



Photothermal lens spectroscopy at ICTP: Evolution, progress, and applications beyond the Gallieno Denardo era

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In memory of Professor Gallieno Denardo, ICTP Italy

The thermal lens technique relies on measuring the temperature increase in a sample caused by nonradiative relaxation of the energy absorbed from a light source. This technique is indeed highly sensitive due to the direct absorption of light and its immediate conversion into heat. Because of its high sensitivity, the thermal lens technique is widely used in fields like material science, nanotechnology, chemistry, and biosensing. It can be used to analyze the optical properties of materials, measure energy absorption, and even detection of impurities in samples. It is also useful for studying the dynamics of photochemical reactions, as it provides detailed information about how energy is absorbed and dissipated in the material. This article reviews the development of thermal lens spectrometry at ICTP in the many years following Gallieno Denardo's passing, focusing on recent advances. This overview begins with an explanation of the technique's underlying theory, followed by a discussion of its instrumentation and applications, highlighting the unique characteristics of the technique. It covers applications for environmental research, material characterization, and biomedical fields. The article concludes with proposals of TLS's for future development, focusing on its potential applications in emerging research fields. © Indian Spectroscopy Society. All rights reserved.

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1 Introduction

The thermal lens (TL) effect was first observed by Gordon *et al* in 1965 [1], marking a key milestone in the development of laser spectroscopy. Their experiment utilized a simple single-beam setup to detect changes in a material's refractive index, caused by localized heating from a laser beam. Since its inception, thermal lens spectrometry (TLS) has been extensively studied and applied for the thermophysical and chemical characterization of a wide range of materials. When light is absorbed by a medium, it generates heat, creating a temperature gradient that alters the material's refractive index [2]. This change causes the light to focus or defocus depending on the propagation medium, like a lens bends light. Over time, the discovery of the TL effect led to more sophisticated experimental designs, incorporating multiple laser beams and advanced detection techniques to enhance the sensitivity and precision of measurements [3,4]. Initially used for nonfluorescent analytes, it has also been applied to fluorescent compounds [3]. The technique is very sensitive because even small changes in temperature can result in significant changes in the refractive index. Since the temperature rise is usually localized, the TL effect can be detected with high precision. Additionally, the ability to measure this effect with high spatial and temporal resolution makes the technique highly sensitive to minute variations in the sample. One of the key features of this technique

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is that it involves nonradiative relaxation of the absorbed energy. This means the energy doesn't escape the material as light or fluorescence but instead is converted entirely into heat. This results in a more direct and sensitive measurement of energy absorption, as all the absorbed light is retained within the material. Therefore, TL has a cumulative effect, resulting from the fact that while the relaxation process is rapid (on the order of 10^{-6} to 10^{-12} seconds), thermal relaxation is much slower (of the order of 10^{-3} seconds). This means that during a single thermal relaxation cycle, a single atom or molecule can be excited and release thermal energy up to 10^3 times, thereby contributing additional thermal energy during each TL excitation cycle. In addition, the TL effect has a phase component (e.g., $\Phi = \frac{2\pi}{\lambda_p} l \frac{dn}{dT} \Delta T$), where the ratio of the sample path length l (typically around 10^{-3} m) to the probe wavelength λ_p (around 10^{-9} m) results in a high ratio, causing a significant phase shift. This amplifies the TL signal, even for small temperature changes ΔT and refractive index gradients dn/dT . These two factors, the accumulation of thermal energy and the enhanced phase shift, provide a clear explanation for the high sensitivity of the TL technique.

The TL technique is often used to study the optical properties of materials, particularly their absorption coefficient and thermal diffusivity [5,6]. The technique is also useful in characterizing nanomaterials, such as nanoparticles, thin films and polymers [7-9]. Since these materials often have unique optical properties due to their small size and surface effects, the TL effect can help in understanding their interactions with light and heat at a very fine scale. TL is particularly sensitive to changes in temperature, so it is an excellent tool for studying fast or highly exothermic chemical reactions. By observing the TL effect before, during, and after a reaction, chemists can gain insights into the dynamics of the reaction and how energy is absorbed and dissipated. The technique employs advanced mathematical models to extract detailed kinetic information from light-driven chemical processes, enhancing both understanding and quantitative analysis across diverse chemical systems [10]. The technique can be used to study the kinetics of photochemical processes by tracking how the temperature of a sample rises over time in response to continuous light exposure [10]. In complex chemical systems, the TL effect can help detect trace amounts of contaminants or impurities. Since even small impurities can significantly affect heat dissipation, this sensitivity is ideal for detecting such variations in chemical mixtures. A (0.6–1 μm) thick Nafion layer on PET was detected after ferroin addition ($\leq 4 \times 10^{-10}$ mol cm^{-2}), corresponding to absorbances of 1×10^{-5} – 5×10^{-4} [11].

TL has been explored for biosensing applications, such as detecting biological molecules or antibodies. When a biological sample absorbs light, it can produce a TL effect that indicates the presence of specific molecules. For example, in immunoassays, antibodies that bind to target molecules can cause localized heating, which in turn produces a measurable TL effect. Alsadig [12] reported an early AuNP nanobody sensing approach that used a mixed self-assembled monolayer of thiolated ssDNA and bio-repellent TOEG6. This was combined with DNA-directed immobilization of DNA protein conjugates to form an advanced biosensing platform. In a subsequent step, ssDNA-modified AuNPs were considered for cancer biomarker sensing using complementary ssDNA conjugated to the C8 nanobody, which targets the extracellular domain of HER2, a receptor overexpressed in 15–30% of breast cancers. Hybridization between ssDNA/TOEG6@AuNPs and the C8-labeled DNA was detected by monitoring refractive index changes near the AuNP surface using the TL technique [12]. Because conventional LSPR lacked sufficient sensitivity to detect HER2-ECD binding, a miniaturized gel electrophoresis chip coupled with online TLS (MGEC-TLS) was used, achieving ~ 100 -fold higher sensitivity than standard SPR by correlating immunocomplex formation with nanoparticle mobility [12]. An electrophoresis-based method integrated with online TLS allows sensitive assessment of AuNP surface energy [13]. Asbaghi *et al* introduced a photothermal dual-mode gel electrophoresis assay that determines DNA surface coverage on AuNPs, offering a new strategy to enhance AuNP-based biosensor sensitivity and to evaluate interactions between thiolated oligonucleotides and AuNPs [13]. This work establishes a versatile AuNP engineering platform with controlled size and surface

functionality, supporting the development of low-cost point-of-care diagnostic technologies to improve human health.

TL method was used to assess the thermoplasmonic properties of the nanoparticles and their ability to convert light into heat efficiently, which is key for photothermal therapy (PTT). This research focuses on the design and application of thermoplasmonic nanoparticles for enhancing cancer therapies [14]. The paper investigates how the morphology of these nanoparticles can be optimized to combine two distinct therapeutic strategies: immunotherapy and PTT [14].

TL technique has been widely used to monitor pollutants in air and water after the action of specific catalyst. For instance, specific pollutants or contaminants that absorb light might generate a TL effect that can be measured. This makes it a potential tool for real-time, sensitive detection of environmental toxins, such as heavy metals, antibiotics or organic pollutants and to follow photodegradation processes [15-17]. Based on the TL principle, highly sensitive sensors can be developed for various applications in environmental and chemical analysis. These sensors might be used for detecting low levels of hazardous substances or monitoring changes in the environment that might otherwise go unnoticed.

In some high-power optical systems, such as laser cavities or amplifiers, TL can become an issue. The heating caused by intense laser light can distort the shape of the lens, affecting the focus or beam quality. Understanding the TL effect helps in designing systems that minimize these distortions [18]. Since the TL effect can be observed with high temporal resolution, it's particularly useful in studying fast processes. Researchers can track the rapid rise and decay of heat within a sample, giving them insight into dynamic processes such as energy transfer, reaction times, or relaxation times. Therefore, TL enables temporal discrimination between the electronic and thermal contributions to the nonlinear refractive index [19].

TLS has been used in conjunction with microscopy to visualize microscopic structures and processes [20]. When combined with a microscope, it allows researchers to examine the thermal properties of materials at the micro or nanoscale, offering insights into material heterogeneity or structural defects that might not be visible using traditional imaging techniques [20]. It's also useful for measuring quantum dot encapsulation efficiency by liposomes [21]. Photothermal digital holography combined with phase-sensitive holography enables non-invasive imaging and characterization of hidden layers in multilayered samples [22-24]. Extensive applications for chemical and biological/biomedical analysis have been found by integrating microscale analytical devices, particularly microfluidic chips. Theoretically, models have been developed to account for the effects of the sample's environment on TL microscopy signals [25].

The TL technique offers several advantages, making it a powerful tool in various applications. Its high sensitivity is one of the key benefits, as the direct conversion of light to heat allows the detection of even the smallest temperature changes in a sample. Additionally, the technique is non-destructive, meaning that the sample remains unaltered and undamaged during measurement, which is ideal for sensitive or fragile materials. The versatility of the TL technique further enhances its utility, as it can be applied to a wide range of materials, including solids, liquids, and gases, making it suitable for both research and industrial purposes. Despite its advantages, TL technique has some challenges and limitations. One such issue is selectivity, as it relies on the excitation wavelength to target specific absorption bands. To measure various absorption bands, a tunable laser is required, which adds complexity to the system. This need for wavelength tuning can make the technique more difficult to use for accurate measurements and contributes to the bulkiness of the setup. The requirement for multiple laser sources or additional optical components further increases system size and cost, limiting its portability and practicality for certain applications. Additionally, the technique's complex interpretation can pose a challenge. While it is highly sensitive, analyzing the TL effect requires careful evaluation of both the temperature rise and the corresponding changes in refractive index to extract meaningful data, which can sometimes complicate the analysis process.

The first part of this review offers a theoretical overview of the technique, providing a foundational understanding while presenting the latest developments in theoretical models and new advancements in instrumental implementations. Various TL configurations are discussed in detail to highlight improvements in sensitivity. Continuing, the review focuses on applications that leverage the unique features of TL technique, including its ultrasensitivity in fields like biochemistry, biosensing, and environment research. It also highlights its small space capabilities (e.g., nanotechnology, gel electrophoresis) and its use for determining thermal properties. Finally, potential future developments of the technique are examined.

2 Theory

Various theoretical explanations of the TL effect under different experimental conditions are discussed in the literature and have been thoroughly reviewed in numerous books and review articles [3, 26-32]. These models are based on a straightforward parabolic approximation [1], where the TL induced by continuous wave (CW) excitation is considered as an ideal thin lens. The parabolic model offers a reasonable approximation for the overall behavior of TL. However, the refractive index change beyond the excitation zone is not parabolic, meaning the TL cannot be treated as a thin lens. A more precise quantitative description of the TL has been provided by accounting for its aberrant characteristics, and by applying diffraction theory to derive expressions for changes in laser beam intensity and the corresponding TL signal [33]. The aberrant model is especially crucial in dual-beam TL experiments, particularly when dealing with a mode-mismatched configuration. A general model for a dual-beam, mode-mismatched TL was later developed by Shen *et al* [34] based on the Fresnel-diffraction approximation for the sample located at a fixed position Z . The model introduced the mode-mismatching parameter which is the ratio of the probe and pump beam radii within the sample $m = (\omega_{1p}/\omega_e)^2$ and the parameter that describes the sample's position relative to the probe beam waist Z_1 ($v = z_1/z_p$), considering that z_p is the confocal parameter of the probe beam, ω_e the radius of the excitation beam within the sample, and z_2 the distance from the sample to the detector position. The probe beam waist within the sample is defined as shown in the schematic of Fig 1:

$$\omega_{1p} = \omega_{0p} \sqrt{1 + (z_1/z_p)^2} \quad (1)$$

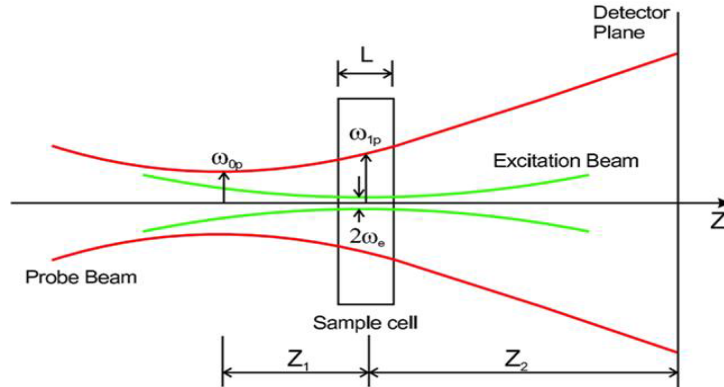


Fig 1. Schematic illustration of parameters in dual-beam mode-mismatched thermal lens spectroscopy.

Later on, Marcano *et al* developed a model for Z-scan experiment based on the same approximation, but the sample was scanned around the waist of the excitation beam [35]. However, the radius of the detector aperture was ignored, giving wrong values of the TL signal when the detector is positioned at very small distance, z_2 ($z_2 < 100$ cm). Therefore, a modified approach was proposed by Rahman *et al* [36], incorporating the effects of the aperture radius (ρ_0) and the detector position (z_2). In this model, the TL signal is calculated as follows:

$$\begin{aligned}
S(z, t) = & \int_1^{t'} \frac{2F(z, 0)H(z, \tau) \Phi_0}{(1 - \exp\{-2\rho_0^2 Y(z)^2 F(z, 0)H(z, 0)\delta(z, \tau)\})} \left[\sin \left\{ \arctan \left[\frac{(\beta(z, 0) - \beta(z, \tau))}{(F(z, 0) + F(z, \tau))} \right] + \eta(z, 0) - \eta(z, \tau) \right\} \right. \\
& - \exp \{ -\rho_0^2 Y(z)^2 (F(z, 0) + F(z, \tau)) \} \\
& \left. \sin \left\{ \arctan \left[\frac{(\beta(z, 0) - \beta(z, \tau))}{(F(z, 0) + F(z, \tau))} \right] + \rho_0^2 Y(z)^2 (\beta(z, 0) - \beta(z, \tau)) + \eta(z, 0) - \eta(z, \tau) \right\} \right] \quad (2)
\end{aligned}$$

where the parameters of the equation are given by:

$$H(z, \tau) = \frac{1}{\sqrt{1 + 2m(z)\tau + v(z)^2}} \quad (3)$$

$$F(z, \tau) = \frac{1 + 2m(z)\tau}{4((1 + 2m(z)\tau)^2 + v(z)^2)} \quad (4)$$

$$\beta(z, \tau) = \frac{v}{4((1 + 2m(z)\tau)^2 + v(z)^2)} \quad (5)$$

$$\eta(z, \tau) = \arctan \{ -v(z)/(1 + 2m(z)\tau) \} \quad (6)$$

$$\delta(z, \tau) = \sqrt{((M_1(z, 0) + M_1(z, \tau))^2 + (M_2(z, 0) - (M_2(z, \tau)))^2} \quad (7)$$

$$v(z) = \frac{(z - a_p)}{z_p} + \frac{z_p}{z_2} \frac{(z_p^2 + (z - a_p)^2)}{z_p^2} \quad (8)$$

$$m(z) = \frac{\omega_p^2(z)}{\omega_e^2(z)} \quad (9)$$

$$\omega_p = \omega_{op} \sqrt{1 + \frac{(z - a_p)^2}{z_p^2}} \quad (10)$$

$$\omega_e = \omega_{oe} \sqrt{1 + \frac{(z - a_e)^2}{z_p^2}} \quad (11)$$

$$Y(z) = \frac{2\pi\omega_p}{\lambda_p L} \quad (12)$$

$$t' = \frac{1}{1 + 2t/t_c(z)} \quad (13)$$

a_p, a_e represent the waist positions of the probe and pump beams, respectively. $t_c(z) = \omega_{oe}^2/4D$ is the characteristic time constant of the TL signal, $D = k/c_p \rho$ is the thermal diffusivity of the sample, k is the thermal conductivity, c_p is the specific heat, and ρ is the density of the sample. The amplitude of the TL signal is given by:

$$\Phi_0 = \frac{P_e \alpha l}{\lambda_p k} \frac{dn}{dT} \quad (14)$$

where P_e is the power of the excitation beam, λ_p is the wavelength of the probe beam, α is the absorption coefficient of the sample and dn/dT is the temperature dependence of the refractive index.

3 Result and Discussion

Along with the pursuit of higher sensitivity, the development of dual-beam instruments was driven by the need to enable multiwavelength capability in TLS measurements. The use of continuously

or line-tunable lasers for sample excitation was employed. Efforts were also made to enable tunability in thermal lens instruments using incoherent white-light sources. Developing efficient TL configurations using incoherent white-light sources enhances the tunability of TL instruments. To improve sensitivity and address the limitations of low power output from incoherent sources, such as lamps (Fig 2) [37] and LEDs (Fig 3) [38], various approaches have been explored. One such method involves using a multi-lens system [39,40] achieved through a double-pass probe beam configuration. These instruments were used to obtain absorption spectra of weakly absorbing samples [37,41], as well as spectra resulting from overtone vibrational transitions [38].

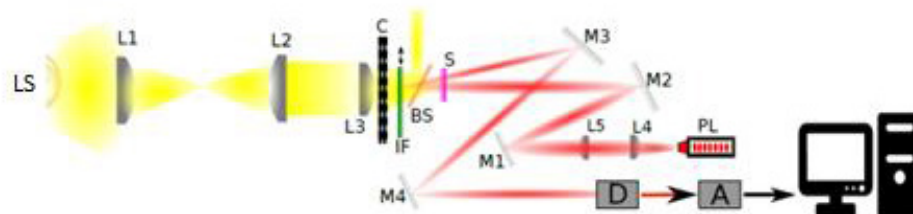


Fig 2. Scheme of the pump-probe white light system with double-pass probe beam. LS: excitation source, L1: collector lens, L2: collimating lens, L3: focusing lens, C: chopper, IF: interference filter, BS: beam splitter, S: cell sample, M1, M2, M3, M4: mirrors, PL: probe laser, L4, L5: collimator lenses, D: silicon detector, A: Arduino board.

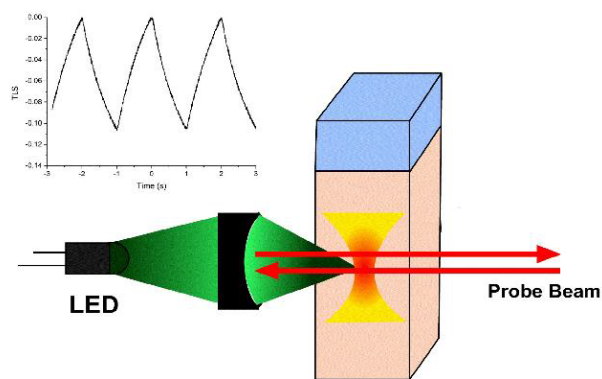


Fig 3. Scheme of the pump-probe LED excitation system with double-pass probe beam configuration.

Online TL microscopy coupled with gel electrophoresis can represent a powerful tool for separating and detecting a wide range of biomaterials. Miniaturization of TL instruments enables low sample consumption and allows their use in combination with microfluidics or gel electrophoresis microchips [42]. Gel electrophoresis combined with TL detection is an advanced technique that brings together two powerful methods: gel electrophoresis and TLS [42]. Combining gel electrophoresis with TL detection offers a high-sensitivity method for analyzing biomolecules that might be difficult to detect with traditional techniques. This work aims to validate the feasibility and practicality of the proposed approach by evaluating its separation capability using synthesized Fe_3O_4 -Au core-shell nanoparticles (NPs), which serve as a proof-of-concept, as shown in Fig 4.

The ability to detect low concentrations and weakly absorbing species without the need for labels or complex sample preparation opens new possibilities for biomolecular research and diagnostics—particularly when integrated with modern miniaturization platforms such as microfluidic chips. In this study, the authors employed a miniaturized gel electrophoresis chip coupled with TLS to enable rapid, sensitive, and real-time

monitoring of ssDNA surface coverage on AuNPs [13]. Unlike conventional methods for determining surface coverage, the design presented in this work does not require long signal acquisition times or tedious post-treatment steps, including chemical modifications. This implementation demonstrates excellent electrophoretic analysis of DNA strands attached to AuNPs and enables rapid nanoparticle separation in gel. Compared to traditional gel electrophoresis techniques, this system can acquire results in significantly shorter running times (< 6 min) while consuming far fewer chemicals.

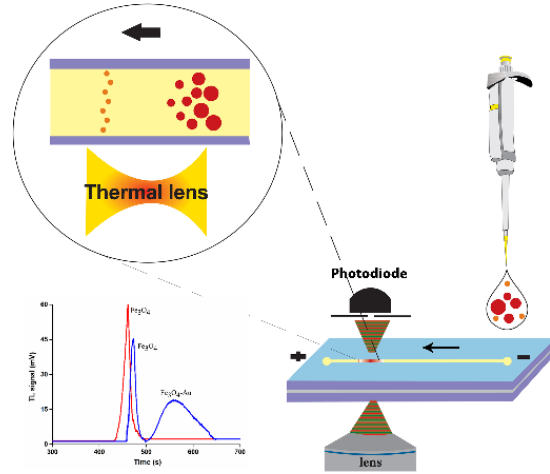


Fig 4. Scheme of the miniaturized gel electrophoresis chip coupled with TL detection.

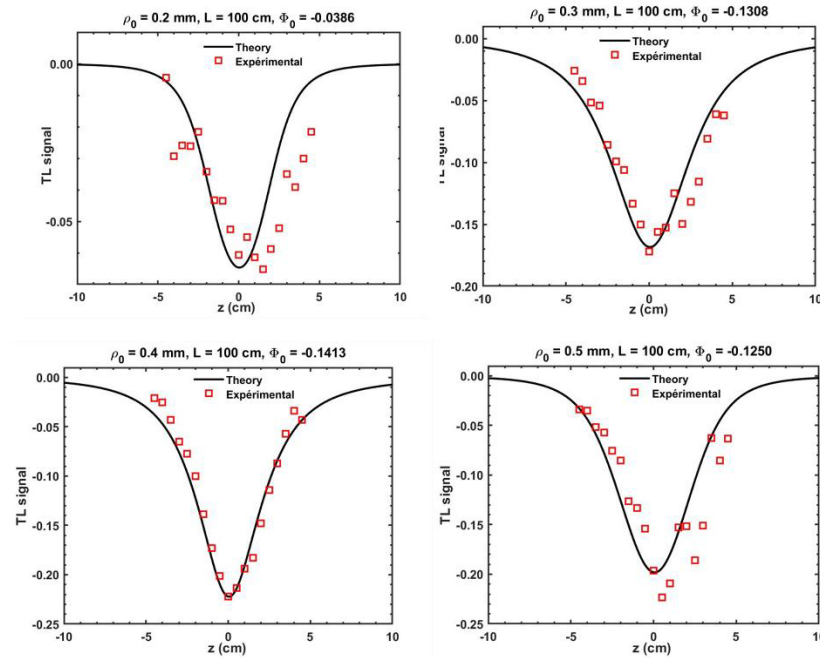


Fig 5. Fitting of experimental values with Eq (2) for pinhole radius (ρ_0) 0.2 0.3; 0.4; 0.5 mm, with $z_p = 100$ cm, $z_e = 0.05$ cm, $a_p = -20$, $a_e = 0$, $D = 0.90 \cdot 10^{-3}$ cm² s⁻¹, $\omega_{p0} = 0.04$ cm, $\omega_{e0} = 0.001$ cm, $t = 0.5$ s.

To evaluate how aperture size influences the TL signal, the TL signal was plotted as a function of L for different values of ρ_0 . Figure 5 shows the z-scan of the TL signal for various values of ρ_0 (i.e., 0.2 mm, 0.3 mm, 0.4 mm, and 0.5 mm) versus L . There is a good agreement between the theoretical model and the experimental results [43], confirming the validity of the corrections applied to the aperture radius in Eq (2) of the exact theoretical model [36].

4 Summary and future outlooks

Future developments in TL technique will likely focus on enhancing its sensitivity and spatial resolution. The use of nanomaterials and nanostructures can significantly improve the technique's ability to detect even smaller temperature changes. Since materials at the nanoscale often exhibit unique optical and thermal properties, combining them with advanced TL could enable researchers to study fine details that were previously challenging to measure. Furthermore, integrating super-resolution imaging techniques could allow the TL effect to be observed at the nanoscale, making it particularly useful for studying the thermal properties of individual nanoparticles or molecular structures. As laser technology advances, time-resolved TL measurements will become even more valuable. Future systems could enable real-time tracking of fast photochemical or photothermal processes, providing deeper insights into the dynamics of energy transfer, chemical reactions, or phase transitions. Researchers are also looking to achieve femtosecond to picosecond resolution, allowing them to capture ultra-fast phenomena in molecular photochemistry, material science, and quantum research [44]. This level of precision would open doors to understanding energy dynamics on timescales previously difficult to achieve with conventional methods. The future of TL will likely involve its integration with other analytical methods to enhance its versatility. For instance, combining TL with gel electrophoresis, fluorescence spectroscopy, Raman spectroscopy, or atomic force microscopy (AFM) would provide a richer, more detailed understanding of a material's properties [13]. This multimodal approach would allow researchers to study not just thermal and optical characteristics but also structural and chemical properties in a single experiment. Additionally, hybrid sensors that incorporate TL along with other detection techniques could be developed for use in fields like biosensing, environmental monitoring, and industrial quality control, offering a more comprehensive tool for real-time analysis [38,45].

One area that holds significant promise for the future is the development of advanced computational models for analyzing TL data. With the power of machine learning and AI, it will become easier to simulate the TL effect more accurately and interpret complex data more efficiently. These tools could help researchers predict and optimize the behavior of materials under different conditions, making it easier to extract meaningful insights from TL measurements. Moreover, techniques like inverse problem-solving could be developed to deduce material properties, such as thermal conductivity, thermal diffusivity or absorption coefficients, from observed TL effects without the need for direct measurements of these properties. In the realm of material science, TL will continue to evolve as a critical tool for characterizing novel materials. As new materials like 2D materials (e.g., graphene), high-temperature superconductors, and advanced polymers are developed, the need for precise thermal characterization will increase [46].

TL has a bright future in the field of biosensing, where it could be used for high-resolution, non-invasive single-cell analysis. By tracking temperature changes within individual cells, researchers could gain valuable insights into cellular metabolism, drug responses, or disease biomarkers, especially in areas like cancer research [14]. TL could also play a role in medical diagnostics, particularly for detecting abnormal tissue growth or tumors that exhibit different thermal signatures than healthy tissue. When combined with other imaging modalities like digital holography microscopy, TL could become a powerful tool for detecting early-stage diseases or monitoring tissue responses in real time [22]. As concerns over pollution and environmental degradation grow, TL could be increasingly used for real-time environmental monitoring. The technique could be employed to detect trace amounts of pollutants in air or water, such as heavy metals,

organic contaminants, or greenhouse gases, based on their ability to absorb light and generate localized heat [37]. The high sensitivity of TL makes it particularly well-suited for detecting these pollutants at low concentrations, offering a more efficient, non-destructive method of environmental analysis. Another exciting future development is the miniaturization of TL systems, which would make the technique accessible for field-based applications. Portable TL sensors could be deployed in remote locations or industrial settings to conduct real-time analysis without the need of bulky laboratory equipment. This could open new possibilities for environmental monitoring, industrial quality control, and even field-based research. As quantum technology advances, TL could play a significant role in the characterization of quantum materials, such as quantum dots and topological insulators [21]. These materials exhibit unique optical and thermal properties that could be better understood through the TL technique. Understanding the thermal properties of these materials could help improve the efficiency and functionality of future quantum devices.

Optical encryption has attracted significant research interest due to the growing demand for secure information. Its appeal lies in the advantages of optical processing, including the multiple degrees of freedom of light and the potential for lightspeed operation. These features make it a compelling alternative to conventional algorithm-based cryptosystems. In this context, TL effect emerges as an important parameter for optical data processing applications, including encryption [47].

5 Conclusion

The future of the TL technique is promising, with potential advancements that could push the boundaries of sensitivity, resolution, and applicability across many fields. As technology evolves, its integration with new materials, advanced sensors, and computational models will continue to unlock new possibilities for research and industry, from materials science to medical diagnostics and environmental monitoring. As these developments unfold, the TL technique could become a central tool in the next generation of high-precision analytical methods.

In conclusion, the TL technique represents a powerful and versatile tool with immense potential for future advancements across various fields. Its ability to detect minute temperature changes with high sensitivity makes it invaluable for applications in material science, biosensing, medical diagnostics, environmental monitoring, and beyond. As technology evolves, the integration of nanomaterials, time-resolved measurements, multimodal sensing, and advanced computational models will enhance its precision and broaden its range of applications. Whether it is contributing to advancing quantum technology, or enabling real-time, non-invasive cellular analysis, the future of TL holds great promise for both scientific research and practical innovation, paving the way for deeper insights and more efficient solutions in numerous industries.

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References

1. Gordon J P, Leite R S, Moore, Porto S P S, Whinnery J R, Long-transient effects in Lasers with Inserted Liquid Samples, *J Appl Phys*, 36(1965)3–8.
2. Franko M, Thermal lens spectrometric detection in flow injection analysis and separation techniques, *Appl Spectrosc Rev*, 43(2008)358; doi.org/10.1063/1.1713919.

3. Bialkowski S E, Astrath N G C, Proskurnin M A, Photothermal Spectroscopy Methods, 2nd edn, (John Wiley & Sons, Inc, Hoboken, NJ), 2019.
4. Franko M, Tran C D, Thermal lens spectroscopy and microscopy, Encyclopedia of Analytical Chemistry, (2025), <https://doi.org/10.1002/9780470027318.a9079.pub2>.
5. Cabrera H, Marcano A, Castellanos Y, Absorption coefficient of nearly transparent liquids measured using thermal lens spectrometry, *Cond Matter Phys* 9(2006)385; doi.org/10.5488/CMP.9.2.385.
6. Marcano A, Cabrera H, Guerra M, Cruz R A, Jacinto C, Catunda T, Optimizing and calibrating a mode-mismatched thermal lens experiment for low absorption measurement, *J Opt Soc Am B*, 23(2006)1408–1413.
7. Swapna M S, Raj V, Cabrera H, Sankararaman S, Thermal Lensing of Multi-walled Carbon Nanotube Solutions as Heat Transfer Nanofluids, *ACS Appl Nano Mat*, 4(2021)3416; doi.org/10.1021/acsanm.0c03219.
8. Mikaeeli A, Korte D, Cabrera H, Chomicki D, Dziczek D, Kharchenko O, Song P, Liu J, Wieck A D, Pawlak M, Measuring Thermal Diffusivity of Azoheteroarene Thin Layers by Photothermal Beam Deflection and Photothermal Lens Methods, *Materials*, 16(2023)6312; doi.org/10.3390/ma16186312.
9. Abbasgholi-N A B, Reza Nokhbeh S R, Aldaghri O A, Ibnaouf K H, Madkhali N, Cabrera H, Thermal Diffusivity and Conductivity of Polyolefins by Thermal Lens Technique, *Polymers*, 14(2022)2707; doi.org/10.3390/polym14132707.
10. Astrath N G C, Astrath F B G, Shen J, Zhou J, Michaelian K H, Fairbridge C, Malacarne L C, Pedreira P R B, Medina A N, Mauro L, Baesso M L, Thermal-lens study of photochemical reaction kinetics, *Opt Lett*, 34(2009)3460; doi.org/10.1364/OL.34.003460.
11. Nedosekin D A, Brusnichkin A V, Lukyanov A Y, Eremin S A, Proskurnin M A, Heterogeneous Thermal-Lens Immunoassay for Small Organic Compounds: Determination of 4-Aminophenol, *Appl Spectrosc*, 64(2010)942–948.
12. Alsadig A, Abbasgholi-N A B, Vondracek H, Medagli B, Fortuna S, Posocco P, Parisse P, Cabrera H, Casalis L, DNA-Directed Protein Anchoring on Oligo/Alkanethiol-Coated Gold Nanoparticles: A Versatile Platform for Biosensing Applications, *Nanomaterials*, 13(2023)78; doi.org/10.3390/nano13010078.
13. Asbaghi A B N, Alsadig A, Casalis L, Parisse P, Niemela J, Bellucci S, Cabrera H, An electrophoresis approach with online thermal lens detection to monitoring DNA surface coatings on gold nanoparticles, *Microchem J*, 173(2022)106961; doi.org/10.1016/j.microc.2021.106961.
14. Alsadig A, Peng X, Boutier H, Loureiro L R, Feldmann A, Hübner R, Cabrera H, Kubeil M, Bachmann M, Baraban L, Exploring Morphology of Thermoplasmonic Nanoparticles to Synergize Immunotherapeutic Fibroblast Activation Protein-Positive Cell Sensitization and Photothermal Therapy, *Small Sci*, 5(2025)2500099; doi.org/10.1002/smssc.202500099.
15. Cedeño E, Cabrera H, Delgadillo-López A E, Delgado-Vasallo O, Mansanares A M, Calderón A, Marín E, High sensitivity thermal lens microscopy: Cr-VI trace detection in water, *Talanta*, 170(2017)260; doi.org/10.1016/j.talanta.2017.04.008.
16. Stegarescu A, Cabrera H, Budasheva H, Soran M L, Lung I, Limosani F, Korte D, Amati M, Borodi G, Kacso I, Opreş O, Dan M, Bellucci S, Synthesis and Characterization of MWCNT-COOH/Fe₃O₄ and CNT-COOH/Fe₃O₄/NiO Nanocomposites. Assessment of Adsorption and Photocatalytic Performance, *Nanomaterials*, 12(2022)3008; doi.org/10.3390/nano12173008.
17. Ebrahimpour Z, Pliekhova O, Cabrera H, Abdelhamid M, Korte D, Gadedjisso-Tossou K S, Niemela J, Lavrencic S U, Franko M, Photodegradation mechanisms of Reactive Blue 19 dye under UV and simulated solar light irradiation, *Spectrochim Acta*, 252A(2021)119481; doi.org/10.1016/j.saa.2021.119481.
18. Koechner W, Solid-State Laser Engineering (Springer, New York), 2006.
19. Andrade A A, Tenório E, Catunda T, Baesso M L, Cassanho A, Jenssen H P, Discrimination between electronic and thermal contributions to the nonlinear refractive index of SrAlF₅:Cr⁺³, *J Opt Soc Am B*, 16(1999)395–400.
20. Liu M, Franko M, Progress in thermal lens spectrometry and its applications in microscale analytical devices, *Crit Rev Anal Chem*, 44(2014)328–353.
21. Batalla J, Cabrera H, Martín-Martínez E S, Korte D, Calderón A, Marín E, Encapsulation efficiency of CdSe/ZnS quantum dots by liposomes determined by thermal lens microscopy, *Biomed Opt Express*, 6(2015)3898–3906.
22. Utadiya S, Singh V, Sheoran G, Cabrera H, Niemela J, Javidi B, Anand A, Photothermal digital holography for imaging and characterization of multilayered structures, *Opt Express*, 33(2025)53028–53045.

23. Utadiya S, Trivedi V, Singh V, Sheoran G, Cabrera H, Srivastava A, Javidi B, Anand A, Digital holographic characterization of multilayered structures by thermal scanning, *Appl Opt*, 64(2025)B134–B142.
24. Javed I, Hassan M B, Khalid R, Dashtdar M, Garcia L G, Fonda C, Crespo M L, Danailov M, Cojoc D, Zubair M, Muhammad Mehmood Q, Cabrera H, Compact inverted digital holographic microscope based on common-path configuration, *Appl Opt*, 64(2025)B65–B71.
25. Liu M, Korte D, Franko M, Theoretical description of thermal lens spectrometry in micro space, *J Appl Phys*, 111(2012)033109; doi.org/10.1063/1.3682481.
26. Franko M, Tran C D, Analytical Thermal Lens Instrumentation, *Rev Sci Instrum*, 67(1996)1–18.
27. Franko M, Thermal Lens Spectrometric Detection in Flow Injection Analysis and Separation Techniques, *Appl Spectrosc Rev*, 43(2008)358–388.
28. Snook R D, Lowe R D, Thermal Lens Spectrometry. A Review, *Analyst*, 120(1995)2051–2068.
29. Fang H C, Swofford R L, 'The Thermal Lens in Absorption Spectroscopy, in *Ultrasensitive Laser Spectroscopy*, (Academic Press), 1983, pp 175–232.
30. Dovichi N J, Thermo-optical Spectrophotometries in Analytical Chemistry, *Crit Rev Anal Chem*, 17(1987)357–423.
31. Gupta R, Theory of Photothermal Effect in Fluids, in *Photothermal Investigations of Solids and Fluids*, (ed) Sell J A, (Academic Press, New York), 1988, pp 81–126.
32. Harris J, Thermal Lens Effect, in *Analytical Applications of Lasers*, (ed) Piepmeier E H, (Wiley-Interscience, New York), 1986, pp 451–554.
33. Sheldon S J, Knight L V, Thorne J M, Laser Induced Thermal Lens Effect: A New Theoretical Model, *Appl Opt*, 21(1982)1663–1669.
34. Shen J, Lowe R D, Snook R D, A Model for CW Laser Induced Mode-mismatched Dual-beam Thermal Lens Spectrometry, *Chem Phys*, 165(1992)385–396.
35. Marciano A, Loper C, Melikechi N, Pump-probe mode-mismatched thermal-lens Z scan, *J Opt Soc Am B*, 19(2002)119–124.
36. Rahman A, Rahim K, Ashraf I, Cabrera H, A Modified Mode-Mismatched Thermal Lens Spectrometry Z-Scan Model: An Exact General Approach, *Optik*, 265(2022)169399; doi.org/10.1016/j.ijleo.2022.169399.
37. Cabrera H, Akbar J, Korte D, Ramírez-Miquet E E, Marín E, Niemela E, Ebrahimpour Z, Mannatunga K, Franko M, Trace Detection and Photothermal Spectral Characterization by a Tuneable Thermal Lens Spectrometer with White-Light Excitation, *Talanta*, 183(2018)158–163.
38. Abbasgholi-NA B, Rahman A, D'Amico F, Cabrera H, LED-based thermal lens spectrometry with a double-pass probe beam optimized configuration, *Meas*, 252(2025)117392; doi.org/10.1016/j.measurement.2025.117392.
39. Cabrera H, Goljat L, Korte D, Marín M, Franko M, A multi-thermal-lens approach to evaluation of multi-pass probe beam configuration in thermal lens spectrometry, *Anal Chim Acta*, 1100(2020)182; doi.org/10.1016/j.aca.2019.12.009.
40. Cabrera H, Cedenio E, Grima P, Marín E, Calderon A, Delgado O, Thermal Lens Microscope Sensitivity Enhancement Using a Passive Fabry–Perot-type Optical Cavity, *Laser Phys Lett*, 13(2016)055702; doi.org/10.1088/1612-2011/13/5/055702.
41. Cabrera H, Akbar J, Korte D, Ashraf I, Ramírez-Miquet E E, Marín E, Niemela J, Absorption spectra of ethanol and water using a photothermal lens spectrophotometer, *Appl Spec*, 72(2018)1069; doi.org/10.1177/0003702818759073.
42. Abbasgholi-NA B, Asadig A, Cabrera H, Online electrophoretic nanoanalysis using miniaturized gel electrophoresis and thermal lens microscopy detection, *J Chromatogr A*, 1657(2021)462596; doi.org/10.1016/j.chroma.2021.462596.
43. Fata K, Segbéya G-T K, Douti D B L, Khammari B, Novidzro K M, Mohou M A, Rahman A, Ibnaouf K, Hannachi R, Cabrera H, Optimizing photothermal signal: Effects of detector position and pinhole radius in mode-mismatched Z-scan, *Appl Opt*, 65(2026)1794–1799.
44. Sakizadeh J D, Rachel Weiss R, Scholes G D, Kudisch B, Ultrafast Spectroscopy and Dynamics of Photoredox Catalysis, *Annu Rev Phys Chem*, 76(2025)203; doi.org/10.1146/annurev-physchem-082423-013952.
45. Hunt HK., Armani A M, Label-free biological and chemical sensors, *Nanoscale*, 2(2010)1544; doi.org/10.1039/C0NR00201A.

46. Cabrera H, Mendoza D, Benítez J L, Flores C B, Alvarado S, Marín E, Thermal diffusivity of few-layers graphene measured by an all-optical method, *J Phys D: App Phys*, 48(2015)465501; doi:10.1088/0022-3727/48/46/465501.
47. Jaramillo-Osorio J A, Velez-Zea A, Cabrera H, Niemela J, Barrera-Ramírez J F, Torroba R, Optical encryption using phase modulation generated by thermal lens effect, *J Opt*, 24(2022)025702; doi.org/10.1088/2040-8986/ac4412.

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