Chapter 2
Packaging of Transmit/Receive Modules

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2.1 Introduction to Packaging of Transmit/Receive Modules

Transmit/Receive (T/R) modules were initially developed as the key component in phased array radar systems, which allowed the antenna beam to be scanned electronically. This was an important innovation over mechanically scanned arrays since it improved reliability, decreased beam scan time, and allowed other functionality. T/R modules are now used or are planned for use in satellites, wireless backhaul communication, mobile phones, Wi-Fi, and 5G mobile communication systems. As a result, development of T/R modules is expanding and shows no signs of slowing. A key to successful T/R modules is the use of the correct electronic packaging.

This chapter is divided into two main parts. The first part briefly describes phased arrays, gives an example T/R module block diagram, and discusses the major components of T/R modules such as integrated circuits, antenna elements, circulators/switches, beam forming network, and cooling sub-system. The first part concludes with examples of how phased arrays can be used with T/R modules in cellular base stations, Wi-Fi indoor location systems, 60 GHz Wi-Fi, and millimeter-wave point-to-point systems.

The second part of the chapter describes three types of packaging for T/R modules. They are a brick module, a tile array module, and a panel array. The particular challenges of each are given along with the typical solutions employed. This chapter ends with a discussion of integrated circuit/wafer level packaging T/R modules and a summary and conclusions.

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K. Kuang, R. Sturdivant (eds.), *RF and Microwave Microelectronics Packaging II*,
DOI 10.1007/978-3-319-51697-4_2

2.1.1 Active Electronically Scanned Arrays

Active electronically scanned arrays (AESAs) scan their antenna beam electronically using phase shifters. This is illustrated in Fig. 2.1, which shows a simplified block diagram of a portion of an AESA. Note how phase shifters exist at each antenna element, which is generally true for most configurations. Normally, the phase shifter is implemented using an integrated circuit with digital control of the phase shifter, though it is possible to use analog control of the phase shift. Each phase state is independently controlled so that a continuous range of phase can be realized. For instance, an ideal block diagram of a 3-bit phase shifter is shown in Fig. 2.2. Note that the maximum phase state that can be achieved for a 3-bit phase shifter is

$$Max_{\text{Phase}} = 360° - LSB_{\text{Phase}} = 360° - 45° = 315°$$

Therefore, the range of phase is from 0° to 315° in 45° steps for a 3-bit phase shifter. This also means that an array constructed with 3-bit phase shifters will have eight distinct beam positions as the beam is electronically scanned. Though the phase shifter is an important component, it is only one of the parts required for T/R module functionality.

2.1.2 T/R Module Block Diagram

A simplified block diagram of a T/R module is shown in Fig. 2.3. Note how there is a circulator that connects the transmit and the receive signal paths to a common antenna. Some systems use a single-pole, double-throw switch for the antenna port connection. For the receive path the first component is the limiter. It is followed by

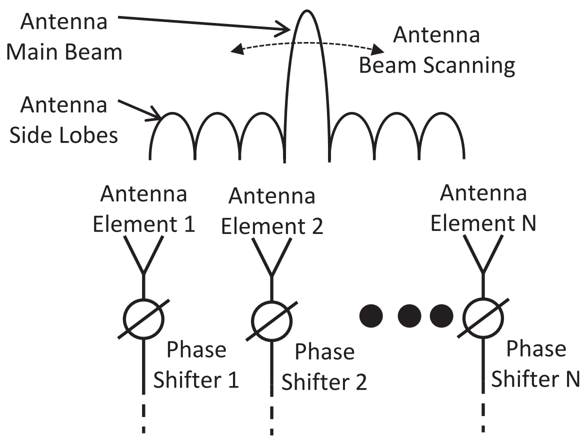

Fig. 2.1 A phased array has multiple antenna elements with independent phased control at each element in the array, which enables beam steering

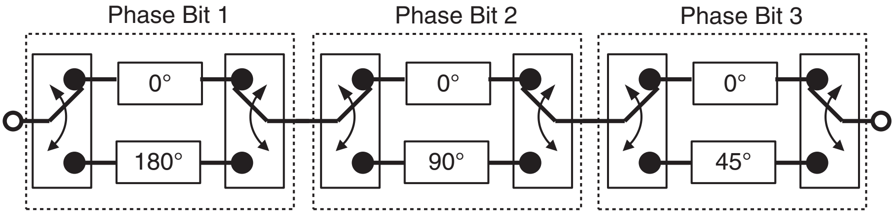

Fig. 2.2 Simplified block diagram of a 3-bit phase shifter using switches

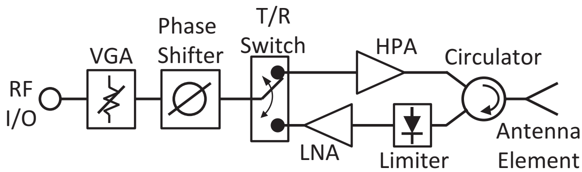

Fig. 2.3 Block diagram of a transmit receive module showing the major functional parts

the low-noise amplifier (LNA) which sets the noise figure of the receive path. This connects to an additional T/R switch that routes the receive signal to the phase shifter and variable gain amplifier and out the module input/output (I/O) port. On transmit, the signal enters the common port and is routed to phase shifter and variable gain amplifier. The T/R switch connects to the driver, which amplifies the signal to the level required by the high-power amplifier (HPA). Each of the components in the T/R modules is described in more detail in the following text.

High-Power Amplifier (HPA): It amplifies the transmit signal to the required output power. Communication systems operate the high-power amplifier in its linear range to minimize distortion of the signal. This typically means that the amplifier is operated below its compression point by 3–6 dB, and pre-distortion is often used to provide additional linearization. A good discussion of linear HPA operation can be found in [1]. Radar systems, on the other hand, often operate with the HPA fully saturated to achieve the highest RF output power possible.

Circulator: The circulator connects the transmit and receive portions together with the antenna. It is a non-reciprocal three-port device that allows one port to be RF electrically isolated from the other ports. Circulators are normally fabricated using ferrite substrates and magnets.

Low-Noise Amplifier (LNA): Amplifies the receive signal while adding minimal noise to the desired signal. The LNA is sensitive to input power and can actually be permanently damaged by a high signal level. The typical maximum input power is in the range of 0–25 dBm depending upon the design and semiconductor material used.

Limiter: The limiter is used to protect the LNA from permanent damage that can occur from signals that leak from the HPA or by signals that enter the antenna and travel past the circulator to the LNA. Limiters are typically fabricated using diodes such as PIN or Schottky. PIN diodes use an undoped intrinsic semiconductor between a p-type and an n-type doped region, which improves switching and limiting performance. As described in [2], PIN diode limiters can achieve fast limiting response and power clamping function.

T/R Switch: The T/R switch can exist in several locations in a T/R module. First, a T/R switch can be used instead of a circulator to provide connection of the transmit and receive function to the antenna. Second, a switch is often used in conjunction with a limiter to provide an additional level of protection for the LNA. Third, a switch is used to route the signals, so only one phase shifter and one variable gain amplifier are required for each T/R module.

Phase Shifter: The phase shifter provides the function that steers the antenna beam. As mentioned earlier, they are often realized using discrete phase bits connected in series. Alternative configurations use a vector modulator, analog control circuit (such as a varactor diode), or ferrite for the phase shifter. Phase shifters are normally implemented in 4–6 bits.

Variable Gain Amplifier: It is common for each element in the phased array to use variable gain amplifiers to perform amplitude calibration and antenna beam shaping.

2.2 Systems Using T/R Modules

The following sections describe how T/R modules are used or are planned for use in a variety of applications and describe some of the packaging methods used. Communication systems are considered first and include cellular base station, Wi-Fi-based indoor location systems, 60 GHz Wi-Fi high data rate connectivity, and millimeter-wave point-to-point systems. Military radar applications of transmit receive modules are also described. These examples show the variety of packaging methods employed for T/R modules.

2.3 T/R Modules in Communication Systems

2.3.1 Cellular Base Stations

Cellular base stations use antenna arrays that are installed on towers. Normally, the antennas are line arrays that are one or two elements by five to ten elements, depending upon the operating frequency and size requirement. The antennas are typically down tilted for efficient focus of the antenna on user locations. Normally, this down tilt is achieved by mechanically tilting the antenna, but this requires a manual modification of the antenna. Other methods use an electromechanical circuit that changes the phase of the signal to each antenna element in the line array to cause down tilt of the antenna beam. An alternative is to use phase shifters at each element in the array to achieve fully electronic beam steering that can be remotely controlled. The challenge is the phase shifters must handle the high power levels for base stations and, in most cases, need to perform beam steering while fully energized.

2.3.2 *Wi-Fi Indoor Location Systems Using Phased Arrays*

An application of phased arrays is used for indoor location systems. In this application, the indoor infrastructure uses multiple phased arrays operating in the Wi-Fi bands. This approach is illustrated in Fig. 2.4, which shows users in an indoor location with several phased arrays. The phased arrays scan to determine the position of mobile phones in the location. One approach uses multiple phased arrays, each measuring received signal strength (RSS) and location angle. Since each received signal from the users is unique (based upon SSID), it is possible to obtain location by advanced triangulation methods [3]. An example system is presented in [4], and it used four-element and eight-element linear arrays of antenna at 2.4 GHz. The analysis compared the linear array using a reflector and without a reflector. Another system is described in [5], which uses a single access point with multiple antennas arranged in a line array spaced at half a wavelength in the 5 GHz Wi-Fi band. The angle of arrival and time of arrival are used to compute the location of users within an environment. In another approach described in [6], a phased array operating in the 2.4 GHz band was used to locate users based upon RSS. It was found that accuracy was improved as the number of elements in the array increased. Also, improvement

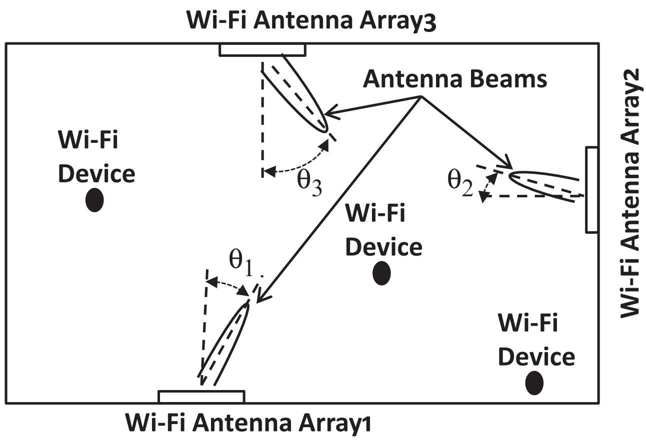

Fig. 2.4 Illustration of how Wi-Fi phased arrays can be used in an indoor location system with Wi-Fi-enabled devices

in location accuracy was increased by using the position found from antenna scanning and from the propagation delay (as in Radar). Phased arrays can be used for indoor location systems.

2.3.3 60 GHz Wi-Fi

The 802.11ad standard, which is also called Wi-GiG (Wireless Gigabit Alliance), will provide high-speed connectivity to mobile devices, televisions, computer displays, peripheral connectivity, peer-to-peer data transfer, and high-speed local area networks (LAN). The key capability for these systems are phased arrays and transmit/receive modules. Early work on the integrated circuit chip sets for these applications included phased arrays and was shown in [7–9]. The packaging used and proposed in these early solutions included low-cost laminate solutions with integrated antennas as shown in [8] and included methods that use low-cost FR-4 as the base laminate with liquid crystal polymer top layers and the use of multi-sector phased arrays for extended azimuth and elevation coverage [10]. The laminate material stack up for this type of approach is illustrated in Fig. 2.5. In these examples, the transmit receive module is fully fabricated in the integrated circuit and includes up/down conversion and analog-to-digital conversion (ADC) and digital-to-analog conversion (DAC). Another example of low-cost 60 GHz phased arrays with highly integrated Si-CMOS integrated circuit is given in [11]. Their approach is to invert the package and use antennas on the backside of the package, which is similar to the approach described in [12] and is illustrated in Fig. 2.6. Note how the package is flipped with solder ball and interconnects to the motherboard. The antenna elements that form the phased array create a radiation pattern with broadside radiation that is perpendicular to the motherboard printed circuit board (PCB). A common in these approaches is the use of Si-CMOS for the integrated circuit chip set and low-cost laminate type packaging.

2.3.4 Millimeter-Wave Point-to-Point Systems

Back haul wireless systems are used to carry data traffic from user end points or points where user traffic is aggregated to locations where it can be trunk connected. Increasingly, these systems are operating at millimeter-wave frequencies. Interesting

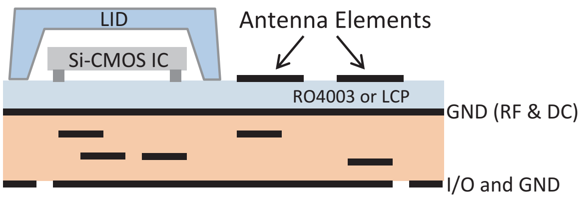

Fig. 2.5 Illustration of how laminates have been proposed for 60 GHz phased arrays on the 802.11ad standard

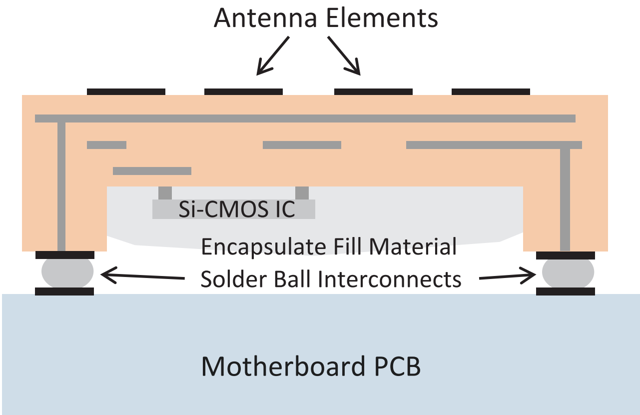

Fig. 2.6 Inverting the IC package allows phased array antennas to be integrated easily into the package

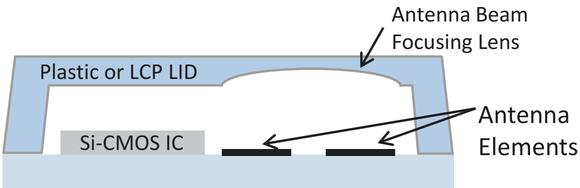

Fig. 2.7 Innovative methods for millimeter-wave antennas can be used, such as antenna focusing lens using plastic or liquid crystal polymer (LCP) lids

approaches have been developed to achieve low-cost packaging of phased arrays and transmit receive modules. One technique is described in [13] for a 60 GHz backhaul system. It uses a lens in a dielectric lid over an array of patch element as illustrated in Fig. 2.7.

The driving need for high-speed millimeter-wave backhaul networks is that wireless networks traffic is projected to increase 5000 fold over the next 15 years [14]. This means new methods must be developed to handle the increased data. The 60 GHz band is particularly attractive since it is unlicensed, has wide bandwidth of 57–64 GHz (in USA) [15], and has RF max power specified in EIRP. A goal in recent FCC rule changes in the USA is to "allow longer communication distances for unlicensed 60 GHz point-to-point systems that operate outdoors and thereby extend the ability of such systems to provide broadband service [15]." This need has created opportunities for phased arrays and transmit receive modules for millimeter-wave point-to-point systems.

One key advantage that phased arrays provide is their ability to provide functionality required for self-organizing networks (SON) [16]. This is because the ability to electronically scan the antenna beam eases network planning and link installation since the network antenna links can be remotely modified after installation and on-the-fly as the network evolves. A particular attraction is installation and alignment costs will be lower. For these reasons, phased arrays with T/R modules provide capability essential to meeting future point-to-point data communication needs.

2.4 T/R Modules in Phased Array Radar

In this section, we consider the electronic packaging used in three different types of phased array radar configurations that use T/R modules. The first is called a brick array and uses modules that are rectangular with signal flow into and out of the T/R module in the same plane as the module itself. The second is called the tile array where the input and output signals are perpendicular to the plane of the T/R module. The third is a panel array where the notion of a module no longer applies, but the T/R functions are integrated with the antennas onto a flat plate usually fabricated using laminates. These three approaches illustrate the packaging used for the majority of phased array radar T/R modules.

2.4.1 Brick Array

An example of a brick T/R module is shown in Fig. 2.8. There are a few variations on the packaging methods used for it, but basically, it contains a ceramic or laminate substrate with radar signal flow that is essentially restricted in the x- and y-axes. There are short radar signal paths in the z-axis to make contact with buried RF stripline. However, the brick module can be considered a 2D module. Another distinguishing factor is that most brick modules contain a single channel of T/R function per module. Some approaches use a metal housing while others use the ceramic substrate as the housing with a ring frame, which is the case illustrated in Fig. 2.8.

2.4.2 Tile Array

Tile array T/R modules are packaged using ceramic substrates that are stacked on top of each other to form a 3D stack with radar signals flowing in all three dimensions. Each module contains four channels of T/R functions, which is an important distinction. The interconnects between substrates are achieved using solderless interconnects [17].

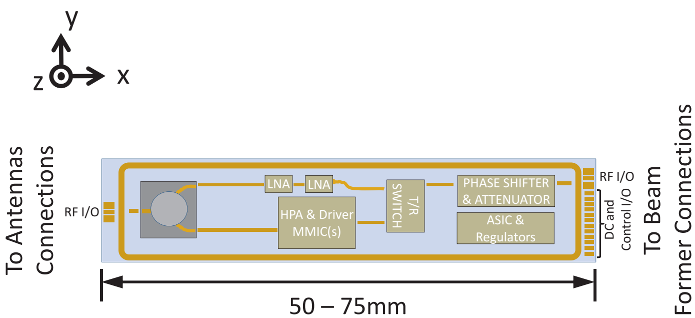

Fig. 2.8 Brick style T/R module

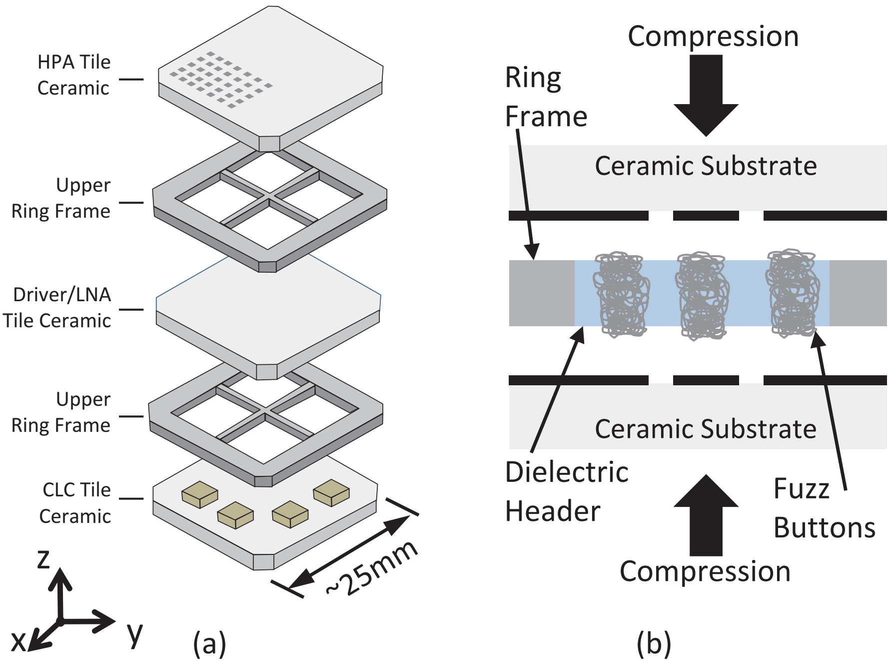

Fig. 2.9 The tile array consists of (**a**) stacked substrates and ring frames to form a 3D stack of substrates and (**b**) solderless interconnects

The configuration is illustrated in Fig. 2.9a. In this design, there are three substrates, each with a particular function for the system. The substrates are separated by aluminum ring frames that also serve the function capturing the solderless interconnects. The solderless interconnects can be formed using several different methods. One approach is to use an elastomeric connector [18, 19]. The elastomeric connector has a multitude of small wire conductors embedded in the elastomer. When it is compressed, the conductive wires make electrical contact between the substrates. Another method to implement the solderless interconnect is to use fuzz buttons [20, 21]. A simplified cross section is illustrated in Fig. 2.9b. Fuzz buttons are wires that are stuffed into a cylindrical shape and placed into a dielectric header. The header is captured by the aluminum ring frame. When the substrates are compressed, the fuzz buttons make contact to the metal conductors on the ceramic substrate. The fuzz button interconnects can be used for bias, control signals, and RF interconnects. The tile array packaging approach is one method to achieve a 3D module that is more compact and lower weight than brick modules.

2.4.3 Panel Array

The idea of a separate T/R module does not apply to the packaging of a panel array. This is because the T/R functions are integrated with the antenna and, in most cases, the hermetic module is eliminated. In some cases, the T/R functions are packaged

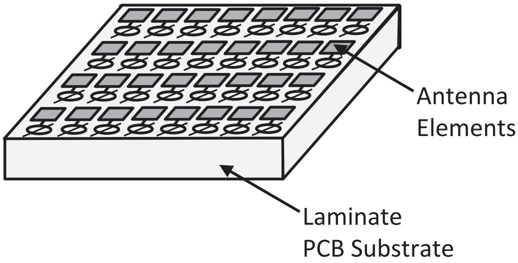

Fig. 2.10 Illustration of a panel array

into a hermetic IC package that is nearly chip scale. In other cases, non-hermetic plastic packaging is used for all of the integrated circuits in the array.

A panel array uses a large format laminate substrate with the antenna elements fabricated as part of the substrate itself. This arrangement is illustrated in Fig. 2.10. Note how each antenna patch element has a phase shifter to achieve beam steering. Most implementations of panel arrays use air cooling as in [22], which also use both vertical and horizontal polarization at each radiator and flip chip SiGe and GaAs integrated circuits. The use of low-cost laminate packaging and silicon-based integrated circuits means that panel arrays can achieve very low cost goals.

2.5 Thermal Packaging Challenges

One of the packaging challenges for T/R modules is the heat dissipated by the high-power amplifiers. The challenge is twofold. First, the amount of heat dissipated can be significant. Consider, for instance, an array with 256 elements that is used in an S-band radar system and each high-power amplifier generating 100 W of output power at 40% efficiency. The dissipated power is given by

$$P_{\text{diss}} = \left(P_{dc} + P_{\text{in}}\right) - P_{\text{out}} = \frac{P_{\text{out}} - P_{\text{in}}}{\eta} + P_{\text{in}} - P_{\text{out}} \tag{2.1}$$

where:
P_{diss} = heat dissipated (W).
P_{in} = RF input power to the high-power amplifier (W).
P_{out} = RF power out of the high-power amplifier (W).
η = efficiency of the high-power amplifier = $(P_{\text{out}} - P_{\text{in}})/P_{\text{dc}}$ (%).
P_{dc} = direct current power required by the high-power amplifier (W).

If we assume that the input power to each amplifier in the array is 1 W, then using (1), we find that the dissipated power is

$$P_{\text{diss}} = \frac{75\text{W} - 1\text{W}}{0.5} + 1\text{W} - 75\text{W} \sim 75\text{W}$$

This means that a 256-element phased array dissipates nearly 19 kW of thermal energy. Of course, this assumes that the amplifiers will be operated at 100% duty cycle, which is not the case for most radar systems. Even if the amplifiers are operated at 25% duty cycle, this is still over 4.7 kW of dissipated power.

As if this problem was not significant enough, the situation is much actually worse when the heat flux is considered for a typical high-power amplifier. Heat flux is the heat density, which can be written as

$$q'' = \frac{Q}{A} \tag{2.2}$$

where:
Q = heat dissipated (W).
A = area of the heat source (cm^2).

An S-band GaN MMIC amplifier is shown in Fig. 2.11. The output stage of the amplifier is where most of the heat is dissipated, the size of the output amplifier field effect transistors is approximately 0.55 mm × 4.42 mm, and the transistor dissipates approximately 75 W of heat. Therefore, the heat flux at the MMIC transistors is

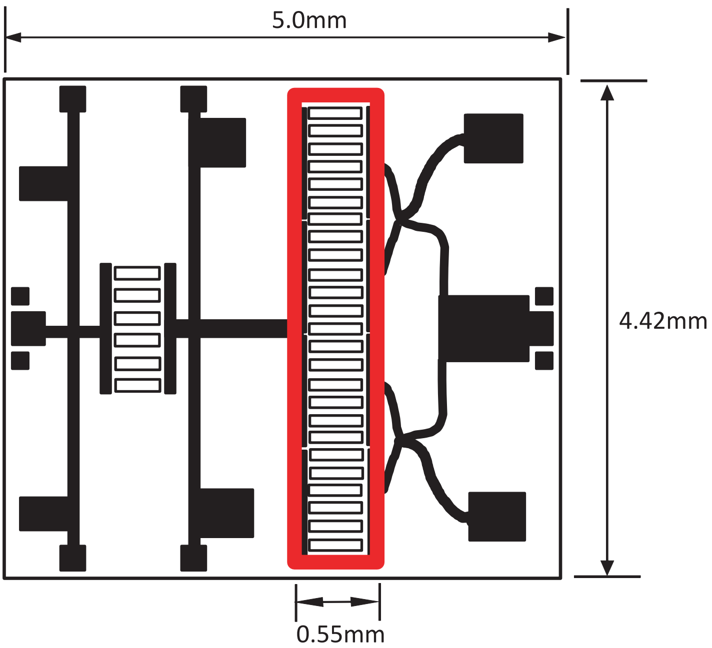

Fig. 2.11 Image of a GaN high-power amplifier showing the heat flux

$$q'' = \frac{Q}{A} = \frac{75\text{W}}{0.42cm \cdot 0.055cm} = 3247\text{W} / cm^2$$

Again, this assumes 100% transmit duty cycle. Most radar systems operate at transmit duty cycles lesser than 100%, which can greatly reduce the average heat flux. If the amplifier in this example is operated at 5% duty cycle , then the average heat flux at the integrated circuit transistors will be approximately 160 W/cm^2. Nevertheless, this level of heat flux requires careful thermal design.

2.6 Wafer Level T/R Module Packaging

For many applications, the lowest cost and most efficient packaging are achieved at the wafer level. This can be done for millimeter-wave T/R modules and phased arrays since the antenna is small enough to be integrated on the semiconductor wafer. At 60 GHz, for instance, a half wavelength is approximately 2.5 mm, which is small enough so that an array of elements can be integrated directly on the silicon wafer. A 64-element phased array was developed at 60 GHz, which occupied a full 2.2 × 2.2 cm^2 reticle in SiGe [23]. The antenna measurements showed beam steering of ±55° in both E- and H-planes with an EIRP of approximately 38 dBm. This method of fabricating 60 GHz phased arrays and T/R modules offers performance and levels that are difficult to achieve with other technologies.

2.7 Conclusions

This chapter described some of the electronic packaging methods used for T/R modules for both commercial applications and military radar. Commercial systems that can benefit from phased arrays and T/R modules were discussed. This includes cellular base stations, Wi-Fi-enabled indoor location systems, 60 GHz Wi-Fi, and millimeter-wave back haul. Packaging examples used in those applications were presented. Three types of phased array radar T/R module packaging approaches were also described. The brick module, tile array, and panel array module packaging were described. Finally, wafer level packaging of millimeter-wave phased array T/R modules was discussed.

Future T/R modules will have reduced functionality in the analog domain. Instead, as digital sampling technology increases in frequency, digital beam forming will become a reality. In these types of systems the packaging of the T/R modules will be much simpler and lower cost with the complexity being transferred to the high-data rate information being generated at each antenna element.

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http://www.springer.com/978-3-319-51696-7

RF and Microwave Microelectronics Packaging II
Kuang, K.; Sturdivant, R. (Eds.)
2017, XII, 172 p. 127 illus., 77 illus. in color., Hardcover
ISBN: 978-3-319-51696-7