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Evolutionary Trends in Transmit/Receive Module for Active Phased Array Radars

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ABSTRACT

Worldwide, defense technologies are rapidly evolving and are currently aiming at integrating diverse functionalities like radar, electronic warfare, communications, on a singular miniaturised platform. Hence, it cannot be denied that the advancements in modern active phased array radar technologies assume a critical role towards the achievement of this goal. A typical active phased array radar comprises of an active antenna array unit (AAAU) consisting of a large number of radiating elements, transmit/receive (T/R) modules with other associated RF and digital circuitry and power electronics. This paper presents mainly the developments in transmit/receive (T/R) module technology, which assimilates various stages of the technological evolution - past, current and futuristic. It discusses how these technologies contribute towards the improvement of efficiency, miniaturisation and reliability without compromising its performance parameters.

Keywords: Active phased array; LTCC; GaAs; LDMOS; GaN; 3D T/R module

1. INTRODUCTION

Over the past few decades, transmit/receive (T/R) modules have undergone significant changes both functionally and technically in semiconductor, device, interconnect, substrate, digital control/interlock circuits and packaging technologies. Subsequently, these technological advancements have made modern active array radars to achieve higher power aperture products, faster target update rates and lower side lobe levels. Semiconductor-based amplifiers in principle can offer a more effective solution and semiconductor transistors have been limited recently in the DC voltage that can be applied to the device by the inherent critical breakdown field that the material can sustain[3]. This paper explores the existing technologies (in-vogue and R&D stage) to identify futuristic trends in T/R modules for active phased array radars.

1.1 T/R Modules

T/R modules form the basic building blocks of any modern active phased array radar. A typical T/R module usually consists of a transmit chain, receive chain, digital controller and a power supply block. Collectively, they perform the following functions.

- Power amplification during transmission with maximised efficiency.
- Phase shift and attenuation control
- Low noise amplification during receive.
- Transmit/receive switching.
- Discrete control and status monitoring.
- Establishing communication with beam steering network and facilitating proper supply voltages

A T/R module is a multichip assembly of solid state device based sub-system which is interfaced to radiating elements of an active phased array antenna. The typical block diagram of a T/R module is as shown in Fig. 1.

1.1.1 Transmit Chain

A pulsed RF signal is applied to the module in the transmit mode. This signal undergoes phase shift in a digital phase shifter and gets amplified by a series of amplifiers in the transmit chain and then interfaced to the radiating element of the array through a duplexer.

Table 1. Typical frequency bands and their power outputs

Frequency band	Typical peak O/p power (W)	Application
L-band	250	Long range surveillance radar
S-band	100	Medium range surveillance and tracking radar
C-band	30	Tracking radar and missile guidance
X-band	10	Tracking, fire control and multirole combat radar
Ku- band	2	Missile seekers
K- band	1	Automotive/highway radars

1.1.2 Receive Chain

In the receive mode, return echo signals are routed through a duplexer, receiver protector and a low noise amplifier, which

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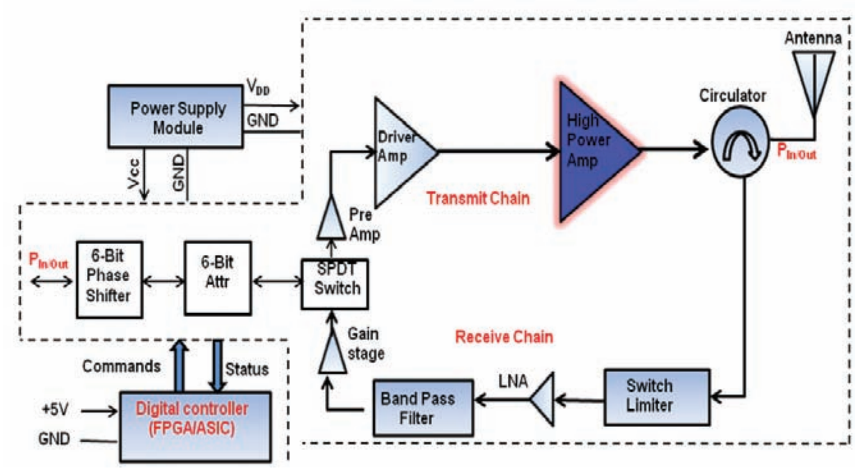

Figure 1. Typical block diagram of T/R module[14].

establishes the system noise figure. The amplified signal is then controlled by a digital attenuator and a digital phase shifter. This signal is then interfaced to the array manifold. The amplitude weighting is usually employed for synthesising low side-lobes in receive mode of the array. The phase shifter, on the other hand, is employed to steer the beam electronically in both transmit and receive modes. SPDT T/R Switch is employed to switch between receive and transmit paths during transmit mode and receive modes respectively. The Radar extended pulse time is utilised in changing the Tx/Rx phase values and in switching the channel select T/R switches. Receive chain is characterised for important parameters like noise figure, gain, return loss at input/output and rejections at out-of-band frequencies[23].

A common control logic circuitry serves as an interface between the module and the array controller provides beam steering, side-lobe level control and timing signals as needed by the T/R Module.

1.1.3 *Digital Controller and Power Conditioning Blocks*

Generally, TRM controllers are implemented using various microcontrollers/ programmable logic devices like field programmable gate arrays (FPGA) or an application specific integrated circuits (ASIC). The main functionality of this TRM controller is to receive (over full duplex differential serial lines) command and control data from a high level controller, called array controller, and configure the TRM as per the commands. These controllers also monitor the Status/Health of the T/R modules[24]. In addition, they provide the following controls:

- Digital phase shift up to 6 bit
- Digital attenuation up to 6 bit
- Receiver protection control
- VDD Pulse control of pre-driver and final stage amplifiers
- Monitors health and temperature of the modules and automatically switch off under any abnormal conditions.

A power conditioning block generates the necessary power supplies required for both the RF and Digital components. This block is generally a combination of DC-DC converters, low voltage regulators and other components like EMI filters and Fuses. The four main blocks are listed below.

i) Power supply – To generate the required supply for TRMs. The power supply module consists of DC-DC converts and generates the required DC voltages for the RF and digital modules of TRM.

ii) Status monitoring – To monitor the supply voltages and temperature of the module.

iii) Digital interface – Serial differential interface from external environment.

iv) Logic control/decoding – To control the output voltage to Transmitter / Receiver and decoding as per the received command. Modules based on T/R pulse and other control logics.

New concepts such as “tile TRMs” are being developed, where the module footprint has to be compliant with the radiating element dimensions for a wideband (6-18GHz)[1] antenna. RF MEMS attenuators, limiters, (true-time-delay) phase shifters, T/R switches and tuneable matching networks can be used within an active electronically scanned arrays (AESA) radar[5].

Low frequency TRMs are generally larger and bulky than higher frequency TRMs owing to the increased values of reactive components and higher power levels. To this end, S-band T/R modules can provide higher loading for an equivalent number of T/R modules[15].

2. T/R MODULE ARCHITECTURES

Radars are deployed in different applications viz, automotive, defence and weather radar. Each of these application requires different features and specifications. This may vary depending on the air, land or sea platform requirements. Hence, a common architecture may not work out for all these Radars. The architecture of T/R modules can be categorised based on manufacturing, technology and frequency.

This section presents the commonly used architectures in the design and development of T/R modules based on the different RF components and their distribution in the module

Based on the distribution of the RF Components – Isolated architecture, common leg architecture and shared (phase shifter, amplifier and attenuator) architectures as depicted in Figs. 2(a) and 2(b), respectively[14].

The isolated architecture is one of the earliest architectures which employ separate phase shifter and attenuator for each Tx and Rx channel. The isolated architecture provides the best performance, but with increased complexity and system cost.

The common leg architecture is the most popular and finds use in the most modern phased array radars. The common-leg approach provides increased level of integration and lowered system cost.

Receive Modules: The receive modules can be used where both Tx and Rx aperture are different. These can be used in multi-static radars, phased array radars and sub array level radars.

Transmit Modules: The transmit modules can also been used where both Tx and Rx aperture are different. Such individual T-module and R- modules will be best suited for

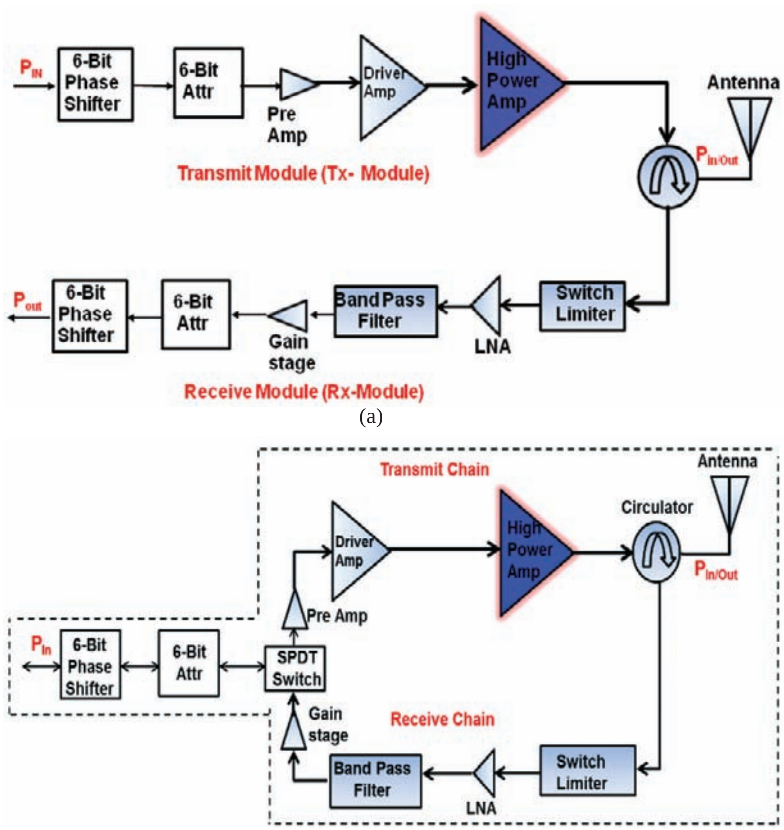

Figure 2. (a) Isolated architecture[14] and (b) Common leg architecture[14].

Bi-static radars. The taxonomy of T/R modules is shown in Fig. 3.

2.1 Typical Specifications of S-band T/R Modules

The evolution of T/R modules can be loosely grouped into three to four generations depending on the combination of semiconductor technology and the device configuration employed. Here, in Table 2, we present a summary of the evolution of S-band T/R module over the course of three generations. Evidently, all three TRMs were using different device (power amplifier) configurations.

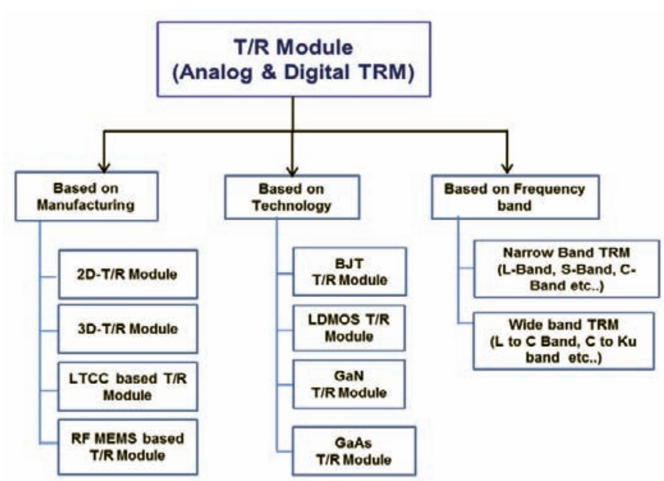

Figure 3. Taxonomy of T/R module.

3. EVOLUTIONARY TRENDS IN T/R MODULES TECHNOLOGY

RF Transistor technology has evolved in leaps and bounds over the past few decades. From the first generation silicon bipolar junction transistors (Si BJT), to laterally diffused metal oxide semiconductor (LDMOS) and eventually overtaken by the advancements in Gallium Arsenide (GaAs) and Gallium Nitride (GaN).

The RF power transistor is the most critical component of the TR module. It dictates the important parameters like output power, efficiency, cost of the T/R module. Therefore, T/R module technology is centred on the selection of suitable technology of power transistor. This is based on parameters like cut-off frequency, wafer yields, power density, efficiency, high power output, bandwidth high operating voltage handling etc.

Si BJT technology is limited to lower duty cycle applications (Max 10 per cent). The LDMOS devices were designed to handle these limitations and could support up to 20 per cent duty cycle. However, the cut off frequencies of these devices were typically limited to around 4 GHz. With the advent of MMICs GaAs proved an immense success in 1990s and found widespread use in radar and communication applications. GaAs HEMTs with its inherent advantages offered high performance and was a perfect solution for TR modules. The wide band gap technology in combination with high electron mobility helped build HEMT structures with 2-dimensional electron gas channel formation. In addition, GaAs offers great bandwidth with its cut-off frequency around 250 GHz. However, limitations on operating voltage handling (max. 12V) and poor thermal performance left room for another alternative in the radar technology space.

A set of GaN MMIC PAs, switches and LNAs have outstanding potential and effective feasibility of T/R modules[7]. GaN with advantages like wide band gap, Higher power density,

Table 2. Typical functional specifications of TRM (Sourced from LRDE Bengaluru, India)

Parameters of TRM	S-Band TRM Specifications		
	1st Gen	2nd Gen	3rd Gen
Power amplifier technology	Si BJT	Si LDMOS	GaN HEMT
Transmit O/p power	100 W(min)		
Max pulse width	100 µs	200 µs	200 µs
Duty cycle	10 %(max)	20 %(max)	2 0%(max)
Power droop	0.8 dB(max)	0.6 dB (Max.)	0.6dB (Max.)
Pulse rise/fall time	200 ns	100 ns	100 ns
Receive chain gain	30 dB ± 2 dB		
Rx noise figure	3.5 dB(max)		
Digital phase shifter	6 Bit, LSB ≤ 5.625º, rms phase error < 4º		
Digital attenuator	6 Bit, Range 0-31.5 dB, rms attenuation error is ± 0.5 dB		
Efficiency	Approx. 25 %	Approx. 37 %	Approx. 43 %

increased power added efficiency (PAE), and high breakdown voltages proved a perfect alternative. GaN addressed the two main shortcomings of GaAs viz, low breakdown and poor thermal dissipation. GaN has better electrical/physical properties and can operate at higher operating voltages (greater than 65 V). With these properties GaN facilitates Low cooling load, significant performance advantages in broadband applications.

3.1 Comparison of Various Technologies

For transmitter, GaN HEMT devices provide a very high ratio of peak current to output capacitance, as well as an extremely high breakdown voltage and power density capability. This unique combination of characteristics helps achieve higher overall amplifier performance compared to competing devices[3].

Significant changes in RF power transistors have been particularly visible in high power outputs and above 1GHz frequency. Process node technology also miniaturised from 15 μm to 0.25 μm indicative of its effect on bandwidth and gains.

Table 3. Semiconductor power amplifier technology comparison

Parameters	Si-BJT	LDMOS	GaN
Max operating frequency	Up to C-band	Up to S-band	Up to X-band
Operating Voltage (V)	36-40	28-36	50-65
Gain (dB)	10	11	12.5
Efficiency (%)	45	40	53
Pulse width	500 μs	1 ms	1 ms
Duty cycle (%)	10	20	CW
Max power output (W)	118-150	200	10W to 1kW
Breakdown voltage(V)	65	60	175
Power density (W/mm^2)	1	1.89	5-7
Thermal conductivity (W/0K/ mm^2)	Moderate	Moderate	390
Current density (A/mm)	<1	<1	1.2
Class of operation	C	AB	AB
Ruggedness (Output VSWR)	10:1	5:1	10:1

(Courtesy: M/s. M/A-Com Tech. and M/s. CREE Inc.).

Although GaN apparently is the clear favourite among the available technologies as presented above - Wafer processing cost and wafer management are on the higher side[15]. Further in wideband gap semiconductors, scaling small periphery devices to higher power levels adds to design complexities. Higher power densities can be achieved for large periphery devices, 50 W - 100 W wide band gap MMICs appear entirely feasible[16].

4. TRENDS IN MANUFACTURING OF T/R MODULE

As the revolution in the manufacturing technology, various trends in T/R module have evolved such as: 3-Dimensional T/R modules, RF micro-electro mechanical system based T/R module and LTCC based modules.

4.1 The 3-Dimensional T/R Modules

The 3D T/R Modules employ multilayer substrates and complex interconnection technologies[4]. The design involves high level integration of MMIC on multilayer substrate using efficient internal, external interconnects ensuring proper thermal handling[4] as shown in Fig. 4.

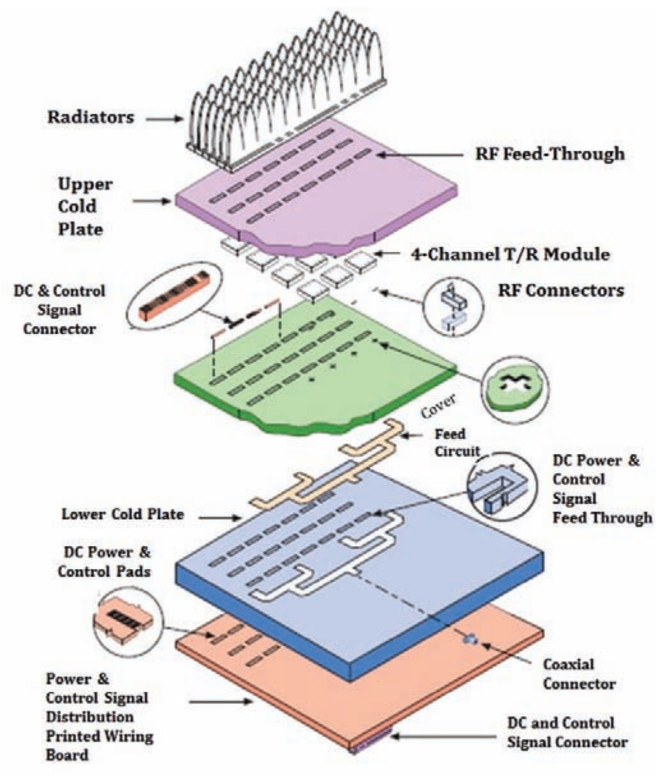

Figure 4. 3D TRM on a Multilayer substrate[4].

4.1.1 Based on Form Factor of the TRM

Transversally integrated and longitudinally assembled (TILA) or Tile architecture and longitudinally integrated and transversally assembled (LITA) or the brick architectures are available.

Brick architectures are the most popular, however, the tile architectures offer greater advantages in conformal arrays. Owing to its shape, it aids in easy 3D integration with the radiating elements. 3D TRMs are just Tile structures aimed at equipping multifunction phased arrays and shared apertures, designed for airborne equipment in a constrained and dense environment[13]. It involves:

- High level integration in manufacturing technology
- The concept of 3D TRM will be evaluated with theoretical analysis models; to demonstrate the close correlation between theoretical, simulation and practical results.

This kind of architecture is best suited for Airborne AESA radars, which leads to reduction of radar weight, volume thus leading to better utilisation of cooling system. There is continuous work towards integration of an increasing number of components in one single integrated circuit called T/R module on chip[18].

4.2 RF Micro-Electro Mechanical System based T/R Module

The Module is based on RF micro-electro mechanical system (RF MEMS) based switches, phase shifter, attenuator. RF MEMS switches exhibit very low insertion loss with multi-octave performance[17]. The conceptualised block diagram of RF MEMS based T/R module[11] is as shown in Fig. 5.

Using RF MEMS it is possible to obtain reconfigurable wide band T/R Module and ultra-wide band antennas for multi-user applications[12]. But the reliability of RF MEMS is a study under progress. The switching speed of most RF MEMS switches is 2-40 µs, due to the mechanical nature. Also due to less On/Off cycles, endurance of RF MEMS devices are not popular in the continuous operation of Radars.

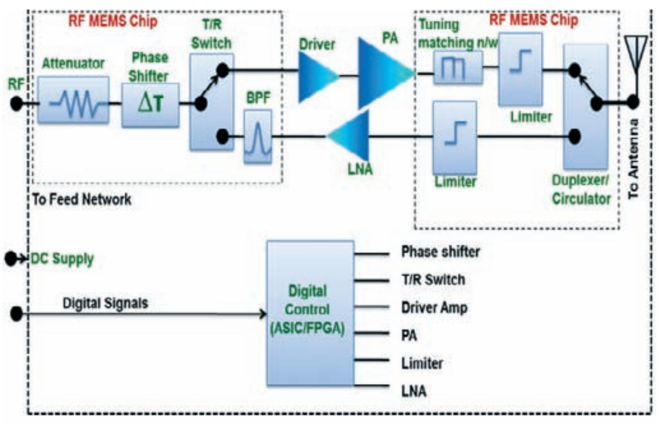

Figure 5. Conceptualised block diagram of RF MEMS T/R module[10].

4.3 LTCC based Modules

Low-temperature co-fired ceramics (LTCC) contributes to a dramatic reduction in size and weight of the T/R module[9]. Concerning the packaging, it offers different technological capabilities: thick film multilayer ceramic circuits, co-fired ceramics based on LTCC processes[2].

The surface-mounted packages on printed circuits boards, collective wiring technology for high density integration and 3D architectures[8]. Also, LTCC offers advantage of repeatability for mass production.

5. FUTURISTIC T/R MODULES

The main challenges are high dynamic range, large power-aperture and long distance sensitivity[19]. To achieve multi-functions digital T/R module will play a key role. Whereas wideband T/R module will be used for shared aperture and electronic warfare radars.

5.1 Digital T/R Module for Multifunction Radars

Digital T/R modules offer frequency agility and element level digital beam formation (DBF). These are basically adaptive beams. A digital transmit module is based on direct digital synthesis technology where the phase and amplitude of each module can be adjusted by a digital technique[6].

Development of digital T/R modules based on GaN power devices, photonic detectors and high speed ADC technology is currently underway. Signal distribution is a great challenge where RF over optical is being developed before the implementation of full digital TRMs and generalised digital beam former[8].

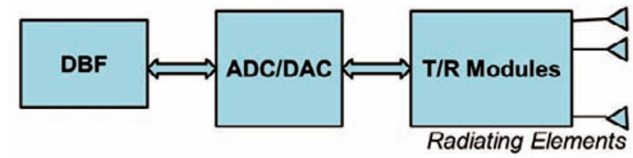

Figure 6. Basic block diagram of digital TRM.

The RF module consists of T/R modules and power distribution network for TX drive and LO. The digital module consists of high speed direct RF sampling ADC, a high end FPGA, power distribution network for ADC clock, photo detectors and associated circuitry. The Power supply module consists of DC-DC converts generates the required DC voltages for the RF and digital module. Digital Transmit/ Receive Module tree structure is shown in the following Fig. 7.

The digital module down converts the received RF input signal into IF/Baseband signal by using single stage super heterodyne down converter and appropriate filter circuitry. The TX drive and LO signals are fed from RF distribution network integrated as part of the RF module. The control and status signals interface shall be provided through digital module. The coupled Rx output from each of the receiver channel is routed to the front panel of Digital TRM.

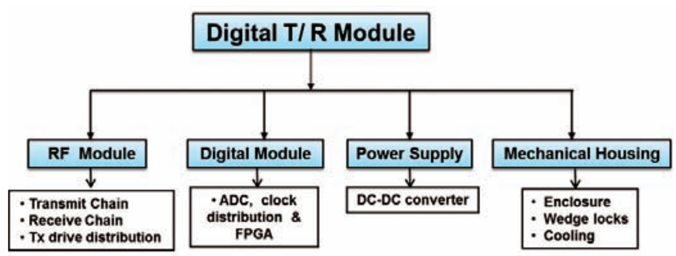

Figure 7. Tree diagram of Digital TRM

5.2 Wideband T/R Module for Shared Aperture and Electronic Warfare Radars

Wideband active phased array antennas would require primarily wideband radiating elements and T/R modules. Further, wideband performance of the T/R Modules is severely limited due to the frequency limitation of passive components such as circulators. Wideband here implies a bandwidth of more than 1-2 octaves. Industry has realised an ultra-wideband T/R Module operating from 10 GHz to 35 GHz for phased array applications[20]. These can be used in novel applications like the Shared Aperture for Radars.

A significant effort towards designing wideband passive components is a foot in the industry leading to feasibility of realising wideband T/R modules. The design approach for a dual polarisation X-Band T/R module and a wideband TRM multipack was described[25]. A wideband component improves thermal conductivity the high power per unit width translates into smaller devices also offer much higher impedance[21]. The Table 4. discussed how RFMEMS based components, will contribute towards the realisation of Modern T/R Module.

Table 4. Study of RFMEMS based components for T/R Module

Components/ devices used in the TRM	Existing technology	Comments based on RF MEMS literature	
Blanking switch	PIN Diode	Can be realised	Adv.: Lower insertion loss Disadv.: Lower power handling
Limiter protector	PIN Diode	Can be realised	Disadv.: Lower power handling
Band pass filter	Microstrip line	Can be realised	Adv.: Small form factor
T/R switch	GaAs MESFET	Can be realised	Adv.: Lower insertion loss Disadv.: Lower speed and lower power handling
Attenuator	GaAs digital MMIC	Doesn’t exist in practical, only on paper	-
Phase shifter	GaAs digital MMIC	Can be realisable (Better performance in Ku band & above)	Adv.: Lower insertion loss, Higher linearity, Lower noise figure and Very low or Ideally NO power consumption Disadv.: Reliability issue.
Digital controls	FPGA/ ASIC	In future FPGA/ASIC and MEMS can be on single Wafer (SOC-concept)	-
Power divider / combiner	Microstrip line	Can be realised	Adv.: Lower insertion loss Disadv.: Lower power handling

5.3 Optical Communication to/from T/R Modules

Fiber-optic links will provide for data transmission, phase and frequency references, and control signals for amplitude and phase tapering[22]. TRMs in phased arrays suffer from the need for large bulky RF feed cables. Optical T/R Modules are a novel way of eliminating the need for these cables.

These radars usually employ optical fiber networks to send and receive optical signals between the array and the TR Modules. Full optical network architecture is engaged right from the processing board up to T/R modules. The basic building blocks of the feed network are: optical sources with facilities for modulation (microwave-to optical converter), fiber optic links and optical detector (optical-to-microwave down converter)/receiver.

6. CONCLUSIONS

We have presented an overview of the evolutionary trends in transmit/receive modules for active phased array radars. These trends are particularly evident in semiconductor technology, manufacturing and packaging of T/R modules.

Past developments have mainly focused on Si BJT devices and LDMOS Transistors for realisation of T/R Modules. However, modern radars have moved well beyond these technologies, with the advent of compound semiconductor technologies viz., GaAs, SiGe, GaN and SiC. As a consequence, device structures saw several improvements with novel configurations like HEMT, MESFET and pHEMT. At packaging and substrate level - there are opportunities abound with evolving technologies like 3D TRM, LTCC and RF MEMS etc. Moreover, several breakthroughs are foreseen in near to midterm in nascent technologies like digital TRM and wideband TRMs.

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In the current study, he has surveyed semiconductor, manufacturing and packaging technologies for T/R modules design. He authored the manuscript and evolved futuristic modules for active phased array radars.

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In the current study, she has provided guidance in executing the results and reviewed the final manuscript preparation.

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