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OPTICAL FARADAY MANIPULATING LONGITUDINAL COMPONENT OF OPTICAL VORTEX BEAMS

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ABSTRACT

In this study, we aim to investigate the novel application of the Optical Faraday effect in manipulating the longitudinal component of optical vortex beams, which are characterized by their unique orbital angular momentum and helical phase structure. The Optical Faraday effect, induced by the interaction of a magnetic field with a specific optical crystal, results in a rotation of the polarization plane of light. This phenomenon is harnessed to exert precise control over the longitudinal component of optical vortex beams, a feature not typically present in conventional light beams. Our theoretical analysis explores the modulation of the longitudinal component, revealing a significant influence on the beam's polarization characteristics, intensity distribution, and phase characteristics. This manipulation breaks new grounds for increasing the precision of optical systems, with potential applications in advanced optical communication, high-density data storage, and quantum information processing. The findings show that by finely tuning the magnetic field and material properties, it is possible to achieve a new kind of control mechanism over the propagation and interaction of optical vortex beams. This work paves the way for further exploration into the dynamic control of structured light, offering promising prospects for future photonic technologies.

Keywords: Faraday effect, OAM, Longitudinal component, Optical vortex.

1 INTRODUCTION

The manipulation and control of light's properties are fundamental in the progression of optical sciences and the development of innovative technologies [1-4]. Among the various types of light beams, optical vortex beams have emerged as a particularly fascinating subject due to their unique capability of carrying orbital angular momentum (OAM) [5,6] This property can be described as a direct result of their helical phase front, which imparts a characteristic 'twist' to the wavefront, resulting in a doughnut-shaped intensity profile with a central null point [7-9]. The potential applications of optical vortex beams are extensive, spanning from advanced optical communication [10,11] systems to quantum information processing [12,13] and high-resolution imaging [14-16].

Optical vortex beams offer a unique avenue for encoding information within the phase structure of the light beam itself [17,18]. This feature can be harnessed to significantly enhance data transmission capacities by using OAM states as an additional degree of freedom for multiplexing [10,11]. Such an approach is crucial in optical communication systems. Furthermore, the distinctive phase and intensity profile of these beams can improve resolution and contrast in imaging applications, which is critical for detailed observations in biological research and materials science [14-16].

One of the key challenges in fully exploiting the potential of optical vortex beams lies in the precise control of their properties, particularly the longitudinal component of the electric field. In traditional light beams, the longitudinal component is typically minimal; however, in optical vortex beams, this component can be substantial due to the complex phase structure and because of reducible beam waist parameters. Controlling this longitudinal component allows for more meaningful and useful manipulation of the beam’s phase and intensity, which is essential for applications requiring precise beam shaping, such as optical trapping and laser machining [19-22].

The Optical Faraday effect offers a compelling theoretical framework for manipulating the properties of light, including the longitudinal component of optical vortex beams. This magneto-optical phenomenon, first observed by Michael Faraday, involves the rotation of the polarization plane of light as it passes through a material under the influence of a magnetic field aligned with the direction of propagation. The degree of rotation, known as the Faraday rotation, depends on the Verdet constant of the material, the strength of the magnetic field, and the wavelength of the light. The ability to control these parameters allows for precise modulation of the light's polarization and, consequently, its intensity and phase characteristics [23-26].

In this theoretical exploration, we aim to develop a comprehensive understanding of how the Optical Faraday effect can be utilized to manipulate the longitudinal component of optical vortex beams. We will explore the mathematical foundations underlying the interaction between optical vortex beams and the magnetic field-induced birefringence. This involves analyzing the propagation dynamics of the beams passing through a magneto-optical material under varying magnetic fields and assessing how these interactions alter the beam's polarization, intensity, and longitudinal component. Theoretical models have been developed to predict the outcomes of these interactions, focusing on identifying the conditions under which the longitudinal component can be most effectively controlled.

The theoretical investigation leads also to the implications of this control for practical applications. In optical communication, for instance, manipulating the longitudinal component could allow for more sophisticated modulation schemes, potentially increasing data throughput. In quantum information processing, precise control over the optical beam's properties is crucial for the manipulation and measurement of quantum states. Additionally, in the realm of optical sensing and metrology, the ability to finely tune the beam's properties could enhance the sensitivity and accuracy of measurements.

By providing a theoretical framework for the manipulation of the longitudinal component of optical vortex beams using the Optical Faraday effect, this study aims to bridge the gap between fundamental optical theory and potential practical applications. The insights gained from this research will not only contribute to the broader understanding of light-matter interactions but also suggest new pathways for technological advancements in fields as diverse as telecommunications, materials science, and quantum computing.

Therefore, the application of the Optical Faraday effect to optical vortex beams represents a promising new frontier in photonics. By leveraging this phenomenon to manipulate the longitudinal component of these beams, we open up new possibilities for their use in a variety of advanced optical systems. This theoretical study lays the groundwork for future experimental validation and technological innovation, positioning optical vortex beams at the forefront of next-generation optical technologies.

Now, we will present the theoretical framework employed to analyze the interaction of an optical vortex beam with a magneto-optic crystal under the influence of an external magnetic field. The analysis begins with the description of polarization modes using the Poincaré sphere, a powerful tool for visualizing and understanding the state of polarization in terms of spherical coordinates. By mapping the polarization states onto this sphere, we can effectively describe the dynamic behavior of the light as it propagates through the crystal.

Next, we introduce the optical vortex structure of the light, characterized by its Laguerre-Gaussian (LG) mode, which features a helical phase front and a doughnut-shaped intensity profile. The optical vortex beam exhibits vector polarization, where the electric field is structured as a superposition of two circularly polarized components with opposite winding numbers. These components, representing right-hand and left-hand circular polarizations, are critical in defining the unique phase and intensity characteristics of the vortex beam.

2 MATERIAL AND METHOD

The electric field of the light after passing through the magneto-optic crystal is mathematically expressed as the combination of these two oppositely polarized components. Importantly, the magneto-optic effect causes the refractive indices of the crystal for the right-hand and left-hand circular polarizations to differ, leading to a phase shift between them. This differential phase shift, induced by the external magnetic field, is crucial in understanding the resultant electric field distribution and the modifications in the polarization state.

Through this theoretical framework, we calculate the resultant electric field by considering the refractive index changes due to the magneto-optic effect, which encompasses the influence of the magnetic field on the crystal. These calculations are pivotal in predicting the behavior of the optical vortex beam as it interacts with the magneto-optic medium, providing insights that align with the experimental observations.

A polarized electric field vector can be effectively described using the polarization modes on the Poincaré sphere. The expression for the polarization state is given by

$$\hat{\epsilon}_l = e^{il\phi}(\hat{x} - i\hat{y})u_P + e^{-il\phi}(\hat{x} + i\hat{y})\mathcal{V}_P \tag{1}$$

where u_P and $\mathcal{V}_P$ are defined as

$$u_P = \frac{1}{\sqrt{2}} sin\left(\frac{\Theta_P}{2}\right) e^{\frac{-i\Phi_P}{2}}\ ;\ \mathcal{V}_P = \frac{1}{\sqrt{2}} cos\left(\frac{\Theta_P}{2}\right) e^{\frac{i\Phi_P}{2}} \tag{2}$$

where $\boldsymbol{\Theta_P}$ and $\boldsymbol{\Phi_P}$ parameters are angular variables on Poincar'e sphere. These parameters determine the orientation and ellipticity of the polarization state. The electric field components can be expressed as

$$F_{l,p}^{(1)}(r) = u_P e^{il\phi} \tilde{F}_{l,p}(\rho);\ F_{l,p}^{(2)}(r) = \mathcal{V}_P e^{-il\phi} \tilde{F}_{l,p}(\rho) \tag{3}$$

where $\widetilde{\boldsymbol{F}}_{\boldsymbol{l,p}}(\boldsymbol{\rho})$ is the vector potential amplitude function, described by the Laguerre-Gaussian mode as

$$\tilde{F}_{l,p}(\rho) = A_0\sqrt{\frac{p!}{(p+|l|)!}}\,e^{-\frac{\rho^2}{\omega_0^2}}\left(\frac{\sqrt{2}\rho}{\omega_0}\right)^{|l|} L_p^{|l|}\left(\frac{2\rho^2}{\omega_0^2}\right) \tag{4}$$

where ρ is the radial coordinate, A_0 is the normalization constant. This function depends solely on the radial distance ρ and the electric field $\boldsymbol{E}$ can be explicitly written as

$$E = (\hat{x} - i\hat{y})F^{(1)}e^{in_-k_zz} - \hat{z}c\left\{\frac{\partial F^{(1)}}{\partial x} - i\frac{\partial F^{(1)}}{\partial y}\right\}e^{in_-k_zz} + (\hat{x} + i\hat{y})F^{(2)}e^{in_+k_zz}$$
$$-\hat{z}c\left\{\frac{\partial F^{(2)}}{\partial x} + i\frac{\partial F^{(2)}}{\partial y}\right\}e^{in_+k_zz} \tag{5}$$

where n_- and n_+ represent the refractive indices of the magneto-optic material for left- and right-circularly polarized light, respectively. In vacuum $\boldsymbol{n}^{(+)} = \boldsymbol{n}^{(-)} = 1$. For the magneto-optic crystal, it is possible to observe the difference between the n_- and n_+ refractive indices due to the change in Faraday angle such that [23]

$$n^{(-)} - n^{(+)} = \gamma\Theta \tag{6}$$

where Θ is the rotation angle given by the standard expression

$$\Theta = VBL \tag{7}$$

where V, B and L are the Verdet constant of the material, applied axial magnetic field and the thickness of the medium, respectively. And the parameter $\gamma = 2\,c/\omega L$ indicates the relationship between the refractive index difference and Faraday angle. The left-hand circular polarisation and the right hand one produce equal but opposite change (in sign) of the rotation angle suggesting the following forms

$$n^{(-)} = n_0 + \left(\frac{\gamma\Theta}{2}\right); \quad n^{(+)} = n_0 - \left(\frac{\gamma\Theta}{2}\right) \tag{8}$$

where n_0 is the refractive index in the absence of the magnetic field.

The z-component in the equation refers to the longitudinal electric field component, indicating that the electric field is polarized in all three spatial dimensions:

x, y and z. It is important to note that the longitudinal component of the wave becomes negligible when the beam waist ω_0 is significantly larger than the wavelength λ, i.e. $\omega_0 \gg \lambda$.

However, recent studies have shown that the longitudinal electric field can contribute significantly to the total electric field when the beam waist is small, even while adhering to the optical diffraction limit (approximately for $\omega_0 > 0{,}7\lambda$).

In our previous study [25], we observed the effect of an external magnetic field applied along the light propagation direction on the polarization of light possessing only a transverse electric component as it traversed through a magneto-optic crystal. Notably, no significant changes were observed in the radial profile of the light. However, in our current investigation, it has become evident that the external magnetic field indeed influences the presence and orientation of the longitudinal electric component. This finding underscores the complex interplay between the magnetic field and the electric field components of light within the magneto-optic medium, suggesting a more nuanced mechanism that governs the light-matter interaction in such environments. This discovery challenges the conventional understanding and opens new avenues for exploring the manipulation of light in advanced photonic applications.

It is not possible to produce an explicit form of the Equation 5. But, we can revise the equation for specific values of $\boldsymbol{E}$

$$E(\rho,\phi,L) = \frac{u(\rho)}{\sqrt{2}}\begin{Bmatrix} \hat{x}\left[e^{(ikLn_0 - i\Theta + il\phi)} + e^{(ikLn_0 + i\Theta - il\phi)}\right] - \\ i\hat{y}\left[e^{(ikLn_0 - i\Theta + il\phi)} - e^{(ikLn_0 + i\Theta - il\phi)}\right] \end{Bmatrix} \tag{9}$$

The Figure 1 presented elucidates the influence of an external magnetic field on the propagation of light through a magneto-optic crystal, particularly focusing on the interplay between the longitudinal and transverse electric field components. In our earlier research, we primarily investigated the impact of an external magnetic field on light possessing only a transverse electric component, noting that while the polarization of the light was affected, there were no observable changes in the radial profile. This suggested that the transverse electric field's interaction with the magnetic field was relatively straightforward and did not invoke significant alterations in the spatial distribution of the light intensity.

However, the current figure delves deeper into the situation by incorporating the presence of a longitudinal electric component, which is subjected to the same external magnetic field. Each subplot in the figure corresponds to a specific Faraday angle, $\boldsymbol{\theta}$, which represents different magnitudes of the applied magnetic field. The color maps and overlaid contour lines provide a detailed visualization of how the electric field distribution evolves under varying conditions.

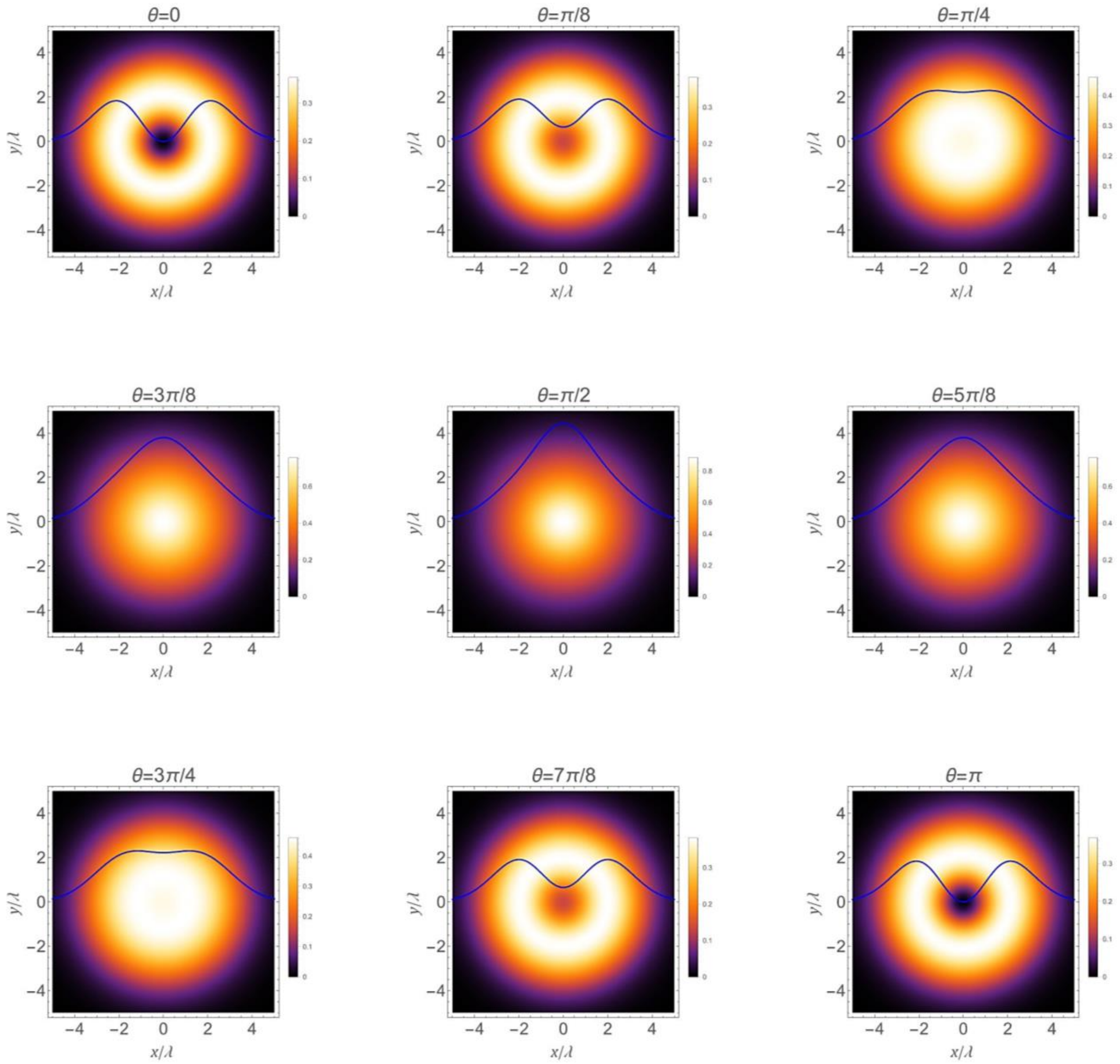

Figure 1. Density profile changes according to Faraday angle for values $\theta_p = \pi/2, \varphi_p = \pi/2, l = 1, p = 0$. The value $\varphi_p = \pi$ corresponds to the azimuthal polarization on the Poincar'e sphere. The impact of an external magnetic field on the electric field distribution within a magneto-optic crystal, as visualized for various Faraday angles (θ) which depends on the magnetic field. Each subplot represents the evolution of the electric field, with both longitudinal and transverse components, as θ increases from 0 to π. The color maps indicate the intensity distribution, while the overlaid contour lines highlight the ρ dependent modulation of the electric field. The figure demonstrates the significant influence of the magnetic field on the longitudinal electric component, revealing complex interactions and symmetry breaking as the field orientation changes.

At $\boldsymbol{\theta} = \mathbf{0}$, the electric field distribution exhibits a certain symmetry, with the transverse component predominantly determining the overall pattern. As the angle $\boldsymbol{\theta}$ increases, representing a change in the magnetic field's strength, there is a noticeable alteration in the electric field distribution. This is especially pronounced in the longitudinal component, which begins to exhibit more complex patterns and deviations from the initial symmetry.

When $\boldsymbol{\theta}$ reaches π/2, the longitudinal component's influence becomes most apparent, as evidenced by the significant changes in the electric field distribution. The figure suggests that the external magnetic field strongly affects the longitudinal component, causing it to vary in a manner that is not observed when only the transverse component is present. As $\boldsymbol{\theta}$ continues to increase, the patterns evolve further, indicating that the longitudinal component's response to the magnetic field is highly sensitive to the field's magnitude.

This comprehensive analysis of the electric field distribution as a function of the Faraday angle meaning of the applied magnetic field highlights the intricate dynamics at play within the magneto-optic medium. The findings depicted in this figure underscore the complex relationship between the external applied magnetic field and the electric field components of the light, particularly emphasizing the critical role of the longitudinal component, which had been previously underappreciated.

We can perform another analysis by investigating the Figure 1 which shows how the magnetic field, that is, the Faraday angle, affects the $\boldsymbol{\theta_p}$ polarization and therefore the total electric field radial profile distribution. In the first place, we assume that the light that will pass through the magneto-optic crystal in the z direction without any external magnetic field is azimuthally polarized ($\boldsymbol{\varphi_p} = \boldsymbol{\pi}$). For the $\boldsymbol{l} = \mathbf{1}$ case, as shown in the figure, to better illustrate the ring-shaped intensity distribution in the x-y plane, a radial distribution graph was obtained with the blue line. Due to the radial symmetry, the intensity distribution and the graph represented by the blue line are independent of the azimuthal angle $\boldsymbol{\phi}$ and represent the singularity. The dark region located in the middle of the ring with radial symmetry and representing the singularity changes with the increase in the value of the Faraday angle, which depends on the magnetic field. The main reason for this

$$I = \frac{2E_0^2 e^{-\frac{2\rho^2}{\omega_0^2}} \left(4c^2 \sin^2\theta\,(\omega_0^2 - \rho^2)^2 + \rho^2\omega_0^4\omega^2\right)}{\omega_0^6} \tag{10}$$

is that the resulting radial profile consists of two parts. The first part, the expression $4c^2 \sin^2\theta\,(\omega_0^2 - \rho^2)^2$, shows the longitudinal wave component. This component contributes to the result according to the θ angle. For $\theta = \pi$ case, the light has azimuthal polarization, and the direction of rotation of the azimuthal polarization vectors for this position (For $\theta = \pi$) is opposite to the For $\theta = 0$ case. Here we come across an interesting fact. Before, we were placing a linear polarizer behind the magneto-optic crystal to understand the change in radial polarization. However, with the contribution of the longitudinal wave component, the need for a linear polarizer is eliminated. Equation 5 that we obtained for the electric field gives us the orientation of the polarization vectors and their change depending on the Faraday angle.

The graph presented in Figure 1 is crucial in advancing our understanding of how an external magnetic field, characterized by the Faraday angle θ, influences the propagation of light through a magneto-optic crystal. This research focuses on the interaction between the longitudinal and transverse components of the electric field within this medium. The figure's significance lies in its detailed visualization of the electric field distribution as the magnetic field strength, and consequently the Faraday angle, increases. The evolution of these patterns, especially the longitudinal component's response, highlights a complex interplay that was previously underestimated. At different Faraday angles, the radial symmetry and the resulting singularities change, providing insights into how the longitudinal component can alter the light's behavior within the magneto-optic crystal.

The practical implications of this study are vast. The ability to manipulate the longitudinal electric field without the need for external linear polarizers, as suggested by the results, opens up new possibilities in photonic applications, such as the design of advanced optical devices that rely on precise control of light polarization. The observed changes in the radial profile due to the Faraday effect can be leveraged to develop highly sensitive sensors or modulators that operate based on the external magnetic field's influence on light.

Moreover, these findings provide a foundational understanding that can support future research. By illustrating how the Faraday angle affects both the radial distribution and the polarization states, this study offers a framework that other researchers can build upon to explore new methods of light manipulation in magneto-optic materials. This could lead to the development of novel technologies in fields ranging from telecommunications to quantum computing, where precise control over light's properties is essential. The figure demonstrates that by carefully controlling the magnetic field, we can achieve significant modulation of light's electric field components, leading to new applications and furthering our understanding of light-matter interactions in magneto-optic environments.

This research provides a comprehensive exploration of the intricate dynamics involved in the polarization of light as it propagates through a magneto-optic crystal under the influence of an external magnetic field. By methodically varying the Faraday angle, we have revealed significant alterations in the spatial distribution and orientation of polarization vectors, which undergo a remarkable evolution from azimuthal to radial configurations. This study not only sheds light on the previously underappreciated role of the longitudinal electric field component but also highlights its critical importance in influencing the overall polarization profile, especially in the presence of strong magnetic fields.

3 RESULTS AND DISCUSSION

Initially, when no external magnetic field is applied, the polarization vectors of the light are arranged in a symmetrical azimuthal mode around the axis of the beam. This alignment serves as a baseline, clearly demonstrating the light's initial polarization state before any magnetic influence is introduced. As the magnetic field strength increases, leading to a corresponding increase in the Faraday angle, the behavior of these polarization vectors begins to change noticeably. At a relatively low Faraday angle, the symmetry of the azimuthal polarization starts to break down, especially near the center of the beam, where new and stronger polarization vectors emerge, deviating towards the longitudinal (z) direction. This deviation indicates a significant transition in the polarization state, one that traditional models based on the Poincaré sphere cannot fully explain, as these models typically assume polarization within a plane perpendicular to the light's direction of travel.

As the Faraday angle increases further, reaching a midpoint value, the transformation of the polarization state becomes more pronounced. The electric field vectors, which initially exhibited a predominantly azimuthal orientation, gradually realign themselves into a radial configuration. This transition is particularly significant because it underscores the external magnetic field's ability to induce a fundamental shift in the light's polarization state, moving from azimuthal to radial polarization. This change is accompanied by a strong orientation of the electric field vectors in the z-direction, especially near the center of the beam, where the influence of the longitudinal component becomes increasingly dominant.

When the Faraday angle reaches higher values, approaching three-quarters of its maximum, the study reveals a reemergence of helical polarization patterns, this time with a counterclockwise orientation. Interestingly, despite the strong z-directional component observed at this stage, its overall intensity diminishes as the magnetic field continues to strengthen. This suggests a complex interplay between the transverse and longitudinal components of the electric field, where the dominance of one over the other is highly sensitive to the precise configuration of the magnetic field. Furthermore, the gradual transition from azimuthal to radial polarization modes, driven by the varying magnetic field, highlights the versatility of magneto-optic materials in enabling precise control over light's polarization state.

At the peak Faraday angle, the study shows a complete reversal of the polarization vectors compared to their initial state. The azimuthal polarization reappears, but with a critical twist: the vectors are now oriented in the opposite direction to their original alignment. This reversal not only completes the cycle of polarization transformation but also demonstrates the magnetic field's capability to control the polarization vectors' direction and intensity with remarkable precision. The fact that the radial profile of the light remains consistent, regardless of this reversal, underscores the robust nature of the polarization state changes induced by the magnetic field.

4 CONCLUSION AND SUGGESTIONS

The findings from this study have significant implications for both fundamental research and practical applications. The ability to manipulate polarization states without the need for external polarizing elements, such as linear polarizers, represents a major advancement in the field of photonics. This capability could lead to the development of new optical devices, such as switches, sensors, and modulators, that rely on the precise control of light polarization in three dimensions. Additionally, the insights gained into the behavior of the longitudinal electric field component offer a deeper understanding of magneto-optic interactions, which could inform the design of future experiments and theoretical models in the field.

Moreover, the results suggest that by carefully adjusting the external magnetic field, a wide range of polarization states can be achieved, each with unique properties that could be exploited for specific technological applications. For instance, in the field of optical communications, the ability to switch between different polarization modes could enhance both the speed and security of data transmission. In sensing technologies, the sensitivity of the polarization state to the external magnetic field could be used to develop highly accurate magnetic field sensors with broad industrial and scientific applications.

The study also paves the way for further research in related fields, such as quantum optics and nanophotonics, where the ability to control light at very small scales is crucial. The techniques demonstrated here for manipulating light polarization could have significant implications for quantum information processing, where precise control over photon states is essential. Additionally, the ability to tailor light polarization in magneto-optic materials could lead to the development of new materials with engineered optical properties, opening up new avenues in material science and photonics.

In conclusion, this research not only advances our understanding of light-matter interactions in magneto-optic materials but also establishes a foundation for future technological developments in photonics. The demonstrated ability to precisely control light polarization through external magnetic fields represents a significant step forward, with far-reaching implications for both fundamental science and practical applications in a wide range of fields.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Fatma Tambağ: Writing, Investigation, Data Curation

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