East European Journal of Physics. 1. 274–280 (2026)
DOI: 10.26565/2312-4334-2026-1-31 ISSN 2312-4334

MODELING OF THERMAL EFFECTS IN A POLYIMIDE TARGET UNDER PULSED LASER IRRADIATION

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Received September 8, 2025; revised December 16, 2025, accepted December 20, 2025

Polyimide is widely valued in modern technology due to its excellent thermal stability and mechanical strength. Understanding how it responds to pulsed laser irradiation is crucial for precise laser-based microfabrication and for interpreting the conditions that can lead to laser induced graphene (LIG) formation. In this study, we use COMSOL Multiphysics to simulate the temperature evolution and heat transfer in a polyimide sample exposed to pulsed laser radiation. The model takes into account temperature dependent thermal properties, laser absorption following the Beer-Lambert law, and the Gaussian energy profile of the laser beam. Our results show how laser fluence and pulse overlap influence heat accumulation within the polymer. While the actual graphene formation process is not modeled here, the thermal analysis provides valuable insight into the photothermal conditions relevant to LIG-related processes.

Keywords: *COMSOL Multiphysics; Thermal properties; Laser radiation; Polyimide*

PACS: 42.70.Hj, 42.62.Fi

1. INTRODUCTION

Polyimide materials have become an integral part of modern materials engineering owing to their outstanding thermal resistance and mechanical stability. These properties make them particularly suitable for applications in aerospace structures, electronic components, and automotive systems, where materials are often exposed to elevated temperatures and harsh operating environments [1, 2]. Despite their robustness, the precise processing of polyimides remains a challenging task, as excessive thermal loading can lead to unwanted material degradation. For this reason, processing techniques that offer both accuracy and controlled energy delivery are of considerable interest. Among such techniques, pulsed laser processing has proven to be an effective tool for polymer modification and micro-scale material treatment. By delivering energy in short, intense pulses, lasers enable localized heating while minimizing damage to surrounding regions [3, 4]. Laser sources such as CO_2 and Nd:YAG lasers are widely employed in materials processing because they provide flexibility in controlling pulse duration, energy density, and interaction time with the target material [2, 5–8]. From a physical perspective, understanding how laser energy is converted into heat and how this heat propagates within a polyimide substrate is essential for achieving reproducible and predictable processing results. However, the quantitative relationship between laser parameters and the resulting thermal distribution is still not fully understood and requires further theoretical and numerical investigation.

At the same time, significant research efforts in laser–matter interaction have been driven by the growing interest in graphene and graphene-related materials. Owing to their exceptional thermal and electrical properties, these materials are being explored for use in energy storage systems, thermoelectric devices, and photothermal applications [9–13]. In particular, laser-induced graphene has attracted attention as a rapid and scalable approach for modifying carbon-rich polymers [10]. Previous studies indicate that laser power, fluence, and irradiation conditions play a decisive role in defining the thermal environment in which structural transformations may occur [11, 12]. Furthermore, investigations of laser-induced plasma formation, surface nanostructuring, and heat accumulation effects have highlighted the importance of accurately describing temperature evolution during pulsed laser irradiation [13–18]. Although the present work does not address the formation or characterization of graphene itself, it focuses on a detailed numerical analysis of thermal processes in a polyimide target exposed to pulsed laser radiation. By modeling heat generation and transport under controlled laser conditions, this study aims to provide a clearer understanding of the thermal response of polyimides, which is a necessary step for interpreting and optimizing laser-based processing techniques, including those related to laser-induced graphene.

2. METHODOLOGY

This work involves modeling the thermal changes that occur when a polyimide material is exposed to laser radiation using COMSOL Multiphysics.

Cite as: J.O. Sadullayev, M.M. Akhmedov, M.E. Vapayev, I.Y. Davletov, G.S.Boltaev, East Eur. J. Phys. 1, 274 (2026), https://doi.org/10.26565/2312-4334-2026-1-31
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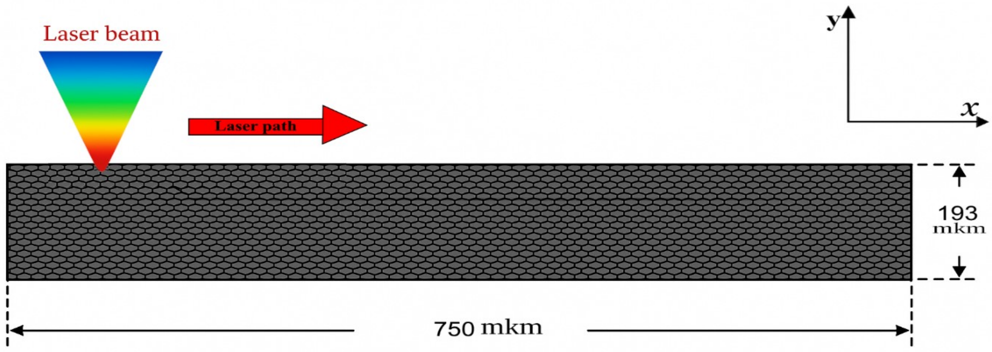

Figure 1. Schematic representation of the 2D-moving laser source simulation.

The parameters of pulsed laser radiation are given in Table 1. The spatial distribution of the incident laser beam on the polyimide surface was modeled, and temperature distribution and heat-related processes were studied. The theoretical model developed is schematically represented in Figure 1. The thermal parameters and geometric dimensions of the polyimide material chosen to model the increase in temperature and the dissipation of heat at the point of impact of the laser beam are given in Table 2.

To better reflect the physical nature of the laser polyimide interaction, the numerical model accounts for the temperature dependence of key thermal properties, including thermal conductivity, heat capacity, and density. Heat transport within the polyimide was described by solving the transient heat conduction equation, while laser irradiation was introduced as a surface heat source with a Gaussian intensity distribution. In addition, reflection losses at the air polyimide interface were considered, and laser energy absorption within the material was evaluated using the Beer–Lambert law. The simulations were carried out under transient conditions in order to capture the time-dependent evolution of temperature during pulsed laser exposure.

Table 1. Laser machining parameters

Nomenclature	Value (units)	Property
f	$10[kHz]$	Number of laser pulses
E_p	$170[\mu J]$	Pulse energy
P_w	250[fs]	Pulse width
D	$150[\mu m]$	Beam diametr
ϵ	0.7	Emissivity
A	0.8	Absorptivity
x_r	$1000[\mu m]$	Reference point to represents the center of the laser beam
x_d	$100[\mu m]$	Standard deviation of the Gaussian laser beam
v	$700mm/s$	Laser scan speed

3. RESULTS AND ANALYSIS

The geometry of the polyimide for modeling was entered into the COMSOL program. The thickness of the polyimide is 168 μm and the density is 1400 kg/m^3. The values of the thermal parameters of the polyimide are given in Table 2. The heat dissipation of the polyimide under the influence of laser radiation was calculated using the Fourier heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q$$

where: ρ is the density of the material, C_p is the heat capacity, k is the thermal conductivity, T is the temperature, and q is the heat source (laser energy). The density, heat capacity, and thermal conductivity vary with temperature.

Table 2. Material properties of polymide parameters

Nomenclature	Value (units)	Property
T_m	723 [K]	Melting temperature
T_v	1173 [K]	Vaporization temperature
L_m	250 [J/g]	Latent heat of melting
L_v	5000 [J/g]	Latent heat of evaporation
β	$5 * 10^-5[1/K]$	Thermal expansion coefficient
γ	$-3 * 10^-4[N/(m * K)]$	Temperature derivative of the surface tension
h_1	$17[W/(m^2 * K)]$	Heat transfer coefficeient
δT	30 [K]	Half-width of the curve
T_a	293.15 [K]	Ambient temperature
T_i	293.15 [K]	Initial temperature
H	$193[\mu m]$	Height of the simple
W	$750[\mu m]$	Simple Width

Table 3. Material properties and heat transfer model equations for polyimide

Name	Equation	No.
Temperature-dependent specific heat at constant pressure (C_p)	$C_p = 1000\left[0.96 + 1.39\left(\frac{T-300}{400}\right) - 0.43\left(\frac{T-300}{400}\right)^2\right]$	1
Governing equation	$\rho C_p \frac{\partial T}{\partial t} = k\left[\left(\frac{\partial^2 T}{\partial x^2}\right) + \left(\frac{\partial^2 T}{\partial y^2}\right)\right]$	2
Beer–Lambert law	$C\frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + \alpha(1-R)I_0 e^{-\alpha z}\sum_{n=0}^{4} e^{-2((x-n\delta x)^2+y^2)/w^2}$	3
	$\sum_{n=0}^{4} f(t - nt_{\text{shift}})$	4
Average laser power density in Gaussian distribution	$P_g = A\left[\frac{E_p}{P_w\left(\frac{\pi D^2}{2}\right)}\right]\exp\left[-\left(\frac{(x-x_f)^2}{2\sigma^2}\right)\right]$	5
Analytic function	$\beta = \text{rect}\left(\text{mod}\left(\frac{t}{t_r}\right)\right)$	6
Thermal conductivity (k)	$k = \begin{cases} 0.213 + 3.416\times 10^{-5}T, & 200\text{K} < T < 729\text{K} \\ -1.314 + 2.130\times 10^{-3}T, & 729\text{K} < T < 1500\text{K} \end{cases}$	7
Reflectivity (R)	$R = \begin{cases} 0.74, & T < 858\text{K} \\ 0.36, & T > 858\text{K} \end{cases}$	8

The relationship between density and temperature is often expressed in terms of the thermal expansion coefficient.

$$\rho(T) = \rho_0 \cdot (1 - \beta(T - T_0))$$

where $\rho(T)$ is the density at temperature T, ρ_0 is the initial density at $T_0 = 293.15\,\text{K}$, and β is the thermal expansion coefficient ($5 \times 10^{-5}\,\text{K}^{-1}$).

Figure 2 shows a graph of the relationship between the density and temperature of polyimide. In this case, the density of polyimide decreases linearly as the temperature increases.

The relationship between the thermal conductivity and temperature of polyimide [8] is given in Equation 6 of Table 3. Polyimide changes in small values from its initial temperature to its melting temperature and increases sharply from the melting temperature to its evaporation temperature (Figure 3). From this we can see that the thermal conductivity is high between the melting and evaporation temperatures of polyimide. This temperature dependent behavior of thermal conductivity provides insight into the thermal regimes that may be relevant for laser induced modification of polyimide based materials

To determine the relationship between the temperature and heat capacity of polyimide, an empirical expression developed by theoretical methods, Equation 1 in Table 3, was used [8]. Using the thermal coefficients of polyimide given in Table 2, a graph of the relationship between heat capacity and temperature was created (Figure 4). In this case, the heat capacity of polyimide increases sharply and begins to decrease when it reaches the evaporation temperature.

By analyzing the temperature dependence of density, thermal conductivity, and heat capacity of polyimide, the present study aims to characterize thermal conditions that are relevant for understanding laser–polymer interaction processes. We define the spatial coherence of laser pulses as the dimensionless number of laser pulses per illuminated [19–22]. The temperature distribution is calculated by the 2D heat transfer equation and the laser pulse acts as a surface heat source, as shown in equation (3) of Table 3. The light reflection coefficient between air and polyimide is calculated and the

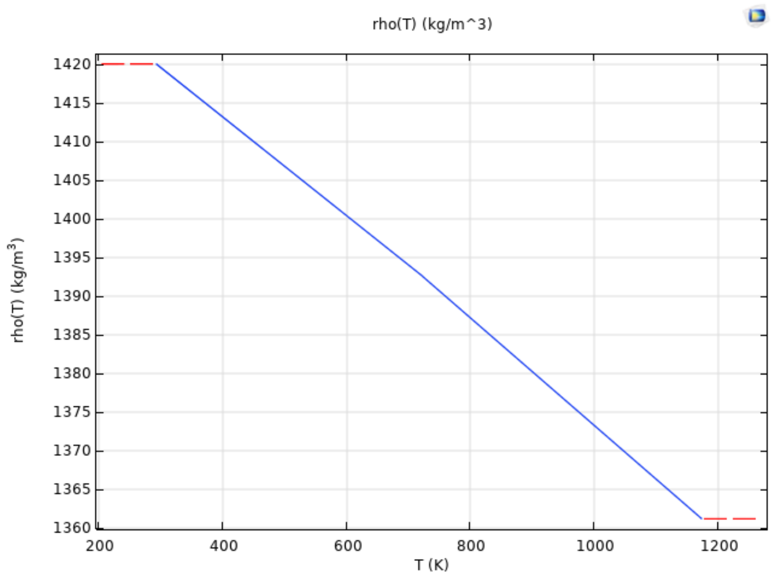

Figure 2. Relationship between density and temperature of polyimide

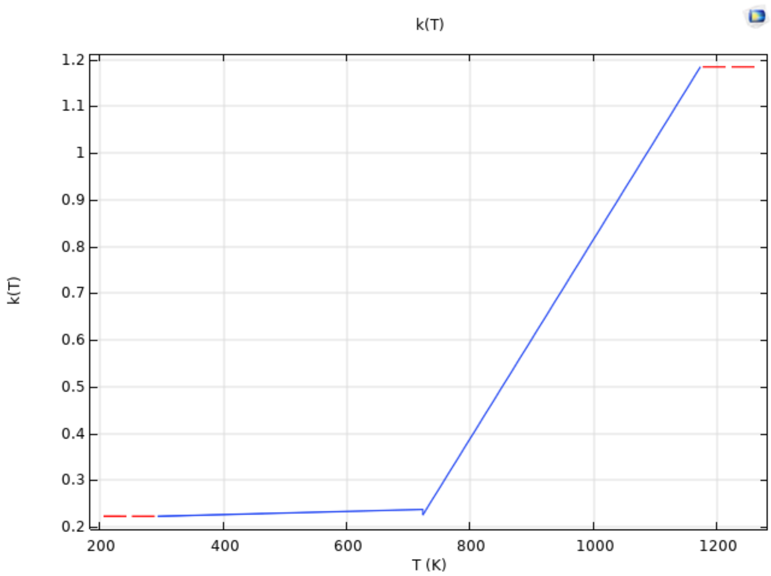

Figure 3. Relationship between temperature and thermal conductivity of polyimide

absorption is based on the Beer-Lambert law. The 2D temperature distribution of the polyimide in the plane is shown in Figures 5(a)–(c). The scanning speed of the laser beam is 40 mm/s and the pulse overlap is 18%, resulting in energy fluxes of (a) 0.7 J/cm^2, (b) 0.9 J/cm^2, and (c) 1 J/cm^2.It should be emphasized that the present analysis is limited to numerical modeling of thermal properties and temperature fields in polyimide under pulsed laser irradiation. While the obtained thermal profiles provide useful insight into temperature regimes relevant to laser–matter interaction in polyimide [23–26], the formation of graphene itself is not directly modeled or experimentally verified in this work [27–30].

4. CONCLUSIONS

In summary, this work presents a numerical study of the thermal behavior of a polyimide target exposed to pulsed laser radiation using COMSOL Multiphysics. The simulations show that the evolution of temperature within the material is mainly controlled by the laser energy flux and the temporal characteristics of the pulses, which together determine the extent of heat accumulation during irradiation. Surface temperature distributions were evaluated for typical processing parameters, including a laser scanning speed of 40 mm/s, a pulse overlap of 18%, and energy flux levels ranging from 0.7 to 1.0 J/cm^2.

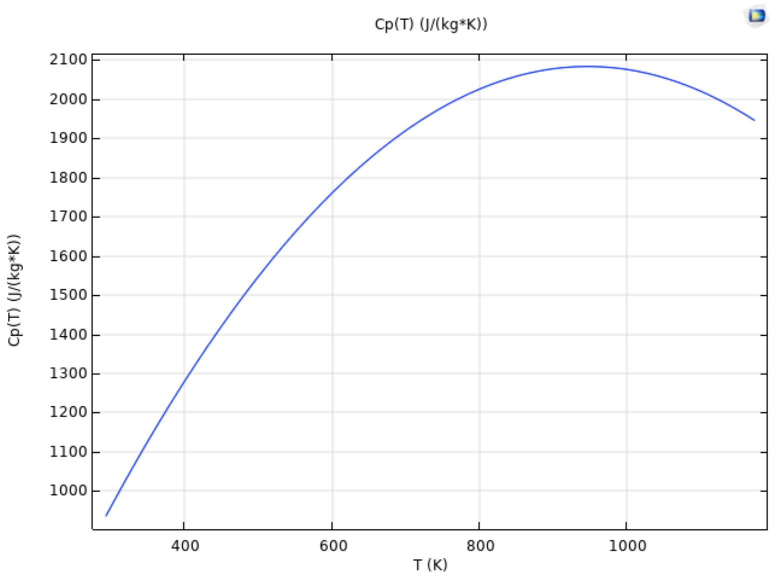

Figure 4. Relationship between heat capacity and temperature of polyimide

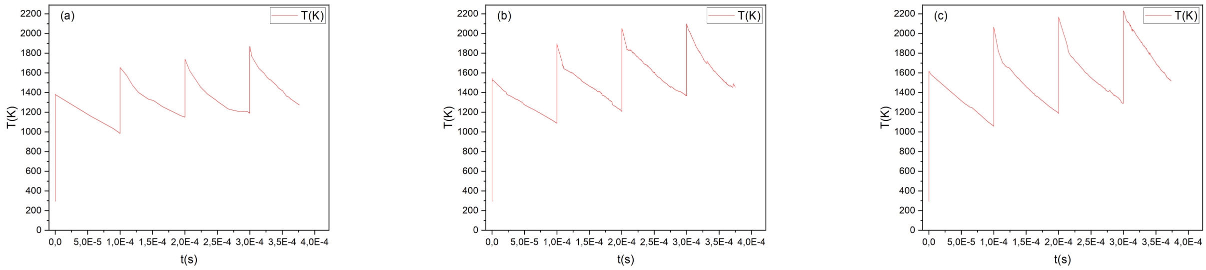

Figure 5. Presents the spatial temperature distribution with an 18.7% overlap between consecutive laser spots for laser fluences of (a) 0.7 J/cm², (b) 0.9 J/cm², and (c) 1 J/cm².

The results indicate that relatively small adjustments in laser parameters can produce noticeable changes in surface temperature, underscoring the need for careful control of processing conditions in applications where high precision is required. While the present study is restricted to numerical modeling and does not include experimental validation, the obtained thermal analysis offers useful guidance for selecting appropriate laser operating regimes and for interpreting heat-related phenomena in polyimide-based materials.

Acknowledgments

We acknowledge the F-FA-2021-510 Grant from the Ministry of Innovative Development of Uzbekistan.

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МОДЕЛЮВАННЯ ТЕПЛОВИХ ЕФЕКТІВ У ПОЛІІМІДНІЙ МІШЕНІ ПІД ВПЛИВОМ ІМПУЛЬСНОГО ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ

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Поліімід широко цінується в сучасних технологіях завдяки своїй чудовій термостабільності та механічній міцності. Розуміння того, як він реагує на імпульсне лазерне опромінення, має вирішальне значення для точного лазерного мікровиробництва та для інтерпретації умов, які можуть призвести до утворення лазерно-індукованого графену (LIG). У цьому дослідженні ми використовуємо COMSOL Multiphysics для моделювання зміни температури та теплопередачі у зразку поліііміду, що піддається впливу імпульсного лазерного випромінювання. Модель враховує температурно-залежні теплові властивості, поглинання лазера згідно із законом Бера-Ламберта та гауссів енергетичний профіль лазерного променя. Наші результати показують, як лазерний флюенс та перекриття імпульсів впливають на накопичення тепла в полімері. Хоча сам процес утворення графену тут не моделюється, термічний аналіз надає цінну інформацію про фототермічні умови, що стосуються процесів, пов'язаних з LIG.

Ключові слова: *COMSOL Multiphysics; теплові властивості; лазерне випромінювання; поліімід*