



MICROWAVE CORPORATION v01.0512 Thermal Management for Surface Mount Components

Thermal Management for Surface Mount Components

General Application Note



Introduction

As the power dissipation and availability of surface mount RF power amplifiers has increased, the need for careful thermal management of the next higher level assembly has become increasingly important. Previous generation RF power amplifiers were generally available in flange mount style packaging that inherently provided a mechanical and thermal mount for these devices directly to a metallic housing. However, these devices could not be surface-mounted on a circuit board and, as a result, increased the product cost. Current generation RF power amplifiers are generally available in surface-mount QFN packages that can be attached to traditional PCB's via mature reflow soldering processes.

With this new package style, the PCB now has to function not only as the RF interconnection between devices, but also the path to conduct heat away from the power amplifier. The ability of the PCB to conduct heat depends directly on the materials, layout and design of the PCB. This application note will detail the methods needed to analyze the PCB design to ensure it will serve as an adequate thermal interface between the RF power amplifier and the heat sink.

Review of Thermal Concepts

Heat Flow

When a temperature difference exists across a material, heat will flow from the higher temperature areas to the lower temperature areas. This process is analogous to an electric current flowing through a circuit from higher potential (voltage) to lower potential. Heat flow is measured in Watts and in electrical circuits is due to the conversion of electrical power (in Watts) to heat.

Thermal Resistance

All materials will conduct heat to some degree. The standard measure of the ability of materials to conduct heat

is thermal conductivity. Values of thermal conductivity are typically specified in units of $\frac{W}{m \cdot ^\circ K}$. Once the thermal conductivity of a material is known, the thermal resistance of a volume of that material can be calculated as:

$$\Theta = \frac{length}{K \cdot Area} \quad (1)$$

where:

K = Thermal Conductivity (W/m-°K)

length = length (or thickness) of object (m)

area = Cross sectional area (m2)

Temperature

Following the analog of an electrical circuit, the temperature difference ΔT across a material with thermal resistance Θ and heat current Q flowing through it is:

$$\Delta T = Q \cdot \Theta$$

where:

ΔT = Temperature difference ($^{\circ}K$ or $^{\circ}C$)

Q = Heat current (W)

Θ = Thermal Resistance ($^{\circ}C/W$ or $^{\circ}K/W$)

Interpretation of Hittite’s Data Sheet

Device Thermal Resistance

Since the thermal resistance of a system is complex and often non-linear with temperature, it is usually necessary to develop a thermal model of the system using finite element analysis. In addition, physical measurements of temperature using infrared photography are employed to determine the actual temperature of device junctions while operating. Based on these analyses and measurements an equivalent thermal resistance can be determined under a specific set of conditions. This equivalent thermal resistance is only valid under the specific conditions at which it was measured and is usually determined at the maximum operating temperature. The thermal resistance of a device can be determined from the datasheet by converting the thermal derating factor (in $mW/^{\circ}C$) to a thermal resistance in $^{\circ}C/W$. A typical Absolute Maximum Ratings table is shown in Table 1. The device thermal resistance is commonly represented by the symbol Θ_{jc} since it represents the thermal resistance from the device junction (j) to package case (c). For QFN packages, the case is assumed to be the metallic slug on the bottom of the package. For non-slug packages, the “case” temperature is the foot of the leads.

Absolute Maximum Ratings

Supply Voltage (Vcc)	+5.5 Vdc
Control Voltage (Vpd)	+5.5 Vdc
Input Power (RFin)	+20 dBm
Channel Temperature	150 $^{\circ}C$
Continuous Pdiss (T = 85 $^{\circ}C$) (derate 72.5 $mW/^{\circ}C$ above 85 $^{\circ}C$)	4.71 W
Storage Temperature	-64 to +150 $^{\circ}C$
Operating Temperature	-40 to +85 $^{\circ}C$

Table 1 – Absolute maximum ratings table

From Table 1, the thermal resistance is calculated as:

$$\Theta_{jc} = \frac{1}{72.5 mW/^{\circ}C} = 13.79^{\circ}C/W$$

Maximum Channel Temperature

The maximum channel temperature is specified in the Absolute Maximum Ratings table for each product and depends on the particular process used for the device. For the example in Table 1, the maximum channel

temperature is specified at 150°C. Exceeding this maximum channel temperature will result in decreased life time and premature device failure. This will be discussed later when considering component reliability.

Operating Temperature Range

The operating temperature range for the part is specified at the package base. It is the user's responsibility to ensure the part is in an environment capable of maintaining the temperature within the specified limits.

Thermal Model of the Device and PCB Environment

To fully understand the complete thermal environment around the device, the various thermal paths and materials must be analyzed. Figure 1 shows a cross sectional schematic of a typical QFN package mounted to a laminate PCB that is attached to a heat sink. In this example, heat is being generated at the device junction (at the top of the DIE) and propagates down through the PCB and into the heat sink. Along this path there are several different materials and series/parallel thermal paths to follow. In order to determine the ultimate temperature at the junction of the device, an equivalent thermal resistance for the system must be calculated. This resistance, used in conjunction with the heat flow, will allow us to calculate the maximum junction temperature. This temperature will then be compared to the maximum specified channel temperature to determine if we will have reliable operation of the device.

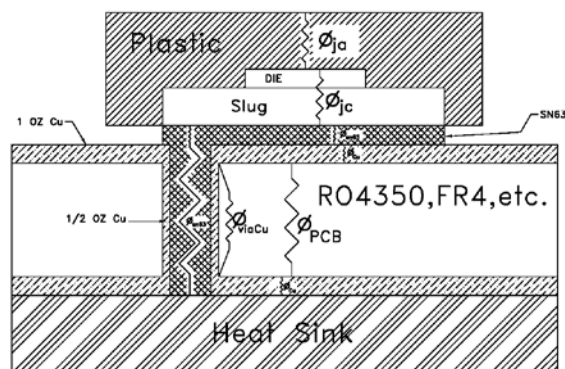


Figure 1 – QFN package mounted to a printed circuit board

In Figure 1, the various thermal paths from the junction to heat sink are depicted as follows:

Θ_{ja} = Thermal resistance from device junction to the top of the plastic package (ambient)

Θ_{jc} = Thermal resistance from junction to case (bottom metal slug of the package)

Θ_{sn63} = Thermal resistance of the solder

Θ_{Cu} = Thermal resistance of the copper plating on the PCB

Θ_{viaCu} = Thermal resistance of the copper plating of the via through holes

$\Theta_{viaSn63}$ = Thermal resistance of the solder filling the via

Θ_{PCB} = Thermal resistance of the PCB laminate material

In an actual circuit board, there will be multiple via holes and possibly multiple layers of printed circuit board. To determine the total thermal resistance, we will construct a thermal "circuit", calculate each thermal resistance and then determine the equivalent thermal resistance by combining the "series" and "parallel" thermal resistances.

Calculation of the Thermal Resistance of the System

For each thermal path, the thermal resistance will be calculated using equation 1. For each thermal resistance the thermal conductivity (K) of that material must be known. For convenience, thermal conductivities for materials commonly encountered in circuit board assemblies are shown in Table 2.

Material	Thermal Conductivity (W/in-°K)
Copper (Cu)	10.008
Aluminum (Al)	5.499
Rogers 4350 (RO4350)	0.016
FR4 or G-10 Laminate	0.008
Alumina (Al ₂ O ₃)	0.701
SN63 Solder	1.270
Thermally Conductive Epoxy	0.020
Gallium Arsenide (GaAs)	1.501
Plastic Mold Compound	0.019

Table 2 – Material thermal conductivities

Inspection of Figure 1 yields the equivalent thermal circuit of Figure 2. In Figure 2, it is assumed that the ambient temperature around the circuit is T_a and is constant. In a real assembly that is contained within an enclosure, this may not be the case and the ambient temperature may increase as power is dissipated. Since, the thermal resistance, θ_{ja} is usually large compared to θ_{jc} , the thermal path to ambient will be ignored in the analysis. Conversely T_{sink} , the temperature of the heat sink, is assumed to be its maximum allowable value and is the location where the heat current is being dissipated in a proper thermal design. How the heat sink is kept below its maximum temperature is beyond the scope of this application note and usually involves a combination of heat capacity, thermal conduction and thermal convection.

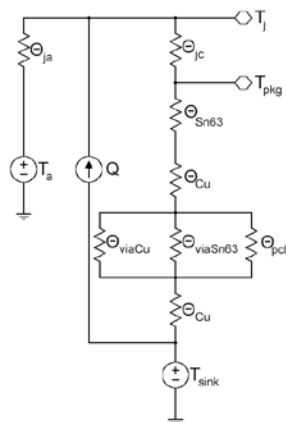


Figure 2 – Equivalent thermal circuit

Thermal Resistance Example: HMC408LP3 Evaluation Board

The HMC408LP3 power amplifier utilizes an evaluation board that is 0.010" thick and constructed of Rogers RO4350 laminate. The ground pad footprint is shown in Figure 3 and consists of a 0.065" x 0.065" area with five 0.012" diameter via holes. The plating on the top and bottom of the circuit board is 1 oz. copper (0.0014" thick). The via holes are plated through with ½ oz. copper (0.0007" thick). During assembly, the via holes are filled with SN63 solder. Analysis will show that nearly all of the heat current will flow through the solder-filled via holes. Therefore, the rest of the circuit board layout can be omitted for this analysis.

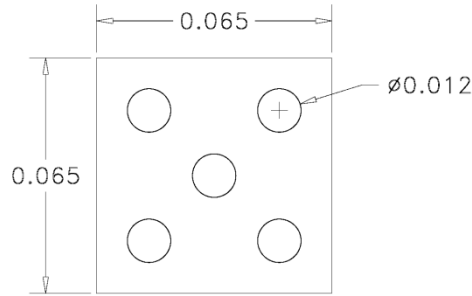


Figure 3 – Ground pad layout

Referring to Figure 2 and using equation 1, we can now calculate each thermal resistance. To calculate Θ_{sn63} , we use a thermal conductivity for SN63 solder of 1.27 W/in-°K, an area of 0.004225 in² (0.065" x 0.065"), and a length (thickness of the solder joint) of approximately 0.002".

$$\Theta_{sn63} = \frac{0.002}{1.27 \cdot 0.004225} = 0.372^{\circ}C/W$$

Next, the copper plating on the top side of the PCB will be calculated in similar fashion. The thermal conductivity of copper is 10.008 W/in-°K, length is 0.0014" (1 oz copper), and area is 0.00366 in².

$$\Theta_{Cu} = \frac{0.0014}{10.008 \cdot 0.00366} = 0.038^{\circ}C/W$$

The copper plating on the via hole has an area that is calculated by the formula:

$$area = \pi \cdot (r_o^2 - r_i^2)$$

where r_o is the outer radius

r_i is the inner radius

For an outer radius of 0.006" and inner radius of 0.0053" the area calculates to 0.00002485 in². The length of the via is the board thickness of 0.010" and the thermal conductivity of copper is 10.008 W/in-°K.

$$\Theta_{viaCu} = \frac{0.010}{10.008 \cdot 0.00002485} = 40.23^{\circ}C/W$$

Since there are 5 via's in "parallel", the equivalent resistance is 1/5th, or

$$\Theta_{viaCu} = 8.05^{\circ}C/W$$

The solder filling in the via's will be calculated in similar fashion as:

$$\Theta_{viaSn63} = \frac{0.010}{1.27 \cdot 0.0000882} = 89.27^{\circ}C/W$$

Again, since there are 5 filled via's, the equivalent thermal resistance is:

$$\Theta_{viaSn63} = 17.85^{\circ}C/W$$

Now, the thermal resistance of the PCB material will be calculated using an area of 0.00366 in², a length of 0.010 in and a thermal conductivity for Rogers RO4350 of 0.016 W/in-°K.

$$\Theta_{PCB} = \frac{0.010}{0.016 \cdot 0.00366} = 170.7^{\circ}C/W$$

From the equivalent circuit, we must take the "parallel" combination of the three thermal resistances Θ_{PCB} , Θ_{viaCu} and $\Theta_{viaSn63}$ which will give us Θ_{equiv} of 5.37 °C/W. So, the effect of filling the via's with solder was to reduce the thermal resistance from 8.05 °C/W to 5.37 °C/W. Finally, adding the "series" combinations of the thermal resistances will yield the thermal resistance of the entire PCB assembly of:

$$\Theta_{Assy} = \Theta_{Sn63} + \Theta_{Cu} + \Theta_{Equiv} + \Theta_{Cu} = 0.372 + 0.038 + 5.37 + 0.038 = 5.81^{\circ}C/W$$

Determining Dissipated Power

Once the thermal resistances have been determined, the heat current Q must be determined for the system. For RF devices, the quantity Q is the difference between the total power entering the device and the total power leaving the device. Total power includes the RF power and the DC power.

$$Q = Pin_{total} - Pout_{total} = (Pin_{RF} + Pin_{DC}) - Pout_{RF} \quad (2)$$

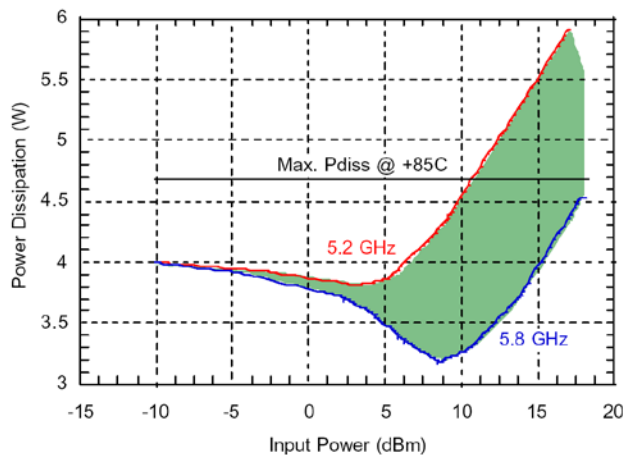


Figure 4 – HMC408LP3 power dissipation

For Hittite's HMC408LP3 power amplifier, equation 2 was used to calculate the power dissipation plotted in Figure 4. Inspection of Figure 4 reveals several interesting features of the amplifier:

The device dissipates approximately 4 watts of power with no RF input signal.

The power dissipation with RF signal applied is frequency dependent.

There is an input power at which the device dissipates minimum power.

From the equivalent thermal resistance Θ_{total} and the total power dissipation Q , the junction temperature can be calculated from $\Delta T = Q \cdot \Theta_{total}$.

$$\Theta_{total} = \Theta_{Assy} + \Theta_{jc} = 5.81 + 13.79 = 19.6^{\circ}C/W$$

For the quiescent condition with no RF input power, $Q = 4$ watts and

$$\Delta T = 4 \cdot 19.6 = 78.4^{\circ}C$$

Since the maximum junction temperature is given at $150^{\circ}C$, this would require the heat sink temperature to be $\leq 71.6^{\circ}C$. For convenience, a thermal worksheet like the one shown in Table 3 can be used to summarize these calculations.

When the HMC408LP3 power amplifier is in normal operation (and not highly compressed), the dissipated power from Figure 4 is actually less than 4 watts, indicating the heat sink temperature can be higher than $71.6^{\circ}C$. A useful feature of the HMC408LP3 amplifier is the V_{pd} current control which allows the user to shut down the amplifier when it is not needed. This effectively takes the power dissipation to near 0 watts and minimizes the problem of quiescent power dissipation.

Description	Line	Value	Units	Comments
Heat sink maximum temperature	1	70	$^{\circ}C$	
Assembly Thermal Resistance, Θ_{Assy}	2	5.81	$^{\circ}C/W$	Calculated from equivalent thermal circuit
Device thermal resistance, Θ_{jc}	3	13.79	$^{\circ}C/W$	From datasheet
Total thermal resistance, Θ_{total}	4	19.6	$^{\circ}C/W$	Add line 2 and 3
Maximum power dissipation, Q	5	4.0	W	
Junction Temperature Do not exceed maximum channel temperature listed on data sheet.	6	148.4	$^{\circ}C$	Line 1 + (line 4 x line 5)

Table 3 – Thermal worksheet

Reliability

The expected life time of a component is strongly dependent on the device operating stress¹, which in the case of power amplifiers, is usually temperature. Manufacturers of electronic components guarantee a minimum lifetime typically of 106 hours (114 years) at the maximum rated junction temperature. Operation at temperatures less than the maximum junction temperature will increase the lifetime of the device while exceeding the maximum can drastically reduce the life time. For this reason, the designer must respect the specified maximum junction temperature and perform a thermal analysis to ensure this maximum temperature is not exceeded under the expected operating conditions.

¹ <http://www.weibull.com/acceltestwebcontents.htm>



Conclusion

The emergence of surface mount power amplifiers in QFN packages requires the PCB to function not only as the RF interconnection between devices, but also the path to conduct heat away from the power amplifier. The ability of the PCB to conduct heat depends directly on the materials, layout and design of the PCB. This application note has detailed the methods needed to analyze the PCB so that it will serve as an adequate thermal interface between the RF power amplifier and the heat sink.

For further information, please visit our website at www.hittite.com, or contact Hittite Microwave Corporation directly at (978) 250-3343.