Highly-Sensitive Calibration-Free Calorimeter with Adjustable Cooling

Abstract: Wide-band-gap (WBG) semiconductors, especially GaN, have enabled power converters operating at high frequencies which can lead to significant increase in power density. However, the precise characterization of the system efficiency at very high frequencies is difficult using electrical measurements because of bandwidth limitations, particularly for current probes, and delay mismatches between current and voltage measurements. Thus, calorimetric methods are preferable as they evaluate losses directly using thermal-based techniques. However, existing calorimetric methods either require system calibration for each measurement, which increases the measurement time and results in extra inaccuracies, or their accuracy depends heavily on minimizing the heat leakage from the system, hindering their usability in measuring small losses (in high efficiency converters). In this work, we propose a closed-type double-chamber calorimeter which operates based on a real-time calibration between two identical chambers, eliminating the need for any compensation for ambient variations or changes in the measurement system itself. By flowing the cooling liquid through both chambers in a closed loop, there is no necessity for flow measurement, enabling a drastic reduction of the flow rate. This is important since measuring small flow rates accurately is challenging. The system can measure a wide range of losses, as its cooling capability is adjustable simply by changing the cooling liquid flow rate or the fan power in the heat exchangers. The calorimeter can measure losses as low as 1 W with high accuracy of 5.3%. This remarkable sensitivity is of great significance to evaluate losses in high-frequency high-efficiency converters, enabling system optimization and device characterization.

1 Introduction

Accurate measurement of converter loss is important for evaluating efficiency, optimizing performance and designing proper cooling systems. Wide band-gap technologies, in particular GaN, enable high switching frequencies, in the MHz range, with nanosecond switching times. Due to their small gate-capacitance and ON-resistance, GaN devices can increase the efficiency of power converters at high-frequencies, which brings forward the need for accurately measuring small losses. For instance, C_{OSS}-related losses for GaN transistors occur predominantly at high-frequencies [1], where electrical measurements, especially current, are extremely challenging due to the limited band-width of measurement probes [2].

TABLE I
TYPES OF CALORIMETRIC SYSTEMS

System	Type	Minimum Power	Accuracy	Accuracy Limit	Reference
Single-Chamber	Open (Air)	74.5 W	0.5 W	Heat leakage, Even air flow	[13]
Double-Chamber	Open (Air)	200 W	15 W	Equal heat leakage, Even air flow	[14]
Single-Chamber	Closed (Water)	10 W	0.4 W	Heat leakage, flowrate measurement	[4]
Double-Chamber	Closed (Water)	1 W	0.053 W	Equal Heat leakage	This work

Loading effect as well as different propagation delays between voltage and current probes lead to large errors and therefore spurious efficiency/loss measurements [3]. Calorimetric methods directly determine losses through the generated heat, which has been applied to power converters [4], [5], pulsed-power generators [6], motors and drives [7], [8], semiconductor devices [9]–[11] and passive components [10], [12]. There are different types of calorimetric techniques proposed in the literature (Table I). Open-type systems use air as coolant, whereas in closed-type systems a cooling liquid, mostly water, is used.

In a calorimetric measurement system, power loss (P) is determined by

$$P = \rho \cdot \left({\partial V}/{\partial t} \right) \cdot c \cdot \Delta T \qquad (1)$$

in which ρ is the volumetric density of the coolant, V and c being fluid volume and specific heat-capacity, respectively, and ΔT is the temperature rise. Single-chamber open-type calorimeters use air flow meters with temperature sensors at the inlet and outlet of a chamber, in which air is blown on the device-under-test (DUT). This method is simple to implement and is practical for measuring large losses [13], [15]. Air parameters such as ρ and c could vary during the test. Thus, to achieve reliable results, extensive calibration or balance test must be performed at the cost of excessive long measurement times. A balance test is performed with heaters imitating the conditions of the main test to compensate for air properties variation, which may also be different during the measurement of the actual DUT. Furthermore, heat leakage through the chamber has to be minimized for high precision [7]. A double-chamber open-type calorimeter can mitigate the need for calibration and balance test [14]. While the method is practical for large losses, equalizing the heat leakage between the two chambers remains a challenge. There is also no guarantee that the airflow in both chambers is the same [3], as it heavily depends on the DUT geometry. By utilizing a heat-exchanger and transferring the heat to a liquid, e.g. water, one can directly extract the power loss with a single chamber closed-type calorimeter [4], [13], [16] using (1). Although utilizing water with its high heat capacity in closed-type systems makes the settling time larger, the accuracy improves significantly. Since single-chamber methods require minimized heat leakage, double-jacketing technique was used in [4], [5], [13]. In [4], a precision of ±0.4 W was reported for measured losses of 10 W. However, measuring smaller losses is much more challenging, requiring a highly sensitive calorimeter with improved precision. In this work, we present a double-chamber closed-type calorimeter that addresses the limitations of previously described, As it:

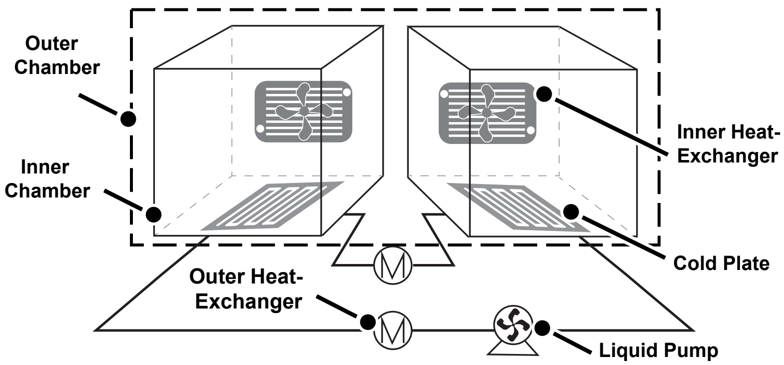

Fig. 1 Closed-type dual-chamber calorimeter. Water flow diagram: the water flows through identical chambers containing DUT and CAL. The heat-exchangers are dominant in convective heat transfer, whereas cold-plates absorb the heat by

- Eliminates flow rate measurement which is difficult for small flow values [13], enabling the measurement of losses down to 1 W.
- Removes the need for a perfect thermal insulation as the heat leakage is equal for identical chambers.
- Provides adjustable cooling to extend the range or increase the sensitivity.

The system achieved an accuracy of 5.3% for measurement of losses as small as 1 W.

2 Methodology

To make the method independent from geometry of the DUT, a closed-type system is used to transfer heat to the cooling liquid (water). We utilize two identical heat-insulated chambers placed inside an outer chamber that isolates the calorimeter from the ambient (Fig. 1). The DUT chamber contains

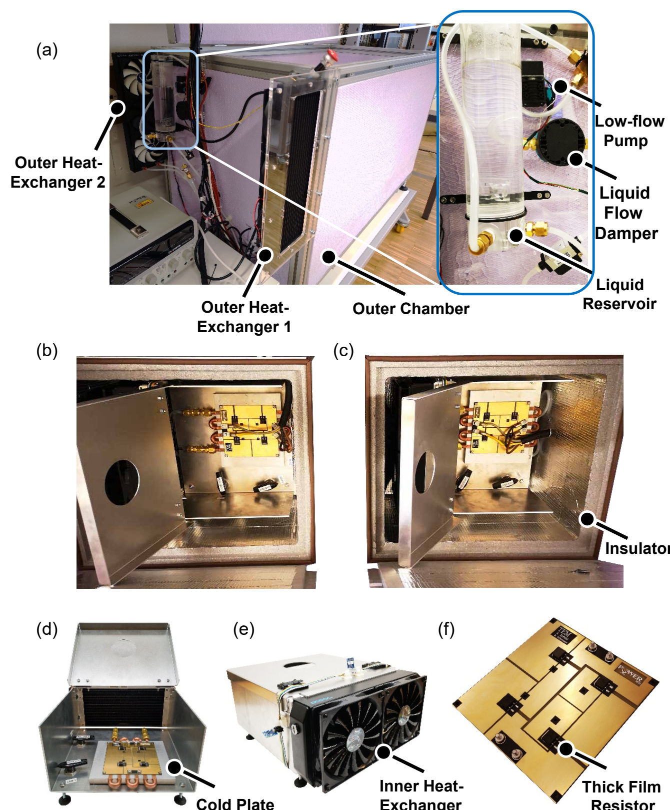

Fig. 2 System demonstrator. (a) The calorimeter external heat-exchangers and the outer chamber. The inset presents the water circuit. (b) DUT and (c) CAL chambers. The inner chambers include an aluminum box for better heat spread, as well as holding the cold-plate and the inner heat-exchanger. (d) Aluminum fixture inside the inner chambers. (e) The front view of the inner heat-exchanger with the fans and air temperature sensor array. (f) Thick-film resistor set mounted on a PCB and placed in both CAL and DUT chambers for DC calibration.

a converter with an unknown power loss, and resistors are placed inside the calibration (CAL) chamber. Heat is transferred by two mechanisms: a heat exchanger equipped with a fan extracts the heat by convection and a cold-plate beneath the DUT absorbs the heat by conduction (Fig. 1). Cooling capability depends on the heat exchanger thermal efficiency and water flow rate. The outer chamber contains fans to circulate air for even temperature distribution. Based on (1), any loss in DUT chamber leads to a gradient in temperature between the water inlet and outlet. This gradient is then measured and fed back to a PI regulator, with the purpose of adjusting the power in CAL chamber such that both chambers have the same gradient at steady state. The water at ambient temperature flows through the DUT chamber and after absorbing the heat generated by DUT, gets cooled down to the ambient temperature using an external heat exchanger (Fig. 1). By flowing water at the same rate through both chambers, we eliminate the need to measure flow rates. The power dissipated in the CAL chamber at steady state is simply determined by DC measurements, which gives the loss in the DUT.

Such method offers a much shorter measurement time since it requires no prior calibration or extra data analysis. The cooling capability or sensitivity can be adjusted using either the pump pressure or the fan power for the inner heat exchangers.

3 System Design and Operation

The system consists of an external chamber (Fig. 2a) and two identical inner chambers (Figs. 2b,c) using polystyrene for thermal insulation. As shown in the inset of Fig. 2a, the water circuit consists of a reservoir connected to a micro-diaphragm pump with pulsation-damper resulting in stable low liquid-flow rate. This is required for measuring small losses, as lower flow rate results in higher temperature rise in the water, increasing the sensitivity of calorimeter. Each of the inner chambers (Figs. 2b, c) enclose an aluminum fixture for the inner heat exchanger and cold-plate, as shown in Figs. 2d, e. The calibrator is a PCB with an array of thick-film resistors (Fig. 2f), which is mounted on the cold-plate.

TABLE II
OVERVIEW OF IMPORTANT DESIGN COMPONENTS

Component	Type	Specifications
Water Temp. Sensor	PT100	Acc. ≤ 0.2 K
Micro-Diaphragm Pump	NFB5KTDCB-4	Max. Pressure = 1 bar
Pulsation-Damper	FPD06KTZ	Max. Pressure = 2 bar
Cold-plate	416101U00000G Aavid	Extruded Aluminum with Copper tubes
Inner Heat-exchanger	Alphacool XT45	2 fans Test pressure up to 2 bar
Outer Heat-exchanger	Airplex PRO 240	3 fans
Power Measurement Unit	Fluke 45	Voltage Acc.: 0.025% + 6 Current Acc.: 0.2% + 7
Data Acquisition	myRIO-1900	LabVIEW environment

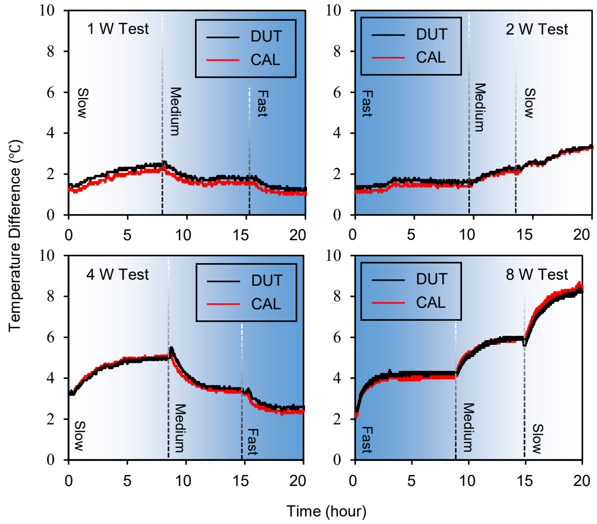

Fig. 4 DC calibration test results. Equal power from 1 W to 8 W are dissipated and the difference in temperature for DUT (black) and CAL (red) are recorded. For each power level, three different flows are tested. The dashed lines separate between intervals in which the flow changes.

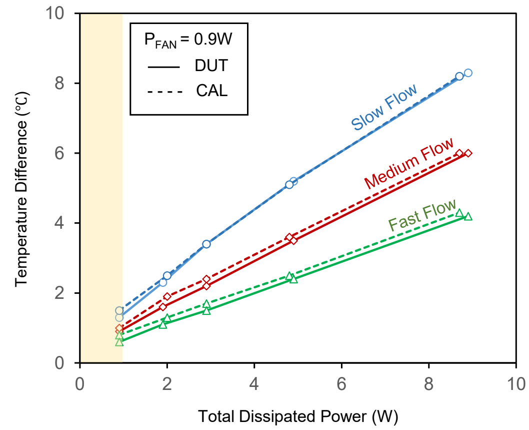

Fig. 3 DC calibration results at steady state. Reducing the flowrate results higher signal-to-noise ratio. The shaded region indicates the offset for power measurement, incurred by the power dissipation in the inner heat-exchanger fans. Flowrate and fan power could be adjusted based on the trade-off between the sensitivity and the cooling requirements of the DUT.

An automation using LabVIEW is responsible for acquisition of data and regulation. Table II lists the main components used in the setup. The size of each inner chamber is 48x42x36 cm and of the outer chamber is 120x66x70 cm. A PI regulator commands a DC supply, which dissipates power in the CAL resistors, and the power is measured by an accurate digital multimeter through consecutive sampling of voltage and current.

4 Experimental Results and Analysis

The transient system response under DC calibration is presented in Fig. 3 for four different power dissipations from 1 W to 8 W and for 3 different flow rates. The red curve is the water temperature gradient in the CAL chamber, which follows that of the DUT chamber shown in black color. The steady state results for CAL and DUT (Fig. 4) revealed an accuracy of 5.3% for measuring losses down to 1 W. The system has two degrees of freedom to measure with better sensitivity or higher cooling capability: the water flow rate and the inner heat exchanger fan power. As Fig. 4 illustrates, reduction of the flow rate increases the signal-to-noise ratio for more accurate measurements. However, if the DUT is dissipating more power, the flow can be increased to avoid overheating and failure, which inevitably sacrifices the accuracy. The shaded region in Fig. 4 represents the dissipated power inside the inner heat exchanger fan (P_{FAN}). For small losses in DUT, P_{FAN} could be reduced to obtain better sensitivity, whereas to provide better cooling, one needs to increase this parameter. Power tracking is shown in Figs. 5a, b for a dynamic test of 7.8 W. The regulator (Fig. 5c) adjusts CAL power (P_{CAL}), which in steady state is equal to the DUT loss (P_{DUT}).

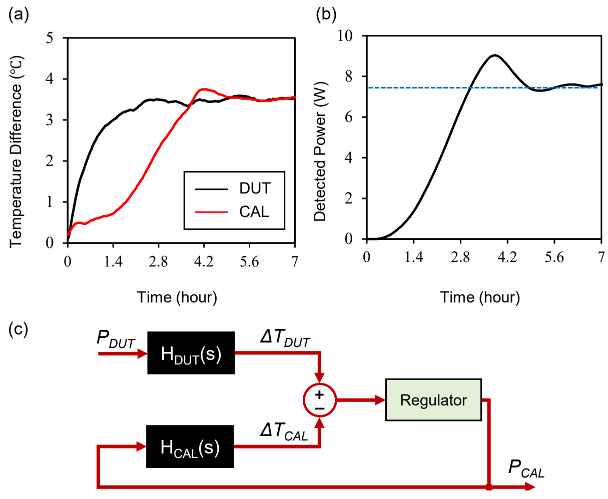

Fig. 5 System transient response for (a) temperature gradients and (b) the corresponding power dissipation applied by the PI regulator. (c) Implementation of the PI regulator. Temperature gradients are compared, and the PI regulator adjusts P_{CAL} to equalize gradients.

5 Conclusion

We proposed a closed-type dual-chamber calorimeter with high sensitivity for loss measurements as low as 1 W with 5.3% accuracy. By applying a real-time calibration, no compensation or further data-processing is required, which reduces the measurement time significantly. The method does not require any flow measurements, enabling the use of very small flow rates. Tuning the pump pressure or heat exchanger fans, cooling capacity or measurement sensitivity can be adjusted based on the requirements of each measurement. Such calorimetric system enables evaluation of losses for optimizing power converters as well as precise characterization of loss mechanisms at high frequencies for active and passive components.

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