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REGULAR ARTICLE

Optimizing Reflectivity in Bi-isotropic Multilayer Mirrors: The Role of Chiral and Tellegen Parameter Ratios

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This work introduces an innovative approach to optimizing the reflectivity of bi-isotropic multilayer mirrors at normal incidence through systematic manipulation of critical design parameters. The study demonstrates that high optical index contrast in material selection, combined with an increased number of bi-layers, significantly enhances reflection by creating multiple interfaces for electromagnetic interaction. By strategically adjusting layer thicknesses, favoring thinner high-index layers and thicker low-index layers, reflectivity can be substantially improved. A pivotal finding reveals that the ratio of bi-isotropic parameters (chirality to non-reciprocity) plays a crucial role in performance optimization, with lower ratios (below unity) achieving reflectivity values exceeding 92 % at $\lambda = 500$ nm, while higher ratios (above unity) progressively reduce reflectivity to approximately 68 %. A mathematical model relating reflectivity to parameter ratios is derived, providing a predictive tool for design optimization. This research leverages the unique electromagnetic properties of chiral and Tellegen bi-isotropic materials, exploring previously untapped characteristics to revolutionize modern optical devices. The originality lies in proposing novel strategies for applications in advanced optics and photonic crystals, unlocking new possibilities for optical communication, sensing technologies, and precision electromagnetic control systems. This comprehensive investigation offers fresh insights into how structural and parametric adjustments impact bi-isotropic mirrors, advancing their practical implementation in next-generation photonic technologies.

Keywords: Bi-isotropic multilayer mirrors, Chirality parameter optimization, Non-reciprocity effects, Photonic crystal structures, Tellegen media.

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1. INTRODUCTION

The study of bi-isotropic media represents a fascinating intersection of electromagnetism and materials science, where the interplay between chirality and non-reciprocity fundamentally governs electromagnetic responses. This relationship traces back to the nineteenth century through pioneering work by Fresnel, Biot, and Pasteur, who established the foundational understanding of optical activity and chiral phenomena [1-4]. Recent decades have witnessed renewed interest in bi-isotropic materials – comprising metallic or ceramic helical inclusions dispersed within polymer or ceramic matrices – due to their unique electromagnetic properties. Although chirality has played crucial roles in chemistry, optics, and particle physics for over a century, its potential in advanced electromagnetic applications remains significantly underexplored.

This study investigates chiroptical and non-reciprocal effects in multilayer structures composed of alternating bi-isotropic layers with high and low refractive indices. While conventional approaches focus on layer count and permittivity optimization, achieving optimal performance requires systematic manipulation of the bi-isotropic parameter ratio, specifically the relationship between chirality and non-reciprocity parameters. Through comprehensive theoretical analysis and computational modeling, we demonstrate that this ratio serves as a critical design variable, with lower ratios enhancing reflectivity to values exceeding 92 % at specific wavelengths. Our systematic investigation reveals how layer composition, arrangement, and parametric adjustments collectively influence the reflective behavior of these sophisticated structures [5-9].

The fundamental challenge in optimizing bi-isotropic multilayer mirrors lies in understanding the complex coupling between electromagnetic field components at multiple interfaces. Unlike conventional dielectric mirrors that rely solely on impedance mismatch, bi-isotropic structures exhibit cross-coupling between electric and magnetic fields through chirality and non-reciprocity parameters. This coupling creates additional degrees of freedom for controlling light propagation, reflection, and transmission characteristics. By systematically varying the ratio between these bi-isotropic parameters, we can effectively engineer the electromagnetic response of the multilayer structure,

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achieving performance levels unattainable with traditional optical materials [10, 11].

This research uniquely leverages the untapped potential of chiral and Tellegen bi-isotropic materials to advance multilayer optical device design beyond traditional refractive index engineering. By introducing the bi-isotropic parameter ratio as a fundamental control mechanism, this work opens innovative pathways for applications in photonic crystals, optical communication, and precision sensing technologies. The originality lies in demonstrating practical implementation strategies for materials exhibiting both reciprocal and non-reciprocal electromagnetic characteristics in multilayer configurations [12-14]. Through this investigation, we provide valuable insights for designing next-generation optical devices with enhanced functionality, paving the way for breakthroughs in electromagnetic control and light-matter interactions.

2. THEORETICAL BACKGROUND

2.1 Structure Configuration

The bi-isotropic multilayer mirror under investigation is represented in Fig. 1. It comprises a periodic arrangement of $\boldsymbol{N}$ alternating layers with distinct electromagnetic properties. This structure represents a generalized form of a chiral multilayer system, where each period consists of two bi-isotropic slabs with contrasting refractive indices: a high-index layer ($\boldsymbol{n_H}$) and a low-index layer ($\boldsymbol{n_L}$). The entire multilayer stack is positioned between two semi-infinite homogeneous media characterized by refractive indices $\boldsymbol{n_0}$ (incident medium) and $\boldsymbol{n_A}$ (substrate medium).

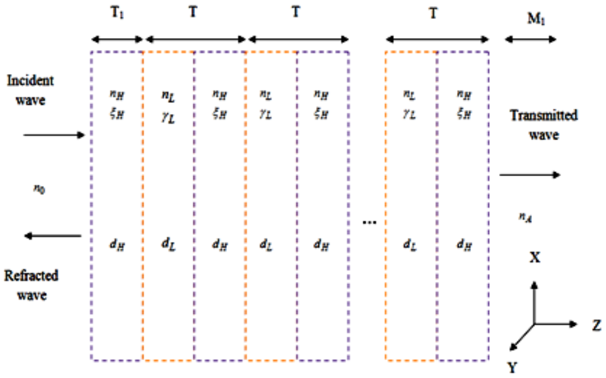


Fig. 1 – Schematic diagram of the bi-isotropic multilayer mirror structure at normal incidence

The electromagnetic response of bi-isotropic media is governed by constitutive relations that couple the electric and magnetic fields. For the high-index ($\boldsymbol{n_H}$) and low-index ($\boldsymbol{n_L}$) layers, these relations are expressed as.

$$\begin{cases} D_H = \varepsilon_H E_H - j\kappa_H B_H \\ H_H = -j\kappa_H E_H + \left(\dfrac{1}{\mu_H}\right) B_H \end{cases} \tag{1}$$

and,

$$\begin{cases} D_L = \varepsilon_L E_L + \gamma_L B_L \\ H_L = -\gamma_L E_H + \left(\dfrac{1}{\mu_L}\right) B_L \end{cases} \tag{2}$$

Where: $\boldsymbol{\varepsilon}$ and $\boldsymbol{\mu}$ are the permittivity and permeability, respectively. $\boldsymbol{\kappa}$ is the non-reciprocity (tellegen) parameter ($\boldsymbol{\Omega^{-1}}$), $\boldsymbol{\gamma}$ is the chirality parameter ($\boldsymbol{\Omega^{-1}}$), and $\boldsymbol{j}$ is the imaginary unit.

These parameters characterize the cross-coupling between electric and magnetic fields, which is the fundamental property distinguishing bi-isotropic media from conventional isotropic materials.

2.2 Transfer Matrix Formulation

To analyze electromagnetic wave propagation through the multilayer structure at normal incidence, we employ the transfer matrix method. The electric field components in each layer can be decomposed into right-circularly polarized (RCP) and left-circularly polarized (LCP) components, denoted as $\boldsymbol{E_R}$ and $\boldsymbol{E_L}$, respectively, as represented in Fig. 2.

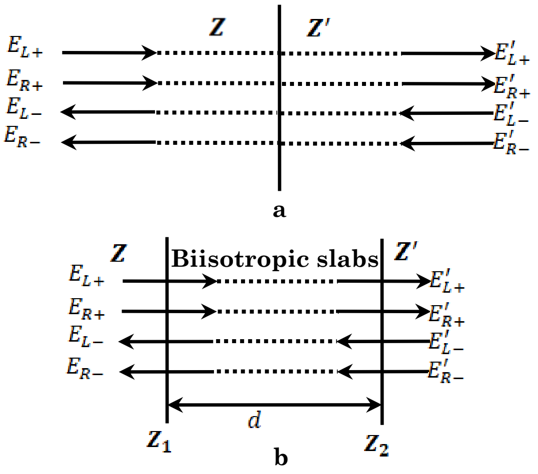


Fig. 2 – Electric field decomposition at: (a) bi-isotropic interface, (b) within bi-isotropic layer

At each interface, the tangential components of the electric field must satisfy continuity conditions. For the $\boldsymbol{x}$ and $\boldsymbol{y}$ components, this yields.

$$\begin{cases} \boldsymbol{E_{L+} + E_{R+} - E_{L-} - E_{R-} = E'_{L+} + E'_{R+} - E'_{L-} - E'_{R+}} \\ \boldsymbol{-E_{L+} + E_{R+} - E_{L-} + E_{R-} = E'_{L+} + E'_{R+} - E'_{L-} - E'_{R+}} \end{cases}, \tag{3}$$

And,

$$\begin{bmatrix} \boldsymbol{E_{L+}} \\ \boldsymbol{E_{R+}} \\ \boldsymbol{E_{L-}} \\ \boldsymbol{E_{R-}} \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} \boldsymbol{E'_{L+}} \\ \boldsymbol{E'_{R+}} \\ \boldsymbol{E'_{L-}} \\ \boldsymbol{E'_{R-}} \end{bmatrix} \tag{4}$$

Where $\boldsymbol{M}$ is the interface transfer matrix connecting fields on either side of the boundary.

Within each bi-isotropic layer, the field propagation is described by the propagation matrix $\boldsymbol{P}$ [5].

$$\boldsymbol{P}=\begin{bmatrix} e^{jk_L d} & 0 & 0 & 0 \\ 0 & e^{jk_R d} & 0 & 0 \\ 0 & 0 & e^{(-jk_L d)} & 0 \\ 0 & 0 & 0 & e^{(-jk_R d)} \end{bmatrix}, \tag{5}$$

Where $\boldsymbol{k_L}$ and $\boldsymbol{k_R}$ are the wave vectors for LCP and RCP waves, $\boldsymbol{d_L}$ and $\boldsymbol{d_R}$ are the propagation distances for each component.

The total transfer matrix $\boldsymbol{T}$ for a single bilayer (one high-index and one low-index layer) is obtained by cascading the individual interface and propagation matrices.

$$\begin{bmatrix} E_{2L+} \\ E_{2R+} \\ E_{2L-} \\ E_{2R-} \end{bmatrix} = \boldsymbol{T}\begin{bmatrix} E_{4L+} \\ E_{4R+} \\ E_{4L-} \\ E_{4R-} \end{bmatrix} = \boldsymbol{T}^2\begin{bmatrix} E_{6L+} \\ E_{6R+} \\ E_{6L-} \\ E_{6R-} \end{bmatrix} = \cdots = \boldsymbol{T}^N\begin{bmatrix} E_{(2N+2)L+} \\ E_{(2N+2)R+} \\ E_{(2N+2)L-} \\ E_{(2N+2)R-} \end{bmatrix}, \tag{6}$$

And,

$$\begin{bmatrix} E_{iTM} \\ E_{rTM} \\ E_{iTE} \\ E_{rTE} \end{bmatrix} = \boldsymbol{T_1}\boldsymbol{T}^N\boldsymbol{M_2}\begin{bmatrix} E_{iTM} \\ E_{iTE} \end{bmatrix}, \tag{7}$$

Where, $\boldsymbol{T_1} = \boldsymbol{M_1 P_H}$ and $\boldsymbol{T_1} = \boldsymbol{M_H P_H M_L P_L}$.

The matrix $\boldsymbol{M_H(M_L)}$ establishes the relationship between fields in the high (low) refractive index regions of the bi-isotropic medium and those in the subsequent medium. Meanwhile, the matrix $\boldsymbol{P_H(P_L)}$ represents the propagation matrix for fields within the bi-isotropic medium, characterized by high (low) refractive indices. The properties of bi-isotropic mirrors are determined by the $\boldsymbol{N^{th}}$ power of the $\boldsymbol{T^N}$ and $\boldsymbol{T}$ bilayers matrix. The behavior of the $\boldsymbol{T}$ matrix is delineated by its eigenvalues.

2.3 Reflection and Transmission Coefficients

From the transfer matrix formulation, the reflection $(\boldsymbol{r})$ and transmission $(\boldsymbol{t})$ coefficients can be extracted for both transverse electric (TE) and transverse magnetic (TM) polarizations, or equivalently for RCP and LCP components. The reflectivity $\boldsymbol{R}$, which quantifies the mirror performance, is calculated as.

$$\boldsymbol{R} = |\boldsymbol{r}|^2 \times \mathbf{100\%}, \tag{8}$$

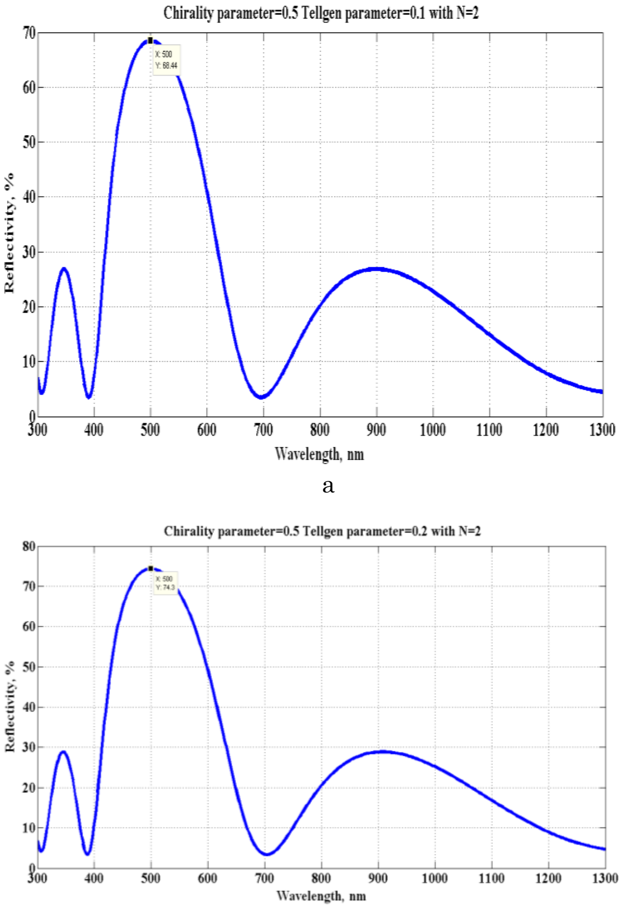
3. RESULTS AND DISCUSSION

3.1 Simulation Parameters and Methodology

To systematically investigate the influence of bi-isotropic parameters on mirror reflectivity, we conducted numerical simulations using a custom-developed computational program based on the transfer matrix formulation presented in Section 2. The multilayer structure consisted of $N = 2$ bilayers with alternating high and low refractive index materials: silicon monoxide (SiO, n_H) and magnesium fluoride (MgF$_2$, n_L). The optical thickness of each layer was set to $d_{H,L} =$ 0.2× $n_{H,L} \times \lambda$, corresponding to a quarter-wave configuration optimized for constructive interference at the design wavelength. We systematically varied the bi-isotropic parameter ratio κ_H/γ_L across a broad range from 0.2 to 5.0 to characterize its effect on the spectral reflectivity under normal incidence conditions.

3.2 Effect of Increasing Bi-isotropic Parameter Ratio

Figs. 3 and 4 illustrate the reflectivity spectra for increasing values of the bi-isotropic parameter ratio: $\kappa_H/\gamma_L = 1$, 1.67, 2.5, and 5. A clear trend emerges showing a systematic degradation in reflectivity performance as this ratio increases.

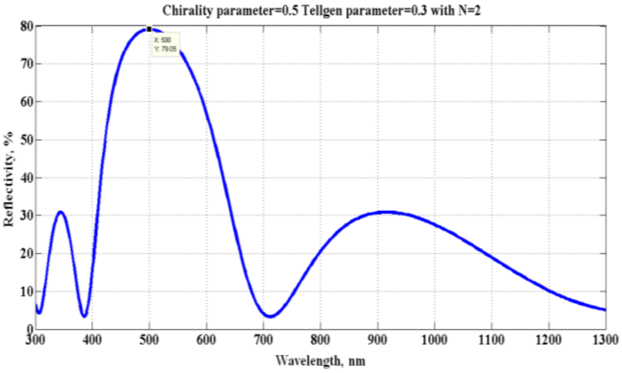


a

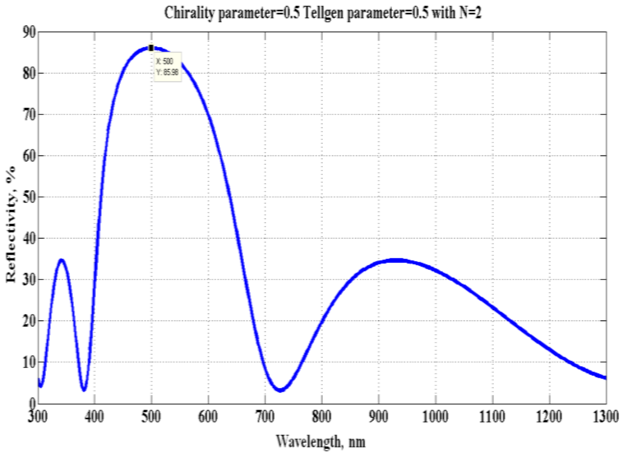
b

Fig. 3 – Reflectivity vs. the wavelength in normal incidence for: n_H (SiO), n_L (MgF2) with N =2: (a) $\kappa_H/\gamma_L = 5$, (b) $\kappa_H/\gamma_L = 2.5$

At the reference wavelength of $\lambda = 500$ nm, the reflectivity decreases progressively from 85.98% ($\kappa_H/\gamma_L =$ 1) to 68.44% ($\kappa_H/\gamma_L = 5$), representing an overall reduction of approximately 17.5 percentage points.



a



b

Fig. 4 – Reflectivity vs. the wavelength in normal incidence for: n_H (SiO), n_L (MgF2) with N =2: (a) κ_H/γ_L = 1.67, (b) κ_H/γ_L = 1

This inverse relationship between the bi-isotropic parameter ratio and reflectivity can be attributed to the increasing dominance of non-reciprocity effects (κ_H) relative to chirality (γ_L), which disrupts the constructive interference conditions that maximize reflection. The spectral profiles also reveal that higher ratios not only reduce peak reflectivity but also broaden the reflection bandwidth, suggesting a trade-off between peak performance and spectral coverage. These findings indicate that applications requiring maximum reflectivity should operate in regimes where the chirality parameter substantially exceeds the non-reciprocity parameter.

3.3 Effect of Decreasing Bi-isotropic Parameter Ratio

Conversely, Figs. 5 through 7 demonstrate the reflectivity enhancement achieved by decreasing the bi-isotropic parameter ratio below unity. For κ_H/γ_L = 0.6, 0.4, and 0.2, the reflectivity at λ = 500 nm increases to 90.82%, 92.36%, and 92.72%, respectively. This represents a significant improvement of 6.74 percentage points compared to the unity ratio case. The enhanced performance in this regime stems from the dominant chirality parameter (γ_L) in the high-index layer, which strengthens the circular polarization selectivity and reinforces constructive interference at the designed wavelength. Notably, the reflectivity enhancement exhibits diminishing returns as the ratio decreases further, suggesting an asymptotic approach to a maximum achievable reflectivity determined by the refractive index contrast and number of bilayers.

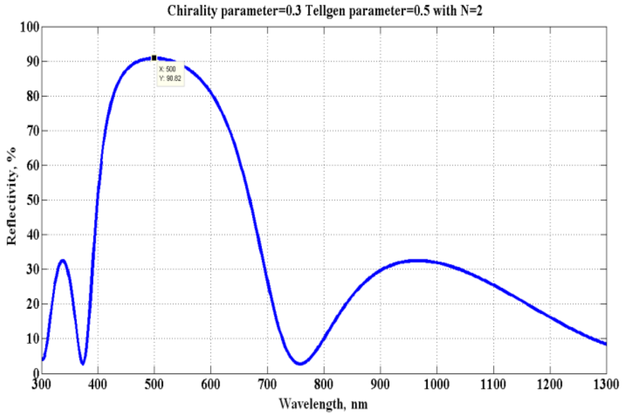


Fig. 5 – Reflectivity vs. the wavelength in normal incidence for: n_H (SiO), n_L (MgF2) with N =2 and κ_H/γ_L = 0.6

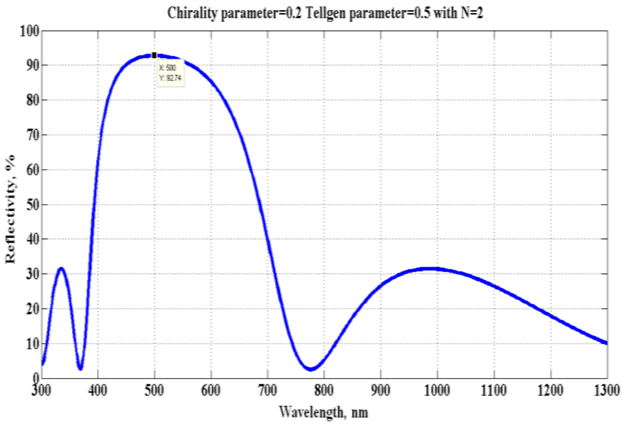


Fig. 6 – Reflectivity vs. the wavelength in normal incidence for: n_H (SiO), n_L (MgF2) with N =2 and κ_H/γ_L = 0.4

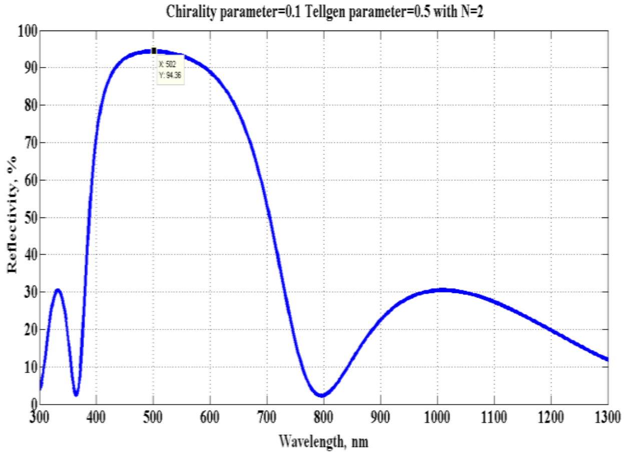


Fig. 7 – Reflectivity vs. the wavelength in normal incidence for: n_H (SiO), n_L (MgF2) with N =2 and κ_H/γ_L = 0.2

The spectral profiles for low ratios also exhibit sharper, more narrowband reflection peaks, making these configurations particularly suitable for applications requiring high selectivity and maximum reflectance at specific wavelengths, such as laser mirrors and narrowband optical filters.

3.4 Parametric Analysis and Optimization

Fig. 8 presents a comprehensive parametric analysis consolidating the reflectivity data across the entire range of investigated bi-isotropic parameter ratios.

The relationship between reflectivity (R) and the ratio ($x = \kappa_H/\gamma_L$) exhibits a distinct non-linear behavior that is accurately captured by a second-order polynomial regression model.

$$R = 1.304x^2 - 12.13x + 96.46, \qquad (9)$$

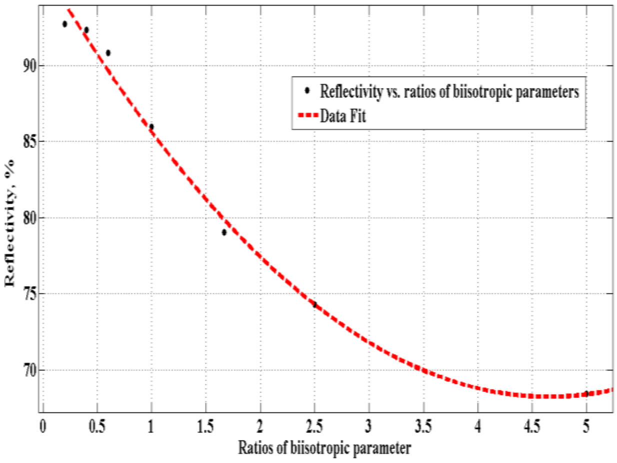


Fig. 8 – Reflectivity as a function of bi-isotropic parameter ratio ($x = \kappa_H/\gamma_L$) with polynomial fit

With a coefficient of determination (R^2) indicating an excellent fit to the computational data. This empirical relationship provides a practical design tool for predicting mirror performance as a function of material bi-isotropic properties. The quadratic nature of this relationship reveals that reflectivity is most sensitive to changes in the bi-isotropic parameter ratio within the intermediate range ($0.5 < x < 2$), while exhibiting reduced sensitivity at extreme values. From a physical perspective, the parabolic dependence suggests competing mechanisms: at low ratios, chirality-driven circular polarization selectivity dominates, while at high ratios, non-reciprocity introduces asymmetric transmission characteristics that degrade mirror performance.

3.5 Optimization Strategy and Design Guidelines

The comprehensive analysis presented above enables the formulation of clear optimization strategies for bi-isotropic multilayer mirrors. To maximize reflectivity, the design should prioritize: (1) minimizing the bi-isotropic parameter ratio κ_H/γ_L, which can be achieved either by increasing the chirality parameter γ_L of the high-index material or by reducing the non-reciprocity parameter κ_H of the low-index material; (2) maximizing the refractive index contrast between alternating layers; (3) increasing the number of bilayers to create additional interference interfaces; and (4) optimizing the optical thickness of individual layers, with emphasis on reducing the physical thickness of high-index layers relative to low-index layers while maintaining quarter-wave optical conditions. These guidelines provide a systematic framework for tailoring bi-isotropic mirror properties to specific application requirements, whether prioritizing peak reflectivity, bandwidth, or spectral selectivity.

3.6 Physical Interpretation and Implications

The observed behavior can be understood through the fundamental electromagnetic properties of bi-isotropic media. The chirality parameter γ introduces cross-coupling between electric and magnetic fields that preferentially interacts with circularly polarized waves, creating distinct propagation constants for RCP and LCP components. This circular Dichroism forms the basis for selective reflection. The non-reciprocity parameter κ, characteristic of Tellegen media, introduces asymmetric transmission properties that break time-reversal symmetry. When κ_H dominates over γ_L, the resulting asymmetry disrupts the balanced interference conditions necessary for high reflectivity. Conversely, when γ_L dominates, the enhanced circular polarization selectivity reinforces constructive interference at the designed wavelength. This fundamental interplay between chirality and non-reciprocity represents a unique degree of freedom in bi-isotropic mirrors, enabling tailored electromagnetic responses unavailable in conventional dielectric multilayers. The ability to tune reflectivity through the bi-isotropic parameter ratio opens new possibilities for adaptive optics, tunable filters, and reconfigurable photonic devices where material properties can be dynamically controlled through external stimuli such as electric or magnetic fields.

4. CONCLUSIONS

This investigation successfully demonstrates that strategic manipulation of the bi-isotropic parameter ratio κ_H/γ_L serves as a powerful mechanism for optimizing reflectivity in multilayer mirrors, achieving values exceeding 92% at $\lambda = 500$ nm when the ratio is maintained below unity. The derived mathematical relationship $R = 1.304x^2 - 12.13x + 96.46$ provides a predictive framework for engineering optical performance through careful material selection and parametric control. By leveraging the unique interplay between chirality and non-reciprocity in bi-isotropic media, this work establishes practical design guidelines prioritizing low parameter ratios, high refractive index contrast, and optimized layer configurations. The findings reveal that chirality-dominated regimes significantly enhance circular polarization selectivity and constructive interference, while non-reciprocity dominance progressively degrades mirror performance. These insights advance the theoretical understanding of electromagnetic wave interactions in complex multilayer structures and unlock new possibilities for next-generation photonic devices, including adaptive optics, tunable filters, and precision optical communication systems. This research thus bridges fundamental electromagnetic theory with practical applications, paving the way for innovative breakthroughs in photonic crystal technologies and electromagnetic control systems.

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Оптимізація відбивної здатності в біізотропних багатошарових дзеркалах: роль співвідношень хіральних та теллегенівських параметрів

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У роботі описаний інноваційний підхід до оптимізації відбивної здатності біізотропних багатошарових дзеркал при нормальному падінні шляхом систематичної маніпуляції критичними параметрами конструкції. Дослідження демонструє, що високий контраст оптичного показника при виборі матеріалу в поєднанні зі збільшенням кількості бішарів значно покращує відбиття, створюючи кілька інтерфейсів для електромагнітної взаємодії. Стратегічно регулюючи товщину шарів, надаючи перевагу тоншим шарам з високим індексом та товстішим шарам з низьким індексом, можна суттєво покращити відбивну здатність. Ключове відкриття показує, що співвідношення біізотропних параметрів (хіральність до невзаємність) відіграє вирішальну роль в оптимізації продуктивності, причому нижчі співвідношення (нижче одиниці) досягають значень відбивної здатності, що перевищують 92% при $\lambda = 500$ нм, тоді як вищі співвідношення (вище одиниці) поступово знижують відбивну здатність приблизно до 68 %. Отримано математичну модель, що пов'язує відбивну здатність зі співвідношеннями параметрів, що забезпечує прогностичний інструмент для оптимізації конструкції. Це дослідження використовує унікальні електромагнітні властивості хіральних та теллегенівських біізотропних матеріалів, досліджуючи раніше невикористані характеристики для революціонізування сучасних оптичних пристроїв. Оригінальність полягає в пропозиції нових стратегій для застосування в передовій оптиці та фотонних кристалах, що відкриває нові можливості для оптичного зв'язку, сенсорних технологій та прецизійних систем електромагнітного керування. Це комплексне дослідження пропонує нове розуміння того, як структурні та параметричні налаштування впливають на біізотропні дзеркала, просуваючи їх практичне впровадження у фотонні технології наступного покоління.

Ключові слова: Біізотропні багатошарові дзеркала, Оптимізація параметрів хіральності, Ефекти невзаємності, Фотонні кристалічні структури, Середовища Теллегена.