Application Report

SWRA672 – May 2020

Thermal Design Guide for Antenna on Package mmWave Sensor

Chethan Kumar Y.B.

ABSTRACT

This application report helps in the thermal design aspect of TI Antenna on package mmWave sensor products. In this document, you will navigate a series of tasks and key care abouts of thermal design aspects such as PCB design, thermal mitigation techniques involving trade-offs on board size, heat sink, power dissipation and use-case scenarios taking TI Antenna on package EVM as a reference. This document discusses design practices that ensure better thermal management, including some common methods for dissipating the heat from a PCB.

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1 Introduction

With the advent of RF CMOS and Antenna on packaging technology brings in the massive integration of complete mmWave sensor solution to extreme form factor level of the order of few 10s of mm. This solution includes mmWave sensor, PMIC, USB2.0 interface, clocking, external Flash interface and passive devices.

This enables a lower cost system solution, however, entire sensor dissipates close to 2.5W-3W power in such a small form factor design, compounds the thermal design problem. In this AOP mmWave sensor junction temperature needs to be kept under 105°C for Industrial and 125°C for automotive use-cases under all conditions.

This application report goes through the thermal design guide for AoP-based mmWave sensors and identifies the thermal hot-spots in the design and mitigates it through development of various techniques such as different duty cycles trade-off for power dissipation under various application scenarios. This includes the PCB sizes trade-off with the junction temperature, board design guideline for mitigating thermal aspects.

If the sensor requires higher performance with higher duty cycles, then heatsink designs will be explored depending upon use-case requirements and Board/System level optimizations.

This document also covers lesson learning through measurements, useful tips for the thermal design, also dwells on the PCB level thermal mitigation technique to dissipate the heat to keep the junction temperature under safe thermal limit.

2 mmWave AoP package

The antenna-on-package (AoP) mmWave sensor uses the under-mount silicon attached package, unlike other flip-chip-chip-scale package packages. In this package, die is exposed outside the package and attached to the substrate from the bottom side of the package.

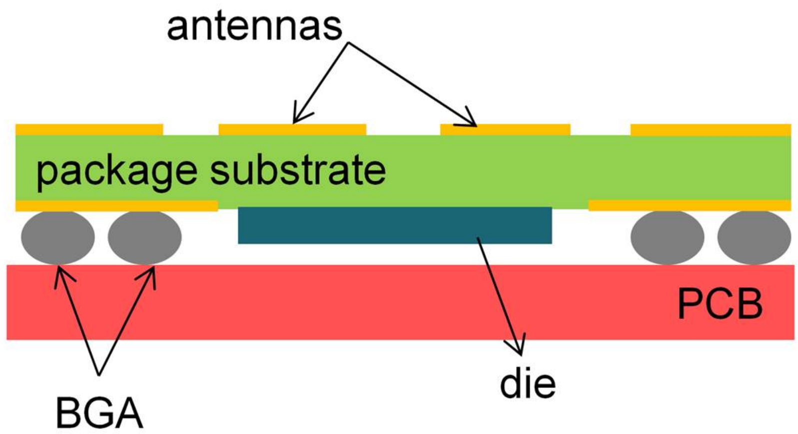

Figure 1. Under-Mount Silicon Package on a PCB

mmWave sensor package is 0.8 mm pitch, 180 balls, 15 mm x 15 mm dimension. This allows easy assembly and low-cost PCB design. BGA has fully populated balls in the package, which allows greater thermal contact to the PCB and also provides better mechanical and board level reliability for the package catering to automotive and industrial applications.

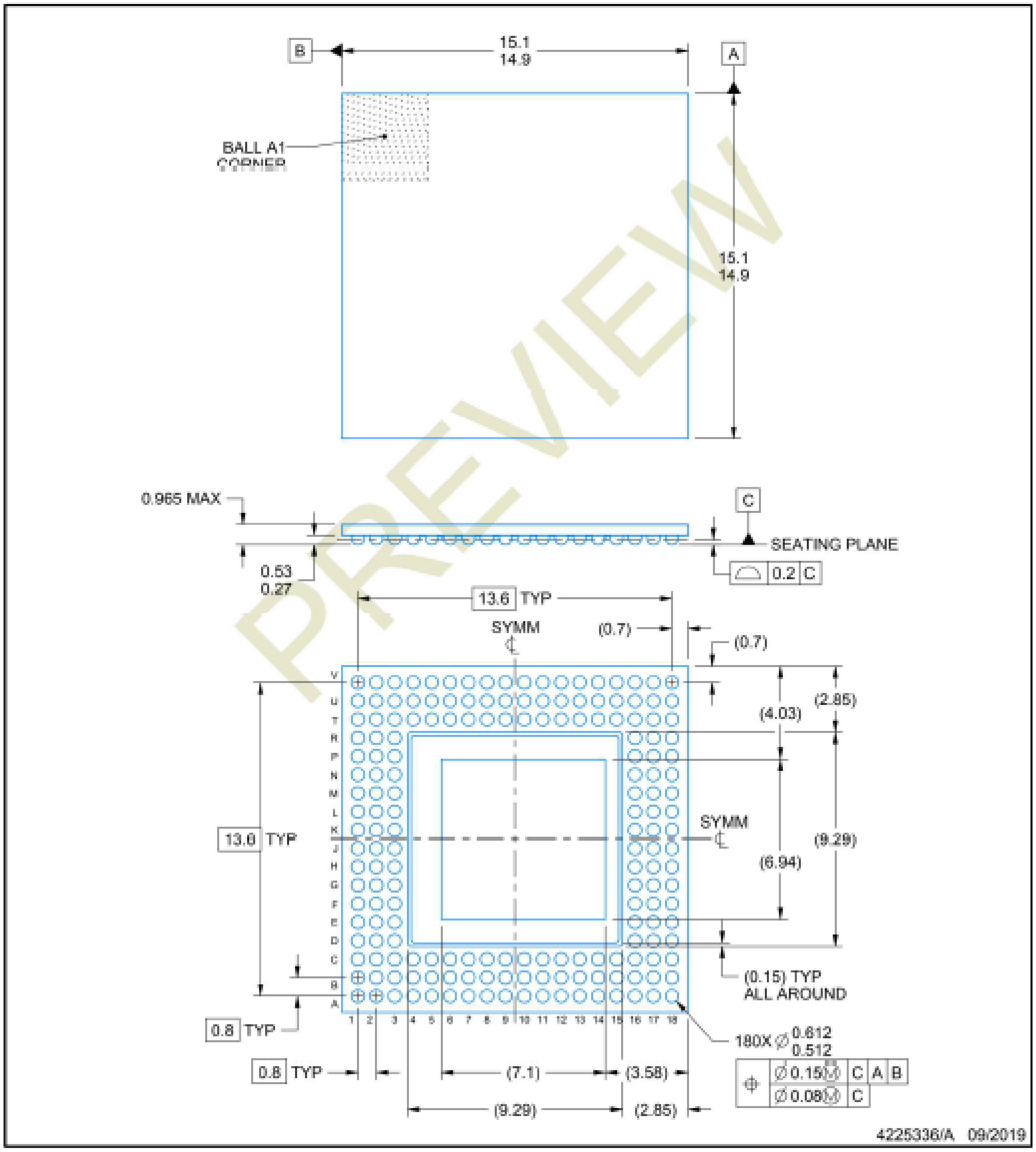

Figure 2. Package Outline Drawing

2.1 Thermal Characteristics of the Package

For the most updated numbers on the thermal characteristics of the package, see the *Thermal Resistance Characteristics* section in the device-specific data sheet. This thermal characteristic would be helpful in performing thermal simulation at a system level. You need to include thermal models of other components in the system such as PMIC, Flash, Heatsink and any other associated components including PCB characteristics.

From the thermal simulations, you could arrive at the right thermal dissipation profile keeping junction temperature of the device under safe operating limits (a maximum of 105°C for Industrial grade and 125°C for automotive grade applications). This also helps in arriving at the right system level thermal resistance needed for the application.

For more information about traditional and new thermal metrics, see *Semiconductor and IC Package Thermal Metrics*.

3 Salient features of AoP EVM

Figure 3 shows the salient components of top and bottom side of the EVM.

EVM is divided into two sections:

- Mission section
- Break away section

Mission section contains key essential components for the mmWave sensor as shown in Figure 3. Break away sections contain switches, connectors, Analog muxes and TI *Bluetooth*® devices that are optional for the system design.

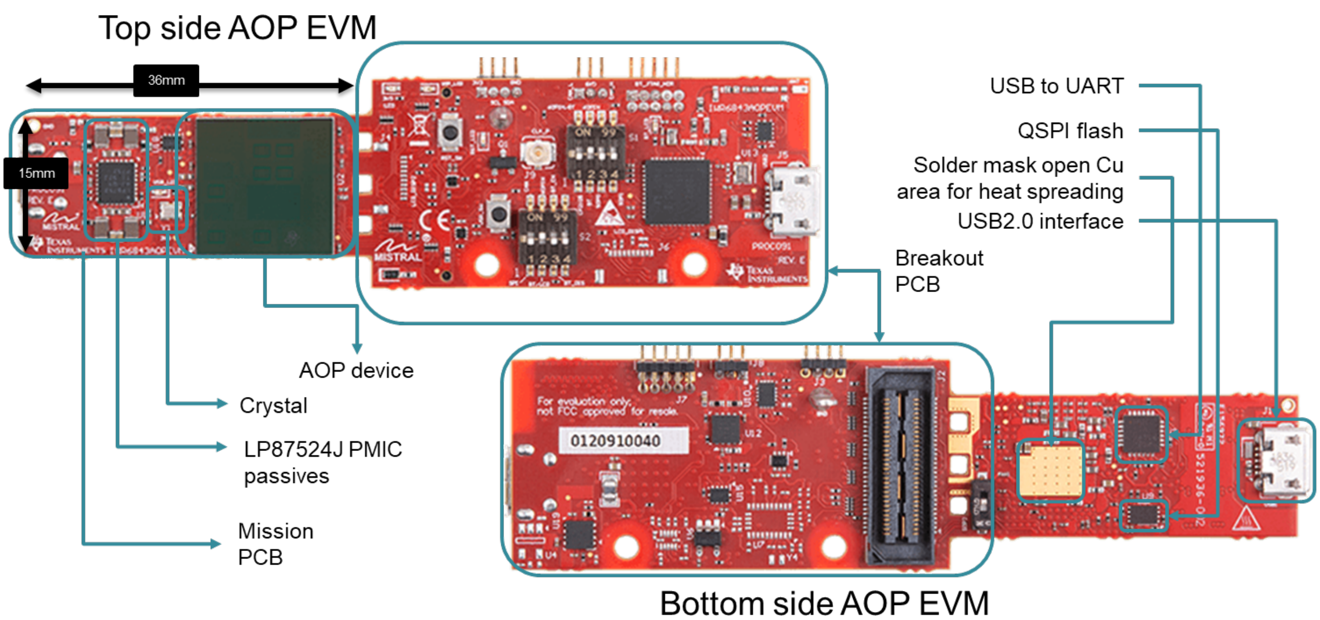

Figure 3. Salient Details of AOP EVM

3.1 Thermal Challenges in Dissipating the Heat

The size of the Antenna on package based mmWave sensor could be very small, for example, AoP EVM mission area where the entire radar system is packed under 15 mm x 36 mm, which poses further challenge to the heat dissipation problem for high performance and higher duty-cycled condition. Since the radar sensor has to be enclosed in a sealed box, there are limited options to dissipate the heat.

TI's Antenna-on-Package (AoP) Radar chip dissipates about 2W of power in a use-case (with 50% duty cycle: Use Case: 3.2 MSPS, 25-ms frame time, 256 chirps, 128 samples/chirp, 8-µs inter-chirp time DSP active). Other essential components of the Radar system such as PMIC and passives and QSPI Flash will dissipate another 0.5W-1.0W causing a total of 2.5W-3W of power dissipation.

The top side of the AoP device is an electromagnetic radiating surface, heat-sink on the top side is not an option. The bottom-side heat-sink is an option, but the size of the heat-sink has to be small due to cost/weight/other reasons.

Larger board size of the PCB is another option without using heat sink or other thermal mitigation techniques. For those use-cases targeted for small form-factor applications with severe size constraints, increasing the board size is not an option, then heat-sink from the bottom side of the PCB need to be explored.

4 Techniques for Mitigating the Heat Dissipation

4.1 Reduce the System Level Thermal Resistance

A low system thermal resistance ensures that the heat is transferred through the material much faster. Thermal resistance is directly proportional to the length of the thermal path and inversely proportional to the cross-sectional area and thermal conductivity of the thermal path.

Thermal resistance could be reduced by:

- Adding multiple thermal vias which transfers heat in vertical direction (preferably directly under the heating elements such as mmWave sensor and PMIC)
- Thicker Copper foils along with thicker traces helps in spreading heat in horizontal direction
- Component that has potential to dissipate heat (PMIC) placed away from the mmWave sensor to avoid hotspot.

Duty cycle of the Radar operation directly impacts the power dissipation and heat dissipation. Experiments are done to understand the effect of duty cycle on the chip temperature. Some of the below demo examples illustrate various duty-cycle options that are available for various applications.

Another major area of thermal management is in designing the low power supply distribution network. PMIC solution such as LP87524J without an LDO helps this cause.

For more details on the power management optimization using LC filter, see *XWR1xxx Power Management Optimizations – Low Cost LC Filter Solution*

mmWave sensor has multiple on-chip temperature sensors distributed across the die, which are used in measuring the die temperature.

There are various types of heat mitigating techniques that exists. In this application report, the following methods are explored:

- Board size scaling up to reduce the system thermal resistance
- Various Heat-sink techniques
- Application of Thermal Interface Material to spread the heat on to the larger PCB surface area
- PCB design techniques to effectively dissipate the heat.
- Lowering the power dissipation of the mmWave sensor itself depending upon application needs

For lowering the power dissipation, one of the easiest knobs is to reduce the frame rate in effect this would reduce the duty cycle, hence, there would be a reduction in the power dissipation. Active duty cycle is defined as time duration at which mmWave sensor is active (active duration of the chirps as compared to frame periodicity). Reduction of frame-rate has system level performance implications that must be examined.

NOTE: If the Tx start + idle time is greater than 10 µsec and the inter-chirp dynamic power save option is not disabled, then this duration would be excluded from the active duration of the chirp. Otherwise, it would be included in the active duration of the chirp in the duty-cycle calculation. For the exact duty-cycle calculation based on the chirp configuration, see the mmWave studio in sensor configuration tab.

4.2 Board Size Scaling

One of the ways to dissipate the heat is to use the board itself as a heat sink. The AoP mmWave sensor is built with FR4 PCB fabrication material designed to absorb the heat. In lot of the cases, it would satisfactorily handle the heat dissipation.

Copper traces/planes will have greater thermal conductivity than dielectric material of the PCB and readily conduct the heat through traces and planes in to larger section of the PCB. Hence, filled Cu material with plated through holes on the top/bottom and inner layers would help in spreading the heat to larger surface areas.

As a case study, various thermal simulations were performed to understand the effect of system thermal resistance on scaling of the board size at room temperature of 25 deg C. First mission side of the AOP board size is chosen and its thermal model is extracted and simulation results are extracted to different board size.

Table 1. Thermal Resistance Characteristics for 10% Duty Cycle for Various PCB Sizes

10% Duty PCB	PCB Area (mm2)	Device P (W)	Total P (W)	Tj (°C)	Case Temp (°C)	Board Temp (°C)	Psi-jc (°C/W)	Psi-jb (°C/W)	Effective Rja (°C/W)
Mission section PCB	580	0.8808	1.2054	85.5	82.9	76.3	2.9	10.4	68.7
Square PCB 30	900	0.8808	1.2054	73.1	70.6	64.5	2.9	9.8	54.6
Square PCB 40	1600	0.8808	1.2054	62.0	59.5	53.3	2.9	9.8	42.0
Square PCB 55	3025	0.8808	1.2054	53.9	51.4	45.2	2.9	9.9	32.8
Square PCB 65	4225	0.8808	1.2054	51.0	48.4	42.3	2.9	9.8	29.5

Table 2. Thermal Resistance Characteristics for 25% Duty Cycle for Various PCB Sizes

25% Duty PCB	PCB Area (mm2)	Device P (W)	Total P (W)	Tj (°C)	Case Temp (°C)	Board Temp (°C)	Psi-jc (°C/W)	Psi-jb (°C/W)	Effective Rja (°C/W)
Mission section PCB	580	1.2589	1.6838	105.1	102.1	92.7	2.4	9.8	63.6
Square PCB 30	900	1.2589	1.6838	88.6	85.6	77.0	2.4	9.2	50.5
Square PCB 40	1600	1.2589	1.6838	74.2	71.3	62.6	2.4	9.2	39.1
Square PCB 55	3025	1.2589	1.6838	63.7	60.8	52.0	2.3	9.3	30.7
Square PCB 65	4225	1.2589	1.6838	59.9	57.0	48.3	2.3	9.3	27.7

Table 3. Thermal Resistance Characteristics for 50% Duty Cycle for Various PCB Sizes

50% Duty PCB	PCB Area (mm2)	Device P (W)	Total P (W)	Tj (°C)	Case Temp (°C)	Board Temp (°C)	Psi-jc (°C/W)	Psi-jb (°C/W)	Effective Rja (°C/W)
Mission section PCB	580	1.9	2.4949	134.3	130.0	116.4	2.3	9.4	57.5
Square PCB 30	900	1.9	2.4949	113.6	109.3	96.4	2.3	9.1	46.6
Square PCB 40	1600	1.9	2.4949	94.4	90.1	77.1	2.3	9.1	36.5
Square PCB 55	3025	1.9	2.4949	80.3	76.0	62.9	2.3	9.1	29.1
Square PCB 65	4225	1.9	2.4949	75.2	70.9	57.9	2.3	9.1	26.4

Figure 4 provides the summary of the effective thermal resistance junction to ambient for various board size and power dissipations.

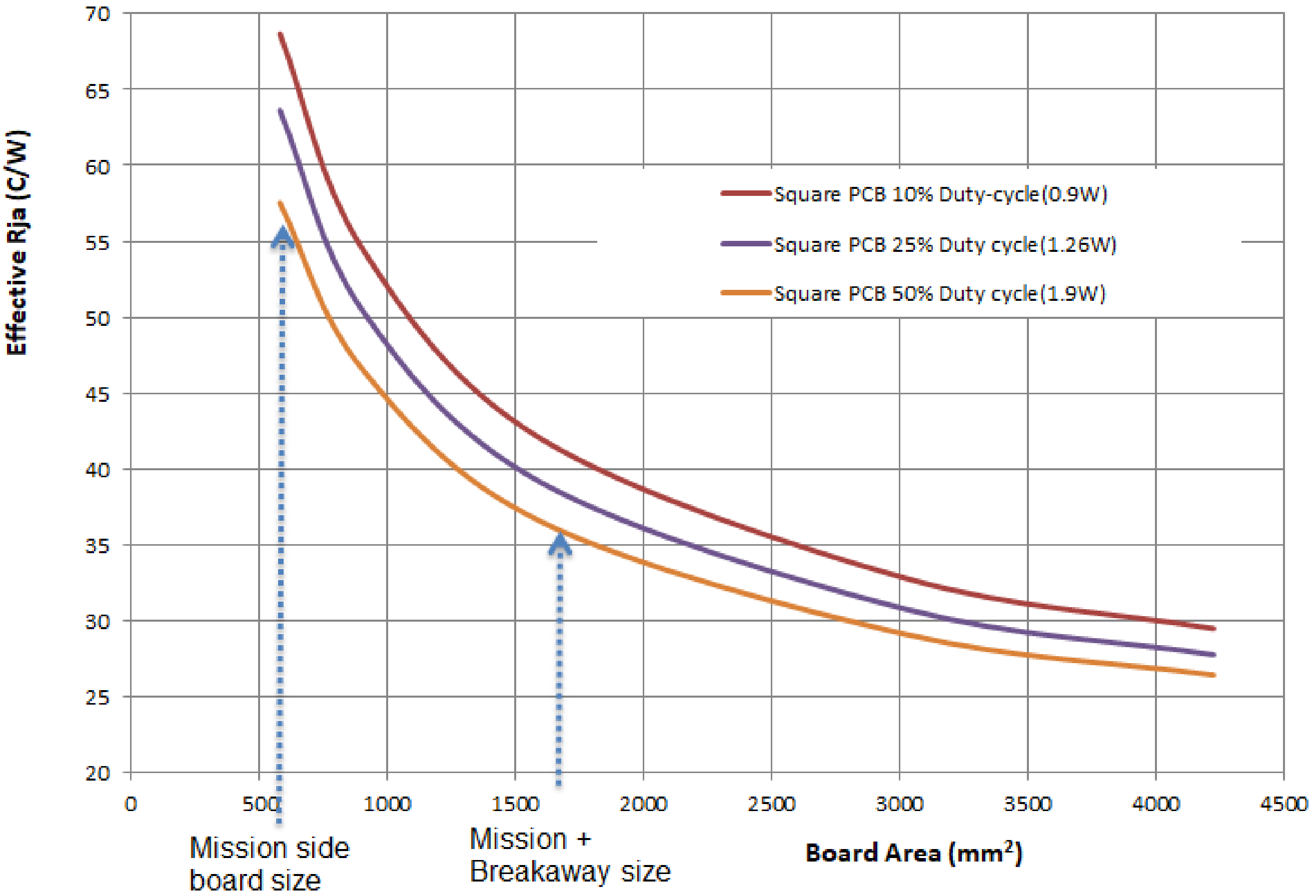

Figure 4. Effective Thermal Resistance vs Board Size for Various Duty Cycles

It can be seen from the graph mission side alone PCB size (580) shows effective thermal resistance Rja close to 57-68 Deg C/W depending upon the duty cycle, Hence it has limited amount of power dissipation it can handle without using additional measures such as heatsink or enclosure to take the heat out from the board. However as PCB size increases it can be seen effective thermal resistance decreases beyond 3000 sq mm there is diminishing return from the board size increase in reducing effective thermal resistance.

Figure 5 and Figure 6 shows the thermal simulation example done on the mission section of the EVM without any heatsink at 10% and 25% duty cycles, 25°C ambient temperatures.

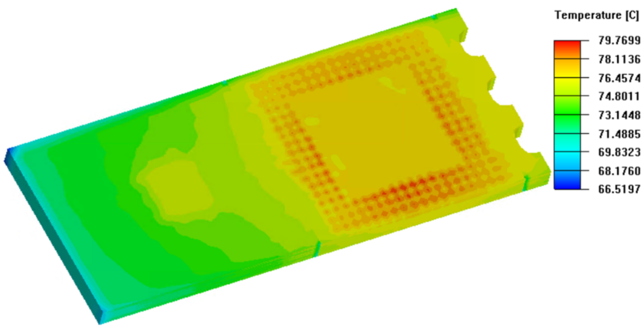

Figure 5. Thermal Simulation of Mission Side EVM With 10% Duty Cycle

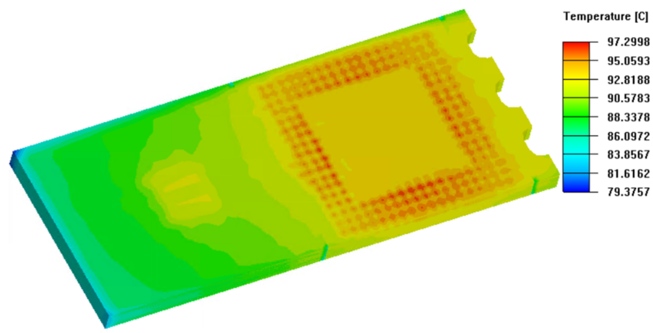

Figure 6. Thermal Simulation of Mission Side EVM With 25% Duty Cycle

It can be seen from the simulation at 25% duty cycle and above, there is very little margin to reach maximum junction temperature. Hence it's recommended to operate under 10% duty cycle without any heatsink or other thermal measures.

4.3 Heatsink Options

4.3.1 Sheet Metal Heat Sink

The heat sink is not a mandatory requirement for AoP mmWave sensor. If the board size is smaller, it is likely to get warmer than other larger sized PCBs, Hence, care must be taken to ensure the junction temperature does not exceed maximum permissible level stated in the mmWave sensor data sheets.

4.3.2 Heat Sink Details

Figure 7 shows an example of the low-cost heatsink made developed using sheet metal. This is mainly designed for AoP EVM. This could be customized depending upon your needs and the desired system level thermal resistance target.

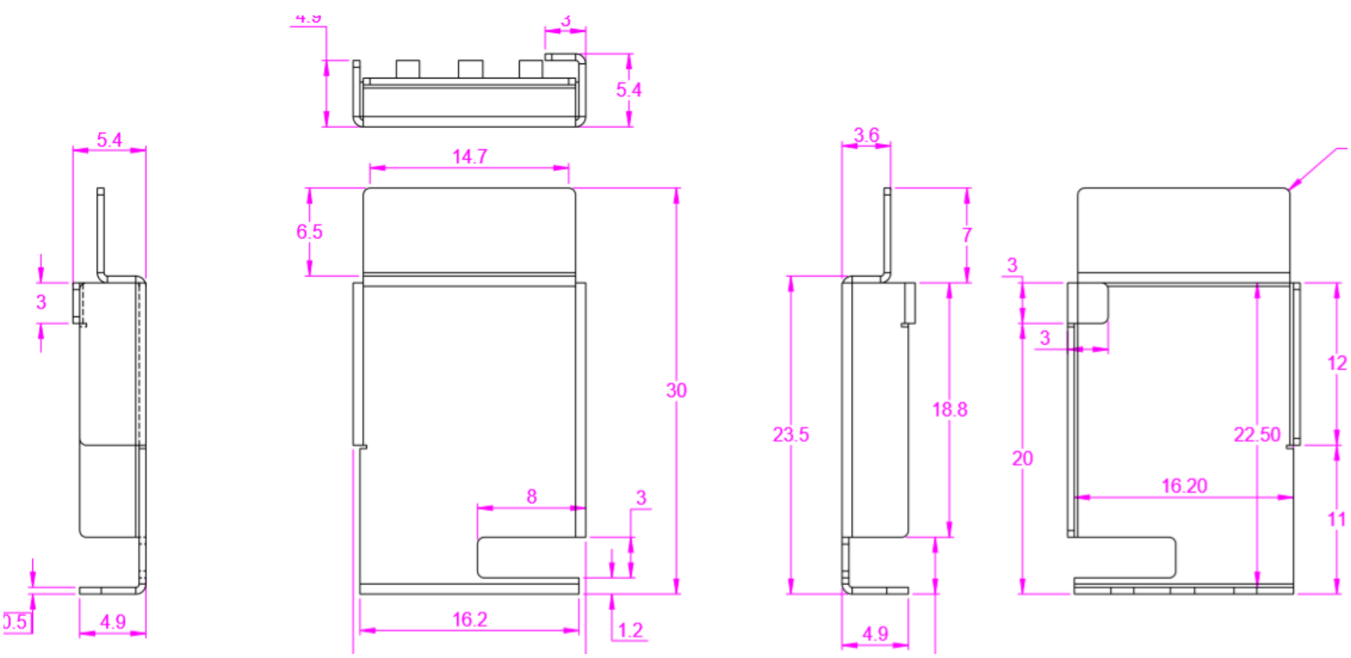

Figure 7. Sheet Metal Dimensional Details

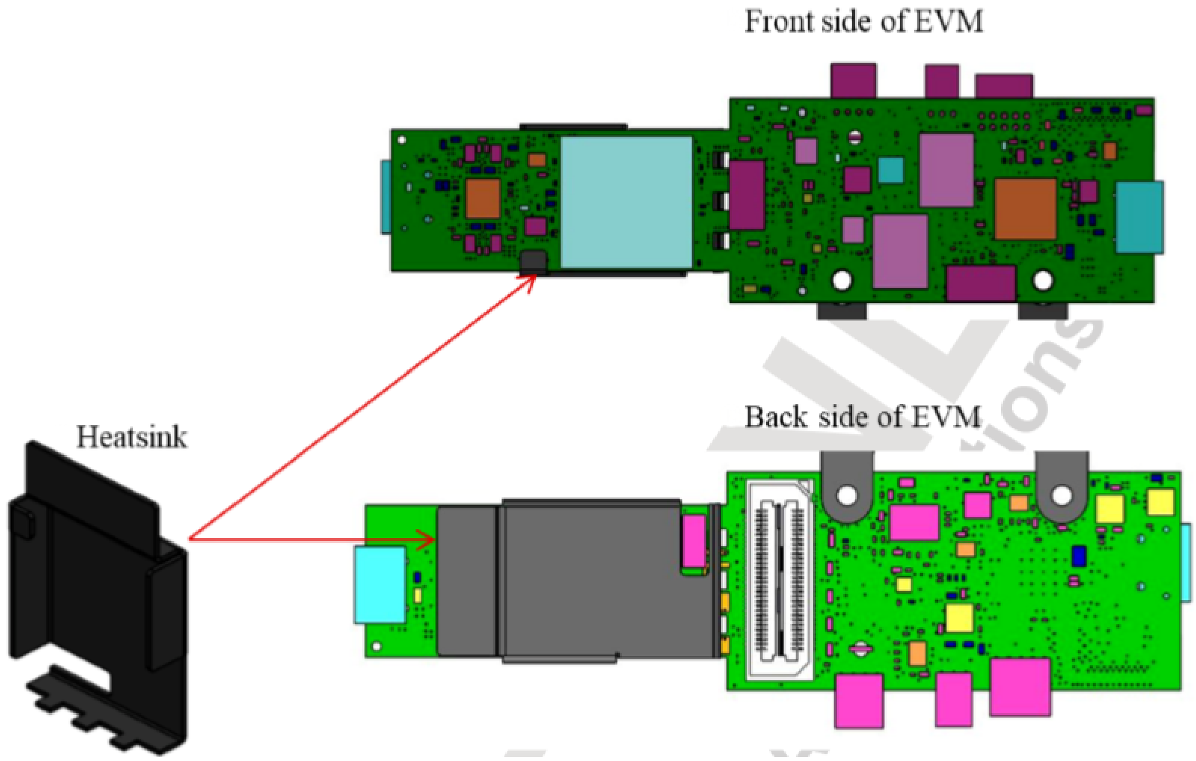

Figure 8. Sheet Metal Heat-Sink Used in the Form-Factor EVM

4.3.3 Mounting Options

Heat sink is mounted from the bottom side of the PCB, as TOP side of the PCB has Antennas on package, any metal elements close to the antenna will affect antenna radiation pattern. Hence, care needs to be taken any heat sink metal elements are away from the Antenna regions. Clamps on the heat sink helps in taking heat from the top layer of PCB and spreads it on the bottom side of the PCB on the heat sink uniformly.

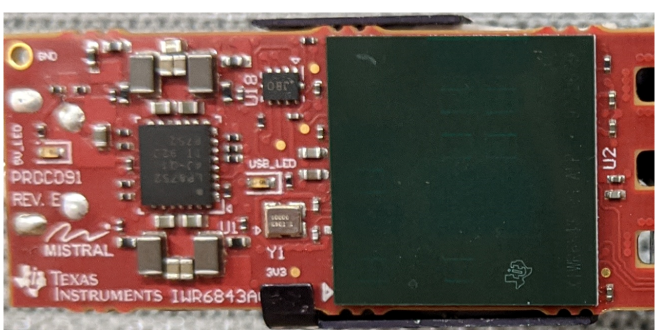

Figure 9. Top Side of the EVM With Heatsink Mounted

Figure 10. Bottom Side of the EVM With Heatsink Mounted

Sheet-metal heat sinks are lower cost, easier to manufacture and customize according to board requirements.

4.3.4 Thermal Characteristics With the Sheet-Metal Heatsink

Figure 11 shows measurement of the junction temperature versus duty cycle taken with and without the heat sink. As seen in the plot, EVM can safely operate up to 50% duty cycle.

In this example two cases are taken:

- PCB without using heat sink
- PCB with sheet metal based heatsink.

Figure 11 shows that sheet-metal based heatsink provides improvement in reducing the junction temperature for various duty-cycle conditions.

NOTE: Linear interpolation is plotted for both the cases.

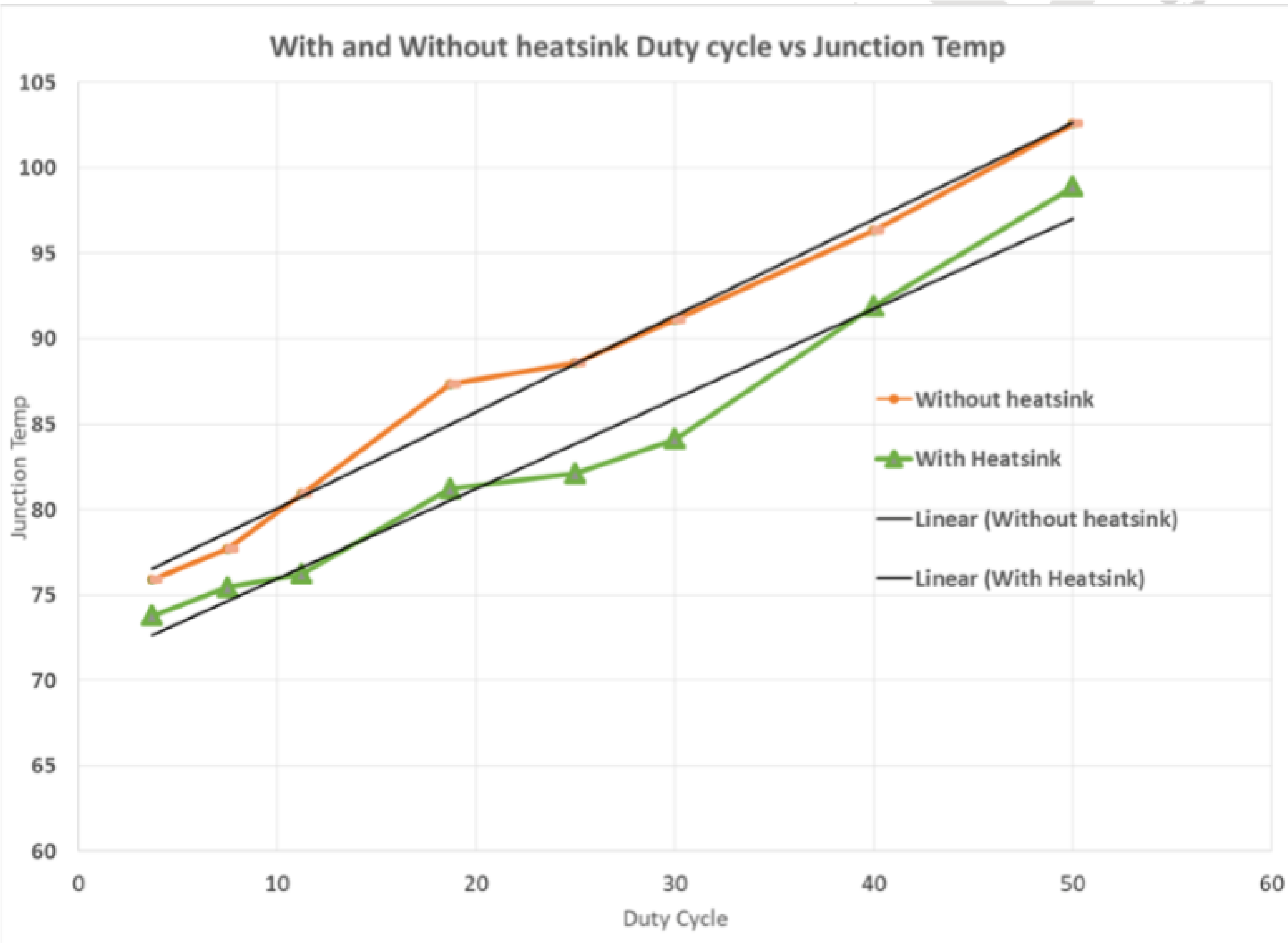

Figure 11. Thermal Characteristics of mmWave AoP Sensor With and Without Sheet Metal-Based Heatsink

Figure 12 is the thermal (infrared) image of the board for one of the previous versions of the board with the sheet metal based heatsink. Thermal image clearly showing heat is transferred from the top side of the board to the bottom side of the board and heat is spread uniformly, hence max junction temperature is reduced on top and bottom surface.

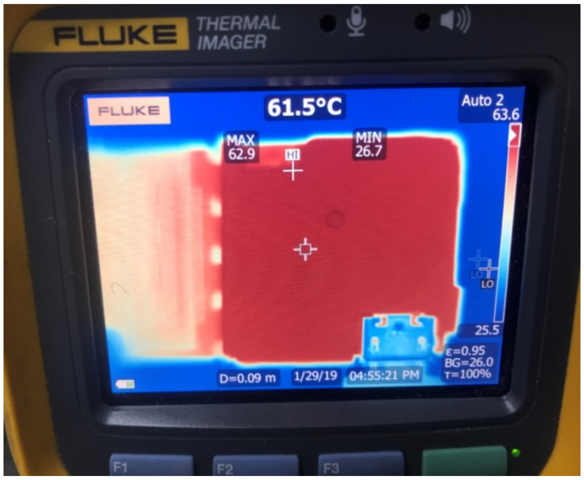

Figure 12. Thermal Imaging of the EVM (top side with heatsink mounted)

Figure 13. Thermal Imaging of the EVM (bottom side with heatsink mounted)

4.4 Heatsink with fins

Heatsink with fins will provide further improvement in thermal performance for the sensor at the expense of larger surface area and complexity in the heatsink design. Fin configuration provides larger surface area to dissipate the heat. In general, the larger the surface area, the better the heat sinking capabilities. This experiment and measurement were done on one of the older version of AoP board.

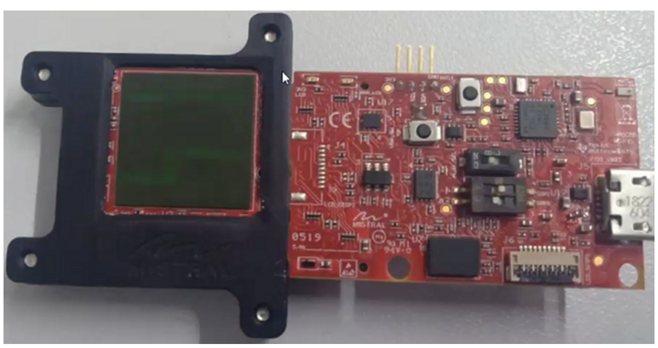

Figure 14. Top Side of the EVM With Heatsink Mounted

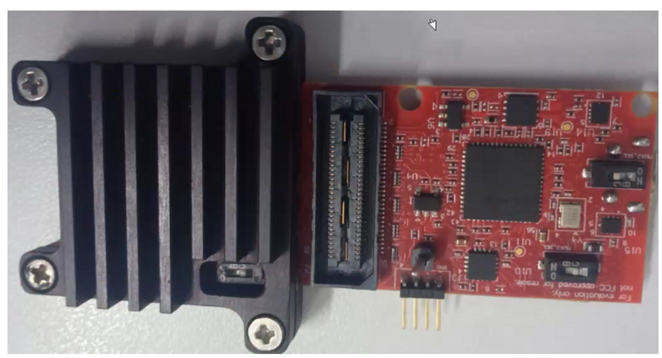

Figure 15. Bottom Side of the EVM With Heatsink With the FINS Mounted

4.4.1 Thermal Characteristics With the Heatsink

Figure 16 shows the thermal characteristics of the mmWave sensor board across different duty cycles using FIN based heatsink.

In this example, two cases are taken:

- PCB without using heatsink
- PCB with FIN metal based heatsink.

Figure 16 shows that FIN-metal based heatsink provides even more improvement in reducing the junction temperature over the sheet metal based heatsinks for various duty-cycle conditions.

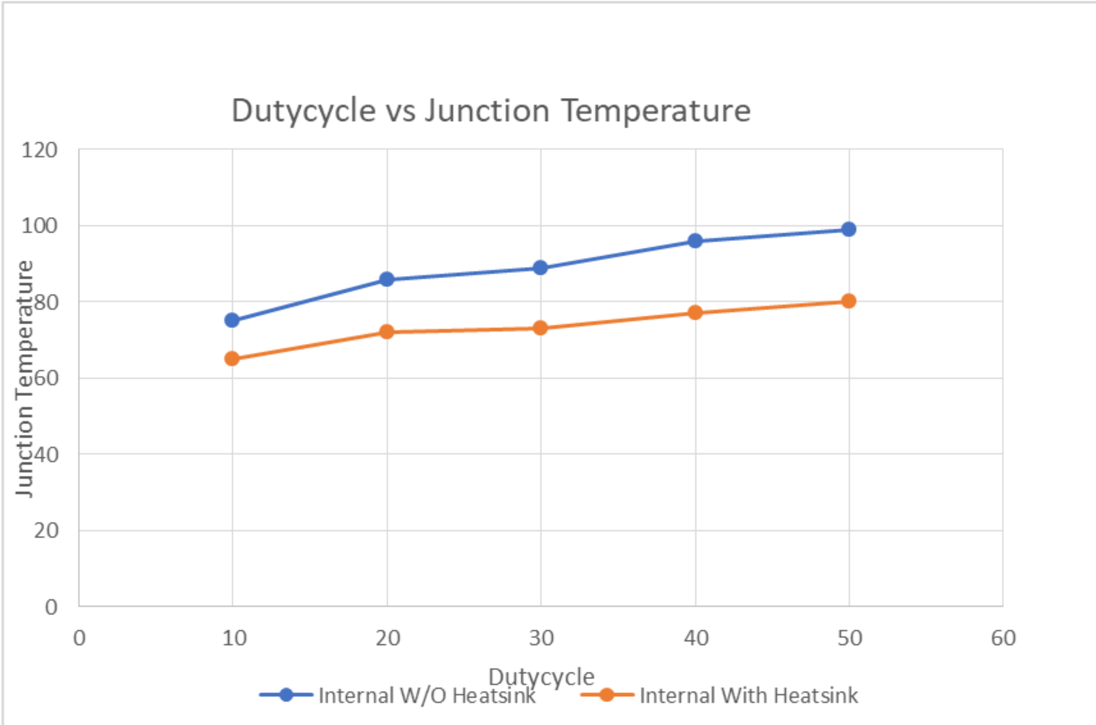

Figure 16. Thermal Characteristics of mmwave AoP Sensor With and Without FIN Metal-Based Heatsink

5 PCB based thermal improvements

Proper PCB layout, focusing on thermal performance, results in lower die temperatures. Wide and thick power traces come with the ability to sink dissipated heat. This can be improved further on multi-layer PCB designs with vias to different planes. This results in reduced junction-to-ambient (RθJA) and junction-to-board (RθJB) thermal resistances and thereby reduces the device junction temperature, TJ. TI strongly recommends performing of a careful system-level 2D or full 3D dynamic thermal analysis at the beginning product design process, by using thermal modeling analysis software.

Figure 17 shows the top and bottom side of the AOP EVM, under the BGA area via array is placed which connects to ground layers in the board.

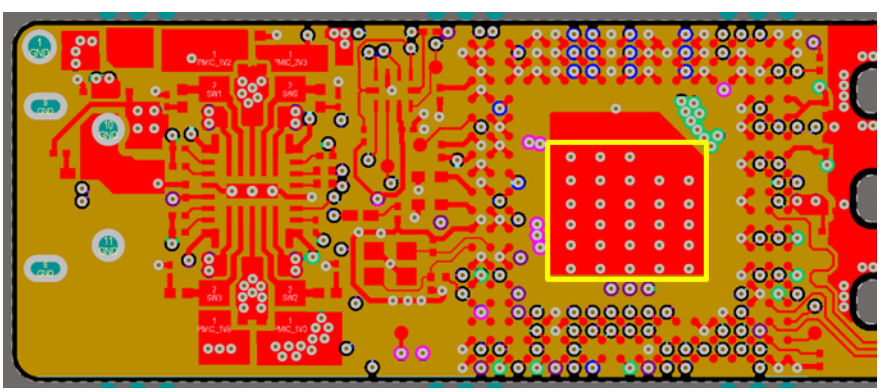

Figure 17. Top Side of the PCB Layout Around the Sensor and PMIC Regions

On the bottom side of the board, below the BGA area solder mask could be opened. This would help in taking the heat out through the heatsink, as shown in Figure 18.

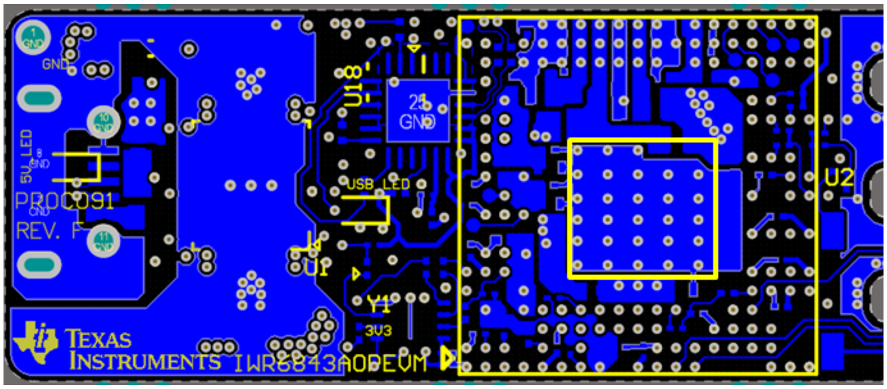

Figure 18. Bottom Side of the PCB Layout Around the Sensor and PMIC Regions

Provision for large GND plane/shape as allowable on the top, bottom and inner layers benefits distributing the heat laterally, especially right near the heat dissipating package would be beneficial for spreading the heat.

5.1 Thermal via array

During the PCB design thermal vias plays important role in spreading the heat.

Plated through Via arrays are provided for planes and grounds in hotspot regions such as PMIC and underneath the sensors, these will help in spreading the heat to inner planes. Thicker plated through vias helps in better thermal conductivity, however excessive larger perforation of the PCB material also not recommended due to weakening power integrity.

Solid filled vias could be employed to conduct heat from thermal pads into ground planes; however, this will slightly increase the cost and complexity of PCB manufacturing process.

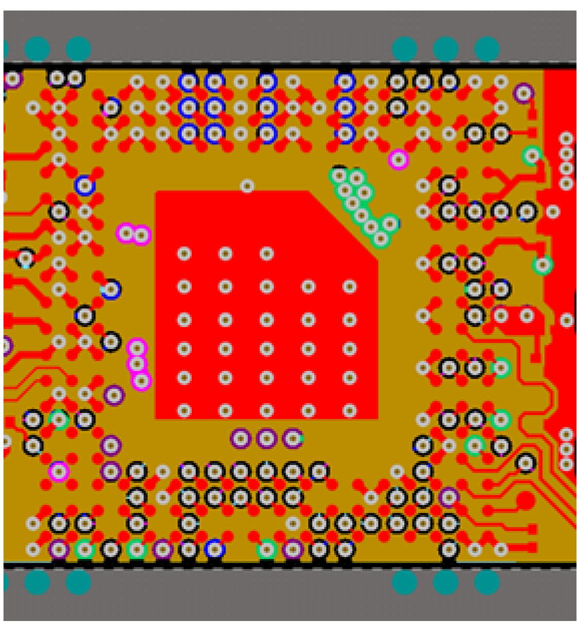

Figure 19. Via Placement Under the BGA Top Side Layout Image

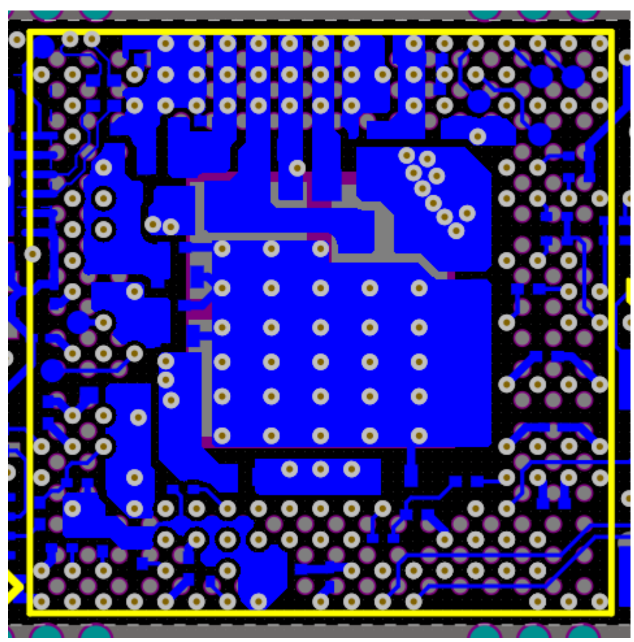

Figure 20. Via Placement Under the BGA Bottom Side Layout Image

Usage of large and multi-layer PCB boards helps to dissipate the heat; in this board 8 layers are used. Thicker copper clad is used in the inner ground/power planes. Thicker copper planes are better such as 2 oz copper in the inner plane and power layers. This also helps in improving the ground and power impedance along with better conductivity for the thermal. Care needs to be taken on the top, bottom routing layers aspect ratio of the traces need to be followed as per PCB fabricators recommendation. Sometimes too thick copper planes might restrict the minim trace width allowed in the design from high volume and reliable manufacturing perspective. Hence, this needs to be discussed with PCB fabricator before arriving right value. Also thicker copper will have slightly higher cost on the PCB manufacturing, hence right balance between cost and thermal design need to be considered.

Layer	Name	Material	Thickness
1	Top Overlay		
2	Top Solder	Solder Resist	0.50mil
3	Top Layer	Copper	1.37mil
4	Dielectric1	FR-4 High Tg	3.70mil
5	GND1	Copper	2.40mil
6	Dielectric3	FR-4 High Tg	4.50mil
7	Sig1	Copper	1.20mil
8	Dielectric2	FR-4 High Tg	12.00mil
9	PWR1	Copper	2.40mil
10	Dielectric4	FR-4 High Tg	8.00mil
11	PWR2	Copper	2.40mil
12	Dielectric5	FR-4 High Tg	12.00mil
13	Sig2	Copper	1.20mil
14	Dielectric8	FR-4 High Tg	4.50mil
15	GND2	Copper	2.40mil
16	Dielectric9	FR-4 High Tg	3.70mil
17	Bottom Layer	Copper	1.37mil
18	Bottom Solder	Solder Resist	0.50mil
19	Bottom Overlay		

Figure 21. Layer Stack-Up and Copper Thickness

6 Application and Demos

Table 4 lists some of the example demos and its chirp design duty cycles. These demos could be configurable depending upon performance requirement from end equipment point of view.

Table 4 illustrates that the EVM allows a maximum temperature without any further thermal mitigation techniques (such as board size increase, thermal interface material or without any enclosure design) for various demo configurations. With additional thermal improvement techniques (heatsink), the maximum allowed temperature can be taken higher.

Table 4. Various TI mmWave Demos and Its Duty Cycles

Demo Examples	Duty Cycle (1)	Margin to 105°C(3)	Max Temp Allowed in °C (from 25°C)(3)	EVM (Mission section only)	Simulated square board size (1)	EVM (Mission + Break-away)	EVM (Mission + Break-away)	Simulated square board size(2)
Board size				540 Sq mm	1600 sq mm	1759 Sq mm	1759 Sq mm	2500 sq mm
Heatsink				No	No	No	Yes	No
Sense and Direct	<35%	17	42	-	√	-	√	√
3D People Counting	>29%	21	46	-	√	-	√	√
Outdoor (Long Range) People counting	>25%	<23	48	-	√	-	√	√
Gesture	~25%	23	48	-	√	√	√	√
Indoor People Counting	>25%	<23	48	-	√	√	√	√
Automated Door	<10%	32	57	√	√	√	√	√
Area scanner:	<10%	32	57	√	√	√	√	√
ROS sense/avoid	<10%	32	57	√	√	√	√	√
OOB demo	<10%	32	57	√	√	√	√	√

(1) Based on Thermal simulation data estimate only with ~15°C margin to 105°C.
(2) Based on Thermal simulation data estimate only with ~20°C margin to 105°C.
(3) These column refer to EVM (Mission + Break-away) with sheet metal heatsink.

Figure 22 shows junction temperature in °C vs % duty cycle. In the graphs various demos are mapped to X-axis indicating its duty cycle used for the demonstration.

It can be seen at lower duty cycle cases, lower power consumption from the sensor is expected, hence it would allow maximum operating temperature margin. At higher duty-cycles sensor power, dissipation is higher, hence the allowed maximum operating temperature margin would be lower. This is a rough guidance on how duty cycle and power dissipation could be traded-off to arrive at the right operating junction temperature. Tick marks indicate lower duty-cycled cases. The EVM has a sufficient thermal margin to operate at higher duty-cycled cases, further thermal considerations (such as heatsink) are needed.

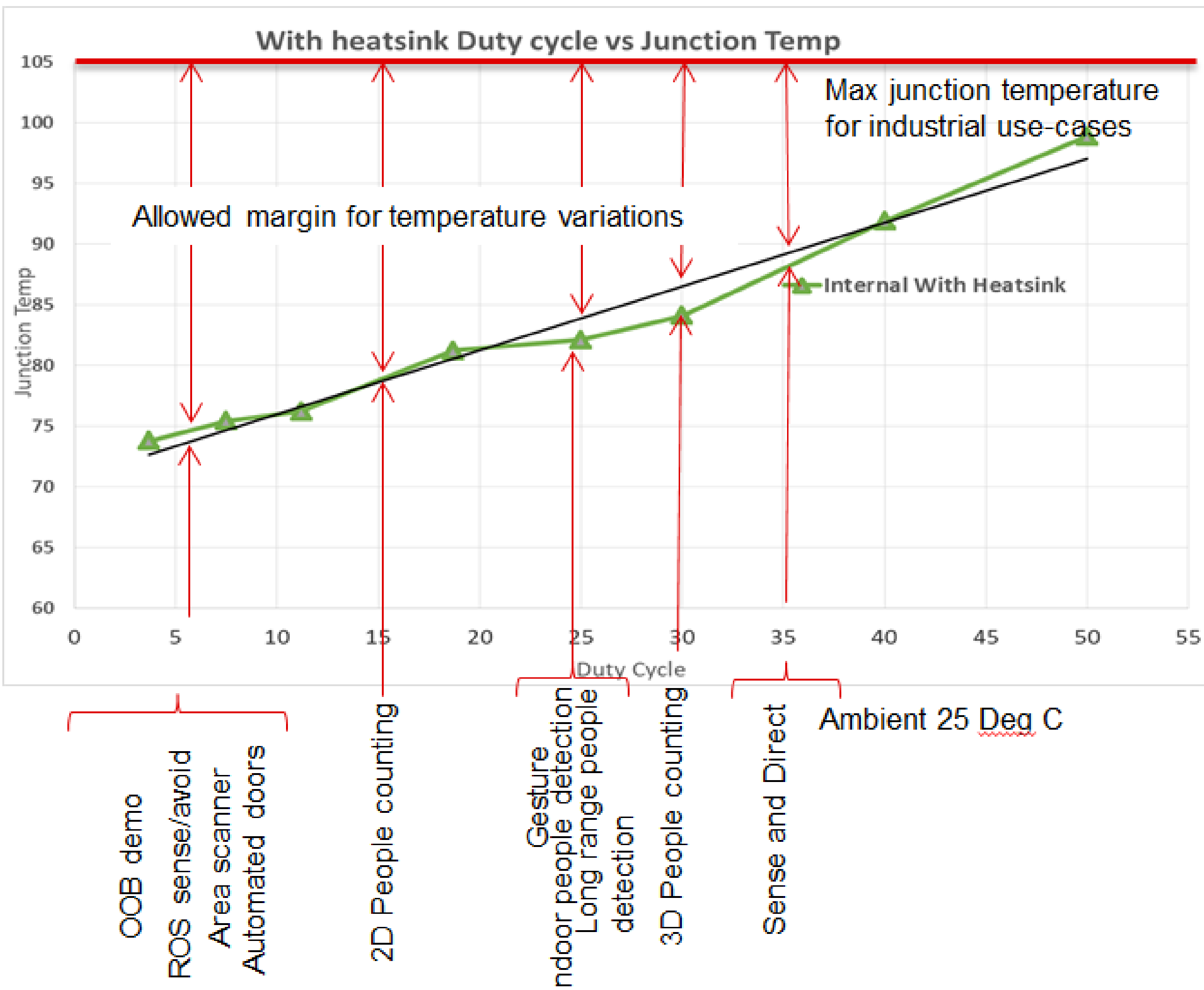

Figure 22. Thermal Characteristics of Various Demos Under Its Operating Conditions

7 Summary

In this application report, an attempt has been made to demonstrate thermal design and measurements on a small form factor AoP EVM. During this development, thermal simulations were carried out to identify trade-off between board size, power dissipation and effective Rja. Also demonstrated various heatsinks and its effect on reduction of junction temperature. This report also explored system level and board level techniques and best practice for the thermal design.

8 Acknowledgment

Author would like to acknowledge Nguyen, Hiep for help in thermal modeling and thermal simulations and Mistral team for the various thermal activities done on AOP development.

Also would like to thank Industrial mmWave sensor team for various support activity during this development.

9 References

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