

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**COMPARATIVE STUDY OF TWO PHOSPHOR
THERMOMETERS WITH DIFFERENT PULSED LASER
SOURCES**

ÖMER FARUK KADI

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF PHYSICS

ADVISOR: PROF. DR. MEVLÜT KARABULUT

JULY 2025

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**COMPARATIVE STUDY OF TWO PHOSPHOR
THERMOMETERS WITH DIFFERENT PULSED LASER
SOURCES**

ÖMER FARUK KADI

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF PHYSICS

ADVISOR: PROF. DR. MEVLÜT KARABULUT

JULY 2025

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

FARKLI ATIMLI LAZER KAYNAKLARINA SAHİP İKİ
FOSFOR TERMOMETRESİNİN KARŞILAŞTIRMALI
ÇALIŞMASI

ÖMER FARUK KADI

YÜKSEK LİSANS TEZİ
FİZİK ANABİLİM DALI

DANIŞMAN: PROF. DR. MEVLÜT KARABULUT

TEMMUZ 2025

MASTER of SCIENCE JURY APPROVAL FORM

A thesis submitted by Ömer Faruk KADI, defended on 23/07/2025 before the jury formed with the 30/06/2025 date and 2025/34 numbered decision of the GTU Graduate Administration Board, has been accepted as a MASTER of SCIENCE thesis in the Department of Physics.

JURY

MEMBER

(THESIS ADVISOR) : Prof. Dr. Mevlüt KARABULUT

MEMBER

: Prof. Dr. Savaş BERBER

MEMBER

: Prof. Dr. Mustafa YÜKSEK

APPROVAL

Gebze Technical University Graduate Administration Board

...../...../..... date and/..... numbered decision.

SIGNATURE/SEAL



*To the memory of
Prof. Dr. Fikret YILDIZ,
with respect and gratitude.*

ABSTRACT

Temperature is a fundamental physical quantity that reflects the average kinetic energy of particles at the microscopic scale and determines the direction of heat flow at the macroscopic level. Its accurate measurement is essential across scientific disciplines and industrial sectors, including manufacturing, defense, healthcare, and daily applications. Among the International System of Units (SI) base units, the kelvin is one of the most frequently used.

Thermodynamic temperature, defined by primary thermometry methods based on fundamental physical principles, differs from practical temperature measurements aligned with the International Temperature Scale of 1990 (ITS-90). Contact-based methods such as resistance thermometry are typically used below 1500 °C, while radiation thermometry is employed at higher temperatures. However, both often require interpolation or extrapolation, leading to uncertainties in SI traceability.

The 2019 redefinition of the kelvin, grounded in fixed fundamental constants, has enabled the development of new, SI-traceable thermometry methods including Johnson noise, acoustic gas, and refractive index gas thermometry. Despite these advances, there remains a pressing need for accurate, non-contact temperature measurement methods for moving objects over broad temperature ranges.

Phosphor thermometry emerges as a promising solution. This optical technique relies on the temperature-dependent luminescence of phosphorescent materials excited by laser or UV light. Its insensitivity to emissivity and robustness in harsh environments make it particularly suitable for extreme conditions.

This Master's thesis investigates the physical and metrological behavior of two phosphor materials under double-pulse excitation. The results contribute to the development of reliable, SI-traceable phosphor-based thermometry systems, expanding their potential for high-accuracy temperature measurements in challenging environments.

Keywords: Phosphor Thermometry, Luminescence, Phosphorescence, Thermodynamic Temperature

ÖZET

Sıcaklık, mikroskobik ölçekte parçacıkların ortalama kinetik enerjisini yansıtan ve makroskobik düzeyde ısı akışının yönünü belirleyen temel bir fiziksel büyüklüktür. Doğru sıcaklık ölçümü, bilimsel disiplinlerden endüstriyel uygulamalara kadar — imalat, savunma, sağlık ve günlük kullanım da dâhil olmak üzere — pek çok alanda büyük önem taşır. SI temel birimleri arasında yer alan kelvin, en sık kullanılan birimlerden biridir.

Termodinamik sıcaklık, temel fiziksel ilkelere dayanan birincil termometri yöntemleriyle tanımlanır ve bu tanım, 1990 Uluslararası Sıcaklık Ölçeği (ITS-90) ile uyumlu pratik sıcaklık ölçümlerinden farklılık gösterir. Genellikle 1500 °C'nin altındaki sıcaklıklarda temaslı yöntemler, örneğin direnç Termometrisi, tercih edilirken, daha yüksek sıcaklıklarda ışıma termometrisi kullanılır. Ancak her iki yöntemde de sıklıkla enterpolasyon (ara değer hesaplama) veya ekstrapolasyon (değer dışı tahmin) yapılması gerekir ve bu da SI birimlerine izlenebilirlikte belirsizliklere yol açar.

2019 yılında kelvinin yeniden tanımlanması, sabit temel fiziksel sabitlere dayandırılarak yapılmış ve bunun sonucunda Johnson gürültü termometrisi, akustik gaz termometrisi ve kırılma indisi gaz termometrisi gibi yeni, SI izlenebilirliğine sahip termometri yöntemlerinin geliştirilmesinin önünü açmıştır. Ancak tüm bu gelişmelere rağmen, geniş sıcaklık aralıklarında ve hareketli nesneler üzerinde hassas, temassız sıcaklık ölçümlerine yönelik ihtiyaç hâlen önemini korumaktadır.

Bu noktada fosfor termometrisi, umut verici bir çözüm olarak öne çıkmaktadır. Bu optik ölçüm tekniği, fosforlu malzemelerin lazer veya UV ışığıyla uyarıldığında gösterdiği ve sıcaklığa bağlı olarak değişen lüminesans (ışıldama) özelliğine dayanır. Yüzey yayım oranına (emissivity) duyarlılığı ve zorlayıcı çevresel koşullarda dayanıklılığı, onu özellikle zorlu ortamlar için uygun hâle getirmektedir.

Bu yüksek lisans tezi kapsamında, çift atımlı uyarım altında iki farklı fosfor malzemenin fiziksel ve metrolojik davranışları incelenmiştir. Elde edilen bulgular, güvenilir ve SI izlenebilir fosfor temelli termometri sistemlerinin geliştirilmesine katkı sağlayarak, bu yöntemin zorlu ortamlarda yüksek doğrulukta sıcaklık ölçümleri için kullanım potansiyelini artırmaktadır.

Anahtar Kelimeler: Fosfor Termometrisi, Lüminesans, Fosforesans, Termodinamik Sıcaklık

ACKNOWLEDGEMENTS

I would like to thank my advisor, Prof. Dr. Mevlüt KARABULUT, for his scientific insight, kindness, and unwavering support, which have greatly inspired and motivated me during both the research and writing phases of this thesis.

I would also like to express my deepest gratitude to my former advisor, Prof. Dr. Fikret YILDIZ, for his valuable guidance, encouragement, and constant support throughout the preparation of this thesis. He is among the distinguished few whose articles continued to be published posthumously. I respectfully honor his memory. His expertise and insightful feedback greatly contributed to the quality of this work.

I would like to thank head of Thermodynamics Meteorology Laboratory, Dr. Humbet NASIBLI for his help, technical support, and invaluable contributions during my research. I would also like to thank the members of the laboratory, Pervin TÜZÜN and Mehtap ERTÜRK, for their constructive suggestions and kind assistance throughout my research process, as well as my colleagues at TUBITAK UME.

I gratefully acknowledge the financial and institutional support provided by TUBITAK UME through the internally funded project “Kuantum Sıcaklık Ölçümlerine Yönelik Fotonik Termometreler” (Project No: G1SI YOG0010), which greatly facilitated the successful completion of this thesis.

I would like to extend my special thanks to my beloved wife, Sevim ŞENACAY KADI, and my dear son, Atilla Gökalp, who have been a constant source of strength and motivation for me with their endless patience, love, and encouragement.

Finally, I sincerely thank my mother, Nuriye KADI, my father, Osman KADI, and my beloved sisters, Süheyla KADI and Rukiye KADI, for their love and dedication.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	vi
ÖZET	vii
ACKNOWLEDGEMENTS	viii
TABLE OF CONTENTS	ix
LIST OF SYMBOLS AND ABBREVIATIONS	xi
LIST OF FIGURES	xii
LIST OF TABLES	xv
1. INTRODUCTION	1
2. THEORETICAL REVIEW	6
2.1. Temperature Measurements Methods	9
2.1.1. Time-Resolved Methods	10
2.1.1.1. Time Domain Methods	10
2.1.1.1.1. Rise Time Method	11
2.1.1.1.2. Decay Time Method	12
2.1.1.2. Phase Shift Method	13
2.1.2. Time-Integrated Methods	14
2.1.2.1. Single Spectral Band Methods	15
2.1.2.2. Multiple Spectral Band Method	16
2.2. Applications	18
2.2.1. Application of Phosphor Thermometry in Combustion Engine Diagnostics	19
2.2.2. Phosphors for Droplet Thermometry	20
2.2.3. Near-Infrared Luminescence Thermometry for Subcutaneous in Vivo Imaging	21
3. EXPERIMENT	23
3.1. Spectroscopy Measurement-Based Thermographic Phosphor Thermometry	23
3.2. Decay Time Measurement-Based Thermographic Phosphor Thermometry	28
3.2.1. Nd: YAG Double Pulse Laser	31
3.2.1.1. Beam Quality Measurements of the Double Pulse Laser	34
3.2.1.2. Energy Measurements of Laser 1 and Laser 2	37
3.2.1.3. Measurement of the Delay Time Between the Pulses	40
3.2.1.4. Measurement of the Beam Diameter of The Double Pulse Laser	43
3.2.2. High-Speed Camera	44
3.2.3. Three-Zone Furnace	45
3.2.3.1. Lateral Temperature Distributions of Furnace	45
3.2.4. Thermocouples	46
3.2.5. Phosphor Samples	47
3.2.5.1. $Mg_4FGeO_6:Mn$ Samples	48
3.2.5.2. $Al_2O_3:Cr$ Samples	51
3.2.6. Software and Data Acquisition	53
4. RESULTS	54

4.1. Measurement Results with the $Mg_4FGeO_6:Mn$ phosphor coated samples	54
4.1.1. Spectroscopic Measurement Results of the $Mg_4FGeO_6:Mn$ Coated Samples	54
4.1.2. Decay Time Measurement Results of the $Mg_4FGeO_6:Mn$ Coated Samples	59
4.2. The Measurement Results of the $Al_2O_3:Cr$ Coated Samples	65
4.3. Uncertainty	73
5. CONCLUSIONS	76
REFERENCES	79
BIOGRAPHY	85
PUBLICATIONS AND PRESENTATIONS FROM THE THESIS	86



LIST OF SYMBOLS AND ABBREVIATIONS

°C	: degree Celsius
K	: Kelvin
m	: meter
cm	: centimeter
mm	: millimeter
µm	: micrometer
nm	: nanometer
mJ	: millijoule
µs	: microsecond
ms	: millisecond
ns	: nanosecond
CCD	: charge-coupled device
FWHM	: full width at half maximum
IEC	: International Electrotechnical Commission
ITS-90	: International Temperature Scale of 1990
LED	: Light-Emitting Diode
NA	: numerical aperture
NIR	: near-infrared
ND	: neutral density
PMT	: photomultiplier tube
PWM	: pulse-width modulation
RF	: radio frequency
SHG	: second harmonic generation
SI	: International System of Units
TPT	: thermographic phosphor thermometry
TP-PIV	: thermographic particle image velocimetry
UME	: National Metrology Institute
UV	: ultraviolet
VIS	: visible spectrum
TUBITAK	: Scientific and Technological Research Council of Türkiye

LIST OF FIGURES

	<u>Page</u>
Figure 2.1: Jablonski energy diagram [34].	7
Figure 2.2: Classification of phosphor thermometry techniques based on measurement principles.	9
Figure 2.3: The temporal evolution of luminescence intensity.	11
Figure 2.4: Excitation and luminescence signals illustrating the phase shift.	14
Figure 2.5: Emission spectra of $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ at 21 °C and 100 °C, illustrating two well-separated spectral bands used in the intensity ratio method.	17
Figure 2.6: Temperature of the intake and exhaust values measured using thermographic phosphors [56].	20
Figure 3.1: Measurement setup designed for peak wavelength shift and dual spectral band intensity measurements.	24
Figure 3.2: Components of the thermographic phosphor thermometer characterization system, a) the spectrometer and b) the 385 nm LED illumination source.	25
Figure 3.3: An optical fiber used as a reflection probe for powders and dense liquids.	25
Figure 3.4: An optical fiber used as a measurement probe for high-temperature measurements at low pressures.	26
Figure 3.5: The image of the characterization and measurement setup for peak wavelength shift and intensity ratio methods of the thermographic phosphor thermometer.	28
Figure 3.6: A schematic representation of the thermographic phosphor thermometry measurement system.	29
Figure 3.7: A picture of the designed thermographic phosphor thermometry system.	30
Figure 3.8: A picture of the double-pulsed laser system.	30
Figure 3.9: Schematic representation of the double pulse laser generation.	31
Figure 3.10: Measurements of the near-field spatial profiles of the L1 and L2 at the output of the laser.	32
Figure 3.11: The far-field spatial profiles of the L1 after a focusing lens with a focal length of 1 m. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, c) and d) cross-section of Gaussian profiles at the x – and y – axes.	32
Figure 3.12: The far-field spatial profiles of the L2 after a focusing lens with a focal length of 1 m. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, c) and d) cross-section of Gaussian profiles at the x- and y – axes.	33
Figure 3.13: Spatial overlapping of L1 and L2 laser beams in the double-pulse laser system. (a) before the adjustment; b) after the adjustment.	34
Figure 3.14: Schematic representation of the beam quality (i.e. M^2) measurement setup.	35

Figure 3.15:	Beam waist (diameter) assessment measurements along the X-axis of the L1.	35
Figure 3.16:	Beam waist (diameter) assessment measurements along the X-axis of the L2.	35
Figure 3.17:	Nonlinear fitting is applied to laser beam diameter & distance curves of L1 and L2 lasers by in-house software written in Python environment.	36
Figure 3.18:	M-USB J-50MB-YAG energy meter.	38
Figure 3.19:	Relative standard deviation of 99 pulse energy measurements for Laser 1 and Laser 2.	39
Figure 3.20:	The relation between the attenuator setting and the laser pulse energy at the target surface for the Laser 1.	40
Figure 3.21:	The relation between the attenuator setting and the laser pulse energy at the target surface for the Laser 1.	40
Figure 3.22:	Pulse lengths and delay time measurement of double-pulses shots.	41
Figure 3.23:	Relation between the inter-pulse delay in a double-pulse pair and the laser control block setting of L1 and L2, respectively.	42
Figure 3.24:	Beam diameter measurement of the double-pulse laser at the focal plane. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, c) and d) cross-section of Gaussian profiles at the x- and y – axes.	43
Figure 3.25:	An image of the high-speed camera (Phantom, VEO 640S).	44
Figure 3.26:	Measurement setup for lateral temperature distributions in the furnace.	45
Figure 3.27:	Lateral temperature distributions of furnace.	46
Figure 3.28:	The luminescence emission spectrum resulting from the excitation of the $Mg_4FGeO_6:Mn$ thermographic phosphor with 385 nm LED light.	48
Figure 3.29:	Pictures of the prepared measurement blocks: a) grafit block b) stainless steel blocks with a hole for thermocouple insertion and a surface coated with $Mg_4FGeO_6:M$ phosphor paint.	49
Figure 3.30:	Normalized luminescence intensities of samples S1, S2, and S3, showing enhanced emission in S2 and S3 due to the revised phosphor–binder formulation.	50
Figure 3.31:	Pictures of the prepared measurement blocks: stainless steel blocks with a hole for thermocouple insertion and a surface coated with $Al_2O_3:Cr$ phosphor paint.	52
Figure 3.32:	The interface of the developed LabVIEW program.	53
Figure 4.1:	Application of cubic-spline interpolation fit to the spectral data obtained from the measurement of the thermographic phosphor's luminescence using the spectrometer.	55
Figure 4.2:	Characterization curve of the 659 nm band peak wavelength-shift of $Mg_4FGeO_6:Mn$ thermographic phosphor.	56
Figure 4.3:	Characterization curve of the 631 nm band peak-wavelength shift of $Mg_4FGeO_6:Mn$ thermographic phosphor.	57
Figure 4.4:	Characterization data and curve of the intensity ratios of the luminescence emission bands at 659 nm and 631 nm of $Mg_4FGeO_6:Mn$ thermographic phosphor.	58

Figure 4.5:	High-speed camera image capturing the thermographic phosphor at its peak luminescence.	59
Figure 4.6:	Observation of the luminescence decay of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained with the high-speed camera.	60
Figure 4.7:	(a) An example of the Decay Time plot of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained with a high-speed camera, and (b) the decay graph obtained by taking the natural logarithm of the original graph.	61
Figure 4.8:	Iterative linear fit algorithm used for calculating the decay time.	63
Figure 4.9:	Convergence of the iterative decay time calculation algorithm to a value by selecting an appropriate fitting window at each iteration (for τ_1 , τ_2 , τ_3 and τ_4 in Table 4.1, respectively).	64
Figure 4.10:	Characterization data and curve of the decay time of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained using a high-speed camera.	65
Figure 4.11:	Decay times of samples S1, S2, S3, S4, and S5 using 99 double pulses of the L1 laser.	66
Figure 4.12:	The decay time stability obtained with 99 separate laser pulses (L1 on the S1 sample, which contains 50% phosphorus-to binder ratio by a mass).	67
Figure 4.13:	Normalized maximum intensity obtained from the S1 sample as a function of fluence of Laser 1.	68
Figure 4.14:	Decay time obtained from the S1 sample as a function of fluence of Laser 1.	69
Figure 4.15:	Normalized maximum intensity of the S1 sample as a function of varying interdelay times between pulse pairs of each double-pulses.	69
Figure 4.16:	Time-resolved luminescence decay of a single pixel under double-pulse excitation with an interdelay between pulse of 100 μs in each double pulsed shot.	70
Figure 4.17:	Variation in the decay times of the a) S1, b) S2, c) S3, d) S4, and e) S5 samples as a function of the delay time between laser pulses.	71
Figure 4.18:	Variation in the decay times of the S1, S2, S3, S4, and S5 samples as a function of the temperature.	72

LIST OF TABLES

	<u>Page</u>
Table 2.1: Electronic transitions and relaxation processes.	8
Table 3.1: Technical specifications of the high-temperature fiber optic probe.	27
Table 3.2: The deviation coefficient of calibrated thermocouple.	28
Table 3.3: The output parameters of the double pulse laser.	37
Table 3.4: Delay times for input values between 0 and 5 in the nanosecond range.	41
Table 3.5: The phosphor–binder mixture prepared for the thermographic phosphor thermometer and the coated samples.	49
Table 3.6: Normalized maximum luminescence intensity of the prepared thermographic phosphor samples.	50
Table 3.7: Phosphor–binder mixture ratio prepared for the $\text{Al}_2\text{O}_3\text{:Cr}$ thermographic phosphor.	52
Table 4.1: The convergence of the decay time values at each iteration of the iterative decay algorithm.	63
Table 4.2: Uncertainty budget for phosphor thermometry at 300 °C.	75

1. INTRODUCTION

Temperature is a fundamental physical quantity integral to characterizing the state of matter in both scientific and practical contexts. At the microscopic level, temperature is defined as a measure of the average kinetic energy of the constituent particles in a substance, providing insight into its thermal state. On a macroscopic scale, temperature governs the direction of thermal energy flow—from regions of higher temperature to lower—which defines its role in the second law of thermodynamics [1]. As such, the measurement and control of temperature underpin all thermal processes, spanning physics, chemistry, biology, and engineering.

Temperature is one of the base units in the International System of Units (SI), with the kelvin (K) serving as the unit of thermodynamic temperature. Following time, temperature is the most frequently used physical measurement in daily life [2-3]. Whether in the calibration of household appliances, environmental monitoring, medical diagnostics, industrial manufacturing, or defense applications, accurate temperature measurement is essential. The reliability of temperature data can significantly impact process efficiency, product quality, safety, and scientific research outcomes.

Thermodynamic temperature, by definition, is independent of the properties of any particular substance. It is realized through measurement techniques that are directly based on physical laws and fundamental constants. Traditionally, practical temperature measurement has relied on the International Temperature Scale of 1990 (ITS-90), which standardizes temperature values through a set of defined fixed points and interpolation methods [4]. While widely used, ITS-90 is an approximation of thermodynamic temperature and thus not perfectly traceable to the physical definition.

The 2019 redefinition of the kelvin as an SI unit based on the fixed value of the Boltzmann constant marked a significant advancement in temperature metrology [5]. By anchoring temperature to a fundamental physical constant, this redefinition removed the reliance on specific materials or apparatuses for scale realization. Consequently, it opened up the possibility of developing diverse, SI-traceable measurement techniques rooted in different physical phenomena.

Modern thermometry methods now extend beyond traditional approaches, incorporating cutting-edge advances in quantum sensing, photonics, and digital processing [6]. Several notable techniques have emerged: Acoustic gas thermometry, which relates temperature to the speed of sound in a gas [7]; Johnson noise thermometry, which utilizes the thermal voltage noise generated in resistors [8]; Refractive index gas thermometry, based on the relationship between temperature and refractive index [9]; Doppler broadening thermometry, which relies on the temperature dependence of spectral line widths [10]; Gas spectral thermometry, using quantum-level spectral absorption modeling [11]. These techniques bring the potential for higher accuracy, lower uncertainty, and broader applicability across the temperature spectrum.

Practical temperature measurement techniques can be broadly categorized according to the temperature range they cover. Below approximately 1500 °C, contact-based methods dominate. These include resistance thermometry, where the electrical resistance of a material changes predictably with temperature, and thermoelectric thermometry, based on the Seebeck effect, wherein a voltage is produced between two dissimilar conductors with a temperature gradient.

Above this range, non-contact radiative methods are often employed, particularly those derived from Planck's law of blackbody radiation. These methods infer temperature from the spectral distribution of emitted radiation. While powerful, radiative techniques often rely on surface emissivity values, which may be uncertain or variable depending on the material and its condition, thus complicating accurate measurement.

Despite advancements, a persistent challenge in temperature metrology is the accurate and reliable measurement of the temperature of moving or hard-to-reach objects. In such contexts, non-contact methods are crucial. Thermal imaging cameras and infrared pyrometers are widely used for this purpose [12]. However, their performance is highly sensitive to the emissivity of the target surface, which can vary depending on material composition, surface texture, and environmental conditions. This emissivity dependence can introduce substantial errors in temperature estimation.

To address this issue, alternative non-contact measurement methods that are less susceptible to emissivity variation are being explored [13]. One promising approach is phosphor thermometry.

Phosphor thermometry is grounded in the physics of luminescence. This optical technique relies on the luminescence properties of certain luminescence materials that emit light when excited by external radiation, typically from a laser, light emitting diodes (LEDs) or ultraviolet lamp [14]. The properties of the emitted light—such as its intensity, decay time, or wavelength—are temperature-dependent and can be calibrated to provide a reliable temperature reading.

Phosphor thermometry has emerged as a highly versatile and robust method for temperature measurement, especially suited for applications where traditional methods fall short. Key advantages include:

- Independence from surface emissivity: Unlike radiative techniques, phosphor thermometry does not rely on the object's emitted thermal radiation [14].
- Applicability in harsh environments: Phosphors can function in high-temperature, chemically reactive, or otherwise challenging settings [12].
- Non-invasive measurement: It allows for temperature monitoring without disturbing the system under observation [15].

The practical principle of phosphor thermometry involves applying a thin coating of a luminescent material to the surface of interest or integrating the phosphor into the system. Upon excitation, the material emits light, the properties of which change with temperature. These changes can be analyzed using time-resolved or spectrally-resolved techniques [15-16].

Recent research efforts have focused on tailoring phosphorescent materials to exhibit desirable temperature sensitivity across a wide range—from cryogenic levels near 0 K to temperatures exceeding 2000 K [17-18]. Selection of appropriate materials and the development of calibration procedures are critical to ensuring measurement accuracy and traceability to SI units.

Building upon these foundational principles, this thesis presents a comprehensive experimental and computational investigation into thermographic phosphor thermometry (TPT), utilizing both spectral and time-resolved techniques. By evaluating the performance of phosphor materials under varied thermal and excitation

conditions, and by developing advanced data analysis algorithms for peak detection and decay time extraction, the study demonstrates TPT's capability for high-resolution, non-contact temperature measurement in challenging environments. These findings aim to support the broader application of TPT in industrial and scientific diagnostics.

Particularly, accurate surface temperature measurement is critically important across a wide range of industrial sectors, including electrical and electronic manufacturing, steel and plastics processing, and the aerospace and automotive industries [19]. These measurements are essential for ensuring product quality, maintaining process control, and enhancing overall manufacturing efficiency. However, achieving precise and reliable temperature readings in harsh industrial environments remains a significant challenge due to factors such as high thermal gradients, radiative interference, and limited access to measurement surfaces.

Conventional contact-based temperature probes are widely used but often suffer from poor characterization, limited response times, and susceptibility to mechanical wear. Non-contact infrared thermometry offers an alternative, yet its effectiveness is constrained by the need for accurate knowledge of surface emissivity and its vulnerability to stray background radiation.

To address these limitations, phosphor thermometry has emerged as a promising technique, gaining increasing adoption in industrial applications [20]. This method is particularly advantageous in high-temperature environments, where nanosecond Q-switched laser-based phosphor thermometry plays a pivotal role. While pulsed laser systems currently dominate the field, their performance under extreme industrial conditions requires further enhancement.

This study presents the development and evaluation of a novel double-pulsed Q-switched nanosecond laser system for phosphor thermometry. By introducing a second laser pulse during the decay phase of the phosphor emission initiated by the first pulse, the system achieves a significant improvement in signal strength and measurement precision. Experimental results demonstrate a 25% increase in overall system performance compared to conventional single-pulse configurations.

A hybrid contact/non-contact measurement system was implemented using a lifetime-based phosphor thermometer driven by the double-pulsed laser setup. Calibration was performed using a reference blackbody system at the TUBİTAK-UME, ensuring

traceability to the SI. The system was further tested under conditions with intense background radiation, confirming its robustness and suitability for deployment in demanding industrial settings. A comprehensive uncertainty analysis yielded an expanded uncertainty ($k = 2$) of less than 2 °C across a temperature range from ambient to 300 °C.

Comparative studies were conducted between the phosphor-based system and traditional contact thermometry under static conditions. The results clearly indicate that double-pulsed phosphor thermometry not only serves as a viable alternative but also offers superior performance in terms of accuracy, response time, and resilience to environmental disturbances.

Future work will focus on integrating multiple harmonic wavelengths in the double-pulse configuration and exploring combinations of different luminescent materials to enhance the spectral characteristics of the thermometer. Additionally, the use of high-temperature phosphor materials capable of operating up to 1700 °C is planned, with the goal of extending SI-traceable surface temperature measurement capabilities beyond the limits of conventional contact thermometry.

2. THEORETICAL REVIEW

Phosphor thermometry has evolved over nearly a century, providing a versatile method for non-contact temperature measurement. Its development reflects a continuous interplay between new materials, innovative techniques, and expanding applications, from simple laboratory experiments to advanced industrial and biomedical uses.

The early work in the 1930s and 1940s laid the foundation for the field. The 1937 patents by Paul Neubert first recognized the thermal sensitivity of certain phosphors [21-22], highlighting copper-doped zinc sulfide as suitable for the 300–500 °C range. Instead of coating the measured surface, the infrared emission from the hot object was projected onto a phosphor-coated screen, where brightness variations revealed the temperature profile. Franz Urbach advanced phosphor research in Vienna and later in the United States, eventually leading the phosphor department at Eastman Kodak and securing a patent in 1951 [23]. His method demonstrated how phosphor coatings could visually reveal temperature variations on everyday objects through color changes. At that time, rare-earth phosphors had not yet been utilized for phosphor thermometry. Subsequent practical applications were demonstrated by Bradley [24], while US Radium acquired the rights from Eastman Kodak and commercialized the technique with new phosphors under the Radelin product line. In the 1950s, Thureau in France introduced the use of spectral distribution ratios to enhance temperature measurement accuracy [25], followed by Byler and Hayes in 1961, who applied Radelin phosphors for thermography [26]. Fry of Bell Labs further exemplified the precision achievable in the field by mapping the temperature of a transistor chip with a 40 μm spatial resolution [27].

From 1980 onward, phosphor thermometry experienced significant methodological and technological advancements. Research expanded to include lasers and LEDs as light sources, decay time approaches, fiber optics, and durable coatings such as E-beam, RF sputtering, and plasma spray. Rare-earth and other phosphors enabled measurements on distant, moving surfaces, and high-power sources extended the measurable temperature range from 400 °C to 1200 °C [22]. In the 21st century, global efforts have further broadened the field, with universities contributing to micro- and nanoscale temperature measurements, often motivated by biological and biomedical

applications [28]. Additionally, phosphor thermometry has branched into allied areas, including rare earth-doped thermal barrier coatings [29], thermal history paints [30], thermographic particle image velocimetry (TP-PIV) [31], and triboluminescence [32].

Overall, the history of phosphor thermometry illustrates a progressive expansion of both technique and application. From its early recognition of thermal sensitivity in phosphors to modern high-resolution and specialized uses, the field continues to provide innovative solutions for precise temperature measurement in diverse scientific and industrial contexts.

A wide variety of phosphor materials are available for temperature measurements across a different range, from just above absolute zero up to approximately 2000 K [17-18].

Phosphorescence of excited electrons can be explained using a Jablonski energy diagram (Figure 2.1). When an electron in a molecule absorbs a photon, it may be excited from the ground state to a higher electronic energy level (e.g., S_1 or S_2) [33]. Electrons in higher excited states can undergo non-radiative transitions to lower vibrational levels or to lower electronic singlet states such as S_1 through a process known as internal conversion.

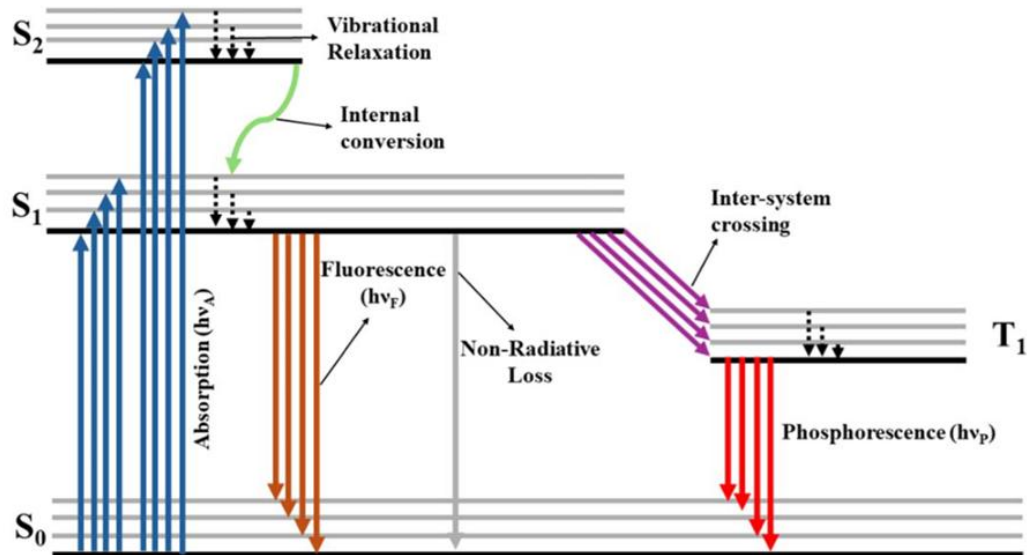


Figure 2.1: Jablonski energy diagram [34].

In some cases, electrons may also undergo a transition from singlet excited states (S_1 , S_2) to triplet states (e.g., T_1), which is referred to as intersystem crossing. When an

excited electron relaxes from a singlet excited state (e.g., S_1) back to the ground state (S_0) and emits a photon during this process, the phenomenon is known as fluorescence. Fluorescence typically occurs on a timescale greater than 10^{-8} seconds [13].

However, if the electron relaxes from a triplet excited state (T_1) to the singlet ground state (S_0) via a spin-forbidden transition, the emitted light is referred to as phosphorescence [35]. Due to the forbidden nature of the transition, phosphorescence occurs over significantly longer timescales compared to fluorescence.

In addition to radiative energy transitions such as fluorescence and phosphorescence, an excited electron can also lose its energy through vibrational transitions, quenching, or non-radiative relaxation processes within the crystal structure, eventually returning to the ground state [12]. In all phosphorescent materials, the phosphorescence process competes with other radiative and non-radiative de-excitation mechanisms.

Among the many factors that influence this competition, temperature is one of the most significant. Because temperature affects the characteristics of the phosphorescent emission, it becomes possible to utilize these changes for temperature sensing applications [36].

Table 2.1: Electronic transitions and relaxation processes.

Transition	Process	Typical Timescale
$S_0 \rightarrow S_1, S_2$	Excitation, Absorption	$10^{-15}s$
$S_2 \rightarrow S_1$	Internal Conversion	$10^{-12}s$
$S_1 \rightarrow S_1, S_2 \rightarrow S_2$	Vibrational Relaxation	$10^{-12}s$
$S_1 \rightarrow S_0$ (<i>radiative</i>)	Florescence	$< 10^{-8}s$
$S_0 \rightarrow S_1$	Quenching and other non-radiative	$10^{-7} - 10^{-5}s$
$S_1 \rightarrow T_1$	Intersystem Crossing	$10^{-10} - 10^{-8}s$
$T_1 \rightarrow S_0$	Phosphorescence	$> 10^{-8}s$

A wide range of electronic transitions and relaxation processes occur in phosphorescent materials, each associated with characteristic timescales. **Table 2.1** summarizes these processes, including fast absorption and excitation from the ground

state (S_0) to higher singlet states (S_1 , S_2) on the femtosecond scale (10^{-15} s), internal conversion and vibrational relaxation within singlet states on the picosecond scale (10^{-12} s), and radiative relaxation via fluorescence from S_1 to S_0 , which occurs typically in less than 10^{-8} s. Non-radiative relaxation, quenching, and intersystem crossing from singlet to triplet states ($S_1 \rightarrow T_1$) span nanoseconds to microseconds. Phosphorescence, resulting from the spin-forbidden $T_1 \rightarrow S_0$ transition, occurs on longer timescales, reflecting the slower dynamics of triplet states. Understanding the relative rates of these radiative and non-radiative pathways is essential for interpreting temperature-dependent luminescence behavior and selecting appropriate measurement strategies.

2.1. Temperature Measurements Methods

When a thermographic phosphor is excited by a light source of an appropriate wavelength (such as a laser or LED), several characteristics of the emitted phosphorescence become temperature-dependent. These temperature-dependent features include the intensity of the phosphorescent emission, peak wavelength, spectral bandwidth, polarization, phase shift, lifetime, and rise time [37-38].

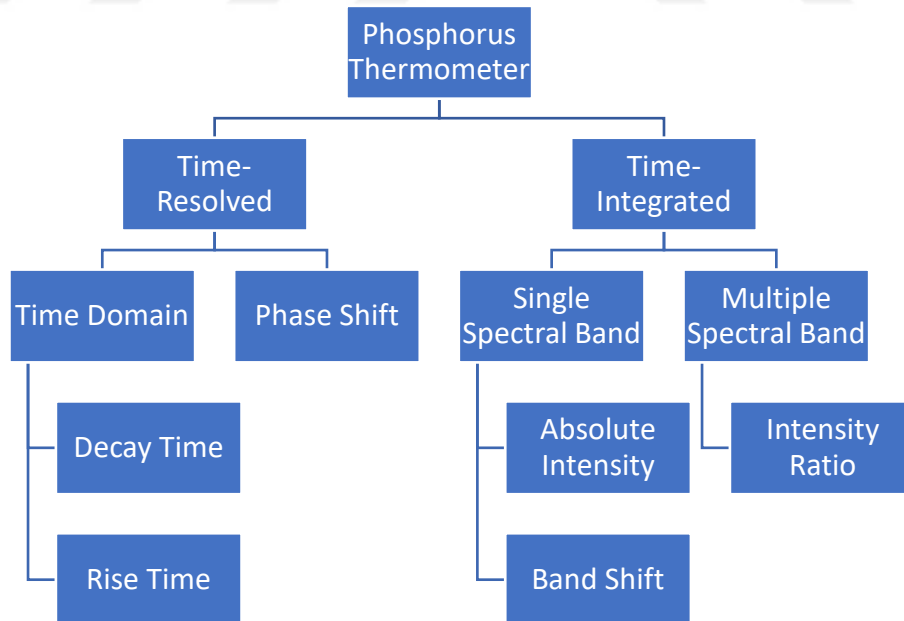


Figure 2.2: Classification of phosphor thermometry techniques based on measurement principles.

If the thermographic phosphor exhibits multiple phosphorescence bands, additional temperature-sensitive parameters such as the intensity ratio between two emission bands can also be utilized for temperature measurement.

Measurement techniques based on the temperature-dependent properties of thermographic phosphors can be categorized into two main groups—time-resolved and time-integrated methods—as illustrated in **Figure 2.2**.

2.1.1. Time-Resolved Methods

After excitation by a light source such as a laser or LED, a thermographic phosphor continues to emit light for a certain period depending on the nature of phosphorescence. Parameters such as the lifetime and rise time of this emission are temperature-dependent. Additionally, measuring the phase shift between the phosphorescence signal and a modulated excitation source represents another time-resolved measurement technique.

2.1.1.1. Time Domain Methods

Time-domain methods are widely employed in thermographic phosphor thermometry due to their ability to directly monitor the temporal evolution of luminescence following pulsed excitation. These techniques rely on analyzing either the rising or the decaying portion of the emission signal, both of which are strongly temperature-dependent. By extracting parameters such as the rise time constant or the decay lifetime, the thermal behavior of the phosphor can be quantitatively characterized. Owing to their relatively straightforward implementation and high accuracy, time-domain methods have become the most commonly adopted strategies in practical applications [36], [39].

Figure 2.3 illustrates the temporal evolution of luminescence intensity after pulsed excitation. The initial excitation is followed by a short rising phase, during which the population of the emitting state increases, and subsequently by a longer decay phase, during which electrons return to the ground state. Both the rise and decay regions contain temperature-dependent parameters that can be exploited for thermometric purposes. While rise time measurements require ultrafast detectors due to their nanosecond-to-microsecond timescales, decay time measurements typically occur in

the microsecond-to-millisecond range, making them more experimentally accessible and widely applied.

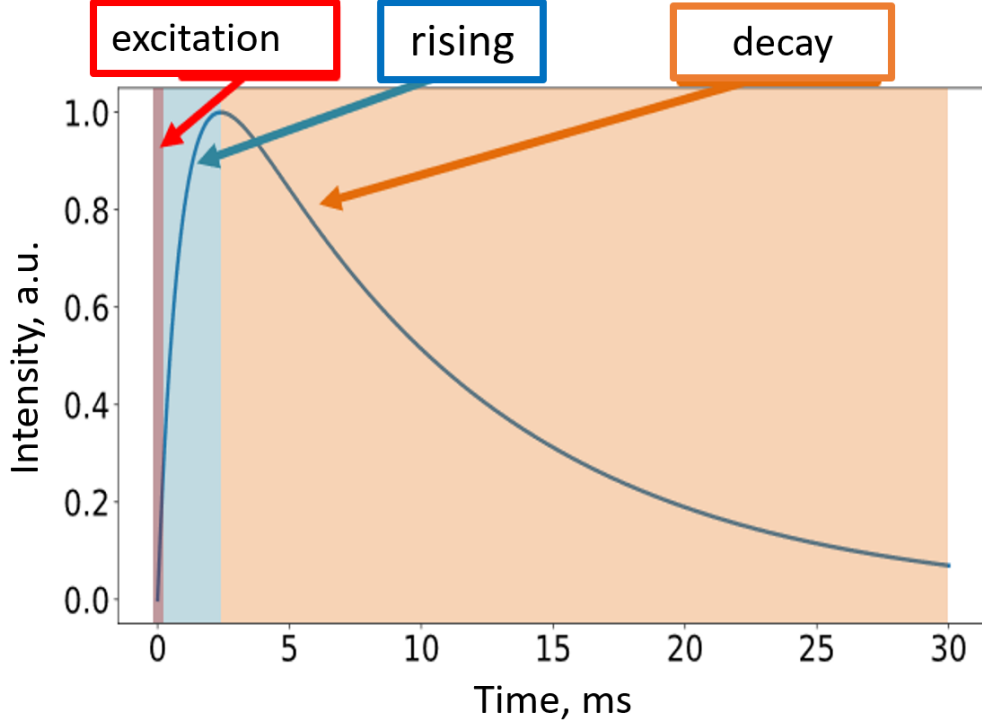


Figure 2.3: The temporal evolution of luminescence intensity.

2.1.1.1.1. Rise Time Method

When a phosphor sample is excited by a pulsed laser, a fraction of the electrons is directly promoted to the emitting energy level, where they can immediately contribute to phosphorescence. At the same time, another portion of the excited electrons is initially promoted to higher non-radiative states and subsequently transferred to the emitting level through internal conversion processes. Consequently, the population of the emitting level, denoted as n_0 , increases over time. This process results in a gradual rise of the luminescence intensity, which can be described by the following expression [40]:

$$n_0 = n_d + n_t \left[1 - \exp\left(-\frac{1}{\tau_r}\right) \right] \quad (2.1)$$

where (n_0) is the total electron population in the phosphorescent energy level, (n_d) is the fraction of electrons undergoing direct radiative transitions, (n_t) is the fraction transferred via internal conversion, and τ_r represents the rise time constant.

The rise time constant τ_r characterizes how quickly the population of the emitting state approaches equilibrium. Although it is not a lifetime in the same sense as the decay time, it can be interpreted as the effective time constant governing the population buildup of the phosphorescent state. Since τ_r is temperature-dependent, it can serve as a sensing parameter for thermographic phosphor thermometry.

However, a significant challenge arises from the different temporal scales of decay and rise times. While the decay time of most phosphors typically lies in the microsecond-to-millisecond range, rise times occur on a much shorter timescale, typically between nanoseconds and microseconds. Consequently, highly sensitive and fast detection systems are required to accurately resolve the rise time like photomultiplier tubes (PTMs) or high-speed cameras [40]. The brevity of this process also reduces measurement precision, which introduces additional experimental challenges [37].

For these reasons, despite its theoretical potential, the rise time method is less frequently adopted compared to the decay time method. The latter not only offers more accessible temporal resolution with conventional detectors but also provides superior measurement accuracy and robustness, making it the preferred approach in most practical phosphor thermometry applications.

2.1.1.1.2. Decay Time Method

Many thermographic phosphors continue to emit light in different temperature-dependent ranges, from several tens of nanoseconds to several milliseconds, after being excited by a pulsed light source of a suitable wavelength. The mathematical equation describing the rate at which electrons, excited to an energy level where phosphorescence occurs, return to the ground state can be expressed as follows:

$$\frac{dN}{dt} = -\lambda N \quad (2.2)$$

The analytical solution quantifying the number of electrons returning to the ground energy level is provided in Equation 2.3.

$$N(t) = N_0 e^{-\lambda t} \quad (2.3)$$

Here, N_0 represents the number of electrons at the phosphorescent energy level at time $t = 0$, while λ denotes the decay constant. During the return of excited electrons to the ground energy level, radiative phosphorescence and non-radiative decay processes are in competition. As temperature increases, the influence of non-radiative decay becomes more significant, resulting in a reduction of the post-excitation emission lifetime due to accelerated decay processes [14], [41]. In summary, the phosphorescence intensity of a thermographic phosphor exhibiting a single-exponential decay behavior can be mathematically represented by Equation 2.4.

$$I(t) = I_0 e^{-t/\tau} \quad (2.4)$$

Here, I_0 denotes the phosphorescence intensity at $t = 0$ immediately after excitation, and τ represents the lifetime parameter characterizing the emission duration. In temperature measurements using thermographic phosphors, one of the most commonly employed methods is decay time analysis [42]. Among the fastest techniques for detecting phosphorescence emission in this context are PMTs and high-speed cameras [43-44]. Capable of detecting even a single photon, PMTs are highly effective detectors for phosphor thermometry [13]. However, they are limited by their ability to perform measurements from only a single point.

2.1.1.2. Phase Shift Method

In phase-shift measurements, the luminescence intensity of a thermographic phosphor, excited by a laser or LED light source of appropriate wavelength modulated in a sinusoidal manner, is typically recorded using photomultiplier tubes or high-speed cameras. As described in Equation 2.5, when a phosphor with a lifetime of τ is excited by a sinusoidal light source, a phase shift occurs in the luminescence signal (**Figure 2.4**) [45-46]. This phase shift is temperature-dependent, and by correlating the measured phase shift with reference temperature data obtained from a contact thermometer, it is possible to characterize the thermographic phosphor under investigation.

$$\tan(\Delta\phi) = 2\pi f\tau(T) \quad (2.5)$$

Here, $\Delta\phi$ denotes the phase shift between the excitation source and the phosphor luminescence, f represents the modulation frequency of the excitation source, and τ is the luminescence decay time. Since the decay time is temperature-dependent, it becomes feasible to establish a calibration curve between phase shift and temperature.

Although both frequency shift and time domain measurements can be performed using the same experimental setup, time domain techniques are generally preferred. This preference arises from their lower computational demands during post-processing and their ability to provide higher accuracy and precision compared to frequency shift methods [47].

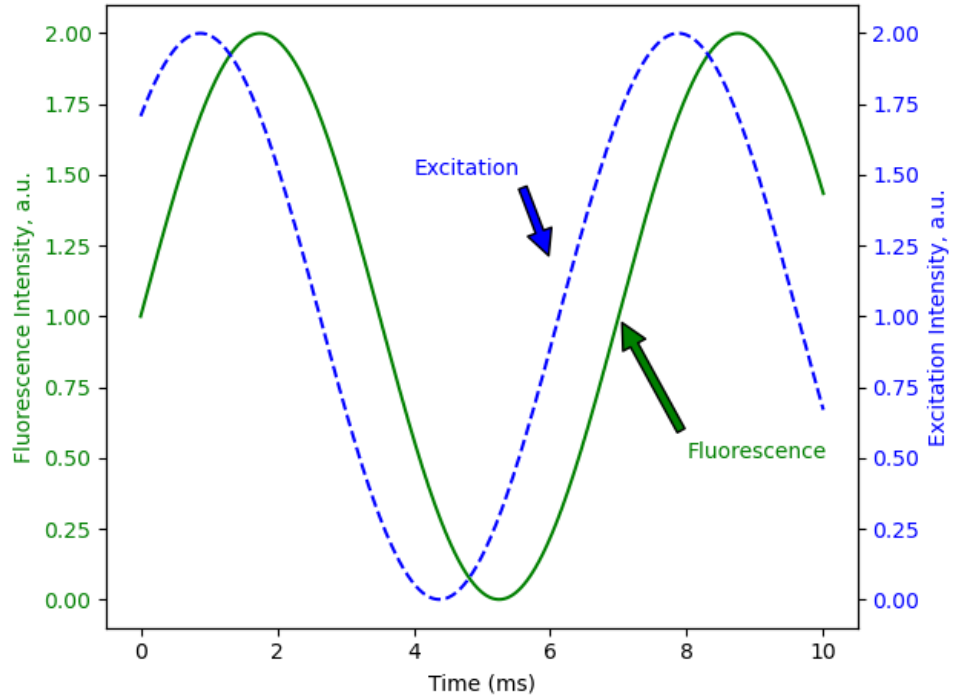


Figure 2.4: Excitation and luminescence signals illustrating the phase shift.

2.1.2. Time-Integrated Methods

Time-integrated phosphor thermometry methods determine the surface temperature by analyzing the luminescence emitted by a thermographic phosphor over a defined detector integration period. These techniques can be classified into two categories: measurements based on a single emission band and those utilizing two distinct emission bands. In the single-band approach, temperature information is extracted either from changes in the absolute luminescence intensity or from the spectral shift of

the emission peak wavelength. In the two-band approach, the temperature is determined by evaluating the intensity ratio between two emission bands, which provides a self-referenced measurement less sensitive to variations in excitation intensity or detection efficiency.

2.1.2.1. Single Spectral Band Methods

In single-band time-integrated phosphor thermometry, the emission from a thermographic phosphor is spectrally filtered using a bandpass optical filter that matches the emission band of interest. Although many phosphors exhibit multiple emission bands, measurements are typically performed on the most intense band to maximize the signal-to-noise ratio. Depending on the evaluation strategy, single-band methods are categorized into two main approaches: the absolute luminescence intensity method and the emission peak wavelength shift (band shift) method.

The absolute intensity method relies on monitoring the emission intensity of the selected band as a function of temperature. However, this approach suffers from significant limitations, as the measured intensity strongly depends on numerous external factors, including coating thickness, excitation fluence, dopant concentration, optical losses, and even slight changes in detector alignment [48]. These dependencies make the calibration process complex and reduce the reproducibility of the measurements, thereby limiting the practical applicability of this technique.

In contrast, the band shift method evaluates the temperature-dependent shift in the peak emission wavelength. Since the emission peak position is largely independent of experimental factors such as coating uniformity, excitation intensity, or detector positioning, this method offers a more robust and reproducible approach [12], [49]. The main drawback, however, is the typically very small magnitude of the wavelength shift, often on the order of ≈ 0.01 nm/K (depending on the phosphor type). As a result, high-resolution spectrometers are required, or alternatively, advanced mathematical algorithms must be employed to accurately determine the peak wavelength position. Despite this limitation, the band shift method is generally preferred over absolute intensity measurements due to its superior reliability and reduced dependence on external experimental parameters.

The underlying cause of the band shift phenomenon is related to temperature-induced changes in the electronic energy levels of the phosphor material. As temperature increases, thermal expansion and phonon interactions can slightly alter the crystal field environment surrounding the luminescent ions (such as rare-earth or transition metal dopants) [36]. These modifications lead to small shifts in the energy gap between the excited and ground states, which in turn cause the observed shift in the emission wavelength. Additionally, non-radiative relaxation processes may become more pronounced at elevated temperatures, subtly modifying the population distribution among different vibrational sublevels and thereby influencing the emission spectrum. The combined effect of these mechanisms results in a systematic and reproducible shift of the emission peak with temperature, which forms the basis for temperature sensing using the band shift method.

2.1.2.2. Multiple Spectral Band Method

In multiple spectral band phosphor thermometry, the intensity ratio method extends the principles of single-band measurements by simultaneously utilizing two or more emission bands of a thermographic phosphor. Unlike single-band approaches, which rely solely on either the absolute luminescence intensity or the peak wavelength shift of a single band, the intensity ratio method evaluates the ratio of emission intensities between two distinct spectral bands as a function of temperature. This comparative approach significantly enhances measurement reliability and accuracy, as it effectively compensates for external experimental factors that similarly affect both bands, such as fluctuations in excitation intensity, variations in phosphor coating thickness, dopant concentration, or small changes in detector alignment. Consequently, the intensity ratio method generally provides more reproducible and robust temperature measurements compared to single-band techniques, making it especially advantageous in environments where experimental conditions cannot be strictly controlled [50].

The implementation of the intensity ratio method can be realized using either spectrometers [51] or bandpass optical filters [14]. Spectrometers offer the advantage of simultaneously capturing the full emission spectrum, enabling precise determination of intensity ratios even for closely spaced bands. In contrast, when using bandpass filters, the selected spectral bands must be sufficiently separated to avoid spectral overlap, which could introduce errors in the calculated ratio. This requirement

imposes a limitation on the choice of phosphors, as not all thermographic phosphors exhibit multiple emission bands with adequate spectral separation. Additionally, careful calibration of the detection system is necessary to ensure that differences in detector sensitivity across the bands do not affect the ratio measurement.

A key requirement for successful application of the intensity ratio method is that the phosphor material possesses multiple well-defined emission bands, whose spectral peaks are clearly distinguishable. Without such well-resolved bands, the intensity ratio becomes ambiguous, leading to reduced sensitivity and potential measurement inaccuracies. An illustrative example is the $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor, whose emission spectra at 21 °C and 100 °C are shown in **Figure 2.5**. In this material, the two emission bands are sufficiently separated, allowing the intensity ratio method to be applied effectively across a practical temperature range. By measuring the emission intensities of these bands and computing their ratio, temperature can be determined with higher precision than single-band methods, while largely mitigating the effects of external experimental variations.

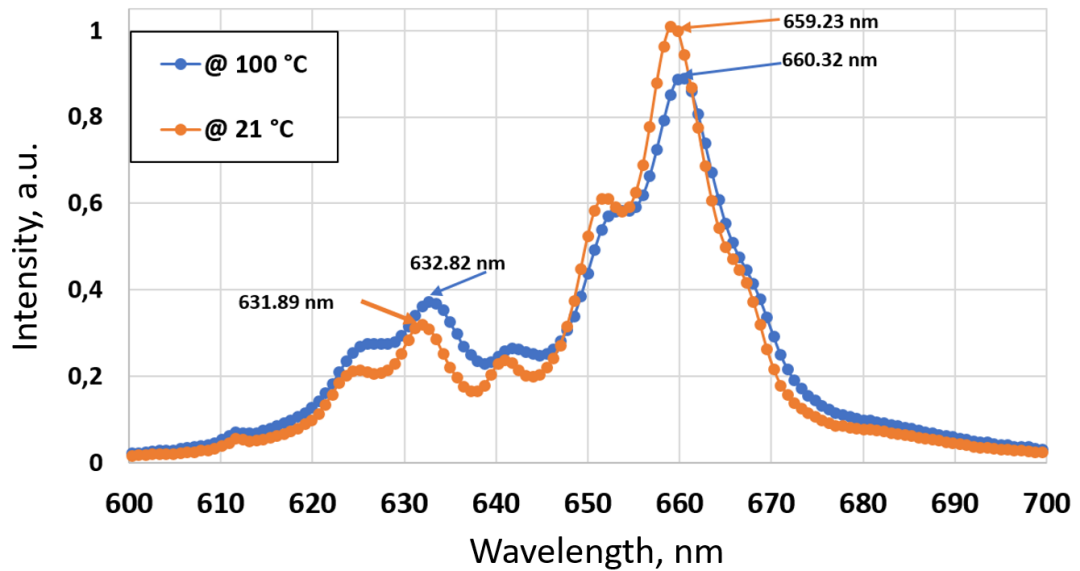


Figure 2.5: Emission spectra of $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ at 21 °C and 100 °C, illustrating two well-separated spectral bands used in the intensity ratio method.

Overall, the intensity ratio method provides a versatile and robust approach for multiple spectral band phosphor thermometry, capable of combining the benefits of absolute intensity and peak wavelength shift techniques, while offering enhanced reproducibility and reduced susceptibility to experimental uncertainties. Its main

limitation remains the requirement for suitable phosphor materials with multiple distinct emission bands, which must be carefully selected to ensure reliable measurements.

2.2. Applications

Surface temperature refers to the heat level of the outermost layer of a material or environment and plays a critical role in industrial applications, where it affects the quality, safety, and efficiency of manufacturing processes. Whether monitoring steel surfaces that can exceed 1000 °C or electronic components requiring precision near room temperature (20–25 °C), accurate surface temperature measurement is essential. Traditional methods such as infrared thermometry and contact-based thermocouples are commonly used but often suffer from significant limitations—infrared techniques are sensitive to unknown emissivity and background radiation [52], while thermocouples can be affected by inconsistent contact and heat-sink effects [53].

Phosphor thermometry offers a promising alternative by using a phosphor coating whose luminescence properties change with temperature when excited by UV or near-UV light. These changes, whether temporal or spectral, can be calibrated against the International Temperature Scale of 1990 (ITS-90) to provide traceable and reliable temperature readings. Unlike conventional methods, phosphor thermometry is largely immune to surface emissivity variations and radiative interference, making it particularly valuable in harsh industrial environments with high thermal gradients and limited access. Its application spans a wide range of sectors, including steel and plastics processing, electronics manufacturing, and aerospace and automotive industries, where precise surface temperature control is vital for process optimization and product integrity.

Therefore, rather than providing a routine overview of phosphor thermometry in industry, we have chosen to highlight three specific applications that best demonstrate its uniqueness, capability, and indispensability, as detailed in the following subsections.

2.2.1. Application of Phosphor Thermometry in Combustion Engine Diagnostics

Phosphor thermometry has been employed to investigate the temperature dynamics of internal components within combustion engines, offering enhanced insight into the thermal behavior and underlying processes during engine operation [13], [54-55]. Accurate surface temperature measurements of components such as intake valves and pistons are critical for understanding fuel-air interactions, heat transfer, and material performance under high thermal loads.

In the studies reported by [54-55], thermographic phosphors were utilized to measure the temperature of an intake valve and a piston. Specifically, $\text{LaO}_2\text{S:Eu}$ phosphor was applied to the stem-side surface of the intake valve. Excitation was achieved using a nitrogen laser delivered through a 1 mm optical fiber routed via the cylinder head. The same fiber was employed to collect the resulting luminescent emissions, which were directed to a PMT. Temperature determination was based on the analysis of the luminescence lifetime decay. The results indicated a rapid initial temperature rise followed by a slower, steady increase in both components.

Further investigations were conducted on an optically accessible laboratory engine, as described in [56]. These measurements aimed to improve understanding of the fuel evaporation process upon contact with high-temperature surfaces. The engine was operated at 1,200 RPM using gasoline and iso-octane fuels. A thermographic phosphor was bonded to the intake and exhaust valves using a commercial binder. Excitation was provided by the fourth harmonic of a Nd:YAG laser (266 nm), directed through a quartz window. Emission signals were collected via a quartz optical fiber and digitized using a PMT coupled with a high-speed oscilloscope. Temperature was again inferred from the luminescence decay lifetime.

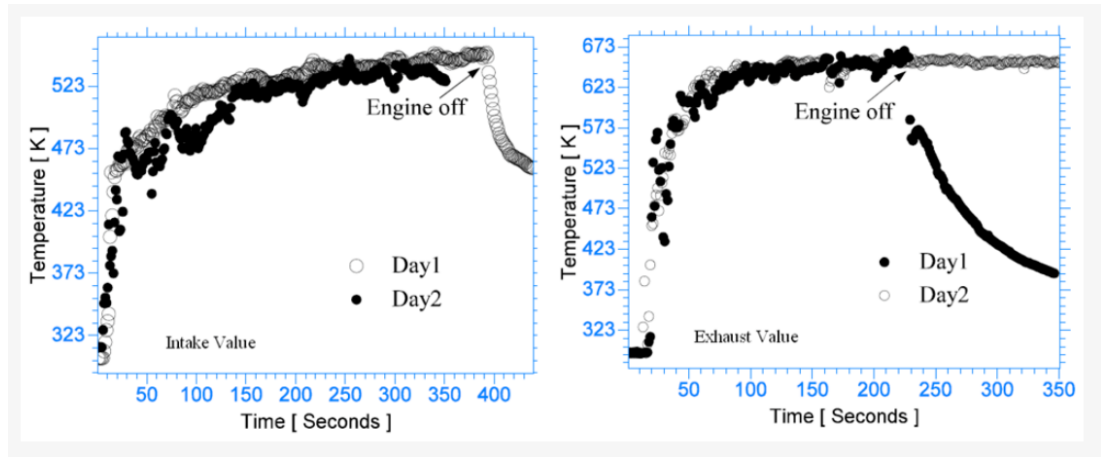


Figure 2.6: Temperature of the intake and exhaust values measured using thermographic phosphors [56].

The results, illustrated in **Figure 2.6**, demonstrate that the exhaust valve begins to heat earlier and reaches a higher temperature than the intake valve. This behavior is attributed to the cooling effect of fresh air entering through the intake valve, which moderates its thermal rise.

2.2.2. Phosphors for Droplet Thermometry

The laser-induced phosphorescence technique offers a robust method for droplet temperature measurement, effectively minimizing interference from background radiation [57]. First demonstrated by Marcus Aldén's team at Lund University in 2004, phosphor thermometry was applied to free-falling water droplets using both spectral intensity ratio and lifetime-based approaches [58]. In these experiments, phosphors ($\text{Mg}_4\text{FGeO}_6\text{:Mn}$ for intensity ratio and $\text{La}_2\text{O}_2\text{S:Eu}$ for lifetime) were dissolved in distilled water, with temperature regulated via heating wires and monitored by a thermocouple. A He-Ne laser triggered the system by detecting droplet passage, activating a UV-emitting Nd:YAG laser. For the intensity ratio method, a 266 nm laser excited the phosphors, and emissions at 631 nm and 657 nm were recorded using a spectrograph and CCD camera. For the lifetime method, a 355 nm laser was used, with emissions at 514 nm detected via a PMT and optical filter. Results showed strong agreement between phosphor thermometry -derived temperatures and thermocouple readings, with minor deviations at elevated temperatures due to heat loss during droplet descent. These discrepancies were corrected using a heat transfer model

accounting for convection and evaporation, confirming the accuracy of the phosphor thermometry technique.

Finally, intracellular and intercellular temperature measurements in biomedicine may be among the most exciting applications of luminescence thermometry [32]. For example, in [59] the incubation of water-dispersible $\text{NaYF}_4:\text{Er}^{3+}, \text{Yb}^{3+}$ nanoparticles into HeLa cancer cells for the monitoring of cell temperature during apoptosis. Under near-infrared 980 nm excitation, $\text{NaYF}_4:\text{Er}^{3+}, \text{Yb}^{3+}$ nanoparticles show green up conversion emission that is typical for Er^{3+} ions. The ratio of intensities of the two emission bands centered at 525 and 545 nm provides a measure of temperature of the environment around the nanoparticles, with good sensitivity. The authors used a metallic platform connected to a resistor to change the cell temperature by varying the voltage across the resistor while simultaneously observing the temperature via luminescence. Transmission optical images were recorded at different temperatures. Images that were taken at 25°C and 35°C have revealed typical morphology of the HeLa cancer cells. An image measured at 45°C showed a small membrane fragment which points to cell death caused by external heating.

2.2.3. Near-Infrared Luminescence Thermometry for Subcutaneous in Vivo Imaging

Today, it is extremely difficult to perform noncontact, accurate subcutaneous in vivo two-dimensional temperature measurements [32]. Accurate, noncontact two-dimensional temperature measurement beneath the skin remains a significant challenge. Conventional thermographic imaging is limited to surface tissues, while luminescence thermometry using visible-spectrum nano thermometers is ineffective due to minimal tissue penetration of visible light. A promising alternative involves near-infrared (NIR)–emitting nanoparticles, which offer deeper tissue penetration and temperature-sensitive luminescence within the physiological range (20–50 °C).

Ximendes et al. in [60] developed a method for subcutaneous in vivo thermal imaging using LaF_3 nanoparticles doped with Er^{3+} , Tm^{3+} , and Yb^{3+} . Excited at 690 nm, these particles emit near-infrared light at 1000, 1230, and 1550 nm, with a temperature-sensitive intensity ratio (5%/K) between 1000 and 1230 nm. Injected into mice, the nanoparticles enabled thermal video recording during controlled heating and cooling

using 690 nm and 808 nm lasers. An InGaAs camera with bandpass filters captured emissions, allowing precise, dynamic temperature mapping beneath the skin.

Thermal imaging was performed by analyzing the emission intensity ratios during both heating and cooling cycles, enabling dynamic monitoring of subcutaneous temperature changes with high spatial resolution.



3. EXPERIMENT

Within the scope of this thesis study, the characterization and measurement methods for the metrological characterization of thermographic phosphors included both time-resolved methods—such as decay time—and time-integrated measurement methods—such as peak wavelength shift and the intensity ratio of two spectral bands. To implement the selected measurement methods for characterizing and measuring the thermographic phosphor thermometer, two different measurement setups were designed and established in the Thermodynamics Metrology Laboratory of UME. The first, a spectroscopy-based measurement system was used for peak wavelength shift and two-band intensity ratio measurements, while the second, a separate setup was designed for the decay time measurements, incorporating a high-speed camera capable to be used in performing two-dimensional surface temperature measurements.

In the experimental studies, two different phosphor materials were used: $Mg_4FGeO_6:Mn$ and $Al_2O_3:Cr$. The $Mg_4FGeO_6:Mn$ phosphor was used in both the decay time measurement system and the peak wavelength shift and two-band spectral intensity ratio measurement system. However, the $Al_2O_3:Cr$ phosphor paint was used in the decay time measurements excited by a double-pulse laser at a wavelength of 532 nm.

3.1. Spectroscopy Measurement-Based Thermographic Phosphor Thermometry

For the spectroscopic characterization of the thermographic phosphors a measurement setup for performing peak wavelength shift and two spectral band intensity ratio analyses were designed and implemented. The system comprises a high-temperature furnace (Carbolite ZTF12-65-550), a spectrometer (Avantes, AvaSpec-HSC 1024×58TEC-EVO), and a UV-LED light source (Avantes, AVALIGHT-HPLED-385). The temperature control and monitoring are achieved using a thermocouple, a thermal bath, and a digital multimeter. A schematic representation of the setup is shown in **Figure 3.1**.

The furnace used in the measurement system has a heating tube with a width of 65 mm and a length of 550 mm. To ensure temperature homogeneity within the tube, the

furnace includes three independently controlled heating zones. These zones can create a region with ± 1 °C homogeneity over a length of 180 mm at the center of the furnace. Specially designed by the manufacturer to provide a long homogeneous temperature region inside, this three-zone furnace can operate stably from room temperature up to 1100 °C.

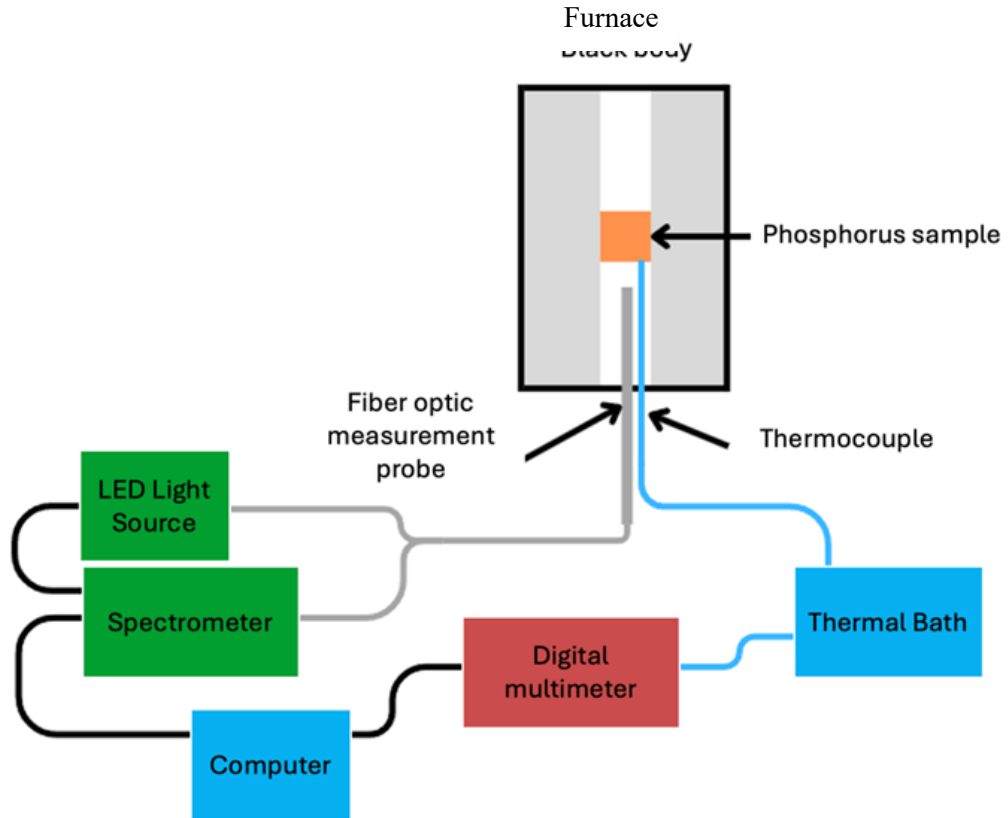


Figure 3.1: Measurement setup designed for peak wavelength shift and dual spectral band intensity measurements.

The spectrometer used in the spectroscopic measurements, (shown in **Figure 3.2a**) is capable of conducting measurements in the wavelength range of 200 nm to 1000 nm. It uses a 1200 line/mm grating. This allows to achieve spectral resolution of approximately 0.7–0.8 nm with small varying across the wavelength range. This high resolution facilitates the accurate detection of the peak wavelength of the thermographic phosphor's luminescence emission band. In thermographic phosphor thermometry based on peak wavelength shift, the change in peak wavelength position with temperature should be occur slowly, making precise determination of the wavelength critically important.

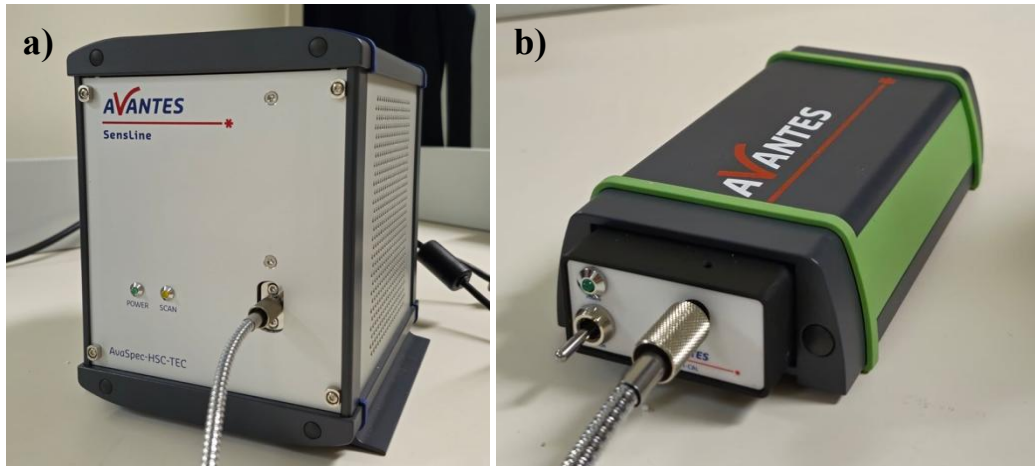


Figure 3.2: Components of the thermographic phosphor thermometer characterization system, a) the spectrometer and b) the 385 nm LED illumination source.

An LED light source with a peak emission wavelength of 385 nm—manufactured by the same company as the spectrometer—was used as the excitation source for the spectrometric measurements. The LED and the optical fiber are used to couple the excitation and emission light and providing them to the target surface and the spectrometer's measurement channel congruently, as it is shown in **Figure 3.2b**. The emission power of the LED can be easily adjusted via pulse-width modulation (PWM), enabling precise control over the excitation intensity during spectroscopic measurements. The fiber-optic probe used to perform thermographic phosphor measurements with the fiber-coupled spectrometer and LED light source is illustrated in **Figures 3.3** and **Figures 3.4**.



Figure 3.3: An optical fiber used as a reflection probe for powders and dense liquids.



Figure 3.4: An optical fiber used as a measurement probe for high-temperature measurements at low pressures.

A high-temperature fiber optic probe (NA = 0.22, 2 m standard length, wavelength range: 250–2500 nm) was employed for the spectroscopic characterization of $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor. The probe features dual SMA-905 connectors, allowing efficient coupling of both excitation and emission light paths. Its stainless steel 316 probe head (length: 140 mm, diameter: 6.0 mm) includes a 5 mm fused silica window (1 mm thickness), providing high thermal and chemical resistance. The optical fibers are housed within a silicone inner tube and a robust flexible outer sheath, available in stainless steel or chrome-plated brass, minimizing mechanical stress during operation. The probe supports operation in harsh environments with temperatures ranging from -25°C to 700°C and up to 10 bar pressure at 25°C . With a minimum bending radius of 20 mm for brief periods, it ensures both flexibility and durability. Additionally, an integrated gas inlet allows for effective cooling of the probe during high-temperature measurements. The detailed specifications of the probe are summarized in **Table 3.1**.

In the spectroscopic measurement setup of the thermographic phosphor thermometer, excitation of the phosphor material is achieved using a 385 nm LED light source. This excitation light is guided to the sample through the fiber-optic measurement probe illustrated in **Figure 3.4**. The probe not only delivers the excitation light but also serves a dual purpose by collecting the luminescence emitted from the thermographic phosphor in response to the excitation. This emitted light is then transmitted back through the same fiber to the spectrometer for spectral analysis. The use of a single probe for both excitation and emission collection ensure precise spatial alignment

between the illumination and detection regions, minimizes optical losses, and simplifies the overall design of the measurement setup. This configuration is particularly advantageous for compact or confined measurement environments, where alignment flexibility and signal efficiency are critical.

Table 3.1: Technical specifications of the high-temperature fiber optic probe.

The Optical Fiber probe	NA= 0.22. Standard in 2-meter length
Wavelength Range	250-2500 nm (UV/VIS/NIR)
Connectors	SMA-905 connectors (2x)
Probe Head	Probe Head: Stainless Steel 316, length 140 mm x diameter 6.0 mm. The probe head is 5 mm in diameter and has a fused silica window with a 1 mm thickness. Water proof.
Cladding	The optical fibers are protected by a silicone inner tube and a flexible outer sheath made of either stainless steel (6.0 mm) or chrome-plated brass (5.0 mm). The sheath/coating also helps reduce mechanical stress.
Temperature	From -30°C to 700°C
Pressure	10 bar @ 25°C
Bending	Minimum bending radius: 20 mm for a few seconds, 120 mm for prolonged periods.

A Type-J thermocouple was employed to measure the temperature of the thermographic phosphor sample during the spectroscopic experiments. The thermocouple enabled reliable monitoring of the thermal conditions inside the three-zone furnace, ensuring accurate correlation between temperature and luminescent response. The thermometer was calibrated in the full range from room temperature to 1100 °C was calibrated by the Contact Temperature Laboratory at TUBITAK UME according to the ITS-90 at UME. The thermal bath used for the thermocouple was set to 0.1 °C, and a digital multimeter was used to read the voltage from the thermocouple. The voltage data obtained from the digital multimeter is then converted into temperature information using the calibration certificate. The deviation of the calibrated thermocouple from the standard reference values is calculated based on the IEC 60584-1:2023 [61] standard reference table, as expressed in Equation 3.1. The coefficients used in Equation 3.1 are presented in **Table 3.2**.

$$\Delta E = E - E_{IEC} = a \cdot T + b \cdot T^2 + c \cdot T^3 \quad (3.1)$$

Table 3.2: The deviation coefficient of calibrated thermocouple.

Coefficient	Value
a	$-3.83229945 \cdot 10^{-1}$
b	$-1.67691803 \cdot 10^{-3}$
c	$-1.52478526 \cdot 10^{-6}$

Using the devices mentioned above, the measurement setup shown in **Figure 3.5** was established within the Thermodynamic Metrology Laboratory for performing time-integrated measurement methods—specifically, peak wavelength shift and two-band spectral intensity ratio measurements—in the thermographic phosphor thermometer.

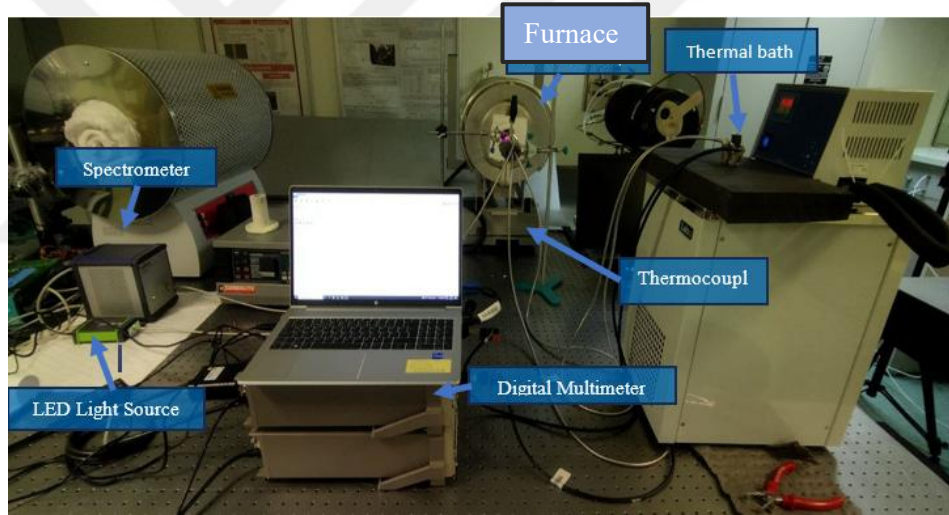


Figure 3.5: The image of the characterization and measurement setup for peak wavelength shift and intensity ratio methods of the thermographic phosphor thermometer.

3.2. Decay Time Measurement-Based Thermographic Phosphor Thermometry

For the characterization of the thermographic phosphor thermometer, two-dimensional surface temperature measurements carried out using a high-speed camera based on the decay time measurement method. A schematic illustration of the experimental setup is shown in **Figure 3.6**. Temperature determination from the decay time measurements

requires fast detectors capable of capturing the luminescence lifetime of the phosphor with high temporal resolution. Although PMTs and silicon-based semiconductor sensors are also suitable for such measurements, a high-speed camera was employed in this study to enable two-dimensional temperature mapping of the phosphor-coated surface.

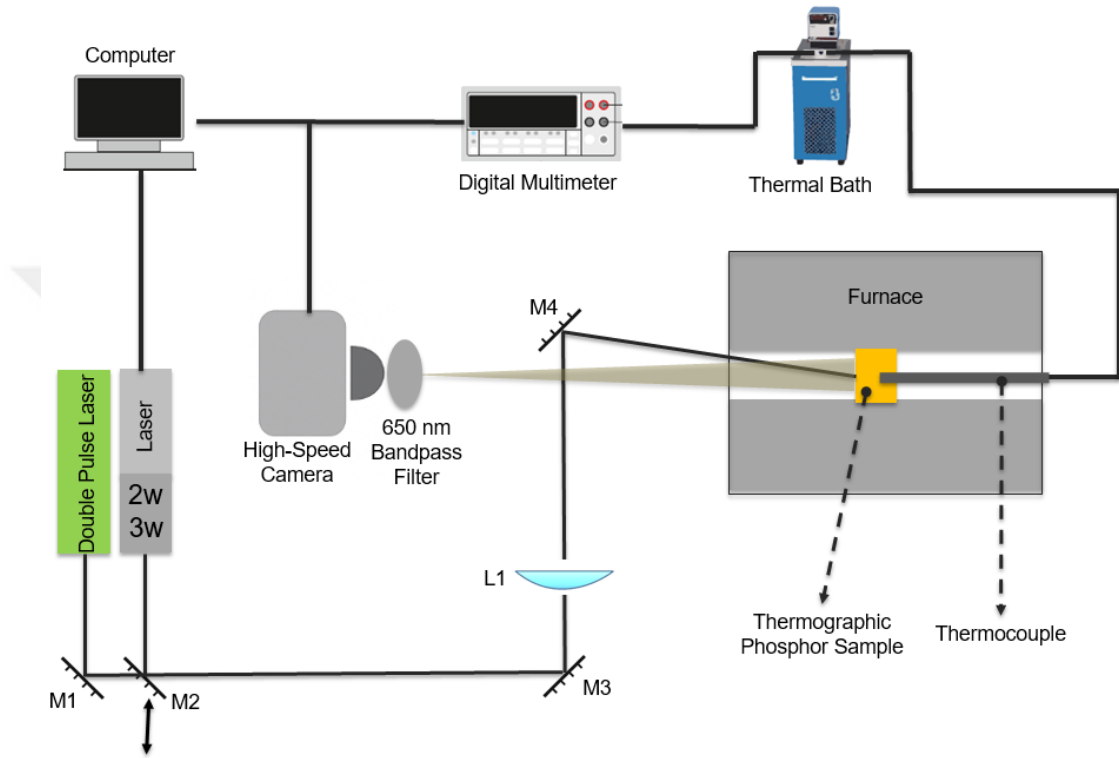


Figure 3.6: A schematic representation of the thermographic phosphor thermometry measurement system.

In this context, the subcomponents of the measurement system used for implementing the decay time measurement method are listed below (see **Figure 3.7** and **Figure 3.8**):

- An Nd:YAG Double-Pulse Laser: 532 nm Nd:YAG double pulse laser (Ekspla, NL300D) used as the excitation source for the thermographic phosphor.
- A High-Speed Camera: A high-speed camera (Phantom, VEO 640S) was used to capture the luminescence emitted by the phosphor surface images.
- The Three-Zone High-Temperature Black Body: The three-zone furnace (Carbolite) is used to provide a controlled thermal environment.

- The temperature measurement system: Includes the thermocouple, thermal bath, and digital multimeter for measuring the temperature of the environment inside the furnace and the temperature of the block coated with the phosphor paint to be characterized.
- Phosphor Materials: Two different phosphor samples - $Mg_4FGeO_6:Mn$ and $Al_2O_3:Cr$ - were used.
- Software and Data Acquisition: Tools for controlling the system and collecting data.

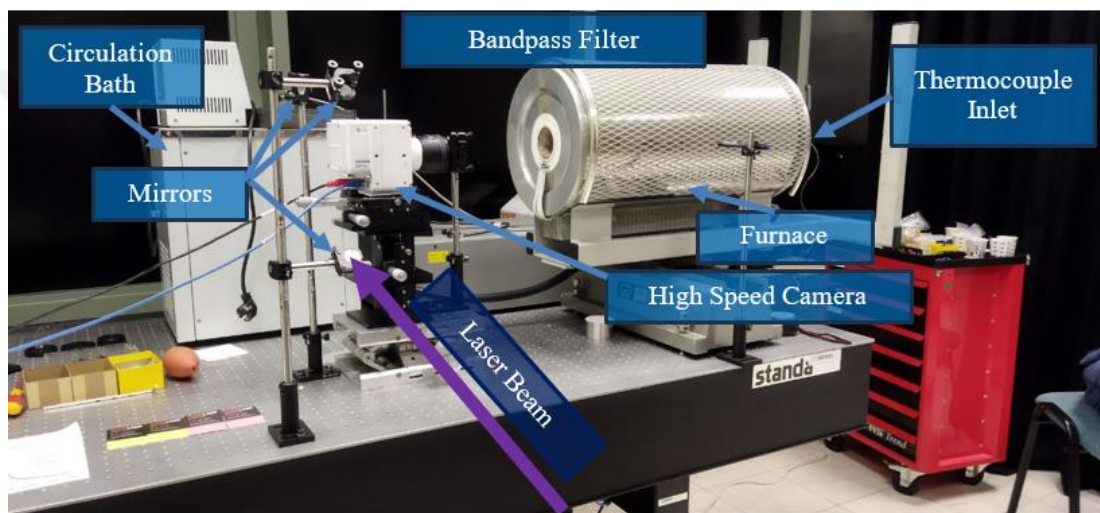


Figure 3.7: A picture of the designed thermographic phosphor thermometry system.

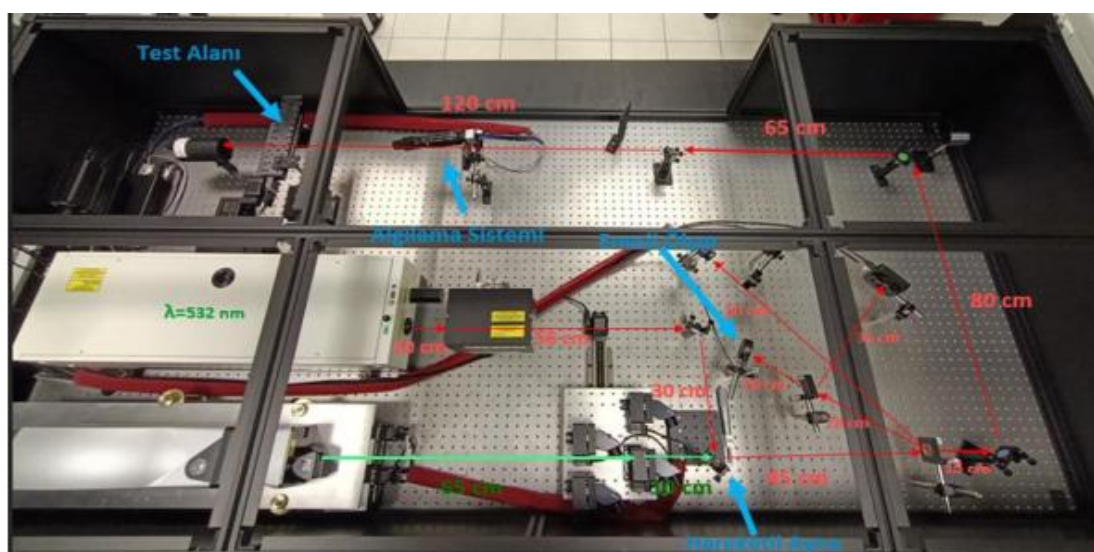


Figure 3.8: A picture of the double-pulsed laser system.

3.2.1. Nd: YAG Double Pulse Laser

In the experimental setup, the Nd: YAG laser system capable of generating spatially overlapped double pulses at a wavelength of 532 nm, with a pulse duration of 6 nanoseconds and a repetition rate of 20 Hz, was employed. The internal configuration of the double-pulse laser is illustrated in **Figure 3.9**. Laser 1 (L1) and Laser 2 (L2), both operating at a fundamental wavelength of 1064 nm and generated from two separate Nd: YAG crystals, are directed toward a second harmonic generation (SHG) crystal via a series of mirrors and a half-wave plate, which serves to adjust the polarization. As both laser pulses originate from the same gain medium, the resulting pulses exhibit identical temporal durations and closely matched spatial and temporal profiles.

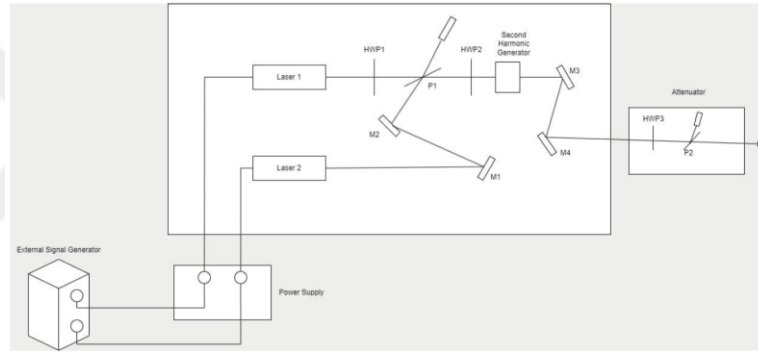


Figure 3.9: Schematic representation of the double pulse laser generation.

As depicted in **Figure 3.10**, the near-field spatial profiles of the laser beams exhibit a non-uniform intensity distribution, which leads to uneven excitation of the phosphor material and introduces localized variations in the measured luminescence decay times. To mitigate this issue, a focusing lens with a 1-meter focal length was used to shape the beam into a more uniform, near-Gaussian profile at the target plane, as shown in the corresponding beam profiles (**Figures 3.11** and **Figures 3.12**). This optical adjustment provided a more homogeneous excitation region on the phosphor surface, enabling the acquisition of a single, representative decay time from the laser-illuminated area.

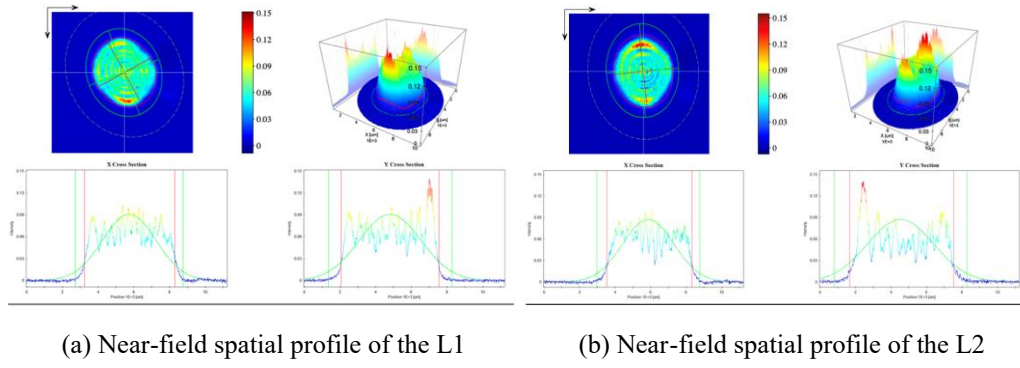


Figure 3.10: Measurements of the near-field spatial profiles of the L1 and L2 at the output of the laser.

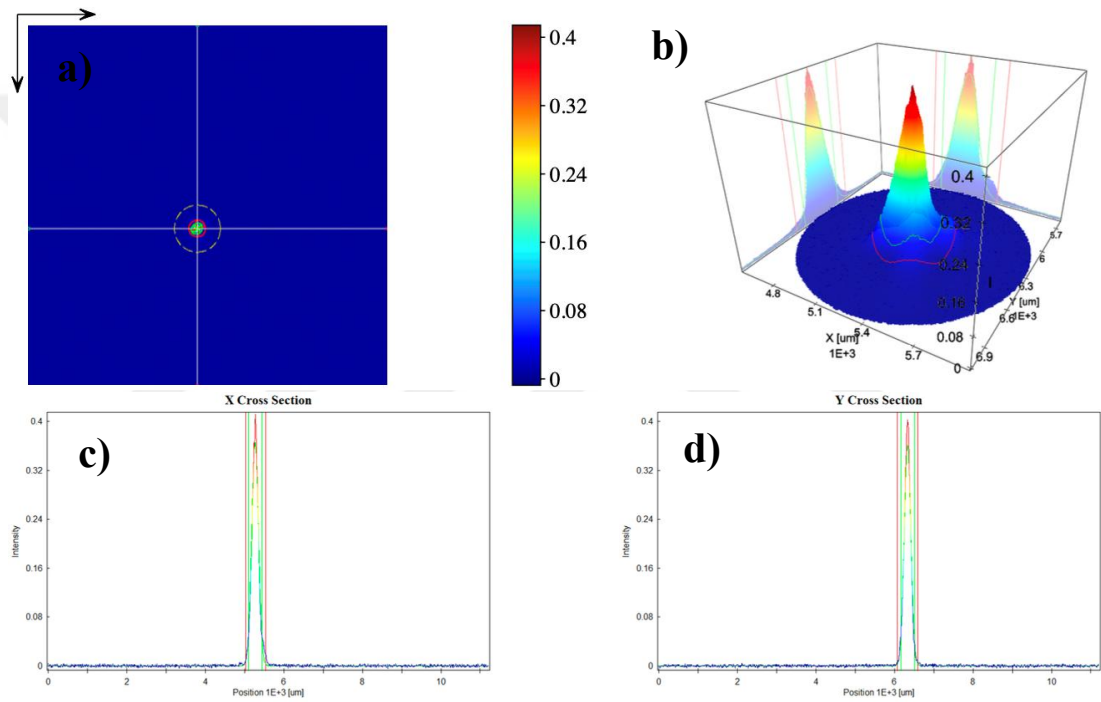


Figure 3.11: The far-field spatial profiles of the L1 after a focusing lens with a focal length of 1 m. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, (c) and d) cross-section of Gaussian profiles at the x – and y – axes.

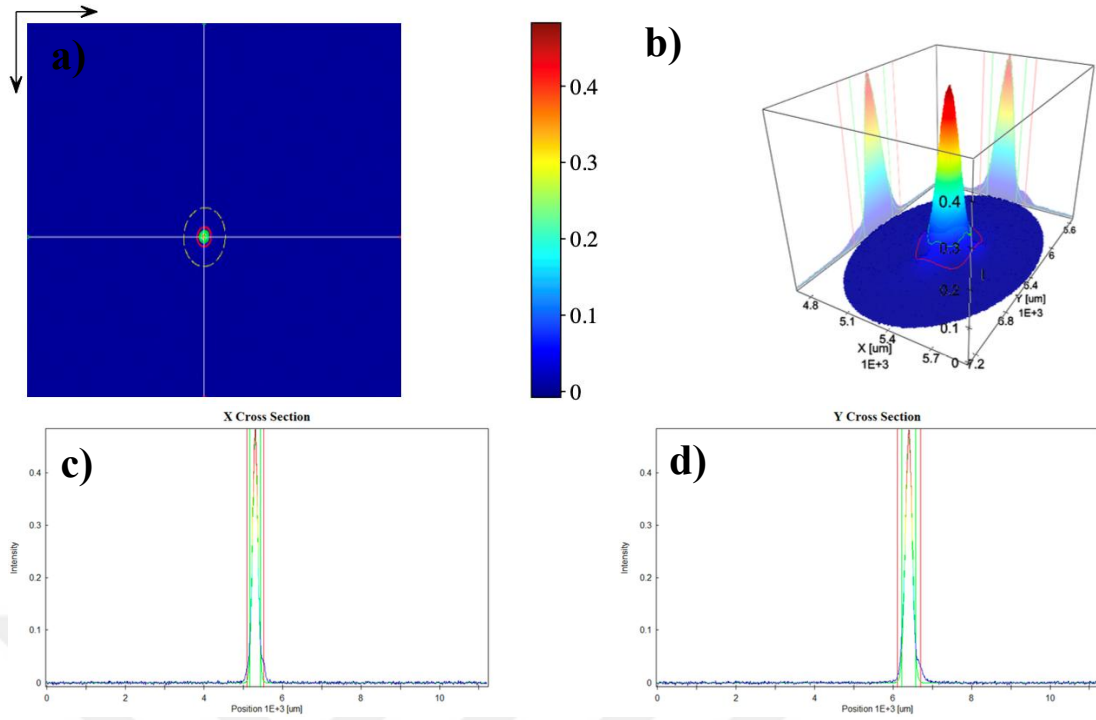


Figure 3.12: The far-field spatial profiles of the L2 after a focusing lens with a focal length of 1 m. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, c) and d) cross-section of Gaussian profiles at the x- and y – axes.

Upon shaping the far-field profiles of both lasers into the near-Gaussian form, it was observed that the L1 and L2 laser beams were focused on spatially distinct locations (see **Figure 3.13a**). To achieve precise spatial overlap of the two beams, the M2 mirror—responsible for directing the L2 beam within the laser head (refer to **Figure 3.8**)—was finely adjusted. As a result of this alignment procedure, the L1 and L2 beams were successfully superimposed, as illustrated in **Figure 3.13b**.

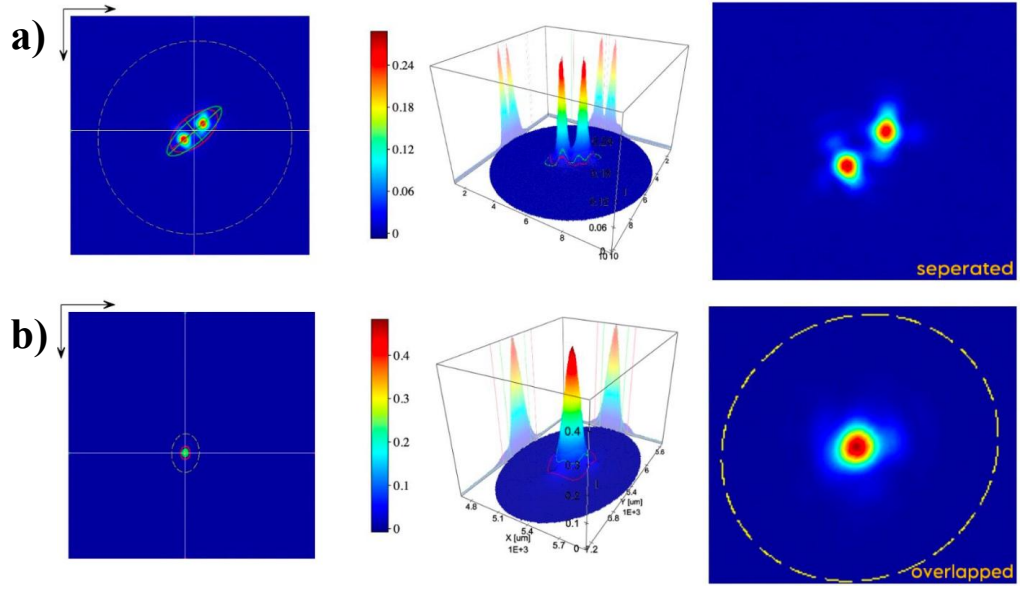


Figure 3.13: Spatial overlapping of L1 and L2 laser beams in the double-pulse laser system. (a) before the adjustment; b) after the adjustment.

3.2.1.1. Beam Quality Measurements of the Double Pulse Laser

In the scope of the current work the laser beam characterization was performed over a criteria M^2 . The M^2 factor serves as a quantitative metric for evaluating the deviation of a laser beam from the ideal Gaussian profile. It characterizes the beam's focusability, divergence, and overall optical quality. The experimental setup used to determine the beam quality factor is illustrated in **Figure 3.14**. The laser source, attenuator, neutral density (ND) filter, focusing lens, and beam profiler are precisely aligned along a common optical axis. The beam profiler is incrementally displaced from the lens in 2.5 cm steps, and at each position, the beam diameter is measured at the $1/e^2$ intensity level of the Gaussian distribution. This procedure yields a beam diameter versus propagation distance profile, which initially decreases and subsequently increases, forming a characteristic waist. The resulting beam diameter measurements along the major axes of the L1 and L2 laser beams are presented in **Figures 3.15** and **Figures 3.16**, respectively.

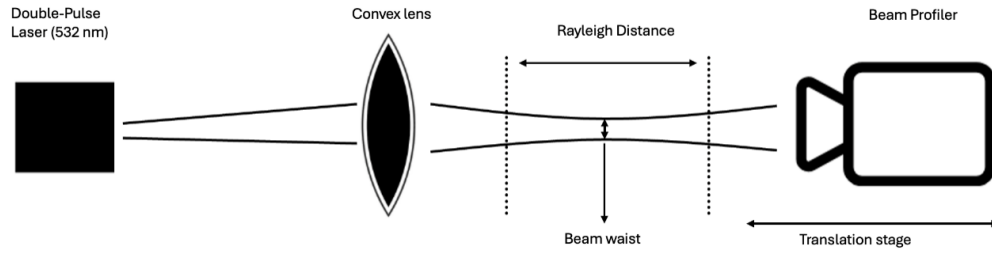


Figure 3.14: Schematic representation of the beam quality (i.e. M^2) measurement setup.

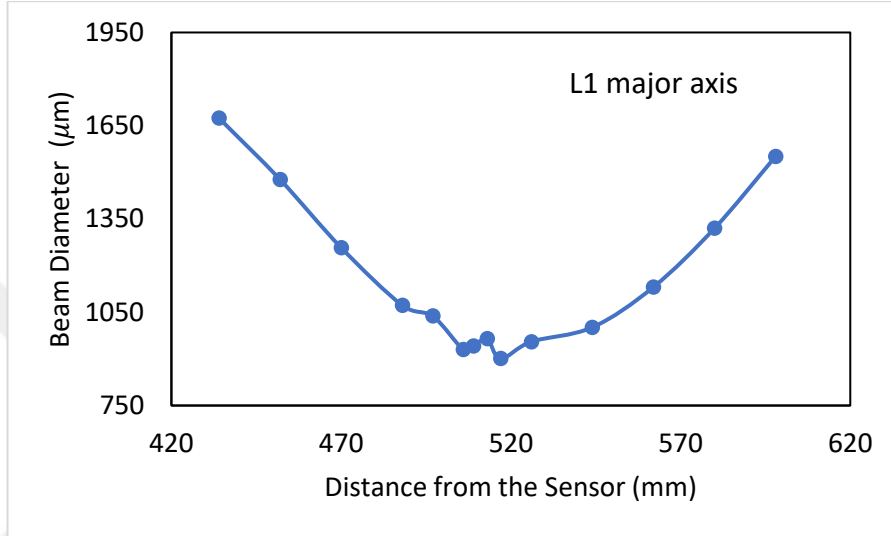


Figure 3.15: Beam waist (diameter) assessment measurements along the X-axis of the L21

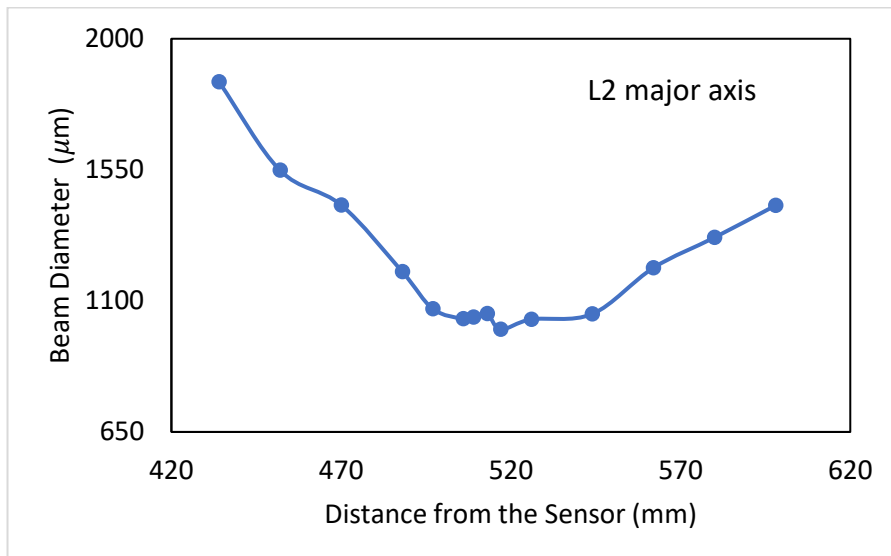


Figure 3.16: Beam waist (diameter) assessment measurements along the X-axis of the L2.

Similar to the distance-dependent beam diameter graphs presented in **Figure 3.15** and 3.16 for the major (X-axis) axes of the lasers have also been obtained for the (Y-axis) minor axes of the laser beams. All the resulting graphs were fitted according to Equation 3.2, which defines the beam diameter as a function of distance.

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{M^2 \cdot \lambda (z - z_0)}{\pi \omega_0^2} \right)^2} \quad (3.2)$$

Where $\omega(z)$ is the beam radius at position z , ω_0 is the minimum beam waist radius, z_0 is the location of the beam waist, λ is the laser wavelength, and M^2 is the beam quality factor. Accordingly, the values of ω_0 , z_0 , and M^2 were obtained from the applied fit. The L1 and L2 curves to which the fits were applied are presented in **Figure 3.17**.

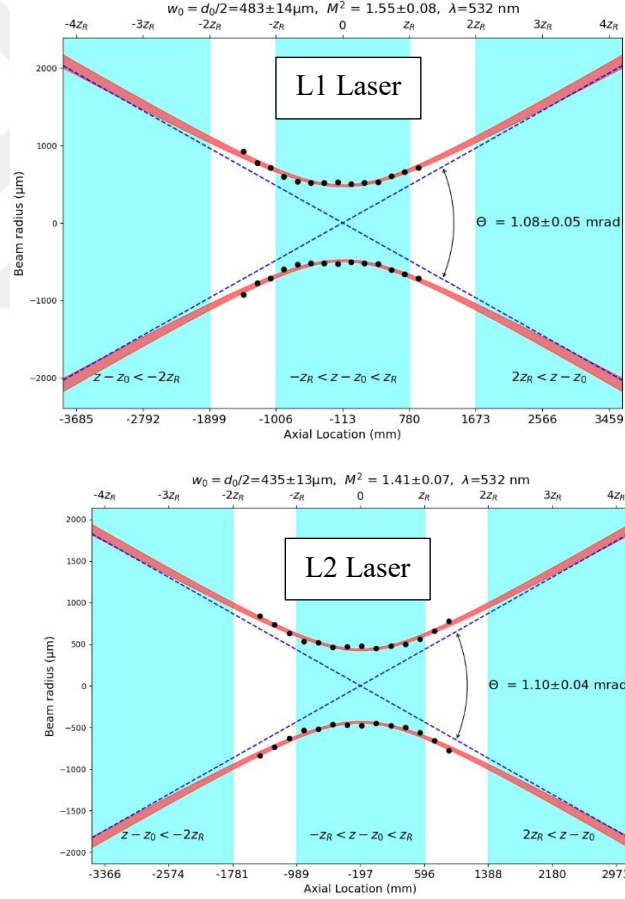


Figure 3.17: Nonlinear fitting is applied to laser beam diameter & distance curves of L1 and L2 lasers by in-house software written in Python environment.

The obtained M^2 values for L1 and L2 are 1.55 and 1.41, respectively. A summary of the specifications of the double-pulse laser employed in this study is provided in **Table**

3.3. These values satisfy the condition $M^2 < 2$, which is desired in Q-switched lasers applied similar to experiments described below.

Table 3.3: The output parameters of the double pulse laser.

	Laser 1	Laser 2
Energy (mJ)	157	157
Stability (% std. dv.), over 1000 pulses	1.2	1.3
M^2	1.55	1.41
Pulse Duration (FWHM), ns	4-6	
Polarization at 532 nm	Linear, horizontal	
Beam profile	"Hat-Top" in near field and near-Gaussian in far field	
Beam diameter, mm	~6	
Beam divergence, mrad	<1.2	

3.2.1.2. Energy Measurements of Laser 1 and Laser 2

Since the thermographic phosphor samples were irradiated using laser pulses with varying energy values, it was necessary to characterize the energy output of the laser system. In this study, the output of a 532 nm laser was reduced using a variable attenuator placed directly at the output of the laser. The attenuator allowed fine control of the laser pulse energy by adjusting its transmittance level from nominal 10 % to 100%. To determine the actual energy delivered to the phosphor sample at each experimental setting, a Coherent EM-USB J-50MB-YAG energy meter was positioned at the sample location (**Figure 3.18**), and the energy of the pulses were recorded.



Figure 3.18: Coherent EM-USB J-50MB-YAG energy meter.

To ensure the accuracy and traceability of the measurements, the energy meter was calibrated at the TUBITAK UME Optical Metrology Laboratory. This calibration ensured that the measured pulse energies correspond accurately to real energy values, providing confidence in the characterization process. For each attenuator transmittance level, 99 consecutive laser pulses were recorded, and their mean value was used to represent the energy at that setting. The standard deviation of these pulses was also calculated to assess energy stability. The relative standard deviation was found to be 1.4% for Laser 1 and 1.7% for Laser 2, as shown in **Figure 3.19**.

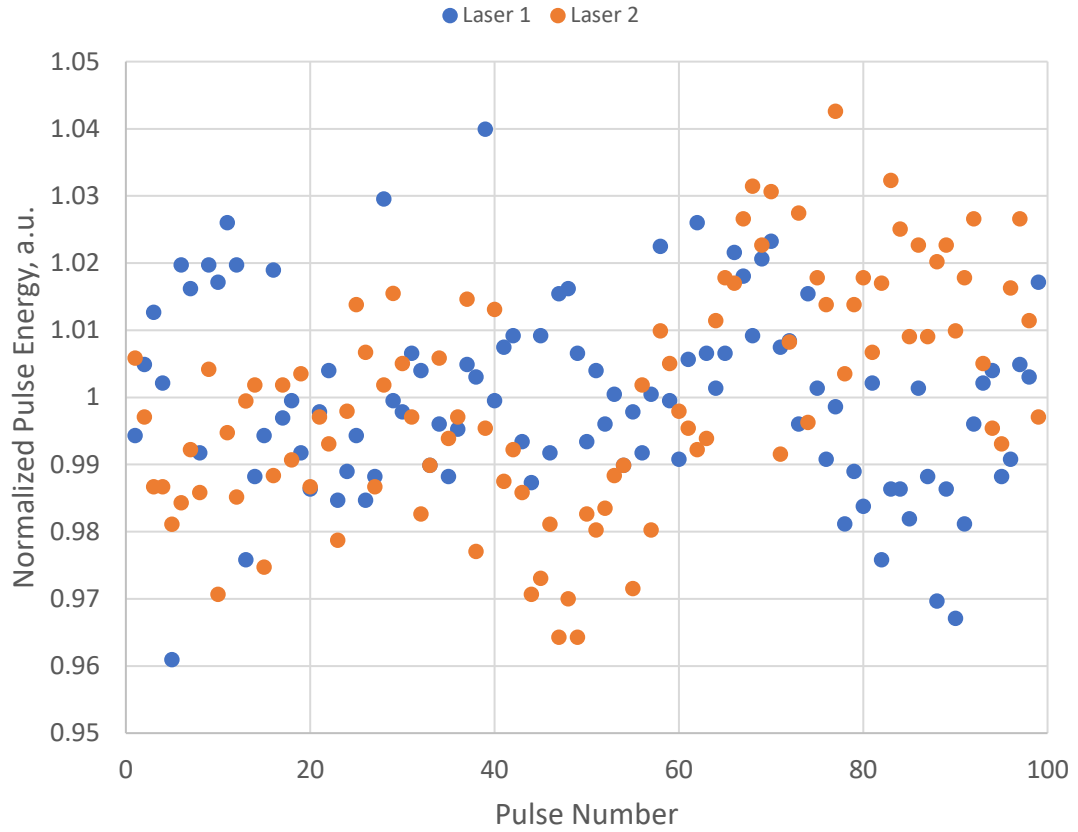


Figure 3.19: Relative standard deviation of 99 pulse energy measurements for Laser 1 and Laser 2.

The relationship between the attenuator transmittance setting and the corresponding mean pulse energy was modeled using a fourth-degree polynomial fit. This calibration curve enabled precise estimation of the laser pulse energy incident on the phosphor surface for any given attenuator setting. The calibration results for Laser 1 and Laser 2 are presented in **Figures 3.20** and **Figures 3.21**, respectively.

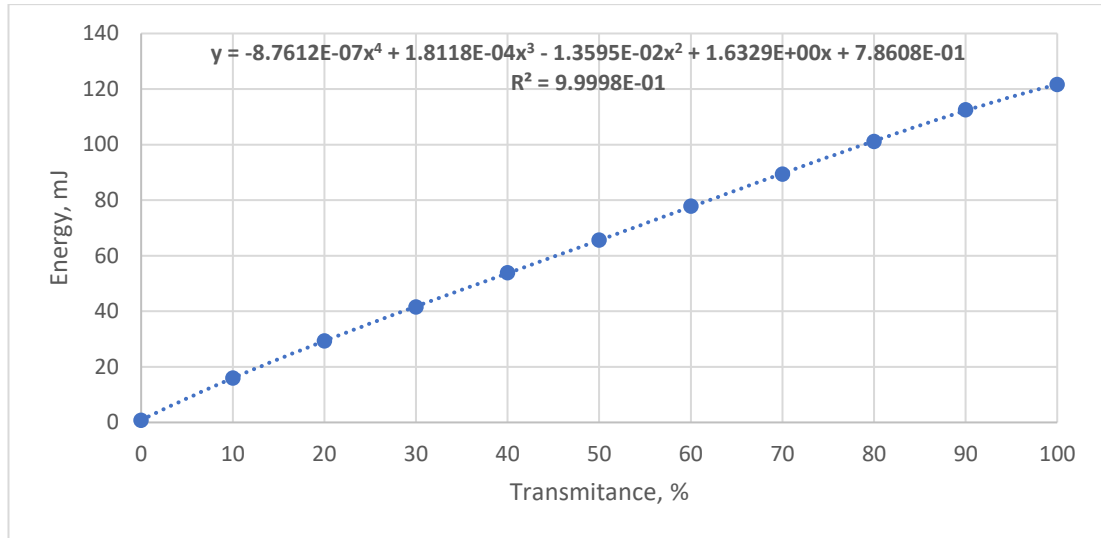


Figure 3.20: The relation between the attenuator setting and the laser pulse energy at the target surface for the Laser 1.

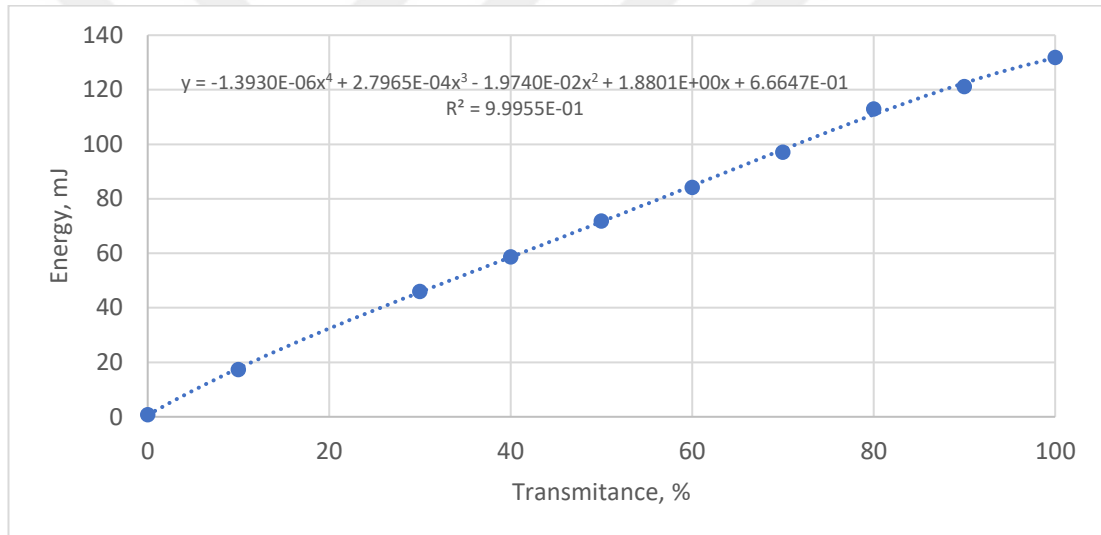


Figure 3.21: The relation between the attenuator setting and the laser pulse energy at the target surface for the Laser 2.

3.2.1.3. Measurement of the Delay Time Between the Pulses

The delay time between two laser pulses was measured by directing the pulses onto a high-speed silicon detector (EOT, ET-2030EXT, S/N: 23-8344) and observing the corresponding signal on an oscilloscope (Rohde & Schwarz, RTM 3004). A representative oscilloscope screenshot is shown in **Figure 3.22**, where a 1 ms delay between two consecutive pulses can be observed. To prevent potential damage to the photodiode caused by the high-energy laser pulses, the beam was first attenuated to

0.1% of its original intensity using a variable attenuator. Following this, two beam splitters were used in series to extract 4% of the remaining signal at each stage, resulting in a final intensity of approximately 0.0016% (or 1.6 parts per million) of the original pulse energy reaching the detector.

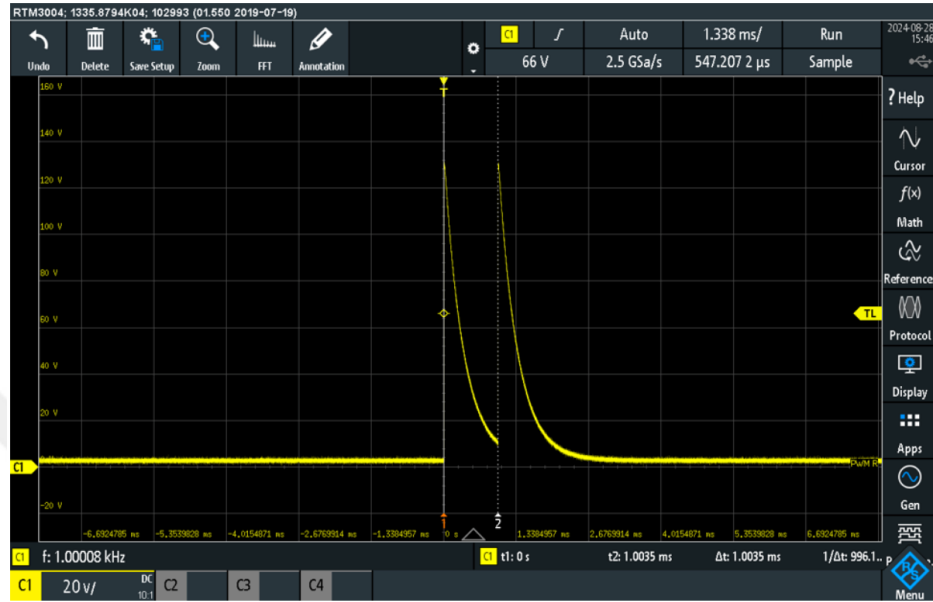


Figure 3.22: Pulse lengths and delay time measurement of double-pulses shots.

To determine the actual time intervals corresponding to these input values, delay times were recorded using the oscilloscope for a wide range of inputs. The range from 400,000 to 100 was linearly fitted with a first-degree polynomial, and the resulting calibration curve is presented in **Figure 3.23a**. Similarly, the range between 100 and 5 was fitted with another linear model, which is shown in **Figure 3.23b**. These two separate fits were necessary due to changes in system behavior across the delay range.

Table 3.4: Delay times for input values between 0 and 5 in the nanosecond range.

Input Value	Delay (ns)
5	668
4	543
3	417
2	292
1	169
0	36

For input values between 5 and 0, delay times could not be adequately modeled by a linear fit due to the rapid transition into the nanosecond regime. Therefore, these values are presented as discrete measurements in **Table 3.4**. The entire delay range—from approximately 50 milliseconds down to 36 nanoseconds—was divided into three distinct scales: milliseconds, microseconds, and nanoseconds. This separation allowed for accurate and meaningful representation of the full dynamic range of delay times across different temporal resolutions.

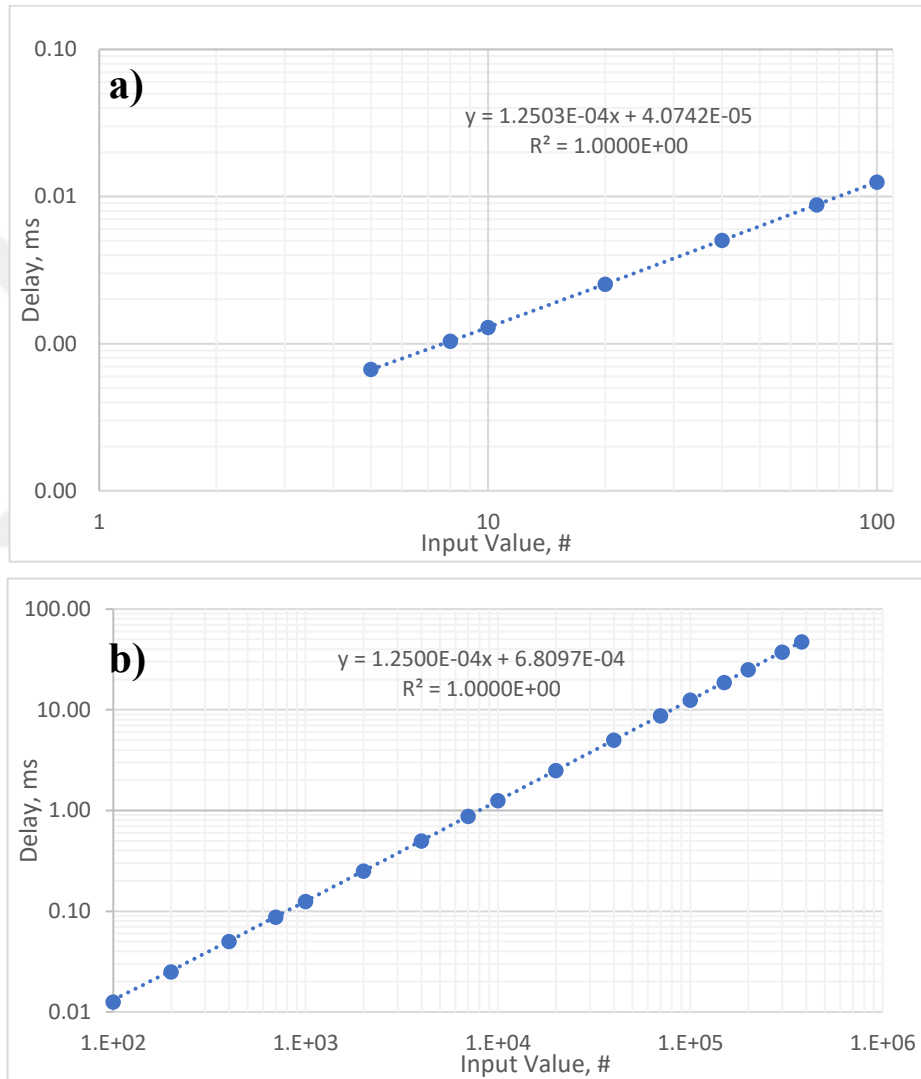


Figure 3.23: Relation between the inter-pulse delay in a double-pulse pair and the laser control block setting of L1 and L2, respectively.

3.2.1.4. Measurement of the Beam Diameter of The Double Pulse Laser

To characterize the spatial energy distribution of the double-pulse laser used in the experiments, the laser beam diameter was measured at the sample location. A beam profiler was positioned exactly where the phosphor samples are normally placed to avoid optical path changes that could affect the beam profile or diameter. The laser pulse energy was attenuated to 0.5% of its original value using the variable attenuator, and an OD2 neutral density filter was placed in front of the beam profiler to prevent sensor damage. The beam diameter (ω) was measured based on the $1/e^2$ criterion and found to be 2232 μm . A visual representation of the measured beam profile is shown in **Figure 3.24**. Using the measured beam diameter, the effective beam area (A_{eff}) was calculated according to Equation 3.3 [62], yielding a value of 1.96 mm^2 .

$$A_{eff} = \frac{1}{8} \pi \omega^2 \quad (3.3)$$

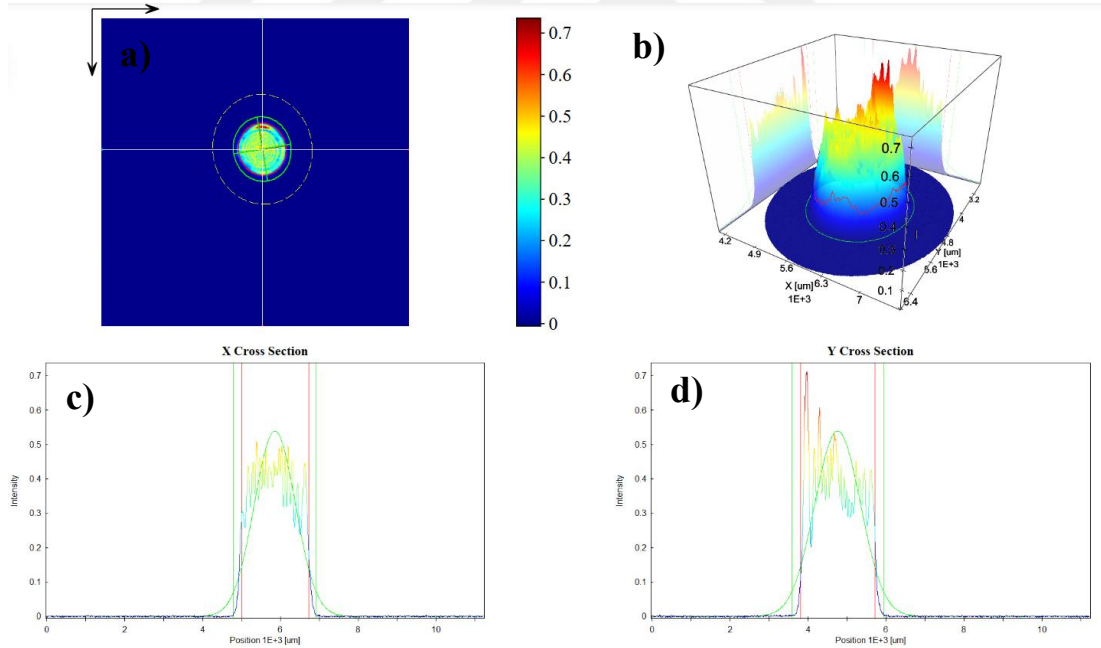


Figure 3.24: Beam diameter measurement of the double-pulse laser at the focal plane. (a) 2D spatial distribution of the intensity, (b) 3D presentation of the intensity, (c) and (d) cross-section of Gaussian profiles at the x- and y – axes.

Based on the calculated effective beam area and the measured pulse energy (E_{pulse}), the fluence (F_{pulse})—defined as the energy per unit area, with the unit of J/cm^2 —was

determined for each measurement point using Equation 3.4. This parameter is critical, as the phosphorescence behavior of phosphor materials depends not only on the total laser energy but also on the local energy density delivered to the surface. Variations in fluence can affect the excitation efficiency and decay characteristics of phosphorescence. Therefore, fluence rather than absolute pulse energy serves as a more accurate and relevant parameter when interpreting luminescence responses in time-resolved thermographic measurements.

$$F_{pulse} = \frac{E_{pulse}}{A_{eff}} \quad (3.4)$$

3.2.2. High-Speed Camera

The high-speed camera (**Figure 3.25**) used to measure the decay time of the thermographic phosphor's luminescence offers a resolution and frame rate ranging from 2560×1600 pixels at 1,400 frames per second to 128×4 pixels at up to 290,000 frames per second. The decay times of most phosphors used for thermographic purposes range from a few microseconds to several hundred microseconds [41]. Since the measurement of phosphor luminescence occurs within such short durations, the system must be fast enough to capture the underlying physical processes. The high-speed camera used in this study provides flexibility to achieve both suitable resolution and operational speed.

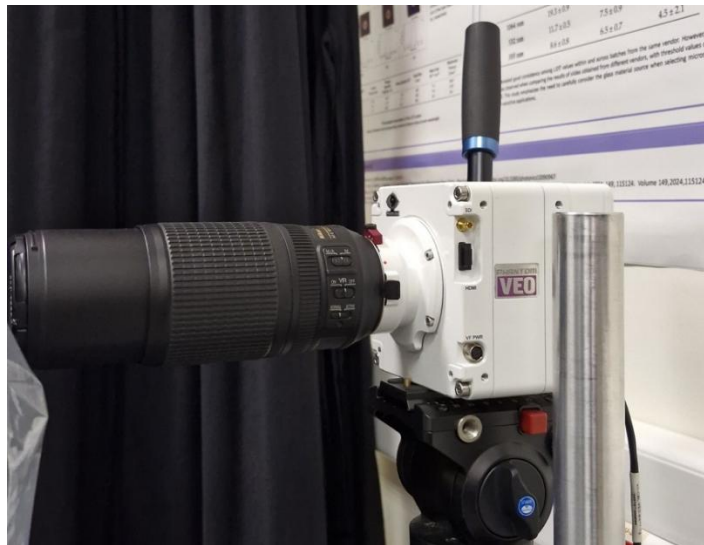


Figure 3.25: An image of the high-speed camera (Phantom, VEO 640S).

3.2.3. Three-Zone Furnace

Within the scope of this thesis, a commercially available furnace with suitable technical specifications was used. Commercially obtained furnaces is an open-ended alumina tube furnace with an inner diameter of 65 mm and a heating length of 650 mm. This three-zone furnace employs indirect heating through wire resistance elements and is capable of operating at temperatures up to 1200 °C.

Thermal uniformity in the central zone of the furnace can be controlled by adjusting the offsets of the side zones. It is equipped with an open-ended alumina tube with a heating length of 600 mm and a fixture at the rear for supplying inert gas.

3.2.3.1. Lateral temperature distributions of furnace

Before the phosphor thermometry measurements, a series of preliminary experiments were carried out to identify the optimum location within furnace where temperature homogeneity was maximized over a length of approximately 100 mm. To achieve this, a dummy cell—fabricated from a high-density graphite cylindrical block (100 mm in length, 30 mm external diameter, and 3 mm internal diameter)—was used in place of the actual sample.

The internal bore of the graphite block served as a guide tube for a type-B thermocouple (without a sealed housing), which was mounted on a motorized linear displacement stage. This setup enabled precise measurement of the temperature profile along the axis of the heating zone.

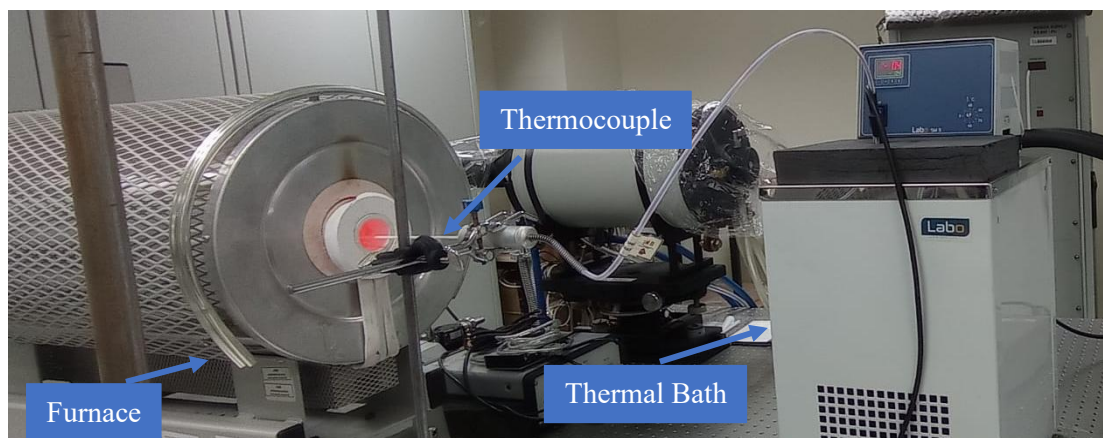


Figure 3.26: Measurement setup for lateral temperature distributions in the furnace.

Once the furnace temperature stabilized at approximately 1154 °C, the thermocouple was scanned along the heating tube, and the resulting temperature profile was recorded (**Figure 3.26**). **Figure 3.27** shows the lateral temperature distributions inside the tube of the furnace in a range of 40 cm centered in the middle of the tube, where the 0 cm distance corresponds to the middle of the central zone of the oven.

The axial temperature gradient within the furnace is a critical factor. The most temperature homogeneous area allows to measure the surface temperature of the phosphor sample and the contact thermometer to be at the same temperature and minimizing the temperature gradient issues. The region exhibiting the highest degree of lateral temperature uniformity was identified and designated as the optimal position for placement of the samples. As can be seen from **Figure 3.27** in the middle part of the tube approximately in a distance of 18 cm the temperature uniformity is better than ± 1 °C, which is sufficient for surface temperature assessments of the phosphor samples.

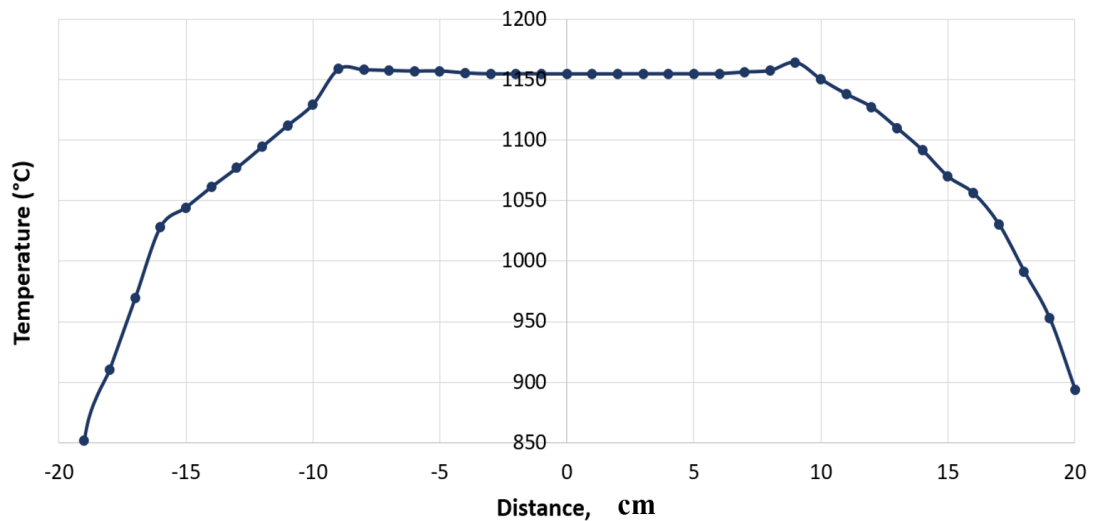


Figure 3.27: Lateral temperature distributions of furnace.

3.2.4. Thermocouples

The Pt/Pd type, used as the reference thermocouple, was fabricated at UME. This thermocouple was constructed using high-purity platinum (99.999%) and palladium (99.997%) wires, both supplied by Johnson Matthey (UK).

Each wire had a diameter of 0.5 mm and a length of 600 mm. The thermoelements were prepared using a standard procedure: after cleaning with ethyl alcohol and distilled water, the wires were electrically annealed in air at approximately 1300 °C for one hour. Following natural cooling to ambient temperature (by switching off the current), the wires were inserted into a 600 mm long twin-bore alumina capillary tube with an outer diameter of 4.5 mm and individual bore diameters of 1.5 mm. This assembly was further protected by a one-end-closed alumina protection tube (7 mm outer diameter, 5 mm inner diameter, 600 mm length). Both tubes were made of high-purity alumina (Al_2O_3 , 99.9%).

The thermocouple junction was formed by directly welding the wires without a coil. The thermoelements extending from the alumina tube were insulated with flexible teflon tubing. For the cold junction, the thermoelements were soldered to copper wires approximately 0.3 mm in diameter.

To eliminate any physical defects introduced during assembly, the thermocouple underwent a two-stage annealing process: first at 1100 °C for about 16 hours, and then at 450 °C for approximately 10 hours.

3.2.5. Phosphor Samples

In this thesis, two distinct sets of phosphor samples were designed, prepared, and utilized for experimental measurements. In the initial phase of the study, $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor—commercially available as EQS25/N-U1 from Phosphor Technology Ltd—was used. This material features a particle size distribution ranging from 4.9 μm to 16.4 μm and was excited using a 355 nm laser source.

In the subsequent phase, $\text{Al}_2\text{O}_3\text{:Cr}$ phosphor, identified as MK24/F-X by the same manufacturer, was employed. The particle size of this phosphor ranged from 2.2 μm to 5.8 μm , and it was excited by a 532 nm double-pulse laser to enable time-resolved thermographic measurements.

In both cases, the phosphor powders were mixed with a high-temperature-resistant binder to ensure adhesion and thermal stability. The resulting suspension was then uniformly applied to the surface of the test specimens using an airbrush technique, enabling consistent coating thickness and surface coverage.

3.2.5.1. $Mg_4FGeO_6:Mn$ Samples

The operating temperature range of the thermographic phosphor used spans a wide interval from 4 K [17], [63] to 1150 K [64], and its luminescence decay time varies between 5×10^{-3} s and 2×10^{-7} s. The emission spectrum of the phosphor, excited by a 385 nm LED light at room temperature, is presented in **Figure 3.28**. The intensity of the LED light reflected from the surface and surroundings of the thermographic phosphor is significantly higher than that of the phosphor luminescence, causing the spectrometer detector to become highly saturated around the excitation wavelength of 385 nm. The luminescence spectrum of the thermographic phosphor exhibits five distinct peaks at 625.15 nm, 631.92 nm, 640.95 nm, 651.85 nm, and 659.21 nm, respectively. Among these, the two most intense peaks at 651.85 nm and 659.21 nm are the most suitable spectral peaks for the calibration and measurements of the thermographic phosphor thermometer.

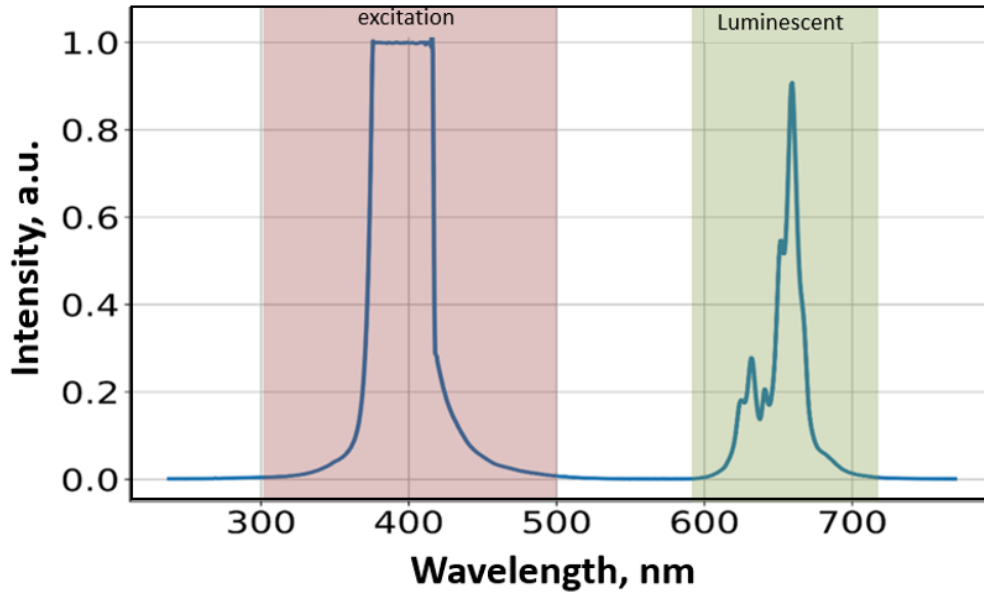


Figure 3.28: The luminescence emission spectrum resulting from the excitation of the $Mg_4FGeO_6:Mn$ thermographic phosphor with 385 nm LED light.

For the thermographic phosphor thermometer, three different calibration and measurement samples (S1, S2, and S3) were prepared using the $Mg_4FGeO_6:Mn$ thermographic phosphor. To enable coating of the samples with the thermographic phosphor, the phosphor in powder form (with a particle size range of 4.9–16.4 μm) was mixed with a water-based binder (ZYP Coating, HPC binder) capable of

withstanding temperatures up to 1500 °C. This mixture was then applied onto the substrates using a spray-coating method with an airbrush (Iwata, Revolution HP-CR). The composition of the thermographic phosphor and high-temperature-resistant binder mixture prepared for each sample is provided in **Table 3.5**.

Table 3.5: The phosphor–binder mixture prepared for the thermographic phosphor thermometer and the coated samples.

Sample	Mass Fraction of Phosphor	Substrate
S1	%10	Grafit
S2	%30	Stainles-Steel
S3	%30	Stainles-Steel

Sample S1, whose photograph and dimensions are presented in **Figure 3.29a**, was fabricated from graphite material. The surface of this sample was coated by spraying, using an airbrush, a mixture containing thermographic phosphor powder at a mass fraction of 10%. Sample S1 was employed exclusively in time-integrated phosphor thermometry methods, specifically the single spectral band peak wavelength shift technique and the dual spectral band intensity ratio technique. Samples S2 and S3, whose photographs and dimensions are shown in **Figure 3.29b**, were manufactured using stainless steel substrates. These samples were coated using the same airbrushing procedure with a mixture containing thermographic phosphor powder at a mass fraction of 30%. While Sample S1 was utilized for time-integrated measurements, namely the peak wavelength shift and two-band intensity ratio techniques, Samples S2 and S3 were employed exclusively in time-resolved measurements based on the luminescence decay time method.

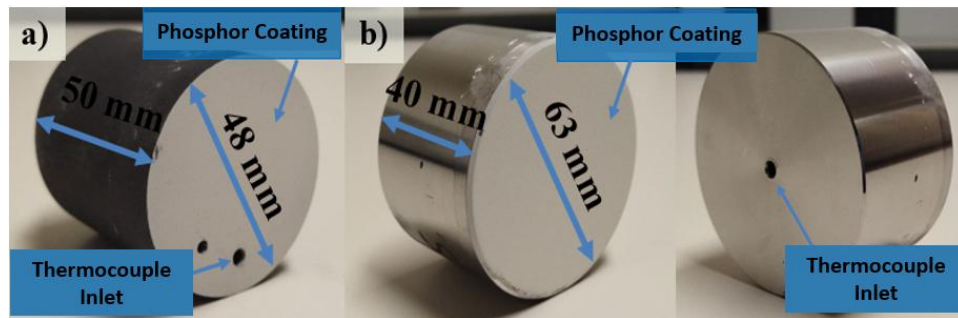


Figure 3.29: Pictures of the prepared measurement blocks: a) grafit block b) stainless steel blocks with a hole for thermocouple insertion and a surface coated with $\text{Mg}_4\text{FGeO}_6\text{:M}$ phosphor paint.

Laser-based experiments conducted with the S1 sample demonstrated that, at the operational frame rates of the high-speed camera, the luminescence emitted by the excited thermographic phosphor was insufficient for reliable detection. To address this limitation, a revised phosphor–binder formulation with a higher phosphor concentration was developed, resulting in the preparation of additional samples (S2 and S3).

Table 3.6: Normalized maximum luminescence intensity of the prepared thermographic phosphor samples.

Sample	Normalized Maximum Luminescence Intensity
S1	1
S2	1.90
S3	2.26

As presented in **Table 3.6** and illustrated in **Figure 3.30**, the normalized luminescence intensities of these revised samples exhibited an over twofold increase compared to the initial formulation. This enhancement in emission intensity significantly improved the detectability of the thermographic phosphor signal by the high-speed camera, enabling accurate decay time measurements under the same experimental conditions.

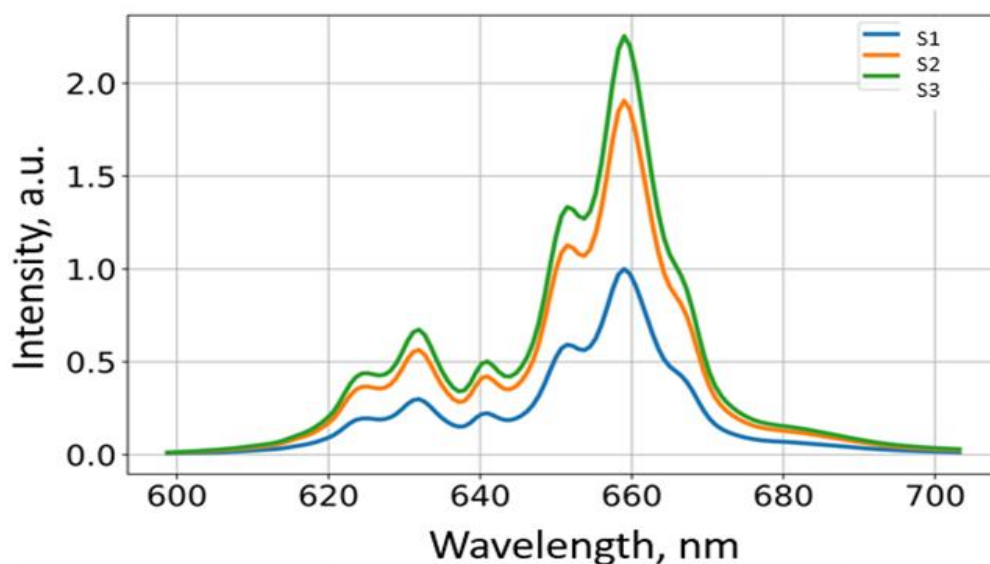


Figure 3.30: Normalized luminescence intensities of samples S1, S2, and S3, showing enhanced emission in S2 and S3 due to the revised phosphor–binder formulation.

3.2.5.2. $\text{Al}_2\text{O}_3\text{:Cr}$ Samples

$\text{Al}_2\text{O}_3\text{:Cr}$ (chromium-doped aluminum oxide), commonly known as ruby phosphor, is a well-established luminescent material valued for its high thermal stability, sharp emission lines, and long luminescence decay times. The characteristic emission peaks around 694.3 nm and 692.9 nm originate from Cr^{3+} ion transitions and are particularly strong under green (532 nm) laser excitation. Due to its excellent thermal and chemical robustness, $\text{Al}_2\text{O}_3\text{:Cr}$ has been extensively used in solid-state laser systems as a gain medium, especially in ruby lasers. Beyond its role in laser amplification, $\text{Al}_2\text{O}_3\text{:Cr}$ has gained significant attention as a thermographic phosphor for non-contact temperature measurements in harsh environments.

As a thermographic phosphor, $\text{Al}_2\text{O}_3\text{:Cr}$ can operate reliably at high temperatures, typically up to $\sim 600^\circ\text{C}$ [65], with decay times that are highly sensitive to temperature variations. Its decay lifetime ranges from several milliseconds at room temperature to below $100\ \mu\text{s}$ at elevated temperatures, making it well-suited for time-resolved phosphor thermometry. The strong, narrowband emission, combined with a monotonic and well-characterized temperature dependence of its decay time, allows for accurate and repeatable temperature measurements even in dynamic thermal environments such as combustion chambers, turbines, or laser-heated surfaces.

The $\text{Al}_2\text{O}_3\text{:Cr}$ phosphor samples were specifically prepared for use in the 532 nm double-pulse laser experimental setup, as this material exhibits significantly stronger phosphorescence than $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor when excited at this wavelength.

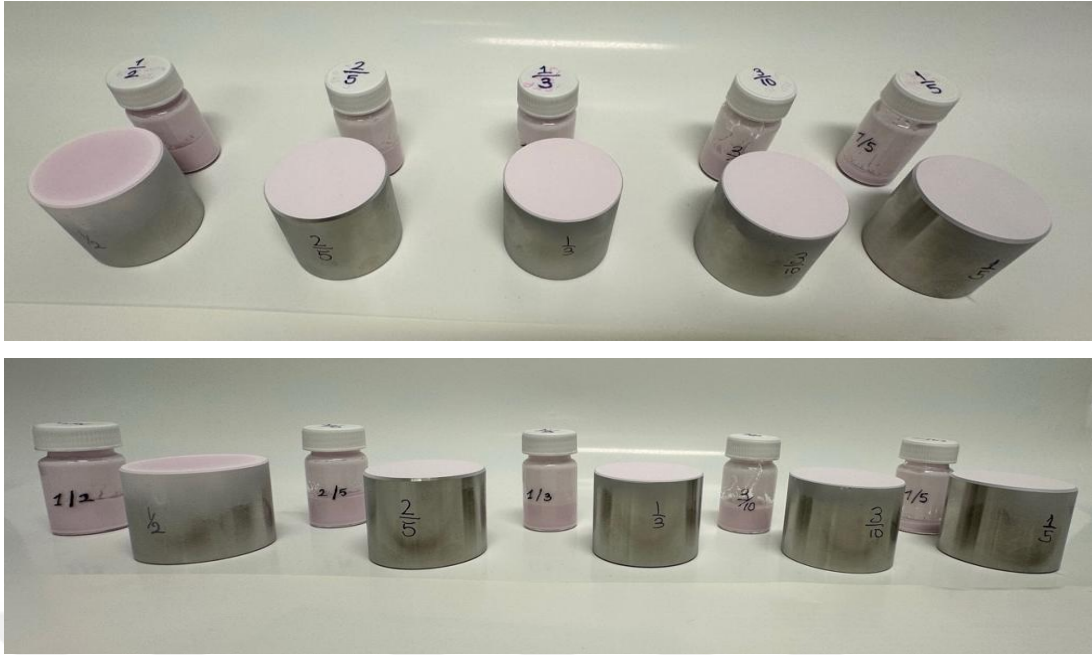


Figure 3.31: Pictures of the prepared measurement blocks: stainless steel blocks with a hole for thermocouple insertion and a surface coated with $Al_2O_3:Cr$ phosphor paint.

To investigate the effect of phosphor composition on the luminescence response at different delay times, five different samples (see **Figure 3.31**) were prepared by varying the binder-to-phosphor ratio. The specific ratios used in each sample are listed in **Table 3.7**. At each measurement point—defined by a specific temperature and delay time—99 double-pulse excitations were applied using the same delay setting, and the resulting luminescence signals were averaged to reduce noise and improve accuracy. Measurements were conducted at temperatures of 25 °C, 150 °C, 300 °C, and 450 °C.

This approach enabled a systematic evaluation of how phosphor concentration affects decay behavior under double-pulse excitation, providing valuable insight for optimizing coating formulations in high-temperature phosphor thermometry.

Table 3.7: Phosphor–binder mixture ratio prepared for the $Al_2O_3:Cr$ thermographic phosphor.

Sample	Mass Fraction of Phosphore	Substrate
S1	%50	Stainles Steel
S2	%40	Stainles Steel
S3	%33	Stainles Steel
S4	%30	Stainles Steel
S5	%20	Stainles Steel

3.2.6. Software and Data Acquisition

In this study, three different software platforms were utilized to control the experimental setup, acquire data, and perform data analysis.

The first software was custom developed in LabVIEW and played a central role in the experimental control system. This program enabled real-time temperature monitoring of the phosphorus samples through a thermocouple, and allowed users to adjust key laser parameters, including the number of pulses for Laser 1 and Laser 2, as well as the delay time between double pulses. The interface provided an integrated control environment for the laser system, optical attenuator, and temperature sensors. A schematic of the LabVIEW control panel is presented in **Figure 3.31**.

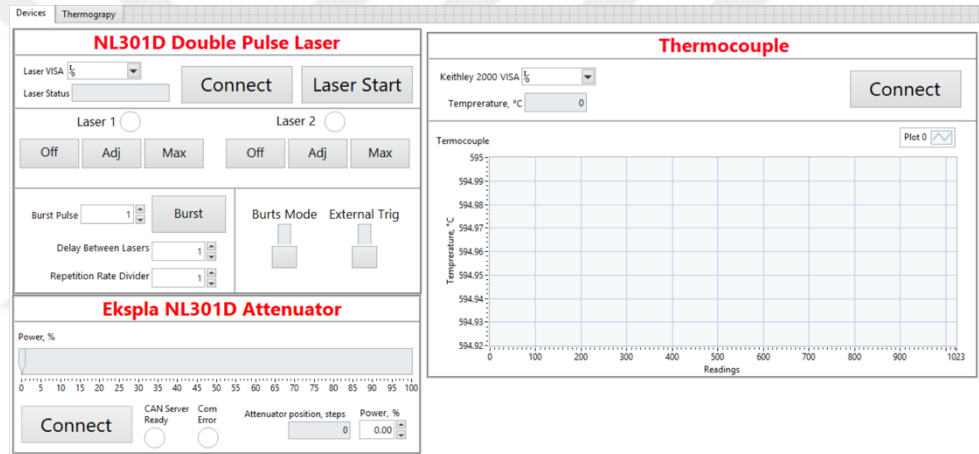


Figure 3.32: The interface of the developed LabVIEW program.

For high-speed imaging, the Phantom Camera Control 3.11 software, provided by the camera manufacturer, was used. This software facilitated the acquisition and basic visualization of the frames captured during the laser-induced events.

Finally, a dedicated Python script was developed to perform the post-processing of the acquired image sequences. This script employs parallel computing techniques to calculate decay times with improved performance, especially when handling large datasets.

Together, these software tools formed an integrated and efficient workflow, enabling precise control, reliable data acquisition, and robust post-experimental analysis.

4. RESULTS

4.1. Measurement Results with the $Mg_4FGeO_6:Mn$ phosphor coated samples

In order to characterize the first phosphor material, $Mg_4FGeO_6:Mn$ in double-pulsed regime, two distinct experimental setups were implemented. In the first measurements the spectroscopic setup was used, in which the phosphor was excited using the UV-LED source, and the emission spectra were recorded over a temperature range from room temperature up to 100 °C. Using this configuration, two analysis approaches were applied: (i) the spectral band shift method, based on the temperature-dependent displacement of a specific emission band, and (ii) the spectral intensity ratio method, utilizing the relative intensities of two distinct emission bands. The second setup was used for time-resolved measurements, in which the phosphor was excited with a 355 nm pulsed laser, and the resulting luminescence decay profiles were recorded using a high-speed camera. In this configuration, measurements were carried out over a temperature range from room temperature up to 400 °C, enabling precise determination of decay times as a function of temperature. Together, these complementary measurement approaches provided a comprehensive basis for evaluating the temperature-dependent luminescent properties of the phosphor, as detailed in the following subsections.

4.1.1. Spectroscopic Measurement Results of the $Mg_4FGeO_6:Mn$ Coated Samples

In thermographic phosphor thermometry based on the peak wavelength shift within a single spectral band, the emission bands with peak wavelengths of 651.85 nm and 659.21 nm at room temperature were selected. Because the temperature-induced peak wavelength shift occurs very gradually and remains below the spectral resolution of the spectrometer, the raw data required post-processing to extract accurate peak positions. To address this limitation, interpolation techniques were applied to refine the spectral profiles, enabling a more precise determination of the peak wavelengths. In this study, cubic spline interpolation was employed, which fits a third-degree polynomial to each interval between successive data points while ensuring continuity of both the first and second derivatives at the junctions. This piecewise-defined yet

continuous function provides a smooth representation of the entire dataset. **Figure 4.1** presents the spectroscopic measurement of the thermographic phosphor luminescence after cubic spline interpolation. As shown, the method significantly improves the accuracy of determining both the peak wavelength and the maximum intensity of the spectral band.

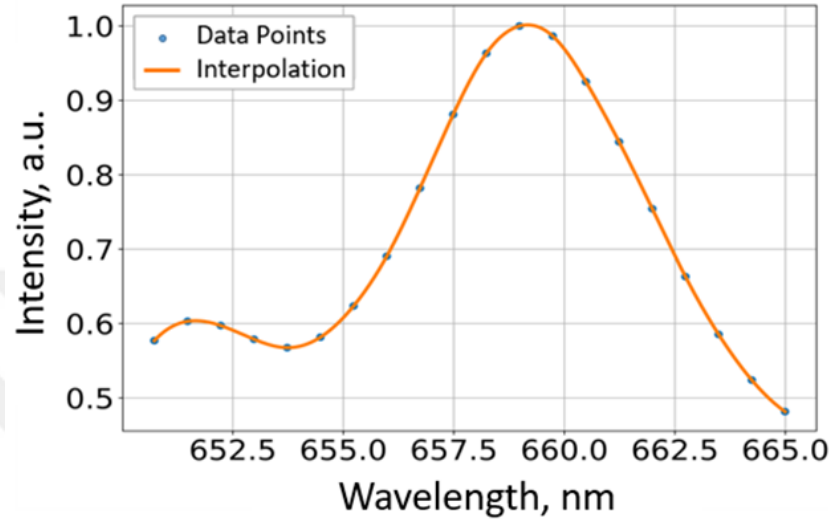


Figure 4.1: Application of cubic-spline interpolation fit to the spectral data obtained from the measurement of the thermographic phosphor's luminescence using the spectrometer.

In the measurement setup employing both the single spectral band peak wavelength shift method and the dual-band intensity ratio method, measurements were performed over a temperature range from room temperature to 100 °C. A three-zone furnace was set to 100 °C, and during the heating phase, spectral data were recorded every 15 seconds using a spectrometer with an integration time of 12 seconds. Once the thermographic phosphor under characterization reached thermal equilibrium at 100 °C, the furnace was allowed to cool naturally to room temperature, while measurements were continuously acquired under the same spectrometer settings.

The spectroscopic characterization and time-integrated measurements of the thermographic phosphor $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ were conducted using an experimental setup designed for single-band peak wavelength shift analysis. In this configuration, the phosphor was excited with a 385 nm LED light source, and its emission bands at 659 nm and 631 nm were selected for single-band peak wavelength shift measurements and characterization.

The characterization data and fitted curve obtained from the peak wavelength shift measurements at the 659 nm band are illustrated in **Figure 4.2**. Measurements were performed over a temperature range from room temperature to 100 °C. For each temperature point, multiple spectral measurements were recorded, and the corresponding peak wavelength values were averaged to obtain a representative measurement for that temperature. The standard deviation calculated from these repeated measurements is shown in the figure as error bars. Across the investigated range, the peak wavelength of the examined luminescence band exhibited a total shift of 0.9 nm between 21 °C and 100 °C. The observed standard deviation corresponds to an uncertainty of approximately ± 2 °C, indicating that the single-band peak wavelength shift method provides a moderate level of temperature measurement precision.

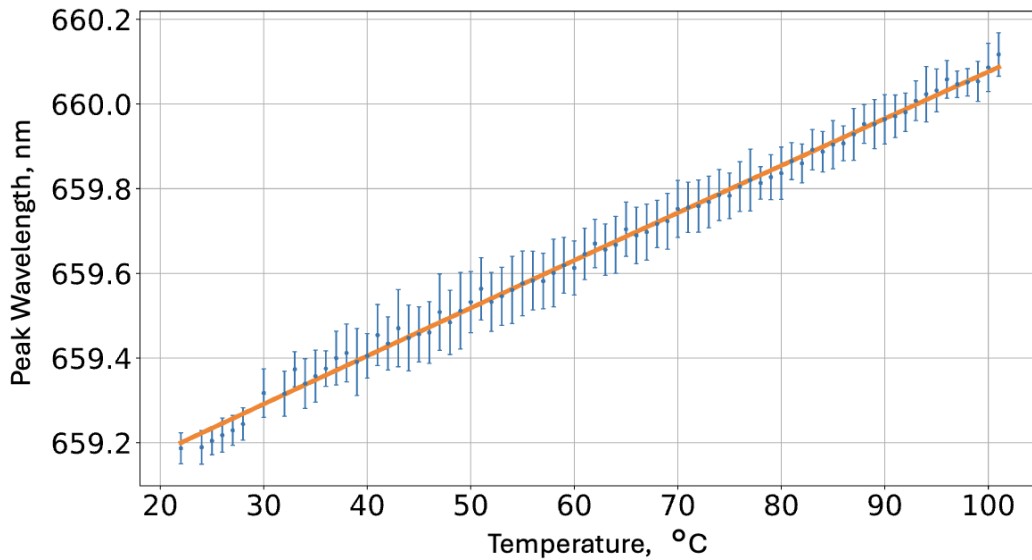


Figure 4.2: Characterization curve of the 659 nm band peak wavelength-shift of *Mg₄FGeO₆:Mn* thermographic phosphor.

The characterization data and fitted curve obtained from the peak wavelength shift measurements at the 631 nm band of the *Mg₄FGeO₆:Mn* thermographic phosphor are illustrated in **Figure 4.3**. Measurements were conducted over the temperature range from room temperature to 100 °C. Similar to the 659 nm band, multiple spectral measurements were taken at each temperature point, and the peak wavelength values were averaged. The peak wavelength exhibited a total shift of 0.9 nm between 21 °C and 100 °C. However, the temperature measurement accuracy based on this band was

lower, with an estimated uncertainty of approximately ± 5 °C. This reduced accuracy may be attributed to the lower emission intensity of the 631 nm band, which likely introduced increased noise into the spectral measurements, thus affecting the precision of the peak wavelength determination.

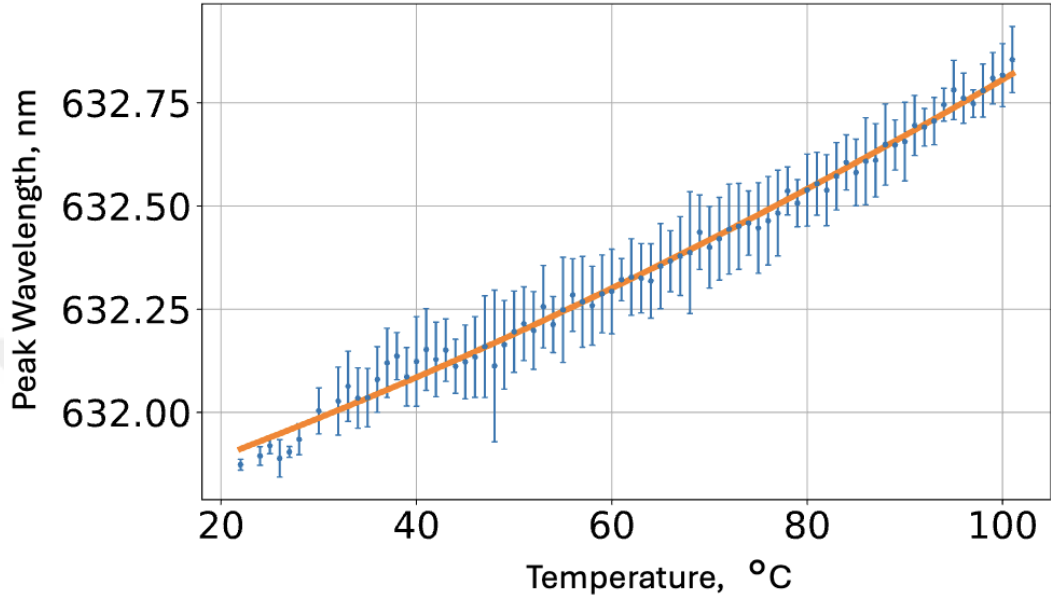


Figure 4.3: Characterization curve of the 631 nm band peak-wavelength shift of $Mg_4FGeO_6:Mn$ thermographic phosphor.

The characterization data and fitted curve obtained from dual-band intensity ratio measurements performed using the spectral thermographic phosphor thermometer setup are presented in **Figure 4.4**. These measurements were conducted over a temperature range from room temperature to 100 °C, utilizing the intensity ratio of the luminescence emission bands at 659 nm and 631 nm. The intensity ratio was found to change at a rate of approximately $9.4 \times 10^{-3} K^{-1}$, indicating a strong temperature dependence. Based on these results, the dual-band intensity ratio method achieved a temperature measurement accuracy of approximately ± 3 °C, demonstrating improved precision compared to the single-band peak wavelength shift methods.

However, this method is limited to phosphors that exhibit emission in at least two distinct spectral bands, such as $Mg_4FGeO_6:Mn$ phosphor. Furthermore, it requires the use of two sensors operating at different wavelengths or a spectrometer capable of resolving both emission bands. Despite these limitations, the dual-band intensity ratio method offers superior accuracy because it relies on the relative intensity changes

between two bands rather than small wavelength shifts within a single band, which are often close to the resolution limits of the spectrometer and more susceptible to noise and instrumental variations.

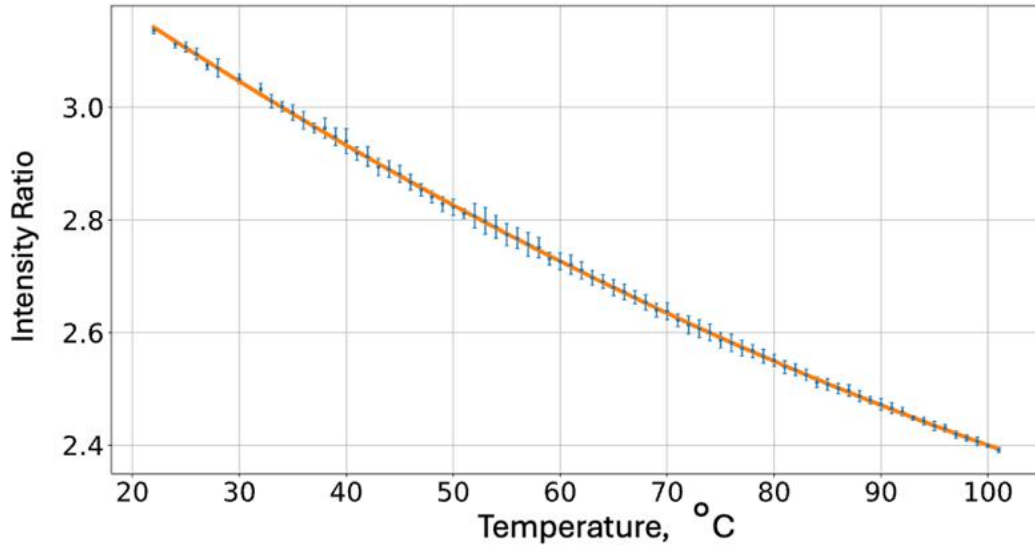


Figure 4.4: Characterization data and curve of the intensity ratios of the luminescence emission bands at 659 nm and 631 nm of $Mg_4FGeO_6:Mn$ thermographic phosphor.

The spectroscopic characterization of the $Mg_4FGeO_6:Mn$ thermographic phosphor revealed distinct temperature-dependent luminescence behaviors across the examined emission bands and measurement methods. The single-band peak wavelength shift method applied to the 659 nm and 631 nm bands showed total wavelength shifts of approximately 0.9 nm over the temperature range from room temperature to 100 °C, resulting in temperature measurement accuracies of ± 2 °C and ± 5 °C, respectively. The lower accuracy observed in the 631 nm band was attributed to its comparatively weaker emission intensity, which introduced greater noise and uncertainty. In contrast, the dual-band intensity ratio method, which utilized the relative intensities of these two bands, demonstrated enhanced temperature sensitivity with a change rate of approximately $9.4 \times 10^{-3} K^{-1}$ and achieved improved measurement accuracy of ± 3 °C. Although this method necessitates more complex instrumentation and phosphors with multiple emission bands, its robustness against spectral noise and instrumental limitations makes it a promising approach for precise thermographic phosphor thermometry. These results collectively provide a comprehensive understanding of the trade-offs between different spectroscopic methods, guiding the

selection of appropriate techniques based on accuracy requirements and experimental constraints.

4.1.2. Decay Time Measurement Results of the $Mg_4FGeO_6:Mn$ Coated Samples

The time-resolved measurement of luminescence decay plays a crucial role in thermographic phosphor thermometry, providing important insights into the temperature-dependent behavior of phosphor materials. By analyzing the decay time of luminescence following pulsed excitation, this method offers an effective approach for temperature sensing that can be used alongside traditional spectroscopic techniques. In this study, the decay time characteristics of the thermographic phosphor $Mg_4FGeO_6:Mn$ were investigated using a high-speed imaging system capable of capturing rapid luminescence dynamics over a wide temperature range.

Figure 4.5 illustrates the moment when the luminescence of the phosphor reaches its maximum intensity, captured by a high-speed camera within the decay time measurement setup. A stainless-steel specimen coated with the phosphor was positioned 60 cm away from the camera, which operated at a resolution of 64×128 pixels, a frame rate of 40,000 frames per second, and an integration time of 23 μs .

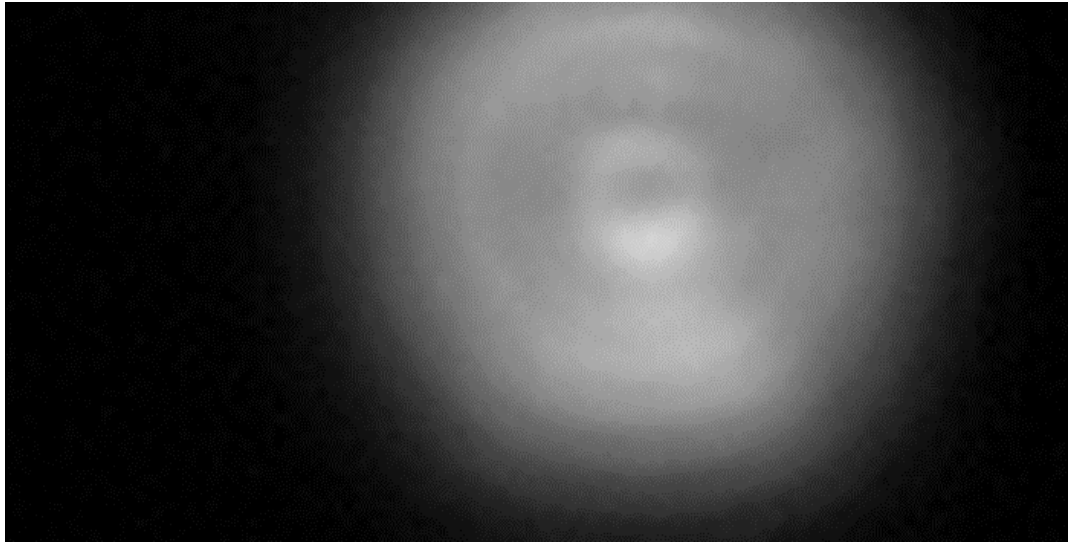


Figure 4.5: High-speed camera image capturing the thermographic phosphor at its peak luminescence.

Measurements were performed from room temperature up to 400 °C using a three-zone furnace. The phosphor was excited with 355 nm pulses from an Nd:YAG laser, delivering approximately 50 mJ per pulse with a beam diameter of 10 mm ($1/e^2$). During heating, five laser pulses were emitted every 12 seconds at 250 ms intervals, and the resulting luminescence was recorded using a high-speed camera. The corresponding luminescence decay curves, together with time-resolved images at various post-excitation intervals, are shown in **Figure 4.6**. The complete measurement cycle lasted about five hours, during which temperature and luminescence data were collected approximately 1500 times using contact thermometers and the imaging system, respectively.

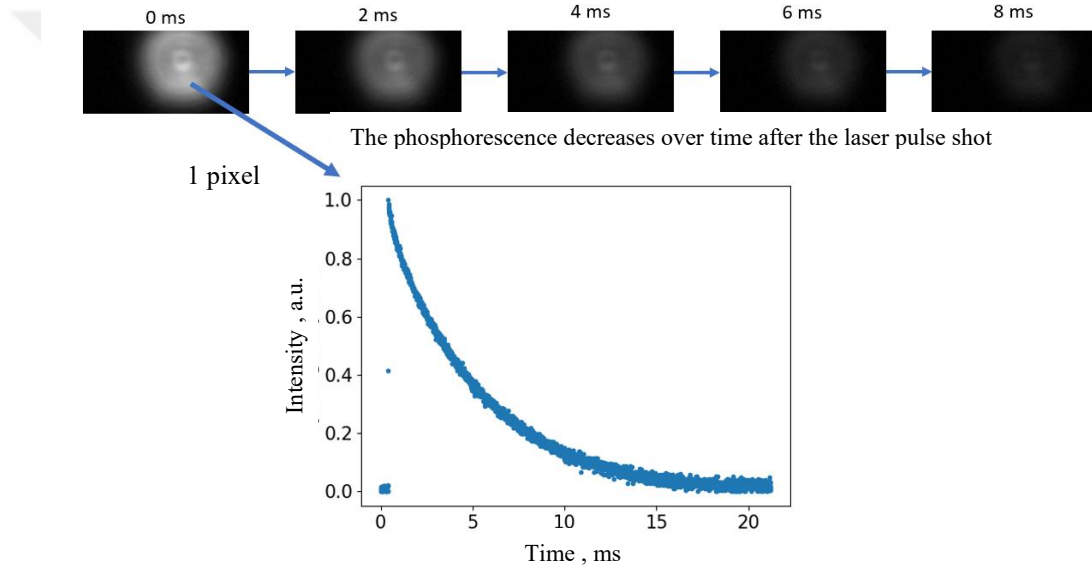


Figure 4.6: Observation of the luminescence decay of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained with the high-speed camera.

During the single measurement, approximately 214 GB of raw image data were generated. To enable the calculation of decay times for each of the 8192 pixels following every laser pulse, a custom software tool was developed using the Python programming language. In order to efficiently process the large volume of data obtained from the measurements, the decay time calculation software was implemented using parallel programming techniques. By leveraging these techniques, the computation of decay times for each laser pulse and each pixel was accelerated by a factor of about five.

Background radiation originating from sources other than the thermographic phosphor luminescence can interfere with accurate decay time measurements. To address this issue, the average background signal obtained from 50 images obtained (acquired prior to each laser pulse with the high-speed camera) and was subtracted from all subsequent luminescence data for every pixel. This preprocessing step effectively eliminates unwanted background contributions that may otherwise distort the luminescence decay profile. Following background correction, the luminescence decay curve was analyzed to identify regions exhibiting single-exponential decay behavior, which is fundamental for accurate determination of decay times. This was achieved by taking the natural logarithm of the decay data, transforming the exponential decay into a linear form. The transformation enables straightforward linear fitting and facilitates the extraction of decay constants. Consequently, Equation 4.1 can be expressed in the time-dependent linear form presented in Equation 4.2, providing a robust mathematical framework for analyzing the decay dynamics of the thermographic phosphor luminescence. As illustrated in **Figure 4.7b**, these linear regions correspond to the single-exponential decay processes described by Equation 4.2.

$$n_f = n_0 e^{-t/\tau_d} \quad (4.1)$$

$$\ln(n_f) = -\frac{1}{\tau_d} t + \ln(n_0) \quad (4.2)$$

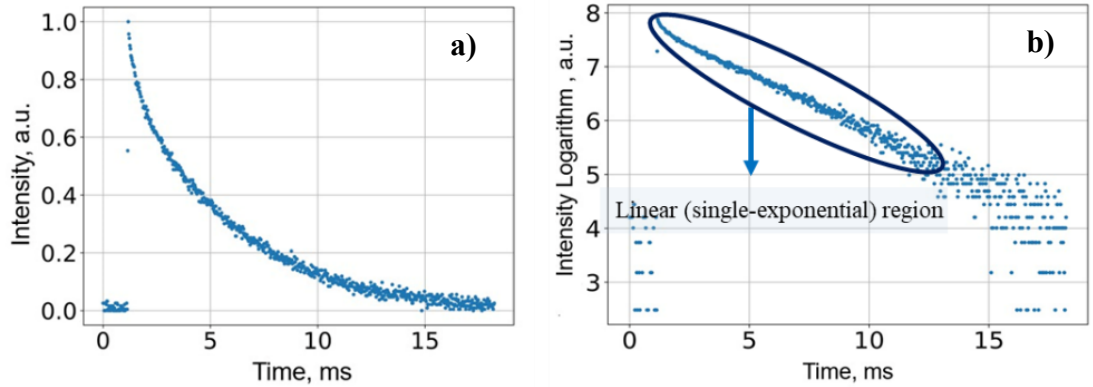


Figure 4.7: (a) An example of the Decay Time plot of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained with a high-speed camera, and (b) the decay graph obtained by taking the natural logarithm of the original graph.

To calculate the decay time from the natural logarithm of the high-speed camera data, the ‘iterative linear fit algorithm’ illustrated in **Figure 4.8** is employed [66]. This

algorithm is specifically designed to identify the region within the log-transformed luminescence decay data that exhibits the highest degree of linearity, which is critical for achieving an accurate and reliable estimation of the decay time. The process begins with an initial estimate of the decay time, denoted as τ_0 , calculated using Equation 4.3. In this equation, c_0 represents a manually selected coefficient that defines the portion of the decay curve to be considered, while Δt corresponds to the duration of the observation window over which the data is analyzed. Based on extensive preliminary tests conducted during the decay time measurements, the coefficient c_0 was empirically determined to be 0.3, as this value consistently yielded optimal fitting results. By iteratively adjusting the fitting window and evaluating linearity, the algorithm refines the decay time estimate, ensuring robust and precise characterization of the phosphor's luminescence decay behavior:

$$\tau_0 = c_0 \Delta t \quad (4.3)$$

Subsequently, the times t_1 and t_2 defining the linear data window for fitting are calculated using Equation 4.4. Here, t_0 denotes the time at which the thermographic phosphor's luminescence reaches its maximum, c_1 and c_2 are manually selected coefficients, and τ_{i-1} represents the decay time obtained from the previous iteration. Based on experimental trials conducted during decay time measurements, the coefficients c_1 and c_2 were determined to be 0.5 and 3.5, respectively.

$$\begin{aligned} t_1 &= c_1 \tau_{i-1} + t_0 \\ t_2 &= c_2 \tau_{i-1} + t_0 \end{aligned} \quad (4.4)$$

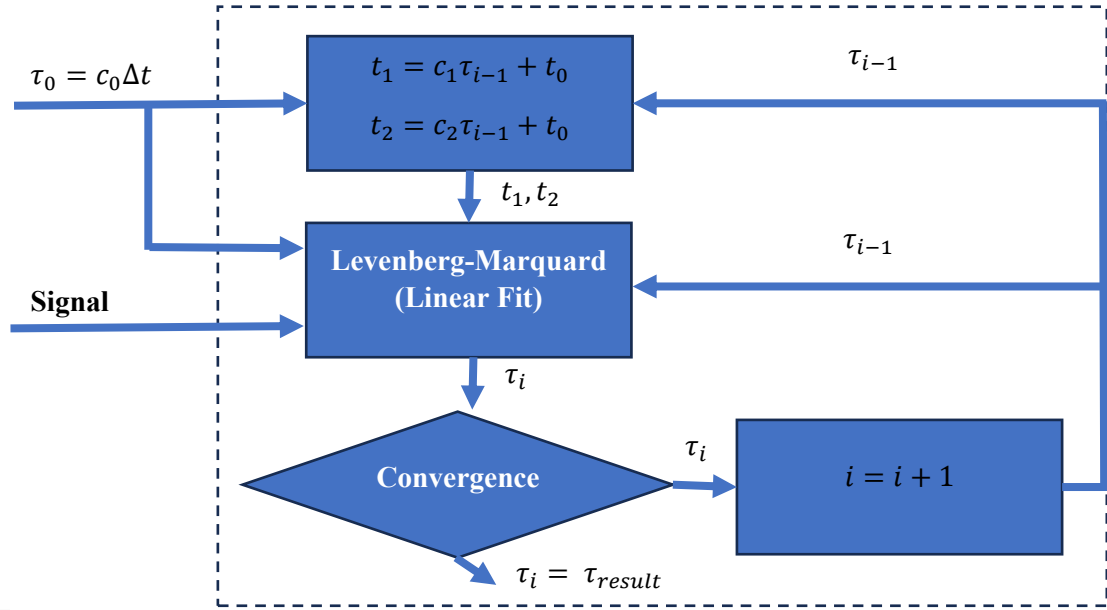


Figure 4.8: Iterative linear fit algorithm used for calculating the decay time.

After computing the times t_1 and t_2 that define the linear data window, a linear fit is applied to the data within this window using the Levenberg-Marquardt algorithm, yielding an updated decay time τ_i . The iterative decay time estimation algorithm terminates once the convergence condition specified in Equation 4.5 is satisfied. This condition requires that the difference between the maximum and minimum of the last three computed decay times be less than 0.005 times their average value. In this way, the iterative algorithm converges toward a stable decay time estimate.

$$\max(\tau_i, \tau_{i-1}, \tau_{i-2}) - \min(\tau_i, \tau_{i-1}, \tau_{i-2}) < 5 \cdot 10^{-3} \times \left[\frac{1}{3} (\tau_i, \tau_{i-1}, \tau_{i-2}) \right] \quad (4.5)$$

The convergence of the iterative decay time algorithm toward a stable value at each step of the calculation is illustrated in **Table 4.1** and **Figure 4.9**.

Table 4.1: The convergence of the decay time values at each iteration of the iterative decay algorithm.

	τ_0	τ_1	τ_2	τ_3	τ_4
Time (ms)	6.382	3.414	3.672	3.656	3.659

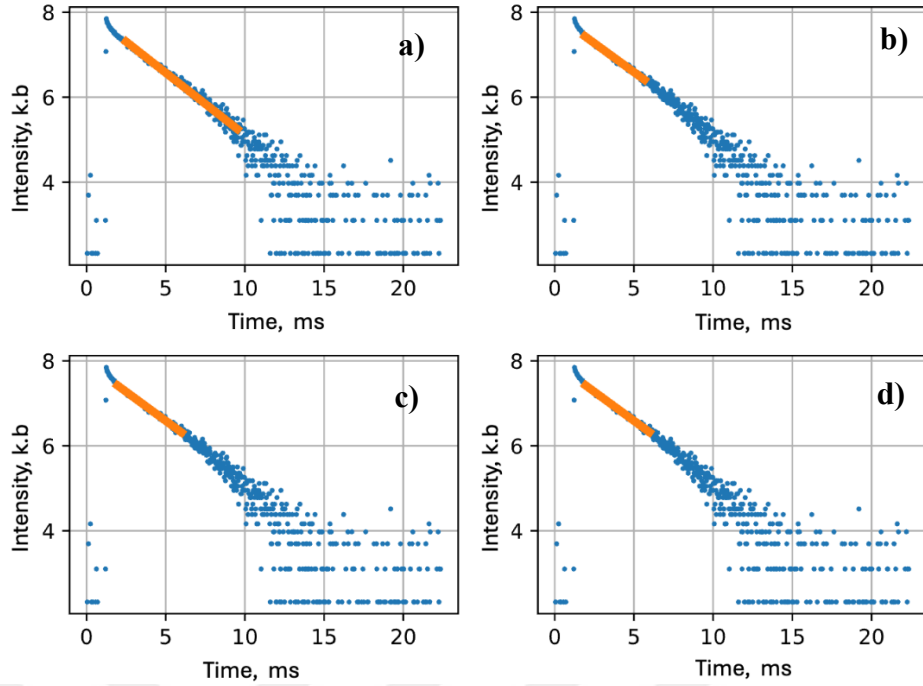


Figure 4.9: Convergence of the iterative decay time calculation algorithm to a value by selecting an appropriate fitting window at each iteration (for τ_1 , τ_2 , τ_3 and τ_4 in **Table 4.1**, respectively).

The experimental configuration utilized the thermographic phosphor $\text{Mg}_2\text{FGeO}_6\text{:Mn}$ to implement phosphor thermometry based on luminescence decay time measurements. Two-dimensional surface images of the phosphor, acquired using a high-speed camera, were processed through an iterative fitting algorithm to determine the decay times at each pixel. The resulting characterization curve, derived from these decay time values, is presented in **Figure 4.10**. Measurements were performed over a temperature range extending from ambient conditions to 400 °C, yielding a decay time temperature sensitivity of approximately 8.67 $\mu\text{s/K}$. Based on this characterization, the achievable temperature measurement accuracy was estimated to be ± 2 °C. Further enhancement of this accuracy could be attained by improving the spatial uniformity of the laser pulse energy incident on the phosphor surface and by ensuring a consistent coating thickness across the entire measurement area.

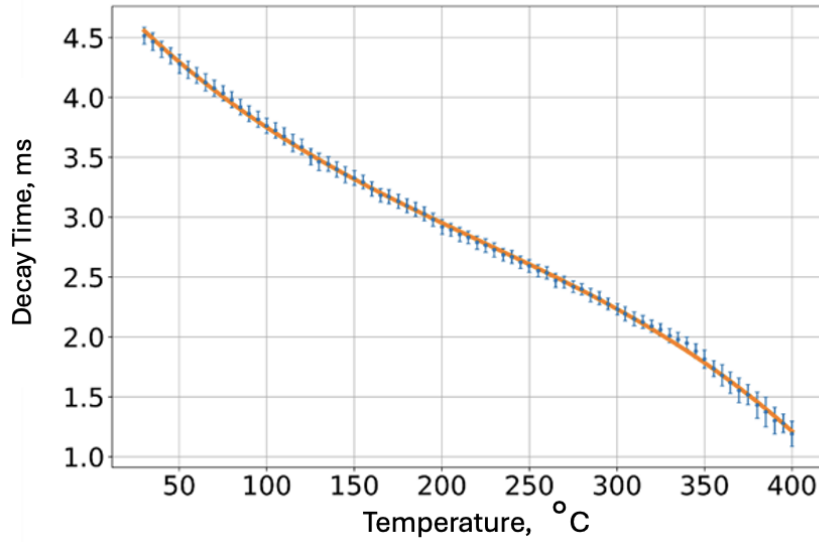


Figure 4.10: Characterization data and curve of the decay time of $Mg_4FGeO_6:Mn$ thermographic phosphor obtained using a high-speed camera.

In summary, the comprehensive investigation of the luminescence decay behavior of $Mg_4FGeO_6:Mn$ phosphor using time-resolved imaging techniques has demonstrated its significant potential for precise temperature measurement across a broad temperature range. The developed iterative algorithm and data processing methods effectively addressed challenges such as background radiation and data volume, enabling robust decay time extraction at the pixel level. While the achieved temperature sensitivity and measurement accuracy are promising, further refinements—particularly in laser pulse uniformity and coating homogeneity—offer clear pathways to enhance the reliability and precision of phosphor-based thermometry. This study thus lays a solid foundation for the continued advancement and practical application of thermographic phosphor techniques in high-resolution temperature sensing.

4.2. The Measurement Results of the $Al_2O_3:Cr$ Coated Samples

The temperature-dependent emission behavior of $Al_2O_3:Cr$ was investigated using the luminescence decay time method. Excitation was provided by the Nd:YAG double-pulse laser operating at 532 nm, enabling precise control over the temporal separation between consecutive laser pulses. The phosphor exhibits two closely spaced fluorescence emission bands at 694.3 nm and 692.9 nm, both of which contribute to

the measured decay signal. To capture the rapid luminescence dynamics, the high-speed camera was positioned approximately 150 cm from the specimen and operated at a frame rate of 120,000 frames per second with a spatial resolution of 64×128 pixels.

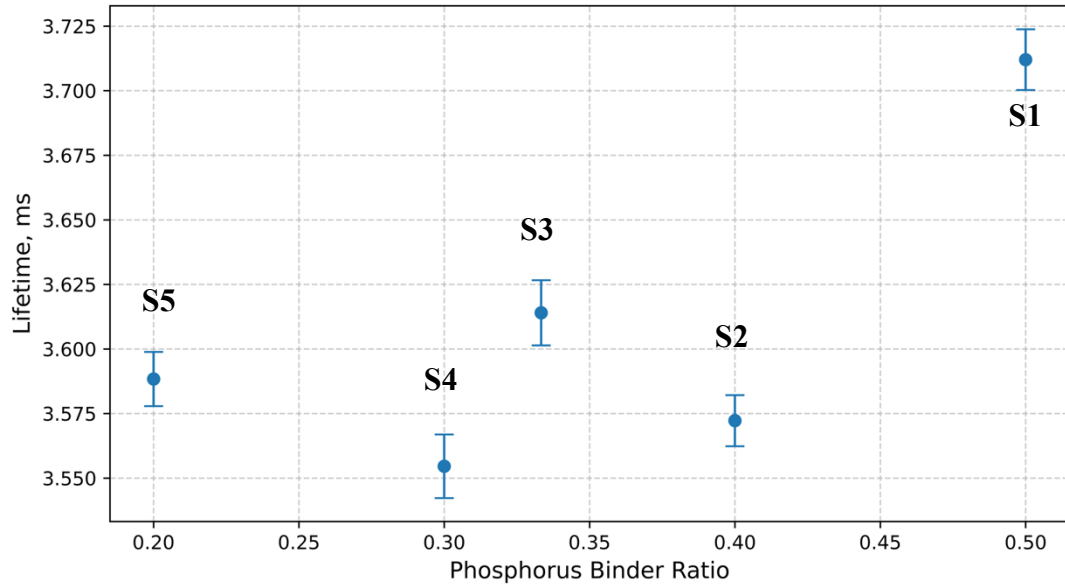


Figure 4.11: Decay times of samples S1, S2, S3, S4, and S5 using 99 double pulses of the L1 laser.

Measurements were conducted over a temperature range from room temperature up to 450 °C, allowing for the characterization of the phosphor's thermal response across a broad operating temperature range. In addition to determining the characteristic decay time versus the temperature, the influence of the inter-delay between the double-pulses of the laser on the phosphorescence characteristics was systematically examined. This approach enabled the assessment of both the temperature dependence and excitation dynamics of $\text{Al}_2\text{O}_3\text{:Cr}$, providing valuable insights into its suitability for high-temperature phosphor thermometry applications.

Figure 4.11 presents the measured decay times of samples S1 through S5, each prepared with different phosphor-to-binder ratios, after excitations with 99 double-pulses of the L1 laser. The results indicate that the decay time exhibits a slight but discernible dependence on the binder ratio. While samples with intermediate binder ratios (0.30–0.40) display relatively similar decay times in the range of approximately 3.55–3.60 ms, the highest binder ratio (0.50) results in a markedly longer decay time

of about 3.71 ms. Conversely, the lowest ratio (0.20) produces a decay time comparable to the mid-range values, suggesting that changes in binder ratio do not lead to a strictly monotonic variation in lifetime. The observed variations may be attributed to differences in the microstructure and packing density of the phosphor particles within the binder matrix, which can influence the efficiency of luminescence quenching processes.

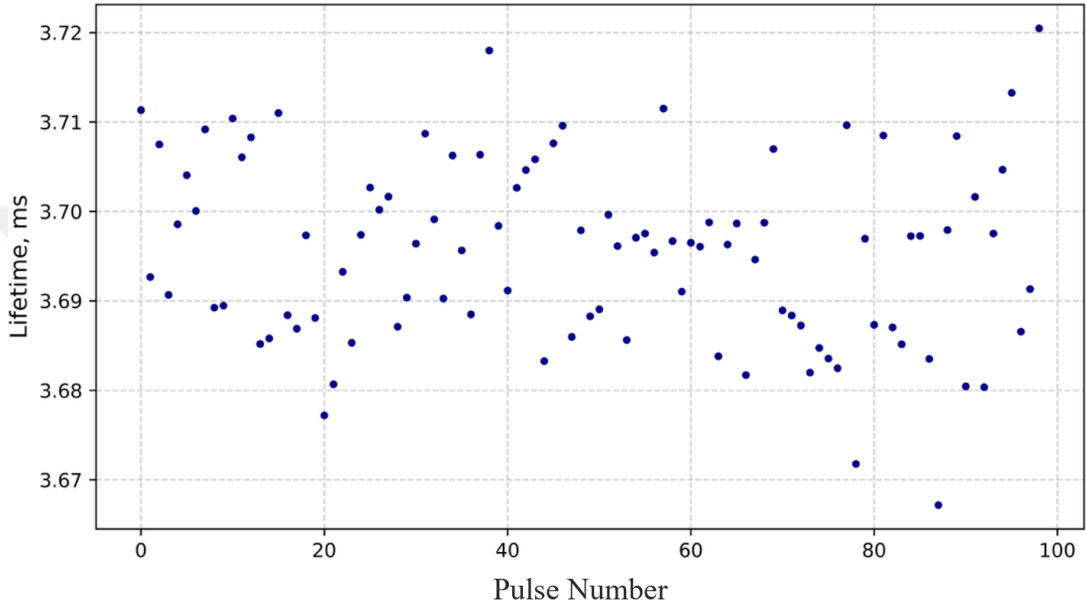


Figure 4.12: The decay time stability obtained with 99 separate laser pulses (L1 on the S1 sample, which contains 50% phosphorus-to binder ratio by a mass).

The S1 sample, comprising 50% phosphor material by mass, was subjected to a sequence of 99 excitation pulses generated by the L1 laser, with each pulse delivered at a fixed interval of 50 ms. For every individual pulse, the corresponding luminescence decay time was determined, and the resulting distribution is presented in **Figure 4.12**. All measurements were performed under ambient laboratory conditions (room temperature of 23 ± 0.5 °C) to minimize external thermal influences. Throughout the sequence of excitations, no systematic increase or decrease in the measured decay times was observed, indicating temporal stability in the luminescent response. This invariance suggests that, within the applied excitation regime, the laser pulses did not induce any appreciable thermal accumulation or degradation effects on the phosphor surface. Consequently, the experimental conditions can be considered

non-perturbative with respect to the thermal state of the sample, thereby ensuring the reliability of the decay time measurements.

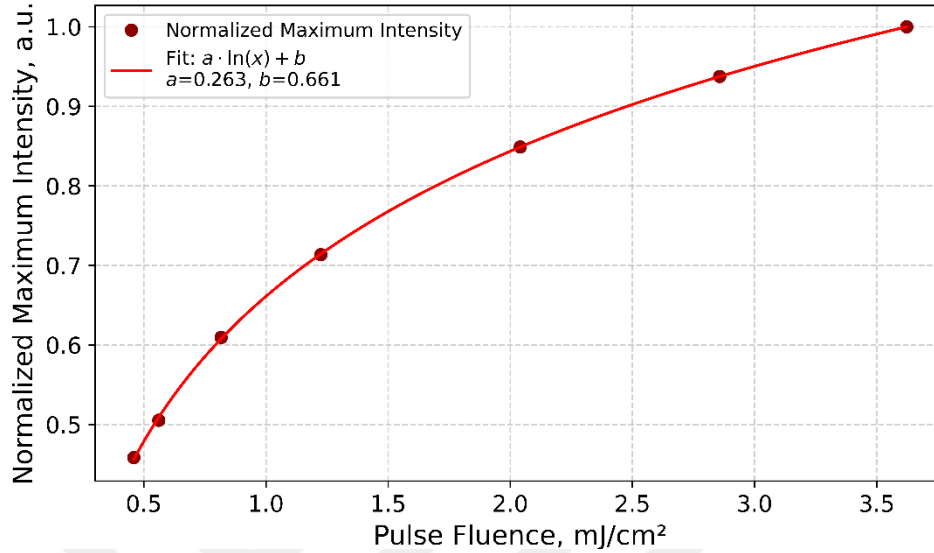


Figure 4.13: Normalized maximum intensity obtained from the S1 sample as a function of fluence of Laser 1.

The S1 material was subjected to 99 laser pulses from Laser 1 at varying output fluence levels, and the maximum intensity on the phosphorescence images corresponding to each fluence level was evaluated. The resulting graph, presented in **Figure 4.13**, illustrates the normalized maximum intensity as a function of the laser energy. The data reveal that the maximum intensity follows a logarithmic increasing trend with respect to the rising fluence levels.

Figure 4.14 illustrates the decay time behavior of the phosphor emission in the S1 sample as a function of laser excitation fluence. For each fluence level, the decay time values were calculated by averaging the emission responses over 99 identical L1 laser pulses to improve signal reliability and reduce statistical noise. The results show a clear logarithmic increase in decay time with rising excitation fluence, consistent with the trend previously observed in **Figure 4.13**.

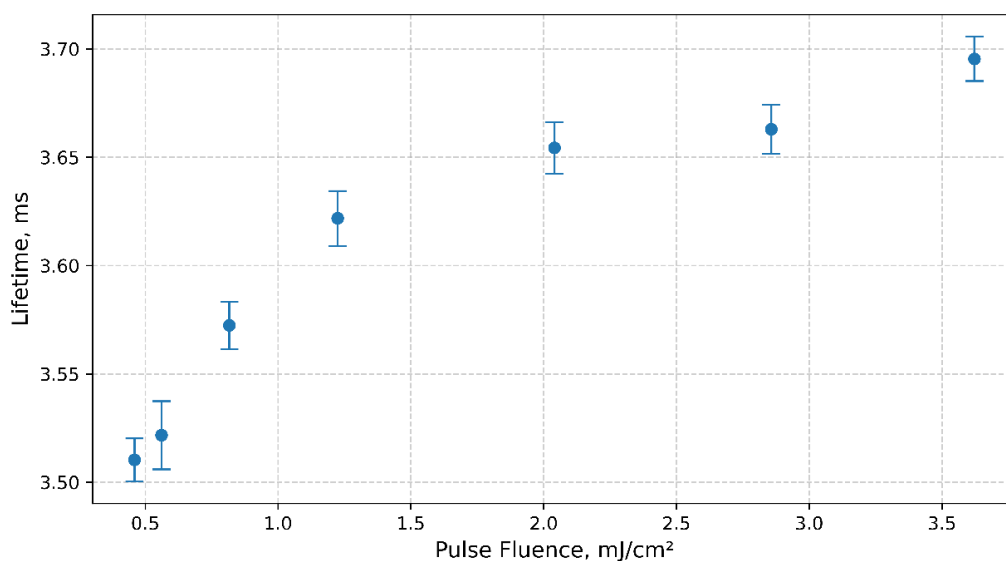


Figure 4.14: Decay time obtained from the S1 sample as a function of fluence of Laser 1.

This logarithmic behavior suggests that as the excitation fluence increases, the recombination dynamics of the excited states become progressively slower, possibly due to enhanced population of long-lived trap states of the material. These findings may have important implications for the optimization of excitation parameters in practical applications involving phosphor materials, particularly where controlled decay times are desirable.

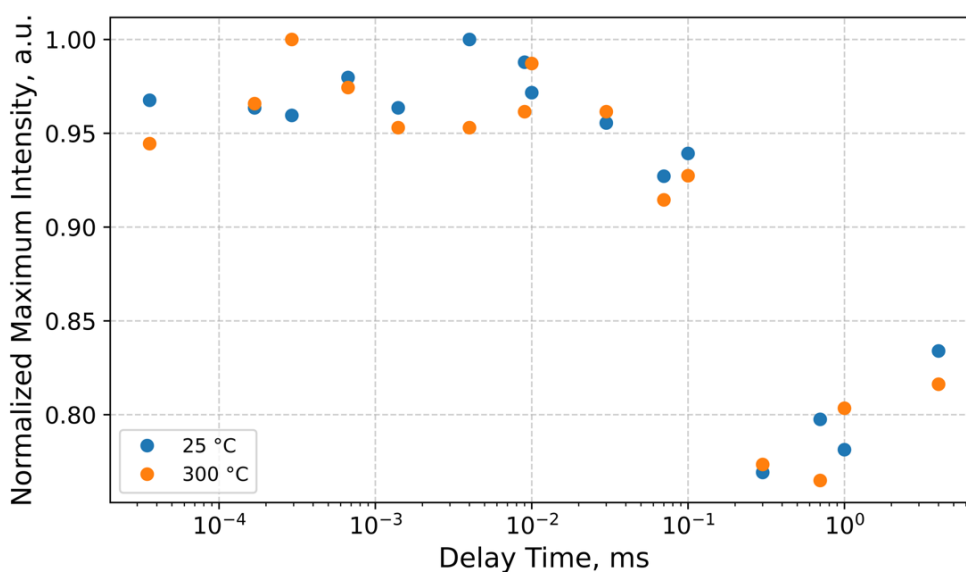


Figure 4.15: Normalized maximum intensity of the S1 sample as a function of varying interdelay times between pulse pairs of each double-pulses.

A total of 99 double laser pulses were applied to the S1 sample under two different furnace temperature conditions, namely 25 °C (room temperature) and 300 °C, in order to investigate the influence of pulse delay time on the luminescent response of the phosphorus-based material. The double-pulses consisted of sequential emissions from the L1 and L2 lasers, where the interdelay interval between each pulse of the double-pulse was systematically varied across a range of values from 40 ns up to 30 ms.

The results of this investigation are summarized in **Figure 4.15**, which illustrates the variation in normalized maximum emission intensity of the sample as a function of the delay time between the two laser pulses. As the delay interval was reduced below 100 μ s, a distinct enhancement in the emission response was observed. This is the main finding of this work, specifically, demonstrating that below 0.01 ms, the decreasing the interdelay between each pulse in a double-pulsed laser increases the efficiency of the phosphor material by a factor up to 25%.

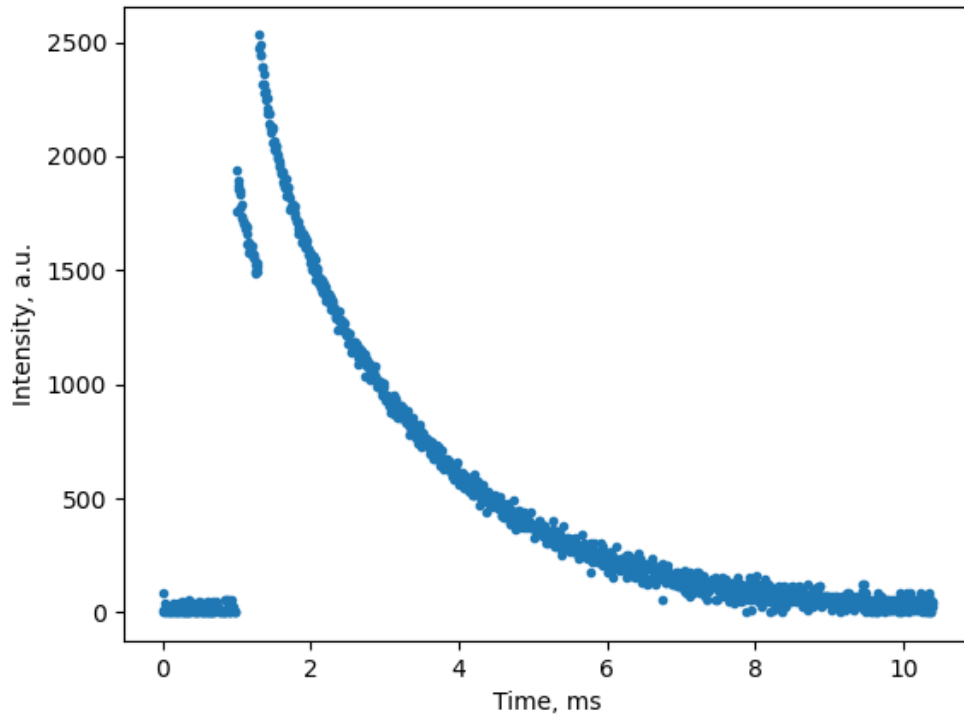


Figure 4.16: Time-resolved luminescence decay of a single pixel under double-pulse excitation with an interdelay between pulse of 100 μ s in each double pulsed shot.

Figure 4.16 illustrates the time-resolved luminescence intensity decay of a single pixel on the S1 sample under double-pulse excitation with a delay interval of 100 μ s. The

plot clearly demonstrates an enhanced maximum intensity in the second pulse, reaching an increase of approximately 25% compared to the first pulse. This enhancement confirms the transient excitation effect, where the residual excited states or thermal conditions induced by the first pulse facilitate a more efficient luminescence response upon the arrival of the second pulse. Such behavior underscores the importance of optimizing pulse delay timing to maximize emission efficiency in phosphor-based thermometry applications.

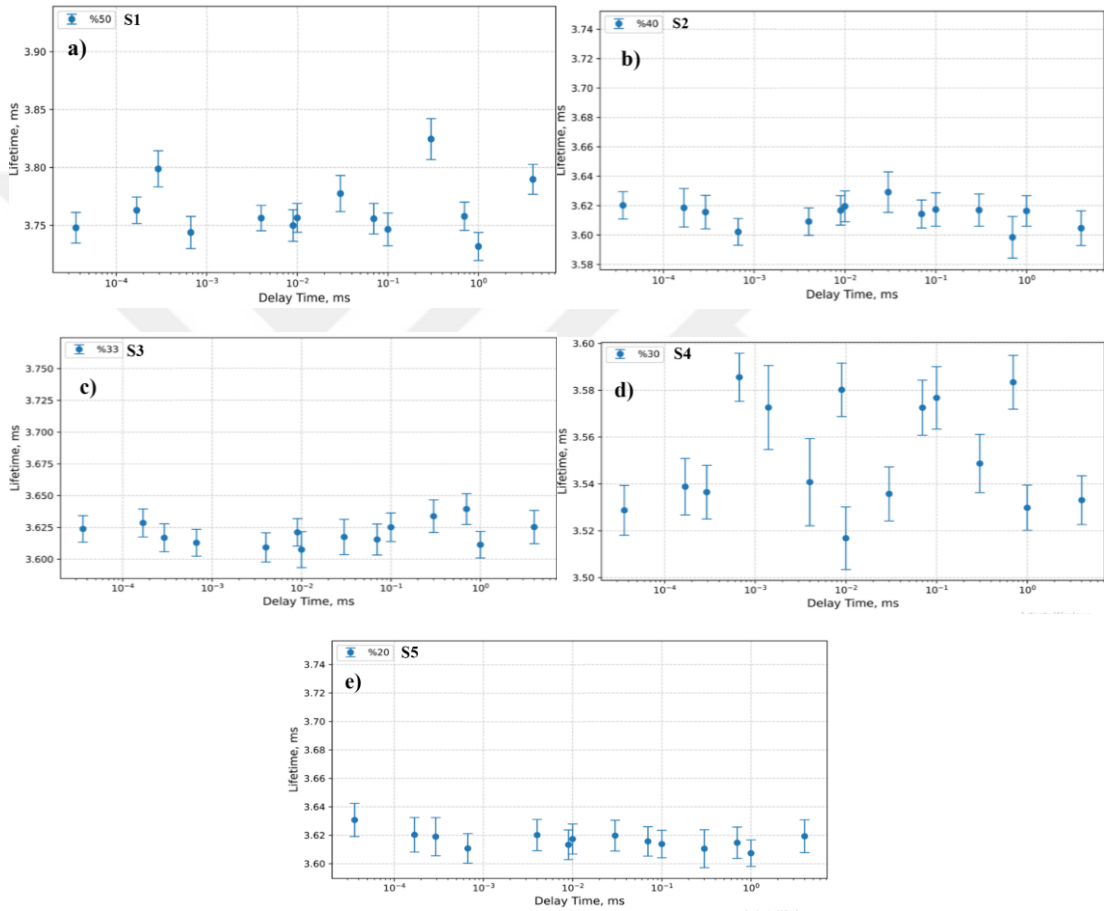


Figure 4.17: Variation in the decay times of the a) S1, b) S2, c) S3, d) S4, and e) S5 samples as a function of the delay time between laser pulses.

This behavior suggests that the energy delivery from the first pulse (L1) may create a transient excited state or thermal condition that enhances the absorption or luminescence efficiency of the second pulse (L2), provided the time gap is sufficiently short. At delay times longer than 100 μ s, this effect appears to diminish, possibly due to relaxation or dissipation mechanisms within the material.

Figures 4.17a, 4.17b, 4.17c, 4.17d, and 4.17e, respectively, illustrate the variation in decay times of the S1, S2, S3, S4, and S5 samples as a function of the interdelay time between each double-laser pulses. It was observed that the decay times of the samples, which contain different phosphorus concentrations by mass, did not significantly change with varying delay times between the laser pulses.

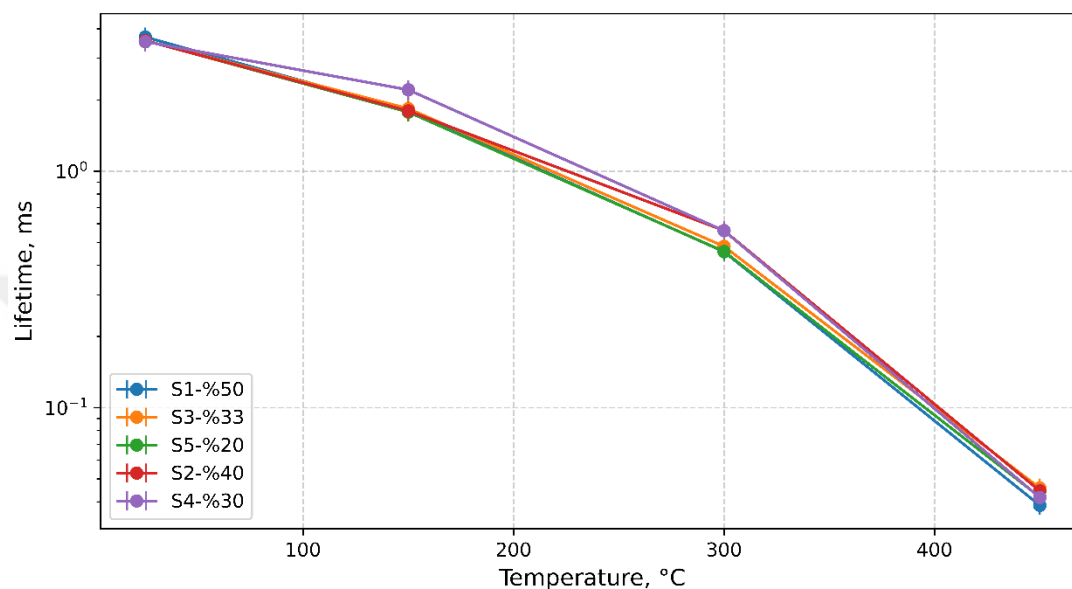


Figure 4.18: Variation in the decay times of the S1, S2, S3, S4, and S5 samples as a function of the temperature.

Figure 4.18 shows the phosphorescence lifetime behavior of five different phosphor samples with varying binder ratios (S1–S5) as a function of temperature. All samples exhibit a clear decrease in lifetime with increasing temperature, which is consistent with thermally activated non-radiative decay processes that dominate at higher temperatures. At lower temperatures (~25 °C to 150 °C), the lifetimes differ slightly depending on the binder concentration, with sample S4 (%30 binder) showing slightly longer lifetimes compared to others. This may suggest that an optimal binder ratio can slightly enhance thermal stability of the phosphorescent emission. However, as the temperature increases to 300 °C and 450 °C, all samples converge to similar low lifetime values below 0.1 ms, indicating that the thermal quenching effect dominates regardless of the binder content. Overall, the results suggest that while binder ratio has a minor influence on phosphorescence lifetime at lower temperatures, its effect becomes negligible under high thermal stress.

In summary, the comprehensive set of measurements conducted on $\text{Al}_2\text{O}_3\text{:Cr}$ phosphors have elucidated the interplay between binder ratio, excitation conditions, and operating temperature in determining the material's luminescence decay characteristics. The results consistently demonstrate that, under controlled ambient conditions, the decay time remains temporally stable even after repeated excitations, indicating negligible thermal or structural degradation within the studied excitation regime. Variations in binder ratio were found to influence the decay time to a limited extent, likely through modifications in particle packing density and microstructural configuration, although no strict monotonic trend was observed. The excitation fluence-dependent measurements revealed a logarithmic increase in both maximum emission intensity and decay time, suggesting the involvement of long-lived trap states whose population grows with higher excitation energies. Furthermore, the double-pulse excitation experiments highlighted a short-delay enhancement effect, where the second pulse benefits from transient excitation induced by the first, leading to an increase in maximum intensity by up to approximately 25% for delay intervals shorter than $\sim 100\text{ }\mu\text{s}$. This enhancement effect vanishes for longer delays. Finally, temperature-dependent lifetime measurements confirmed the strong influence of thermally activated non-radiative processes at elevated temperatures, which dominate over any binder-related effects. Collectively, these findings provide a robust framework for optimizing excitation parameters and material composition for high-speed, high-temperature phosphor thermometry applications.

4.3. Uncertainty

A rigorous evaluation of measurement uncertainty is essential for establishing the reliability of phosphor thermometry. In this work, the uncertainty budget was calculated for $\text{Al}_2\text{O}_3\text{:Cr}$ (ruby) phosphor at $300\text{ }^\circ\text{C}$, using the lifetime decay method. The analysis follows a similar approach to recent studies in which phosphor thermometry has been validated against SI-traceable standards and applied in industrial and nuclear environments [67-68].

The total uncertainty is composed of several independent contributions, summarized in **Table 4.2**. Each contribution is associated with a probability distribution and, where relevant, a sensitivity coefficient for propagation of uncertainty from the measured parameter (e.g. decay time) to the derived temperature.

- Thermocouple uncertainty (0.250 °C): This term reflects the calibration certificate uncertainty of the type-J thermocouple used during calibration and validation of the phosphor. Since the thermocouple provides the temperature reference, its traceability directly limits the accuracy of the phosphor thermometer. Please, note that the uncertainty provided here also includes the uncertainty component that originated from the thermal conductivity of the phosphor and binder thin film as well.
- Exponential fit (0.462 °C): When extracting lifetimes from decay curves, a single-exponential function is fitted to the measured signal. The residuals of this fit provide a measure of the fitting error, which is propagated into the temperature domain through the sensitivity coefficient (0.212 °C/μs).
- Repeatability of the lifetime (0.254 °C): This contribution quantifies the variability of lifetime measurements performed under identical conditions but at different times. It accounts for short-term fluctuations in the excitation source, detector noise, and environmental stability.
- Calibration residuals (0.432 °C): Once a calibration curve relating lifetime to temperature is established, the residuals of the fitted curve relative to the reference data introduce an additional source of error. This term reflects the degree to which the polynomial or exponential model captures the true lifetime-temperature dependence of Al₂O₃:Cr.
- Spatial repeatability (0.644 °C): In practice, the homogeneity of the phosphor coating and the spatial distribution of excitation fluence can lead to pixel-to-pixel variations in measured lifetime. This contribution was estimated using high-speed camera data, where lifetimes were extracted on a per-pixel basis across the coated area.

Table 4.2: Uncertainty budget for phosphor thermometry at 300 °C.

Uncertainty Component	Standard Uncertainty	Probability Distribution	Sensitivity Coefficient	Uncertainty
Thermocouple uncertainty	0.250 °C	Normal	1	0.250 °C
Exponential fit	2.18 μs	Normal	0.212 °C/ μs	0.462 °C
Repeatability of the lifetime	1.20 μs	Normal	0.212 °C/ μs	0.254 °C
Calibration residuals	2.04 μs	Normal	0.212 °C/ μs	0.432 °C
Spatial repeatability (fluence variability, coating inhomogeneity)	3.04 μs	Normal	0.212 °C/ μs	0.644 °C
Standard Uncertainty (k=1)				0.97 °C
Expanded Uncertainty (k=2)				1.94 °C

All contributions are assumed to be uncorrelated and normally distributed. Therefore, the combined standard uncertainty ($k = 1$) is obtained by taking the square root of the sum of the squared components, yielding 0.97 °C. To provide a 95 % confidence interval, the expanded uncertainty ($k = 2$) is reported as 1.94 °C.

These values are consistent with published studies, where expanded uncertainties below 2 °C have been demonstrated for phosphor thermometry over a wide temperature range [67]. The relatively balanced contribution of fit, calibration, and spatial repeatability terms confirms that both instrumentation and coating methodology play a decisive role in uncertainty performance. In future applications, improvements in coating homogeneity and signal-to-noise ratio are expected to further reduce the combined uncertainty.

5. CONCLUSION

This thesis presents an extensive and methodologically rigorous investigation into the principles, implementation, and validation of thermographic phosphor thermometry, employing both spectral and time-resolved measurement techniques. The research focused on the thermometric performance of two phosphor materials— $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ and $\text{Al}_2\text{O}_3\text{:Cr}$ —under a wide range of experimental conditions. In addition, the influence of double-pulse laser excitation on the decay time characteristics of the phosphors was systematically examined to assess transient excitation effects and their implications for measurement accuracy. The primary aim was to evaluate the precision, sensitivity, and operational robustness of these materials for high-resolution, non-contact temperature sensing.

The study addressed key challenges in phosphor thermometry, including spectrometer resolution limitations in detecting gradual peak wavelength shifts, the need for scalable data processing algorithms for large datasets, and the influence of material composition on luminescent response under varying thermal and excitation conditions. A multimodal experimental framework was developed, integrating spectrometric analysis, high-speed imaging, controlled furnace heating, pulsed laser excitation, and custom computational algorithms for data interpolation and decay analysis. This holistic approach enabled a thorough exploration of each thermometric strategy's strengths, limitations, and practical applicability across diverse environments.

In the spectral domain, single-band peak wavelength shift thermometry was implemented using luminescence bands at 659 nm and 631 nm of the $\text{Mg}_4\text{FGeO}_6\text{:Mn}$ phosphor. Due to the sub-resolution nature of the thermally induced wavelength shifts (less than 1 nm over the 21 °C to 100 °C range), a cubic spline interpolation algorithm was applied to estimate peak positions with improved accuracy. This technique reliably identified spectral peaks beyond the hardware limits of the spectrometer. Temperature accuracies of $\pm 2^\circ\text{C}$ and $\pm 3^\circ\text{C}$ were achieved for the 659 nm and 631 nm bands, respectively. Furthermore, the dual-band method, based on the intensity ratio between these bands, provided significantly improved accuracy of $\pm 1^\circ\text{C}$, while offering enhanced resistance to noise and signal instability—making it especially suitable for practical applications.

The time-resolved component of the research expanded the usable temperature range of the thermographic phosphor thermometry system to 400 °C. A high-speed imaging setup was implemented, featuring a 355 nm Nd:YAG pulsed laser and a camera operating at 40,000 frames per second with 64×128 pixel resolution. The resulting datasets (over 214 GB) were processed using a custom Python-based software tool leveraging parallel computation to efficiently calculate decay times across 8,192 pixels per frame. An iterative linear fitting algorithm was applied to identify regions of high linearity in logarithmically transformed decay curves, yielding robust and accurate decay lifetime estimates resilient to noise and background fluctuations. The resulting thermal maps achieved a spatial accuracy of ± 2 °C, enabling detailed two-dimensional temperature profiling suitable for surface diagnostics.

For the $\text{Al}_2\text{O}_3\text{:Cr}$ phosphor under 532 nm double-pulse laser excitation, the results demonstrated a subtle dependence of decay time on the phosphor-to-binder ratio, with the highest ratio producing the longest lifetimes. These variations are likely linked to microstructural differences affecting luminescence quenching efficiency. Additionally, the excitation energy exhibited a logarithmic relationship with both decay time and intensity, suggesting saturation-like behavior and greater occupation of long-lived trap states at higher excitation levels.

Decay measurements under repeated pulsing showed consistent emission profiles, confirming minimal photodegradation. Moreover, laser energy-dependent measurements (**Figures 4.13** and **Figures 4.14**) reinforced the observed logarithmic trend in both decay dynamics and emission strength.

When a variable delay was introduced between dual laser pulses, decay times remained largely unchanged. However, a 25% increase in emission intensity was consistently observed when the inter-pulse delay was under 100 μs . This intensity enhancement, independent of phosphorus concentration, points to excitation timing—rather than material composition—as the primary driver. The likely mechanism involves transient excited-state population or thermal conditioning from the first pulse, which boosts radiative efficiency during the second. These findings have practical implications for real-time diagnostics in pulsed thermal systems, where inter-pulse delay can be used as a control parameter to optimize signal strength and signal-to-noise ratios.

Temperature-dependent lifetime measurements confirmed the expected trend of thermal quenching, with luminescence lifetimes decreasing as temperature increased. While minor differences in decay stability were observed at lower temperatures—most notably in sample S4—these differences disappeared above 300 °C, where non-radiative decay dominated. This demonstrates that binder composition can fine-tune performance at moderate temperatures, but its influence is negligible under high thermal stress, underscoring the importance of intrinsic material stability for high-temperature applications.

Altogether, the results validate thermographic phosphor thermometry as a reliable, high-precision, non-contact technique for thermal measurements in challenging environments. Spectral methods offered strong performance in steady-state conditions, while time-resolved analysis enabled dynamic, spatially resolved thermal mapping with high temporal resolution. The development and integration of customized computational tools—such as spline interpolation, iterative decay fitting, and parallel data processing—addressed key analytical and processing requirements in thermographic phosphor thermometry research.

Beyond laboratory applications, the broader implications of this work are substantial. The methods and findings have clear potential for use in industrial process monitoring, turbine blade inspection, combustion diagnostics, thermal control in aerospace systems, and microelectronics cooling. Moreover, the insights gained into phosphor behavior under varying excitation energies, pulse sequences, and material formulations will inform the design of next-generation thermal sensors—particularly in scenarios requiring minimal physical contact, fast response times, and robustness to harsh environments.

In conclusion, this thesis has successfully demonstrated a comprehensive experimental and computational approach to thermographic phosphor thermometry, with a primary focus on elucidating the effects of double-pulse laser excitation on luminescence dynamics. By integrating spectral and temporal techniques, optimising data analysis algorithms, and investigating material-specific responses, it provides both a fundamental understanding and a practical framework for advancing the field. The methodologies and insights presented here aim to contribute to ongoing research efforts in high-performance, non-invasive thermal diagnostics within both academic and industrial contexts.

REFERENCES

- [1] Machin G., (2018), “The kelvin redefined”, *Measurement Science and Technology*, 29 (2), 022001. DOI: 10.1088/1361-6501/aa9ddb
- [2] Nicholas J. V., White, D. R., (1994), “Traceable temperatures: An introduction to temperature measurement and calibration”, 1st Edition, *Measurement Science and Technology*, Wiley.
- [3] Childs P. R., Greenwood J. R., Long, C. A., (2000), “Review of temperature measurement”, *Review of Scientific Instruments*, 71 (8), 2959-2978. DOI: 10.1063/1.1305516
- [4] Preston-Thomas H., (1990). “The International Temperature Scale of 1990(ITS-90)”, *Metrologia*, 27 (1), 3-10.
- [5] BIPM, (2019), “The International System of Units (SI)”, 9th Edition, Bureau International des Poids et Mesures.
- [6] Dedyulin S., Ahmed Z., Machin G., (2022), “Emerging technologies in the field of thermometry”, *Measurement Science and Technology*, 33 (9), 092001. DOI: 10.1088/1361-6501/ac75b1
- [7] Moldover M. R., Gavioso R. M., Mehl J. B., Pitre L., de Podesta M., Zhang J. T., (2014), “Acoustic gas thermometry”, *Metrologia*, 51 (1), R1. DOI: 10.1088/0026-1394/51/1/R1
- [8] White D. R., Galleano R., Actis A., Brixy H., De Groot M., Dubbeldam J., Reesink A. L., Edler F., Sakurai H., Shepard R. L., Gallop, J. C., (1996), “The status of Johnson noise thermometry”, *Metrologia*, 33 (4), 325. DOI: 10.1088/0026-1394/33/4/6
- [9] Rourke P. M., Gaiser C., Gao B., Ripa D. M., Moldover M. R., Pitre L., Underwood R. J., (2019), “Refractive-index gas thermometry”, *Metrologia*, 56 (3), 032001. DOI: 10.1088/1681-7575/ab0dbe
- [10] Gianfrani L., (2016), “Linking the thermodynamic temperature to an optical frequency: recent advances in Doppler broadening thermometry”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374 (2064), 20150047. DOI: 10.1098/rsta.2015.0047
- [11] Rubio J., Anders J., Correa L. A., (2021), “Global quantum thermometry”, *Physical Review Letters*, 127 (19), 190402. DOI: 10.1103/PhysRevLett.127.190402
- [12] Lou J., Finegan T. M., Mohsen P., Hatton T. A., Laibinis P. E., (1999), “Fluorescence-based thermometry: principles and applications”, *Reviews in Analytical Chemistry*, 18 (4), 235-284.

- [13] Khalid A. H., Kontis, K., (2008), “Thermographic phosphors for high temperature measurements: principles, current state of the art and recent applications”, *Sensors*, 8 (9), 5673-5744. DOI: 10.3390/s8095673
- [14] Heyes A. L., Seefeldt S., Feist J. P., (2006), “Two-colour phosphor thermometry for surface temperature measurement”, *Optics & Laser Technology*, 38 (4-6), 257-265. DOI: 10.1016/j.optlastec.2005.06.012
- [15] Aldén M., Omrane A., Richter M., Särner G., (2011), “Thermographic phosphors for thermometry: a survey of combustion applications”, *Progress in Energy and Combustion Science*, 37 (4), 422-461. DOI: 10.1016/j.pecs.2010.07.001
- [16] Brübach J., Zetterberg J., Omrane A., Li Z. S., Aldén M., Dreizler A., (2006), “Determination of surface normal temperature gradients using thermographic phosphors and filtered Rayleigh scattering”, *Applied Physics B*, 84 (3), 537-541. DOI: 10.1007/s00340-006-2243-9
- [17] Cates M. R., Beshears D. L., Allison S. W., Simmons C. M., (1997), “Phosphor thermometry at cryogenic temperatures”, *Review of Scientific Instruments*, 68 (6), 2412-2417. DOI: 10.1063/1.1148125
- [18] Cates M. R., (2003). “YAG: Dy and YAG: Tm Fluorescence Above 1400 °C”, Technical Report No: R03-117983, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, US.
- [19] Dubey V., Sharma A. K., Singh R. K., (2020), “A technological review on temperature measurement techniques in various machining processes” In: Prakash C., Krolczyk G., Singh S., Pramanik A., Editors, *Advances in Metrology and Measurement of Engineering Surfaces*, Lecture Notes in Mechanical Engineering, Springer
- [20] Zheng T., Sójka M., Woźny P., Martín I. R., Lavín V., Zych E., Lis S., Du P., Lou L., Runowski M., (2022), “Supersensitive ratiometric thermometry and manometry based on dual-emitting centers in Eu²⁺/Sm²⁺-doped strontium tetraborate phosphors”, *Advanced Optical Materials*, 10 (20), 2201055. DOI: 10.1002/adom.202201055
- [21] Paul N., (1937), “Device for Indicating the Temperature Distribution of Hot Bodies”, U.S. Patent No. 2,071,471.
- [22] Allison S. W., (2019), “A brief history of phosphor thermometry”, *Measurement Science and Technology*, 30 (7), 072001. DOI: 10.1088/1361-6501/ab1d02
- [23] Franz U., "Measurement of Temperature Tistribution on the Surface of Solid Bodies." U.S. Patent No. 2,551,650.
- [24] Bradley III L. C., (1953), “A temperature-sensitive phosphor used to measure surface temperatures in aerodynamics”, *Review of Scientific Instruments*, 24 (3), 219-220. DOI: 10.1063/1.1770668

- [25] Thureau P., (1955), "Etude d'une Methode de Mesure des Temperatures Utilisant la Sensibilite Thermique des Couleurs de Fluorescence", Doctoral Thesis, University of Paris.
- [26] Byler W. H., Hays F. R., (1961), "Fluorescence thermography", *Nondestructive Testing*, 19, 177.
- [27] Fry E. M., (1971), "Thermographic phosphor surface measurement technique", *Temperature: Its Measurement and Control in Science and Industry*, 4, 577-583.
- [28] Brites C. D. S., Millán A., Carlos, L. D., (2016), "Lanthanides in luminescent thermometry", *Handbook on the Physics and Chemistry of Rare Earths*, 49, 339-427.
- [29] Feist J. P., Heyes A. L., (2000), "Europium-doped yttria-stabilized zirconia for high-temperature phosphor thermometry", *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 214 (1), 7-12. DOI: 10.1177/146442070021400102
- [30] Biswas S. K., Pilgrim C. C., Sollazzo P. Y., Berthier S., Feist, J. P., (2014). "Thermal history paints-principles and progress", *IET & ISA 60th International Instrumentation Symposium 2014*, 1-6, London, UK, 24-26 June. DOI: 10.1049/cp.2014.0538
- [31] Abram C., Fond B., Beyrau F., (2018), "Temperature measurement techniques for gas and liquid flows using thermographic phosphor tracer particles", *Progress in Energy and Combustion Science*, 64, 93-156. DOI: 10.1016/j.pecs.2017.09.001
- [32] Dramićanin M., (2018), "Luminescence Thermometry: Methods, Materials, and Applications", 1st Edition, Woodhead Publishing.
- [33] Bell J. H., Schairer E. T., Hand L. A., Mehta, R. D., (2001), "Surface pressure measurements using luminescent coatings", *Annual Review of Fluid Mechanics*, 33 (1), 155-206. DOI: 10.1146/annurev.fluid.33.1.155
- [34] Yu J., Xiao K., Xue W., Shen Y. X., Tan J., Liang S., Wang Y., Huang, X., (2020), "Excitation-emission matrix (EEM) fluorescence spectroscopy for characterization of organic matter in membrane bioreactors: Principles, methods and applications", *Frontiers of Environmental Science & Engineering*, 14 (2), 31.
- [35] Adachi C., T. Tsutsui, (2007), "Luminescence of Organic Compounds," In: Yen W. M., Shionoya S., Yamamoto H., Editors, "Fundamentals of Phosphors", 1st Edition, CRC Press.
- [36] Allison S. W., Gillies G. T., (1997), "Remote thermometry with thermographic phosphors: Instrumentation and applications", *Review of Scientific Instruments*, 68 (7), 2615-2650. DOI: 10.1063/1.1148174
- [37] Marciniak L., Kniec K., Elżbieciak-Piecka K., Trejgis K., Stefanska J., Dramićanin M., (2022), "Luminescence thermometry with transition metal ions. A

review”, *Coordination Chemistry Reviews*, 469, 214671. DOI: 10.1016/j.ccr.2022.214671

[38] Brites C. D., Marin R., Suta M., Carneiro Neto A. N., Ximendes E., Jaque D., Carlos L. D., (2023), “Spotlight on luminescence thermometry: basics, challenges, and cutting-edge applications”, *Advanced Materials*, 35 (36), 2302749. DOI: 10.1002/adma.202302749

[39] Brübach J., (2009), “Error analysis in thermographic phosphor thermometry” ISA's 55th International Instrumentation Symposium, League City, TX, USA, 1-5 June.

[40] Khalid A. H., Kontis K., (2009), “2D surface thermal imaging using rise-time analysis from laser-induced luminescence phosphor thermometry”, *Measurement Science and Technology*, 20 (2), 025305. DOI: 10.1088/0957-0233/20/2/025305

[41] Brübach J., Pflitsch C., Dreizler A., Atakan B., (2013), “On surface temperature measurements with thermographic phosphors: a review”, *Progress in Energy and Combustion Science*, 39 (1), 37-60. DOI: 10.1016/j.pecs.2012.06.001

[42] Jahanbazi F., Mao Y., (2021), “Recent advances on metal oxide-based luminescence thermometry”, *Journal of Materials Chemistry C*, 9 (46), 16410-16439. DOI: 10.1039/D1TC03455C

[43] Feuk H., Nilsson S., Richter M., (2022), “Laser excitation effects in lifetime-based high-speed phosphor thermometry”, *Journal of Luminescence*, 250, 119106. DOI: 10.1016/j.jlumin.2022.119106

[44] Fuhrmann N., Schneider M., Ding C. P., Brübach J., Dreizler A., (2013), “Two-dimensional surface temperature diagnostics in a full-metal engine using thermographic phosphors”, *Measurement Science and Technology*, 24 (9), 095203. DOI: 10.1088/0957-0233/24/9/095203

[45] Liu T., Sullivan J. P., (2005), “Pressure and Temperature Sensitive Paints”, 1st Edition, Springer.

[46] Allison S. W., Beshears D. L., Cates M. R., Paranthaman M., Gilles G. T., (2001). “LED-induced fluorescence diagnostics for turbine and combustion engine thermometry”, *SPIE 4448 Optical Diagnostics for Fluids, Solids, and Combustion*, 28-35, 26 November, San Diego, CA, US. DOI: 10.1117/12.449386

[47] Raja R., Cunningham G. T., ISA I., (2002), “Experimental investigation of phosphor thermography using a blue led optical excitation source”, *Technical Papers-ISA*, 422, 771-778.

[48] Szmackinski H., Lakowicz J. R., (1995), “Fluorescence lifetime-based sensing and imaging”, *Sensors and Actuators B: Chemical*, 29 (1-3), 16-24. DOI: 10.1016/0925-4005(95)01658-9

- [49] Feng G., Zhang H., Zhu X., Zhang J., Fang, J., (2022), “Fluorescence thermometers: intermediation of fundamental temperature and light”, *Biomaterials Science*, 10 (8), 1855-1882.
- [50] Cheng Y., Gao Y., Lin H., Huang F., Wang Y., (2018), “Strategy design for ratiometric luminescence thermometry: circumventing the limitation of thermally coupled levels”, *Journal of Materials Chemistry C*, 6 (28), 7462-7478. DOI: 10.1039/C8TC02401D
- [51] Brites C. D., Lima P. P., Silva N. J., Millán A., Amaral V. S., Palacio F., Carlos, L. D., (2012), “Thermometry at the nanoscale”, *Nanoscale*, 4 (16), 4799-4829. DOI: 10.1039/C2NR30663H
- [52] Yamada Y., Ishii J., (2015), “Toward reliable industrial radiation thermometry”, *International Journal of Thermophysics*, 36 (8), 1699-1712.
- [53] Hennecke D. K., Sparrow E. M., (1970), “Local heat sink on a convectively cooled surface—application to temperature measurement error”, *International Journal of Heat and Mass Transfer*, 13 (2), 287-304. DOI: 10.1016/0017-9310(70)90108-0
- [54] Allison S. W., Gates M. R., Beshears D. L., Gillies G. T., (2003), “Phosphor thermometry at ORNL”, *TEMPERATURE: Its Measurement and Control in Science and Industry, Volume VII, Eighth Temperature Symposium*, 1033–1038, Chicago, IL, US, 21-24 October.
- [55] Armfield J. S., Domingo N., Storey J. M., Allison S. W., Beshears D. L., Cates M. R., (1997), “Powertrain Component Temperature Measurements via Phosphor Thermometry”, *World Car Conference*, Ref. No. 97WCC018, 19-22, Riverside, CA, US, 19–22 January.
- [56] Omrane A., Ossler F., Aldén M., (2004), “Temperature measurements of combustible and non-combustible surfaces using laser induced phosphorescence”, *Experimental Thermal and Fluid Science*, 28 (7), 669-676. DOI: 10.1016/j.expthermflusci.2003.12.003
- [57] Liu S., Huang Y., He Y., Zhu Y., Wang Z., (2022), “Review of development and comparison of surface thermometry methods in combustion environments: principles, current state of the art, and applications”, *Processes*, 10 (12), 2528. DOI: 10.3390/pr10122528
- [58] Omrane A., Juhlin G., Ossler F., Aldén M., (2004), “Temperature measurements of single droplets by use of laser-induced phosphorescence”, *Applied Optics*, 43 (17), 3523-3529. DOI: 10.1364/AO.43.003523
- [59] Vetrone F., Naccache R., Zamarrón A., Juarranz de la Fuente A., Sanz-Rodríguez F., Martinez Maestro L., Rodriguez E. M., Jaque D., Solé J. G., Capobianco J. A., (2010), “Temperature sensing using fluorescent nanothermometers”, *ACS Nano*, 4 (6), 3254-3258. DOI: 10.1021/nn100244a

- [60] Ximendes E. C., Rocha U., Sales T. O., Fernández N., Sanz-Rodríguez F., Martín I. R., Jac, Jaque, D., (2017), “In vivo subcutaneous thermal video recording by supersensitive infrared nanothermometers”, *Advanced Functional Materials*, 27 (38), 1702249. DOI: 0.1002/adfm.201702249
- [61] IEC, (2013), “Thermocouples - Part 1: Reference tables”, IEC 60584-1:2023, International Electrotechnical Commission
- [62] ISO, (2011), “Lasers and laser-related equipment. Test methods for laser-induced damage threshold. Part 1: Definitions and general principles”, ISO 21254-1:2011, International Organization for Standardization.
- [63] Beshears D. L., Capps G. J., Cates M. R., Simmons C. M., Schwenterly, S. W., (1990), “Laser-induced fluorescence of phosphors for remote cryogenic thermometry”, *Fiber Optic Smart Structures and Skins III*, 365-376, San Jose, CA, US, 16-21 September. DOI: 10.1117/12.24869
- [64] Muhs J. D., Cates M. R., Tobin K. W., Capps G. J., Beshears, D. L., (1989), “Fiber-optic sensors for composite cure analysis and lifetime nondestructive evaluation” *ICALEO 89 th International Congress on Applications of Lasers & Electro-Optics*, 63-72, Orlando, FL, US, 15-20 October. DOI: 10.2351/1.5058351
- [65] Seat H. C., Sharp J. H., (2004), “Dedicated temperature sensing with c-axis oriented single-crystal ruby (Cr³⁺:Al₂O₃) fibers: temperature and strain dependences of R-line fluorescence”, *IEEE Transactions on Instrumentation and Measurement*, 53 (1), 140-154. DOI: 10.1109/TIM.2003.822010
- [66] Brübach J., Janicka J., Dreizler A, (2009), “An algorithm for the characterisation of multi-exponential decay curves”, *Optics and Lasers in Engineering*, 47 (1), 75-79. DOI: 10.1016/j.optlaseng.2008.07.015
- [67] Rosso L., Tabandeh S., Beltramino G., Fernicola V., (2019), “Validation of phosphor thermometry for industrial surface temperature measurements”, *Measurement Science and Technology*, 31 (3), 034002. DOI: 10.1088/1361-6501/ab4b6b
- [68] Sposito A., Heaps E., Sutton G., Machin G., Bernard R., Clarke S., (2021), “Phosphor thermometry for nuclear decommissioning and waste storage”, *Nuclear Engineering and Design*, 375, 111091. DOI: 10.1016/j.nucengdes.2021.111091

BIOGRAPHY

Ömer Faruk KADI received his bachelor's degree in Physics Engineering Department at Istanbul Technical University, Faculty of Science and Letters, in 2022. Since then, he has been pursuing his master's studies in the Gebze Technical University, Graduate School, Department of Physics. His graduate research focuses on the comparative evaluation of two phosphor thermometers operating with different pulsed laser sources.

During his academic training, he worked as a researcher at the Thermodynamic Metrology Laboratory of TÜBİTAK National Metrology Institute, conducting studies on Laser-Induced Damage Threshold (LIDT), radiation, and phosphor thermometers. As a graduate fellow in the same laboratory, he was actively involved in experimental data acquisition and analysis using tools such as Python, MATLAB, and LabVIEW. He also contributed to the development of a Magneto-Optical Kerr Effect (MOKE) experimental setup at the Nanotechnology Institute of Gebze Technical University and served as an imaging specialist at Nanomagnetic Scientific Devices, working with RT-AFM and STM microscopes.

The author has contributed to several national and international scientific publications in the fields of image processing, optical systems, and temperature measurement.

PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

[1] Kadı Ö. F, Atağ A. H., Yurtseven S., Nasibli H., Karabulut M., (2025), “Enhanced phosphor thermometry using double-pulse laser for temperature measurements”, 9. GTÜ Lisansüstü Araştırmalar Sempozyumu, Gebze, Kocaeli, Türkiye, 26 - 27 May

