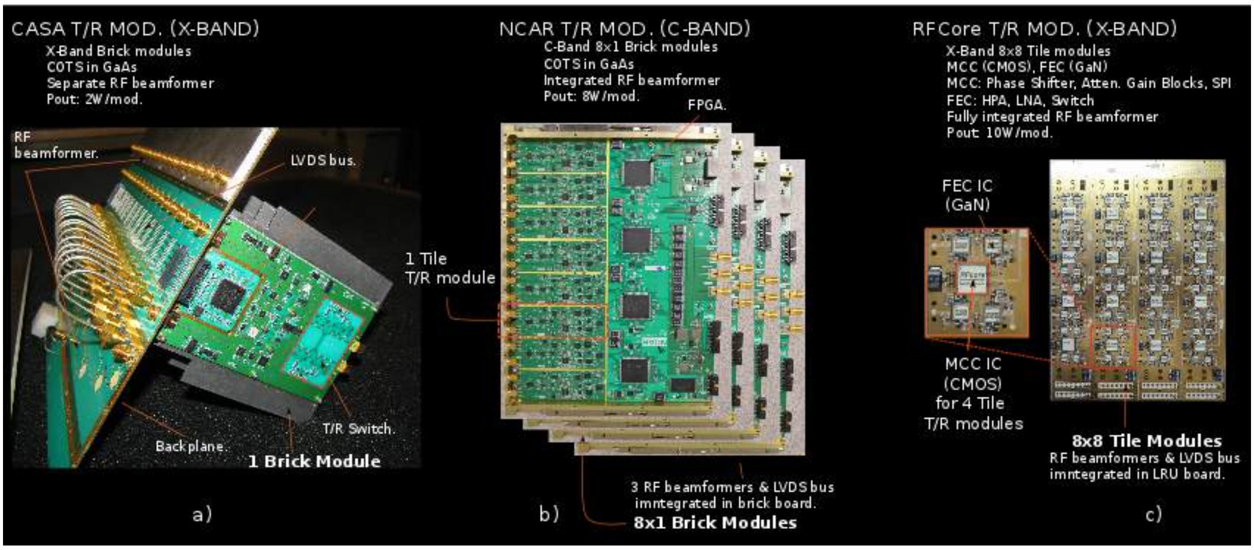

Figure 2. T/R modules for weather phased array radars. a) CASA low power ATAR brick module based on COTS components. b) NCAR Airborne Phased Array Radar ATAR 8x1 brick module based on COTS components. c) RFcore 8x8 X-band CMOS and GaN tile module.

modules in a single chip in a tile configuration. Brick modules typically make use of connector and cables with the antenna and other subsystems.

IV. T/R MODULE DVELOPMENTS

A. *X-band brick T/R module*

The NSF CASA Engineering Research Center at the University of Massachusetts developed an X-band 1-D e-scanning phased array antenna composed of 72 x 32 elements where the 64 elements in azimuth plane were excited by ATAR T/R modules [11], [13]. ATAR modules reduce the number of control components per channel and provide a better dynamic range compared with other architectures. 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 transmit channel is designed to have a net gain of about 30 dB 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. The receive channel is designed to have a net gain of approximately 29 dB and a noise figure of 4.3 dB. Both channels use a 6-bit 32 dB digital attenuator with attenuation steps of 0.5 dB and a 6-bit digital phase shifter that provides 360° phase coverage with a phase shift step of 5.625°. A custom-designed diversity switch uses a star configuration of four single-pole single-throw (SPST) switches. Each pole is independently controlled by a bipolar control. 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.

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 to the specifications of the components.

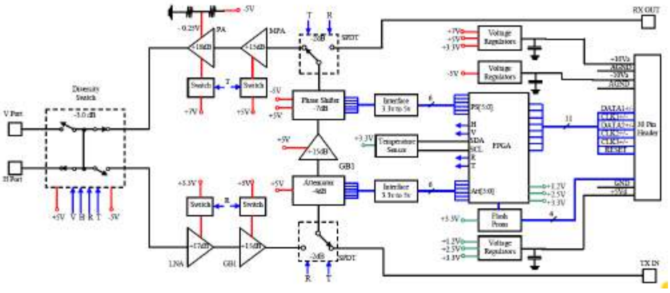

Figure 3. Schematic diagram of ATAR CASA X-band T/R module.

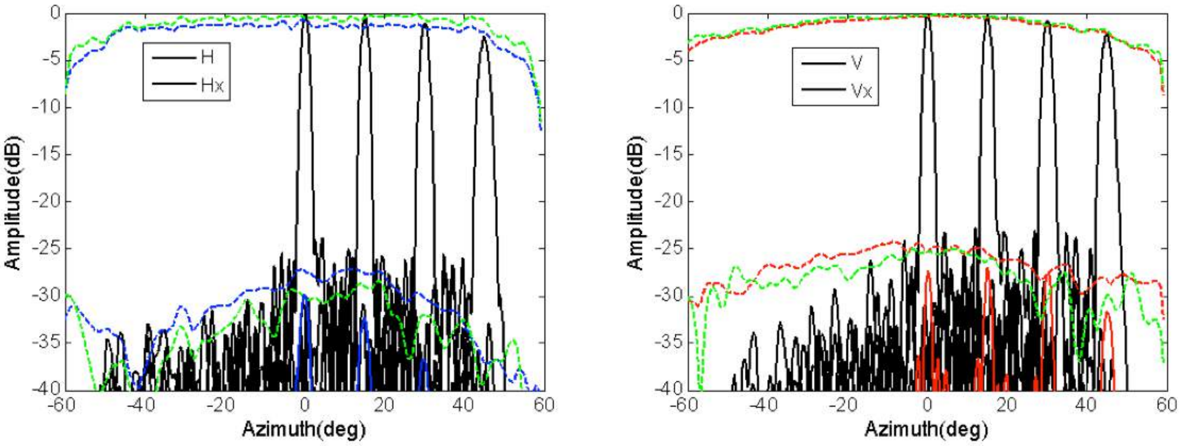

Figure 4. Measured scanned antenna patterns in azimuth plane overlapped with embedded element pattern of column 32 and also with average element pattern for H and V polarization. About 64 ATAR calibrated T/R modules were used.

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. 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. The onboard 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. 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. Figure 5 shows a picture of the front end and back end of the CASA X-band dual-polarized phased array antenna using the ATAR T/R modules.

Antenna measured patterns for scanning positions 0°, 15°; 30° and 45° were taken in reception mode, and for both polarizations were calibrated for an amplitude taper distribution that corresponds to Taylor -25 dB for n=4. Figure 4 shows the measured (co-polar and cross-polar) patterns normalized to broadside beam for H and V polarizations. The first sidelobe levels for both polarizations are below -25 dB, except at 15° and 30° in V polarization, where the first sidelobe levels are 1.8 dB higher (-23.2 dB). The sidelobe roll-off for H and V decrease from the main beam, indicating small errors in the excitation of the array elements. The cross-polarization levels corresponding to each beam position are below -30 dB for H polarization and below -27 dB for V polarization.

B. C-band brick T/R module

The Earth Observing Laboratory (EOL) of the National Center for Atmospheric Research (NCAR) is conducting a two-year project to develop a small prototype array that will be used as proof of concept for the future airborne phased array radar (APAR). This project consists of developing one line replacement unit (LRU) of the 224 LRUs required for the full four-aperture APAR system [6]. The LRU architecture was originally conceived to be in a tile configuration in order to meet the low-profile requirement of APAR. Given the available funding and tight schedule, it was decided to adopt a brick configuration for the prototype LRU. In this way, the previously tested aperture could be combined with a transmit and receive module consisting of commercial components to provide a fully functional LRU.

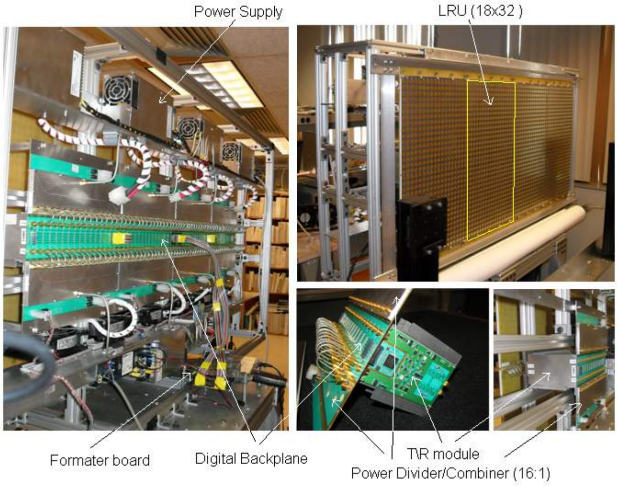

Figure 5. Picture of the front end and back end of the CASA X-band dual-polarized phased array antenna.

The proposed T/R module architecture will operate in alternate transmit, alternate receive (ATAR) polarization mode. A block diagram for the proposed Brick T/R module is shown in Figure 6. The module contains eight transmit/receive (T/R) modules providing eight pairs of bidirectional ports that can be connected to individual dual polarized antennas. Two independent RF distribution networks (an 8-way power divider and an 8-way power combiner) split and combine the RF signals to and from the T/R modules, respectively, allowing the implementation of analog beamforming in the phased array. The common ports from these networks are interconnected to external RF ports (TX RF and RX RF), which can be connected to external beamforming networks to form a 2-D phased array unit. Four FPGAs having two digital controllers each provide the control signals needed by the T/R module functionalities. Digital controllers are controlled by means of serial commands and two-level signals that are sent from an external controller. These signals are communicated to the controller through serial communication buses that are implemented in a backplane system. A flash PROM provides the configuration data to the four FPGAs when the module is powered up. The voltages to the RF components and the digital components have external power supplies and internal voltage regulators. Power planes implemented in a multilayer PCB distribute the different internal voltages to the components.

In addition to the main functions, the module includes a built-in test system that allows measuring the individual characteristics of each T/R module. The system can be used for two purposes: for monitoring the T/R module health and for calibration of the T/R modules. Transmit and receive transfer functions of individual T/R modules are obtained by injecting calibration signals with a calibration distribution network and couplers at the T/R module antenna ports. Both channels share a common control circuitry for the RF signal, allowing the design to reduce the number of control components with respect to other architectures. The common control circuitry includes a 6-bit attenuator (ATT), a gain block (GB1), a 6-bit phased shifter (PS), and two T/R switches (SW1 and SW2). The transmit channel also has a medium power amplifier (MPA) and a power amplifier (PA), while the receive channel has a low noise amplifier (LNA) and gain block (GB2). Three MOSFET switches (DSRs) control the pulsed drain current needed for each amplifier during their portion of the pulse repetition time.

The pulsed current maximizes the module efficiently while minimizing the possibility of oscillation caused by feedback in the T/R closed loop. A high-power switch (SW3) that provides transmit and receive diversity to the module completes the RF hardware design. Since the module uses transmit/receive and polarization switches, the radar operation is limited to alternate transmit and alternating polarization mode. In addition to transmit and receive channels, there is an FPGA that provides the control signals to the attenuator, phase shifter, T/R switches, polarization switch, and drain current switches. The FPGA serves to interface the module to the array controller, translating beam steering commands (or amplitude and phase settings) to parallel signals that can be interpreted by the module.

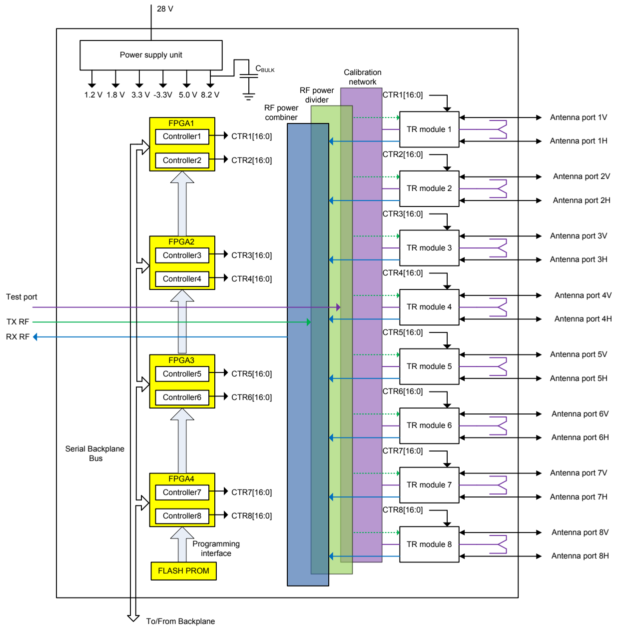

Figure 6. Block diagram of the brick module composed of 8x1 ATAR T/R modules based on COTS components.

Figure 7. Picture of a brick module composed by 8x1 ATAR T/R modules based on COTS components.

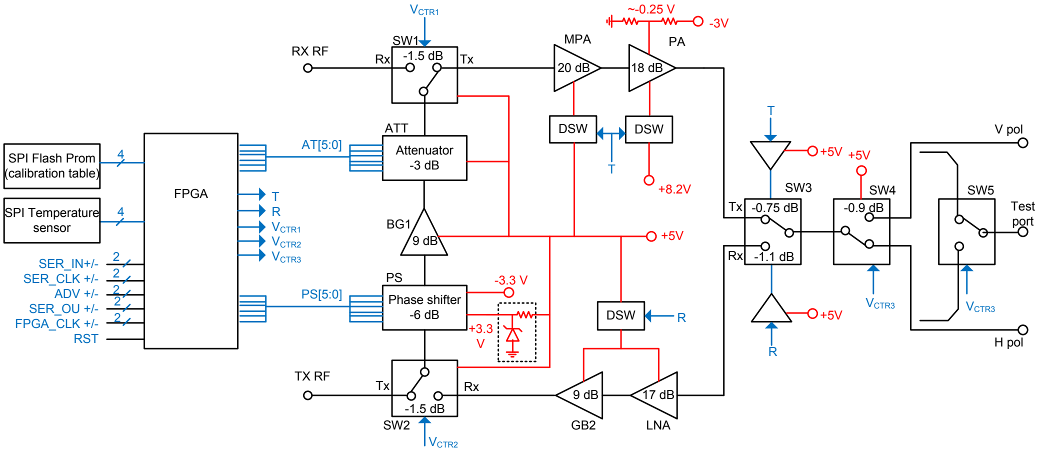

Figure 8. NCAR functional block diagram for ATAR T/R module.

To minimize the cross-polarization degradation of the dual-polarized antenna designed by NCAR, the polarization switch must have high isolation between the diversity ports. It is known that the cross-polarization of isolated antennas can be affected when their terminals are connected to a single pole double throw switch (SPDT);. In particular, the switched antenna obtained from the connection of a dual-polarized antenna having 25 dB isolated cross-polarization and a SPDT switch having 45 dB of isolation will have a cross-polarization level of 24 dB, which is equivalent to 1 dB of cross-polarization degradation.

Among all available commercial high-power switches, the Peregrine Semiconductor's PE42423 is the only switch that can provide an isolation greater than 40 dB in the desired frequencies range. This component was chosen to implement the polarization switch (SW4). It has 43 dB of isolation and 0.9 dB insertion loss at 5.4 GHz. A disadvantage of the component is that the maximum input power of this device is limited to 37.3 dB. The T/R switch is implemented with the MACOM's MASW-007921.

Although this switch provides less isolation than Peregrine Semiconductor's PE42423, it can handle more input power. Isolation is about 35 dB and the maximum input power is 40 dBm when the control voltage is 5 V, while it has an insertion loss of 1.1 dB at 5.4 GHz. Because switches SW3 and SW4 have a net insertion loss of 2 dB and the required transmit power for the module is 36 dBm (4 Watts), the power amplifier (PA) must provide at least 38 dBm (6 Watts) of peak power. A component that satisfies this condition is MACOM's MAAP-011027. This power amplifier provides 18 dB of compressed gain and 39 dBm (8 Watts) of saturated power amplifier over the bandwidth when a drain voltage of 9 V is used. Alternatively, it can provide 38 dBm of saturated power if the drain voltage is adjusted to 8.2 V. At this voltage, the PA has specified a power-added efficiency of 37%.

The medium power amplifier (MPA) drives the power amplifier. The criterion used in choosing this component is that 1 dB compression point at the output should be greater than 20 dBm, which is the minimum input power to operate the PA under compression. From an extensive list of products, the Hittite's HMC415LP3E was chosen. It has a gain of 20 dB and 1 dB compression point of 22 dBm. For the low-noise amplifier (LNA) the requirement is a noise figure less than 1.5 dB. Among all low-noise amplifiers available, the Hittite's HMC717LP3 was chosen because it requires minimal external matching and bias decoupling components. This amplifier has a noise figure of 1.2 dB, a gain of 17 dB, and single supply voltage of 5 V. The digital attenuator (ATT) must provide 6 bits of resolution and 31.5 dB of gain control. The Hittite's HMC624LP4E satisfies these requirements. Its dual-control interface allows this component to accept serial and 6-bit parallel control. The HMC624LP4E can be biased with +3 V supplies, which is suitable for control. The control interface is compatible with standard LVTTL level outputs generated from a FPGA.

TABLE I. PERFORMANCE COMPARISON OF THE X-BAND CORE CHIPS.

	[15]	[16]	[17]	[18]	[19]-[20]
Technology	GaAs	GaAs	SiGe 0.25 um	SiGe 0.25 um	CMOS 0.13 um
Operation frequency (GHz)	8.5-11	8-12	8-11	8-11	9-10
Phase shift range/step (°)	360/5.6	360/5.6	360/11.2	360/11.2	360/5.6
Attenuation range/step (dB)	31/1	24.7/0.4	31/1	31/1	31/1
Tx/Rx gain (dB)	22/22	8/8	17/17	30/20	12/9[a]
RMS phase error (°)	1.5	5 @ 10 GHz	6	6	2.3
RMS attenuation error (dB)	0.3	0.3 @ 10GHz	2	1.5	0.4
Output P1dB in TX mode (dB)	21	13	12	18	11[b]
Power Consumption (W)	2.1	0.8	0.8	1.5	0.8/channel[c]
Negative supply	O	O	X	X	X
Number of channels	1	1	1	1	4
Chip Size (mm^2)	5.0 x 4.0 (20/channel)	4.4 x 4.2 (18.5/channel)	3.8 x 4.1 (15.6/channel)	3.5 x 2.4 (8.4/channel)	6.9 x 1.6 (2.8/channel)

[a] Insertion losses of a 4-way power combiner is included.

[b] This work is based on bi-directional topology as in Fig. 2 while the others are Tx/Rx separated as in Fig.1. Insertion loss of a SPDT switch is included.

[c] Additional power consumption due to the LDO voltage drop is included.

The digital phased shifter (PS) must provide 6-bit of resolution and 360° of phase control. Among all commercial phase shifters available, MACOM's MAPS-010165 was chosen. The reasons for choosing this component are its relatively low cost compared to other phase shifters and that it accepts a +3.3 V control signal from the FPGA. In contrast, other available phase shifters request negative control signals to set the insertion phase, requiring the use of external interfaces to make the control compatible with the output levels from digital components. The MAPS-010165 is a device that accepts serial and 6-bit parallel controls. The RMS phase error is 4° and RMS attenuation error is 0.4 dB. These amplifiers have been chosen to maximize the linear dynamic range of the receive channel. The maximum input power accepted by the gain block GB1 imposes a restriction on the maximum input power that can be applied at the input of the receive channel. This value and the noise floor define the dynamic range of the receive channel. The MGA-82563 has a gain of 9 dB and maximum input power of 13 dB. The T/R switches (SW1 and SW2), as well as the calibration SW3, must be designed with high isolation SPDT absorptive switches, having an internal 50 Ohms resistor that can match the impedance of RF beamforming networks. The SKY13286-359LF designed by Skyworks satisfies these requirements. With an isolation of 45 dB and insertion loss of 1.5 dB, this component is ideal for the brick T/R module.

C. X-band tile T/R module

T/R modules are key components in the radar system that represents a significant portion of the overall cost. Therefore, cost and size reduction of a T/R module is one of main issues for the next-generation phased array system. Currently, core chips based on GaAs pHEMT are commercially available in the market [15], [16]. GaAs provides excellent RF performance; RMS phased errors, and gain and transmit power are better than other developments in SiGe [17], [18] and CMOS [19], [20]. For ATAR, GaAs core chips are two times bigger than SiGe 0.25 um and almost seven times bigger than CMOS 0.13 um. Power consumption in GaAs is about 3 times higher that SiGe 0.25 um and CMOS 0.13 um. Table 2 presents a more detailed comparison of the performance of core chips available in GaAs pHEMT, SiGe 0.25 um, and CMOS 0.13 um. It seems that the fast progress in silicon core chips become promising with lower cost, acceptable RF performance, and higher integration levels. Another advantage of silicon-based core chips is the fact that digital and analog components can be easily integrated in a single core chip. In terms of cost, a GaAs core chip price is around $120 to $140 for a QFN single-channel chip core for a volume of 10,000. However SiGe and CMOS can offer an attractive cost not higher than $45 apiece for the same volume.

Figure 9 presents a picture of MCC IC and a block diagram of the T/R modules for GaAs, SiGe 0.25 um and CMOS 0.13 um [15]-[20]. RFcore shows an impressive reduction in chip size and cost using CMOS 0.13 um. Four bi-directional topologies present an important advantage over GaAs and SiGe. This new features enables the implementation of an STSR /R module for higher-frequency phased array antennas. The drawback of the bi-directional topology is additional SPDT switches and reduced core chip output power. However, the switch losses can be compensated for in the front-end chip (FEC). The four-channel core chip consists of a 6-bit phase shifter, 5-bit step attenuator, BDGB, and BDA in each channel. The attenuation coverage is 31, the LSB is 1 dB, and the phase shift coverage is 360° with an LSB of 5.625°. Detailed circuit topology and measurement results of phase shifters, step attenuators and BDGB are presented in our previous publication [7] for a single channel core chip.

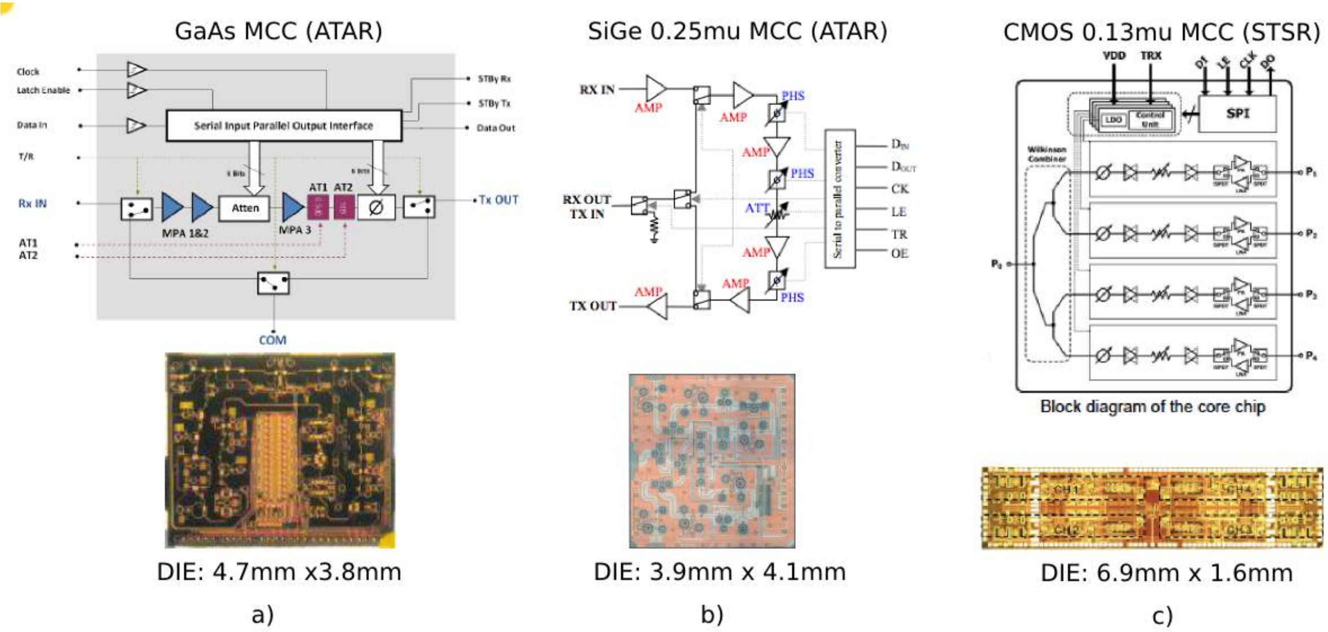

Figure 9. Block diagrams and multi-core-chips for a) GaAs, b) SiGe 0.15 um and c) CMOS 0.13 um

I. CONCLUSIONS

Current technology enables the development of active phased array radars for civil application. The cost and module performance levels that have been achieved demonstrate the possibility of developing active phased array antennas for dual-polarized radar systems for atmospheric applications. Phased array antennas can make a significant contribution to remote sensing research. Extremely fast scanning updates and dual-polarization capabilities can significantly impact the study of atmospheric events. During the past five years the use of T/R modules for active phased array antennas for civil application shows the cost and complexity of modules for different polarization modes can be feasible. The big obstacles of cost and integration are not issues anymore. Current technology offers affordable cost and small size modules that can be integrated in tile array architectures. Three types of T/R modules developed and presented in this paper show the evolution and trend of T/R module technology for civil applications.

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