

5.3. Improving Switched-Mode Power Supplies Performance with Modified Thermal Interface Material

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ABSTRACT

In modern power electronics design, especially within switched-mode power supplies (SMPS), there is a growing focus on both energy efficiency and effective thermal management. To manage the heat produced by switching components, heatsinks are widely used. These are often paired with thermal interface materials (TIMs). TIM provides additional properties, such as electrical insulation or filling air gaps to improve thermal performance. However, this thermal management setup introduces a new challenge: electromagnetic interference (EMI). TIM can lead to the creation of unwanted parasitic capacitances, which in turn generate common-mode (CM) currents. This paper explores the EMI implications of using a heatsink in conjunction with thermal interface material to cool a mosfet, with a particular focus on the CM noise that results. As a potential solution, the study investigates a hybrid material approach that combines TIM with thin copper layers. This configuration is designed to reduce both thermal resistance and EMI issues. The effectiveness of this hybrid setup is tested using a DC-DC boost converter, where CM current levels are measured and compared across different cooling configurations, including the standard TIM-heatsink arrangement and the proposed hybrid solution.

TRENDS & OVERVIEW

The trend that electronics is following is the use of switched-mode power supplies (SMPS) in more devices. This is due to an issue with energy efficiency. SMPS is closely related to the concept of power density. Power density is defined as the equipment's power output per unit volume. Therefore, SMPS are required to use a small space with high power density. This requirement or trend of SMPS can be achieved by using high switching speeds, high dv/dt . The high switching speeds enable the SMPS' components, primarily the inductor, to have lower inductance and, therefore, be smaller. Thus, by requiring less space, the power density is higher. Voltage converters use a switching element; in most cases, this component is the mosfet. The mosfet can reach high temperatures during operation. Therefore, thermal solutions are added to reduce the temperature.

The most popular and extended thermal solution is to use a metal structure that dissipates the heat. This metal structure can be a heatsink or the product's chassis itself. Although these structures are used to dissipate heat and ensure that the components' temperatures remain at an optimal level, it may be necessary to add some extra elements to improve their performance or provide additional features. The following are some of the most popular thermal interface materials (TIM).

Thermal Gap Filler

Thermal gap fillers (TGFs) are elastomeric pads. Due to the elastomeric material, these pads are compliant and adaptable. These properties make TGFs perfect for filling microscopic gaps. Additionally, they are particularly suitable for filling irregularities between surfaces when using components with different heights, which can cause irregularities. These pads facilitate enhanced thermal conductivity, ensuring optimal heat dissipation and, consequently, the longevity and reliability of electronic devices. The pad itself is composed of three main components – see Fig.1.

The flexible, elastomer-based design of the component enables it to easily adapt to contact surfaces, effectively filling voids and displacing air. The main structure is composed of either silicone or vinyl (for silicone-sensitive environments) and is infused with ceramic particles to enhance its thermal conductivity. Then, thinner pads need an extra element to maintain mechanical stability when subjected to high levels of compression. Therefore, a fiberglass layer is added, which does not impair the thermal properties.

Finally, there are two PET layers, one on the upper side and one on the lower side. These layers are simply protective and must be removed before using the TGF pad.

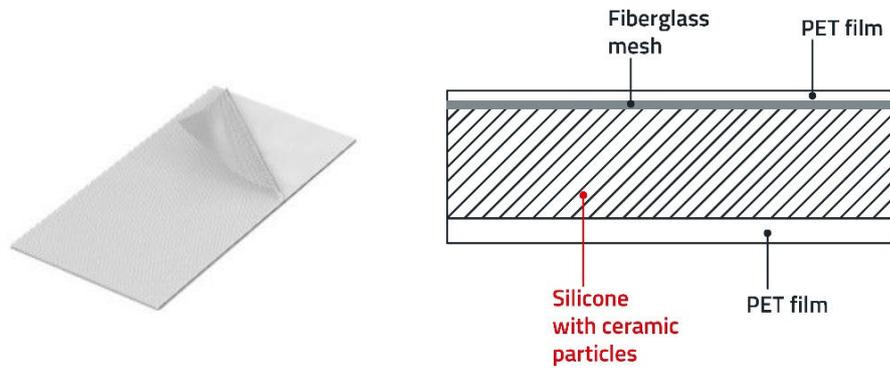


Fig.1. Thermal gap filler cross-section.

Fig.2 shows how the metal housing encloses a printed circuit board (PCB). In Fig. 2a, air surrounds the PCB. Instead, on Fig.2b, the TGF pad has been added. The heat transfer from the higher temperature components to the metal casing is impaired due to the low air transfer coefficient; however, when TGF is added, the transfer improves. This thermal management solution is the ideal choice due to the irregularity of the PCB. The fiberglass side does not impair the heat transfer, but it is recommended to be on the flat side.

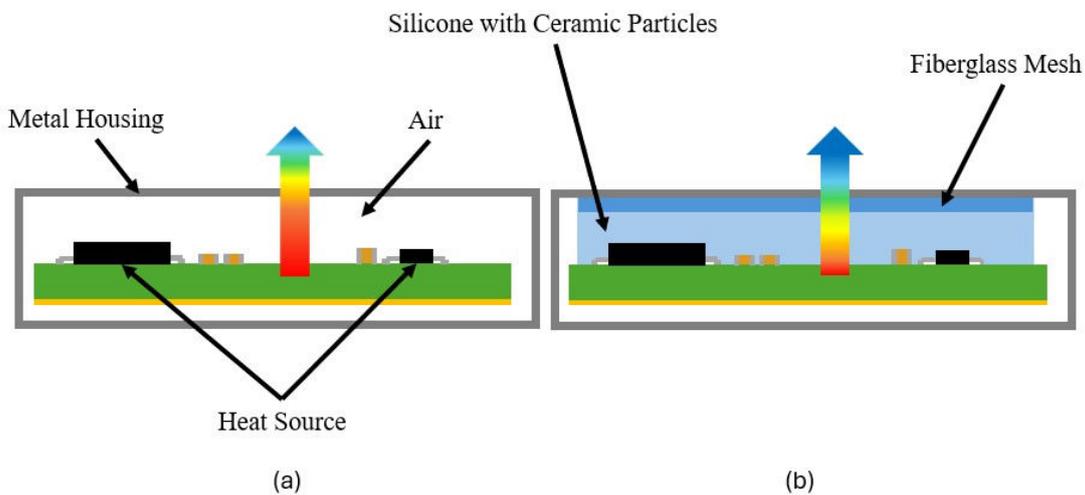


Fig.2. Heat dissipation when there is (a) air and (b) thermal gap filler surrounding the PCB.

TGF is specifically formulated to perform reliably across a wide temperature range while providing excellent electrical insulation, making it ideal for applications in both low- and high-power electronics. Its elastomeric properties contribute to effective vibration damping, while its inherent flexibility ensures consistent contact pressure in fluctuating thermal conditions. This helps maintain efficient and uninterrupted thermal conductivity throughout operation.

Thermal Transfer Tape

Thermal transfer tape is an advanced thermal interface material designed to securely bond heat sinks or cooling modules to low-power components, eliminating the need for mechanical fasteners such as screws, clips, or bolts. Its double-sided, thermally conductive adhesive not only ensures efficient heat transfer but also contributes to space-saving PCB designs, making it ideal for compact and high-density electronic assemblies.

Designed to meet the demanding thermal requirements of modern electronics, this solution provides reliable heat dissipation in space-constrained environments. Its compact form factor and effective thermal performance make it a strategic choice for consumer devices where maintaining temperature control is vital to ensure efficiency, stability, and product longevity. In LED lighting systems, it plays a key role in preserving performance and extending the lifespan of LED modules by effectively managing thermal buildup. The thermal transfer tape is composed of three integral layers, each designed to deliver optimal thermal conductivity and robust adhesive strength – see Fig.3.

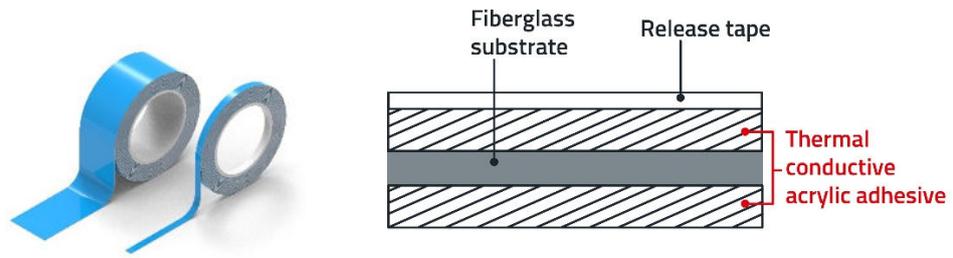


Fig.3. Thermal transfer tape cross-section.

The first face is the release tap, which protects the adhesive from foreign particles. The next layer is the thermal conductive acrylic adhesive. This layer provides good heat transfer and is also adhesive. Finally, a fiberglass core is incorporated to provide some stiffness to the tape during compression.

Graphite Sheet

Graphite sheets are specifically engineered to optimize heat dispersion across surfaces, ensuring efficient thermal regulation in areas with concentrated power density. This enhanced thermal spreading is especially beneficial when the cooling solution is considerably larger than the heat source, effectively reducing the risk of localized overheating. By mitigating hotspots, these graphite sheets contribute to improved reliability and sustained device performance. The graphite sheet comprises three core components, each meticulously designed to enhance thermal conductivity and structural integrity – see Fig.4.

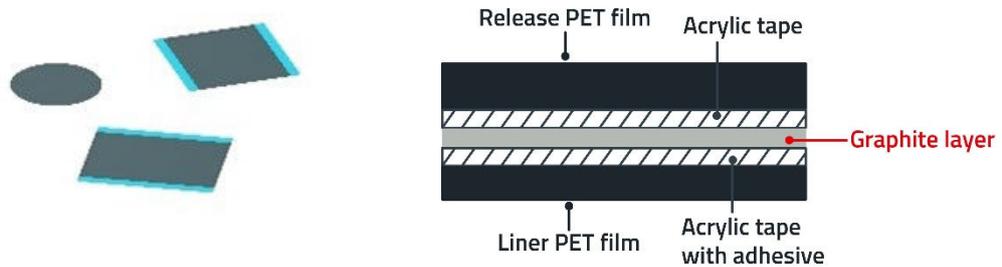


Fig.4. Graphite sheet cross-section.

The core of the graphite sheet is composed of synthetic graphite with molecules aligned horizontally, resulting in exceptional thermal conductivity along the in-plane axis and moderate conductivity through the thickness. This core is sandwiched between two acrylic adhesive layers that provide essential electrical insulation. Additionally, protective PET films cover both the top and bottom surfaces, which must be carefully removed prior to installation to ensure optimal thermal performance.

Fig.5 shows how the graphite sheet performs. In Fig.5a, the surface area of the heatsink in contact with the component is much smaller than the total surface area. Therefore, the heat transfer generates a hot spot around the surface in contact with it. In contrast, in Fig.5b, the graphite sheet is added and helps the heat to be distributed horizontally as well. In this way, the heatsink is utilized more effectively, resulting in higher performance.

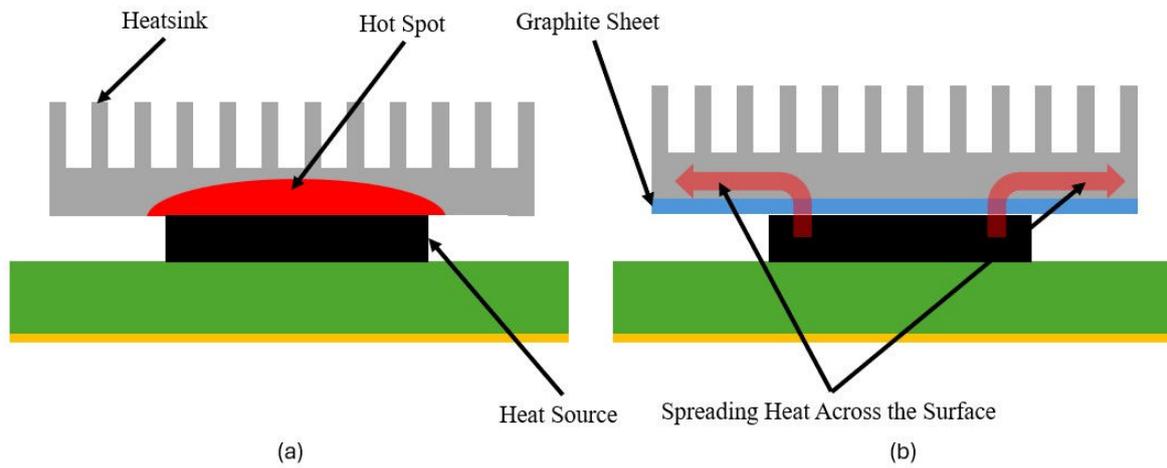


Fig.5. Heat dissipation when there is (a) no graphite sheet and (b) with a graphite sheet.

Graphite Foam Gasket

The graphite foam gasket integrates a foam substrate with a layer of natural graphite, capitalizing on the graphite's superior in-plane thermal conductivity. Engineered as an interface material, it facilitates efficient heat transfer between integrated circuits (ICs) and heatsinks. The gasket is constructed from four key components, each designed to optimize both thermal performance and mechanical resilience – see Fig.6.

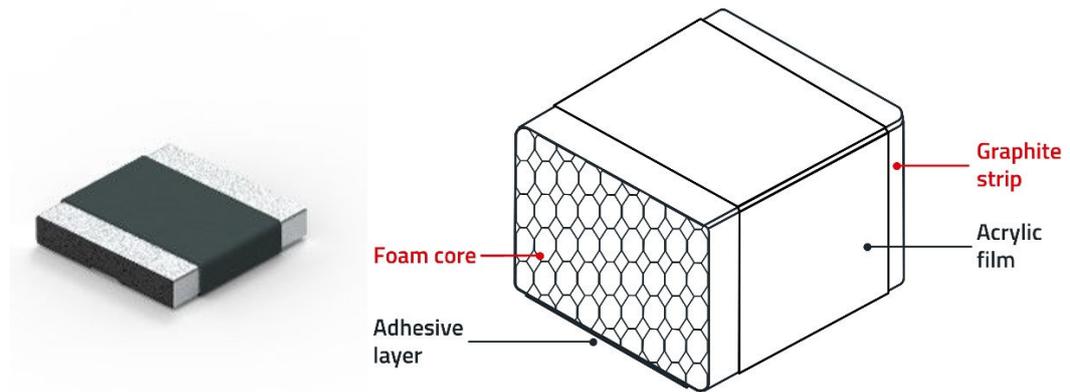


Fig.6. Graphite foam gasket cross-section.

The core consists of foam, providing the pad with elasticity and applying moderate pressure to components to ensure effective thermal contact. This foam core is encased in a layer of natural graphite, which enhances heat transfer. An acrylic film envelops the graphite, offering reliable electrical insulation between contact surfaces. Finally, an adhesive layer on the underside secures the gasket in place until compression is applied.

The Graphite foam gasket's goal is very similar to TGFs, but it also brings some additional characteristics to gap fillers. Gaskets can be used in non-planar contact surfaces. Furthermore, non-tacky surfaces that allow the disassembly of designs without the need to replace the pads as well as for sliding insertions.

Thermal Conductive Insulator

Thermal conductive insulator (TCI) is designed to provide a robust thermal interface capable of withstanding significant compression forces while ensuring electrical insulation between contact surfaces.

The contact surfaces of the pad are constructed from dry silicone rubber, delivering a soft, compliant interface that adapts seamlessly to mating components. Its reworkable nature affords exceptional flexibility during assembly and maintenance, allowing for repositioning or adjustments without degrading performance. This thermally conductive insulator pad comprises two fundamental components engineered to maximize thermal transfer and mechanical resilience – see Fig.7.

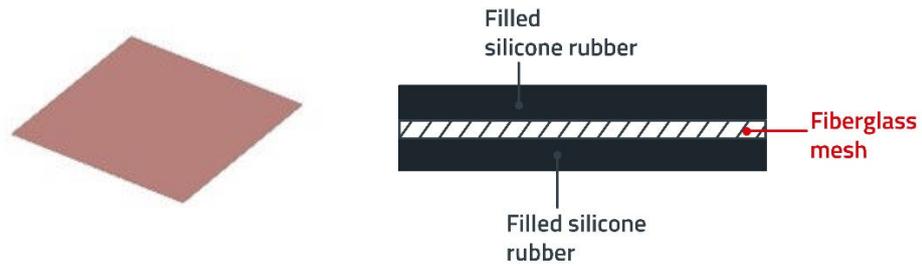


Fig.7. Thermal conductive insulator cross-section.

The core consists of fiberglass mesh, delivering mechanical stability under significant compression forces. Surrounding this core is silicone rubber, which creates a conformable surface capable of accommodating moderately rough contact areas. Thanks to its rubber properties, the contact surfaces remain dry, allowing the pad to be easily reworked and repositioned during assembly and maintenance.

The thermal conductive insulator is widely used in SMPS because it is often necessary to electrically isolate the heatsink or chassis from the rest of the circuit for safety reasons. The added value that thermally conductive insulator pads bring when compared to elastomeric pads is that they can withstand higher compressive pressure. Thus, they are more reliable if we want to maintain isolation at all costs.

references [1], [2], [3], [4], [5]

COMMON-MODE CURRENTS IN SMPS CAUSED BY THE TIM

In electronics, there is a duality between thermal management and electromagnetic compatibility (EMC). This is because most solutions to thermal problems are detrimental to performance in terms of electromagnetic compatibility, and vice versa. This is especially noticeable in SMPS, so it is common to read that a trade-off between both topics is necessary. When a thermal conductive insulator pad is used to create electrical isolation between a heatsink (or chassis) and a mosfet base plate, the thermal interface material is cut to the exact dimensions of the mosfet and is fixed between the two surfaces through a screw – see Fig.8.

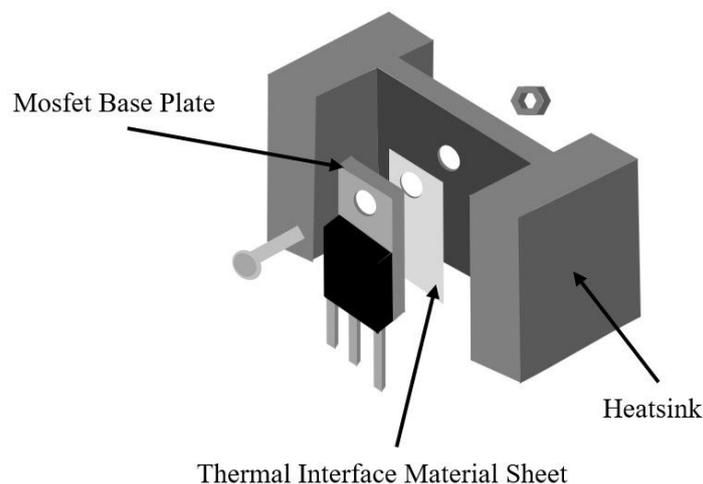


Fig.8. Thermal interface material between heatsink and switching element.

However, this structure is a source of conducted emissions from common-mode (CM) currents. Therefore, using a thermal interface material without considering its electrical performance can generate high levels of CM currents, which can lead to failures during EMC testing.

The increase in CM currents when TIM is used between the two metal surfaces is because the structure they create is identical to a parallel plate capacitor, with a dielectric separating two conductive surfaces. Since it is a parasitic capacitance, its influence on CM currents depends on multiple factors. It is known that the current flowing through a

capacitor depends on the value of the capacitance (C) and the rate of voltage variation (dv/dt). The voltage variation to which the parasitic capacitance is subjected is high in the SMPS, especially in the boost converter topology, which is the one we will study in this project. The mosfet is used as a switching component. Therefore, the pulsed signal is applied to the gate pin. In addition, the vast majority of mosfets have conductivity between the drain and its base plate. Thus, the dv/dt to which the parasitic capacitance is subjected is the same as that of the drain pin – see Fig.9.

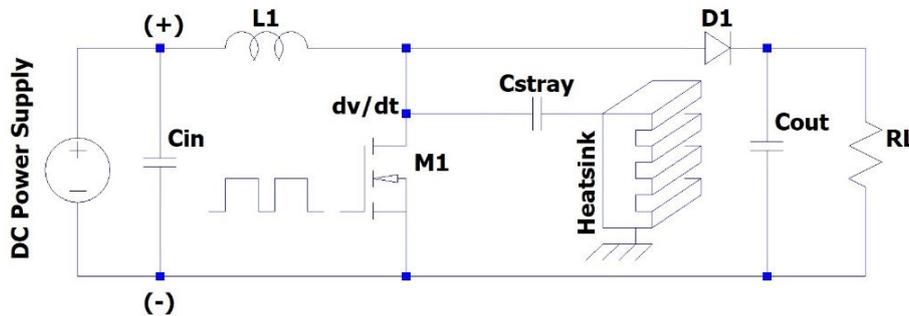


Fig.9. Equivalent model of TIM as parasitic capacitance.

Another factor influencing conducted emissions is the nominal value of the parasitic capacitance. The larger the conductive surface facing each other and the smaller the spacing between them, the higher the capacitance. The dimensions depend on the mosfet's package. The distance between the heatsink and the mosfet depends on the thickness of the TIM sheet used.

references [6], [7], [8], [9]

HYBRID THERMAL INTERFACE MATERIAL FOR CM CURRENTS REDUCE

There are several ways to reduce common-mode currents caused by parasitic capacitances between the switching element and the heatsink. One of the most effective techniques is to modify how the heatsink is connected to the rest of the circuit. The two most common alternatives include connecting the heatsink to the circuit reference plane or leaving it floating. However, using a floating heatsink can lead to problems with radiated emissions. Additionally, for safety reasons, other types of connections are not recommended compared to the one used in this project. Therefore, while there are various options available, they may not be suitable for our design.

Since modifying the heatsink's wiring is not often an option, hybrid material is proposed to mitigate the effects of conducted emissions while maintaining electrical insulation and minimizing thermal performance. The proposed hybrid material is a combination of a thermal conductive insulator pad combined with a copper foil - see Fig.10.

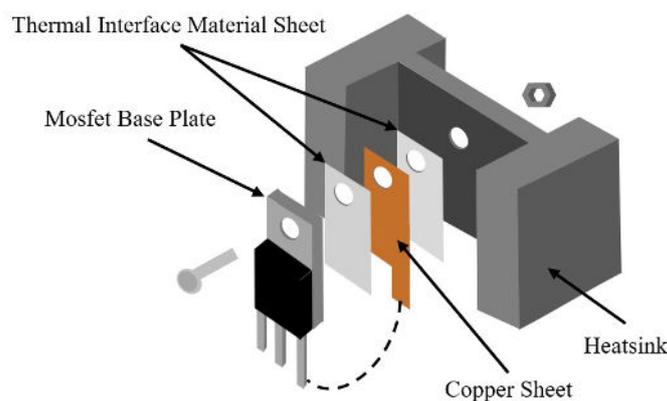


Fig.10. Hybrid solution.

It can be seen that the order of the material is a sheet of thermal conductive insulator, followed by a sheet of copper, and finally another sheet of TCI. The order is crucial for maintaining the necessary electrical insulation. In addition, the copper foil has a piece at the bottom that must be soldered to the source pin of the mosfet. The name for this hybrid solution is Shielded Thermal Interface Material (Shielded TIM).

The hybrid material can be modeled as two capacitors in series. Between the mosfet base plate and the copper foil, a parasitic capacitance equal to that generated by a single TIM material is generated. In addition, another parasitic capacitance is generated between the copper foil and the heatsink, resulting in two capacitances in series. The copper foil has a strip that must be soldered to the source pin of the mosfet. Therefore, the node that joins both capacitances must be connected to the source pin of the mosfet - see Fig.11.

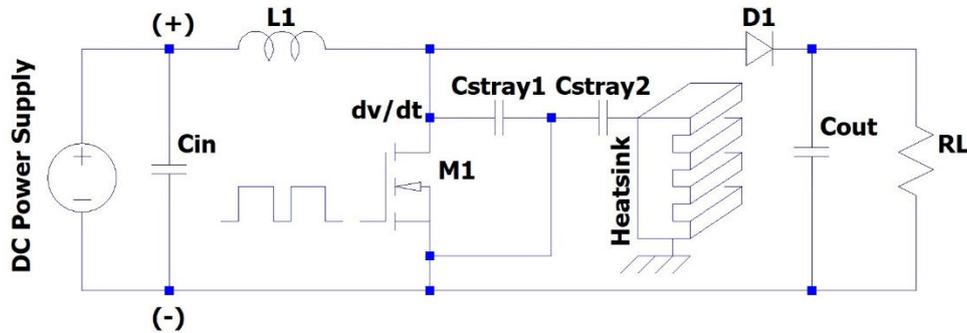


Fig.11. Equivalent model of applying shielded TIM.

references [10], [11], [12], [13]

SHIELDED TIM TESTS

To validate the proposed solution, two complementary test campaigns were conducted. The first examines electrical behaviour by monitoring common-mode currents, while the second quantifies thermal performance. The device under test is a 3.3 V to 10 V boost DC-DC converter that draws 1.5 A. An LTC1871 controller drives a TO-220 mosfet at 300 kHz with a 60 % duty cycle. The selected TIM is a Thermal Conductive Insulator from Würth Elektronik. This type of TIM has been selected because it is the most common in DC-DC applications—featuring a 0.25 mm thickness and a relative permittivity of 3.5. In keeping with common practice and representing a worst-case scenario for EMC, the heatsink is tied to ground, as illustrated in Fig.9.

Common-Mode Currents Test

To perform the measurements in the laboratory, conducted emission measurements have been carried out, focusing on common-mode emissions. Since this is a DC-DC circuit, 5 μ H LISNs are required. Two 5 μ H LISNs are used along with a LISN Mate to separate the CM currents from the differential-mode (DM) currents. The remaining elements are a DC power supply, the DUT and a spectrum analyzer with a transient attenuator at the input. It should be noted that some components are placed directly on the metal plane, while the DUT rests on a 5 mm thick piece of polystyrene - see Fig.12.

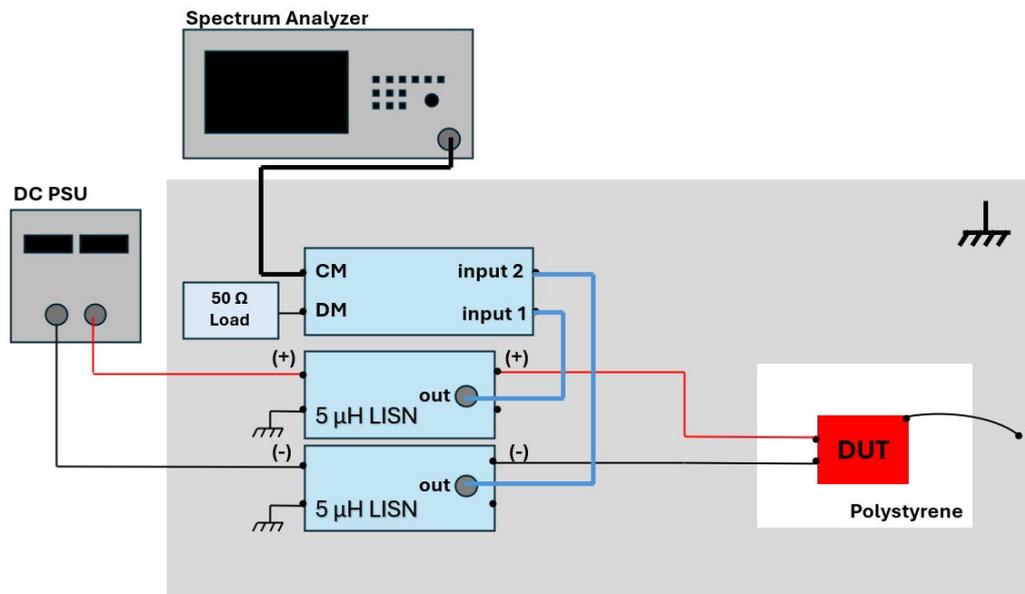


Fig.12. Setup diagram of the setup used in the measurements.

The black trace corresponds to the conducted common-mode emissions when a TCI pad is inserted between the mosfet and the heatsink (Fig.8). The red trace is the when the proposed solution is inserted between the mosfet and the heatsink (Fig.10). In both traces the peaks occur at the switching frequency of the SMPS and its harmonics, but the black trace has a higher level, especially at 10 MHz and above. The green trace illustrates the difference between the black and red traces. The difference between the two traces is 10 dB for the fundamental harmonic and up to 30 dB for some harmonics – see Fig.13.

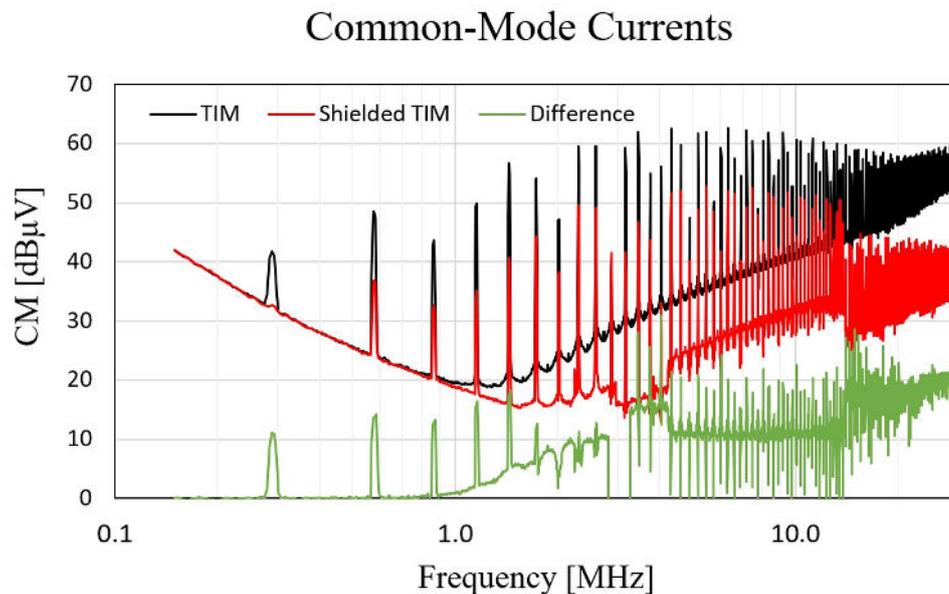


Fig.13. Results of experimental measurements: Single sheet of TIM (black trace), shielded TIM (red trace) and difference between measurements (green trace).

Thermal Performance Test

When a thermal conductive insulator pad is introduced between the mosfet and the heatsink to generate electrical insulation, the thermal resistance is intended to be minimal so as not to degrade heat transfer and dissipation is maximized. However, shielded TIM introduces three extra layers, two of thermal conductive insulator and one of copper. Therefore, the thermal resistance may be drastically increased, resulting in a significant reduction in thermal performance. Thus, it is necessary to evaluate the thermal performance.

To perform the tests, a thermocouple is placed on the mosfet base plate and the temperature is measured in both cases, a single TCI sheet and the proposed solution, while the DC-DC boost converter is working. The orange trace corresponds to the problem, and the blue trace to the use of the hybrid solution. The initial temperature is higher when using a single TCI sheet, so this option heats up earlier. As time passes in both cases the mosfet stabilizes at a similar temperature – see Fig.14.

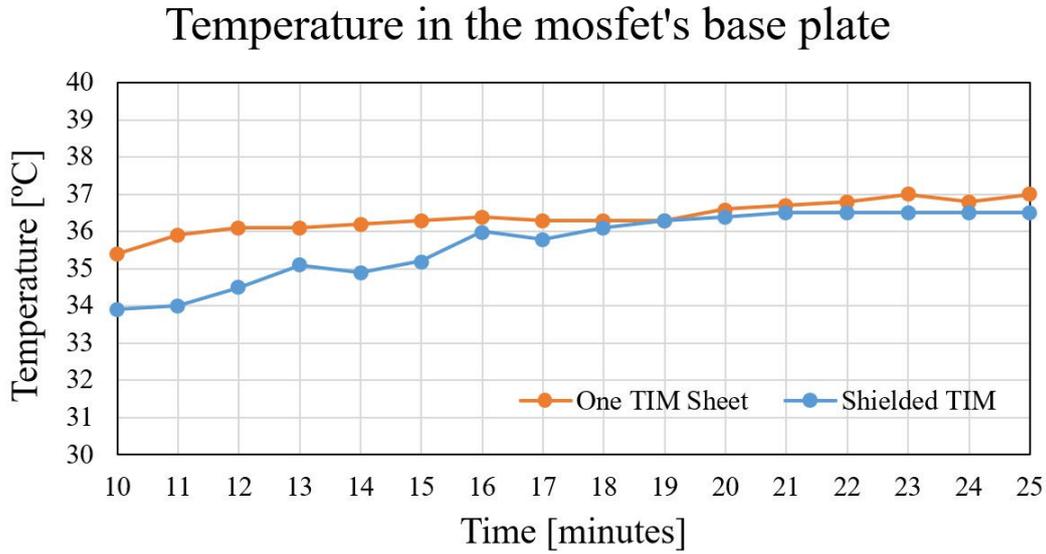


Fig.14. Temperature on the mosfet's base plate: with a single sheet of TCI (orange trace) and shielded TIM (blue trace).

references [14], [15], [16]

EVALUATING TIM'S EFFECT DURING CIRCUIT DESIGN

During the explanation, it was considered that the equivalent model of using a TIM between the mosfet base plate and the heatsink is a parasitic capacitance. Therefore, it is possible to introduce this effect in any electrical circuit simulation software. In this way, the effect can be evaluated during the design phase.

In the first case, where there is only one TIM sheet and it is the undesired case because it generates a high level of common-mode conducted emissions, the equivalent model is a simple capacitor. This capacity can be calculated with Equation 1.

$$C_{stray} = \epsilon_o \cdot \epsilon_r \cdot \frac{A}{d} \quad (1)$$

To calculate the area it must be considered to be the area of the thermal pad of the mosfet, whose encapsulation is a TO-220 in this case. The distance between the mosfet and the heatsink is the thickness of the TIM foil, and the permittivity is that of the TIM as well. A summary of the values is presented in Table 1. It can be seen that the value of the parasitic capacitance to be added in the simulation model is 15.7 pF.

| ϵ_o [F/m] | ϵ_r | A [mm ²] | d [mm] | C_{stray} [pF] |
|-----------------------|--------------|------------------------|----------|------------------|
| $8.85 \cdot 10^{-12}$ | 3.5 | 126.8 | 0.25 | 15.7 |

Table 1. TIM parameters and parasitic value.

To study the effect that the TIM and shielded TIM will have during the design process, equivalent models of the TIM have been added to the circuits used to simulate the operation of the DC-DC boost converter during its design - see Fig.15.

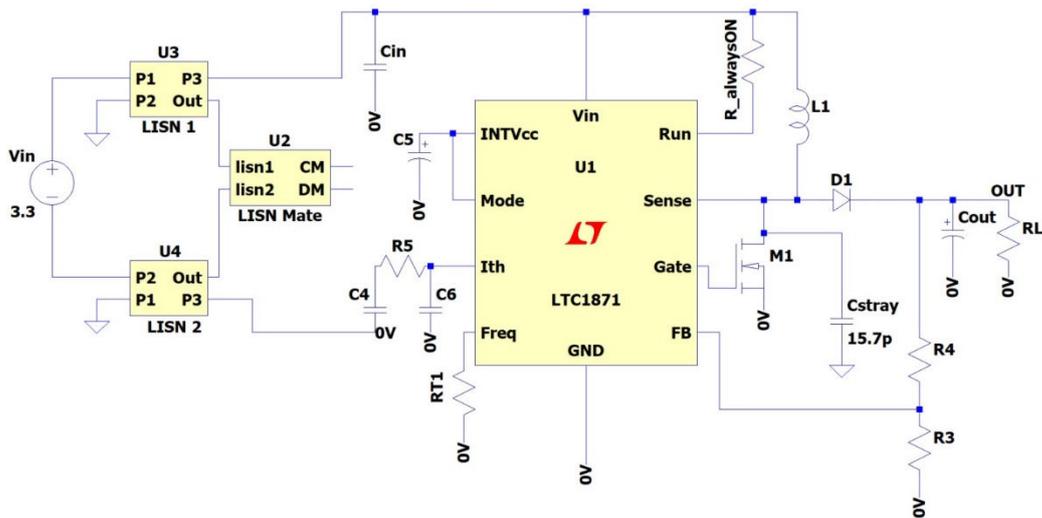


Fig.15. Simulation schematic: with equivalent model of a single TIM sheet.

The results of the simulations demonstrate that the effect can be simulated - see Fig. 16. This graph compares the simulated (grey trace) and measured common-mode currents from the previous section (black trace) for a single TIM sheet. In this case, it can be seen that the peaks appear at the switching frequency and its harmonics. The level of the peaks is very similar.

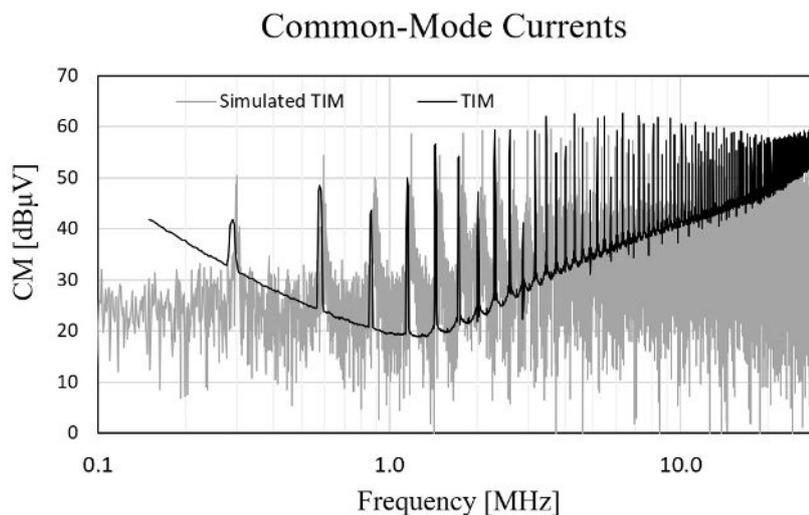


Fig.16. Comparison of measured and simulated results (black trace – measured and grey trace – simulated).

references [17]

SUMMARY AND CONCLUSIONS

The use of TIM is necessary to improve heat dissipation or to provide other features such as electrical insulation. Although TIM brings some disadvantages, common-mode currents are drastically elevated. This phenomenon is due to the occurrence of parasitic capacitances. To solve the problem, a hybrid material has been proposed that still provides the thermal and electrical isolation characteristics while reducing the CM currents.

Experimental measurements have shown that indeed, the use of TIM causes high peak common-mode currents. In contrast, the shielded TIM can bypass such currents, causing a reduction in the level. Moreover, the thermal performance of the shielded TIM is not drastically impaired. Thus, the shielded TIM maintains the initial required characteristics and also reduces the CM currents.

Finally, it is possible to characterize this effect during the design stage by utilizing equivalent parasitic capacitance models. Thus, it becomes possible to evaluate the risk of CM currents when a thermal interface material is to be used.

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