НАУЧНО-ТЕХНИЧЕСКИЙ ВЕСТНИК ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ, МЕХАНИКИ И ОПТИКИ
май–июнь 2024 Том 24 № 3 http://ntv.ifmo.ru/
SCIENTIFIC AND TECHNICAL JOURNAL OF INFORMATION TECHNOLOGIES, MECHANICS AND OPTICS
May–June 2024 Vol. 24 No 3 http://ntv.ifmo.ru/en/
ISSN 2226-1494 (print) ISSN 2500-0373 (online)

НАУЧНО-ТЕХНИЧЕСКИЙ ВЕСТНИК
ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ, МЕХАНИКИ И ОПТИКИ

doi: 10.17586/2226-1494-2024-24-3-375-383

Magneto optical properties of atmospheric air molecules

Saddam Husain Dhobi[1]✉, Jeevan Joyti Nakarmi[2], Kishori Yadav[3], Suresh Prasad Gupta[4]

[1] Nepal Academy of Science and Technology, Lalitpur, 44700, Nepal
[2,3,4] Tribhuvan University, Lalitpur, 44700, Nepal
[3,4] Innovative Ghar Nepal, Lalitpur, 44700, Nepal

[1] saddam@ran.edu.np✉, https://orcid.org/0000-0001-6425-7647
[2] nakarmijj@gmail.com, https://orcid.org/0000-0002-5470-8675
[3] yadavkishori70@gmail.com, https://orcid.org/0009-0005-9666-8076
[4] guptasir@gmail.com, https://orcid.org/0000-0001-9075-468X

Abstract

The magneto-optical properties of atmospheric air molecules describe how air molecules interact with both magnetic fields and light. Studying these properties is crucial for understanding atmospheric dynamics, enhancing remote sensing for environmental monitoring, developing new materials for sensors and optical devices, refining medical imaging techniques like Magnetic Resonance Imaging, and advancing fundamental scientific knowledge with potential practical applications. The objective of this study is to investigate the magnetic optical properties of air within a weak magnetic field ranging from 0.122 T to 0.986 T using experimental methods. The analysis focuses on the variations in transmittance across the visible spectrum with changes in magnetic field intensity. Results indicate a decrease in transmittance with increasing wavelength, demonstrating a direct correlation between transmittance and magnetic field strength. The magneto-optical properties, specifically transmittance, exhibit a decreasing trend with increasing wavelength, with minimum and maximum transmittance values recorded at 460 nm and 664.755 nm, respectively. Additionally, the transmittance of air spectrum is directly influenced by the applied magnetic field. Moreover, the intensity ratio associated with Raman spectra shift decreases with increasing Raman spectra shift, with higher intensity ratios observed in the presence of a magnetic field compared to non-magnetic conditions. Furthermore, the magneto-optical response tends to shift towards higher wavelengths with increasing magnetic field strength.

Keywords

magneto-optical properties, weak magnetic field, transmittance, visible spectrum, air molecules, Raman spectra

Acknowledgments

We extend our sincere gratitude to the institutions that have been instrumental in supporting our research endeavors. The Department of Physics at Patan Multiple Campus, Tribhuvan University, Lalitpur-44700, Nepal, has provided invaluable resources and guidance. We also acknowledge the contributions of Innovative Ghar Nepal and the Robotics Academy of Nepal, both located in Lalitpur-44700, Nepal, whose support has been crucial to our work. Additionally, we appreciate the assistance and resources provided by the Nepal Academy of Science and Technology, Khumaltar Lalitpur-44700, Nepal. These institutions have played a significant role in advancing our research efforts, and we are immensely grateful for their contributions.

For citation: Dhobi S.H., Nakarmi J.J., Yadav K., Gupta S.P. Magneto optical properties of atmospheric air molecules. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2024, vol. 24, no. 3, pp. 375–383. doi: 10.17586/2226-1494-2024-24-3-375-383

УДК 551.510

Магнитооптические свойства молекул атмосферного воздуха

Саддам Хусейн Дхоби[1]✉, Дживан Джиоти Накарми[2], Кишори Ядав[3], Суреш Прасад Гупта[4]

[1] Непальская академия наук и технологий, Лалитпур, 44700, Непал
[2,3,4] Университет Трибхуван, Лалитпур, 44700, Непал
[3,4] Инновационный Гар Непала, Лалитпур, 44700, Непал

[1] saddam@ran.edu.np✉, https://orcid.org/0000-0001-6425-7647
[2] nakarmijj@gmail.com, https://orcid.org/0000-0002-5470-8675
[3] yadavkishori70@gmail.com, https://orcid.org/0009-0005-9666-8076
[4] guptasir@gmail.com, https://orcid.org/0000-0001-9075-468X

Аннотация
Магнитооптические свойства атмосферного воздуха описывают взаимодействие молекул воздуха как с магнитными полями, так и со светом. Изучение этих свойств имеет важное значение для понимания динамики атмосферы, совершенствования дистанционного зондирования для мониторинга окружающей среды, разработки новых материалов для датчиков и оптических устройств, совершенствования методов медицинской визуализации, таких как магнитно-резонансная томография, и для продвижения фундаментальных научных знаний с возможным практическим применением. В работе исследованы магнитооптические свойства воздуха экспериментальными методами в слабых магнитных полях от 0,122 до 0,986 Тл. Изучены изменения коэффициента пропускания в видимом спектре при разной интенсивности магнитного поля. Полученные результаты показали уменьшение коэффициента пропускания с увеличением длины волны, что указывает на прямую корреляцию между коэффициентом пропускания и величиной магнитного поля. Отмечено снижение магнитооптических свойств, в частности коэффициента пропускания, при увеличении длины волны. Зафиксированы минимальные и максимальные значения коэффициента пропускания при длинах волн 460 нм и 665 нм соответственно. Замечено, что отношение интенсивностей, связанное со сдвигом спектров комбинационного рассеяния света, уменьшается с увеличением его смещения. При этом более высокие отношения интенсивностей наблюдаются в присутствии магнитного поля по сравнению с немагнитными условиями. Магнитооптический отклик имеет тенденцию смещаться в сторону больших длин волн с увеличением напряженности магнитного поля.

Ключевые слова
магнитооптические свойства, слабое магнитное поле, пропускание, видимый спектр, молекулы воздуха, спектры комбинационного рассеяния света

Благодарности
Авторы выражают благодарность учреждениям, которые сыграли важную роль в поддержке выполненных исследований. Факультет физики в кампусе Patan Multiple Campus Университета Трибхуван, Лалитпур-44700, Непал, предоставил неоценимые ресурсы и рекомендации. Авторы признательны за вклад компании Innovative Ghar Nepal и Непальской академии робототехники, расположенных в Лалитпур-44700, Непал, поддержка которых сыграла решающую роль в настоящей работе. Авторы ценят помощь и ресурсы, предоставленные Непальской академией наук и технологий, Хумалтар Лалитпур-44700, Непал.

Ссылка для цитирования: Дхоби С.Х., Накарми Д.Д., Ядав К., Гупта С.П. Магнитооптические свойства молекул атмосферного воздуха // Научно-технический вестник информационных технологий, механики и оптики. 2024. Т. 24, № 3. С. 375–383. (на англ. яз.). doi: 10.17586/2226-1494-2024-24-3-375-383

Introduction

The presence of oxygen in air shows air has a spectrum paramagnetic and hence air buoyancy accounts for roughly 3 % of the diamagnetic force while for pure oxygen gas, the buoyancy increases by 15 % [1]. Since the magnetic field affects the different properties of air and water the dielectric constants for air is ϵ_a equal to 1 and water is ϵ_w equal to 80 [2]. The polarization occurs when atoms and molecules are exposed to external electric/magnetic fields are applied. The polarization of constituent molecules in a mixed-element gas-like air can be difficult to understand. In general, for gas the effective electric field ($\mathbf{E}'$) can be used to calculate the average dipole moment of the medium $\langle \mathbf{p} \rangle$ as, $\langle \mathbf{p} \rangle = \epsilon_0 \gamma_{mol} \mathbf{E}'$.

Where ϵ_0 denotes the permittivity of free space, and γ_{mol} denotes the molecular polarizability of the gas [3]. The composition of air primarily comprises oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), and water vapor (H_2O). Oxygen (O_2) is notably paramagnetic, while N_2, CO_2, and H_2O are diamagnetic [4–6]. This distinction in magnetic properties results from the molecular structures of these constituents: O_2 possesses unpaired electrons, leading to its paramagnetic behavior, whereas N_2, CO_2, and H_2O have all electrons paired, rendering them diamagnetic. Thus, when exposed to a magnetic field, O_2 is attracted to it, while N_2, CO_2, and H_2O are weakly repelled [7].

Paramagnetic materials exhibit positive magnetic susceptibility, whereas diamagnetic materials display negative susceptibility. Among common atmospheric gases, carbon dioxide, nitrogen, and most combustion byproducts are diamagnetic, whereas oxygen possesses paramagnetic properties [8]. This distinction implies that when subjected to an external inhomogeneous magnetic field, oxygen tends to be attracted to certain areas while combustion products are repelled from these regions. However, the impact of relatively low magnetic field strengths on combustion enhancement is primarily attributed to the paramagnetic nature of oxygen. This is because diamagnetic materials typically exhibit only a weak magnetic dipole moment [9]. Early investigations by Ueno and Esaki [10] laid the foundation for such studies, focusing on the effects of magnetic fields on the combustion of methanol catalysis. They noted significant fluctuations in combustion temperature with varying frequency and amplitude when magnetic field strengths exceeded 0.9 T. These fluctuations were attributed to the paramagnetic characteristics of oxygen and the forces exerted on air by the magnetic field [11].

The research gap identified in this study is the limited understanding of the combined behavior of air molecules in the presence of magnetic fields and their consequent optical properties at Standard Temperature and Pressure conditions. While some research has investigated the magnetic properties of individual molecules in magnetic

fields ranging from 0.1 to 1 T, there is a notable absence of studies focusing on the optical effects. Despite knowledge about the paramagnetic nature of oxygen and the diamagnetic properties of nitrogen, carbon dioxide, and water vapor, there remains a gap in comprehensively understanding their collective behavior under magnetic influence. Addressing this gap is crucial for gaining insights into fundamental air behavior under magnetic fields and unlocking potential applications across various disciplines.

Literature Review

Oxygen and nitrogen molecules are paramagnetic or diamagnetic, with a permanent or induced magnetic dipole moment, respectively. The electromagnetic force experienced by molecules with an induced magnetic or electric dipole moment is substantially weaker than the force experienced by paramagnetic or polar molecules, which have a permanent dipole moment. As a result, only induced dipole moments affect the mobility of molecules. Unpaired electron spins produce a magnetic dipole moment is $\mu_s = \sqrt{n(n+2)}\mu_e$, where n is the number of electrons (unpaired). Because an oxygen molecule, O_2, has two unpaired electrons, $n = 2$, the μ_s for oxygen is 2.8 μ_e. The oxygen molecule has paramagnetic characteristics due to its nonzero magnetic dipole moment value [12]. The effects of a crossing magnetic field on nanosecond pulsed corona discharge show that corona discharge creates more routes and develops uniformly in space. The application of a magnetic field to the discharge can also impact discharge uniformity. Due to frequent particle collisions and a small energy difference between rotational levels, a dynamic equilibrium between the rotating motion of N_2^+ and the translational motion of O_2 and N_2 is easily attained in atmospheric air. As a result, the rotational temperature of N_2^+ is nearly identical to the temperature of the gas. As the airflow velocity increases, the intensity of Optical Emission Spectrum (OES) increases, which correlates to an increase in discharge [13].

The lack of symmetry between left and right circularly polarized spectrum in the presence of a magnetic field causes Magneto-Optical (MO) phenomena. In two-dimensional monolayers, optical excitations in the presence of a magnetic field allow manipulation of valley pseudospin degrees of freedom. Although wave functions in the presence of even a small magnetic field differ dramatically from those in the absence of the magnetic field, the density matrix gauge-invariant counterpart changes perturbative. While the position operator in responses to electric fields can be replaced by a derivative with respect to the wave vector in the modern theory of polarization the description of magnetic fields is more complicated because it introduces vector coupling to electron dynamics and leads to non-perturbative changes in wave functions [14]. The electromagnetic fields produced by the induced electric and magnetic dipoles can be thought of as the optical response of a single spherical Si particle of specific size. The spectra of reflection and transmission for arrays with particle spacing is less than the wavelength of incident spectrum. It has been observed that the condition of negligibly modest reflection generated transparency exists. The spacing between the particles must be greater than several particle diameters for studying the optical response of particle arrays. The optical response and local field distributions are greatly influenced by particle shape and size, particle interaction, and the polarization of incident spectrum, whereas electromagnetically coupled pairs of gold nanoparticles have a substantial magnetic response at visible-spectrum frequencies [15].

A large number, approximate 10^2 of single-domain magnetic nanocrystallites can be found in the characteristics of the static magnetic response of multicore magnetic nanoparticles. An external magnetic field causes the magnetic moments of a multicore particle to change. The key point is that the internal rotation of the magnetic moment within each nanocrystallite determines a multicore particlemagnetic response.

Due to random orientations of the core easy axes, the weak-field magnetic response of a multicore particle seems to be independent of anisotropy energy [16]. Total scattering, elastic scattering, momentum transfer, excitations of rotational, vibrational, and electronic states, dissociation, ionization, and attachment are some of the processes that are included in the cross sections for electron and photon collisions with oxygen molecules (O_2). Photon impact is calculated using ionization and dissociation processes. Collisions of photons and electrons with oxygen molecules have been examined far less than those with nitrogen molecules because oxygen molecules rapidly disintegrate [17]. The mechanism of molecules absorbing quanta of energy to alter vibrational and rotational states causes molecule absorption. Although nitrogen, oxygen, and argon dominate the terrestrial atmosphere, species with low quantities but active vibration-rotation bands, such as water vapor, carbon dioxide, ozone, and nitrous oxide, dominate infrared absorption. A spectrum ray passing through the atmosphere bends due to changes in molecule density and the associated gradient in the index of refraction [18].

Method and Materials

Spectrum forces on small particles are often described using the dipole or gradient force as well as the radiation pressure or scattering force. In response to a spectrum magnetic field, small particles form a magnetic dipole moment. To draw the induced dipole, field intensity gradients compete with radiation pressure owing to momentum transfer from photons in the beam. Intense spectrum fields can cause significant forces between particles. The induced electric and magnetic dipole moments, **p** and **m**, are generally represented in terms of the particle electric and magnetic polarizabilities, α_e and α_m, respectively, proportional to the external (polarizing) fields, **E** and **B**. The relationship is described as follows [19]:

$$\mathbf{p} = \epsilon_0 \epsilon_h \alpha_e \mathbf{E},\ \mathbf{m} = \frac{1}{\mu_0}\alpha_m \mathbf{B} = \alpha_m \mathbf{H},$$

where $\alpha_e = i\frac{6\pi}{k^3}a_1$, $\alpha_m = i\frac{6\pi}{k^3}b_1$. Here e index is for electric and m is for magnetic field, k is wavenumber, a_1 and b_1 are

two Mie coefficients, ϵ_h is relative dielectric permittivity, ϵ_0 is dielectric permittivity. The scattering, σ_s and particle extinction, σ^{ext} cross-sections are written in terms of the polarizabilities [20]:

$$\sigma_s = \frac{k^4}{6\pi}\{|\alpha_e|^2 + |\alpha_m|^2\},$$

$$\sigma^{ext} = \sigma_e^{ext} + \sigma_m^{ext} = k\mathrm{Im}\{\alpha_e + \alpha_m\}.$$

Here σ^{ext} is the sum of cross-section due to electric and magnetic field and also known as imaginary sum (Im) of polarization due to electric and magnetic field.

The Raman effect is the idea of polarizability of a molecule, and it is derived from classical theory. When a molecule is exposed to a static electric field, the electronic cloud is drawn to the positive pole of the field, whereas positively charged nuclei are drawn to the negative pole. The magnitude μ_i is determined by the intensity of the electric field **E** as well as the molecule deformability or polarizability (α).

$$\mu_i = \alpha\mathbf{E}.$$

When a sample of molecules is subjected to a beam of radiation of frequency v_i, each molecule in it experiences an electric field which varies according to the equation [21]

$$\mathbf{E} = E_0\sin(2\pi v_i t).$$

A time dependent dipole moment is therefore induced in the molecule

$$\mu_i = \alpha E_0\sin(2\pi v_i t).$$

An oscillating dipole emits radiation with the same frequency as its oscillation frequency according to electromagnetic theory. Furthermore, if the molecule undergoes any motion, such as vibration or rotation, which affects the polarizability on a periodic basis, the dipole (which oscillates at the frequency of the applied field) will have vibrational or rotational oscillation overlaid on it. Consider the case of a vibration of frequency v_v that alters the polarizability. The polarizability can be expressed as for tiny deviations from the equilibrium distance as

$$\alpha = \alpha_0 + \beta\sin(2\pi v_0 t),$$

where α_0 is the polarizability in the equilibrium position and β represents the change in polarizability during the vibration. Consequently, the induced dipole moment is given by

$$\mu_i = \alpha\mathbf{E} = (\alpha_0 + \beta\sin(2\pi v_0 t))E_0\sin(2\pi v_i t).$$

The Raman shift is calculated by using $\left(\frac{1}{\lambda_0} - \frac{1}{\lambda_i}\right)$ cm^{-1}, where λ_0 is laser wavelength and λ_i is scattered wavelength and the MO response are calculated as $\frac{T[t] - T[0]}{T[0]}$. Here $T[0]$ is transmittance without field and $T[t]$ is transmittance after applying the field.

Experimental setup

The experimental setup began with the establishment of a magnetic field using a solenoid. The sample under study was positioned within the magnetic field generated by the solenoid. The intensity of the magnetic field was measured using a gauss meter ensuring accurate calibration. The overall arrangement of the experimental setup, including the solenoid, sample placement, and measurement instruments, is depicted in Fig. 1. Following the setup of the magnetic field, the experiment proceeded by connecting a detector, specifically a web camera, to the Theremino spectrometer software for data collection and analysis.

Phenomena of the Experimental Setup and Experimental Observation

The experimental setup depicted in Fig. 1 facilitated data collection under varying magnetic field conditions. Initially, the magnetic field was established using an electromagnetic induction device directing the current to the solenoid. The intensity of the magnetic field generated by the solenoid was accurately measured using a gauss meter. Subsequently, the prepared sample was positioned within a tube stand. An unpolarized white spectrum was then passed through the sample, and a detector placed opposite to the spectrum source captured the data. Finally, the collected data was transmitted to a computer using the Theremino spectrometer software for analysis.

Result and Discussion

Transmittance of Visible Spectrum through Air Molecules at Normal Atmospheric Condition

Fig. 2 illustrates the investigation into the MO properties (transmittance) of air molecules. The study reveals that under very weak magnetic fields, transmission primarily occurs in the low wavelengths of the spectrum (400 nm to 550 nm), while absorption becomes more prominent in the higher wavelengths (beyond 550 nm to 700 nm). The magnetic field induces a dipole moment in the air molecules impacting their size and vibration [1]. As air is slightly paramagnetic due to the presence of oxygen, it tends to be pulled towards the center of the magnetic field, with a greater effect observed at higher field strengths. Consequently, the transmittance is higher in stronger magnetic fields compared to weaker ones. Notably, the influence of the magnetic field is more pronounced in the higher wavelength region, where the size of air molecules

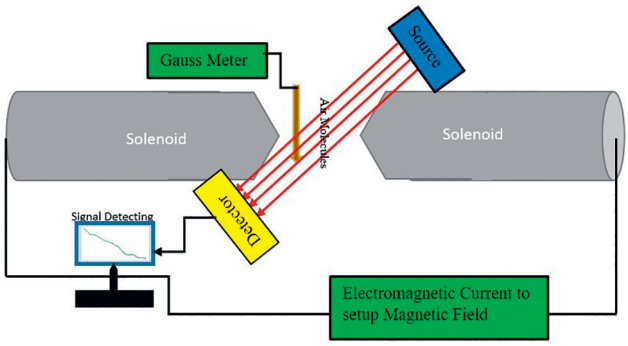

Fig. 1. Experimental arrangement

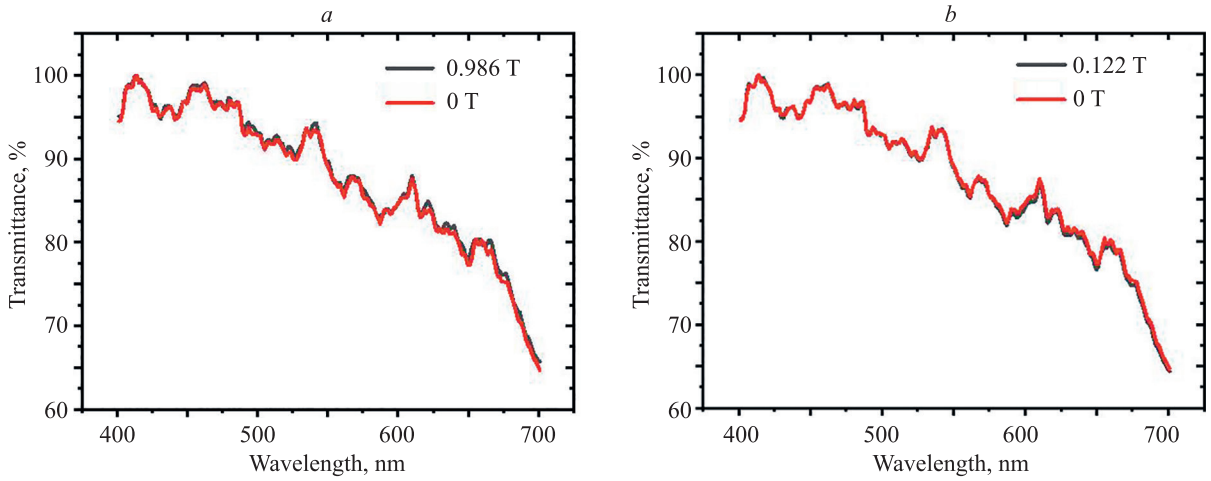

Fig. 2. Transmittance of spectrum through air at 0.986 T (*a*) and 0.122 T (*b*)

is significantly affected. In the magnetic field range of 0.349 T to 0.703 T, fluctuations in transmittance and absorbance occur due to molecular randomness. However, beyond this range (0.720 T to 0.986 T), transmittance exhibits a plateau-like curve, indicating a stable magneto-optic influence on wavelength-dependent transmittance and absorbance. Additionally, the transmittance curve displays several Gaussian peaks within specific wavelength ranges, as depicted in Fig. 2.

The study results reveal that under magnetic fields ranging from 0.143 T to 0.194 T, the maximum transmittance of air molecules is 0.7 % at a wavelength of 460 nm, higher than in the absence of applied field. Conversely, peak absorbance occurs at multiple wavelengths, including 593.59, 648.36, 655.97, 678.12, and 689.85 nm, with a maximum absorbance of 0.7 % compared to the non-applied field condition. In stronger magnetic fields (0.720 T to 0.986 T), the maximum transmittance increases to 1.7 % at a wavelength of 664.755 nm, exceeding that observed without magnetic field. Simultaneously, the maximum absorbance decreases to 0.6 percent at 544.55 nm compared to the non-applied field. Additionally, within the magnetic field range of 0.720 T to 0.880 T, the highest absorbance value is recorded at a wavelength of 431.34 nm. Overall, the greatest absorption occurs at 544.55 nm within the magnetic field range of 0.918 T to 0.986 T. These findings demonstrate that both the wavelength of light and the strength of the magnetic field influence the transmittance and absorbance of air molecules. The observed variations underscore the intricate interplay between magnetic fields and the optical properties of air molecules, suggesting the potential for magnetic field control to guide transmittance and absorption, offering opportunities for MO guidance [22].

Raman Spectra Shift with Intensity Ratio for Air Molecules

Fig. 3 illustrates the relationship between the Raman shift and the intensity ratio. In the low Raman spectra shift zone, the intensity ratio is observed to be high, whereas in the high Raman spectra shift region it decreases. Notably, the intensity ratio exhibits larger variations in strong magnetic fields compared to low magnetic fields. For instance, with the greatest Raman shift measured at 10643.4 cm^{-1} in a low magnetic field, the minimum intensity ratio is found to be 0.645. Conversely, under the same magnitude of Raman shift, the minimum intensity ratio in a high magnetic field is determined to be 0.657 T.

This observed phenomenon can be attributed to the vibration of molecules in the presence of air, leading to the formation of a dipole moment. As the size of molecules increases from low to high magnetic fields (0.122 T to 0.986 T), the dipole moment also increases. The incident spectrum energy is transmitted to the molecules, causing them to vibrate more and become more polarizable. Consequently, this results in a modest amount of transmittance and a decrease in the ratio of transmitted to incident spectrum intensity, ultimately leading to the observed Raman shift effect on air molecules. Additionally, the MO effects on the air molecules contribute to a higher Raman shift as the magnetic field strength increases.

Magneto-Optical Response in the Presence of Magnetic Field in Air Molecules

The MO response of air at normal atmospheric conditions, as depicted in Fig. 4, demonstrates notable variations across different magnetic field strengths. In the low magnetic field range of 0.122 T (Fig. 4, *a*)

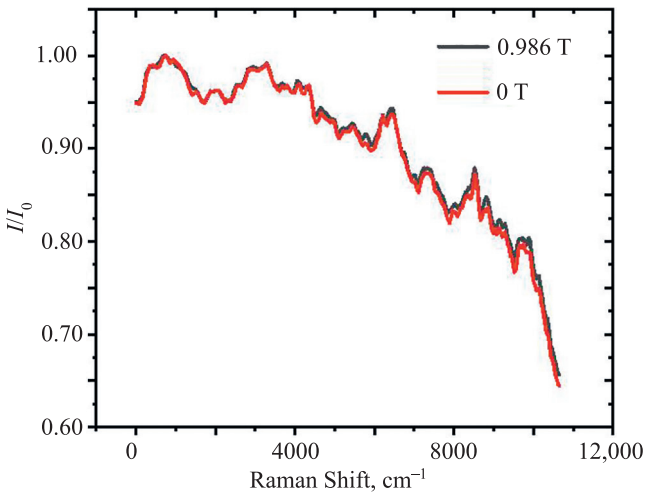

Fig. 3. Raman shift versus ratio of intensity of transmitted and incident spectrum (I/I_0)

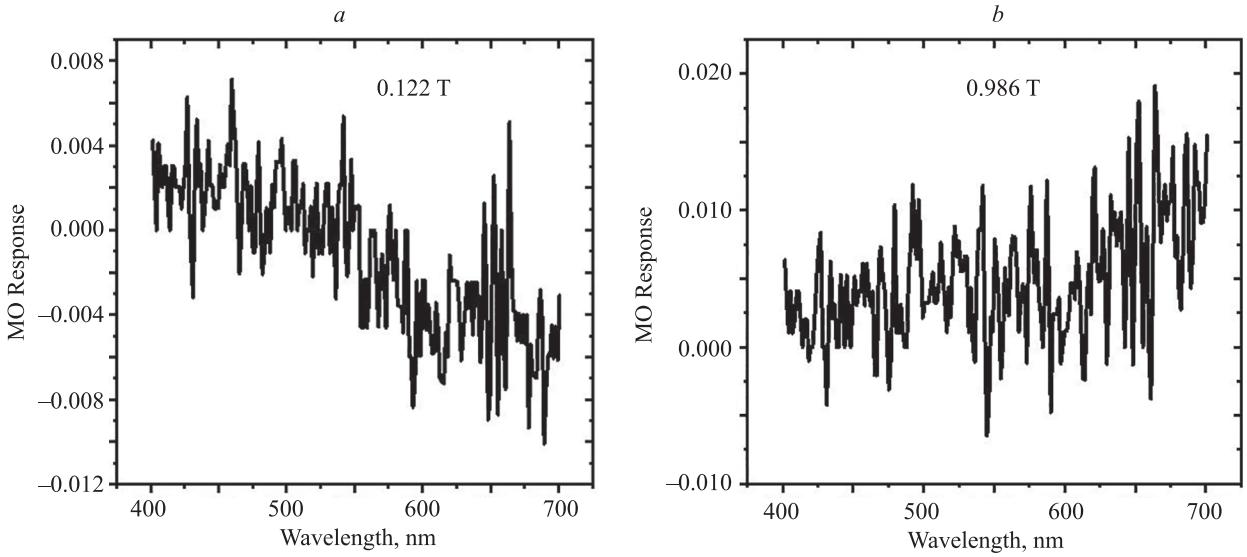

Fig. 4. Observation of the MO response of the air at 0.122 T (*a*) and 0.986 T (*b*)

and 0.986 T (Fig. 4, *b*), the MO response decreases with increasing wavelength of the incident spectrum. Specifically, the maximum and minimum values of the MO response are observed at wavelengths of 541.9 nm and 689.4 nm, respectively. However, in the magnetic field range of 0.194 T to 0.703 T, a significant fluctuation in the MO response is observed. Here, the maximum MO response values exhibit larger variations across different wavelengths, with the highest values recorded at 663.9 nm. Conversely, the minimum values of the MO response also show fluctuations across various wavelengths, with the lowest values observed at 661.1 nm. In contrast, under magnetic fields ranging from 0.720 T to 0.986 T, the MO response increases with increasing wavelength of the incident spectrum. The maximum MO response values are observed at high wavelengths, particularly at 652.5 nm and 663.9 nm, while the minimum values occur at lower wavelengths such as 431.2 nm. Comparing the cases of 0.0, 0.122, and 0.986 T, it is evident that the MO response is significantly influenced by the strength of the magnetic field. In the absence of a magnetic field (0 T), the MO response exhibits relatively stable behavior across different wavelengths. However, as the magnetic field strength increases to 0.122 T, there is a noticeable decrease in the MO response, particularly at higher wavelengths. This suggests that a weak magnetic field has a suppressive effect on the MO response of air molecules. On the other hand, at a higher magnetic field strength of 0.986 T, the MO response shows a significant increase, especially at high wavelengths. This indicates that a stronger magnetic field enhances the MO response of air molecules, likely due to increased interactions between the magnetic field and the air molecules. Findings highlight the intricate relationship between magnetic field strength and the MO response of air molecules, with potential implications for understanding MO phenomena and their applications in various fields.

Effect of Magnetic Field on Transmittance of Spectrum

Fig. 5 demonstrates the correlation between magnetic field strength and air transmittance, with notable implications for understanding the MO behavior of air molecules. As the magnetic field intensity increases, a corresponding rise in air transmittance is observed, particularly evident at a constant wavelength of 541.9 nm. This phenomenon can be attributed to the influence of the magnetic field on the molecular vibrations of air molecules. The gradual increase in magnetic field strength induces a dipole moment in the molecules amplifying their vibrations. This amplification process results in enhanced transmittance of the air, signifying the heightened interaction between the magnetic field and the molecular structure of air. However, as the magnetic field continues to increase, the molecular vibrations become more random leading to a temporary decrease in transmittance before reaching a sharp peak. This decline can be attributed to the disruptive effect of increased particle randomness on the transmittance of the spectrum. Ultimately, the elevation of transmittance in high magnetic fields can be elucidated by the heightened particle randomness, which increases entropy and polarizability within the air molecules. Thus, the observed trends underscore the intricate interplay

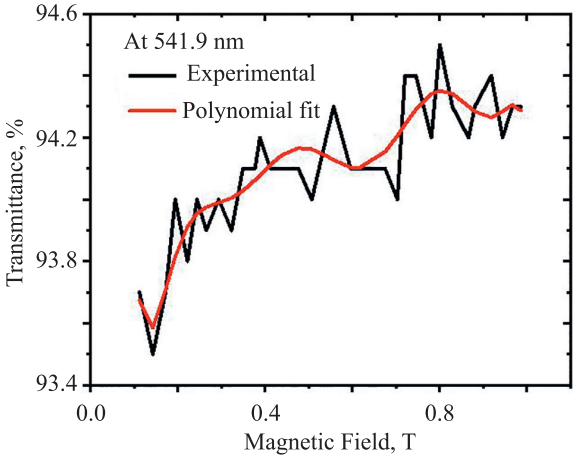

Fig. 5. Magnetic field effect on the transmittance in the air at 541.9 nm

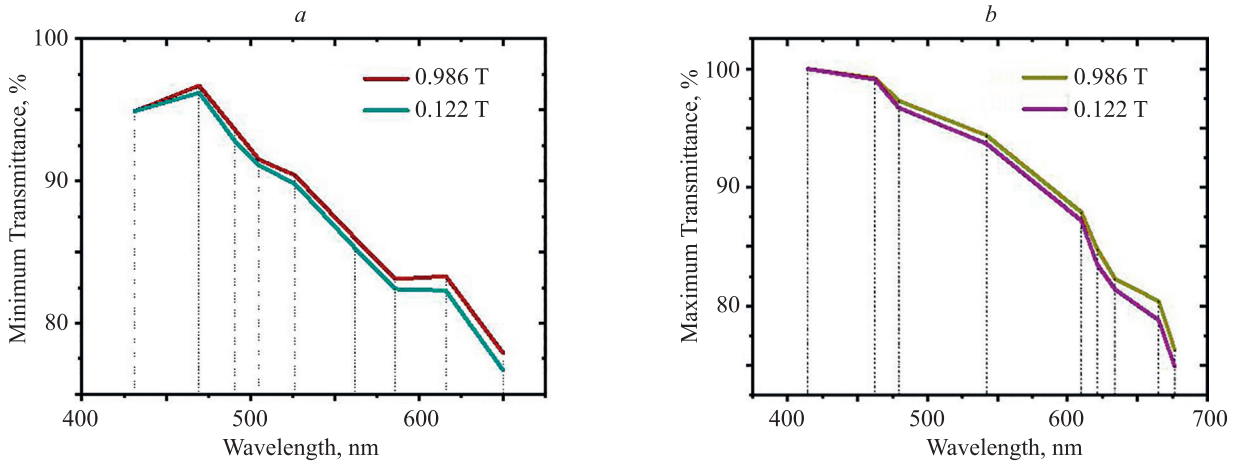

Fig. 6. Transmittance (*a*) for minimal and (*b*) maximal at certain wavelength

between magnetic field strength, molecular vibrations, and air transmittance, offering valuable insights into the underlying mechanisms governing MO phenomena.

The fitted equation with polynomial 9 degrees for Fig. 5 is obtained as

$$T = 109.48 - 402.12B + 4503.87B^2 - 25872B^3 + \\ + 89019.34B^4 - 191831.45B^5 + 260613.49B^6 - \\ - 216503.43B^7 + 100332.12B^8 - 19857.034B^9.$$

Here T is transmittance in % whereas B is applied magnetic field.

Nature of Maximum and Minimum Transmittance at same Wavelength and same Magnetic Field

Fig. 6 provides a detailed illustration of transmittance variations showcasing distinctive patterns of minimum dips (Fig. 6, *a*) and maximum bumps (Fig. 6, *b*) across a spectrum of incident wavelengths. As depicted in Fig. 6, *a*, there is a consistent trend of decreasing transmittance with increasing wavelength across all magnetic field intensities (0.122 T to 0.986 T). This trend signifies that longer wavelengths tend to yield lower transmittance values, evident in the lowest minimum transmittance observed across each magnetic field case and the highest maximum transmittance observed among each magnetic field case in Fig. 6, *b*. Notably, at a wavelength of 431.2 nm, the transmittance reaches a minimum of 95 % across all magnetic field strengths. Conversely, the lowest transmittance value of 76.7 % is observed at a wavelength of 649.7 nm. Furthermore, the maximum transmittance peaks consistently at 98.1 % at a wavelength of 414.1 nm across all magnetic field cases. This consistency in peak transmittance underscores the robustness of air molecules in response to fluctuations in magnetic field strength emphasizing the importance of these findings in elucidating the optical behavior of air under diverse magnetic field conditions.

The article investigates the behavior of air molecules under weak magnetic fields, with a focus on their MO properties. Through experimental methods, the study observes changes in transmittance across the visible spectrum with varying magnetic field strengths. Findings reveal that transmittance decreases with increasing wavelength, while it also varies with magnetic field strength. Notably, the research demonstrates that the MO response of air molecules is directly proportional to the applied magnetic field, with intensity ratios in Raman spectra shifting towards higher wavelengths under magnetic influence.

The practical implications of this research are significant spanning diverse fields, such as optical sensing, environmental monitoring, material science, and potential applications in medical and biological contexts. Understanding these MO properties offers insights into fundamental air behavior and opens avenues for technological advancements across various disciplines.

Magneto-Optical Properties of Air Practical Application

Understanding the MO properties of air molecules holds significant implications across diverse fields. In atmospheric science, the effect of magnetism on light and air molecules is crucial. Understanding how magnetic fields influence both light and air molecules aids in unraveling atmospheric phenomena and refining remote sensing techniques for accurate environmental monitoring. In medicine, this knowledge contributes to refining Magnetic Resonance Imaging technology, improving diagnostics. Additionally, it fosters advancements in material science, facilitating the creation of novel materials with tailored properties for sensors and optical devices. Hence this studying MO properties of air molecules fosters innovation and progress in multiple scientific and technological domains.

Conclusion

The investigation into the MO properties of atmospheric air under normal conditions revealed variations across magnetic field strengths ranging from 0.122 T to 0.986 T. Notably, the magneto-optical property demonstrated an increasing trend with rising magnetic field strength, while exhibiting a decrease with increasing spectrum wavelength. The minimum transmittance recorded was 0.7 %, observed at a wavelength of 460 nm, whereas the maximum transmittance of 1.7 % was noted at 664.755 nm

spanning the magnetic field range from 0.122 T to 0.986 T. Additionally, the transmittance of the spectrum through atmospheric air displayed a direct, albeit nonlinear, proportionality to the applied magnetic field, indicating that higher magnetic fields corresponded to higher transmittance levels. Investigations into the intensity ratio with Raman spectra shift revealed a decreasing trend with increasing Raman shift spectra. The magneto-optical response exhibited an inverse relationship with the wavelength of the visible spectrum, wherein as the magnetic field increased gradually, the magneto-optical responses transitioned from a decreasing phase to a normal phase, and then to an increasing phase with the increment of wavelength in the incident spectrum. Particularly, the magneto-optical response was notably high in a high magnetic field at the higher wavelengths of the spectrum.

References

1. Kitazawa K., Ikezoe Y., Uetake H., Hirota N. Magnetic field effects on water, air and powders. *Physica B: Condensed Matter*, 2001, vol. 294–295, pp. 709–714. https://doi.org/10.1016/s0921-4526(00)00749-3
2. Bossa G.V., Bohinc K., Brown M.A., May S. Dipole moment of a charged particle trapped at the air–water interface. *The Journal of Physical Chemistry B*, 2016, vol. 120, no. 26, pp. 6278–6285. https://doi.org/10.1021/acs.jpcb.6b02703
3. Madsen M.J., Brown D., Krutz S.R., Milliman M. Measuring the molecular polarizability of air. *American Journal of Physics*, 2011, vol. 79, no. 4, pp. 428–430. https://doi.org/10.1119/1.3533354
4. Dröge W. Free radicals in the physiological control of cell function. *Physiological Reviews*, 2002, vol. 82, no. 1, pp. 47–95. https://doi.org/10.1152/physrev.00018.2001
5. Khudyakov I.V., Minaev B.F. Molecular terms of dioxygen and nitric oxide. *Physchem*, 2021, vol. 1, no. 2, pp. 121–132. https://doi.org/10.3390/physchem1020008
6. Minaev B.F. Dioxygen and reactive oxygen species' paramagnetic properties are important factors in dermatology. *International Journal of Dermatology and Clinical Research*, 2022, vol. 8, no. 1, pp. 16–23. https://doi.org/10.17352/2455-8605.000046
7. Minaev B. The spin of dioxygen as the main factor in pulmonology and respiratory care. *Archives of Pulmonology and Respiratory Care*, 2022, vol. 8, no. 1, pp. 28–33. https://doi.org/10.17352/aprc.000081
8. Swaminathan S. *Effects of Magnetic Field on Micro Flames*. Master Thesis. Louisiana State University, 2005, 126 p. https://doi.org/10.31390/gradschool_theses.1333
9. Yamada E., Shinoda M., Yamashita H., Kitagawa K. Experimental and numerical analyses of magnetic effect on OH radical distribution in a hydrogen-oxygen diffusion flame. *Combustion and Flame*, 2003, vol. 135, no. 4, pp. 365–379. https://doi.org/10.1016/j.combustflame.2003.08.005
10. Ueno S., Esaki H., Harada K. Magnetic field effects on combustion. *IEEE Translation Journal on Magnetics in Japan*, 1987, vol. 2, no. 9, pp. 861–862. https://doi.org/10.1109/tjmj.1987.4549634
11. Ruan X. Experimental research on the promotion of combustion in diffusion flames by gradient magnetic field. *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*, 2006, vol. 27, no. 5, pp. 742–745. (in Chinese)
12. Franchetti G., Zimmermann F., Rehman M.A. Trapping of neutral molecules by the beam electromagnetic field. *Physical Review Accelerators and Beams*, 2021, vol. 24, no. 5, pp. 054001. https://doi.org/10.1103/physrevaccelbeams.24.054001
13. Guo F., Liu Y.H., Li X., Li H., Daughton W., Kilian P. Recent progress on particle acceleration and reconnection physics during magnetic reconnection in the magnetically-dominated relativistic regime. *Physics of Plasmas*, 2020, vol. 27, no. 8, pp. 080501. https://doi.org/10.1063/5.0012094
14. Lebedeva I.V., Strubbe D.A., Tokatly I.V., Rubio A. Orbital magneto-optical response of periodic insulators from first principles. *npj Computational Materials*, 2019, vol. 5, pp. 32. https://doi.org/10.1038/s41524-019-0170-7
15. Evlyukhin A.B., Reinhardt C., Seidel A., Luk'yanchuk B.S., Chichkov B.N. Optical response features of Si-nanoparticle arrays. *Physical Review B*, 2010, vol. 82, no. 4, pp. 045404. https://doi.org/10.1103/PhysRevB.82.045404
16. Ivanov A.O., Ludwig F. Static magnetic response of multicore particles. *Physical Review E*, 2020, vol. 102, no. 3, pp. 032603. https://doi.org/10.1103/physreve.102.032603
17. Itikawa Y., Ichimura A., Onda K., Sakimoto K., Takayanagi K., Hatano Y., Hayashi M., Nishimura H., Tsurubuchi S. Cross sections

Литература

1. Kitazawa K., Ikezoe Y., Uetake H., Hirota N. Magnetic field effects on water, air and powders // Physica B: Condensed Matter. 2001. V. 294–295. P. 709–714. https://doi.org/10.1016/s0921-4526(00)00749-3
2. Bossa G.V., Bohinc K., Brown M.A., May S. Dipole moment of a charged particle trapped at the air−water interface // The Journal of Physical Chemistry B. 2016. V. 120. N 26. P. 6278–6285. https://doi.org/10.1021/acs.jpcb.6b02703
3. Madsen M.J., Brown D., Krutz S.R., Milliman M. Measuring the molecular polarizability of air // American Journal of Physics. 2011. V. 79. N 4. P. 428–430. https://doi.org/10.1119/1.3533354
4. Dröge W. Free radicals in the physiological control of cell function // Physiological Reviews. 2002. V. 82. N 1. P. 47–95. https://doi.org/10.1152/physrev.00018.2001
5. Khudyakov I.V., Minaev B.F. Molecular terms of dioxygen and nitric oxide // Physchem. 2021. V. 1. N 2. P. 121–132. https://doi.org/10.3390/physchem1020008
6. Minaev B.F. Dioxygen and reactive oxygen species' paramagnetic properties are important factors in dermatology // International Journal of Dermatology and Clinical Research. 2022. V. 8. N 1. P. 16–23. https://doi.org/10.17352/2455-8605.000046
7. Minaev B. The spin of dioxygen as the main factor in pulmonology and respiratory care // Archives of Pulmonology and Respiratory Care. 2022. V. 8. N 1. P. 28–33. https://doi.org/10.17352/aprc.000081
8. Swaminathan S. Effects of Magnetic Field on Micro Flames: Master Thesis / Louisiana State University, 2005. 126 p. https://doi.org/10.31390/gradschool_theses.1333
9. Yamada E., Shinoda M., Yamashita H., Kitagawa K. Experimental and numerical analyses of magnetic effect on OH radical distribution in a hydrogen-oxygen diffusion flame // Combustion and Flame. 2003. V. 135. N 4. P. 365–379. https://doi.org/10.1016/j.combustflame.2003.08.005
10. Ueno S., Esaki H., Harada K. Magnetic field effects on combustion // IEEE Translation Journal on Magnetics in Japan. 1987. V. 2. N 9. P. 861–862. https://doi.org/10.1109/tjmj.1987.4549634
11. Ruan X. Experimental research on the promotion of combustion in diffusion flames by gradient magnetic field // Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica. 2006. V. 27. N 5. P. 742–745. (in Chinese)
12. Franchetti G., Zimmermann F., Rehman M.A. Trapping of neutral molecules by the beam electromagnetic field // Physical Review Accelerators and Beams. 2021. V. 24. N 5. P. 054001. https://doi.org/10.1103/physrevaccelbeams.24.054001
13. Guo F., Liu Y.H., Li X., Li H., Daughton W., Kilian P. Recent progress on particle acceleration and reconnection physics during magnetic reconnection in the magnetically-dominated relativistic regime // Physics of Plasmas. 2020. V. 27. N 8. P. 080501. https://doi.org/10.1063/5.0012094
14. Lebedeva I.V., Strubbe D.A., Tokatly I.V., Rubio A. Orbital magneto-optical response of periodic insulators from first principles // npj Computational Materials. 2019. V. 5. P. 32. https://doi.org/10.1038/s41524-019-0170-7
15. Evlyukhin A.B., Reinhardt C., Seidel A., Luk'yanchuk B.S., Chichkov B.N. Optical response features of Si-nanoparticle arrays // Physical Review B. 2010. V. 82. N 4. P. 045404. https://doi.org/10.1103/PhysRevB.82.045404
16. Ivanov A.O., Ludwig F. Static magnetic response of multicore particles // Physical Review E. 2020. V. 102. N 3. P. 032603. https://doi.org/10.1103/physreve.102.032603
17. Itikawa Y., Ichimura A., Onda K., Sakimoto K., Takayanagi K., Hatano Y., Hayashi M., Nishimura H., Tsurubuchi S. Cross sections

for collisions of electrons and photons with oxygen molecules. *Journal of Physical and Chemical Reference Data*, 1989, vol. 18, no. 1, pp. 23–42. https://doi.org/10.1063/1.555841
18. Fenn R.W., Mill J.D., Clough S.A., Rothman L.S., Gallery W.O., Shettle E.P., Good R.E., Volz F.E., Kneizys F.X. Chapter-18. Optical and infrared properties of the atmosphere. *Handbook of Geophysics and the Space Environment*. Air Force Geophysics Laboratory, Hanscom AFB, MA, 1985.
19. Nieto-Vesperinas M., Sáenz J.J., Gómez-Medina R., Chantada L. Optical forces on small magnetodielectric particles. *Optics Express*, 2010, vol. 18, no. 11, pp. 11428–11443. https://doi.org/10.1364/OE.18.011428
20. Gomez-Medina R., Garcıa-Camara B., Suarez-Lacalle I., González F., Moreno F., Nieto-Vesperinas M., Saenz J.J. Electric and magnetic dipolar response of germanium nanospheres: interference effects, scattering anisotropy, and optical forces. *Journal of Nanostructures*, 2011, vol. 5, no. 1, pp. 053512. https://doi.org/10.1117/1.3603941
21. Banwell C.N. *Fundamentals of Molecular Spectroscopy*. 4th ed. McGraw Hill International, 1983, 338 p.
22. Van Tiggelen B.A., Rikken G.L.J.A. Manipulating Light with a Magnetic Field. *Topics in Applied Physics*, 2002, vol. 82, pp. 275–276. https://doi.org/10.1007/3-540-44948-5_13

for collisions of electrons and photons with oxygen molecules // Journal of Physical and Chemical Reference Data. 1989. V. 18. N 1. P. 23–42. https://doi.org/10.1063/1.555841
18. Fenn R.W., Mill J.D., Clough S.A., Rothman L.S., Gallery W.O., Shettle E.P., Good R.E., Volz F.E., Kneizys F.X. Chapter-18. Optical and infrared properties of the atmosphere // Handbook of Geophysics and the Space Environment. Air Force Geophysics Laboratory, Hanscom AFB, MA, 1985.
19. Nieto-Vesperinas M., Sáenz J.J., Gómez-Medina R., Chantada L. Optical forces on small magnetodielectric particles // Optics Express. 2010. V. 18. N 11. P. 11428–11443. https://doi.org/10.1364/OE.18.011428
20. Gomez-Medina R., Garcıa-Camara B., Suarez-Lacalle I., González F., Moreno F., Nieto-Vesperinas M., Saenz J.J. Electric and magnetic dipolar response of germanium nanospheres: interference effects, scattering anisotropy, and optical forces // Journal of Nanostructures. 2011. V. 5. N 1. P. 053512. https://doi.org/10.1117/1.3603941
21. Banwell C.N. Fundamentals of Molecular Spectroscopy / 4th ed. McGraw Hill International, 1983. 338 p.
22. Van Tiggelen B.A., Rikken G.L.J.A. Manipulating Light with a Magnetic Field // Topics in Applied Physics. 2002. V. 82. P. 275–276. https://doi.org/10.1007/3-540-44948-5_13

Authors

Saddam Husain Dhobi — Master of Science, PhD Student, Physical Science Unit, Nepal Academy of Science and Technology, Lalitpur, 44700, Nepal, SC 57226722149, https://orcid.org/0000-0001-6425-7647, saddam@ran.edu.np
Jeevan Joyti Nakarmi — PhD, Professor, Tribhuvan University, Lalitpur, 44700, Nepal, SC 35115267400, https://orcid.org/0000-0002-5470-8675, nakarmijj@gmail.com
Kishori Yadav — PhD, Professor, Tribhuvan University, Lalitpur, 44700, Nepal; Research Coordinator, Innovative Ghar Nepal, Lalitpur, 44700, Nepal, SC 57375388500, https://orcid.org/0009-0005-9666-8076, yadavkishori70@gmail.com
Suresh Prasad Gupta — PhD, Professor, Tribhuvan University, Lalitpur, 44700, Nepal; Research Coordinator, Innovative Ghar Nepal, Lalitpur, 44700, Nepal, SC 57755185600, https://orcid.org/0000-0001-9075-468X, guptasir@gmail.com

Авторы

Дхоби Саддам Хусейн — магистр, аспирант, Непальская академия наук и технологий, Лалитпур, 44700, Непал, SC 57226722149, https://orcid.org/0000-0001-6425-7647, saddam@ran.edu.np

Накарми Дживан Джиоти — PhD, профессор, Университет Трибхуван, Лалитпур, 44700, Непал, SC 35115267400, https://orcid.org/0000-0002-5470-8675, nakarmijj@gmail.com
Ядав Кишори — PhD, профессор, Университет Трибхуван, Лалитпур, 44700, Непал; научный координатор, Инновационный Гар Непала, Лалитпур, 44700, Непал, SC 57375388500,https://orcid.org/0009-0005-9666-8076, yadavkishori70@gmail.com
Гупта Суреш Прасад — PhD, профессор, Университет Трибхуван, Лалитпур, 44700, Непал; научный координатор, Инновационный Гар Непала, Лалитпур, 44700, Непал, SC 57755185600, https://orcid.org/0000-0001-9075-468X, guptasir@gmail.com

Received 12.10.2023
Approved after reviewing 26.04.2024
Accepted 27.05.2024

Статья поступила в редакцию 12.10.2023
Одобрена после рецензирования 26.04.2024
Принята к печати 27.05.2024