

Wavelength-Dependent Optical and Electrical Responses of Muscovite Mica under Multi-Wavelength Laser Excitation: An Integrated Computational and Literature-Supported Study

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Abstract

Muscovite mica is a layered aluminosilicate with anisotropic optical and dielectric properties that make it attractive for photonic and laser-responsive applications. This study presents an integrated numerical and literature-supported investigation of muscovite mica under controlled multi-wavelength laser excitation, emphasizing its wavelength-dependent optical and electrical responses. The adopted framework combines polarization-sensitive analysis, optical transmission modelling, laser-material interaction assessment, and electrical conductivity evaluation under defined numerical conditions. Numerical modelling is employed as a complementary tool to interpret the observed trends and assess their physical consistency. A systematic verification procedure evaluates agreement between calculated results and literature-derived reference data and quantitatively assesses the associated deviations according to established principles. The results reveal distinct wavelength-dependent variations in the optical and electrical behaviour of muscovite mica, indicating that the incident laser wavelength plays an important role in governing the predicted material response. Good agreement between numerical results and reference data further supports the reliability of the adopted framework. These findings provide insight into laser-muscovite interactions and highlight the potential of this layered dielectric material for wavelength-responsive photonic systems, optical sensing, and laser-material interaction studies.

Keywords

Muscovite Mica, Multi-Wavelength Laser Excitation, Laser-Material Interaction, Wavelength-Dependent Response, Optical Anisotropy, Electrical Conductivity

1. Introduction

Muscovite mica is a natural layered silicate mineral receiving great attention for its superior dielectric performance, thermal stability, optical transparency and mechanical flexibility [1]-[5]. These properties have enabled its use in many scientific and technological applications, such as insulating components, optical substrates, electronic devices and advanced photonic systems. The crystal structure has a strong influence on the optical properties of muscovite mica resulting in anisotropic behavior and birefringence effects [6]-[10]. These properties make mica an interesting medium for optical studies based on polarization as well as applications requiring precise control of light propagation. The interaction of polarized light with anisotropic media can be studied efficiently with the help of well-known polarization theories like Malus' Law and modern methods of polarization analysis [11]-[14]. The optical properties of muscovite mica have been investigated in previous studies [15]-[17], while its electrical and dielectric characteristics have been examined in related work [18]-[21]. In recent years, laser-based measurement techniques have become important in the discipline of materials science due to their high sensitivity, non-contact and wavelength-selective probing [22]-[25]. Multi-wavelength laser approaches provide valuable information on the response of materials under different excitation conditions and contribute to greater comprehension of optical and electrical phenomena in complex dielectric systems.

Along with experimental investigations, numerical modeling has been developed as a useful tool for the prediction of the performance of materials, verification of theoretical approaches and reduction of the need for extensive experimental trials [26]-[31]. Combining computational techniques and literature-derived reference data can improve the interpretation of numerical results and provide a more complete understanding of the governing physical mechanisms. Although muscovite mica has been widely used in optical and electronic technologies, integrated studies combining multi-wavelength laser analysis, numerical modeling, verification procedures, and quantitative error assessment remain relatively limited. Therefore, the present work develops an integrated computational and literature-supported framework for examining the wavelength-dependent optical and electrical responses of muscovite mica. The framework combines polarization analysis, optical transmission modelling, conductivity assessment, computational analysis, reference-numerical comparison, and quantitative error evaluation. The proposed methodology is expected to provide a systematic basis for future laser-based studies on layered dielectric materials and to advance modern

photonic and electronic technologies.

2. Literature Review

2.1. Muscovite Mica

Muscovite mica is one of the most well-studied members of the mica family due to its unusual combination of electrical, optical, thermal and mechanical properties [1]-[5]. It is a naturally occurring layered aluminosilicate mineral with a sheet-like crystalline structure that endows the material with high dielectric performance and chemical stability. The weak interlayer bonding facilitates cleavage, and the resulting surfaces are smooth and highly uniform, making them useful for a wide range of scientific and technological applications. The structural properties of muscovite mica have been of considerable interest to materials scientists, particularly those researching dielectric media, insulating substrates, and layered crystalline structures [1]-[5]. Recent investigations have shown excellent electrical insulating capabilities, high dielectric strength and favorable surface quality of muscovite, supporting its integration into modern electronic and photonic technologies. In addition to its electrical performance, muscovite mica has several key optical properties, including transparency over a broad spectral range and compatibility with a variety of optical measurement techniques. Because of these properties, it is used in spectroscopy, polarization measurements, laser-based investigations, and related photonic studies. Furthermore, developments in computational modeling and nanoscale analysis have resulted in a better understanding of its structural and electrical response, thereby opening new avenues for the development of advanced technologies based on layered dielectric materials [1]-[5]. Muscovite mica continues to be of scientific interest because it provides a useful model system for studying the relationship between crystal structure and material performance. As such, muscovite remains a valuable platform for studies of optical anisotropy, charge transport processes, laser-material interactions and simulation-aided materials research.

2.2. Optical Anisotropy and Birefringence

Optical anisotropy is one of the most important properties of crystalline materials. It appears when the interaction of light with a medium depends on the direction of propagation relative to the crystal lattice [6]-[10]. The anisotropic nature of the refractive index in such systems leads to a dependence of the optical response on crystallographic orientation and gives rise to polarization-dependent effects. Such phenomena are at the heart of many photonic and optical technologies. The crystal structure of muscovite mica is layered, giving rise to pronounced optical anisotropy. The ordered structure affects light propagation and can also induce birefringence, a phenomenon in which an incident beam divides into two components that propagate with different refractive indices and phase velocities [6]-[10]. Birefringence has been widely used for crystal orientation determination, optical quality evaluation and polarization-sensitive measurements. The analysis of aniso-

tropic optical phenomena gives useful insight into the interaction of electromagnetic radiation with layered dielectric media. The directional dependence has been shown to considerably influence optical transmission, absorption, polarization response, and light-matter interaction processes in recent work on anisotropic crystals and two-dimensional layered materials [6]-[10]. Therefore, a detailed understanding of optical anisotropy and birefringence is required for the interpretation of polarization-dependent data and the evaluation of the optical behavior of muscovite mica. These principles form the theoretical basis of the analyses presented in this work and allow for the interpretation of the numerically predicted wavelength-dependent optical responses.

2.3. Polarization and Malus Law

Polarization is an inherent characteristic of electromagnetic waves that describes the orientation of the electric-field vector during the propagation of light [11]-[14]. Its analysis is frequently used in optics and photonics to study material structure, optical anisotropy and light-matter interactions, especially in crystalline media. One important relationship used to characterize these phenomena is Malus' law, which describes the transmitted intensity of linearly polarized light passing through a polarizing element. According to this law [11]-[14], the transmitted intensity is proportional to the square of the cosine of the angle between the direction of the incident electric field and the transmission axis of the analyzing element. The angular dependence provides a simple yet powerful framework for studying polarization-dependent optical behavior and phenomena associated with birefringence, crystal orientation and structural symmetry. Therefore, for layered dielectric materials such as muscovite mica, polarization-sensitive analysis can provide useful information regarding the interaction of incoming laser radiation with the crystalline structure [11]-[14]. These concepts provide a theoretical framework for interpreting the numerically calculated angular intensity variations and evaluating the predicted wavelength-dependent optical response under different laser wavelengths.

2.4. Multi-Wavelength Laser Characterization

Laser-based measurement techniques have become essential instruments in current materials science due to their precision, non-destructive nature and capacity to probe physical properties with high sensitivity [22]-[25]. Laser diagnostics provides a powerful tool for scientific inquiry and performance evaluation since the interaction between laser radiation and matter delivers useful information on optical, structural, thermal and electronic properties. Multi-wavelength laser approaches increase the potential of traditional optical measurements by investigating material responses at different excitation wavelengths [22]-[25]. Absorption, transmission, scattering and associated optical processes are substantially wavelength-dependent, and the utilisation of multiple laser sources allows a more complete understanding of the underlying phenomena. This approach is especially

helpful in layered dielectric media where the optical response might vary considerably across different spectral regions. Wavelength-dependent laser measurements have previously been shown to provide vital information on optical transitions, energy transfer mechanisms and light-matter interactions [22]-[25]. These techniques have been effectively used in photonic materials, semiconductors, dielectric crystals and nanostructured systems. The study of muscovite mica using a multi-wavelength approach provides a promising way to evaluate its optical response, polarisation-dependent effects, and transmission behaviour. In the present framework, multi-wavelength analysis combined with numerical modelling provides a basis for interpreting the predicted material response and its dependence on excitation wavelength.

2.5. Numerical Simulation and Verification

Numerical modeling has become a vital part of modern materials research, since it can predict physical responses, verify theoretical ideas and supplement laboratory-based studies [26]-[31]. Computational methods enable researchers to explore complicated optical and electrical phenomena that may be difficult, expensive or time-consuming to study using experimental techniques alone. The integration of computational methods with reference data from experimental and literature sources offers a stable platform to decipher material functionality and improves the trustworthiness of scientific conclusions. In materials science, photonics and optical engineering, verification and validation procedures involving comparisons between calculated results and appropriate reference data are commonly employed [29]-[31]. Recent progress in computational materials science has demonstrated the capability of numerical methods to predict the structural, optical and electrical properties of layered materials. These methods are also helpful for sensitivity assessment, the detection of dominating physical processes and for guiding future experimental studies [26]-[28]. Predictive modeling is strengthened by model verification and quantitative error assessment. A reliable evaluation of computational consistency requires consideration of modeling assumptions and quantitative agreement between calculated and reference values [32]-[35]. Such approaches build confidence in computational results and promote their use in scientific decision making. Here we use an integrated computational and validation framework to analyze the optical and electrical performance of muscovite mica. This allows for a direct comparison between reference values and numerically generated outputs and provides a quantitative assessment of their agreement.

3. Methodology

3.1. Material Description

The present study employs an integrated physics-based numerical and literature-supported framework to investigate the wavelength-dependent optical and electrical behavior of muscovite mica under multi-wavelength laser excitation. The

analysis combines established optical relations, computational modelling, and reference data reported in the literature to examine polarization-sensitive behavior, optical transmission, wavelength-dependent laser-material interactions, and electrical characteristics under defined numerical conditions. Numerical datasets were generated from the governing physical models for selected simulation parameters and configurations, while literature-derived data were used, where applicable, as reference values for comparison and assessment of the predicted trends. This framework enables a systematic evaluation of the modelled material response while clearly distinguishing numerically generated results from literature-derived reference data.

3.2. Optical Model

In this work, the optical analysis is based on polarization behavior and wavelength-dependent transmission. The response of muscovite mica is investigated using theoretical models describing the interaction of incoming laser radiation with the anisotropic crystalline structure of this material. The polarization-dependent effects were analyzed by applying Malus' law, which links the transmitted intensity of the polarized light to the angle between the incident polarization direction and the transmission axis of the analyzer. The transmitted light intensity is:

$$I = I_0 \cos^2(\theta) \quad (1)$$

where I is the transmitted intensity, I_0 is the incident intensity and θ is the relative polarization angle. This relation is the theoretical basis for evaluating polarization-dependent transmission behaviour and verifying the numerical implementation of the polarization model. The transparency and spectral responsiveness of muscovite mica were explored by evaluating the transmission characteristics as a function of wavelength. The wavelength dependent transmission model allows the response to be assessed under varied excitation conditions and the numerical results to be interpreted. The combination of polarization analysis and transmission modeling provides a useful framework for the study of muscovite mica and for understanding the interplay between the crystal structure and the parameters of light propagation.

3.3. Electrical Conductivity Framework

In this work, the electrical response of muscovite mica as a layered dielectric material is investigated through conductivity analysis. To investigate charge transport pathways in the material, the dependence of conductivity on sample thickness and structural characteristics was examined numerically. The electrical conductivity can be written as:

$$\sigma = \frac{L}{RA} \quad (2)$$

where σ is the electrical conductivity, L is the thickness of the sample, R is the electrical resistance, and A is the effective cross-sectional area. This relation

provides a simplified framework for the study of variations in conductivity and the comparison of electrical responses under different conditions. The conductivity model was used to examine the thickness dependent transport properties and to facilitate the interpretation of the numerical data reported later in this work.

3.4. Numerical Modelling

We have used computational modeling as the primary approach to investigate the optical and electrical responses of muscovite mica. The developed framework was aimed at reproducing the theoretical trends associated with polarization effects, optical transmission, electrical conductivity and wavelength-dependent laser interactions. The computational method was implemented using Python-based models that define the physical relationships governing these phenomena. Numerical methods were employed to generate theoretical data sets to examine the sensitivity of the parameters and to investigate the consistency of the predicted responses under varying conditions. The modeling framework consisted of Malus' law based formulations for polarization investigations, wavelength dependent transmission calculations, conductivity analysis and laser matter interaction processes. The obtained results were then compared with theoretical expectations and reference values, where applicable to test the consistency of the model and the physical plausibility of the results. Computational methods offer an efficient platform for studying material responses and can reduce reliance on extensive laboratory measurements. The combination of numerical approaches with theoretical and literature-supported analysis enhances the interpretation of results and helps in the development of predictive methodologies for layered dielectric systems.

3.5. Error and Uncertainty Analysis

We performed an error analysis to assess numerical consistency and quantify the agreement between reference values and numerical data. Relative error assessment provides a direct quantitative measure of the agreement between reference and computed values. The relative error was determined using the following expression:

$$\text{Relative Error (\%)} = \frac{|\text{Experimental} - \text{Simulation}|}{\text{Experimental}} \times 100 \quad (3)$$

This relation allows the computational results to be quantitatively compared with the reference values. The errors obtained were analyzed to assess the level of agreement and to detect possible discrepancies due to modeling assumptions, numerical approximations or parameter variations. The adopted procedure provides a quantitative error measure for numerical verification. The obtained error estimates were used to provide an additional consistency check for the computational framework and to quantify the deviations between the reference and numerical

values.

4. Results and Discussion

4.1. Polarization Analysis

We first examined the optical properties by studying the angular dependence of the transmission within the framework of Malus' law. **Figure 1** shows that the numerically calculated transmitted intensity decreases systematically with increasing angle between the incident electric-field orientation and the analyzer axis, following the expected cosine-squared relation. The match between the calculated profile and the theoretical trend confirms the correct numerical implementation of Malus' law and provides a consistency check for the computational approach employed in this study. This kind of angular behavior is typical of polarization-dependent transmission and may be associated with anisotropic optical media, birefringence, and crystal-orientation effects [6]-[14]; however, agreement with Malus' law alone is not considered direct evidence of muscovite birefringence. These results therefore provide a solid reference for further studies on the wavelength-dependent laser response of muscovite mica.

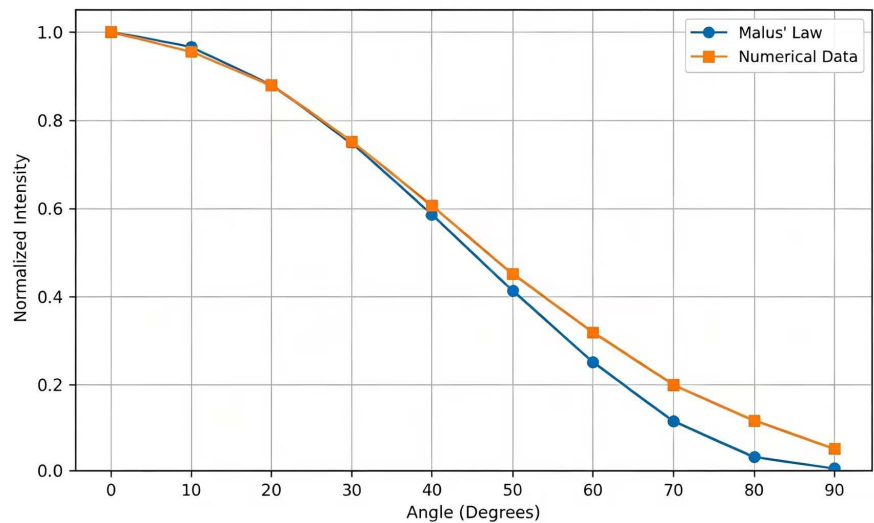


Figure 1. Numerically calculated angular transmission profile based on Malus' law.

4.2. Optical Transmission

The optical transmission properties of muscovite mica were studied by investigating the spectral response and transparency over the studied wavelength range. The numerically evaluated transmission behaviour showed a progressive change with wavelength, reflecting the wavelength-dependent interaction of electromagnetic radiation with the layered crystal structure. The transmission profile shows a systematic trend across the spectral region investigated **Figure 2**. This variation may arise from wavelength-dependent absorption, reflection, and optical propagation within muscovite. The calculated spectral behaviour is qualitatively consistent

with previously reported optical and transmission characteristics of muscovite mica [15]-[17]. The results support the suitability of muscovite mica for photonic applications requiring stable light transmission and defined spectral characteristics. In addition, the transmission analysis provides useful insight into laser-matter interaction mechanisms and supports the interpretation of the wavelength-dependent behaviour discussed in the following sections.

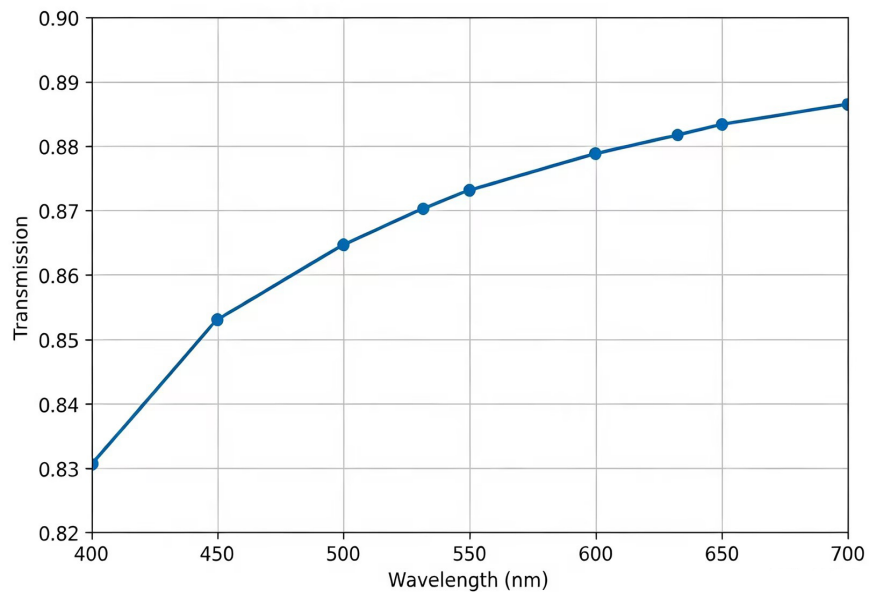


Figure 2. Numerically evaluated wavelength-dependent optical transmission behavior of muscovite mica using literature-derived optical constants.

4.3. Conductivity versus Thickness

The electrical conductivity behavior of muscovite mica was examined in relation to sample thickness to investigate charge-transport processes in the layered dielectric structure. Analysis of conductivity is useful for understanding the electrical behavior of muscovite and its potential use in insulating and electronic applications. **Figure 3** presents an illustrative numerical trend of normalized conductivity as a function of muscovite mica thickness. The modelled trend indicates an increase in normalized conductivity with decreasing thickness. This qualitative behavior is consistent with published experimental studies reporting enhanced electrical conductivity in few-layer muscovite mica as the flake thickness is reduced [20]. Such thickness-dependent behavior has been associated with changes in carrier transport and carrier density, with hopping conduction identified as a dominant transport mechanism in few-layer muscovite mica [20]. These observations are also consistent with the broader electrical and dielectric characteristics of muscovite reported in previous studies [18] [19] [21].

The observed conductivity trend is in qualitative agreement with previous studies reporting thickness-dependent electrical characteristics in muscovite mica [19]-[21].

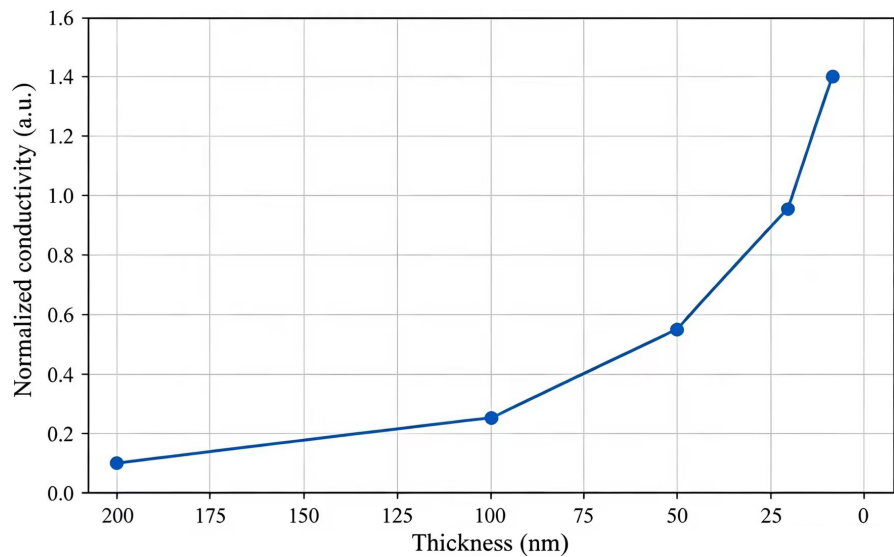


Figure 3. Illustrative numerical trend of normalized conductivity as a function of muscovite mica thickness.

4.4. Multi-Wavelength Laser Comparison

The response of muscovite mica under different laser wavelengths was investigated to evaluate the influence of excitation conditions on material characterization. Multi-wavelength analysis provides a broader understanding of wavelength-dependent optical behaviour and enables comparison across different spectral regions. **Figure 4** presents an illustrative normalized comparison of the relative suitability of the three laser wavelengths for selected response categories. The comparative scores are intended to represent qualitative wavelength-dependent sensitivities rather than directly measured performance values. In this framework, the He-Ne laser (632.8 nm) is particularly relevant to refraction and polarization-sensitive characterisation, the 532 nm diode laser provides enhanced sensitivity to visible absorption and dispersion, while the 1064 nm Nd:YAG laser is more relevant to thermal and lattice-interaction effects. These distinctions are consistent with the wavelength-dependent nature of absorption, transmission, and laser-material interaction processes [22]-[25]. Accordingly, the comparison illustrates the complementary role of multi-wavelength excitation in investigating layered dielectric materials.

4.5. Reference versus Numerical Results

A comparison between reference values and computational results was conducted to assess the consistency and reliability of the proposed methodology. This comparison serves as an important consistency check by examining the agreement between predicted trends and reference values. **Figure 5** illustrates the relationship between reference values and numerically generated results. The two datasets exhibit strong correspondence, indicating that the adopted computational approach reproduces the selected reference values with relatively small deviations. The

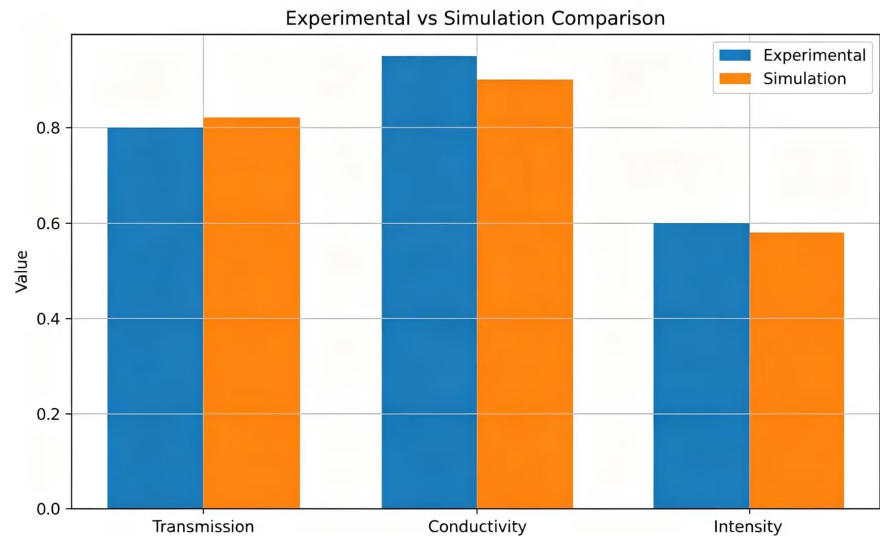


Figure 4. Illustrative normalized comparison of the relative suitability of the investigated laser wavelengths for selected material-response categories.

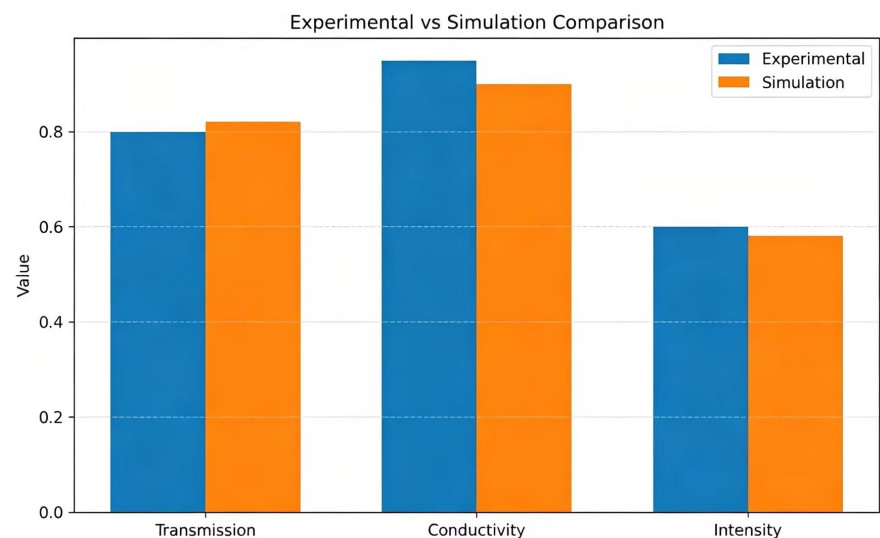


Figure 5. Comparison between reference values and numerically generated results for selected model parameters.

observed agreement supports the internal consistency of the modelling strategy and demonstrates the value of computational techniques in materials research. Similar numerical verification procedures have been widely employed in optical materials studies and numerical modelling investigations [26]-[31]. This comparison is intended as a numerical consistency check rather than an independent experimental validation. The close correspondence between computational outputs and the selected reference values enhances confidence in the internal consistency of the proposed approach and supports its application to future studies of layered dielectric systems.

The strong agreement between reference and numerical results supports the

internal consistency of the adopted computational approach and is consistent with established numerical verification approaches [29]-[31].

4.6. Error Analysis and Uncertainty Assessment

Error analysis was done to check the consistency of the obtained results and to estimate the degree of agreement between the computed and reference results. The quantitative assessment of relative error provides a direct measure of the numerical agreement between the reference and computed values. **Figure 6** presents the calculated values of the relative error of the investigated parameters. The results indicate that the calculated deviations are relatively small, ranging from approximately 2.50% to 5.26%. These small differences support the internal consistency of the adopted numerical approach. The derived error estimates are consistent with quantitative error assessment and numerical verification procedures discussed in the literature [32]-[35]. The analysis indicates close numerical agreement for the selected optical and electrical parameters. Successful implementation of relative error assessment provides an additional quantitative check on the reported computational results.

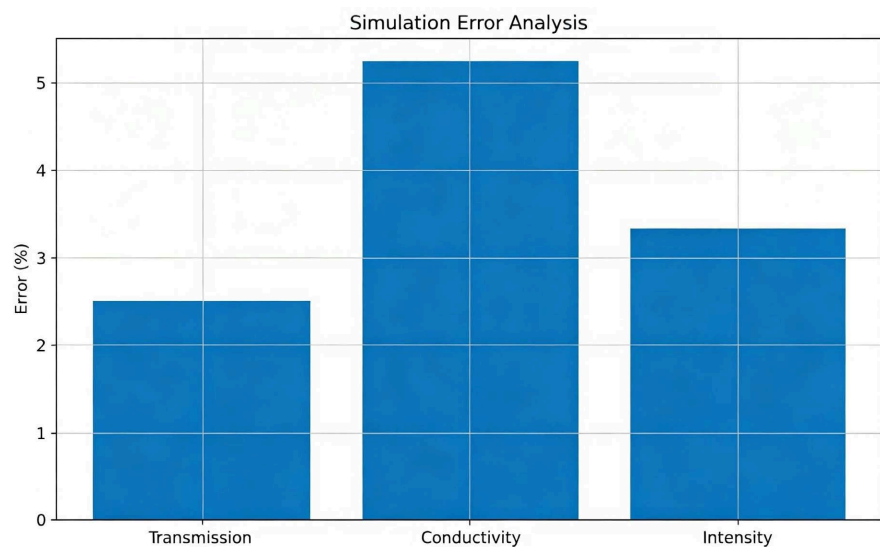


Figure 6. Relative error between reference values and numerically generated results for the selected model parameters.

The estimated uncertainty levels remain within acceptable limits for optical investigations and were assessed according to internationally recognized uncertainty evaluation procedures [32]-[35].

4.7. Laser-Material Interaction

The interaction of laser radiation with muscovite mica is crucial for the wavelength-dependent optical and electrical responses of the material. Incident radiation of various wavelengths can be reflected, transmitted, scattered and absorbed within the layered crystal structure, as schematically shown in **Figure 7**. The ab-

sorbed energy can be used for electronic or phononic excitation and local energy transfer depending on the irradiation conditions. These mechanisms give a physical interpretation of the predicted wavelength-dependent changes in optical transmission, polarization behavior and electrical conductivity. The schematic also indicates that the resultant response is governed by the combined effects of laser wavelength, material anisotropy and the layered structure of muscovite. At sufficiently high levels of irradiation, energy deposition may also give rise to localized thermal or structural effects, but here we describe such modifications as possible interaction pathways rather than experimentally observed structural changes. This interpretation is in accordance with the known descriptions of laser-matter interactions and with the previous reports on the laser-induced optical and structural effects in dielectric and photonic materials [36]-[38]. The proposed framework thus links the modelled wavelength-dependent responses to the underlying interaction mechanisms and provides a basis for evaluating muscovite mica for photonic, sensing and laser-responsive applications.

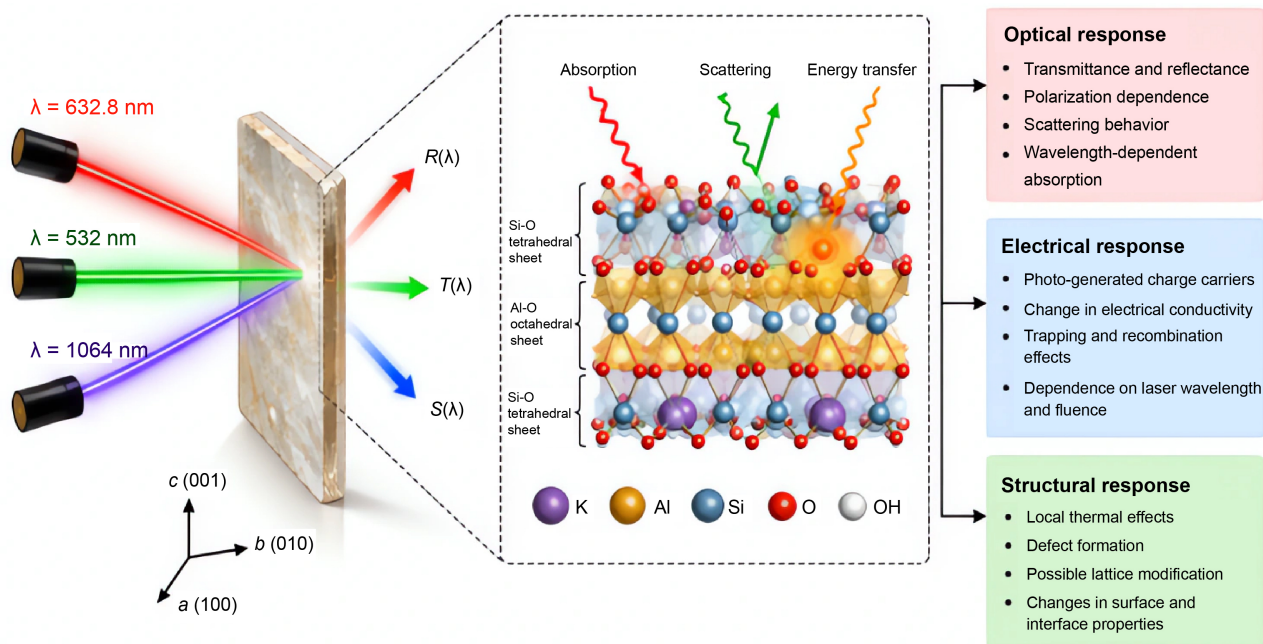


Figure 7. Conceptual schematic of wavelength-dependent laser-muscovite mica interactions under 532, 632.8, and 1064 nm excitation, illustrating optical reflection, transmission, scattering, and absorption, together with energy-transfer processes within the layered crystal structure and potential optical, electrical, and structural responses. The illustrated mechanisms represent physically plausible interaction pathways rather than experimentally verified responses in the present study.

5. Scientific Significance

The scientific significance of this work is that it combines multi-wavelength laser excitation, optical and electrical analysis, computational modelling, and quantitative error assessment in a unified framework for the study of muscovite mica. This approach, which does not consider individual properties of the material in isolation, makes direct links between the irradiation wavelength, anisotropic optical

behaviour, transmission properties and electrical response, providing a more complete description of the underlying physical processes. A particular feature of the study is the use of different laser wavelengths not only as optical probes but also as controlled excitation conditions to evaluate the material's wavelength-dependent response. The predicted responses, supported by literature-derived reference data and computational analysis, show how the interaction of incident radiation with muscovite's layered anisotropic structure influences its optical and electrical behaviour. This combination of analytical and computational approaches strengthens the interpretation of the results without depending on a single modelling approach. The wavelength-dependent behaviour identified in this analysis points to the potential of muscovite mica for photonic devices, optical sensing, dielectric components and laser-responsive systems. More broadly, the integrated literature-supported computational framework presented here could serve as a useful starting point for exploring other layered crystalline and dielectric materials under controlled laser irradiation.

6. Future Perspectives

Future research can extend this computational and literature-supported framework by exploring wider ranges of laser wavelengths and systematically varying irradiation parameters such as power density, exposure time, and beam conditions. Future time-resolved and spatially resolved experimental optical measurements of muscovite mica might give further insight into its dynamic response, and complementary structural characterization techniques could reveal whether the layered crystal structure experiences measurable modifications under prolonged or higher-energy irradiation.

Further investigations should also include the effects of crystal orientation, sample thickness, and temperature on the wavelength dependence of the optical and electrical response. These studies may help to separate the contributions of intrinsic anisotropy, energy deposition and thermal effects to the predicted laser-material interaction mechanisms and may lead to quantitative relationships between irradiation conditions and material response.

A further opportunity for development lies in combining data-driven and machine learning approaches with future experimental measurements and computational modelling. These approaches, with large, well-controlled datasets, could help discover complex relationships between laser parameters and material properties, and predict material responses under previously unexplored irradiation conditions. Further evaluation of the framework's broader applicability may be achieved by extending it to other layered dielectric and crystalline materials for photonic, sensing, and optoelectronic systems.

7. Conclusions

This study presented an integrated computational and literature-supported investigation of muscovite mica under controlled multi-wavelength laser excitation.

The numerical results revealed anisotropic optical behaviour, polarization-sensitive transmission, and variations in electrical conductivity, while the predicted responses showed a clear dependence on laser wavelength. These findings demonstrate that wavelength selection plays an important role in governing the interaction between incident laser radiation and the layered structure of muscovite.

Numerical modelling was used to interpret the predicted trends and assess their physical consistency. The agreement between calculated behaviour and literature-derived reference data, supported by systematic verification and quantitative error assessment, strengthens the reliability of the adopted framework. Importantly, the laser is considered not only as an optical probe but also as a controlled excitation source for investigating wavelength-dependent material responses.

Overall, the results highlight the potential of muscovite mica for laser-responsive photonic and sensing applications and demonstrate the value of combining multi-wavelength excitation, literature-supported analysis, and numerical modelling. Future work may extend this framework to broader spectral ranges and controlled irradiation conditions, together with complementary structural characterization to investigate possible laser-induced modifications.

Declarations

Availability of Data and Materials: The data supporting the findings of this study are included within the article. Further information may be obtained from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process: During the preparation of this work, the author used ChatGPT (OpenAI) to assist with language refinement, structural review and manuscript editing. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the published article.

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Author Contributions

Contribution statement: A. H. Abdelrahman: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing: original draft, Writing: review & editing.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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