Designing Cost Competitive E-band Radio Front-ends

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Abstract

E-band spectrum at 71 to 76GHz and 81 to 86GHz offers worldwide availability of wide operating bandwidths under a light license system [1]. This makes it attractive for very high data rate applications such as cellular backhaul. The development of E-band radio front-ends with adequate performance at commercially acceptable prices holds a number of significant challenges. These include component availability, performance and cost as well as the engineering difficulties associated with implementing and manufacturing the radio. This paper describes these challenges and discusses the best approaches for addressing them.

Introduction

Consumer demand for wireless data is seemingly insatiable. As soon as data capacity exits new ways of exploiting it are developed. This results in a huge amount of data that must be carried over back-haul links. Microwave point to point links in the 6 to 40GHz range are a well established technology for this application. Radio links at 71-76GHz and 81-86GHz (commonly known as "E-band") are also receiving a lot of interest despite the additional difficulties posed by the very high operating frequencies.

The use of E-band offers worldwide availability of a large amount of spectrum under a "light license" basis. This scheme operates in the US, the UK and many other countries and allows licences to be obtained quickly and cheaply whilst retaining the benefits of interference protection [1]. The availability of wide channel bandwidths facilitates higher data rates and allows the back-haul of the huge amounts of data traffic generated on the network. The link between carrier frequency and data rate is very well illustrated by Figure 1, copied with permission from [1].

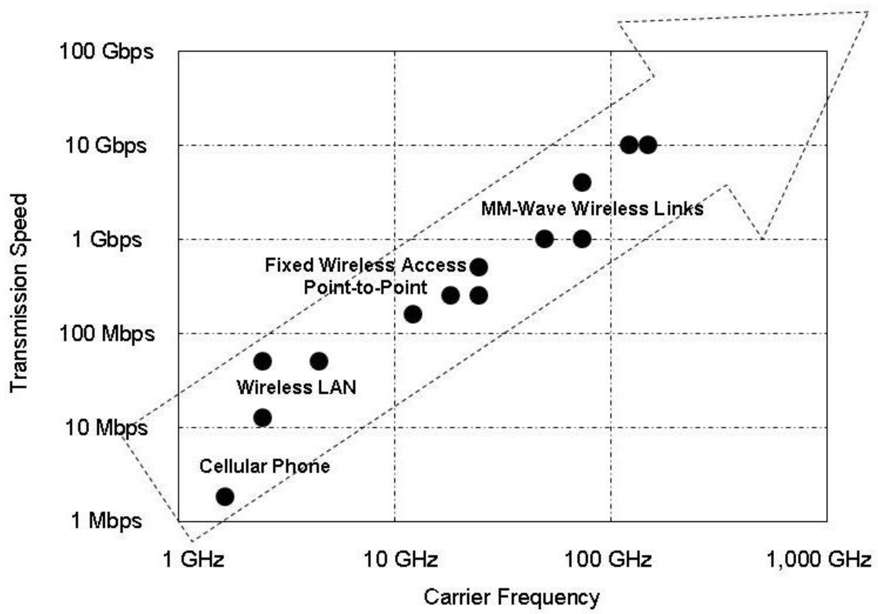

Figure 1: Relationship between data rate and operating frequency (from [1])

As operating frequencies increase, component availability decreases whilst the costs of both components and equipment rises. The development of radio front-ends operating at E-band is a technically demanding challenge and producing equipment at a low-cost adds to this challenge.

Design and Assembly Challenges

One of the first challenges that becomes evident to those attempting to design E-band radio front-ends is that of component availability (specifically MMICs). At the time of writing (March 2013) the range of available E-band components is just a fraction of that available in the more established point to point radio bands below 40GHz. This is primarily a result of component manufacturer's lack of confidence in the market size. If adequate market demand could be assured then the cost of developing E-band components, although higher than the cost of developing components at lower frequencies, could easily be recovered.

For the components that are commercially available there are two other issues:

- Performance limitations
- Lack of characterisation data

As operating frequencies increase it becomes more difficult to design MMICs exhibiting low noise performance and high linearity [2]. Even using the most capable commercially available processes it is not possible to achieve the levels of performance routinely available at lower microwave frequencies. Improvements in component performance are starting to come through [3] and this situation will gradually improve but for the foreseeable future it will remain a challenge.

Lack of characterisation data essentially stems from the availability (cost) of test equipment. Many E-band components have missing characterisation data that would typically be provided for components operating at lower microwave frequencies. The end-user is left with the options of measuring the performance themselves (not always possible and seldom simple) or making an informed estimate of the likely performance and updating this once the performance of the equipment they design has been evaluated.

The first assembly challenge is the lack of SMT packaged components. At operating frequencies up to 40GHz MMICs are now routinely available in SMT packages [4]. A lot of development effort is currently underway to push the practical operating frequency of SMT packaged components higher, most notably for automotive radar products at 77GHz [5] but work to develop SMT packaged E-band radio ICs is also underway [6]. The approaches meeting with most success use some form of flip-chip wafer level packaging. However, E-band radio front-ends manufactured today use bare die components.

Whilst the use of bare die components gets around the problems of packaging parasitics it by no means removes all assembly related issues. The most obvious issue is that of series RF bond wire inductance. A 1mm length of bond wire has a reactance of around 500Ω at 80GHz! At lower microwave frequencies the bond wire inductance of SMT packaged ICs is tolerated by capacitive compensation [4]. Careful optimisation of the parasitic shunt capacitance at each end of the wire bond allows its inductance to be absorbed into a Low Pass Filter (LPF) offering low insertion loss across the operating band.

This same approach can be used at E-band but the maximum inductance that can be absorbed into the LPF is much lower. Figure 2 is a plot of maximum inductance versus frequency. This is the value of inductance that can be absorbed into a very well matched LPF versus cut-off frequency (i.e. the maximum operating frequency for the assembly under consideration). At 80GHz the value of this inductance has fallen to below 0.1nH. Clearly every effort must be made to minimise the inductance of the bond interface.

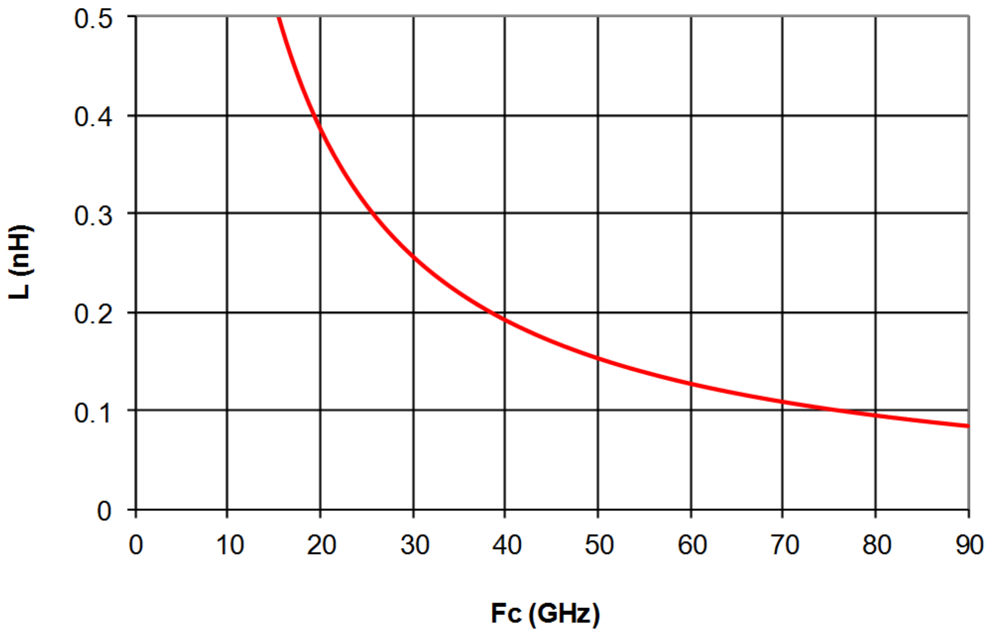

Figure 2: Maximum inductance for absorption into broadband LPF

Minimising bond inductance means minimising the physical length of the bond. The first step in doing this is to adopt an assembly approach that ensures each end of the bond is at the same level. This means either direct die to die bonding or ensuring the surface of the interface substrate is at the same level as the surface of the die. Assembly options are discussed in more detail below but assuming this first step has been achieved two options can then be considered to reduce the inductance of this minimum length bond:

- Use two bond wires in a "V-bond" configuration
- Use tape (ribbon) bonding

The V-bond uses two bond wires and attempts to ensure separation between the bond contact points at one end. This means that the bond wires are not parallel and so mutual inductance does not reduce the benefit of using two wires. It works particularly well when bonding between an IC and an interface substrate as the transmission line on the interface substrate tends to be wider than the bond pad on the die, which naturally facilitates a V-bond. Figure 3 shows a mm-wave assembly making used of V-bonds at the RF ports. In this case the operating frequency was 42GHz and the IC is sitting on the surface of a grounded pad on the substrate, which would not be suitable for E-band operation.

The tape, or ribbon, bond simply uses a wide gold tape in place of a bond wire. The wide tape has lower inductance for the same length of bond. Figure 4 depicts die to die tape bonding between two Plextek RFI designed E-band MMICs (an amplifier and a sub-harmonic image reject mixer). The ground pads as well as the signal pad are connected, which can provide an improved RF transition.

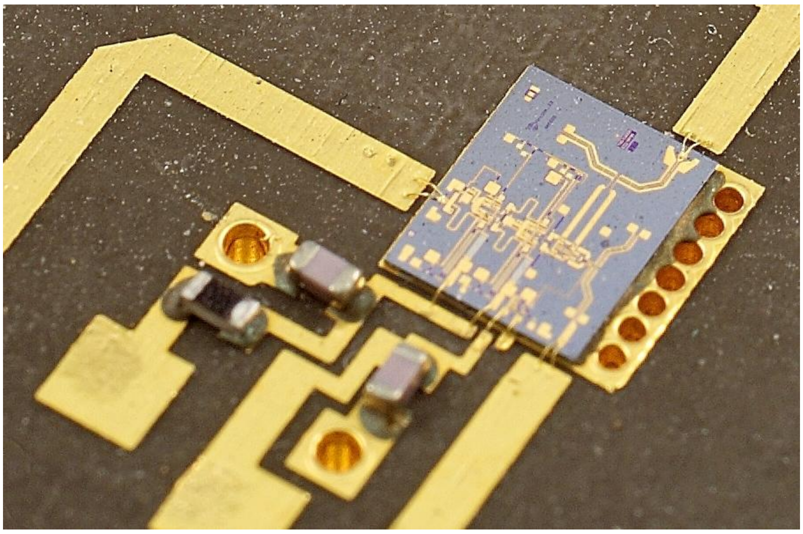

Figure 3: MMIC assembly using “V-bonds”

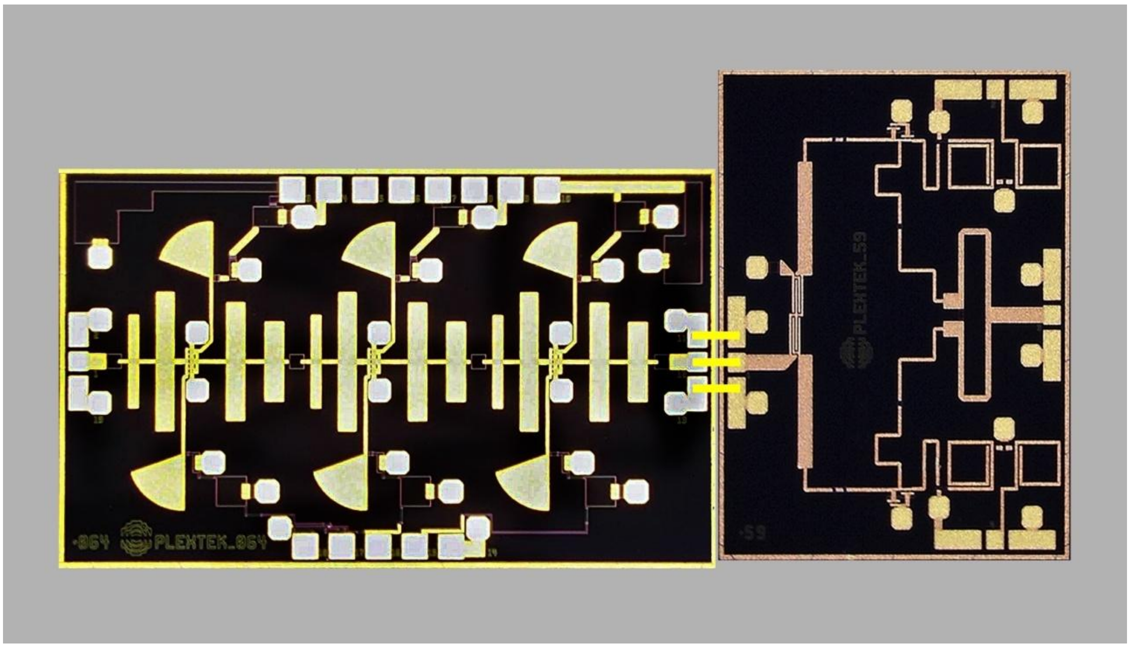

Figure 4: Die to die tape bonding

The die to die bonding approach depicted above works well. In addition to minimizing the bond distance it minimizes the number of bonds as the use of an interface or routing substrate between the two ICs would require an extra transition. The routing of E-band signals should generally be kept to a minimum with the adoption of a module layout strategy that facilitates this. However, at some point it is likely that the routing of E-band signals on a suitable substrate material will be necessary.

Care must be taken with the selection of the substrate material. Not only must consideration be given as to how the surface of the substrate can be configured to be at the same level as the surface of the die, there is also a maximum recommended operating frequency for substrate materials. Table 1 presents a list of mm-wave substrate materials that could be considered for use at E-band. It includes details of typical substrate thicknesses, the width of a 50Ω microstrip transmission line and the “maximum” operating frequency. This maximum is based on Plextek RFI’s experience. It is the frequency at which the substrate thickness is one tenth of a wavelength (λ/10) in the substrate material. At frequencies beyond this the material becomes increasingly dispersive, radiation increases and other propagation modes (e.g. substrate modes and transverse resonance modes) start to have a significant effect.

Material	ε_r	**Substrate Thickness (μm)**	**Width of 50Ω Microstrip (μm)**	**"Max" Freq. (GHz)**	**Hard/Soft**
GaAs	12.9	100	70	84	Hard
Alumina (99.5%)	9.9	127	114	75	Hard
Fused Quartz	3.8	127	250	121	Hard
RT Duroid/5880	2.2	127	310	159	Soft
LCP	2.9	100	240	176	Soft
LCP	2.9	50	114	352	Soft

Table 1: Potential mm-wave substrate materials

There are essentially two options for assembling an E-band module containing MMICs and a suitable substrate material:

- Mount the die in holes cut into pockets in a soft substrate such as RT Duroid or LCP
- Mount the die on a metal carrier along with routing track realized on pieces of hard substrate such as quartz or alumina

Whichever approach is used a substrate thickness is normally selected that is close to the thickness of the MMICs. E-band MMICs tend to be either 50μm or 100μm thick. A thin substrate material should be used to avoid excessive dispersion and it can be seen from Table 1 that typical substrate heights will mate well with a 100μm thick die. If 50μm thick die are used in some places a metal shim or raised carrier can be considered to bring the die surface level with the substrate. Alternatively some substrate materials are available at thicknesses of 50μm.

With the soft substrate approach it is possible to buy material with a thick metal backing. In this case pockets can be laser cut into the substrate and the die mounted onto the bared backing material. This was the approach taken for the assembly shown in Figure 5. It is also possible to machine pockets but it is difficult to control the depth to the desired accuracy. If the non-backed soft substrate material is used pockets can be stamped or cut prior to its attachment to the housing or carrier.

Figure 6 is from [7] and shows a cascaded assembly of bare die and quartz substrate tiles mounted on a metal carrier. This module operates at W-band. The quartz tiles at input and output contain waveguide probes that implement a transition from microstrip to waveguide. An overview of options for microstrip to waveguide transitions can be found in [8].

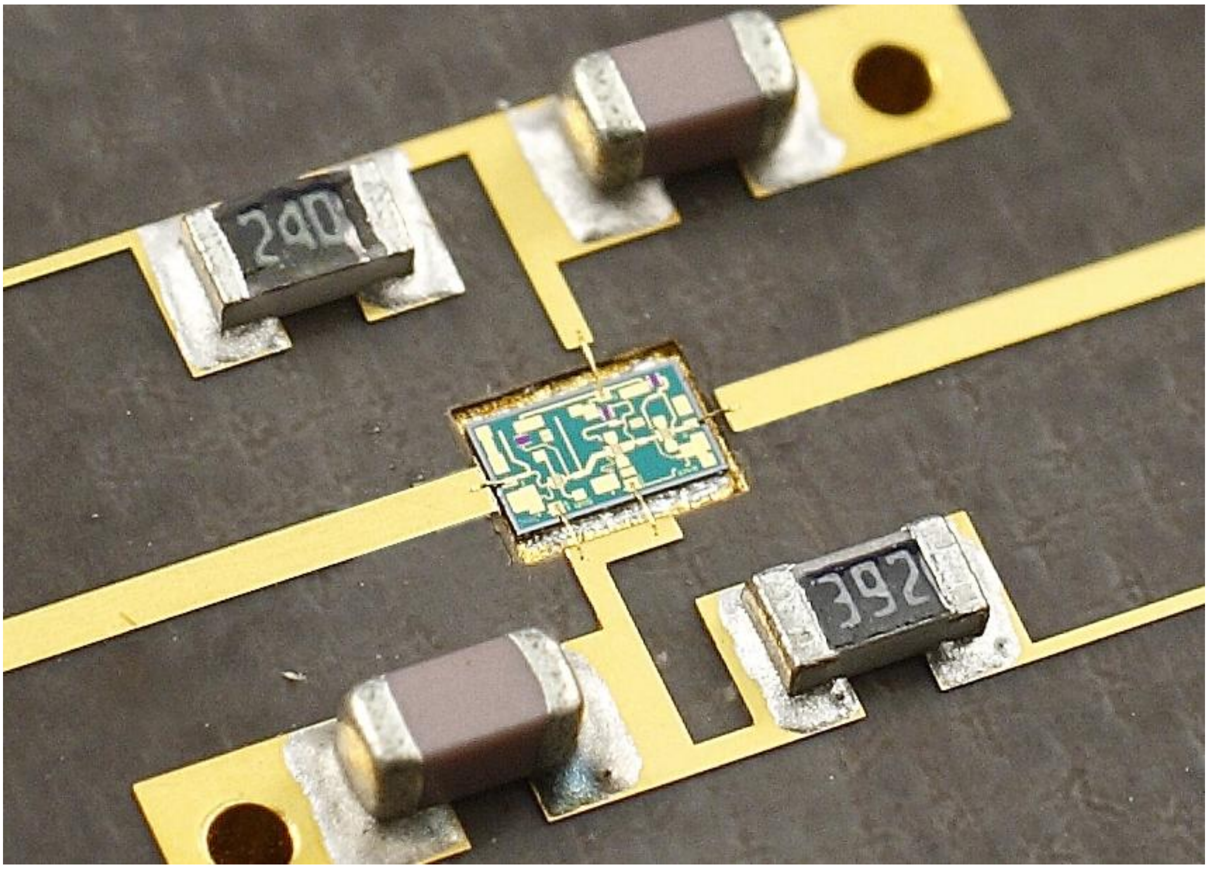

Figure 5: Die mounted in pocket in soft substrate, with SMT de-coupling

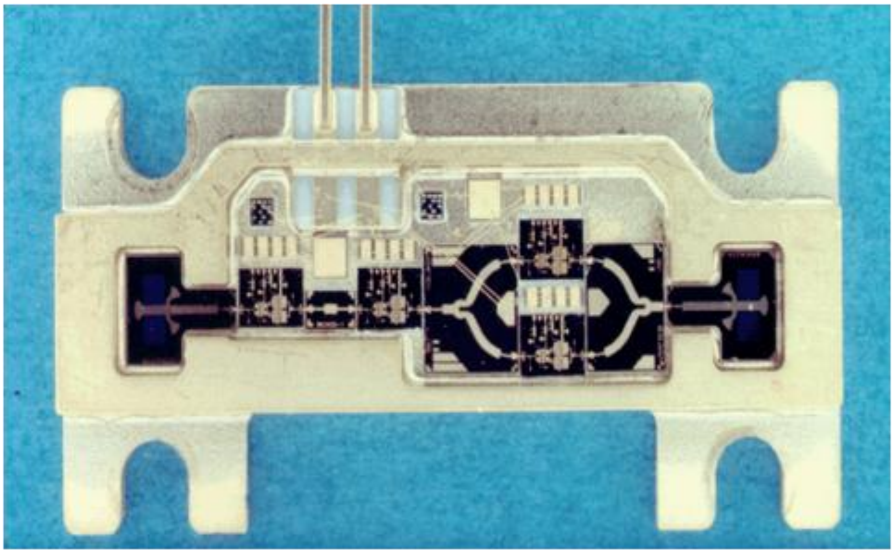

Figure 6: Cascaded die and quartz substrates on metal carrier from [7]

Guidelines for Cost Reduction

The first rule in keeping cost down is to keep the module as simple as possible. Keep the parts count down and avoid complex assembly approaches wherever possible. Whilst this might sound obvious, it is all too easy for module complexity and parts count to creep up as small additions are made to address potential issues. It is important to maintain a top level view of the module and to develop a solution that addresses the overall functional and performance requirements.

Many microwave and mm-wave MMIC suppliers recommend the use of Single Layer Capacitors (SLCs) located in close proximity to the die for de-coupling. SLCs (depicted in Figure 7) offer resonance free performance at microwave frequencies. However they are much more expensive than SMT alternatives and are often unnecessary. A well designed mm-wave MMIC will have all necessary microwave and mm-wave de-coupling on-chip. The required off-chip capacitance should be for the provision of low impedance de-coupling at RF frequencies and below. As such, SMT capacitors, although having higher parasitic inductance, should be perfectly adequate. The mm-wave ICs shown in Figure 3 and Figure 5 above make use of SMT de-coupling.

There are, however, sometimes benefits in using an SLC, such as de-coupling when assembling die on to a metal carrier (as shown in Figure 6). It is possible to use the SLC as a bonding post to simplify the overall assembly. As mentioned above, simplification of the overall assembly is a key factor in reducing the cost of E-band modules.

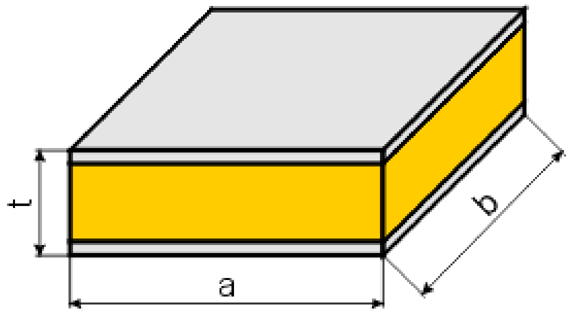

Figure 7: Single Layer Capacitor (SLC)

Co-axial connectors with a 1mm interface have mode-free operation to 110GHz and are suitable for use at E-band. However, they are precision machined components and are expensive. A transition from microstrip (or CPW) to waveguide can be implemented using a number of low loss, low cost approaches [8] and is preferred. The use of coaxial connectors should be avoided whenever possible.

The use of custom designed E-band MMICs can also save cost. This may, at first, seem counter-intuitive. However at the time of writing (March 2013) a leading supplier of E-band MMICs offers LNAs at a price of over $100 per part in 1000-off quantities. A similar part, designed on a commercially available 0.1µm gate length PHEMT process, could be manufactured for less than $7 per IC. This is based on the following assumptions:

- Wafer diameter is 150mm (≈ 6”)
- All edge sites lost
- Yield is 85%
- Wafer area devoted to PCM is 5%
- RFOW test cost is $0.2 per IC (passed and failed parts tested)

Whilst the unit cost of below $7 does not include amortised NRE, the first 5000 parts will save over $450,000.

The high cost of the commercially available E-band LNAs is down to a number of factors including smaller diameter wafers, the need to amortise the costs of NRE, marketing, sales and application support. There also needs to be some profit for the supplier. The other factor influencing cost is undoubtedly the lack of competitive parts in the market.

It is apparent that the production volumes required to make custom designed E-band MMICs a cost competitive proposition is relatively modest. Figure 8 shows a selection of custom MMICs designed by Plextek RFI. These include E-band and V-band (60GHz) examples.

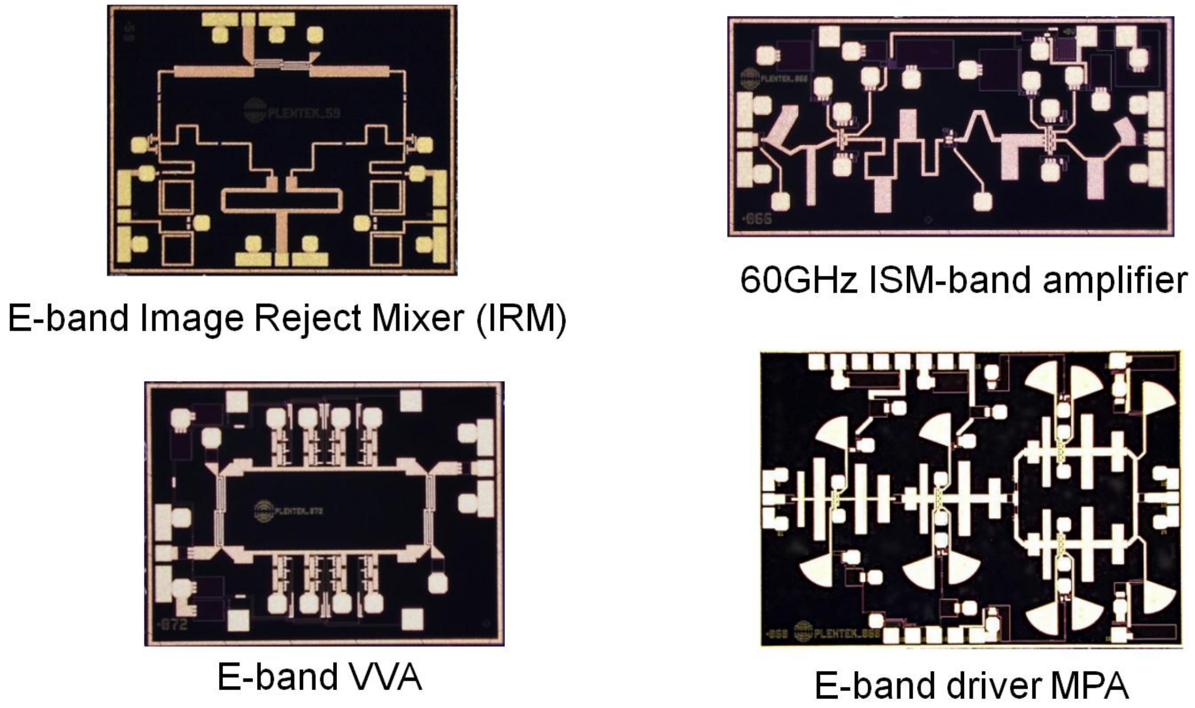

Figure 8: Selection of V-band and E-band custom MMIC designs from Plextek RFI

The final rule for reducing cost is to manufacture in very high volumes. Whatever you're buying, if you require more of them the price will fall as your bargaining power increases. It is recommended that discussions on volume pricing commence relatively early in the module development process as it is easier to command discounted pricing when a component is a potential option rather than a designed in item. Changing to alternative parts can be onerous at lower frequencies and this is exacerbated at E-band where availability and choice is more limited.

Production Issues

One of the key production challenges facing the manufacturer of E-band modules is coping with unit to unit production variation. Extremely tight uniformity of bond wire (or bond tape) length is required as is accurate die placement. Another issue to consider is the potential unit to unit performance spread of the ICs themselves. This must be acceptable, well understood and adequate tolerance must be incorporated into the module design.

The difficulties of production test should also not be overlooked. E-band test equipment is extremely expensive and measurements must be undertaken with great care and skill to ensure accuracy and repeatability.

Future Challenges

Managing the cost expectations of the customer is an on-going challenge for suppliers of E-band modules. One common question is "Why is my E-band transceiver so much more expensive than my

38GHz transceiver"? There must also be cost erosion over time, customers expect to see year on year reductions in selling price.

As data rates continue to increase there will be demand for E-band equipment operating with higher order modulation schemes. This leads to demands for higher performance components and modules, which must be satisfied as E-band technology matures. Specifically:

- Power Amplifiers with higher linear output power capability
- Higher linearity receivers, potentially adopting new architectures
- Lower phase noise Local Oscillators

Customers will also expect that none of these performance improvements will result in increased cost.

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