Design and Testing of Heat Pipe Based Cooling Solution for Efficient Thermal Management of FPGA on Space Application

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Abstract. The rapid advancement of high-density electronics, such as Field-Programmable Gate Arrays (FPGA), requires efficient thermal management to ensure optimal performance, especially in space applications, where conventional cooling methods like convection are not feasible. This paper explores the challenges of heat dissipation in FPGA devices in space environments, where conduction and radiation are relied upon for heat management. A heat pipe assembly was designed to transfer 30W of power dissipation from the FPGA heat source to the housing.Two configurations were tested: one with a heat sink containing embedded heat pipes and another with a standard heat sink. These were evaluated under different base plate temperatures. Additionally, a high-temperature thermo-vacuum test simulated space conditions, testing the heat pipe assembly's performance in extreme temperatures and vacuum. The results showed that the heat pipe assembly was significantly more effective than the standard heat sink in managing heat dissipation, successfully transferring 30W of heat while maintaining stable temperatures even in harsh conditions.This highlights the potential of heat pipe technology as a reliable thermal solution for space applications, where conventional methods fail.

1 Introduction

Field-Programmable Gate Arrays (FPGA) are increasingly utilized in space applications due to their high computational power and flexibility. However, the high-density nature of FPGA devices leads to significant challenges in thermal management [1], as excessive heat can adversely affect their performance and reliability. In space environments [2], where conventional heat transfer mechanisms such as convection are ineffective due to the vacuum, efficient thermal management becomes a critical concern. As a result, conduction and radiation are the only viable heat dissipation methods in such settings. In many electronic systems, aluminium heat sinks are commonly used as a straightforward and efficient solution for heat dissipation. Aluminium is an excellent material for heat transfer due to its high thermal conductivity and low weight, making it an ideal choice for cooling applications in both terrestrial and space environments. In the case of FPGA thermal management, an aluminium heat sink is positioned between the housing wall and the FPGA

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to facilitate the transfer of heat from the device to the housing [3][4]. The heat generated by the FPGA is conducted through aluminium heat sink, which then disperses the heat to the housing [5]. While aluminium heat sinks can effectively reduce the temperature of an electronic component to some degree, their performance is limited by the overall thermal conductivity and surface area available for heat dissipation [6]. In space applications, where convective heat transfer is non-existent, aluminium heat sinks alone may not be sufficient to ensure effective cooling.

To overcome this limitation and further improve heat dissipation, heat pipes [7] can be integrated into the same heat sink structure. Heat pipes, with their ability to transfer heat via phase change, offer a much higher thermal conductivity [8][9] than aluminium alone. When heat pipes are embedded within the aluminium heat sink, they create an enhanced thermal path that significantly improves the overall heat transfer efficiency. The heat generated by the FPGA is not only conducted through the aluminium heat sink but also transferred more effectively through the heat pipes, which rapidly transport the heat from the FPGA to the housing. The presence of heat pipes reduces the temperature gradient across the system by providing an additional means of heat transfer, thereby improving the thermal performance and reducing hot spots that could otherwise arise. For the testing, a mechanical housing was specifically designed to accommodate the printed circuit board (PCB) and ensure proper integration with the thermal management system. The heat source was designed to dissipate 30W of power, simulating the heat load typical of high-performance FPGA devices. A heat sink was mounted to the inner top cover of the Hybrid Microcircuit Package, mimicking the FPGA's thermal environment. This design was chosen because using actual FPGAs for R&D is cost-prohibitive, and functional circuits are required to simulate the heat dissipation behaviour in an FPGA. The heat source was detached in such a way that nearly all the generated heat was transferred to the heat sink, ensuring efficient thermal management. The unit underwent comprehensive testing, and the results were thoroughly studied.

This study introduces a novel approach to thermal management for high-performance FPGA devices in space applications by integrating heat pipes within aluminium heat sinks. While aluminium heat sinks are commonly used for thermal dissipation, their limitations in space environments—where convection is unavailable—are addressed through the innovative incorporation of heat pipes, significantly enhancing heat transfer efficiency. The research focuses on a mechanical housing design that mimics the FPGA thermal environment, simulating typical power dissipation loads, and testing the combined heat sink and heat pipe system under these conditions. The novel integration of heat pipes offers a promising solution to the challenges of thermal management in space, improving the efficiency and reliability of FPGA systems where conventional cooling methods are ineffective. This approach not only enhances the heat dissipation capacity but also provides valuable insights into the design and testing methodologies for space-based electronics.

2 Mechanical design

The test assembly consisted of several key components: the mechanical housing, heat sink, heat source, three heat pipes, and mounting screws. The housing was designed to securely hold the PCB and other components in place, while the heat sink was mounted over the heat source to facilitate efficient heat transfer. The heat source, designed to dissipate 30W of power, was positioned to ensure maximum heat transfer to the heat sink. Three heat pipes were strategically placed within the heat sink to enhance overall heat dissipation efficiency. The components were securely fastened using mounting screws to maintain stability during testing and ensure accurate results.

The outer dimensions of the mechanical housing are 240mm x 210mm and it is constructed using Aluminum 6061 T6, chosen for its excellent strength-to-weight ratio and high thermal conductivity. This design ensures proper integration and efficient heat transfer, while providing the structural integrity necessary for testing and performance validation.

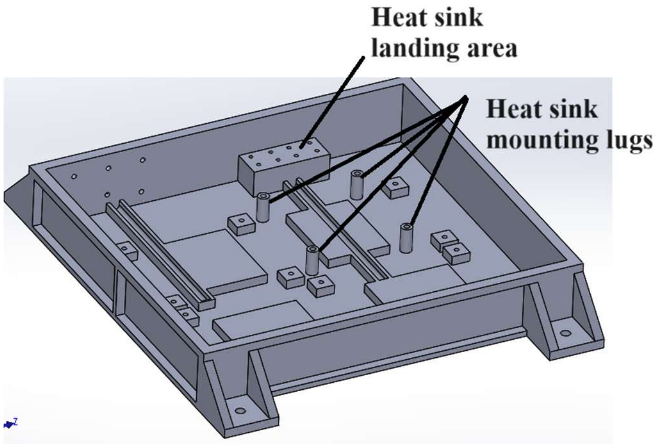

Fig. 1: Housing CAD Model

The heat sink is designed to enclose three heat pipes, ensuring effective heat dissipation from the heat source. The outer dimensions of the heat sink are 98mm x 58mm x 3mm, and it is constructed using Aluminum 6061 T6, which offers excellent thermal conductivity and durability. To enhance the attachment of copper heat pipes, the heat sink is plated with electro less nickel. This nickel plating provides good solder ability, ensuring a reliable and durable bond between the heat sink and the copper heat pipes, as will be discussed in the subsequent sections

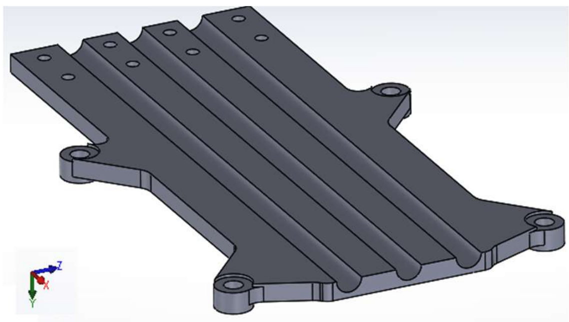

Fig. 2. Heat Sink CAD Model

In this design, a heat pipe with a heat transfer capacity of more than 10W has been selected and implemented within the heat sink. This heat pipe effectively facilitates the transfer of heat from the heat source to the heat sink, ensuring efficient thermal management. The high-performance copper heat pipe, combined with the heat sink, enhances the overall heat dissipation, ensuring that the FPGA operates within its optimal temperature range. This

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integration plays a key role in preventing overheating and maintaining the reliability and longevity of the system [10].

Table1: Heat pipe Spécification

Parameter	**Specification**
Heat pipe description	Heat Sinks Heat Pipe, Copper, High Performance, Round, 100mm, 4mm dia.
Operating Temperature	+30°C to +120°C
Working Fluid	Distilled Water
Surface Finish	N/A
Heat Transfer Capacity	More than 10W

The heat source in this design is required to dissipate at least 30W of power, and it is carefully engineered to meet this requirement. The heat source is developed and fabricated using a printed resistor circuit on an alumina substrate. The first resistor is printed on the substrate to achieve the necessary resistance, ensuring that the power dissipation requirement is met. Once the resistor is printed, the alumina substrate is attached to the top cover of the Hybrid Microcircuit (HMC) package using 5025E able film, ensuring a secure and thermal-efficient bond. The HMC top cover is then attached to the HMC housing using Anna bond adhesive, providing structural integrity to the assembly. A provision is made in the HMC housing to power up the substrate, enabling the heat source to operate efficiently and dissipate the required 30W of power. This design ensures effective heat generation and distribution for optimal testing and performance evaluation

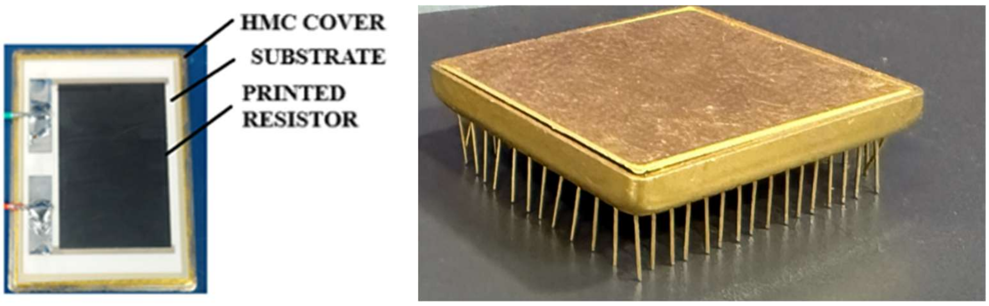

Fig. 3. Heat Source and HMC package

All the components are carefully assembled, and the resulting assembly appears as follows:

- Mechanical Housing: This encloses the entire setup, securely holding the heat sink, heat pipes, PCB, and heat source in place. The housing is designed to provide structural support and facilitate heat transfer.

- Heat Sink: Mounted over the heat source, the aluminum heat sink houses the three embedded heat pipes, which help transfer the dissipated heat effectively. The heat sink is plated with electro less nickel to improve solder ability for the copper heat pipes.
- Heat Source: A printed resistor circuit on the alumina substrate is attached to the HMC top cover. The resistor is designed to dissipate 30W of power, and the alumina substrate is securely bonded to the HMC top cover using 5025E able film.
- Heat Pipes: The three copper heat pipes embedded in the heat sink enhance the thermal management by improving heat transfer from the heat source to the surrounding housing.
- Power Supply Provision: The HMC housing has a provision to power the printed resistor circuit, enabling the heat source to operate and dissipate the required power.

This assembly configuration ensures optimal heat dissipation and serves as a reliable testing setup for evaluating the thermal performance and effectiveness of the cooling system.

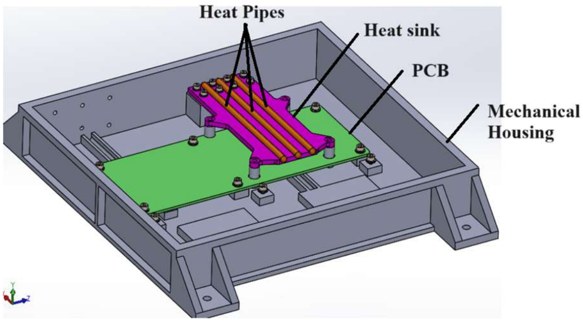

Fig. 4. Mechanical Assembly CAD Model

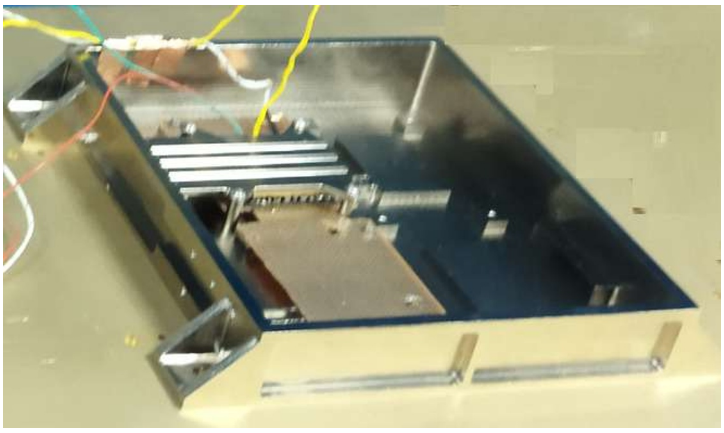

Fig. 5. Mechanical Assembly without heat pipes on heat sink

2.1 Thermal Testing

To evaluate the performance of the heat pipe with heat sink assembly, the following iterations were carried out:

1. Heat Sink Tested Without Heat Pipe:
   The heat sink was tested without the inclusion of heat pipes, using a cold plate to simulate the heat dissipation at a base temperature of 45°C at room temperature. This test served as a baseline to evaluate the effectiveness of the heat sink alone.
2. Heat Sink with Heat Pipe Assembly:
   The heat sink was tested with the heat pipe assembly, again using a cold plate to maintain a base temperature of 45°C at room temperature. This test aimed to evaluate the improved heat dissipation performance provided by the heat pipes integrated into the heat sink.
3. Heat Sink with Heat Pipe Assembly Inside Thermo-Vacuum Chamber:

   The heat sink with the heat pipe assembly was subjected to testing inside a thermo-vacuum chamber to simulate space conditions [11]. The assembly was tested with a base plate temperature of 45°C. This test allowed for the evaluation of the heat dissipation performance under extreme conditions, similar to those encountered in space, where convection is not present.

These iterations provided critical insights into the thermal performance of the heat sink with and without the heat pipe assembly under various conditions, helping to assess the effectiveness of the heat pipe-enhanced design in managing heat dissipation.

The assembly process begins by securing the PCB to the housing using appropriate fasteners. The Hybrid Microcircuit (HMC) package, which serves as the heat source, is then soldered onto the PCB. The heat sink is mounted on top of the HMC, with graphite thermal interface material (TIM) placed between the heat source and the heat sink to ensure efficient heat transfer. The entire assembly is then fixed onto the base plate, initially a cold plate at room temperature, and later used as a thermo-vacuum base plate inside the testing chamber. Thermocouples are strategically mounted at key locations such as the heat source, heat sink, and base plate to monitor temperatures during testing. The heat source is connected to a power supply, and the base plate temperature is set to the desired value. The heat source is powered up, and the required heat dissipation is achieved by adjusting the voltage to simulate different power levels. Finally, thermocouple readings are monitored and recorded after the system reaches thermal equilibrium to assess the heat dissipation performance under various conditions.

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Fig. 6. Fabricated heat sink attached on heat source

The heat source has a resistance of 23 Ω, and it is designed to dissipate 30W of power. Given the power dissipation requirement, the current and voltage supplied are 26.3V and 1.14A, respectively. These values were selected to ensure that the heat source generates the necessary amount of heat to simulate the thermal load in the system. Temperatures are monitored at key locations within the assembly to assess the thermal performance of the system. Temperature readings are taken at the heat source to track the amount of heat being generated, at the heat sink to evaluate its effectiveness in transferring heat away from the heat source, and at the housing (H) to ensure proper heat dissipation to the surrounding environment. Additionally, the temperature of the cold plate (CP) is measured to assess how well the base plate is maintaining the thermal conditions for the assembly. These temperature measurements provide valuable data on the system's heat dissipation efficiency and help evaluate its performance under different test conditions.

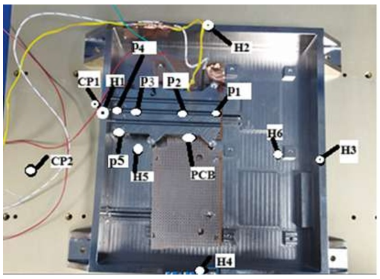

Fig. 7. Temperature monitored locations

3 Results

1. Heat sink tested without heat pipe on cold plate with base temperature 45°c

Temperatures are measured using K-type thermocouples, and the temperatures recorded at various points in the system are listed below: Refer figure 7 for monitored locations.

Table 2. Monitored temperature details (All temperatures are in °C)

CP	Ambient Temperature	Substrate temperature	p1	p2	p3	p4	p5	H1	H2	H3	H4	H5	H6	PCB	CP2	CP1
45	25	114	96	95.5	64.2	56.5	54	52	46	45.5	46	50.2	46	49	45	46

At location p4, the measured temperature is 56.5°C, and the temperature difference between location p2 and location p4 is 40°C. This significant temperature difference indicates that the heat dissipation across the heat sink is not as efficient as desired. To minimize this temperature difference and improve the overall thermal management of the system, heat pipes are embedded in the heat sink, as discussed in the following sections.

By embedding the heat pipes, the goal is to reduce the temperature gradient between location p2 and location p4, leading to more uniform heat distribution. This will help reduce the temperature of the heat source, preventing it from reaching potentially harmful levels. Efficient heat transfer through the heat pipe will ensure better thermal conductivity, thus enhancing the overall performance and stability of the system.

2. Heat sink tested with heat pipe on cold plate with base temperature 45°c

Three heat pipes are soldered to the heat sink to further enhance the thermal performance. The heat sink, equipped with the three heat pipes[12][13], is tested on a cold plate with a base temperature of 45°C. This configuration is designed to improve heat transfer efficiency by increasing the capacity to move heat from the heat source to the heat sink and ultimately to housing.

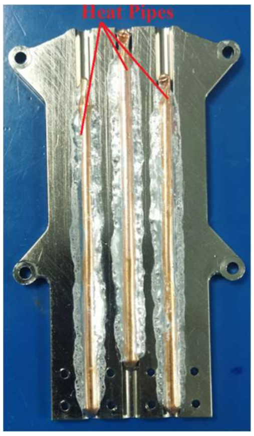

Fig. 8. Heat pipe heat sink assembly

The heat sink with three embedded heat pipes was tested on a cold plate with a base temperature of 45°C. The test results below show the measured temperatures at various locations within the assembly. Temperature monitoring points are same as mentioned in Figure 7 (Even though test conditions are different, the temperature monitored locations are same for the table 3).

Table 3. Monitored temperature details (All temperatures are in °C)

CP	Ambient Temperature	Substrate temperature	p1	p2	p3	p4	p5	H1	H2	H3	H4	H5	H6	PCB	CP2	CP1
45	25	83.5	68	67.8	65.8	63.3	60	54.5	46.1	45.3	46	51	45.2	52.4	45	45.6

For 30W power dissipation, with the heat pipe embedded in the heat sink, the maximum temperature observed on the heat sink is 68°C at location p1, where the heat source is located, with the cold plate temperature set to 45°C. At location p4, the temperature is 63.3°C, demonstrating an effective Heat transfer. A significant reduction in temperature gradient was observed, with only a 5°C temperature difference between location p2 and location p4. This is a major improvement compared to the previous tests without heat pipes. The temperature drop along the length of the heat sink is now only 5°C, indicating efficient heat transfer across the heat sink. The heat pipes in the assembly are performing effectively as thermal conductors, facilitating the rapid and uniform distribution of heat from the source. Essentially, the heat pipes are acting as superconductors for heat transfer, allowing the heat to spread evenly and reduce thermal gradients significantly. This enhancement plays a critical role in keeping the heat source temperature low and maintaining the system within optimal operating conditions.

3. Heat sink tested with heat pipe[14] inside thermo vacuum chamber with base temperature 45°c

The heat sink with heat pipes was also tested by placing the entire assembly inside a thermo-vacuum chamber with a base temperature of 45°C. This test was designed to simulate the extreme conditions encountered in space applications, where conventional heat transfer methods may not be sufficient due to the lack of convection. By subjecting the assembly to a vacuum environment, the heat sink's performance in the absence of convective heat transfer was evaluated. The heat pipes were expected to function effectively in this vacuum, relying solely on conduction and radiation to dissipate the heat.

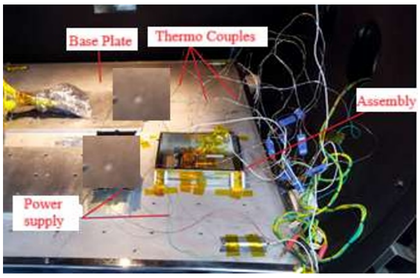

Fig. 9. Test set up inside thermo vacuum chamber

The results of the thermo-vacuum test provide valuable data on the heat sink's performance under space-like conditions, ensuring that the heat dissipation system can effectively manage thermal loads in environments where traditional heat transfer mechanisms are absent. The test further confirms the reliability and efficiency of the heat pipe-integrated heat sink, demonstrating its ability to maintain optimal temperatures even in extreme, low-pressure environments [15,16]. Inside the thermo-vacuum chamber, temperatures were monitored at specific locations to evaluate the performance of the heat sink with heat pipes under space-like conditions [17]. The temperature measurements were taken at locations p2, p4, H5, H6, and the PCB, as shown in Figure 7. These locations were selected to assess the heat distribution across the assembly in the absence of convective heat transfer, simulating the extreme conditions encountered in space. Monitoring these key points allows for an in-depth analysis of the heat dissipation efficiency and the effectiveness of the heat sink and heat pipes in maintaining the system's thermal stability in a vacuum environment.

Table 4: Monitored temperature details (All temperatures are in °C)

Base plate	Ambient Temperature	Substrate temperature	p2	p4	H5	H6	PCB
45	45	83.5	67.8	63.3	51	45.2	52.4

At 45°C base plate temperature and 30W dissipation inside the thermo-vacuum chamber, the maximum heat sink temperature reached 63°C, with a temperature difference of 3°C between location p2 and location p4 on the heat sink.

4 Conclusion

- The integration of heat pipes significantly enhances thermal management in high-power dissipation applications.
- Temperature difference between locations on the heat sink was reduced to 3-5°C with heat pipes, compared to 40°C without them.
- The heat pipe-enhanced heat sink successfully maintained stable heat dissipation in both room and vacuum conditions.
- Heat pipes acted as thermal superconductors, improving heat transfer efficiency.
- This solution provides efficient thermal management for high-density electronics, especially in space applications where conventional cooling methods are less effective.

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