How to Design Low-Cost MM-Wave Equipment

Liam Devlin, Plextek Ltd (lmd@plextek.co.uk)

Plextek Ltd, London Road, Great Chesterford,

Essex, CB10 1NY, Tel. 01799 533 261

Abstract

This paper provides guidelines for the design and implementation of low-cost mm-wave equipment. Adherence to these guidelines should allow significant cost savings to be made for the production of high-volume mm-wave equipment. The suggested techniques are described and their benefits, as compared to alternative approaches, are discussed. Where possible indications of the likely cost savings have also been given. All costs included in this paper are current at the time of writing (Summer 2003).

Introduction

The traditional applications for mm-wave equipment were military systems and radio astronomy. In both cases the volume requirements were low and high unit cost was tolerated. More recently other applications for mm-wave electronics with much higher potential volumes have arisen. These include point to point links for telecommunications systems, automotive radar and subscriber equipment for broadband wireless access systems. Although great progress has been made in reducing the cost of mm-wave equipment it is not yet at the level that will allow true high volume commercial deployment. This paper gives guidelines that should allow significant cost savings to be made in the manufacture of mm-wave equipment and allow true high volume deployment to become a reality.

The guidelines that the author believes will facilitate a significant reduction in the high volume manufacturing cost of mm-wave equipment are listed below:

- Design all mm-wave circuit functions as custom MMICs
- Avoid the use of single-layer microwave de-coupling capacitors
- Avoid using precision mm-wave co-axial connectors (such as K Connectors)
- Use a low cost carrier substrate
- Keep assembly as simple as possible
- Produce the equipment in very high volumes

This is not an exhaustive list of guidelines and does not seek to resolve all of the important design issues that must be addressed in order to produce mm-wave equipment of satisfactory performance. Ground plane continuity, for example, is crucial at microwave and mm-wave frequencies yet this is not discussed. The guidelines do, however, provide a route to achieving very low cost volume manufacture for well designed mm-wave equipment. Each of the above points is discussed separately below.

Design all mm-wave circuit functions as custom MMICs

The advent of mm-wave Monolithic Microwave Integrated Circuit (MMIC) technology has allowed the design of compact mm-wave circuit functions that can be readily manufactured in high volumes with highly repeatable performance. Prior to the availability of MMICs, microwave and mm-wave circuit functions were normally realised using discrete chip transistors (or diodes), chip and wire assembly with distributed matching networks and single layer microwave capacitors. Whilst reasonable performance could often be achieved, unit to unit performance variation could result in yield problems and manual tuning of individual circuits to achieve the required performance was common place.

The cost of MMICs has been steadily falling as the technology matures and the diameter of the GaAs wafers, on which the MMICs are manufactured, increases. The primary factor that determines the cost of manufacturing an IC on a given process is the die area. The smaller the die area the lower the cost. There are of course other aspects associated with the design and the process that can also affect the cost of an MMIC, these include:

- If the part is not designed to accommodate the production spread of the process RF yield can be reduced due to process spread
- Poorly controlled processes can result in devices outside the expected process spread which again increases cost due to reduced yield
- Processes with higher defect densities will have reduced yields

However, for a well designed MMIC on a well controlled process the die area determines cost. As wafer sizes increase, more die can be fabricated on each wafer. The cost of the processed wafer also increases but at a rate that is considerably less than the proportional increase in wafer area. Thus larger wafer diameters result in lower die cost.

GaAs Integrated Device Manufacturers (IDMs) need to sell their ICs at a price that allows the cost of manufacturing the IC to be recovered together with an element of profit. In addition to this they also need to account for other costs, such as:

- NRE for designing the part
- Evaluation and characterisation costs
- Advertising and marketing costs
- After sales support
- Development of new processes

In addition to this IDMs may choose to charge a premium for parts that they feel offer a unique advantage over their competitor’s products.

Some GaAs IDMs also offer a foundry service. This is where a customer designs the IC themselves and has it manufactured by the IDM’s fabrication facility (foundry). The foundry guarantees their standard wafer release criteria, which ensures that the wafer has been manufactured within the process limits. They do not, however, offer any guarantees as to the performance of the individual MMICs manufactured on the wafer. This means that RF circuit yield is the responsibility of the designer rather than the foundry. In addition to this the foundry does not have to account for many of the additional costs of selling an MMIC outlined above. This means that the wafer level costs can be low enough to allow mm-wave ICs, manufactured through a foundry, to be produced at a significant cost saving compared to commercially available parts from an IDM.

In addition to this there are now a number of pure-play GaAs foundries with high-end processes manufactured on 6” diameter wafers. A pure-play foundry does not design or manufacture its own MMICs. Its business model is based on selling complete wafers of GaAs ICs, containing parts designed by their customers. This removes a potential conflict of interest in the case of IDMs who offer a foundry service but also have their own MMIC product line.

A simple analysis has been undertaken in order to compare the cost of commercially available mm-wave ICs to the potential costs of producing custom designs of similar parts on a pure-play foundry process. The commercially available mm-wave ICs considered were mixer, LNA and PA parts. Costs were obtained for representative die manufactured by cost competitive mm-wave IC vendors. Knowing the area of the die and the costs of a suitable pure-play foundry process allows an estimate to be made for the cost of manufacturing custom designs of similar parts.

The pure-play process considered is a 0.15µm gate length Pseudomorphic High Electron Mobility Transistor (PHEMT) process manufactured on 6" diameter wafers. The cost of wafers manufactured on this process in volumes of 10-off is approximately $14000. Knowing the area of a particular MMIC an estimate of the die cost has been made using the following assumptions:

- Wafer area lost to Process Control Monitor (PCM) cells: 5%
- All edge sites around the wafer lost
- RF yield 80%
- Test costs: $0.05 per die (functional and non-functional)

Design NRE and mask set costs for the custom design have not been included as their amortised additional cost would vary enormously depending on the volume of parts ultimately used. Obviously these costs need to be accounted for when determining the overall cost of the MMIC.

Table 1 shows the cost comparison of the commercially available mm-wave ICs to the estimated cost of a custom design. This indicates that the cost of custom designed MMICs could be as little as 10% of the cost of commercially available parts. It should be noted that the commercial IC prices are not for huge volumes and these parts will get cheaper as volumes increase. However, the cost of the custom designs is only based on an order for 10 wafers and in the case of the largest PA, 11 wafers would be required to yield 10,000 parts. It should also be remembered that the costs of the complete wafers will also fall significantly as volumes increase.

Function	Area (mm^2)	1000-off price	10 000-off price	Custom design unit cost
20-30GHz LNA	2.8	$37	$28	$3.02
38GHz Mixer	2.3	$32	$26	$2.57
28GHz, 1W PA	12.3	$115	$89	$13.99
35GHz, +31dBm PA	13.5	$143	$142	$15.45

Table 1: Comparison of MMIC pricing to potential cost of similar custom part

In summary, provided that the volume usage is high enough, the development of custom mm-wave ICs can offer very significant cost savings compared to buying commercially available parts.

Avoid the use of single-layer microwave de-coupling capacitors

Virtually all manufacturers of mm-wave ICs provide assembly instructions indicating that the bias pads should be de-coupled using single layer microwave capacitors in close proximity to the die. Figure 1 shows the assembly instructions provided for the P34-5140 from Bookham (a 20-40GHz, +21dBm amplifier). In this case 5 single layer capacitors are used. These capacitors offer good performance to high microwave frequencies and are available from companies such as Johanson. Figure 2 depicts the physical structure of this style of capacitor. They cost around $1 in 1000-off quantities falling to $0.30 in 100,000-off quantities. Whilst this may not sound expensive it is many times the cost of a standard 0402 SMT capacitor and can add significantly to the cost of a mm-wave module as a significant number of de-coupling capacitors may be required. Furthermore, the use of these single layer microwave capacitors is often unnecessary.

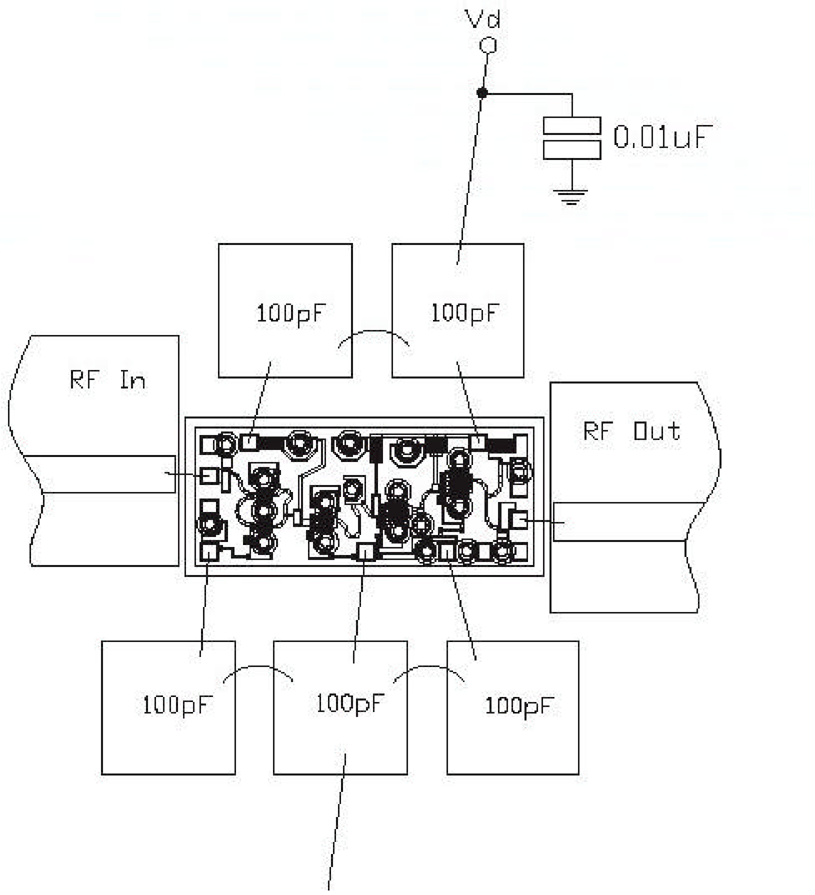

Figure 1: Assembly diagram for the P35-5140

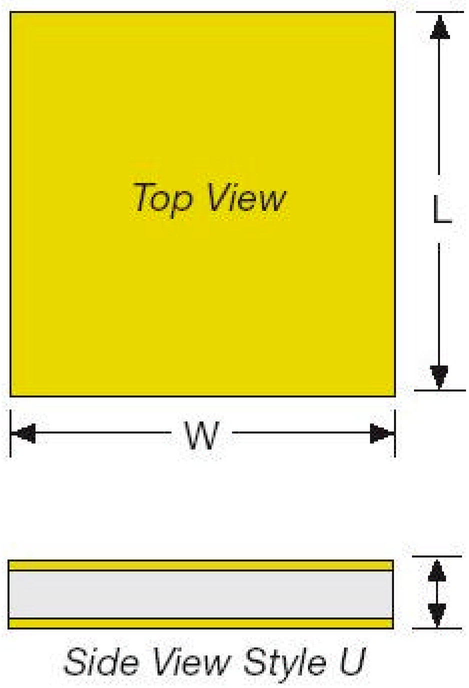

Figure 2: Physical structure of single layer microwave capacitor

The inclusion of integrated capacitors on an IC takes up die area and can therefore add to the cost. For this reason excessive de-coupling is not normally included on-chip. Indeed with lower frequency IC designs on-chip de-coupling is sometimes omitted altogether. With microwave and mm-wave designs, on-chip de-coupling is included to ensure good in-band (and above-band) grounding of bias/matching components. The purpose of off-chip de-coupling should be to provide additional de-coupling at RF and lower frequencies. To this ends, with well designed mm-wave ICs, it should not be necessary to use microwave capacitors for bias de-coupling, conventional 0402 SMT capacitors should be perfectly adequate.

The author has conducted comparative trials of mm-wave ICs de-coupled using single layer microwave capacitors and inexpensive 0402 capacitors. The results of these trials were that no discernible difference in performance was evident as a consequence of the different de-coupling techniques. Figure 3 shows a photograph of one of the assemblies used in these trials. It contains two Plextek designed mm-wave LNAs. One is de-coupled using two single layer microwave capacitors, the other is de-coupled using an 0402 SMT capacitor.

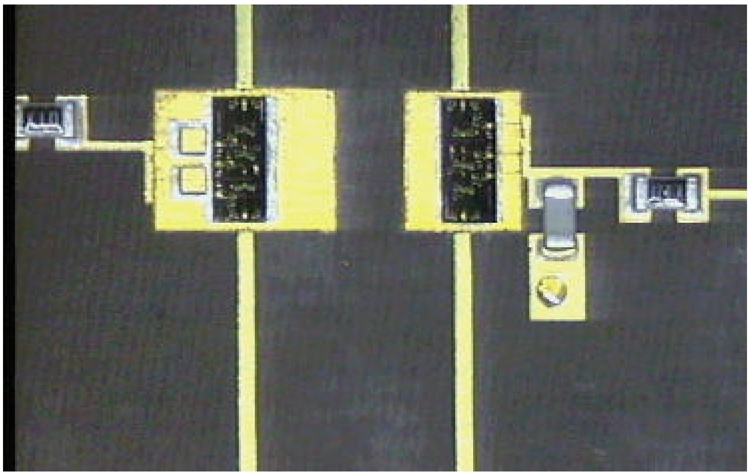

Figure 3: Photograph of two mm-wave LNA assemblies, one using microwave de-coupling the other 0402 SMT de-coupling

In summary it should not be necessary to use single layer microwave capacitors to de-couple the bias ports of mm-wave ICs. Well designed parts will include mm-wave and microwave de-coupling on-chip and adequate RF and lower frequency de-coupling can be provided off-chip with inexpensive SMT capacitors.

Avoid using precision mm-wave co-axial connectors

Conventional SMA co-axial connectors can be used at operating frequencies up to 18GHz. If co-axial connectors are required at frequencies beyond this, precision connectors, such as 3.5mm or Anritsu's K Connectors, can be adopted. K Connector launches can be used to provide low reflection transitions between co-axial and microstrip media at frequencies to beyond 40GHz. A cross-section of such a transition is shown in Figure 4. Whilst such connectors are well engineered and can provide very good performance, the cost implications can be significant as they can cost over $40 each in small volumes.

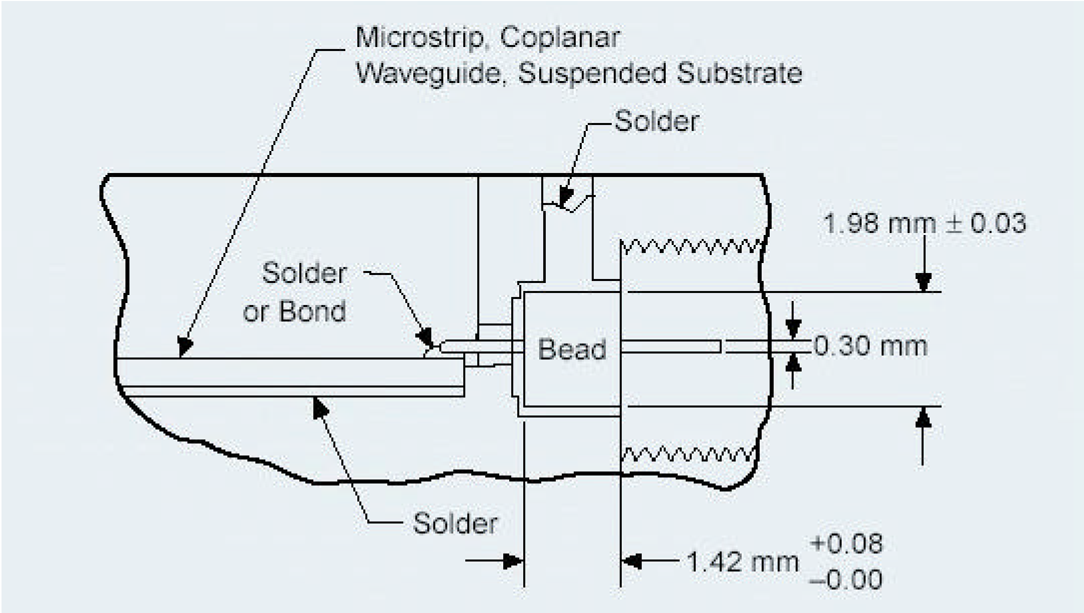

Figure 4: K Connector to microstrip tansition

A waveguide interface can be included as an integral part of a housing design and can offer a substantial cost saving compared to a precision co-axial connector. Various techniques exist for performing a transition from microstrip to waveguide [1] but the most simple and compact is the E-plane probe transition depicted in Figure 5.

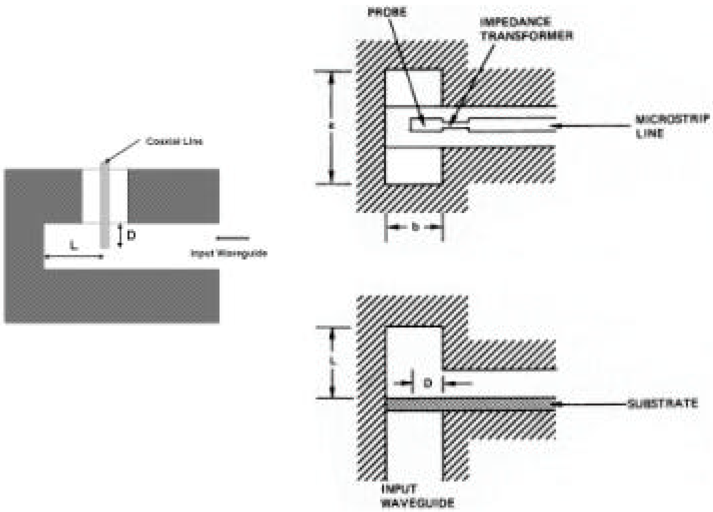

Figure 5: E-plane probe transitions – coaxial and microstrip line (from [1])

In addition to being compact, E-plane probe transitions can be very low loss. Figure 6 shows a Plextek designed waveguide rotary joint that incorporates two E-plane probe transitions in addition to the rotating section and two short waveguide feeds. The whole structure had a typical insertion loss of 0.3dB from 27.5 to 29.5GHz and could be manufactured as a diecast part for very low cost in high volume.

Figure 6: Waveguide rotary joint incorporating two E-plane probe transistions

Use a low cost carrier substrate

For use at mm-wave frequencies, a substrate should have the following characteristics:

- Readily available in thin substrate heights (to reduce dispersion and radiation losses)
- Well controlled substrate thickness (reduces performance variation)
- Low dielectric constant (helps reduce effects of tolerance variations and avoids dimensions of distributed structures becoming impractical)
- Well controlled dielectric constant (reduces performance variation)
- Low dissipation factor (low loss)

Conventional low-loss ceramic microwave substrate materials (such as alumina) are not a particularly good choice at mm-wave frequencies as they have a high dielectric constant (9.9) and become very fragile when thinned. However, there are various “soft substrates”, usually some form of PTFE composite, that offer a means of realising thin substrates heights with low loss and low dielectric constants. Although such substrate material is not brittle, handling can become difficult as the thin material can be very flexible. The use of metal clad substrates is one solution to this problem. Rogers RT Duroid® 5880 is an example of such a substrate material. It is a glass microfibre reinforced PTFE composite, with a dissipation factor (tan d) of 0.0009 and a relative dielectric constant (ε_r) of 2.2 (standard tolerance of ±0.02). It is available in substrate heights as low as 0.005”.

Non-PTFE alternatives include the Rogers RO4000® series, which are glass reinforced hydrocarbon/ceramic laminates. This results in a low loss material that can be processed using standard FR4/epoxy techniques. RO4350® is available in a thickness of 0.004” with a relative dielectric constant (ε_r) of 3.36 (standard tolerance of ±0.05) and a dissipation factor (tan d) of 0.0037. Whilst this is a reduced cost material, compared to the PTFE composites it should be noted that it also has higher losses.

In summary, costly substrate materials can and should be avoided. Careful thought should be given to selecting a low cost substrate material that can provide adequate performance for the functionality and frequency of interest.

Keep assembly as simple as possible

Excess stray inductance can seriously degrade the performance of mm-wave components. Great effort is therefore often expended in minimising the discontinuity between MMICs and the carrier substrate. This can include mounting MMICs on miniature metal carriers to raise the die surface to be flush with the carrier substrate or using multiple carrier substrates to interface between MMICs as a means of minimising the MMIC/carrier substrate gap. Whilst it is vitally important to keep the discontinuity to an acceptable level and to be able to accurately predict its effect, some of the techniques adopted can have a high associated cost. Simpler, less expensive, techniques may offer adequate performance at a much lower associated cost.

For substrate material with a thick metal backing, it is possible to mount bare MMIC die into pockets cut into the substrate. As well as providing a good electrical ground contact and good heat sinking, this can result in the surface of the die being almost level with the surface of the substrate, so minimising bondwire lengths. It is possible to machine such pockets but very accurate depth control can be difficult and may leave the surface of the MMIC sitting below the substrate surface. Laser cutting of the pocket is also possible and removes only the substrate material. In both cases cost is added to the substrate manufacture by the inclusion of the additional, precision process step.

An alternative approach is to mount the MMICs on the surface of the carrier substrate, on an array of through substrate vias to ground. This provides a low inductance contact to ground and has been successfully adopted at frequencies of up to 40GHz [2]. Die attachment is made using conductive epoxy, which provides a degree of compliance between the die and the die attach area, so helping to compensate for the different expansion rates. The cross-section of such an assembly is shown in Figure 7. This technique is not suitable for very high power devices where additional heat-sinking may be required.

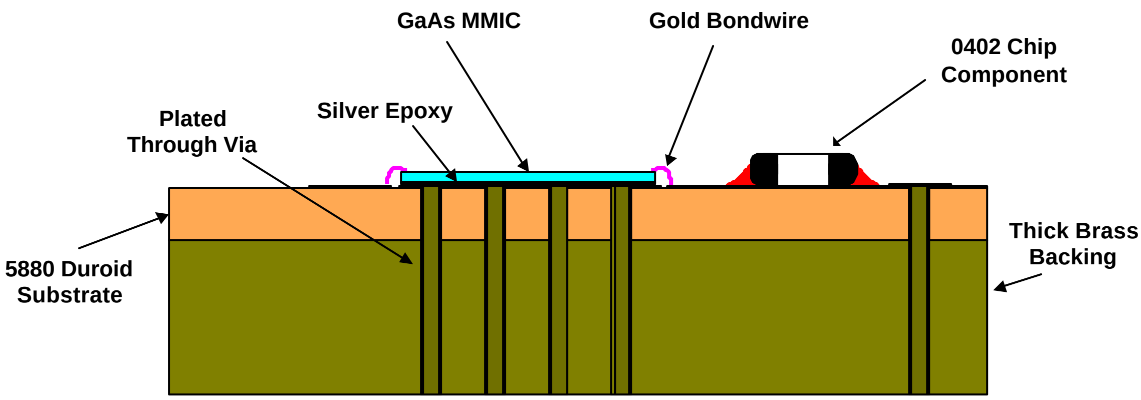

Figure 7: Cross-section of a simple mm-wave assembly

It is well understood that bondwire connections have an associated inductance that can degrade the performance of a die at microwave and mm-wave frequencies. Even a 0.3mm length of 25µm (0.001") diameter bondwire will have an associated inductance of around 0.3nH. At lower frequencies the reactance that this represents is very low and can be ignored. At mm-wave frequencies even such a low inductance as this can cause significant performance degradation. At 28GHz 0.3nH has an inductive reactance of 53Ω.

The use of gold tapes in place of bondwires can be used to reduce the associated RF interface inductance. However, it does add to the assembly time and complexity. Although the use of gold tape may be the only practical option for MMIC assembly at high mm-wave frequencies (60GHz and above), it is often possible to use goldwire bonding at frequencies up to 45GHz.

The first step is to try and keep the bondwire inductance as low as possible. This means keeping the separation between the MMIC and the bondwire attach point as small as possible in order to keep the bondwire length down. Wedge-wedge bonding should be adopted as this allows the lowest bond loop height to be achieved. Another obvious, low-cost route to reducing bondwire inductance is to use two parallel bondwires. As a result of the mutual inductance between the two bondwires, the inductance isn't halved for two parallel bonds but it is substantially reduced.

Even when the steps above are taken the bond inductance is still likely to be high enough to substantially affect the performance of the MMIC at mm-wave frequencies. There are, however, two options that can allow this inductance to be accommodated:

- Design the MMICs for optimum performance with the anticipated bondwire inductance present at all RF ports
- Compensate for the bondwire inductance by incorporating it in a Low Pass Filter (LPF)

Designing the MMIC for optimum performance with the anticipated bondwire inductance present requires knowledge of the assembly route at an early stage in the design process. It also means that in order to achieve optimum performance precise control of bondwire inductance is necessary. The bondwire actually becomes part of the MMIC matching circuitry and any variation in bond inductance will affect the circuit performance.

Provided the bondwire inductance is low enough, it is possible to incorporate it into a 50Ω matched, third order low-pass filter. The bondwire itself is essentially a series inductance. Open circuit shunt stubs can be realised on the carrier substrate to provide a shunt capacitance to ground and a narrow width of series line can be realised to act as a series inductance. The whole structure forms a third order low pass filter, as depicted in Figure 8. If the cut-off frequency of the low-pass filter can be set to beyond the required operating frequency, this will provide a degree of tolerance to bond inductance variation.

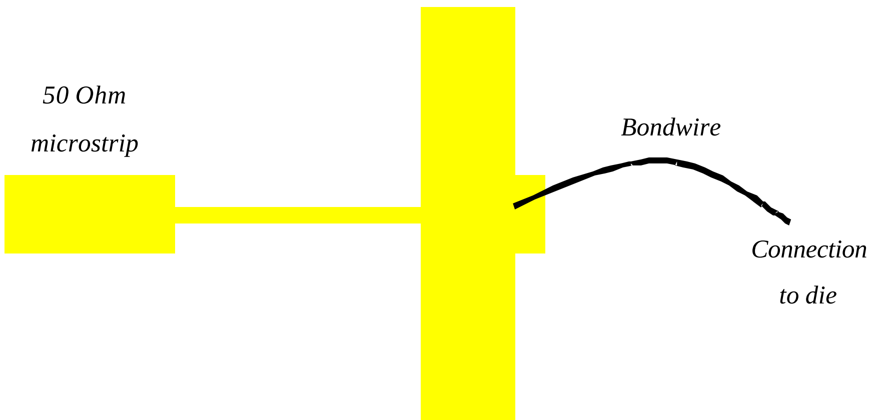

Figure 8: Compensating for bondwire inductance

Assuming a flat pass-band (0.01dB ripple) for the filter, the maximum cut-off frequency of a third order filter for a given series inductance can be determined [3]. This allows the maximum frequency at which this technique can be adopted to be calculated for a given value of bondwire inductance. This is depicted graphically in Figure 9.

Thus to use this technique optimally to 28GHz requires the in-band inductance to be less than 0.18nH and to use it to 40GHz less than 0.125nH. It should be noted that slightly higher values of inductance can be accommodated but a degree of compromise with respect to bandwidth or in-band ripple and return loss will be necessary.

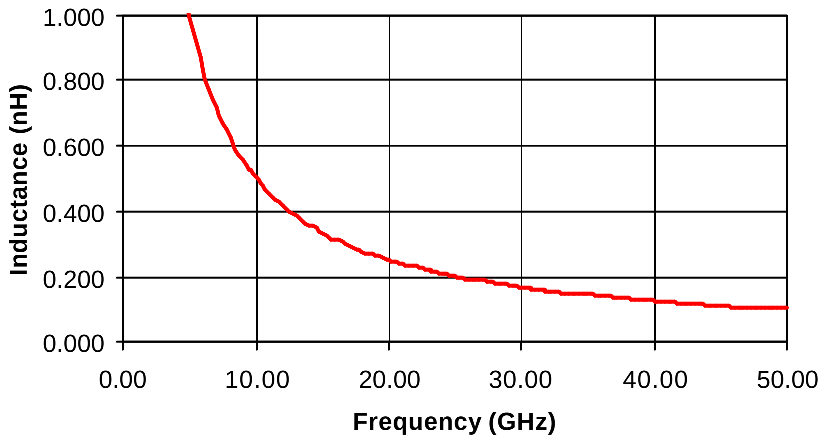

Figure 9: Maximum bondwire inductance versus cut-off frequency for incorporation into a flat, third-order, low-pass filter

In summary, every effort should be made to adopt the simplest assembly route possible. Wherever feasible simple gold wire bonding should be used and die should be mounted onto the surface of the microwave substrate rather than in precision cut holes or on custom carriers. Techniques such as the bondwire compensation filters, discussed above, should be considered as a means of extending the frequency range to which these straightforward assembly techniques can be adopted.

Produce the equipment in very high volumes

The price of electronic components falls as the volume of ordered increases. The more of a particular part you use the cheaper it gets. An example of price erosion with volume is shown in Figure 10. In this case the 10,000-off price falls to less than 30% of the low volume price. As volumes increase beyond 10,000 further price reductions can be obtained and for quantities of one million-off the price may halve again to around 15% of the low volume price. The example shown was for a TCXO but similar price reductions with volume will be obtainable for most electronic components.

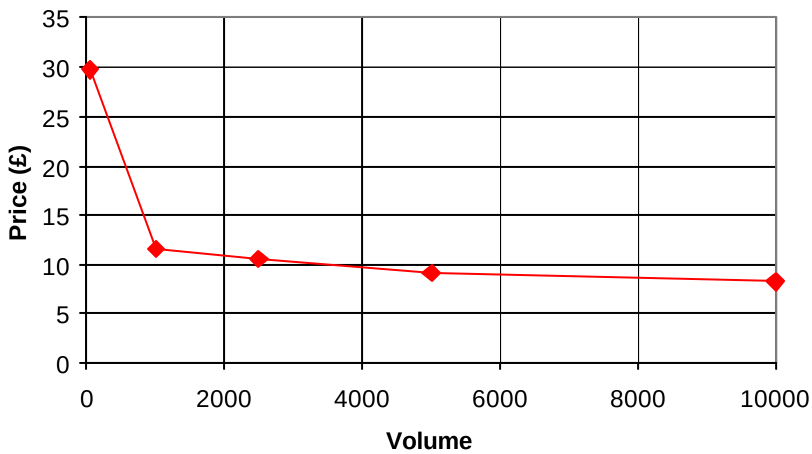

Figure 10: Example of price versus volume for an electronic component

It is not just the fall in the price of component parts which will facilitate a reduction in the cost of equipment manufactured in high volumes. If the volumes are high enough it is possible to adopt automated assembly and test techniques. These incur high up-front investment costs but can significantly reduce the manufacturing cost of each unit. Obviously these up-front investment costs must be amortised across the production volumes. However, if these volumes are high enough the amortised cost of the capital investment can be small.

MM-wave equipment is not yet being manufactured in high enough volumes to allow all of the associated cost benefits described above to be realised. Applications such as automotive radar hold the promise of true commercial production volumes. If mm-wave products do start to be manufactured in such high volumes, there is no reason why they cannot be truly low cost.

Summary and Conclusions

Guidelines have been presented that should allow the design of mm-wave equipment suitable for low-cost, volume manufacture. All of the necessary techniques and processes are available today. The biggest stumbling block to producing very low cost mm-wave equipment is having a product that will be required in sufficiently high volumes. Automotive radar is a promising candidate but whatever the application ultimately is, it is only a matter of time until low cost mm-wave equipment is a commercial reality.

References

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