

**DEVELOPMENT OF PHOTONIC-BASED MULTI-POINT
TEMPERATURE SENSING FOR POWER ELECTRONICS
APPLICATIONS**

BY

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This work is dedicated to Almighty Allah.

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LIST OF ABBREVIATIONS

PES	:	Power Electronic Systems
PSS	:	Power Switching Semiconductors
MOSFET	:	Metal Oxide Semiconductor Field-effect Transistor
IGBT	:	Insulated Gate Bipolar Transistor
SiC	:	Silicon Carbide
T _j	:	Junction Temperature
TC	:	Thermocouple
TM	:	Thermistor
PBT	:	Physical Based Technique
EBT	:	Electrical Based Technique
OBT	:	Optical Based Technique
TSEP	:	Temperature Sensitive Electrical Parameters
TSED	:	Temperature Sensitive Electrical Parameters
EL	:	Electroluminescence
IRC	:	Infrared Camera
FBG	:	Fiber Bragg Grating
PRT	:	Platinum Resistance Thermometers
RTD	:	Resistance Temperature Detector
t _{off}	:	Turn-off
AC	:	Alternating Current
DC	:	Direct Current
OSA	:	Optical Spectrum Analyzer

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ABSTRACT

Full Name : Ridwanullahi Oluwakayode Isa
Thesis Title : Development Of Photonic-Based Multi-Point Temperature Sensing for Power-Electronics Applications
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Power-switching semiconductors (PSS) are widely used in power electronics systems to regulate electrical signals and maintain operational stability. The junction temperature (T_j), which is the temperature at the junction region of a PSS chip, rises significantly owing to the frequent and severe electrical pulses they encounter in power circuits. To avoid excess T_j and subsequent power system failures resulting from PSS malfunctions, it is common practice to continuously monitor the PSS junction temperature. Previous research focused on two distinct temperature sensing techniques: optical and non-optical methods. Among these, the optical fiber Bragg grating (FBG) technique has garnered recent attention as a cutting-edge, compact optical solution. It has gained prominence owing to its resilience against disturbances within power electronics circuits. Previous studies have implemented single-point junction temperature sensing for insulated gate bipolar junction transistors (IGBT) by directly attaching the sensor to the semiconductor chip. However, this approach has limitations when it comes to typical electronic applications that necessitate simultaneous monitoring of multiple power modules. Considering these challenges, this study proposes a novel multi-point junction temperature sensing approach. It utilizes an array of FBG sensors multiplexed to monitor the junction temperatures of multiple IGBTs integrated into a three-phase power converter circuit. Notably, these sensors are positioned beneath the IGBT baseplate, as opposed to direct on-chip placement, mitigating the risks associated with potential damage when removing the ceramic encapsulation of IGBTs.

ملخص الرسالة

الاسم الكامل: رضوان الله أولواكاويدي عيسى

عنوان الرسالة: تطوير استشعار درجة الحرارة متعدد النقاط القائم على الفوتونية لتطبيقات إلكترونيات الطاقة

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: الخميس، ١٩ أكتوبر ٢٠٢٣ م

تستخدم أشباه الموصلات التي تحول الطاقة (PSS) على نطاق واسع في أنظمة إلكترونيات الطاقة لتنظيم الإشارات الكهربائية والحفاظ على الاستقرار التشغيلي. ترتفع درجة حرارة التقاطع (T_j) ، وهي درجة الحرارة عند منطقة التقاطع لشريحة PSS، بشكل كبير بسبب النبضات الكهربائية المتكررة والشديدة التي تصادفها في دوائر الطاقة. لتجنب فائض (T_j) وفشل نظام الطاقة اللاحق الناتج عن أعطال PSS، من الممارسات الشائعة مراقبة درجة حرارة تقاطع PSS بشكل مستمر. ركزت الأبحاث السابقة على تقنيتين متميزتين لاستشعار درجة الحرارة: الطرق البصرية وغير البصرية. من بين هذه التقنيات، حظيت تقنية صريف براج الألياف الضوئية (FBG) باهتمام حديث باعتبارها حلاً بصرياً متطوراً ومدمجاً. وقد اكتسبت مكانة بارزة بسبب مرونتها ضد الاضطرابات داخل دوائر إلكترونيات الطاقة. نفذت الدراسات السابقة استشعار درجة حرارة تقاطع نقطة واحدة لترانزستورات الوصل ثنائية القطب ذات البوابة المعزولة (IGBT) عن طريق ربط المستشعر مباشرة بشريحة أشباه الموصلات. ومع ذلك ، فإن هذا النهج له قيود عندما يتعلق الأمر بالتطبيقات الإلكترونية النموذجية التي تتطلب مراقبة متزامنة لوحدات الطاقة المتعددة. وبالنظر إلى هذه التحديات، تقترح هذه الدراسة نهجاً جديداً لاستشعار درجة الحرارة بتقاطع متعدد النقاط. وهي تستخدم مجموعة من أجهزة استشعار فيج متعددة لرصد درجات حرارة تقاطع من إيجبتس متعددة متكاملة في دائرة تحويل الطاقة ثلاث مراحل. والجدير بالذكر أن هذه المستشعرات موضوعة تحت اللوح الأساس IGBT، على عكس التنسيب المباشر على الرقاقة، مما يخفف من المخاطر المرتبطة بالضرر المحتمل عند إزالة التغليف الخزفي لـ IGBTs.

CHAPTER 1

INTRODUCTION

1.1 Background of Power Electronics

In datacenters, automobiles, and power plants alike, power electronic systems are responsible for controlling and switching electrical circuits. In situations where the circuits are under adverse load conditions, they are prone to overheating that exceeds the specified operational limits due to thermal stress. Device malfunctions, fatigue of the solder layer of devices, sudden system breakdowns, and, in extreme cases, explosions can result from such circumstances, which have the potential to disrupt the entire system's operation [1].

Thermal stress has consistently been the predominant factor affecting the reliability of power electronic systems (PES). Approximately 55% of the overall stress and failures observed in power electronics can be attributed to it [2]. Specifically, power electronics switches, particularly those made of silicon and extensively utilized in various applications, are responsible for 21% of the total root failures in power systems [3], Fig. 1.1 and Fig. 1.2 visually represent this information. Power-switching semiconductors (PSS) play a crucial role, accounting for over 60% of power control in industrial applications and the distribution of electrical energy in developed nations.

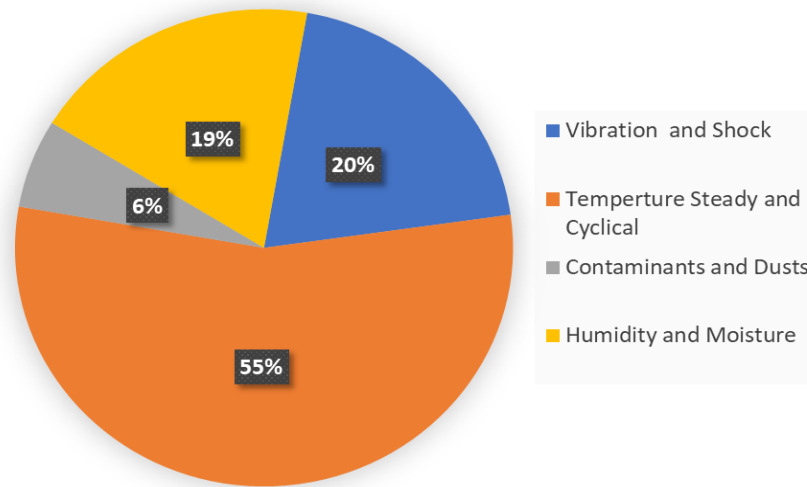


Figure 1.1: Source of Failure in PES [1].

PSS are employed to enhance reliability in the realm of intelligent power control [4], [5]. Utilizing PSS in power electronics offers several advantages, including a broad frequency range of operation and robust power-handling capabilities extending to hundreds of kilowatts.

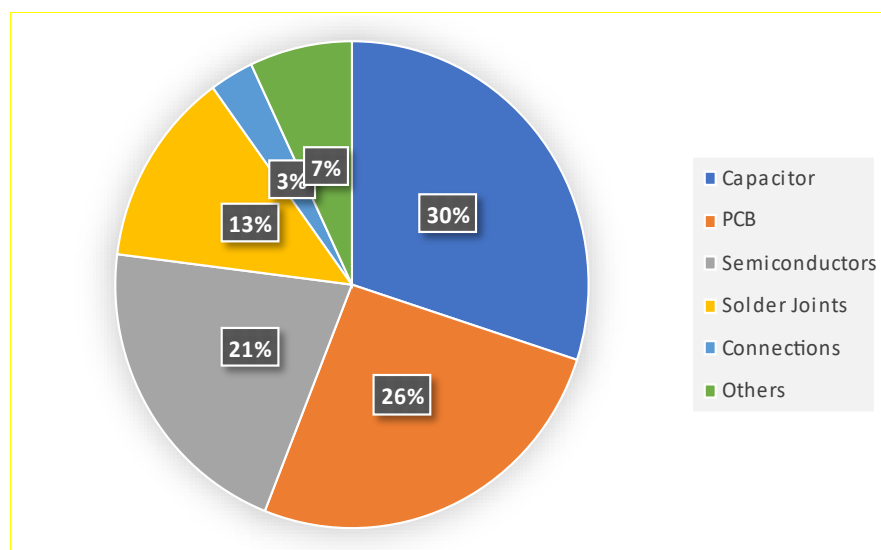


Figure 1.2: Failure distribution of PES components [3].

PSS are employed to enhance reliability in the realm of intelligent power control [4], [5]. Utilizing PSS in power electronics offers several advantages, including a broad frequency range of operation and robust power-handling capabilities extending to hundreds of kilowatts. Among the most employed PSS devices are the Silicon Carbide Metallic Oxide Semiconductor Field Effect Transistor (SiC MOSFET) and the Silicon (Si) Insulated Gate Bipolar Transistor (IGBT). These devices are currently being deployed in converters, replacing the Silicon Metal Oxide Semiconductor Field Effect Transistor (Si MOSFET), which operates at frequencies below 100 kHz.

Power-switching semiconductors within a converter circuit experience power and thermal fluctuations during operation, primarily caused by sudden shifts in pulse signals and terminal loads. Consequently, these fluctuations increase the temperature above the ambient conditions at both the junction and other areas of the module, as the weakest layer in the PSS devices such as IGBT is the chip [6]. Furthermore, the continuous rise and fall of junction temperature is a result of power dissipation and recurring thermal pulses at the junction. As such, the fluctuation of junction temperature stands as a prominent factor contributing to the failure of many PSS devices [7]–[10]. However, the literature has put forth methods for sensing PSS junction temperature to safeguard the overall circuit's integrity. These methods encompass thermal detection using physical instruments as well as techniques reliant on electrical circuits or parameters relying on electrical signals for measurement. Another developed approach is the optical-based method, which employs light signals rather than electrical signals for thermal detection.

The electrical-based sensing method involves the utilization of electrical components or electrical characteristics to estimate temperature. Conventional electrical devices for this purpose encompass temperature-sensitive components that employ electronic elements like diodes or temperature-dependent resistors to quantify temperature levels. However, these components often contribute to the complexity of the system. Alternatively, temperature-sensitive electrical parameters (TSEP), including parameters like gate threshold voltage, saturation current, and short-circuit current, can also be utilized for the purpose of junction temperature sensing. However, it's important to note that this method incurs to power losses within the system [11]–[13]. The physical technique involves the use of a thermistor and a thermocouple that measure temperature differences between two points external to the system. This approach requires sticking an external probe to the point where temperature is to be measured manually, as shown in Fig. 1.3.



Figure 1.3: Physical technique of temperature measurement using thermocouple [14].

Although it has a good spatial resolution, it requires disassembly of the system for probe placement, which is difficult for measuring the temperature of inner components in power circuits. Furthermore, noise induced from the power circuit, especially at high frequencies, is also a constraint for this technique [15], [16]. As such, optical-based techniques (OBT) have recently been developed for thermal monitoring in power grid and industrial plant operations.

OBT techniques are generally immune to electromagnetic interference (EMI) [17]–[19], it includes infrared camera (IRC), electroluminescence (EL), and fiber Bragg grating (FBG) techniques. IRC employs radiation emitted from the objects to detect temperature at a distance, while EL techniques extract the photon emission that occurs in silicon semiconductors at forward bias to characterize the thermal variation at the semiconductor device's junction. In contrast, FBG utilizes the wavelength shift that occurs due to temperature influence over the grating portion of the optical fiber. One added advantage of FBG is that it can detect temperatures up to 650 °C, even though the maximum junction temperature of typical power switches is below 175 °C. The aim of this work is to design a multipoint junction temperature sensor using an optical fiber Bragg grating sensor (FBG), which is stuck on power switches in a typical power system for real-time temperature sensing. This would allow studying the thermal behavior of multiple PSSs concurrently to prevent sudden failure of the power circuit.

1.2 Motivation

Power electronic devices' reliability is crucial in power plants, as sudden failures can cause power interruptions and damage to other electronic devices. In various sectors, such as automotive, data storage, and manufacturing, power-switching semiconductor failures due to overheating are the primary cause of power interruptions and sudden failures. It is therefore desirable to be able to avoid overheating by monitoring the junction temperature of power-switching semiconductors. Thus, this thesis investigates the development of a temperature sensor system that can accurately monitor several power-switching semiconductor devices.

1.3 Objectives

The thesis aims to explore FBG technology and identify the most effective approaches to developing multi-point temperature sensors for power electronics. To accomplish this, the following specific objectives are set:

- To develop an analytical model for heat transfer within the IGBT components and heat transfer to the FBG sensor.
- To implement an FBG-based sensor for single-point junction temperature measurement in a three-phase power converter.
- To optimize the performance of the developed single-point junction temperature

measurement and improve the measurement accuracy.

- To extend the implementation of single-point junction temperature measurement to multi-point junction temperature measurement in a three-phase power converter.
- To validate and evaluate the performance of the developed systems with infrared camera.

1.4 Scope of the study

The scope of this study is to develop a portable multi-point photonic sensor for a typical inverter circuit, where the sensor will be embedded to map the junction temperature of the IGBTs used in the circuit. Due to the device capacity specified by the manufacturer, the temperature range shall be examined between 30 and 120 °C at a maximum voltage of 415 V. The electronic AC load used for this work is limited to 5 KW in power rating due to equipment limitations.

1.5 Thesis Organization

The first chapter of this thesis introduces the significance of power electronic systems and PSS, along with the challenges they pose in today's technology landscape.

A thorough background analysis and a review of relevant previous studies are presented in the second chapter. This includes a comparison of the three categories of temperature sensing methods, namely physical, electrical, and optical-based thermal sensing, which serves to justify the selection of the Fiber Bragg Grating (FBG) technique.

The third chapter includes an in-depth discussion of the heat transfer model and a theoretical analysis of the proposed methodology, while Chapter 4 covers the system component description, technical details, and integration of the modular units.

The fifth chapter delves into the examination and comparison of results derived from calibration, single-point, and multipoint temperature sensing. It also explores the impact of thermal conductivity on the measurements. Finally, the concluding fifth chapter wraps up the thesis, offering limitations and future recommendations for the commercialization of the developed thermal sensor.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The rise of power electronics has ushered in the creation of intelligent devices capable of effectively managing the operation of power circuits. Traditional components like resistors, capacitors, and transistors have become inadequate for managing the power and frequency demands of contemporary technology. Consequently, power-switching semiconductors (PSS) are manufactured by combining two or more of these conventional components in a specialized arrangement and configuration. This is done to achieve higher operational power and frequency capabilities.

The central concept behind PSS revolves around the manipulation of the input electrical signal based on the device's state until the desired output is achieved. Although several types of PSS have been developed for a wide range of applications over the past two decades, the most recently developed power switches have emerged as particularly suitable devices for controlling electric signals in modern power circuits. They are directly employed in converters, three-phase and single-phase inverters, and power circuits because of their compatibility with high-frequency switching applications, including electric vehicles, aerospace systems, and traction motors.

2.2 Power-Switching Semiconductor Devices

Common power-switching semiconductors encompass a range of devices, including thyristors, silicon (Si) controlled rectifiers (SCR), triodes for alternating current (TRIAC), insulated gate bipolar transistors (IGBT), and silicon metal oxide semiconductor field effect transistors (Si MOSFET). These devices are employed for power circuit switching applications, albeit with variations in terms of switching speed, efficiency, operational frequency, and power-handling capacity. [20]. However, today's technology application requires devices with fast switching speeds. Si MOSFET was adopted early for its high operating frequency features, but it operates in a low power range.

The limitations of Si MOSFET brought about Si IGBT and SiC MOSFET, which are widely used in today's power circuits. Although Si IGBT can withstand high power up to several hundreds of kilowatts, it still operates in low- to moderate-frequency applications. As such, SiC MOSFET is a better replacement for Si IGBT due to its high switching speed. A comparison of the three devices is depicted in Fig. 2.1. However, Si IGBT possesses a low switching loss compared to Si MOSFET, and as such, they are frequently used in auxiliary power supply systems as switches [21]–[23].

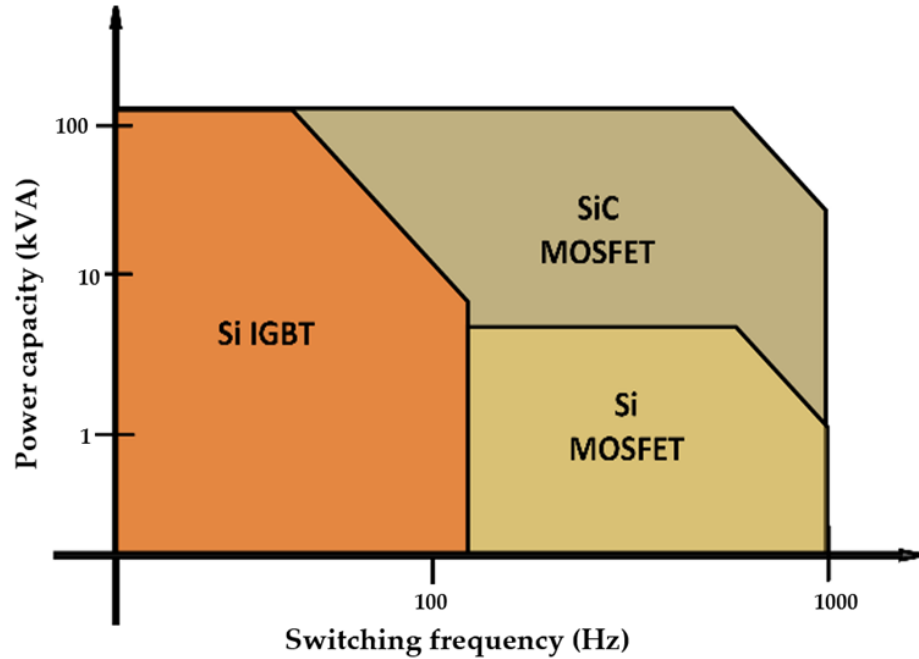


Figure 2.1: Comparison of the operating power and frequency of Si, SiC and IGBT.

2.3 Junction Temperature Sensing

Junction temperature stands as a pivotal parameter when it comes to designing power semiconductor devices, as it exerts a significant impact on their lifespan and reliability. Junction temperature in a power semiconductor module refers to the maximum operational temperature reached by the semiconductor device. The case temperature of the device may align with when the device is not active. However, when a load is connected during the device's operation, the frequent switching of the device and the conduction losses lead to an increase in junction temperature, which subsequently results in power dissipation. The expression given in (2.1) depicts the relationship between the two temperatures and power dissipation. To ensure safe operation of PSS, junction temperatures should be kept below the maximum operation level in the power circuits.

$$T_j = T_c + (P_d R_{jc}) \quad (2.1)$$

where T_j is the junction temperature, T_c represents the chip's case temperature, P_d and R_{jc} represent the power dissipation and the case thermal resistance, respectively. Several temperature sensing methods have been explored in the literature, the three common methods of T_j in the literature are categorized into electrical, physical, and optical method [24].

The physical method is not well-suited for commercial applications; it is often reserved for laboratory temperature measurements. Most electrical methods are suitable for real-time measurements but might require the integration of a separate module into the system. On the other hand, state-of-the-art optical-based sensing techniques, including contactless IR cameras for surface temperature measurement, electroluminescence (EL) extraction, and optical fiber technology, offer alternatives. It is worth noting that physical and electrical methods rely on electrical signals or parameters for measurements, whereas optical methods operate based on light signals, involving photons' radiation and reflection. The diagram of the three classifications is illustrated in Fig 2.2.

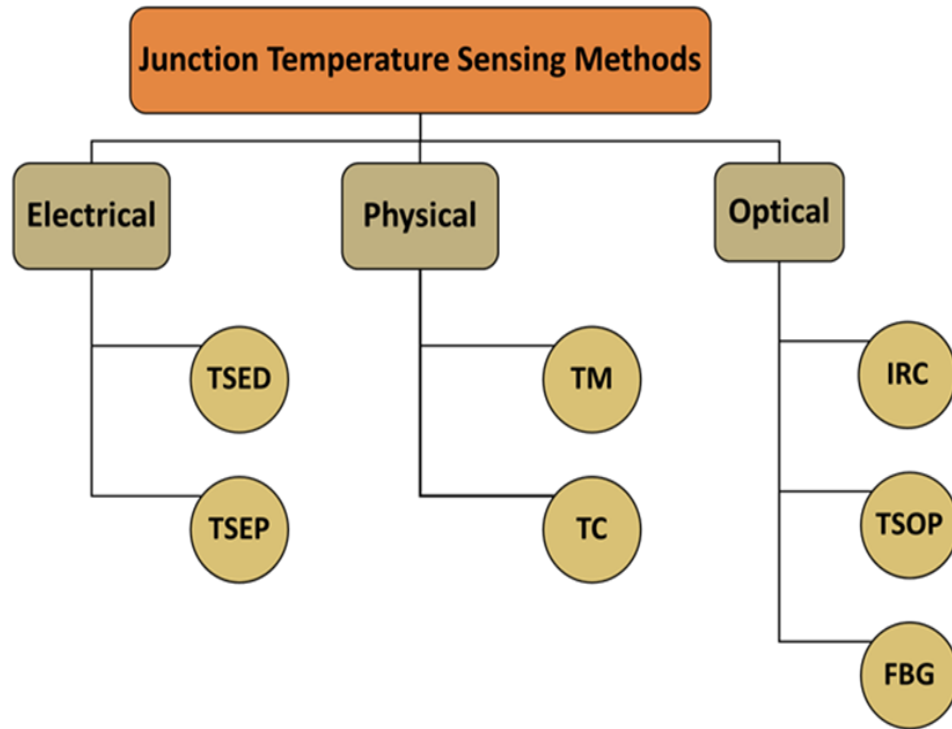


Figure 2.2: Classification of junction temperature sensing methods.

2.4 Physical-Based Temperature Sensing (PBT)

Physical-based techniques involve the use of probe contacts for temperature measurement. For PSS junction temperature sensing, this method includes thermocouples [15], [16], [25], and thermistors [26], [27]. One major benefit of PBT is that high spatial resolution can be obtained based on the small size of the probe tip. As such, they are widely used for temperature measurement validation in the laboratory.

2.4.1 Thermocouple (TC)

TCs are commonly used as simple and low-cost temperature sensors, with a low to moderate response speed depending on the thermal response times of the probe or particles [16]. The basic principle involves the detection of a temperature difference between two different conductors, which results in the generation of an electromotive force (emf). Typically, a pre-determined reference temperature or reference junction temperature of 0°C is provided with a Peltier cooler or ice water with respect to the desired point to be measured on PSS components. The emf generated due to the temperature gradient between both junctions and the TC is then measured by an instrument such as a digital voltmeter or an amplifier combined with a digital converter for direct temperature reading. As shown in Fig. 2.3, the measured voltage V_M by the instrument can be expressed as:

$$V_M = V_{TC} - V_{CJ} \quad (2.2)$$

$$V_{CJ} = V_{CJ1} + V_{CJ2} \quad (2.3)$$

Where V_{TC} , and V_{CJ} are the thermocouple and the reference junction voltage at the measured temperature, V_{CJ1} , V_{CJ2} are the two voltages at the cold reference junction.

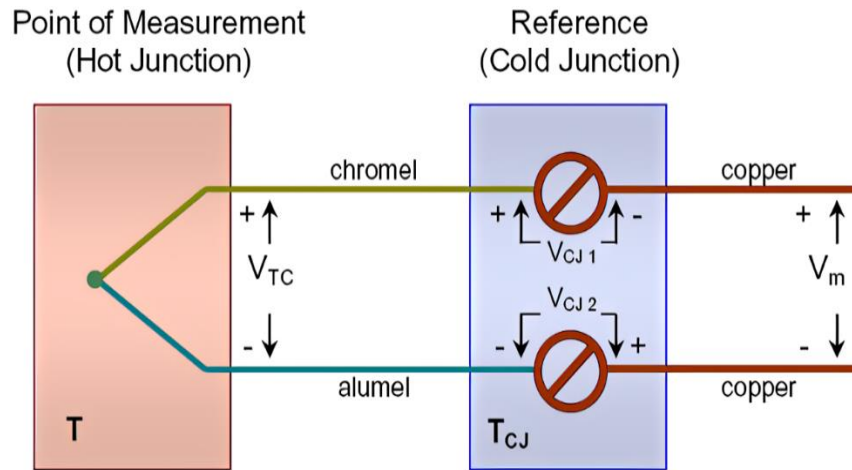


Figure 2.3: Operation principle of Thermocouple for junction temperature sensing [28].

There are several types of thermocouples depending on the type of material used for external conductors; this includes K, B, N, and S types. All of which are different in terms of operating temperature range, sensitivity, chemical stability, and range of output voltage. The most widely used in the laboratory is the K type, which has a temperature range of 250 to 1100 °C and an output voltage of 40 to 250 μ V. Although the B type has a higher operating temperature of about 1750 °C, its minimum operating range is 100°C, and it is more expensive than the K type. The major limitation particular to the thermocouple is that voltage may be induced in the conductor due to surrounding EMI, which will in turn severely affect the reading accuracy.

2.4.2 Thermistor (TM)

Modern thermistors consist of temperature-sensitive semiconductor materials such as nickel, titanium, and manganese. Typical thermistors have either a positive resistance coefficient (PTC) or a negative resistance coefficient (NTC). However, the most widely used type is the NTC, which has a typical operating temperature range of 25 to 250°C and

an accuracy of $\pm 1^{\circ}\text{C}$. Thermistors are suitable for estimation of junction temperatures, baseplates, and substrates, especially when high spatial resolution is desired. The major setback particular to the thermistor is that it only extracts the average substrate temperature of the power device. In addition, the response time is lower than 5 ms due to its thermal capacitance and often requires re-calibration for a particular circuit model to obtain an accurate measurement since they are sensitive to model inaccuracies [26].

Even though probe sensing methods are of high spatial resolution in order of nanometers, the major concern is that they are prone to error under the influence of EMI, due to self-heating because of the voltage induced from circuit during the operation state of PSSs.

2.5 Electrical-Based Temperature Sensing (EBT)

Several types of EBT have been reported in the studies, ranging from the techniques that rely on embedded dedicated temperature-sensitive electrical devices (TSED) that include diodes [29]–[31], resistant temperature detectors (RTD) [32]–[34], and sensitive electrical parameters such as shunt current, forward voltage, threshold voltage, and so on [35]–[37]. The underlined principles and features for each of the categories of EBT will be discussed in the subsequent paragraphs. The EBT approach for junction temperature sensing in semiconductor modules can be grouped into temperature-sensitive electrical devices and temperature-sensitive electrical parameters.

2.5.1 Temperature-Sensitive Electrical Device (TSED)

This approach uses added sensing elements; the commonly used elements include transistors and diodes, which are fixed on the chip for junction temperature measurement. TSEDs are fast in response and capture transient temperature changes, but the temperature measurement is not always reliable due to error induction from the main device circuit at low temperatures.

2.5.2 Silicon Diode

Devices such as Si, GaAs, and Zener diodes exhibit a linear relationship between the forward voltage and temperature changes; the forward voltage has a positive temperature coefficient, i.e., temperature increases with a decrease in the forward voltage. Thus, the voltage-temperature relationship approach was used by Motto et al. [29] to detect variation in junction temperature in a power semiconductor module with a fabricated diode fixed on the die surface.

Si diode has been used in many cases other than Zener diodes and GaAs diodes [30], [31], because of its stability and low cost, although it has a lower output temperature compared to GaAs, as shown in Fig. 2.4. The typical temperature measurement range of a silicon diode is between 55 and 150 °C, with an accuracy of about 0.8 and 1.1 °C. Even though fabricated diodes on chips can provide accurate measurement, they in turn increase the complexity of the power module as well as the active area of the chip.

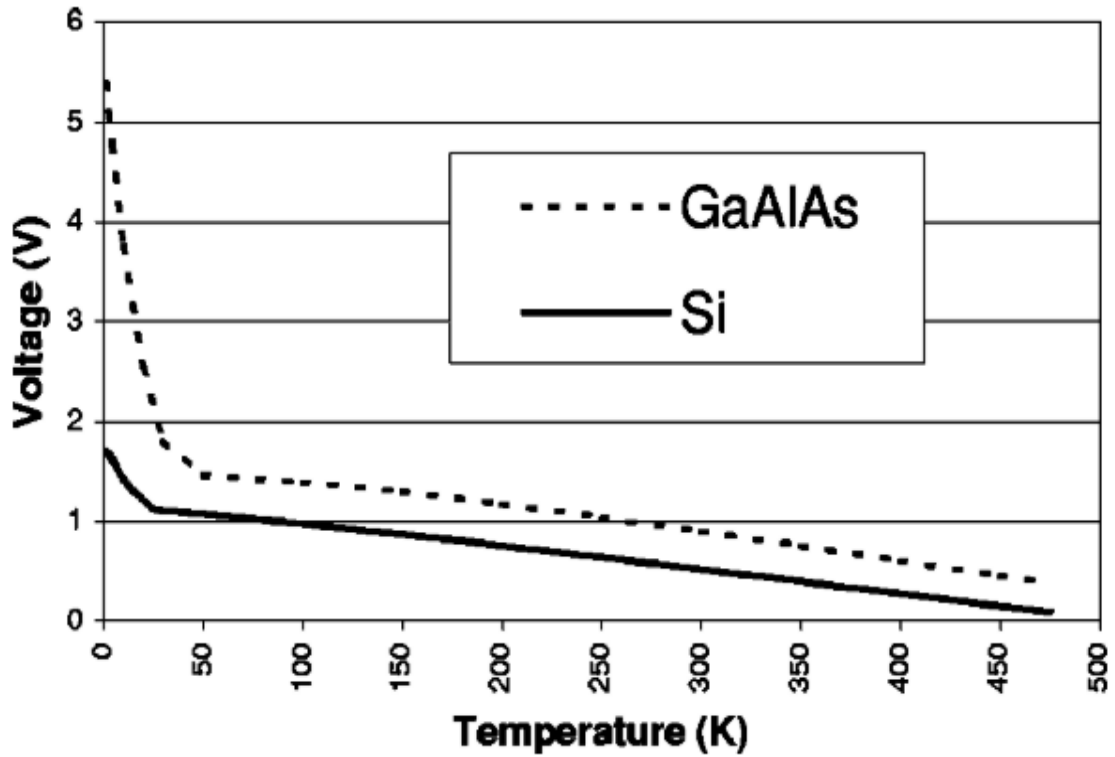


Figure 2.4: Voltage temperature relationship for GaAlAs and Si semiconductors [26].

2.5.3 Resistance Temperature Detector (RTD)

RTDs, otherwise known as platinum resistance thermometers (PRTs), consist of sensors fabricated with semiconductor chips. Such chips contain materials that exhibit variations in electric resistivity with respect to the material's temperature. The resistance measured by the sensor in Fig. 2.5 is typically converted into voltage by a Wheatstone bridge, which is excited by a constant reference voltage. It is then passed to a differential amplifier to increase the sensitivity and minimize the noise signal.

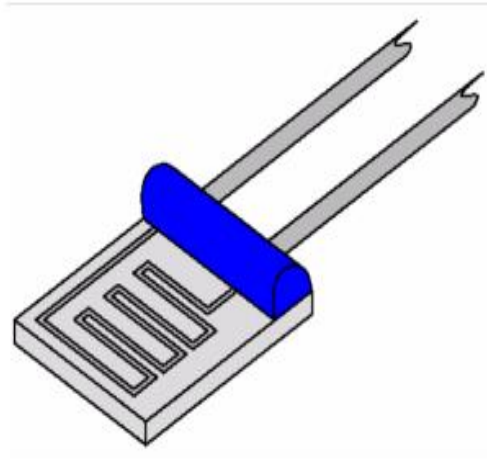


Figure 2.5: Resistance Temperature Detector sensor [38].

The sensitivity of the RTD is then computed based on the temperature coefficient of the RTD, which represents the change in resistance per one degree of the change in temperature expressed [$\Omega/\Omega/^{\circ}\text{C}$]. The expression for the variation in resistance ΔR is given as:

$$\Delta R = \alpha_R R_0 \cdot \Delta T \quad (2.4)$$

where R_0 is the nominal sensor temperature resistance and ΔT is the change in temperature of the device in degrees Celsius. Thus, the value of the resistance at any temperature T is given as:

$$R_T = R_0 + \Delta R \quad (2.5)$$

The device sensitivity is proportional to the resistance temperature coefficient of resistance, and it is expressed as:

$$K_{RTD} = \alpha_R R_0 \quad (2.6)$$

Typically, the temperature range of RTD is between -264°C and 1064 °C, with a sensitivity range of (0.1–0.385)Ω/°C [26]. The experimental work carried out by Moiseea et al. [34] established the measurement stability of PRTs, and it was also proven in [33] that PRTs can provide an accurate estimation of a chip's temperature if optimally placed. However, the complexity and implementation cost of this method are the major drawbacks that limit its usage for commercial applications. RTDs are immune to EMI and can provide more accurate temperature measurement, but they are bigger in size due to bulky wiring compared to Si diodes. Thus, they occupy more space in the power circuit.

TSED provides high-accurate measurement and fast response times. However, they undergo self-heating, which incurs significant errors in the measurement. Also, power circuits tend to be more complex because of added elements, which also require additional packaging terminals.

2.5.4 Temperature Sensitive Electrical Parameter (TSEP)

The TSEP sensing technique offers active thermal control, and condition monitoring of IGBT-based power converters [39]. This approach involves the extraction of electrical parameters of the power module, such as the on-state resistance [40], the internal gate resistance [15], [41], the threshold voltage [42], the turn-off delays [43], [44], switching frequency [45], and so on, which are further correlated to the device junction temperature provided by the manufacturer. Typical IGBTs and SiC MOSFET manufacturers provide datasheets that indicate collector-emitter versus junction temperature relationships (V_{CE} -

T_J), threshold voltage versus junction temperature relationships ($V_{TH}-T_J$) for IGBTs, and on-state resistance versus junction temperature relationships ($R_{DS}-T_J$) for MOSFETs. TSEP methods employ these relationships to estimate junction temperature. A detailed discussion of the highlighted TSEP approach is discussed in the following subsections.

2.5.5 On-State Resistance

One of the frequently utilized methods based on temperature-sensitive electrical parameters (TSEP) is the measurement of on-state resistance. This method is preferred due to its high sensitivity and the fact that it does not necessitate any modification to the power module. In MOSFETs, the on-state resistance is otherwise known as the drain-source resistance (R_{DS-on}). R_{DS-on} is a junction temperature-dependent parameter that is calculated by combining V_{DS-on} and I_{DS-on} . As depicted in Error! Reference source not found., the drain-source voltage V_{DS-on} is to be measured by a voltage sensor across the power module terminals, while the on-state current I_{DS-on} can be measured through the device with a current transducer. The value of R_{DS-on} is then estimated using the expression in (2.7), and R_{DS-on} is further correlated with the R_{DS} -temperature curve specified in the datasheet to obtain the corresponding junction temperature values [46].

$$R_{DS} = \frac{V_{DS_{on}}}{I_{DS_{on}}} \quad (2.7)$$

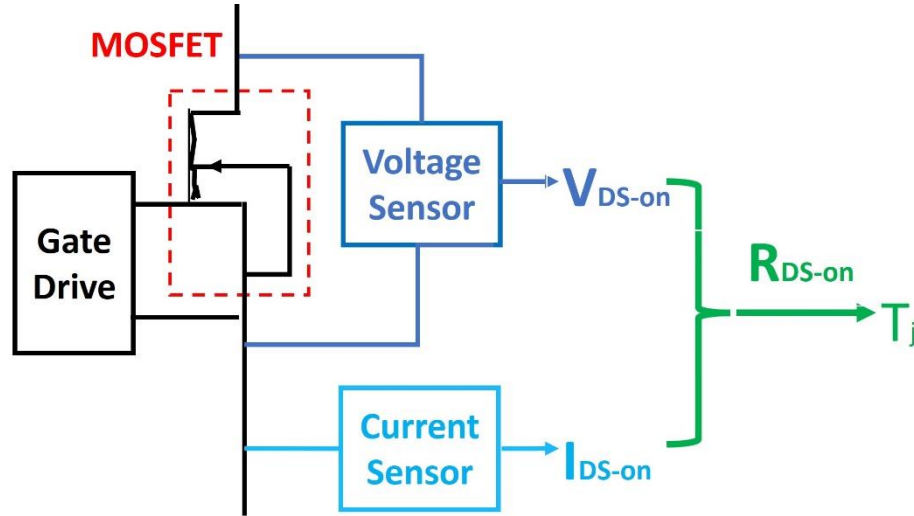


Figure 2.6: On-state Resistance measurement in MOSFET values [46].

Like MOSFET, the IGBT on-state collector-emitter voltage V_{CE} is also T_j dependent. In the case of IGBT, it is worth noting that V_{CE} is also dependent on collector-emitter current I_{CE} [40], which means that I_{CE} is required to measure V_{CE} . As shown in Fig. 2.7, a 3D correlation of V_{CE} , I_{CE} , and T_j was used in [47] for junction temperature estimation.

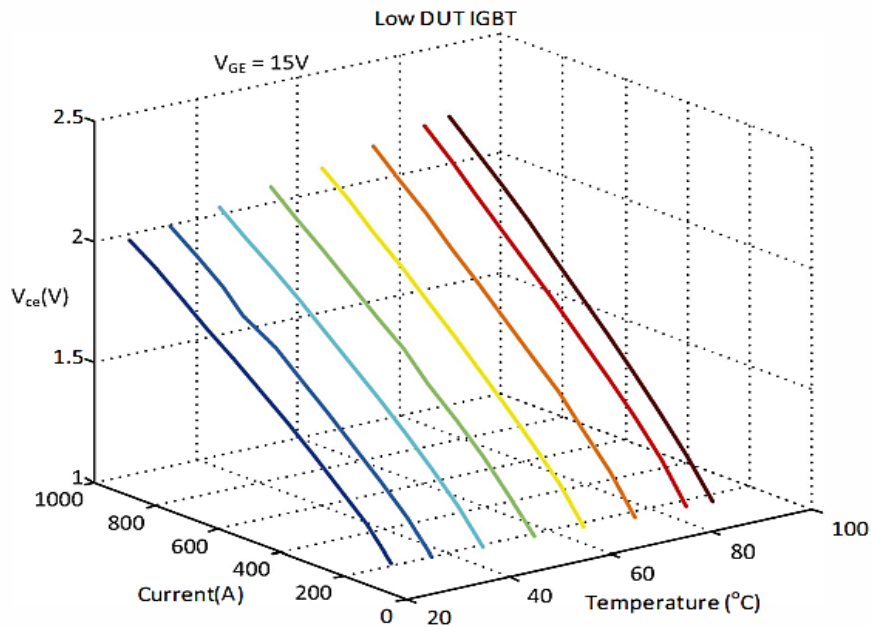


Figure 2.7: The IV characteristics for the low side freewheeling diode [47].

The voltage sensor is invasively linked across the SiC MOSFET or IGBT terminals for both devices to measure voltage, while the current sensor measures the device's current to measure the junction temperature. As such, galvanic isolation is required for the voltage sensor, and the voltage sensor should have a good bandwidth (around 100 kHz) necessary for VDS or VCE measurement. This method is suitable for temperature sensing in bulk converters and simple rectifiers; it is easy to implement, and its temperature sensitivity is between 2 mV/C and 3 mV/C for the current range of 550 A to 922 A. But the drawback is that the noise generated by the power converter can cause errors in the on-state properties of the device during operation, and a slight deviation of the ICE or IDs will cause a significant error in the T_j estimation.

2.5.6 Internal Gate Resistance (R_{G-int})

The internal gate resistance of an IGBT is located at the center of the die; it is the lumped equivalent of the distributed resistance of the polysilicon gate and metal contacts in a MOSFET device [37]. It has been reported that the value of R_{G-int} varies for both IGBT and MOSFET, depending on the design parameters of the device, such as the doping, geometry, gate contact resistance, and so on [48]. The temperature dependency of R_{G-int} has also been established for junction temperature estimation in [15], [41]. To obtain R_{G-int} , a known current is to be fed to the internal gate resistor to cause a voltage drop V_R across the R_{G-int} as shown in Fig. 2.8. The R_{G-int} temperature response of the device can also be measured with an LCR meter and a heater to establish the junction temperature calibration curves as implemented by Bhalla and Wang [49].

The experimental approach of R_{G-int} carried out by [15] reported a sensitivity of $0.75 \text{ m}\Omega/^{\circ}\text{C}$ for IGBTs below a temperature of 150°C . R_{G-int} exhibit a fast measurement response and can be used for real-time junction temperature measurement because the internal gate resistance is located in the die, although it is difficult to access the die in commercially distributed IGBTs. However, since the R_{G-int} value is several $\text{m}\Omega/^{\circ}\text{C}$ a high-resolution voltage sensor will be required to measure V_R . Also, the integration of the measuring circuit may be affected by the switching noise in the power module, which will in turn affect the measurement accuracy since R_{G-int} is situated on the chip.

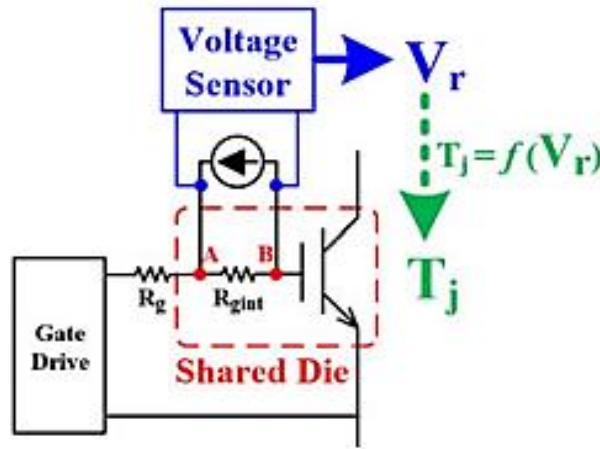


Figure 2.8: Method of internal gate resistor for temperature measurement [15].

2.5.7 Threshold Voltage (V_{th})

The threshold voltage of a semiconductor device is the minimum gate-source voltage required to switch on the device [37]. V_{th} is the minimum bias required to create a conductive channel between the collector-emitter and drain-source in IGBT and MOSFET, respectively. The V_{th} approach of junction temperature estimation relies on the shift of the

threshold voltage, which is due to the decrease of bandgap and increase of carrier concentration with junction temperature. Typically, V_{th} varies with temperature; this variation is induced by the change of the Fermi level with the intrinsic concentration, which can be expressed as:

$$V_{th} = V_{th0} + K_T \left(\frac{T}{T_0} - 1 \right) \quad (2.8)$$

where T_0 is the ambient temperature in Kelvin, V_{th0} is the threshold voltage at ambient temperature and K_T is a temperature coefficient for MOSFETs in V/°C. The temperature variation with respect to the threshold voltage is given in [42] as:

$$\frac{dV_T}{dT} = \frac{d\psi_B}{dT} \left[2 + \frac{1}{C_{ox}} \sqrt{\frac{\epsilon_{si} q N_A}{\psi_B}} \right] \quad (2.9)$$

while

$$\frac{d\psi_B}{dT} = \frac{1}{T} \left[\frac{E_g}{2q} - |\psi_B| \right] \quad (2.10)$$

where V_{th} is the threshold voltage, ψ_B is the distance of the Fermi level from mid-gap, ϵ_{si} is the dielectric constant of *si*, q is the electron charge (1.6×10^{-19} C), N_A is the doping density, E_g is the bandgap at $T = 0$, and C_{ox} is the intrinsic gate-channel oxide capacitance. V_{th} and temperature are functions of the oxide thickness t_{ox} , and the doping density N_A , as depicted in Fig. 2.9. Although the theoretical analysis made by [50] claimed that V_{th} is

influenced by the gate resistance and reference voltage, the experimental results established that the threshold voltage method has a good temperature sensitivity and is suitable for online junction temperature sensing, with a T_j between 5.2 mV/°C and 19.6 mV/°C for SiC MOSFET. The limitation of the threshold voltage method is that it decreases with an increase in DC bus voltage, which in turn decreases the temperature sensitivity, most especially in SiC MOSFET.

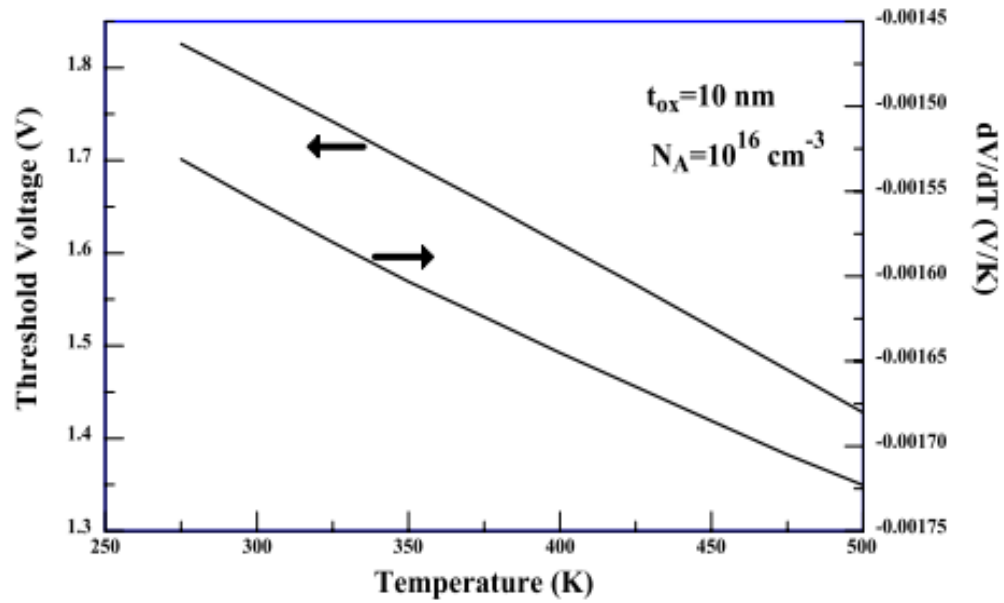


Figure 2.9: Temperature vs threshold voltage for power MOSFET [42].

2.5.8 Turn-Off Transient (t_{off})

This method utilizes the time delay between the turn-on and turn-off events to estimate the junction temperature. t_{off} refers to the delay duration from when the driver voltage begins to change until the circuit collector current decreases [35]. This change is influenced by the junction temperature, collector-emitter voltage V_{CE} , and the collector current I_C . The turn-off transient increases as collector-emitter voltage V_{CE} , and the junction temperature T_j

increases monotonically while the collector current I_C decreases. The relationship is given as:

$$t_{off} = f_{t_{off}}(T_j, V_{CE}, I_C) \quad (2.11)$$

The experimental work carried out by [43], [44] employed the turn-off delay of an IGBT to estimate junction temperature in real-time across various collector current levels. A temperature sensitivity of 0.5 mV/°C and 3.5 mV/°C was obtained at I_C of 200 A and 1200 A, respectively. Additionally, Luo et al. [51], examined the impact of load current and DC bus voltage. They observed a positive, nearly linear relationship between the turn-off delay time and junction temperature. This correlation is illustrated in Fig. 2.10 and Fig. 2.11 depict the turn-off transient vs. temperature curve obtained under different bus voltage and load current conditions.

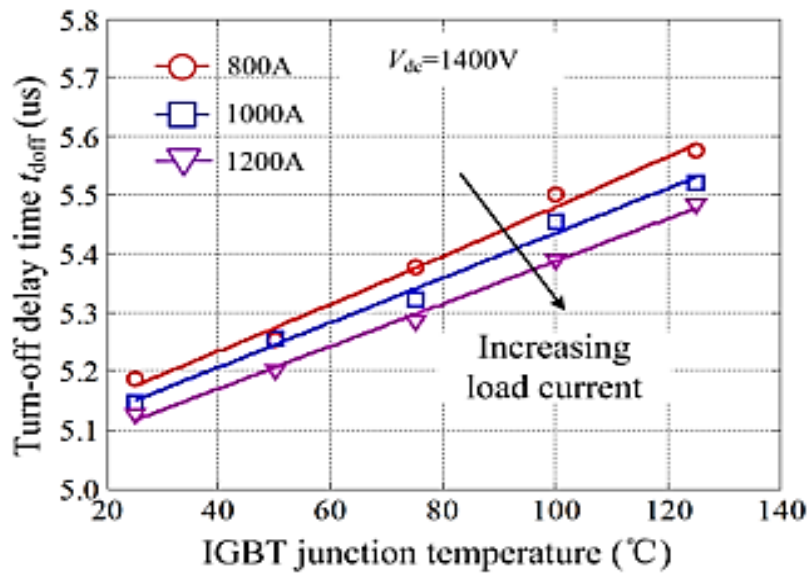


Figure 2.10: t_{off} vs T_j curve for IGBT at constant Vdc of 1400V [51].

While the turn-off approach is appropriate for real-time junction temperature estimation, it necessitates the use of a high-bandwidth voltage comparator and precise time counters with a resolution of approximately 1 ns per step to ensure accurate results. Furthermore, it is essential to establish a galvanic connection between the IGBT collector and emitter to prevent noise interference from the power module.

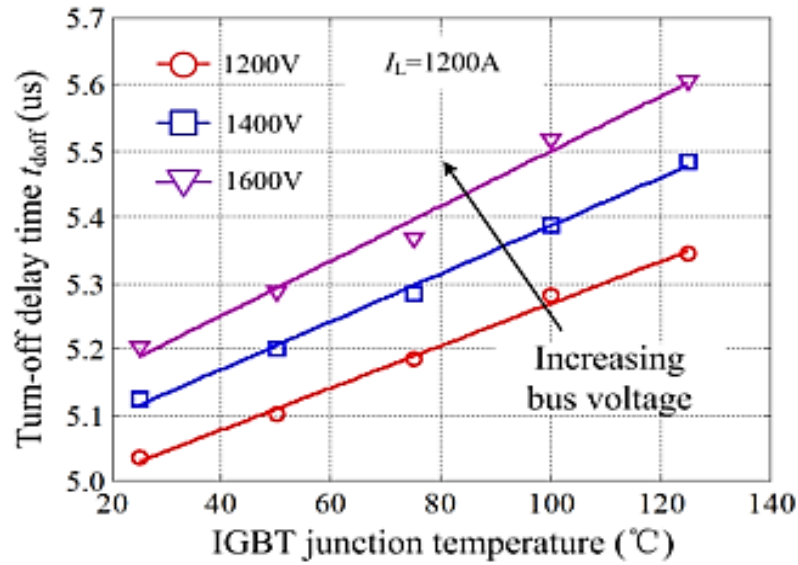


Figure 2.11: t_{off} vs T_j curve for IGBT at constant T_L of 1200A [51].

To improve the accuracy of TSEP measurement, a self-correcting Cauer network model could be integrated to mitigate the impact of solder layer aging, using common mode interference current amplitude to accurately predict the junction temperature of an IGBT as experimented in [52].

TSEP techniques entail the necessity to account for various circuit parameters like load current and transient voltage, particularly under operational conditions beyond just the junction temperature. Additionally, achieving accurate measurements with TSEP often demands complex measurement circuitry or modifications to the power switch or the

overall structure of the power circuit. The substantial limitations for its commercial utilization lie in the demanding calibration process, circuit modifications, and intrusiveness of the measurement process. The subsequent paragraph provides detailed information on optical junction temperature sensing methods, which address these limitations.

2.6 Optical Based Temperature Sensing (OBT)

OBT employs a light signal for junction temperature measurement instead of the electrical signal used in the physical and electrical-based methods discussed earlier, which are immune to electromagnetic interference (EMI) and non-invasive to the measurement. Several types of OBT have been reported in the literature, but due to their complexity and high cost of implementation, optical methods such as Raman spectroscopy [53], [54], reflectance [55], [56], are not commonly used. The widely used methods for junction temperature detection in power switching devices include IR camera [57], electroluminescence [48] and fiber Bragg grating [58], [59]. The working principle and notable features of OBST are discussed in the subsequent paragraphs. The optical approach for junction temperature sensing in semiconductor modules can be grouped into two categories: infrared camera, electroluminescence, and fiber Bragg grating.

2.6.1 IR Camera (IRC)

The IR camera method relies on naturally emitted infrared radiation from objects to characterize temperature distribution, as such radiation is captured at a distance without physical contact with the chip surfaces[60]. A typical IR camera provides a 2D display of

the surface temperature distribution in real time, which makes it suitable for commercial applications [61]. As shown in Fig. 2.12, the emitted radiation captured by the IR camera is a summation of the emission due to the material temperature, the surrounding atmosphere, and the radiant energy striking the target, which can be expressed as:

$$W_{total} = E_{obj} + E_{atm} + E_{refl} \quad (2.12)$$

where the E_{obj} , E_{atm} , and E_{refl} are the emission of the target object, the reflection from the surrounding and the atmosphere, respectively. The expression for the emission from the target surface E_{obj} , E_{atm} , and E_{refl} can be further expressed as

$$E_{obj} = \varepsilon_{obj} \tau_{atm} \sigma_{atm} (T_{obj})^4 \quad (2.13)$$

Also,

$$E_{atm} = \varepsilon_{obj} \tau_{atm} (T_{atm})^4 \quad (2.14)$$

$$E_{refl} = (1 - \varepsilon_{obj}) \tau_{atm} \sigma_{atm} (T_{refl})^4 \quad (2.15)$$

where, ε_{obj} is the emissivity of the object, σ_{atm} is the Stefan-Boltzmann's constant which is given as $5.670 \times 10^{-8} \text{ W/m}^2/\text{k}^4$, T_{obj} , T_{atm} , T_{refl} is the temperature of the object, atmosphere and due to reflection respectively, while τ_{atm} is the transmittance of the atmosphere.

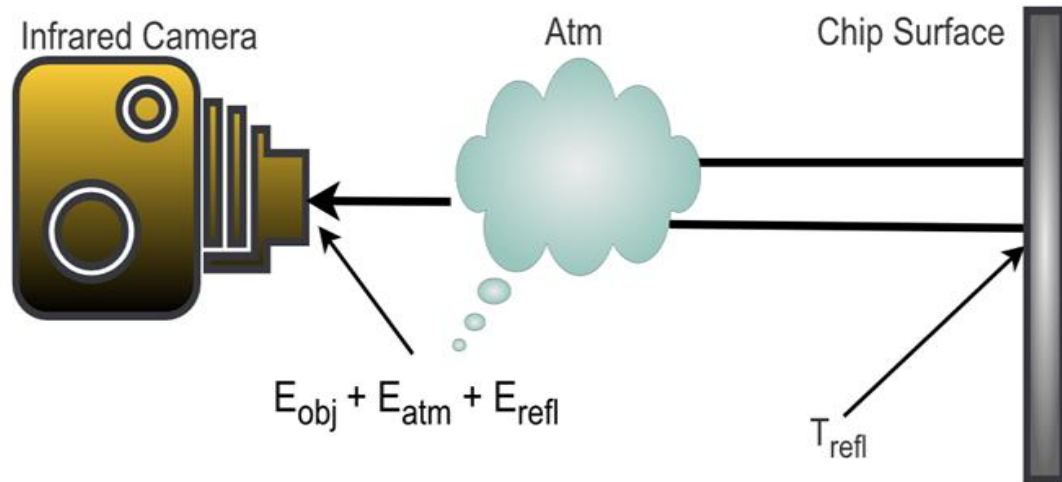


Figure 2.12: Radiation captured by IR camera.

IR cameras are extensively utilized in both industrial and commercial contexts today; they are user-friendly and provide an improved visualization of surface temperatures, as shown in Fig. 2.13. However, they necessitate manual operation and require an unobstructed line of sight between the camera and the surface for precise temperature mapping. Additionally, uniform emissivity of the targeted surface is essential to achieving a clear depiction of temperature distribution.



Figure 2.13: Temperature sensing using IR camera [61].

In a typical power circuit setup, power semiconductor components like IGBT and MOSFET are typically encased within ceramics or plastic in addition to the external housing. This makes it challenging to employ infrared IR camera because there is no direct, unobstructed path from the MOSFET to the camera. Also, to ensure accuracy, several factors must be taken into account, including the resolution and sampling rate, both of which are contingent on the manufacturer's device specifications [62]. Therefore, it is preferable to use an IR camera with high resolution and a rapid sampling rate to achieve precise measurements and effectively monitor rapid changes in thermal distribution.

2.6.2 Electroluminescence (EL)

EL is the emission that occurs as a result of excitation made through the recombination of electrons and holes across a p-n junction [63]. The peak energy EL exhibits depends on its temperature and the spatial resolution of the EL [16]. However, since the process of EL extraction for junction temperature measurement in PSDs entails simultaneous treatment for both current and temperature of the semiconductor at forward bias, current needs to be extracted separately for proper estimation of the junction temperature [64]–[66]. EL is only applicable to PSDs that possess a forward-biased p-n junction with a direct band gap; as such, they are feasible for Si and SiC MOSFETs when they operate in the 3rd quadrant; this is where the conditions of forward bias and photon emission can be met [67]. For IGBTs, its p-n junction acts as a parasitic light-emitting diode in 1st quadrant operation; to establish 3rd quadrant operation, antiparallel freewheeling diodes need to be integrated.. [68], [69].

The excitation made during the recombination process causes the release of photons, and the relationship between the photon's wavelength λ and energy E is given as:

$$\lambda = \frac{1240}{E} \quad (2.16)$$

The experimental work in [70], investigated the electroluminescence of SiC MOSFET, the electrothermal-optic model developed revealed the relationship between the junction temperature, light intensity and the forward current, which is given as:

$$I_{EL} = a_o i (1 + k_1 \Delta T) + b_o i^2 (1 + k_2 \Delta T) \quad (2.17)$$

where a_o and b_o are the coefficients because of junction temperature. i is the forward current, k_1 and k_2 are the constant coefficient, and ΔT is the variation in the device T_j under test DUT.

Typical implementation of EL employs a low-nonlinear quartz fiber for transmission of emitted photons from the silicon die, as shown in Fig. 2.14. Visible light is emitted around the SiC chip during the conduction of the body diode; the emitted light is then passed through the sampling circuit and spectrogram for junction temperature estimation and display, respectively.

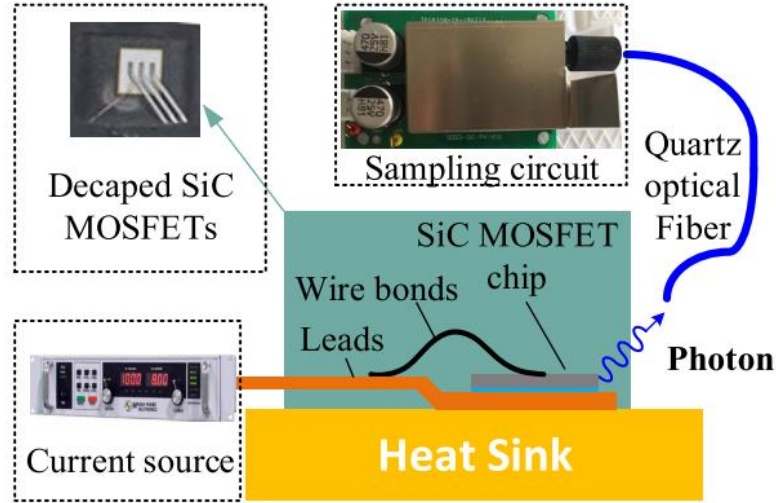


Figure 2.14: Electroluminescence extraction for SiC MOSFET [71].

2.6.3 Fiber Bragg Grating (FBG)

The FBG approach uses a typical optical fiber sensor: a fiber portion with a uniform or specially grating at a particular wavelength to reflect light based on the temperature changes over the grating portion of the fiber. Typical optical fiber has a diameter between 20 and 25 mm and is double and neither easily degraded in performance nor affected by aging due to the flow of photons. As such, they are portable and can easily be multiplexed and embedded in power modules without occupying a significant amount of space or size [72]. These attributes give FBG an added advantage over the IRC and EL methods. When a light signal generated from a typical broad band source is fed to the fiber, the spectral signal known as the Bragg wavelength is reflected, depending on the refractive index and the grating period, as shown in Fig. 2.15. The expression is given as:

$$\lambda_B = 2 n_{eff} \Lambda \quad (2.18)$$

where, Λ is the grating pitch, n_{eff} is the effective refractive index of the single mode fiber, and λ_B is the wavelength shift [73]. This wavelength shift is linearly temperature-dependent; as such, in the cases where the FBG sensor is stuck to the IGBT or Si MOSFET chip and the external effect stress and surrounding temperature are isolated, the equivalent wavelength shift represents the junction temperature of the device under test.

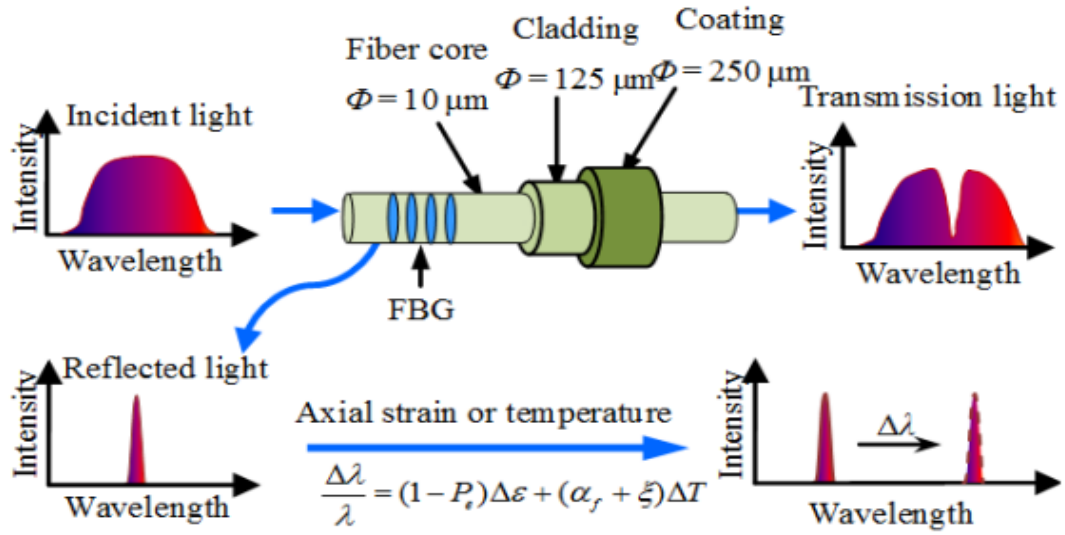


Figure 2.15: Schematic of FBG sensing [74].

The application of FBG for temperature sensing in power electronics entails fixing the sensor to the targeted semiconductor chips. The fiber can then be illuminated with a light source such as a broadband light source (BBS). A circulator is then used to direct the transmitted light to the sensor. Due to the variation in object temperature that is already stuck to the grating portion of the fiber, the thermo-optic effect alters the core refractive index [75], which in turn causes shifts in the central wavelength [74]. The reflected Bragg wavelength shift is redirected through the circulator to the interrogator for measurement.

The relationship between the temperature variation and the wavelength shift can be expressed as:

$$\frac{\Delta\lambda}{\lambda} = [(+ a_f + \xi)\Delta T] + (1 - P_e)\Delta\varepsilon \quad (2.19)$$

where, $\Delta\lambda$ is the wavelength shift, λ is the initial center wavelength of that FBG, a_f is the thermal expansion coefficient of the fiber, ξ is the coefficient of thermal-optic and P_e is the strain-optic coefficient. Assumed the change in strain is constant i.e. ($\Delta\varepsilon = 0$), in the case eqn. 2.20 can be expressed as:

$$\frac{\Delta\lambda_b}{\lambda_b} = (a_f + \xi)\Delta T \quad (2.20)$$

Several factors, such as the sensor head length, housing type, and sensor-object thermal emissivity, impact the performance of the FBG technique. The influence and performance of fiber Bragg grating for different head lengths were experimented with in [76], and the housing type and sensor-chip interface effect were investigated in [77] and [58] respectively. It is established that careful selection of fiber head length, with the use of thermal paste to match the thermal conductivity of the sensor-chip interface, would offer more accurate temperature sensing. Temperature sensing ranges of 23 to 430°C have also been reported for FBG in [78], with an accuracy of 0.02°C in [58]. Thus, we can deduce that FBG outperforms OBT, EBT, and other optical methods discussed so far. Details of the physical implementation of the FBG technique for power electronics applications will be discussed in Chapter 3.

2.7 Summary of Related Work

This section provides an overview of the discussed junction temperature techniques and a comparison of their performance in terms of accuracy, operating temperature range, cost, and application. In addition, the limitations of the three techniques are highlighted.

Table 2.1: Summary of junction temperature measurement techniques.

Group	Method	Temp. Range	Accuracy (° C)	Sensitivity	Limitations	Ref
Physical	Thermocouple	-270 - 2300°C	±0.5 to ±2 °C	10 - 68 mV/°C	EMI interference	[12]-[22]
	Thermistor	-150 to 700°C	±0.01 to ±0.0°C	10mV/°C	Slow response	[26], [27]
Electrical	Silicon Diode	-55 to 156°C	±0.8 to ±1.3°C	±1%	Slow response	[29]–[31]
	Platinum Resistor	-264 - 1060°C	±0.2 to ±0.5°C	0. 10 mV/K	Complexity	[32]–[34]
	R _{DS-ON}	<100°C	±1.5°C	1.5 -2m V/°C	Noise	[40]
	Internal Gate Resistance	30-150°C	---	0.75mΩ/°C	Noise	[15], [41]
	Turn-Off Transient	20 - 140°C	---	(1 to 2) ns/°C	Complexity	[42]
	Threshold Voltage	250 to 500K	± 0.7 to ±3° C	(-0.5 to 8) mV/°C	Synchroniza tion	[43], [44]
Optical	IR Camera	35- 160°C	±2 ° C	--	Required uniform emissivity	[79]- [80]

Electroluminescence	30-150°C.	± 1.2 to ± 5 ° C	(0.10 to 3.2) mV/°C	Difficult to Implement	[81], [67]
FBG		± 0.1 ° C	(10.2 to 0.02) nm /°C	Fragile	[82], [75]

2.8 Thesis Objectives

This thesis focuses on the deployment of FBG sensor as a thermal sensing element for power electronics applications. In contribution to the FBG method outlined in existing literature, this study will delve into development of multi-point thermal sensing for power circuits, a departure from conventional single-point FBG temperature measurement. Furthermore, enhancements will be made to the FBG sensor's precision by optimizing the conductivity of the sensor-chip interface. The experimental results obtained from these measurements will undergo validation using a high-resolution thermal infrared camera to ensure accuracy and alignment with the expected outcomes.

2.9 Research Gap

Research into measuring IGBT junction temperature using FBG sensors has garnered attention due to its promising applications in power electronics and industrial systems. Presented below is a summary of the gaps in existing research within this field:

- There is a lack of in-depth analysis regarding the heat transfer between the IGBT and FBG sensor interface, which is an essential factor in characterizing thermal loss.
- A detailed investigation of the impact on electrical performance and heat dissipation of removing the IGBT ceramic encapsulation for FBG sensor on-chip installation has not been conducted.
- Current research primarily employs single-point sensing; however, it is necessary to investigate multi-point sensing methods that can offer a more comprehensive mapping of temperature variation for many IGBT modules.
- To the best of my knowledge, there has been no empirical research investigating how ambient temperature and vibration affect the accuracy and stability of the sensor.
- Additionally, none of the literature currently available includes an analysis of how the air gap impacts the IGB-FBG interface or how the configuration of sensor installation affects the accuracy and response time of the FBG sensor.

CHAPTER 3

HEAT TRANSFER MODEL

3.1 Introduction

This chapter provides a heat transfer model for IGBT components using resistance thermal networks. It showcases the heat conduction from the IGBT junction through the chip to the copper baseplate for single and parallel IGBT and diode. Furthermore, the expression for IGBT junction temperature value measured at the copper plate is formulated for a single and multiple IGBT modules mounted on a single heatsink.

3.2 IGBT Structure

In the context of power converters comprising power switching modules such as IGBTs mounted on a common heatsink, it is essential to analyze the thermal characteristics of the module's components to estimate the heat loss at each layer. IGBT is made up of several layers from the IGBT and diode chips at the junction, to the solder layer, and the copper plate as shown in Fig. 3.1. Each layer exhibits different mechanical and electrical properties, as such the heat loss across these layers from the junction to the heatsink varies. This behavior can be represented using a resistance thermal network. Additionally, the heat transfer through these layers can be estimated once the power dissipated through the module, and the thermal resistance coefficient for each layer is known.

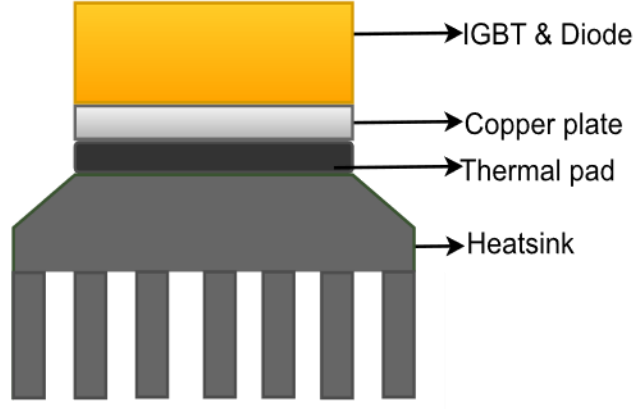


Figure 3.1: IGBT component layers.

3.3 Single Point Model

For a single IGBT module with direct on-chip sensor placement, a simplified static thermal resistance model can be used to estimate heat transfer across the chip-sensor interface. Assuming that mechanical stress remains constant over the sensitive part of the FBG sensors, the reflected wavelength solely depends on thermal variation along the sensor's head length. In this case of the IGBT-FBG sensor interface, the coupling effect between the switches is neglected. The equivalent junction temperature can be estimated with the thermal resistance network shown in Fig. 3.2, provided that the sensor is held closest to the IGBT's chip. Assuming the measurement is made in an enclosure with ambient temperature, the expression for T_j is:

$$T_j = [P_{di}R_{th(j-a)}] + T_a \quad (3.1)$$

where, P_{di} is the allowable dissipated power across the device, $R_{th(j-a)}$ is the junction-to-ambient thermal resistance. In this study, the sensor was placed between the IGBT's baseplate and the heat sink. Thus, (3.1) can be modified to capture the heat loss across the various layers of the module.

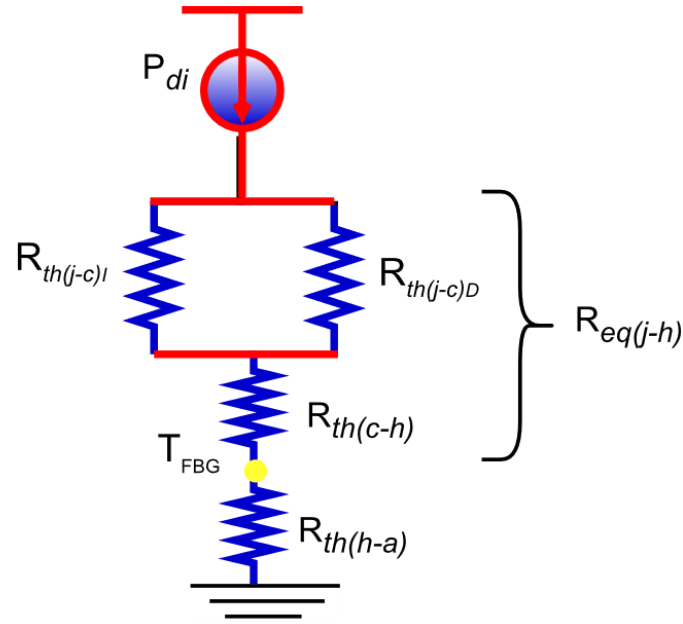


Figure 3.2: Thermal network of a single IGBT module referenced to FBG sensor.

As shown in Fig. 3.2, MOSFETs and IGBTs used in high-power applications typically have an additional diode in parallel to provide a reverse current path for inductive loads. The corresponding junction-to-case thermal resistance for such a module $R_{eq(j-c)}$, can be expressed as an equivalent sum of the anti-parallel diode and IGBT as:

$$R_{eq(j-c)} = \frac{[R_{th(j-c)I} R_{th(j-c)D}]}{[R_{th(j-c)I} + R_{th(j-c)D}]} \quad (3.2)$$

$$R_{eq(j_h)} = R_{eq(j_c)} + R_{eq(c_h)} \quad (3.3)$$

where, $R_{th(j_c)I}$ and $R_{th(j_c)D}$ are the thermal resistances for the anti-parallel diode and IGBT, respectively. Typically, $R_{eq(j_c)}$ and $R_{th(c_h)}$ are commonly specified by the device's manufacturer. Generally, $R_{th(c_h)}$ which is thermal resistance of the case-to-heatsink can be merely estimated as a function of the thermal conductivity of the thermal pad using the following relation.

$$R_{th(c_h)} = \frac{T}{kA} \quad (3.3)$$

where, T is the thickness of the interface layer between the module package and the heatsink, A represents the area occupied by the thermal paste, and k is the specified thermal conductivity of the thermal material. The equivalent thermal resistance for junction-to-ambient $R_{th(j_a)}$ is a sum of $R_{eq(j_h)}$ and $R_{eq(h_a)}$ which are the thermal resistances for junction-to-heatsink and heatsink-to-ambient, and is given as:

$$R_{th(j_a)} = R_{eq(j_h)} + R_{th(h_a)} \quad (3.4)$$

The estimated junction temperature for a point measurement, with reference to the measured sensor temperature T_{FBG} , fixed to the IGBT baseplate, is:

$$T_j = [R_{eq(j_c)} + R_{th(c_h)} + R_{th(h_a)}]P_{di} + T_{FBG} \quad (3.5)$$

Thus, the thermal resistance of the heatsink -ambient can be expressed as:

$$R_{th(h_a)} = \frac{T_j - T_{FBG}}{P_{di}} - [R_{th(j_c)} + R_{th(c_h)}] [K/W] \quad (3.6)$$

3.4 Distributed Heat Transfer Model

As depicted in Fig. 3.3, a typical power circuit consists of several silicon semiconductor devices. Such devices may be IGBTs, MOSFETs, or rectifier modules. To keep track of the thermal behavior of these devices, a distributed sensor is required. Installation of a separate sensor for each device will not be economical and will eventually make the circuit bulky. Similar to the single point model, the approach for static thermal network resistance measurement is valid for three-phase inverters if all IGBTs are assumed to experience the same losses, except in the case of a half-bridge operating as a bulk converter [83]. Suppose the sensor is situated on the IGBT chips along a fiber cable, while the cable functions as a continuous sensor that can identify temperature changes at each sensing point.

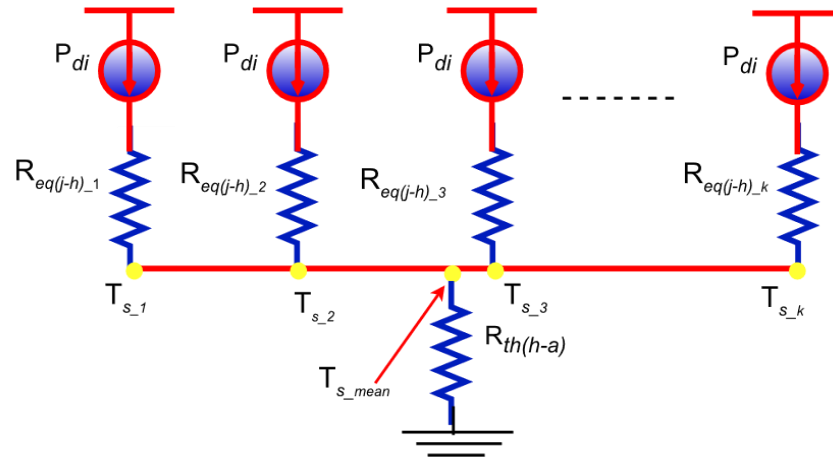


Figure 3.3: Thermal resistance network of multiple IGBT on a heatsink.

Then the equivalent T_j value for these devices is:

$$T_j = [P_{di}R_{th(j-a)}]n + T_a \quad (3.7)$$

where, n is the number of PSS devices mounted on a particular heatsink, $R_{eq(j_h)}$ and P_{di} are the thermal resistance and dissipated power in each semiconductor device.

If the FBG sensor is placed outside the device's case for T_j measurement for a packed rectifier. The equivalent junction-to-case thermal resistance $R_{eq(j_c)R}$, of the rectifier is:

$$R_{eq(j_c)R} = \frac{1}{\frac{1}{R_{D1}} + \frac{1}{R_{D2}} + \frac{1}{R_{D3}} \dots \dots \dots \frac{1}{R_{DN}}} \quad (3.8)$$

where: R_{D1} to R_{DN} represent the parallel combination of the N diodes used for rectification.

For an isolated system, the IGBT case temperature for the rectifier stud, $T_{c(R)}$, is a function of the P_{di} in the rectifier stud and $R_{eq(j_c)R}$

$$T_{c(R)} = P_{di} R_{eq(j_c)R} \quad (3.9)$$

The thermal resistance of the junction-to-heatsink for any kth device $R_{th(j_h)_k}$, is:

$$R_{th(j_h)_k} = \left[\frac{T_{j_k} - T_{s_k}}{P_{di}N} - R_{th(j_c)} \right] + R_{th(c_h)} \quad (3.10)$$

where N is the number of discrete semiconductors packed in the module stacked on the heatsink. For brevity, a single three-phase bridge on a heatsink will have $n = 1$, and $N = 6$ as it consists of six diodes packed on a single stud. while the total dissipated power on the heatsink is equal to $P_{di}N$. Thus, the estimated junction temperature T_{j_k} for the kth device module referenced to the temperate sensor is:

$$T_{j_k} = P_{di} R_{eq(j_h)_k} + T_{s_k} \quad (3.11)$$

The equivalent $R_{eq(j_h)}$ for all the modules i.e., $R_{eq(j_h)_1}$, $R_{eq(j_h)_2}$, ... $R_{eq(j_h)_k}$ are parallel combination of all the modules on the heatsink, and is given as:

$$R_{eq(j_h)} = \frac{1}{\frac{1}{R_{eq(j_h)_1}} + \frac{1}{R_{eq(j_h)_2}} + \frac{1}{R_{eq(j_h)_3}} \dots \dots \dots \frac{1}{R_{eq(j_h)_k}}} \quad (3.12)$$

Also, the expression for the equivalent $R_{th(j-a)}$ and mean sensor temperature are:

$$R_{th(j_a)} = [(R_{eq(j_h)})n_R + (R_{eq(j_h)})n_I \dots \dots + (R_{eq(j_h)})n_o] \quad (3.13)$$

$$+ R_{th(h_a)}$$

$$T_{s_mean} = \frac{T_{s_1} + T_{s_2} + \dots T_{s_K}}{n} \quad (3.14)$$

where: $R_{eq(j_h)no}$ represents the thermal resistance of junction-to-heatsink for other PSS devices mounted on the heatsink, n_R , n_I and n_o represents the number of rectifiers, IGBT modules, and other PSS devices stacked on the heatsink, respectively. Considering the equivalent sum of P_{di} at each semiconductor module, the mean junction temperature for all the semiconductors combined on a heatsink $T_{j(mean)}$, is given as:

$$T_{j(mean)} = \frac{P_{di}R_{th(j_h)}}{F} + T_{s_mean} \quad (3.15)$$

where F is the safety factor for operation temperature. To avoid using devices beyond the maximum allowable temperature, the manufacturers typically recommend a safety factor of 0.8 to 0.9.

3.5 Summary

So far, the heat transfer model for FBG-based temperature measurement using an optical sensor has been presented with the expressions for junction temperature for a single and multiple IGBT studs and other semiconductor devices have been established under different installation circumstances. Moreover, this section has presented the related equation for direct placement of sensors for temperature measurement on the device's chip, as well as the outer casing and temperature gradient of the heatsink. In the forthcoming chapter, detailed installation, and calibration process of the FBG sensor will be discussed.

CHAPTER 4

SYSTEM COMPONENTS AND METHODOLOGY

4.1 Introduction

This chapter outlines the research methodology, procedures, and components employed in this study. Furthermore, it provides a detailed description of the complete system set up , calibration and installation features. The system is assembled and implemented in discrete components, which are then modularized to simplify the design process and reduce complexity. The methodology provides detailed components of hardware integration and testing.

4.2 Research Methodology

In line with Fig. 4.1, the itemized research methodology utilized in this study is as follows:

- 1) Analysis of the heat transfer model for single-point and multi-point temperature sensing using the thermal resistance network and power loss in relation to the IGBT layers.
- 2) Calibration of optical fiber Bragg sensor by heating it to various temperatures to estimate its sensitivity.

- 3) Set up a three-phase inverter circuit, driven by Semikron IGBT, was set up.
- 4) Installation of optical fiber sensors in a three-phase inverter that covers three IGBT modules and their integration into a distributed FBG temperature sensor.
- 5) Isolation of the designed system from varying environmental temperature to improve the measurement accuracy.
- 6) Integration of electronic loads into the converter at different load conditions.
- 7) Mapping the terminal voltage, load power, and load current changes with the wavelength shift produced by the fiber sensor on the spectrum analyzer.
- 8) Translate the wavelength shift into temperature value using the estimated sensitivity.
- 9) Validation of estimated T_j with an infrared camera.

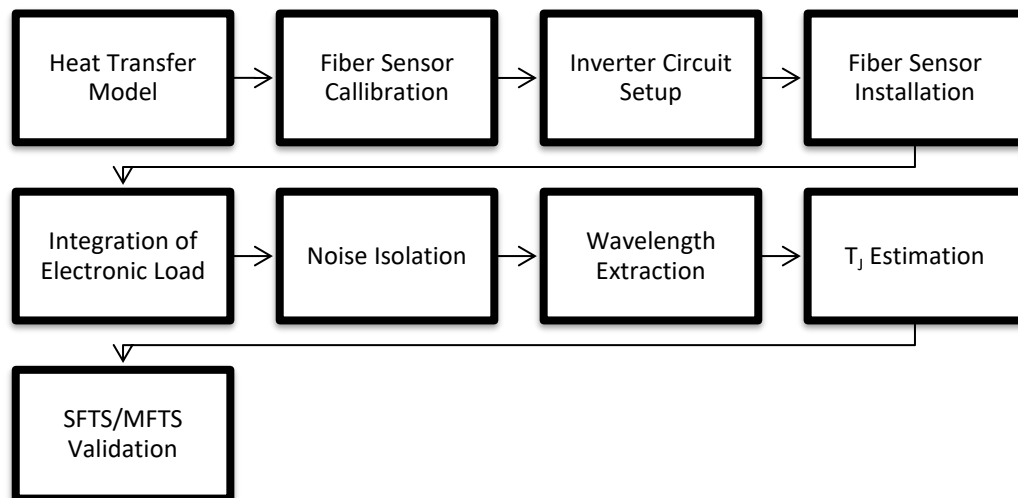


Figure 4.1: Research Methodology Process.

4.3 Overview of the Multi-point FBG Temperature Sensing (MFTS)

The MFTS system, as shown in Fig. 4.2, comprises of optical and electrical control units, as indicated in the schematic diagram. The optical monitoring unit consists of an optical light source, FBG sensors for temperature sensing, and an optical spectrum analyzer that displays the wavelength changes. The electrical control unit features an electric converter, a power supply that activates the inverter circuit, and an electronic load that adjusts the inverter for various load currents.

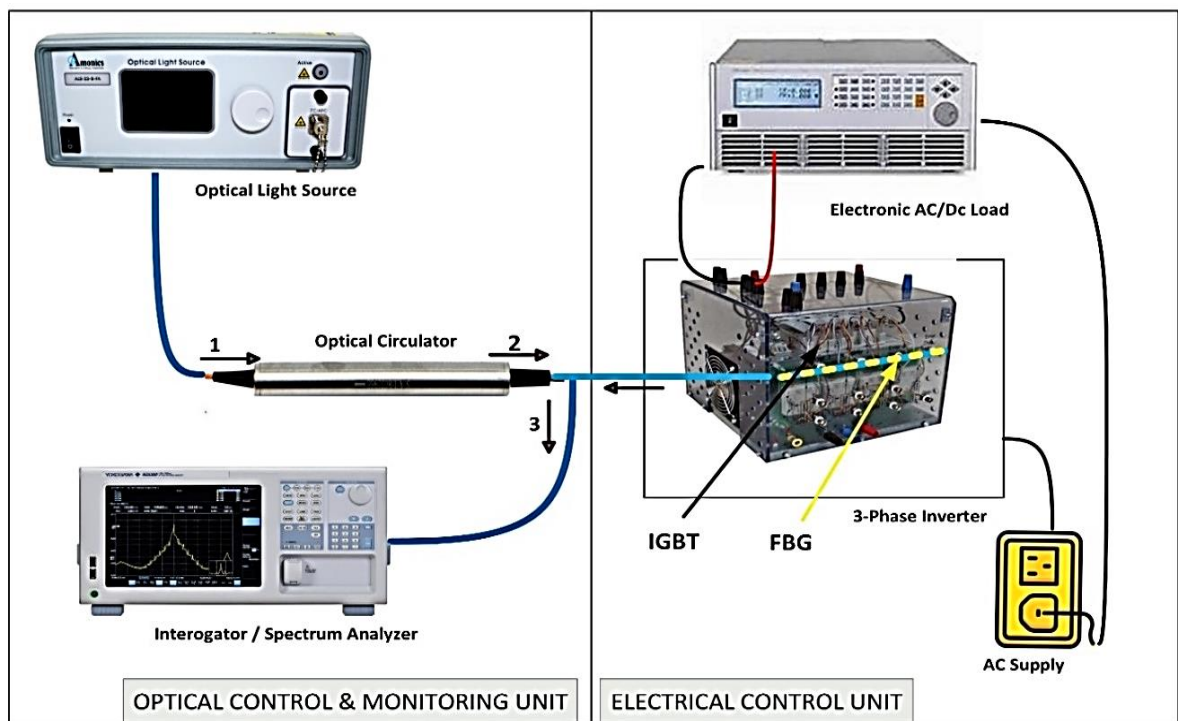


Figure 4.2: Schematic diagram of multipoint FBG temperature sensing.

4.4 Optical Control Unit (OCU)

The optical control unit controls the routing of optical signals through the fiber and the FBG sensors using an optical circulator. Its primary function is to provide a representation of the reflected signals, specifically the wavelength corresponding to the temperature value, on the spectrum analyzer. This enables the measurement of the junction temperature of the IGBT module, as illustrated in Fig. 4.2.

4.4.1 Optical Fiber Sensor

The FBG sensor used in this study consists of a microstructure grating with a periodic inscription that reflects light based on the temperature transferred from the PSS interface to the microstructure. A distinct wavelength shift is produced by the slight change in the FBG periodicity, which is used to determine the sensor's sensitivity. Further specifications for the sensor are outlined in Table 4.1.

Table 4.1: FBG sensor specification

Parameters	Specifications
Cladding Diameter	125 ± 1.0 mm 9.8 mm
Core Diameter	145 ± 5 mm 0.7
Operating Temperature	-50 to +450 ° C
Attenuation	<0.5dB/km
Operating wavelength	1300 -1600 nm
Grating Length	5mm
Center wavelength	1530nm / 1555nm

4.4.2 Optical Circulator

An optical circulator is a non-reciprocal device used to route light signals sequentially from one port to another. Fig. 4.3 illustrates how a light signal from the broadband source is received at port 1 of the optical circulator; it is then further transmitted to the FBG sensor at port 2 and redirected to port 3 where it connects to the optical interrogator or spectrum analyzer for wavelength display. Typically, optical circulators facilitate bi-directional ports, which allow a single fiber to be used for the transmission and reception of optical signals simultaneously.

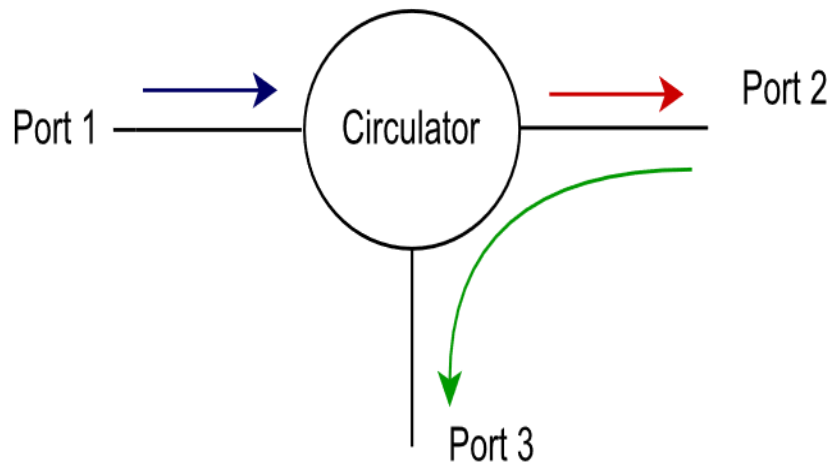


Figure 4.3: Schematic diagram of an optical circulator.

4.4.3 Optical Interrogator/ Optical Spectrum Analyzer (OSA)

An optical interrogator is a data acquisition system capable of capturing both dynamic and static readings such as wavelength and light intensity from the FBG sensor. Fig. 4.4 shows the I-MON interrogator used in this study; it has a sample rate of 3000 Hz for spectrum monitoring. This device encompasses software installed on a personal computer, which offers an interface for high-resolution spectrum measurement across a wide range of wavelengths. The resulting data can then be viewed by the user through a universal serial bus (USB) interface. The detailed specification of the interrogator is provided in Table 4.2.

Table 4.2: I-MON Optical Interrogator Specification.

Parameter	Specifications
Maximum Number of FBG's	> 37
Wavelength Range	1525 nm - 1570 nm
Wavelength Fit Resolution	< 0.5 pm
Input Optical Power Range	-70 to -22 dBm
Measurement Frequency	3 kHz max
Fiber Length	1 m
Connector	FC/APC connector



Figure 4.4: I-MON 256 optical interrogator [84].

4.5 Electrical Control Unit (ECU)

To investigate the variations in IGBT junction temperature, it is essential that the IGBT in the inverter circuit is driven by the electronic load at a current greater than 10% of the rated current. Additionally, both the inverter and electronic load must be activated using a power supply, as outlined in subsequent subsections.

4.5.1 Three-phase inverter

In this study, a SEMITEACH educational three-phase inverter kit was utilized. This kit is equipped with Semikron IGBTs rated at 50A. The AC input from the three-phase supply

transforms into DC power through a six-diode power rectifier. The resulting power operates an electronic direct current load, which raises the junction temperature of IGBT. The Semikron inverter kit is shown in Fig. 4. 5, while Table 4.3 highlights the inverter's specifications.



Figure 4.5: Semiteach three-phase inverter kit [83].

Table 4.3: Electronic unit components specification.

Components	Parameter	Specification
Power	DC Supply	100V
Inverter	Rated Output Current	30A
	Rated output voltage	400V, 3-phase
	Rated output Power	20KW
	Output Frequency	50Hz
IGBT	Model	Semikron SkM50 GB12T4

	Current rating	<50A
	Max Voltage rating	<1200V
	Gate voltage V_{GE}	+15V/ -7V
	Junction Temperature T_j	-40 to 175 °C
IGBT Driver	Model	SKHI 22A
	Supply voltage primary side	Min 14.5V
	Turn on gate voltage output	+15V
	Output peak current	8A
PWM generator	Output voltage	$\pm 15V$
	Waveform	Rectangular waveform
	Duty cycle	50 - 100
Electronic Load	Power rating	4500W
	Input Voltage	350V max
	Input Current	45A max
	Frequency range	40 - 440Hz

4.5.2 Insulated Gate Bipolar Transistor (IGBT)

An IGBT is a power switch that employs a bipolar transistor with an isolated gate structure and has high input impedance. It provides a fast switching speed of up to 100 kHz without significant loss. Table 4.3 indicates that it supports high-voltage and high-frequency applications. Fig. 4.6 exhibits the pictorial diagram of the Semikron 50GBT124 IGBT that this study employed. It consists of two parallel IGBTs with a parasitic diode, as depicted in Fig. 4.7.



Figure 4.6: SKM50GB124 module [85].

This IGBT model was selected because it is the most widely used IGBT in inverters and high-power circuits. To enable sensor placement for temperature measurement, the ceramic could either be stripped or a slot could be created through the base plate where the FBG sensor is carefully slotted to measure the temperature variation across the IGBT.

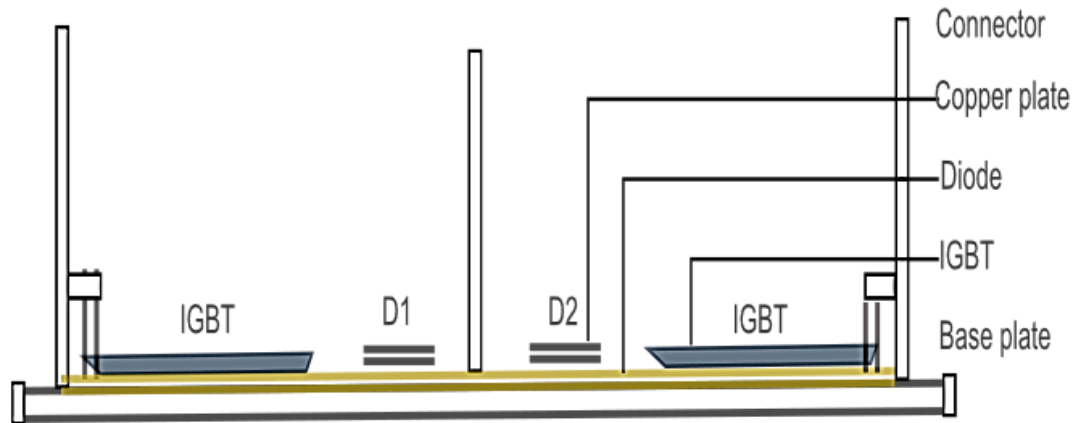


Figure 4.7: Layout of Semikron IGBT module.

4.5.3 IGBT Driver

The IGBT driver used in this study is manufactured by SKYPER Inc., model SKHI 22A. According to Error! Reference source not found., this is a hybrid MOSFET driver typically employed for half-bridge inverters and other related applications with a maximum DC bus voltage of 1200 V. It is controlled through rectangular pulse width modulation (PWM), which in turn affects the electrical signals received at the Semikron IGBT's gate terminal. The driver module yields short-circuit protection and regulates the IGBT's switching speed for on-off states. The driver offers a distinct advantage over other MOSFET drivers, as it integrates requisite components like the external resistor, noise filter for input signals, and VCE monitoring that controls the collector-emitter voltage for safe driving. The driver module also includes error monitoring. A few wires and components are necessary,

including the RG-on and RG-off resistors for adjusting switching speed, to integrate with the IGBT.

The in-built short-circuit protection can detect the forward voltage of the IGBT and turn off the module when it exceeds the threshold. The Semikron driver described is shown in Fig. 4.8.



Figure 4.8: SKHI 22A IGBT gate driver [83].

4.5.4 Programmable Electronic Load

This study employed a Chroma 63802 programmable AC/DC electronic load, as shown in Fig. 4.9. It was connected to the output terminal of the inverter kit for load simulation. This device is specially designed for testing off-grid inverters, AC sources, and other power electronic devices such as switches and circuit breakers. It is capable of simulating load conditions with or without distorted voltage waveforms within the frequency range of 40–440 Hz and varying power factors with real-time compensation. It supports various

constant-load operating modes, including constant-current (CC), constant-power (CP), and constant-resistance (CR), enabling users to efficiently control the system.

Additionally, the embedded screen provides access to measurements of a related circuit's parameters, negating the necessity for external measuring equipment.



Figure 4.9: Electronic DC load [86].

4.6 Summary

This section presents the design and integration of a photonic-based system for measuring junction temperature. The study outlines the functionality of the optical and electrical control units comprising the system. It also provides detailed information on the components and their configuration. In the upcoming chapter, an analysis of the results obtained from the system's installation and calibration process will be provided.

CHAPTER 5

EXPERIMENTAL RESULTS & DISCUSSION

5.1 Introduction

This chapter presents the measurements resulting from the experimental work outlined in Chapter 4. The FBG sensors were calibrated in accordance with the research methodology before their inclusion in the converter circuit. The initial stage involved determining junction temperature estimates for a single IGBT, followed by simultaneous measurements of multiple IGBTs using optical fiber sensors of varying wavelengths. To validate the proposed methodology in this study, the measurements obtained through our method were compared with data obtained from a commercially available off-the-shelf IR thermal camera. For the sake of clarity, the numerical data from the experimental results are presented in tables, while the graphical representations and images are presented in figures.

5.2 Sensor Calibration

This section outlines the approach for obtaining the temperature-wavelength ($T-\lambda$) relationship of the FBG sensors used in the experiment. This measure is imperative for assessing the sensitivity of the sensors and evaluating any likely sensitivity alterations post-installation. The FBG sensors employed in the experiments have diverse central

wavelengths; they are designated as FBG1, FBG2 and FBG3, with values of 1530 nm, 1540 nm, and 1550 nm, respectively.

As illustrated in Fig. 5.1, a broadband light source was set up to transmit an optical light signal at a power of 102 mW, which is equivalent to 3 dB, through the optical circulator to the FBG sensor positioned on a digital control heater for calibration purposes.

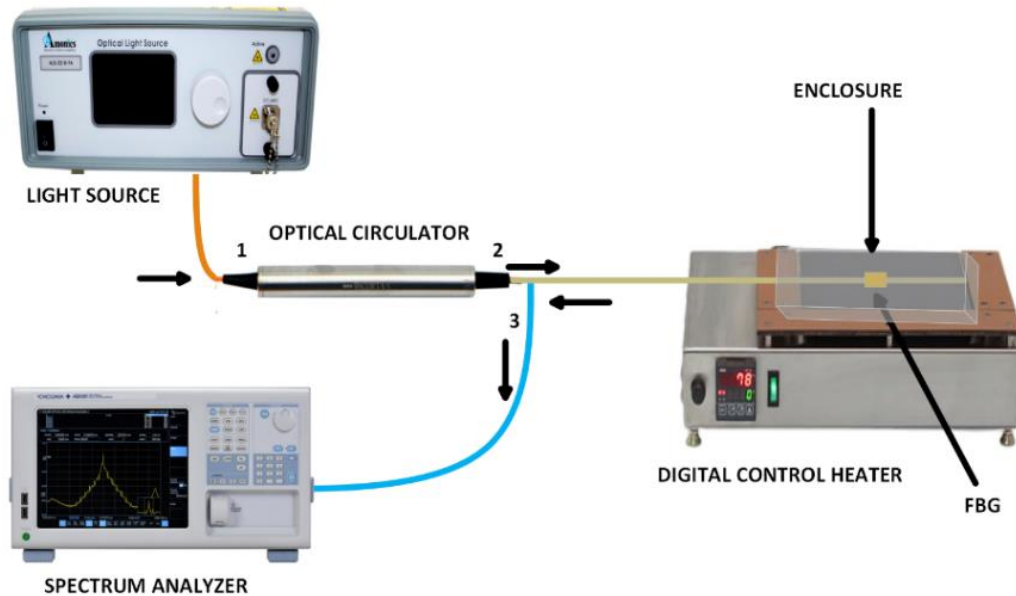


Figure 5.1: Schematic of the calibration setup.

At the outset, the initial wavelength was acquired at ambient temperature. The reflected wavelength produced is directed via the circulator to the Yokogawa Optical Spectrum Analyzer (OSA), depicted in Fig. 5.2, which is used to measure and display the wavelength shift at a resolution of 0.05 pm.

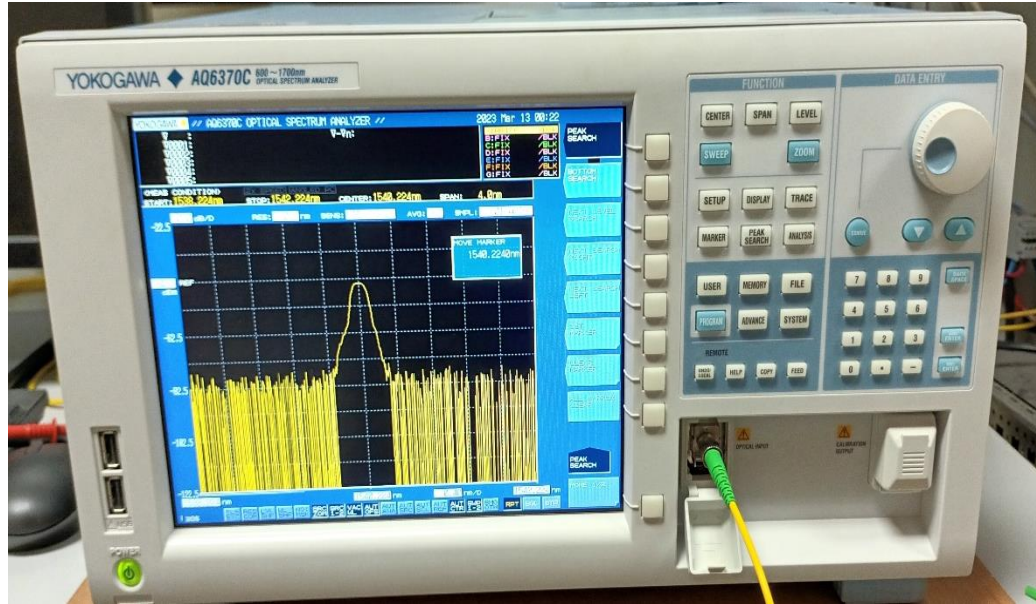


Figure 5.2: Wavelength Shift Display on OSA.

To experimentally compute the sensitivity of the fiber sensor, the heater temperature was varied from the level of ambient temperature up to 110 °C, while the corresponding wavelength for each temperature was recorded as highlighted in Table 5.1. Reference source not found.. MATLAB software was used to establish a temperature-wavelength relationship through linear regression (represented as $y = mx + c$) based on this data." Here, 'c' represents the initial Bragg wavelength at room temperature. 'm' and 'y' refer to the Bragg wavelength and temperature at each specific level, respectively. 'X' represents the slope of the curve in picometers per degree Celsius (pm/°C).

The estimated slope is 9.1 pm/°C, representing the sensitivity of the FBG sensor, which is the minimum detectable change in temperature by the sensor. The temperature-wavelength curve obtained for the sensor calibration in Fig. 5.3 demonstrates a linear relationship between temperature and wavelength shift. The correlation coefficient's R2 value obtained is 0.9997.

Table 5.1: Temperature vs wavelength shift during calibration.

Temperature(°C)	Wavelength λ (nm)
21.9 (ambient)	1529.92017
30	1529.94881
40	1530.03175
50	1530.11469
60	1530.19762
70	1530.28056
80	1530.36350
90	1530.44644
100	1530.52938

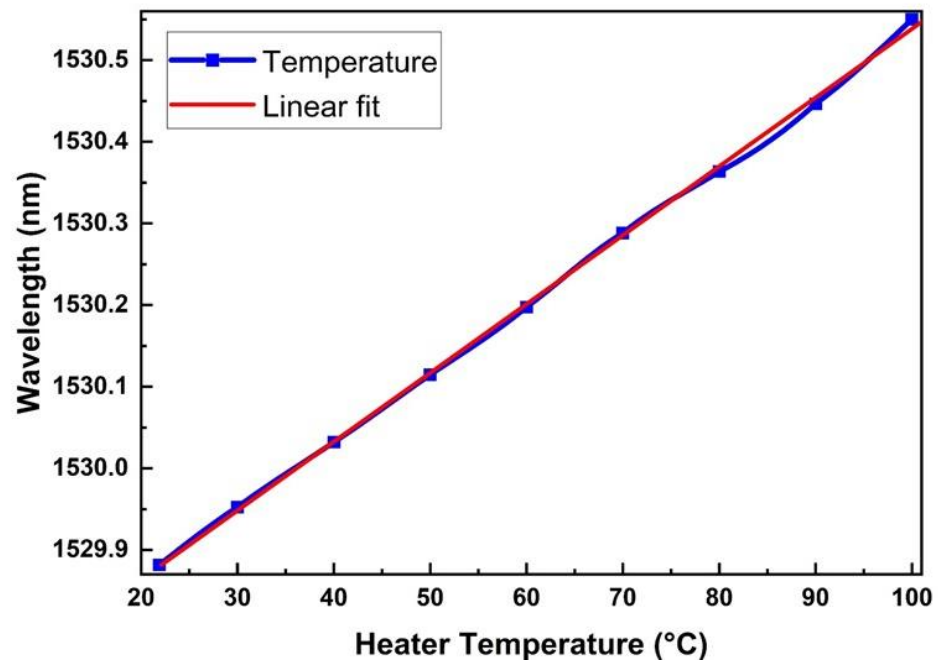


Figure 5.3: Temperature -wavelength shift curve.

5.3 Sensor Installation

To assess the sensor's responsiveness within the converter circuit, an FBG sensor was carefully positioned beneath the IGBT, positioned between the base plate and the heatsink of the SEMIKRON inverter. To ensure proper contact, a thermal paste was applied between the sensor and the IGBT interface, following the guidelines in references [67] and [71]. The resulting temperature measurements, reflecting the wavelength response of the FBG sensor over a 70-millisecond duration at ambient, is illustrated Fig. 5.4.

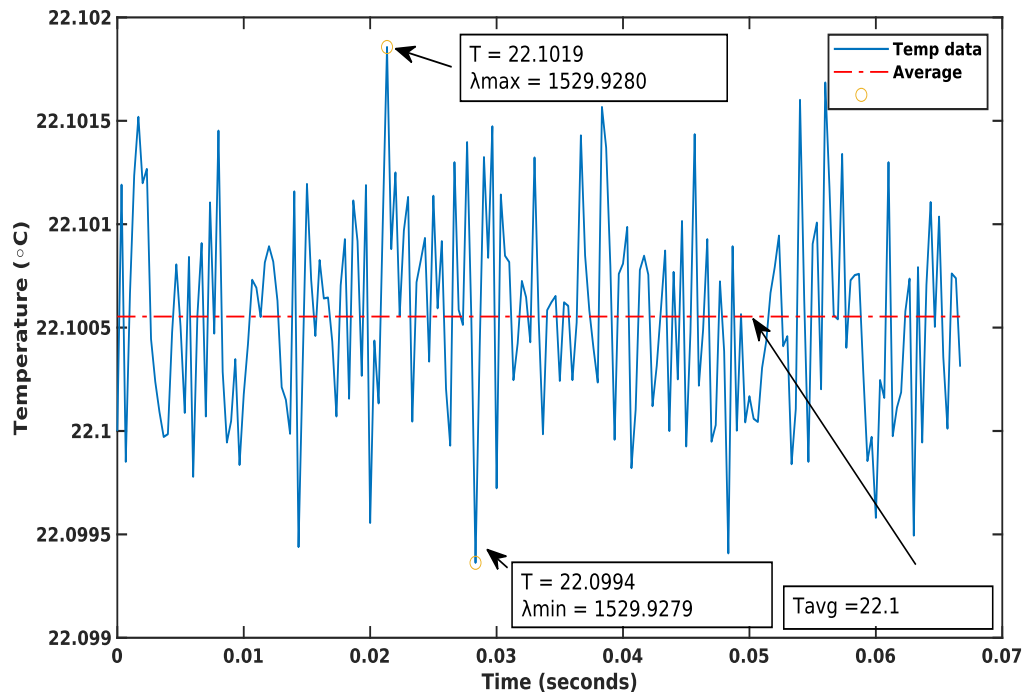


Figure 5.4: FBG measurement at ambient temperature.

The average estimated ambient temperature measured by the FBG sensor is 22.1°C, whereas that of the thermal camera is 22.3 °C. The minimum and maximum temperature values of the sensor at ambient are 22.0994°C and 22.1019°C, respectively, and the standard deviation is approximately 0.00048°C, which shows that the amplitude fluctuation is $\pm 0.003^\circ\text{C}$, which is within the acceptable level for standard measurement.

5.4 Test Rig Setup

To simulate variations in IGBT junction temperature, the inverter circuit is employed to operate the programmable electronic load, as detailed in Section 4.4.3. A three-phase power source is linked to the inverter, which subsequently converts it into both DC and AC supplies using a six-diode rectifier and IGBTs to power the electronic load. This arrangement causes heat to be generated across the IGBTs because of the load connected to the converter output terminal. The temperature at the IGBT junction is then monitored by the FBG sensor positioned beneath the copper plate of the IGBT. The detail specification of the inverter is presented in Table 5.2

Table 5.2: Connection setup parameters.

Symbol	Quantity	Value	Units
$R_{eq(j-c)I}$	Thermal resistance of junction-to-case of IGBT	0.27	K /W
$R_{eq(j-c)D}$	Thermal resistance of junction-to-case of the diode	0.48	K /W
$R_{th(c-h)}$	Thermal resistance of the device case-to-heatsink	0.05	K /W

n	Number of IGBT modules	-	3
$R_{eq(j-c)R}$	Thermal resistance for rectifier junction - case	0.16	K /W
N	Number of rectifier stud	-	1
$R_{eq(h-a)}$	Thermal resistance of heatsink-ambient	0.38	C/W
TH	Inverter temperature range	-40 - 175	C
F	Temperature safety factor	0.85	
P_{outt}	Rated output power	20	KW
I_{max}	Rated output current	30	A
V_{out}	Rated output voltage	400	V

The complete laboratory setup for this experiment is shown in Fig. 3.6. Throughout the course of this experimental study, the electronic load was configured in either constant current (CC) or constant power (CP) mode to measure temperature fluctuations at specific current and power levels, both of which were set below 30A and 4500W, respectively. This choice was made because the current capacity of the inverter circuit is limited to 30A, and the programmable electronic load is also restricted to 4500 W/45 A.

5.5 Single-Point Junction Temperature Estimation

Fig. 5.5 shows the laboratory set up for the experiments, comprising optical and electrical units as described in Section 4.3. Table 5.3 shows the measurements for the load power,

the DC current, the estimated FBG, and the IRC temperature measurement for a Semikron IGBT mounted on the heatsink in the inverter circuit. The sensitivity of the sensor was obtained after the calibration made in Section 5.1. As described in 5.3, the electronic load is first set to CP mode, and the load power P_{load} is varied with 500 W interval, while the load current I_{load} is obtained directly from the electronic load system.

The estimated temperature measurement corresponding to the FBG wavelength shift obtained is denoted as T_{FBG} . To minimize the error of the thermal camera due to ambient temperature fluctuation, the average temperature reading of the camera was obtained and represented as T_{IRC} . T_{DIF} is the difference between the estimated FBG and thermal camera temperature measurement.

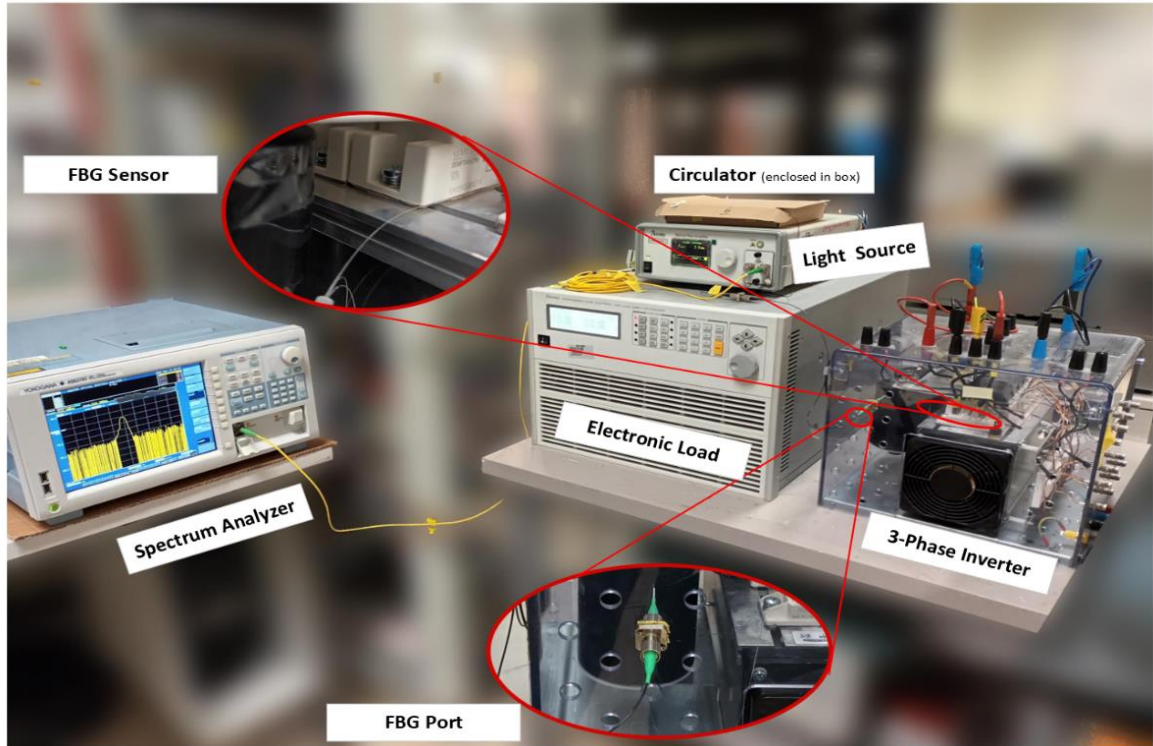


Figure 5.5: Laboratory setup showing the connection of the instruments.

Also, in Fig. 5.6, it is clearly shown that the temperature increases with an increase in load power due to the increase in current flow through the IGBT module. Comparing the estimated FBG temperature measurement with the temperature values from the IR camera in Fig. 5.6(a) and Fig. 5.7(a), there is a deviation between both temperature measurements; this error could be the effect of the little air gap between the sensor and the IGBT interface.

Table 5.3: Experimental results for PFBG and IR camera temperature measurement.

P_{load} (W)	I_{load} (A)	T_{FBG} (°C)	T_{IRC} (°C)	T_{DIF}
500	3.02	25.76	25.8	0.04
1000	6.16	27.69	28.9	1.21
1500	9.42	31.39	32.3	0.91
2000	12.74	35.41	36.2	0.79
2500	16.2	39.13	38.7	0.43
3000	19.9	45.06	44.9	0.16
3500	23.69	48.91	49.3	0.39
4000	27.61	52.77	53.7	0.93

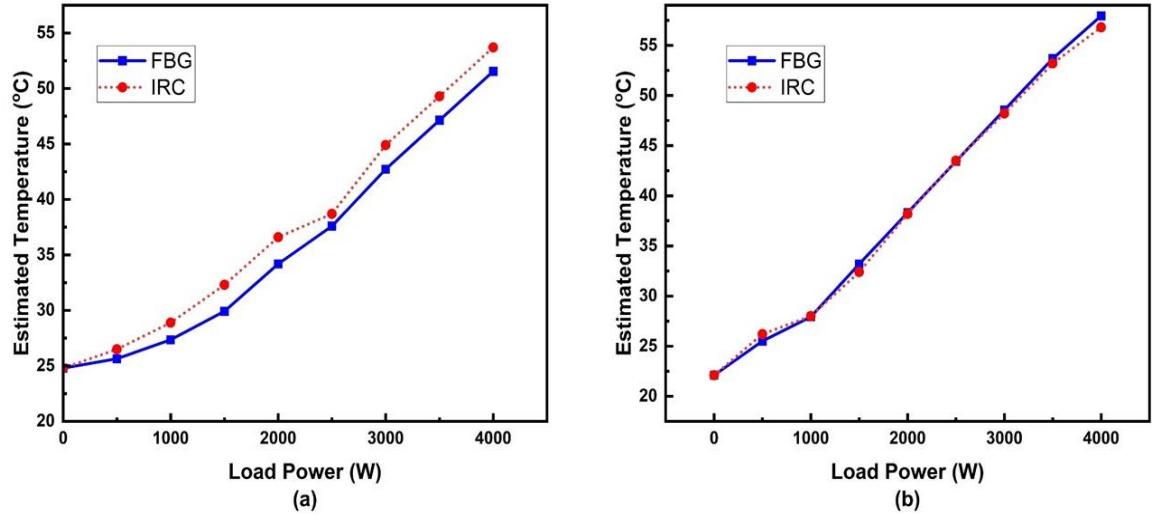


Figure 5.6: Estimated TFBG for constant load power. (a) without thermal pad. (b) with thermal pad.

To reduce the error caused by the air trapped between the IGBT and FBG interfaces, a thermal pad was placed between them to enhance heat transfer between the interfaces. As evident from the curves in Fig. 5.6(b) and Fig. 5.7(b) the accuracy of the sensor measurement increased significantly. The plotted curve of IR and the estimated FBG temperature indicate that the temperature response of FBG agrees with the known standard temperature measuring instruments. This implies that the FBG sensor could be reliably implemented for thermal distribution mapping in power electronics applications. The next section will discuss the further applicability of this method for multi-point temperature sensing using three FBG sensors as a case study.

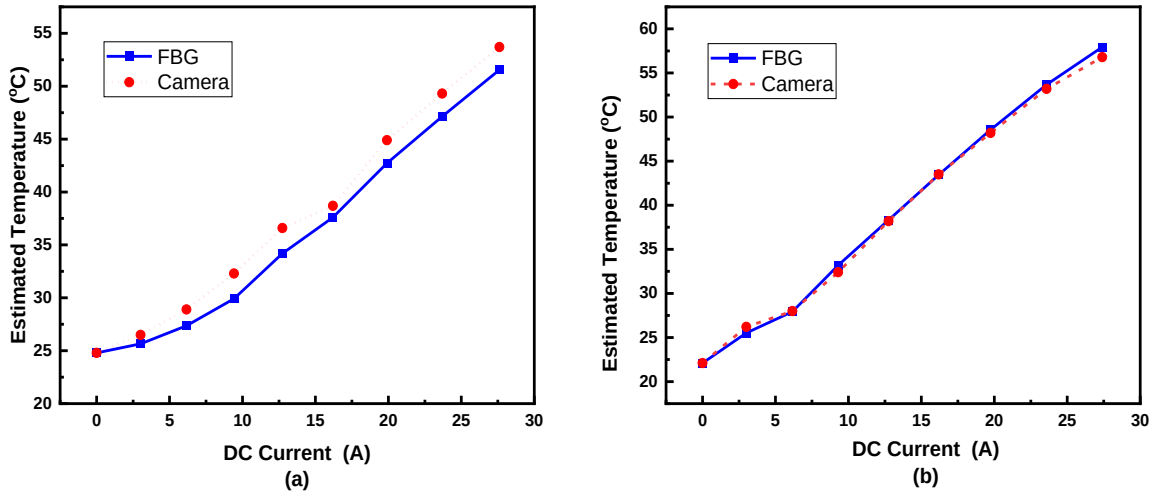


Figure 5.7: Estimated TFBG for the applied DC current. (a) without thermal pad. (b) with thermal pad.

5.6 Multi-Point Junction Temperature Estimation

In a standard power circuit, there are usually between two and ten silicon semiconductor devices, which could be IGBTs, MOSFETs, or rectifier modules mounted on a shared heatsink within a typical converter circuit, as shown in Fig. 5.8. To effectively monitor the thermal performance of these devices, a distributed sensor system is essential. Installing a separate sensor for each individual device would not be cost-effective and would increase the circuit's overall bulkiness. Like the single-point optical sensing method mentioned earlier, this section outlines the implementation of multi-point junction temperature sensing using FBG sensors. It is important to mention that the head length of the three fiber sensors used in this experiment measures 5 mm.

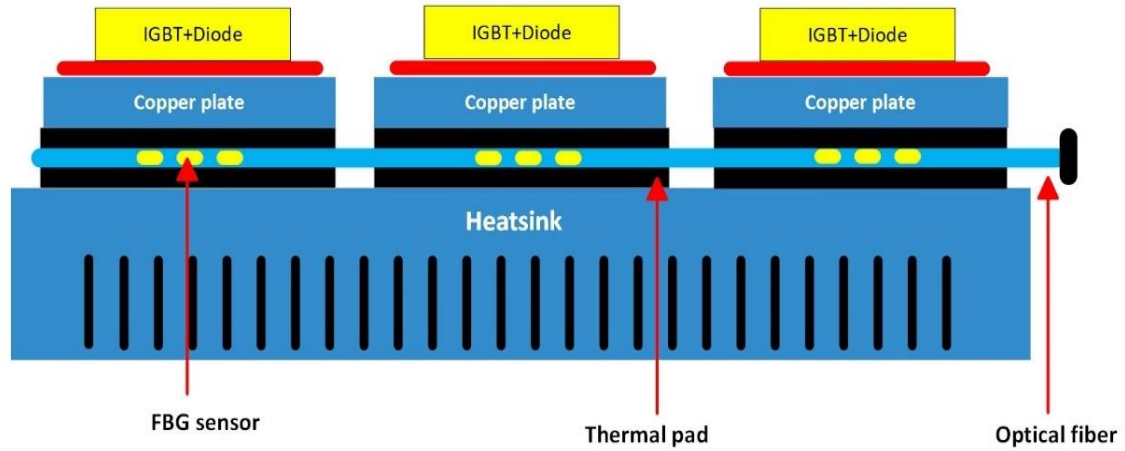


Figure 5.8: Schematic of multiple IGBTs arranged on the heatsink.

5.6.1 Experimental Setup

All the three FBG sensors, FBG1, FBG2 and FBG3, with central wavelengths of 1530nm, 1540 nm, and 1555 nm respectively, were calibrated using a digitally controlled heater in the same manner as the FBG sensor (FBG1) with a central Bragg wavelength of 1530 nm, as was done in Section 4.1. The sensitivities determined for these sensors were 9.09 pm/°C and 9.89 pm/°C, respectively. The relationship between the control heater temperature and the wavelength shifts for all three FBG sensors is depicted in Fig. 5.9.

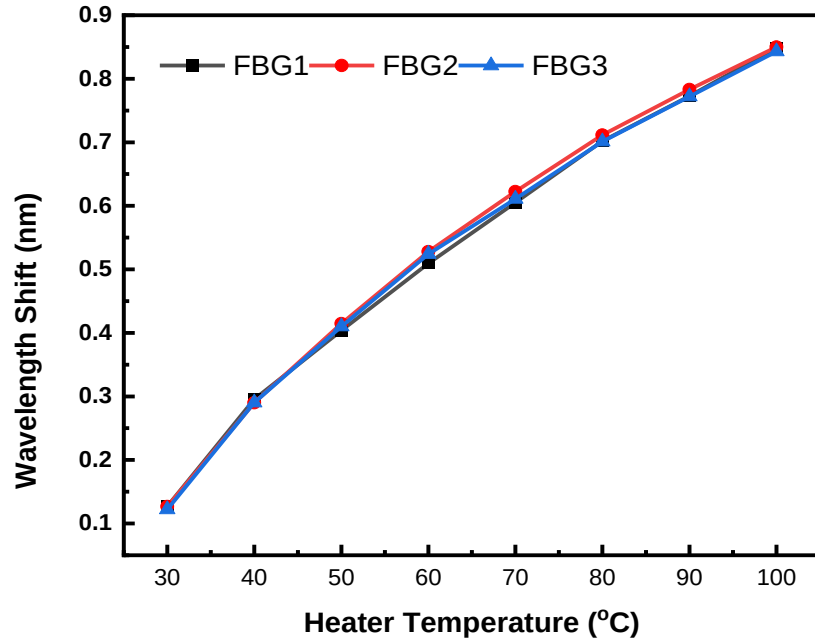


Figure 5.6: Temperature-wavelength shift curve of the FBG sensors.

5.6.2 FBG Array Implementation

The three FBG sensors, referred to as FBG1, FBG2, and FBG3, are connected sequentially to create a single fiber arrangement, as illustrated in Fig. 5.10(a). The Semikron inverter used in this experiment comprises four IGBT studs and one three-phase rectifier stud, all mounted on a shared heatsink with the IGBT. For this study, two of the IGBTs and the rectifier module, as depicted in Fig. 5.10(b), were used for the experiment. To install the fiber sensor, the rectifier and IGBT studs were loosened from the heatsink, and the surface was cleaned thoroughly with isopropyl alcohol. The sensors' responses along the fiber were examined using two different orientations, as shown in Fig. 5.10(c) and Fig. 5.10(d).

In the first approach, referred to as "FIBER 1," the fiber was placed underneath the module's plate, spanning the two parallel IGBT and diode chips, cutting vertically through

the plate as shown in Fig. 5.10(c). In the second method, labeled "FIBER 2," the fiber ran parallel to the plate, cutting horizontally through the module's plate, as depicted in Fig. 5.10(d). In both cases, the sensor heads were positioned at the midpoint of the IGBT plate carefully, following the guidance provided in [87], to ensure precise results. Subsequently, the modules were affixed to the heatsink, taking care to maintain torque within acceptable limits to prevent excessive stress that could lead to fiber drift or damage.

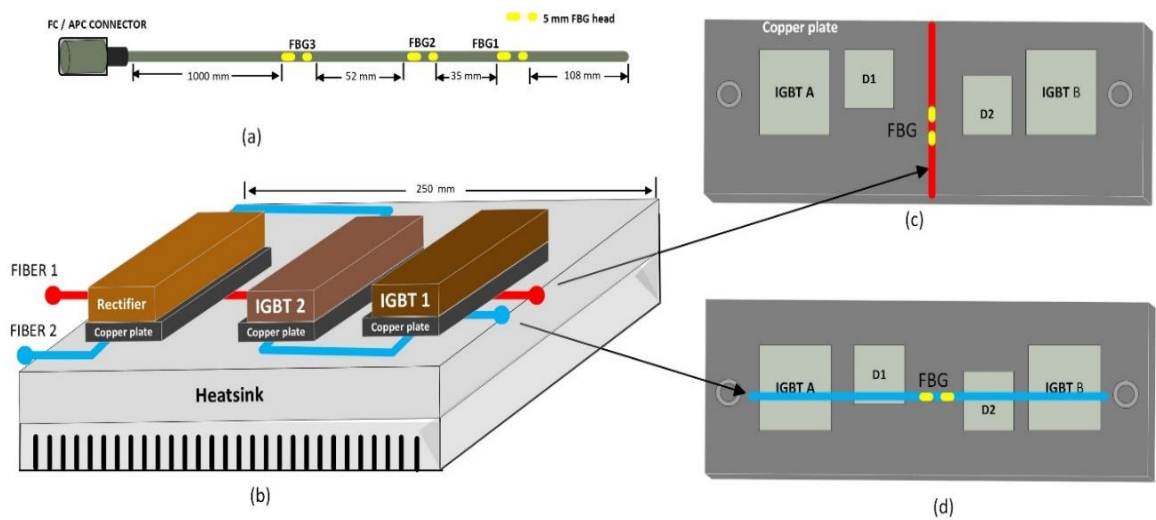


Figure 5.7: (a) FBG array in a single optical fiber. (b) Installation settings of the sensors in the inverter circuit. (c) Sensor placement orientation in vertical, FIBER 1. (d) Sensor placement orientation along the baseplate in parallel, FIBER 2.

After the calibration of the sensors, the fiber was laid through the opening of the transparent plastic case of the inverter to the IGBTs. The FBG port as shown in Fig. 5.5 was held to the case of the inverter to make it easy for connection or disconnection. Firstly, the performance of the two settings, FIBER 1, and FIBER 2, is compared to determine the suitable placement for thermal sensing. Also, the FBG sensors were re-calibrated to

examine the effect of stress on their sensitivity. To ensure the sensors are not subjected to excessive strain.

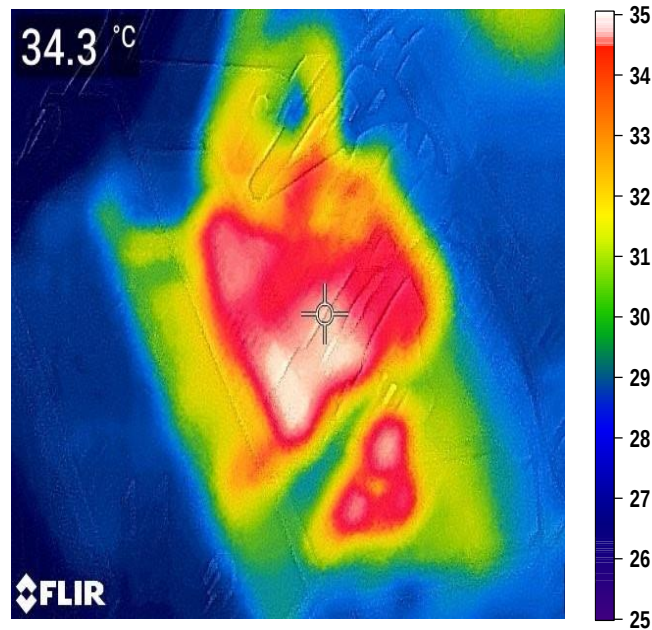


Figure 5.8: The thermal image taken by the thermal IR camera at P_L of 1.5 KW.

The inverter circuit was powered by a three-phase AC supply and was used to drive the electronic load to raise the temperature of the IGBTs. This exposes the FBG array sensors to a variety of static thermal stresses. Since the FBG sensors are already installed in the inverter, it is not practicable to place the whole inverter in a chamber for re-calibration. However, sensor calibration after installation is necessary to ascertain the Bragg wavelength obtained for the air-interface calibration in Fig. 5.9, which is preserved after the installation of the IGBT-FBG interface. As such, the array sensors were calibrated in the thermal range of 22.2 °C to 100 °C.

At first, the installation setting FIBER 1 prescribed Fig. 5.10(c) was implemented. The wavelength measurements were made at each evaluated thermal steady state on the analyzer. A thermal camera, “FLIR E53,” placed 10 cm from the baseplate was used to validate the FBG temperature measurement. As shown in Fig. 5.11, the ambient temperature measured by the IR camera was 34.3 °C, corresponding to a Bragg wavelength of 1530.29 nm and 1540.02 nm for FBG1 and FBG2 on the optical spectrum analyzer shown in Fig. 5.12.

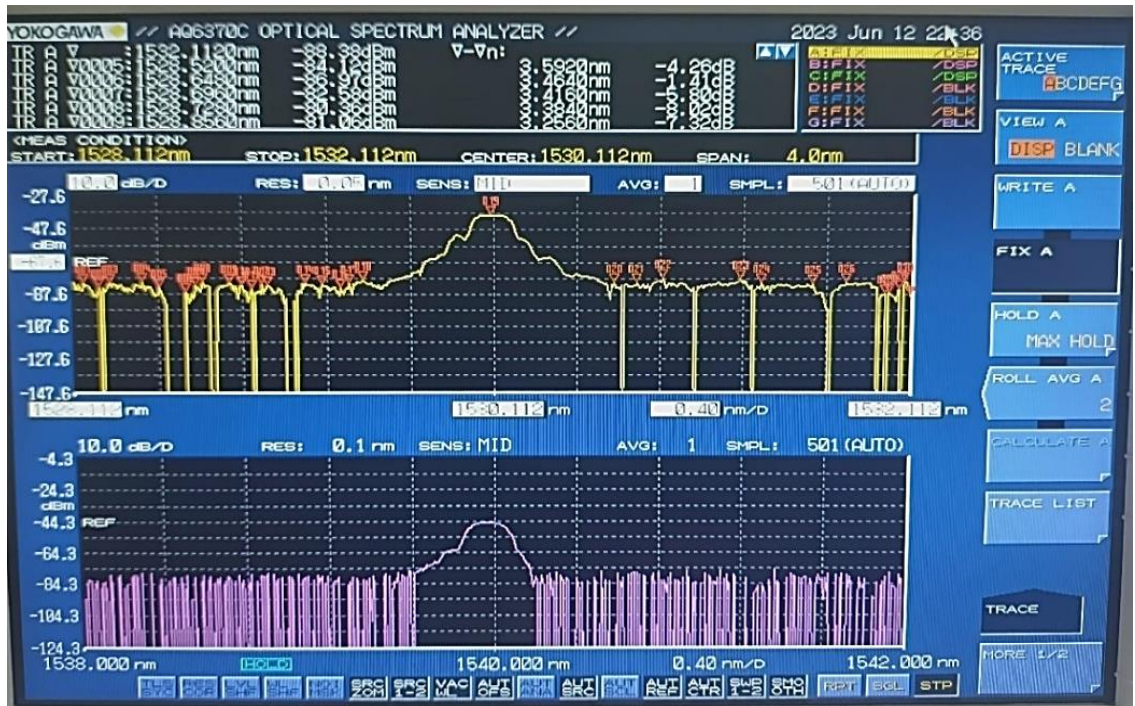


Figure 5.9: Wavelength extraction for multiple FBG sensors.

The procedure for FIBER 1 was thereafter repeated for the FIBER 2 settings. Table 5.4 shows the estimated parameters for the second-order polynomial fit curves and the mean square error (MSE) for the three FBG sensors. It will be observed that the three FBGs exhibit good linearity with a correction factor coefficient greater than 0.999.

Table 5.4: Estimated fit curve parameters for FIBER 1 and FIBER 2 settings.

Configuration	FIBER 1			FIBER 2		
	Intercept	MSE	R-square	Intercept	MSE	R-square
FBG1	1529.7	0.00628	0.9997	1529.7	0.00679	0.9996
FBG2	1539.85	0.00329	0.9999	1539.86	0.00321	0.9999
FBG3	1555.04	0.0044	0.9999	1555.01	0.00497	0.9998

Fif. 5.13 shows the data recorded during the calibration test of the FBG array installed in the inverter system. A slight shift in the sensitivity of the sensors is observed compared to that of the pre-installation calibration. The new sensitivity obtained for the three sensors FBG1, FBG2, and FBG3 is 9.1 pm/°C, 9.3 pm/°C, and 10.1 pm/°C, respectively. The maximum shift observed for the sensitivity is approximately 2 pm.

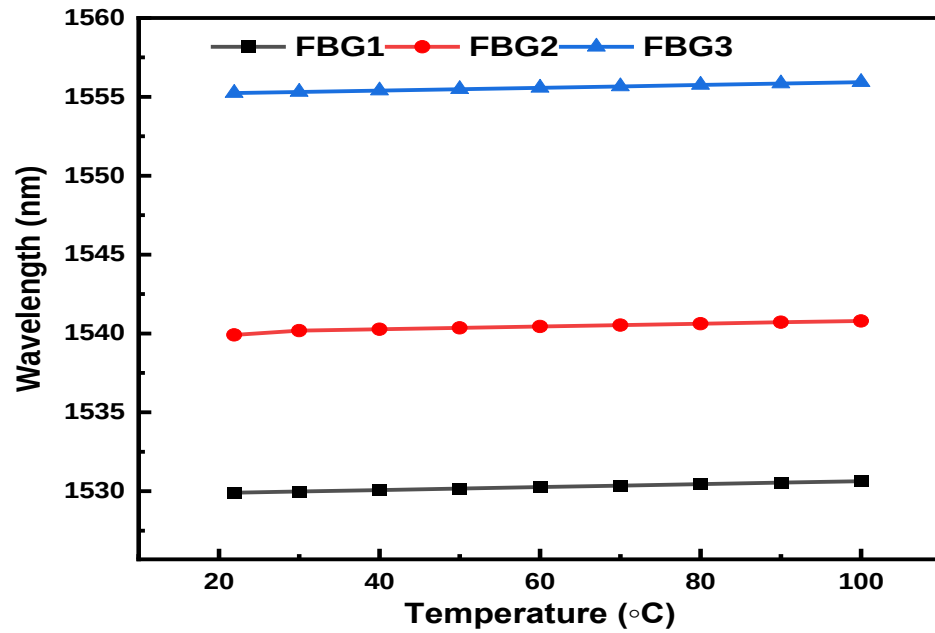


Figure 5.10: Calibration characteristics of the installed FBG array sensors.

5.7 Load Power vs IGBT Temperature

After the sensitivity of the installed sensors has been determined, the spectrum analyzer's resolution was adjusted to 0.05 pm, with a span length of 4 nm. The electronic load circuit was configured to operate in different constant power modes, ranging from 0 to 4 KW, due to equipment limitations. For the values of load power, P_L shown in Table 5.5, the temperature measured by the three sensors $FBG1$, $FBG2$, and $FBG3$ along the IGBT baseplate was estimated using the Bragg wavelength shifts obtained on the spectrum analyzer. The wavelength is closely related to the temperature of the IGBT in contact with the sensor. Additionally, T_{IRC} represents the temperature recorded by the thermal camera for the respective IGBTs along the baseplate. T_{DIF} indicates the difference between the temperature by the sensor and the thermal camera.

Table 5.5: Temperature measurement for IGBT at constant load power.

P_L	$FBG1$	T_{IRC}	T_{DIF}	$FBG2$	T_{IRC}	T_{IRC}	$FBG3$	T_{IRC}	T_{DIF}
(KW)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
0	22.10	22.1	0.00	22.8	22.8	0.00	22.60	22.6	0.00
0.5	25.51	26.2	0.69	27.68	27.8	0.12	25.24	24.6	0.64
1	28.93	29.0	0.07	31.33	31.5	0.17	27.01	26.9	0.11
1.5	33.49	34.3	0.79	34.85	34.6	0.25	28.55	29.5	0.95
2	38.32	38.2	0.12	37.50	37.4	0.10	33.18	33.5	0.32
2.5	44.44	44.9	0.46	41.02	40.6	0.42	36.71	36.5	0.21
3	48.2	48.56	0.36	44.55	45.2	0.65	39.35	39.5	0.15
3.5	53.2	53.68	0.48	50.72	50.5	0.22	40.89	41.4	0.51
4	56.84	57.85	1.1	55.8	56.2	0.4	43.76	44.2	0.44

As shown in Fig. 5.14, the temperature rises as the load power increases, primarily because of the heightened current passing through the IGBT module. It is noticeable that the FBG

sensor's temperature measurements differ, and this is attributed to non-uniform thermal gradients. The non-uniformity arises due to variations in thermal spreading resistance, which are influenced by the relative position and surface area of the IGBT in relation to the heatsink's surface.

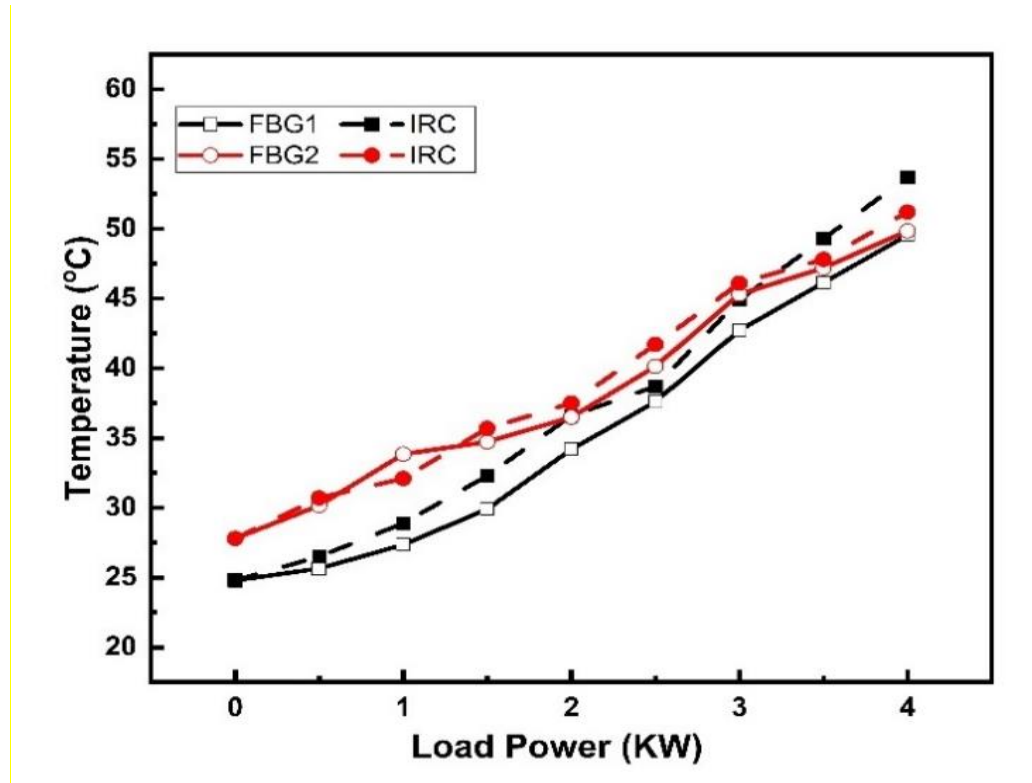


Figure 5.11: Load power vs average temperature without thermal pad for IGBT1 and IGBT2.

Specifically, FBG1 and FBG2 were positioned in proximity beneath the two central IGBTs on the heatsink, and are subjected to equal load, as subjected power dissipate through the two IGBTs are almost equal. Whereas FBG3 was affixed to the adjacent rectifier, situated 52 mm away from the IGBTs, and had lower switching losses. As such it experiences lower power dissipation, and consequently lower junction temperature compared to the two IGBTs as shown in Fig. 5.15.

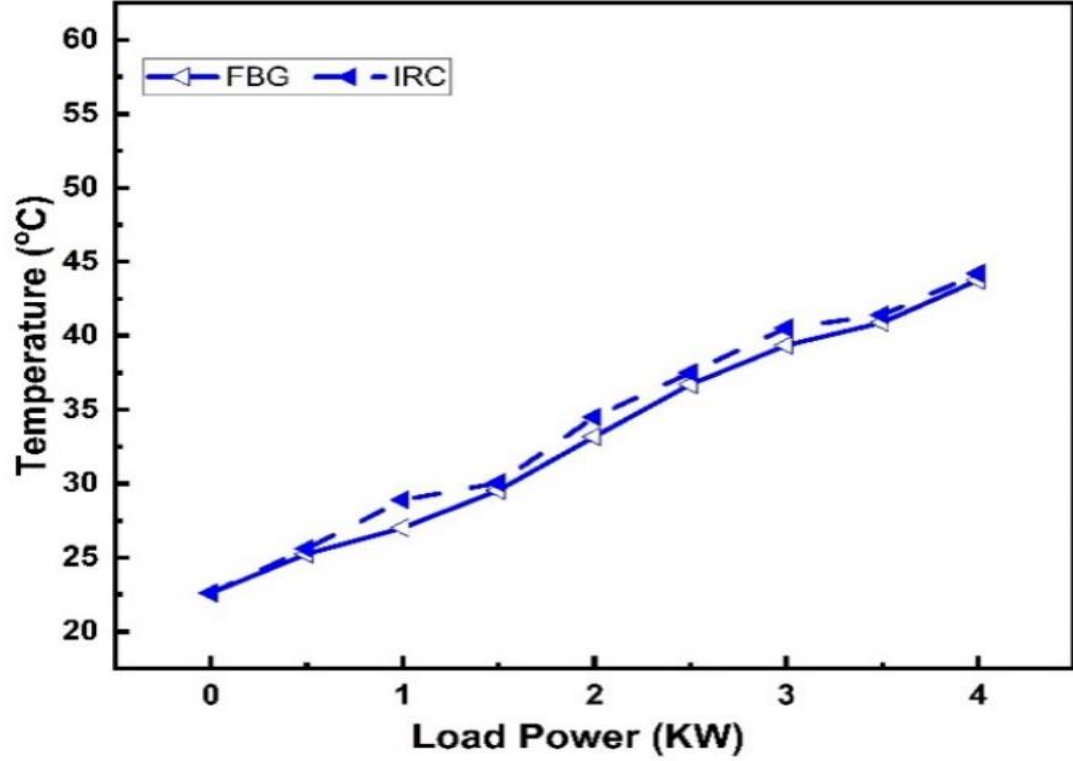


Figure 5.12: Load power vs average temperature without thermal pad for rectifier module.

FBG sensor measurements reveal the thermal gradient of the respective IGBTs on the heatsink, which showcases the capability of FBG array sensors for distributed thermal sensing. However, the disparity between the sensor and camera measurement is due to the inherent error internal to the spectrum analyzer, the interface mismatch, and the resistance imposed by the tiny air gap across the IGBT-FBG interface.

5.8 Noise Isolation

To minimize T_{DIF} that occurs due to the IGBT-FBG interface mismatch, varying room temperature, and the air gap between the temperature-sensitive part of the sensor and the

IGBT baseplate, which is about 60 μm , a thermal pad with a conductivity of about 5.2 W/mK was situated between the interfaces to enhance heat transfer from the IGBTs to the FBG sensors. The procedure used to obtain the load power vs temperature curve presented in Fig. 5.14 was repeated to obtain Fig. 5.16.

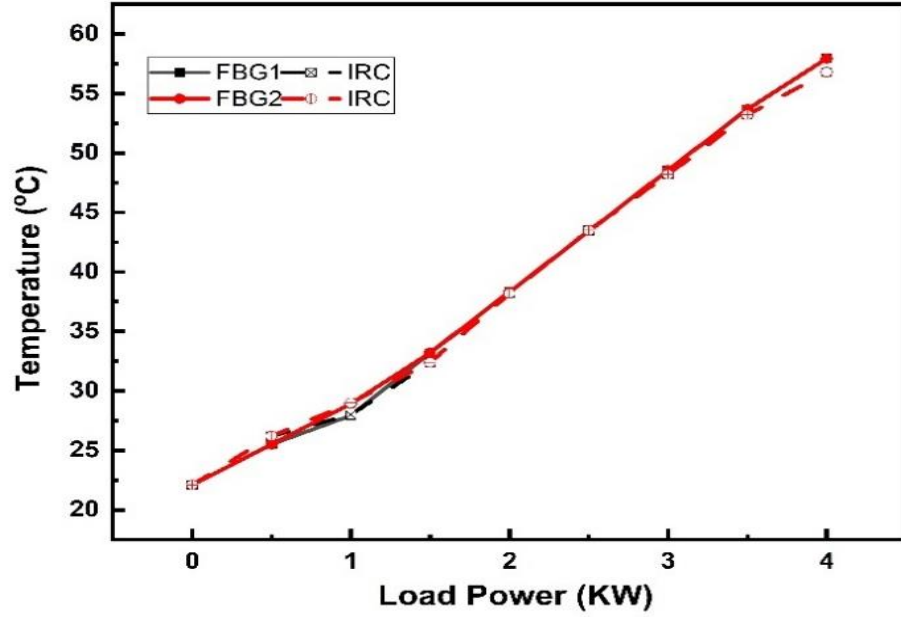


Figure 5.13: Load power vs average temperature with thermal pad for IGBT1 and IGBT2.

From Fig. 5.17, it can be observed that the accuracy of the sensor measurement increases significantly as T_{FBG} and T_{IRC} matched closely for the two plots. The mean square error obtained for this curve is 0.37 compared to the former, which is 2.1. The variation in the temperature curve of IR and estimated FBG temperature indicate that the thermal gradient across the device's layer depends on the P_L . This implies that the FBG sensor could be reliably implemented for temperature sensing in power electronics applications.

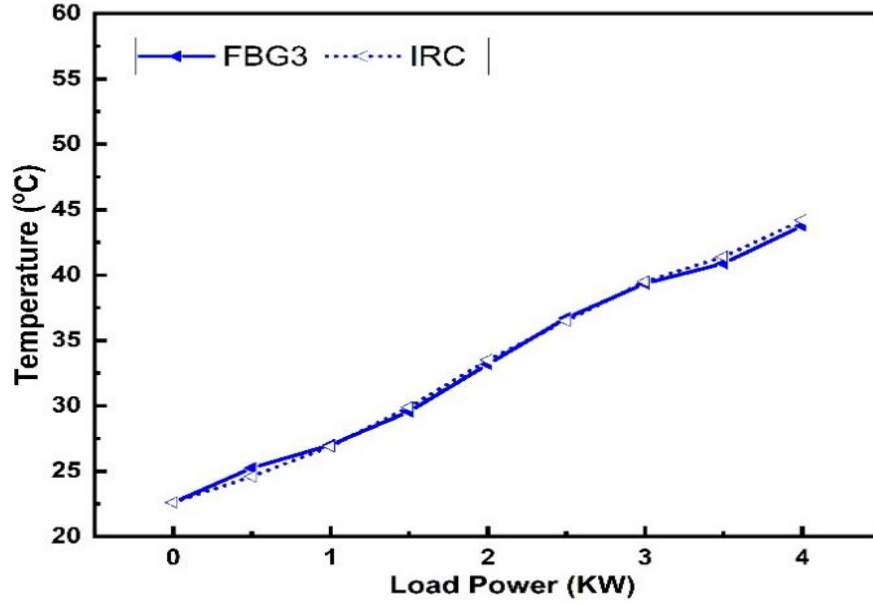


Figure 5.7: Load power vs average temperature with thermal pad for rectifier module.

5.9 Summary

This section has discussed an experimental investigation involving single-point and multi-point optical junction temperature sensing for several IGBTs within a typical converter circuit. The experimental results have demonstrated that FBG sensors exhibit a linear response to temperature fluctuations, and their accuracy can be improved by enhancing the heat transfer across the FBG-IGBT interface using a thermal pad. The FBG sensor's portability enables its convenient integration into power circuits, which facilitates tracking of IGBT junction temperatures.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This section presents a summary of the research undertaken in the thesis. It highlights the significant findings from the study and draws relevant conclusions. In addition, the limitations encountered during this research are outlined, and potential directions for future research in these areas are suggested.

6.1 Summary of the Work

The widespread adoption of IGBTs in power electronics systems has prompted the exploration of compact optical fiber sensors as an alternative to conventional, bulky, and cost-inefficient temperature sensors for monitoring junction temperatures. Optical fibers transmit light signals at specific wavelengths and reflect these signals with a wavelength shift corresponding to the temperature detected by the FBG sensors. FBG sensors show promise in this context due to their immunity to electromagnetic interference and their ability to be multiplexed. However, integrating FBG sensors presents a significant challenge, requiring expert installation.

The objective of this thesis is to investigate methodologies and identify optimal approaches for monitoring the junction temperature of multiple power-switching semiconductor devices commonly used in power circuits. To achieve this goal, both single-point and

multi-point temperature sensing techniques were developed and evaluated through a combination of theoretical analysis and practical experiments.

Chapter 2 provides a comprehensive overview of junction temperature sensing techniques relevant to the thesis. This chapter classifies temperature-sensing techniques into three major categories: electrical, physical, and optical methods. Within optical-based methods, this chapter investigates three frequently utilized techniques: electroluminescence, thermal imaging with an IR camera, and the employment of FBG sensors. However, in order to fully exploit the capabilities of FBG technology, several challenges need to be addressed, such as handling hotspots, identifying sensor configuration, compatibility of the sensor and the device interface, and accommodating environmental temperature fluctuations, all of which can influence the accuracy of FBG measurements.

Chapter 3 explores the application of a resistance thermal network to model the heat transfer process across the layer of IGBT, considering the power loss and resistance coefficients of the materials comprising the IGBT. Single point model accounts for the equivalent junction temperature of an individual IGBT from its baseplate. Multi-point employed wavelength multiplexing, enabling the installation of multiple sensors across multiple IGBT chips to collect temperature data from numerous points without interference.

Chapter 4 describes the system components and methodology of the proposed system. It showcases the functionalities of the optical and electrical control units that make up the whole system and further discusses the specifications and justification for the chosen components.

Chapter 5 outlines the procedures for calibrating and installing FBG sensors, along with an assessment of the fiber's performance in various orientations and conditions. This evaluation is conducted both with and without the use of a thermal pad to bridge the air gap between the IGBT and the FBG interface. The findings demonstrate that employing a thermal pad for proper interface matching results in improved sensing accuracy compared to the previous method.

In contribution to the existing work, this study proposes a novel method of monitoring IGBT junction temperature at the base plate instead of direct on-chip sensor installation, eliminating the need to remove the ceramic encapsulation of the IGBT modules. This allows easy installation and prevents possible damage to the IGBT circuit.

In addition, this work implements multi-point temperature sensing using FBG sensors of different wavelengths, which allows multiple IGBT junction temperatures to be monitored remotely and simultaneously without interference or crosstalk. This approach offers a hopeful avenue for attaining economically feasible distributed FBG sensors, which may ultimately result in increased acceptance of this technology.

6.2 Limitations and Recommendations for Future Work

This study has enhanced the comprehension and application of FBG sensing technology within power distribution systems. Nevertheless, there are certain factors that could have constrained the breadth and depth of our findings. This section will address the study's limitations and offer recommendations for future research to expand upon.

- The results presented in this thesis are subject to variations due to differences in device performance and environmental temperatures. These differences may lead to divergent results upon replication of the experiments. To ensure reproducibility, it is paramount to consider the influence of device variability and the inherent errors and resolution of the equipment. For the purpose of enabling replication and facilitating the comparison of results, we have included detailed descriptions and information provided by the manufacturer for all devices used in our experiments in Chapter 5.
- Among temperature sensor technologies, the FBG sensing technique stands out for its noteworthy advantage of demonstrating linear sensitivity. Nonetheless, they necessitate calibration due to the fluctuations in ambient temperature. As such, an auto-calibration can be integrated into the system to compensate for the noise caused by fluctuating ambient temperatures in the vicinity.
- Machine learning can be integrated to forecast or enhance the effectiveness of the FBG measurement technique. This could be achieved by utilizing the ambient temperature and pre-existing data to calculate FBG sensitivity or predict the junction temperature using specified inputs from the machine learning model. These inputs might include load magnitude on the power module, operating frequency, duration of usage, and component aging. The deep learning model's insights drawn from these key features could also be employed to assess component reliability, life expectancy, and performance under different load currents and components' aging using historical data for model training.

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