Electrical, Thermal, Reliability and Cost Considerations for Millimeter-Wave Surface Mount Packages

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Abstract

Package electrical effects grow in significance with frequency, and must be factored into chip design early in the design cycle. Similarly, the thermal properties of the package must be taken into account for higher power parts like amplifiers. Package choice is also determined by reliability requirements and cost. These factors combine to determine the ultimate suitability of package types and associated performance envelopes. This paper discusses the trade-offs in package design and technology selection, from standard QFN through to custom laminate packages.

INTRODUCTION

In recent years need has grown for surface mount packages for millimeter-wave components as new markets emerge in automotive radar, point-to-point radio and wireless networking. These new applications are price sensitive and the package is often a major part of the total manufacturing cost. Nevertheless, the replacement of chip-and-wire assembly with pick-and-place technology has enabled aggressive cost reduction due to simplified board design, component storage and handling. There is increasing pressure to reduce the cost of millimeter-wave packages without sacrificing electrical and thermal performance or component reliability. This has been and will continue to be achieved by adapting the efficient manufacturing techniques already used for low frequency packages and by developing new techniques and technologies specifically for millimeter-wave products.

The key specifications for a package design depend on the application but it is usually essential that the millimeter-wave transitions have low insertion loss and present low reflection in a 50-ohm environment. The package must have a low thermal resistance to keep die temperatures at safe levels at all times. It must be sufficiently reliable to withstand the expected operating conditions and also the stresses imposed during board assembly. Finally the package materials and assembly cost must be compatible with the intended application and market. It is not uncommon for a millimeter-wave package to be more expensive than the MMIC it contains. Thus the package becomes an important part of any cost reduction program.

M/A-COM Technology Solutions has successfully used standard-leadframe, plastic-overmolded QFN (quad-flat no-leads) packaging for high performance applications to 40 GHz [1-3]. This was achieved by optimization of the bondwire configurations and profile, and compensation for the bondwire and package transition on the MMIC die. Above approximately 40 GHz compensation becomes impractical as the low-pass response of the transition dominates and in-band resonances occur. Therefore at higher frequencies cavity laminate packages have been used [4-5] which allow more flexibility in the design of internal compensation (matching structures) in the package itself. Other options for millimeter-wave packaging include micro-coax interconnect [6], ceramic packages [7], liquid crystal polymer [8] and QFN or laminate packages with electromagnetic coupling in place of package leads or vias [9]. There has also been some effort devoted to millimeter-wave chip-scale packaging [10].

In this paper we begin by discussing the performance and characteristics of the standard plastic overmolded QFN leadframe package for millimeter-wave applications. We also describe cavity laminate packages which have improved electrical performance while retaining a footprint compatible with QFN outlines. Finally we discuss ongoing development work that may lead to new cost-effective packaging technology applicable to millimeter-wave products.

OVERMOLDED QFN PACKAGES

The overmolded QFN [11] consists of an etched leadframe fabricated in array form, onto which the die is attached and bonded. The bonded assembly is overmolded by a plastic compound before saw singulation. Traditionally QFN packaging has been used for low frequency products and some cost-sensitive applications up to 6 GHz where the package transition and overmold losses have a small impact on performance. In recent years several IC vendors have used overmolded QFN packaging for products at higher frequencies where careful design and compensation of the package transition is essential. The bondwire inductance and losses must be minimized through the use of minimum loop height [12] and reverse bonding. The remaining inductance must be incorporated into a low-pass network using die compensation to minimize the discontinuity. In this way it is possible to use the overmolded QFN with standard assembly procedures up to about 40 GHz. Above 40 GHz manufacturing variations become problematic and it is impractical to compensate the inductance of a minimum length bondwire.

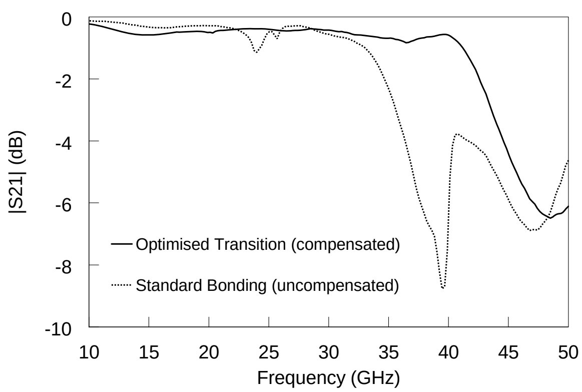

Fig. 1: Insertion loss of 3×3 mm QFN THRU.

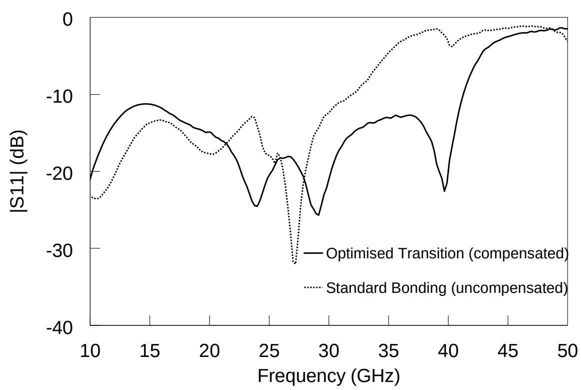

Fig. 2: Return loss of 3×3 mm QFN THRU.

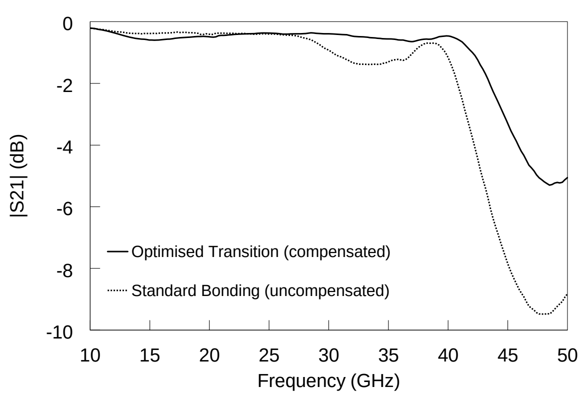

Fig. 3: Insertion loss of 4×4 mm QFN THRU.

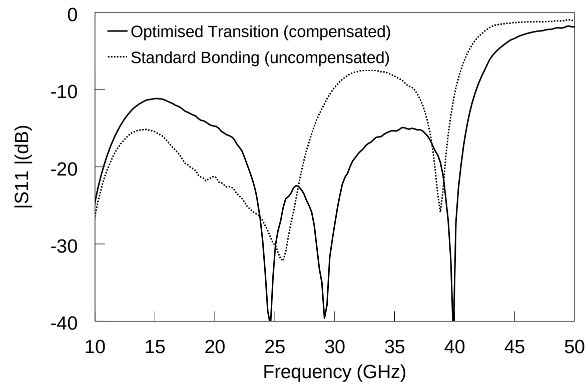

Fig. 4: Return loss of 4×4 mm QFN THRU.

The measured performance of 3×3 mm and 4×4 mm overmolded QFN packages containing THRU die are shown in Figs. 1-4. In each case we compare the performance of the THRU with uncompensated transition vs. the optimized and compensated transition. It can be seen that, even with compensation, the package is unusable above about 40 GHz.

The thermal performance of the QFN package is very good due to the solid copper leadframe to which the die is attached. Thermal resistance depends on die size due to increased spreading resistance for very small die as shown in Fig. 5. A finite element model for a typical packaged power amplifier, where the die size is slightly smaller than the die attach pad, is shown in Fig. 6. Where thermal performance is critical it may be possible to further reduce the package thermal resistance through the use of custom leadframes (with fused leads), highly conductive epoxies and high performance leadframe alloys. However, the thermal performance is also strongly dependent on the board materials, construction and layout [13].

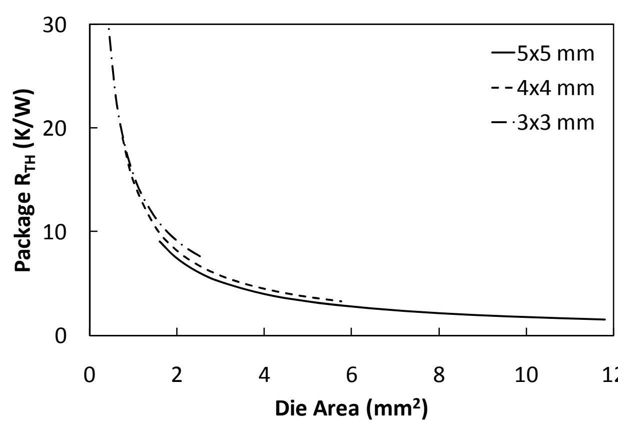

Fig. 5: QFN package thermal resistance vs. die area.

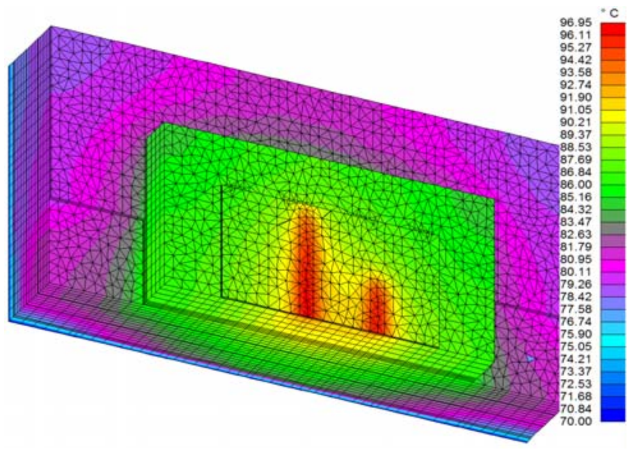

Fig. 6: Thermal model of power amplifier die in a 7×7 PQFN package (epoxy/die junction layer shown).

The QFN package is well characterized in terms of reliability due to its use for many high volume products at lower frequencies. It offers reasonable moisture protection [14] and is suitable for lead-free solder reflow. For millimeter-wave applications there may be additional factors to consider due to the particular semiconductor technology used. In particular, the die passivation can be critical to the reliability in a QFN package since plastic overmold is an imperfect moisture barrier. Smaller packages can achieve MSL1 ratings, though larger packages with large die may achieve no better than an MSL3 rating.

The manufacturing and assembly of QFN packages involves relatively few processing steps and is done economically using large array panels. Therefore it is currently the lowest cost alternative for applications below 40 GHz. Furthermore, it is fully compatible with standard pick-and-place assembly lines and typical solder reflow profiles.

Cavity Laminate Packages

For applications above 40 GHz, or where electrical performance is paramount, cavity laminate packages may offer advantages over the cheaper QFN leadframe. Laminate packages for millimeter-wave applications may be constructed in a number of different ways. The simplest and cheapest laminate package consists of a flat package base that has been drilled, plated and etched (in array form) in much the same way as a conventional printed circuit board. The die is attached to a plated copper region over an array of drillholes that have been filled with plated copper or epoxy, and wire bonded to leads on the laminate that connect via plated drillholes to QFN-like patterned copper on the bottom side. Alternatively, improved thermal performance can be achieved by replacing the drillhole array with a solid copper plated pedestal or coin. Both plated pedestal and coin require an additional controlled depth milling step before plating of the pedestal or insertion of coin. The requirement for controlled depth milling introduces additional limitations on the size of panel that can be processed to the required tolerance. For both cases, a matching lid array panel can be attached prior to singulation. The laminate package is more expensive than QFN due to additional fabrication complexity, material costs and fewer packages per array in volume manufacture.

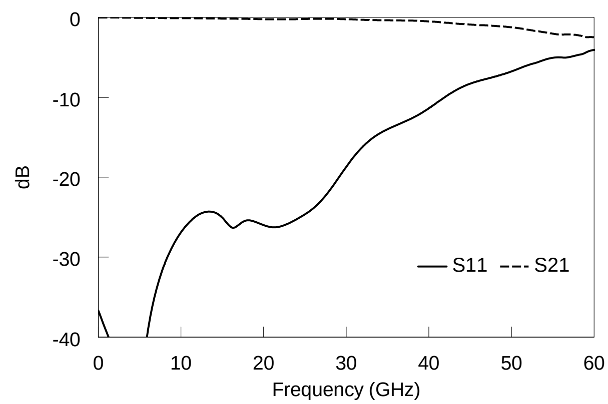

Fig. 7: Simulated transition for a 2.4 mm die in a 4×4 PQFN package.

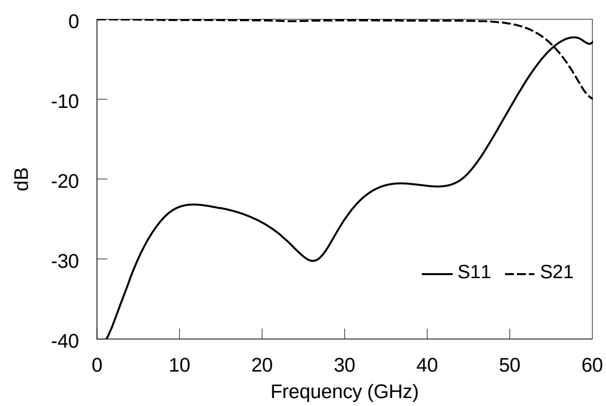

Fig. 8: Simulated transition for a 2.4 mm die in a custom 5×5 cavity laminate package.

To illustrate the improvement possible in package transition performance for a cavity laminate package compared to a QFN overmolded package, consider Fig. 7 and Fig. 8. In both cases, the application is for a 2.4mm die. These plots for transition insertion and return loss from PCB to die are generated by a 3D-EM solver [15] as it's not feasible to confidently measure a single transition from PCB to die, and the modeled transition S-parameters are incorporated into the design of any chip that uses the package. Fig. 7 shows the transition performance for a 4×4mm QFN with optimized bondwire configuration, with performance degrading above 40GHz. On the other hand, Fig. 8 illustrates the improvement possible in a 5×5 cavity laminate package with a custom matching network on the laminate. The laminate package needs to be slightly larger than the QFN, for the same sized die attach paddle, to allow for the package lid walls. In this example, the laminate material is Rogers 4350B which offers a good compromise between cost, ease of processing and dielectric losses, though superior and more costly materials are available. This package incorporates a solid copper pedestal for the die and a matching network on the top side of the laminate for millimeter-wave input and output transitions. The matching network compensates for the parasitic inductance of the bondwire and the laminate via connecting package pin to the internal bond pad.

A laminate base constructed with a filled drillhole array can result in significant thermal resistance due to the sparse copper fill between the die attach pad and package base (solder). Typical design rules result in a maximum copper fraction of about 25% by area in an array of copper filled drillholes at minimum pitch. Drillhole arrays have anisotropic thermal properties that are strongly influenced by the density of holes and hole fill material, resulting in poor lateral heat spreading inside the package. Consequently laminate packages with drillhole arrays under the die have a thermal resistance three to four times higher than a solid copper pedestal. In such cases the thermal resistance of the laminate package can be a very significant part of the overall temperature rise and may necessitate larger die size or sub-optimal operating conditions.

Care must be taken at millimeter-wave frequencies with the possibility of parasitic coupling into the resonant structure formed by the drillhole array [16]. This is further motivation to maximize the density of drill holes and to use small diameter (laser drilled) holes for high frequency applications.

Cavity laminate packages have inferior reliability compared to QFNs, though MSL3 ratings have been achieved for large GaAs dies in 6×6 and 7×7 laminates.

CONCLUSION

Plastic overmolded QFN leadframes have been used successfully, with die-level compensation, for millimeter-wave applications up to 40 GHz. Above 40 GHz, or for demanding applications, cavity laminate packages offer improved electrical performance and greater flexibility to optimize performance for a particular product. Low material costs as well as array-form manufacturing and assembly have enabled low to moderate package cost at these frequencies and the replacement of chip-and-wire technology with surface-mount pick-and-place. This has driven continued growth in millimeter-wave applications and cost-effective access to underutilized spectrum for high data-rate applications. Thermal, electrical, reliability, and cost concerns are all addressed by QFN and cavity laminate packages, with trade-offs around performance and cost.

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REFERENCES

[1] A. Bessemoulin, Y. H. Suh, D. Richardson, S. J. Mahon, and J. T. Harvey, "A Compact 500-mW Ku-band Power Amplifier MMIC in 3×3-mm2 Quad Flat (QFN) Packages," in *European Microwave Integrated Circuits Conference, 2006. The 1st*, 2006, pp. 229-232.

[2] A. Bessemoulin, "A broadband 20- to 40 GHz linear driver amplifier MMIC in surface mount QFN 3×3-mm package," in Microwave Integrated Circuits Conference (EuMIC), 2010 European, 2010, pp. 310-312.

[3] E. R. Convert et al., "Packaged, Integrated 32 to 40 GHz Millimeter-Wave Up-Converter," in *2010 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, 2010, pp. 1-4.

[4] S. J. Mahon, A. P. Fattorini, E. R. O. Convert, R. G. Mould, P. W. Evans, and J. T. Harvey, "Packaged Q band medium power amplifier," in *2011 IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS)*, 2011, pp. 1-3.

[5] E. R. O. Convert et al., "Q band up-converter," in *2011 IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS)*, 2011, pp. 1-3.

[6] E. A. Sanjuan and S. S. Cahill, "QFN-based Millimeter Wave Packaging to 80GHz," in *IEEE MTT-S International Microwave Workshop Series on Signal Integrity and High-Speed Interconnects, 2009. IMWS 2009*, 2009, pp. 9-12.

[7] Young-Ho Suh, D. Richardson, A. Dadello, S. Mahon, and J. T. Harvey, "A low-cost high performance GaAs MMIC package using air-cavity ceramic quad flat non-leaded package up to 40 GHz," in *Microwave Conference, 2005 European*, 2005, vol. 3.

[8] M. J. Chen and S. A. Tabatabaei, "Broadband, Thin-Film, Liquid Crystal Polymer Air-Cavity Quad Flat No-Lead (QFN) Package," in *Annual IEEE Compound Semiconductor Integrated Circuit Symposium, 2009. CISC 2009*, 2009, pp. 1-4.

[9] P. F. Alleaume, C. Toussain, T. Huet, and M. Camiade, "Millimeter-wave SMT low cost plastic packages for automotive RADAR at 77GHz and high data rate E-band radios," in *Microwave Symposium Digest, 2009. MTT '09. IEEE MTT-S International*, 2009, pp. 789-792.

[10] S. Masuda et al., "A 100-GHz distributed amplifier in chip-size package," in *Microwave Symposium Digest, 2003 IEEE MTT-S International*, 2003, vol. 2, pp. 1029- 1032 vol.2.

[11] JEDEC Solid-State Technology Association, MO-220 Issue K, June 2006.

[12] Tan Boo Wei, Wang Lei, K. Niu, and Lu Hai Long, "Application Of Ultra Low Loop gold wire bonding technique in Super Thin (Jedec Package Profile Height Sub Code 'X2') Quad Flat No Lead Package (QFN)," in *Electronic Manufacturing Technology Symposium (IEMT), 2008 33rd IEEE/CPMT International*, 2008, pp. 1-6.

[13] T. Montes de Oca, B. Joiner, and T. Koschmieder, "Impact of board variables on the thermal performance of a QFN package," in *The Eighth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, 2002. ITHERM 2002*, 2002, pp. 512- 519.

[14] Minshu Zhang, S. W. Lee, J. Zhang, H. Yun, D. Starkey, and Hung Chau, "Correlation between material selection and moisture sensitivity levels of quad flat no-lead (QFN) packages," in *Microelectronics and Packaging Conference, 2009. EMPC 2009. European*, 2009, pp. 1-6.

[15] CST Microwave Studio, http://www.cst.com/

[16] T. Tischler, M. Rudolph, A. Kilk, and W. Heinrich, "Via arrays for grounding in multilayer packaging - frequency limits and design rules," in *Microwave Symposium Digest, 2003 IEEE MTT-S International*, 2003, vol. 2, pp. 1147- 1150 vol 2.