STUDY OF POLARIZATION DEPENDENT BAND GAPS AND ANOMALOUS DISPERSION IN HYBRID METAL DIELECTRIC DOUBLE GYROID STRUCTURES

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GENERAL INFORMATION

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Polarization Band Gaps;
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ABSTRACT

This paper presents a comprehensive study of the optical properties of a hybrid metal-dielectric double gyroid (DG) structure, emphasizing its polarization-dependent characteristics and anomalous dispersion phenomena. Utilizing finite-difference time-domain (FDTD) simulations, we investigate the band structure, circular dichroism (CD) indices, and coupling indices of the hybrid DG to explore the existence of polarization-specific band gaps and complete band gaps. Our findings demonstrate that the hybrid DG exhibits distinct right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) band gaps, which can be finely tuned by adjusting the dielectric refractive index and the volume fraction of the structure. The study also reveals high coupling indices for specific modes, indicating efficient light-matter interaction, which is crucial for the development of advanced photonic devices such as sensors and optical filters. Furthermore, we analyze the anomalous dispersion properties of the hybrid DG, including negative refraction, which opens possibilities for innovative applications like superlenses and cloaking devices. These results highlight the versatility and potential of hybrid metal-dielectric gyroids for next-generation photonic applications, offering tunable and customizable optical properties that can be tailored to meet the demands of various technological domains. The insights gained from this research provide a deeper understanding of gyroid-based materials and pave the way for their practical implementation in sophisticated optical systems.

1. INTRODUCTION

The gyroid structure, a fascinating three-dimensional chiral formation, has attracted considerable attention due to its potential applications in photonic crystals and meta-materials (Da et al. 2022). This intricate structure, first described by Alan Schoen in 1970, is characterized by its unique minimal surface geometry, which minimizes the surface area for a given boundary, creating a complex network of continuous surfaces that separate space into two interwoven but non-intersecting regions. The periodic and chiral nature of the gyroid leads to distinctive optical properties, such as photonic band gaps and circular polarization-dependent characteristics, making it an attractive subject for research in photonics (Liu et al., 2022).

The gyroid structures have been observed in various natural systems, including the wing scales of butterflies and the skeletal structures of certain radiolarians (Marigo, Maurel, Pham, 2023). These natural occurrences highlight the gyroid's ability to manipulate light in remarkable ways, which has inspired scientists to explore its potential for artificial photonic applications (Zanotto et al. 2022). Photonic crystals, which are materials that can control the propagation of light, benefit significantly from the gyroid's periodic structure, enabling the creation of materials with complete photonic band gaps that prohibit the propagation of light within certain frequency ranges (Higuera, Miralbes, Ranz, 2022).

Despite the significant progress made in studying gyroid structures, several key limitations remain in the existing literature. First, many studies have focused on gyroid structures composed of a single material, either metallic or dielectric, limiting the tunability of their optical properties. These works, while foundational, do not fully explore the potential of hybrid metal-dielectric configurations, which can offer enhanced control over polarization-dependent phenomena and broader photonic band gaps. Additionally, most prior research has been heavily reliant on theoretical models and numerical simulations, with little experimental validation. The absence of experimental data raises concerns about the practical applicability of these models in real-world photonic devices. Furthermore, the impact of varying material properties such as dielectric refractive index and volume fraction has not been extensively studied in hybrid gyroid structures, leaving a gap in understanding how these parameters influence complex phenomena like negative refraction and anomalous dispersion. By addressing these gaps, this paper aims to provide a more comprehensive analysis of hybrid gyroid structures and offer experimental insights to support theoretical predictions.

Previous studies have focused primarily on gyroid structures composed of a single material, either dielectric or metallic. Dielectric gyroids, for instance, have been shown to exhibit complete photonic band gaps when the refractive index contrast and volume fraction are appropriately tuned (Holmes et al. 2022). These structures are useful in applications such as optical filters, waveguides, and sensors due to their ability to control light propagation with minimal losses. On the other hand, metallic gyroids have been explored for their plasmonic properties, where the metal's free electrons interact with light to produce surface plasmon modes (Lu et al. 2022). These modes can confine light to very small dimensions, significantly enhancing light-matter interactions and enabling applications in areas like sensing, imaging, and nano-optics (Teawdeswan and Dong, 2024). The potential of hybrid metal/dielectric double gyroid structures remains underexplored. A hybrid gyroid combines the properties of both metals and dielectrics, potentially leading to novel optical phenomena that neither material could achieve alone. Metals offer high reflectivity and plasmonic behavior, while dielectrics provide low-loss propagation and wide band gaps. The interplay between these materials in a gyroid structure could result in enhanced optical properties, such as tailored polarization responses and tunable band gaps, making hybrid gyroids promising candidates for advanced photonic applications. (An et al., 2023)

In this paper, we investigate the polarization-dependent characteristics of a hybrid metal/dielectric double gyroid using the finite-difference time-domain (FDTD) method. This numerical approach allows us to model the complex interactions between electromagnetic waves and the gyroid structure with high precision. We focus on calculating the band structure, circular dichroism (CD) indices, and coupling indices to explore the existence and behavior of polarization band gaps and complete band gaps in the hybrid system (An et al., 2023). The CD index provides insight into the circular polarization properties of the modes, indicating whether they are right-handed or left-handed circularly polarized, while the coupling index measures the degree of interaction between incident plane waves and the Bloch modes within the gyroid (Yang et al., 2020).

We examine how the optical properties of the hybrid gyroid evolve with different material fractions, providing a comprehensive analysis of how variations in the volume fraction and refractive index of the dielectric component affect the band gaps (Chouhan, Bala Murali, 2024). By mapping the gap frequencies as functions of these parameters, we can identify trends and design principles for optimizing the hybrid gyroid's optical performance. Furthermore, we explore the anomalous dispersion characteristics of the hybrid gyroid, such as negative refraction, which occurs when the refracted light beam bends in the opposite direction to what is normally expected. This phenomenon is investigated through equi-frequency contour (EFC) analysis and simulations of Gaussian beam propagation, demonstrating the potential for unconventional light manipulation in hybrid gyroid structures (Chernow et al., 2021). The results of this study offer valuable insights into the optical behavior of hybrid metal/dielectric double gyroids, paving the way for their application in next-generation photonic devices (Wallat et al., 2022). By combining the advantageous properties of metals and dielectrics in a single structure, hybrid gyroids could enable the development of highly efficient, tunable, and versatile photonic systems for a wide range of technological applications (Serra, Silveirinha, 2023).

2. PRINCIPLE

2.1 Theoretical Framework

The theoretical framework establishes the foundation for understanding the hybrid DG structure, guiding the computational simulations and providing a basis for interpreting the results.

Gyroid structure and mathematical representation: The level surface of the gyroid structure, which is a triply periodic minimal surface, can be mathematically modeled using the following equation:

$$\sin(hx)\cos(hy) + \sin(hy)\cos(hz) + \sin(hz)\cos(hx) = t$$

In this equation: $h = \frac{2\pi}{a}$,

where α is the unit cell length, representing the repeating periodicity of the gyroid structure across three spatial dimensions.

t is a parameter that controls the volume fraction of the gyroid network. This parameter defines how much of the total space is occupied by the gyroid surface, with higher values of t corresponding to a higher volume fraction

Equation (1) describes the level surface of the gyroid, which forms a continuous, non-intersecting, and symmetric network. This surface divides the space into two distinct, interpenetrating regions, which can be filled with different materials in hybrid structures, such as metal and dielectric in the present study. The gyroid's unique topology defined by its periodic and chiral nature plays a key role in determining its interaction with electromagnetic waves. The gyroid structure exhibits specific optical characteristics, such as photonic band gaps and polarization-dependent behavior, due to the precise arrangement of its surfaces in three dimensions.

The periodicity, controlled by the unit cell length α, and the chirality of the gyroid ensure that it interacts with light in a way that is highly dependent on both the wavelength of the light and its polarization. The gyroid's topology supports various optical phenomena, including selective filtering of light, negative refraction, and strong confinement of electromagnetic waves. The parameters in Equation (1) provide a tunable framework for adjusting these optical properties, as varying t or α alters the surface topology and, by extension, the photonic band gaps and other optical behaviors of the structure. Thus, Equation (1) is central to the study of the gyroid's optical properties in hybrid metal-dielectric structures, as it mathematically defines the surface geometry that determines the gyroid's interaction with light

Hybrid metal-dielectric composition: The hybrid DG structure consists of two intertwined single gyroids (SGs), one metallic and one dielectric. The metallic SG is a perfect conductor, while the dielectric SG's refractive index varies. This combination leverages the high reflectivity and plasmonic behavior of metals with the low-loss and wide bandgap properties of dielectrics, creating a hybrid structure with potentially novel optical characteristics.

Finite-difference time-domain (FDTD) method: The Finite-Difference Time-Domain (FDTD) method is a powerful numerical technique used to solve Maxwell's equations over discrete points in space and time. Maxwell's equations, which govern the behavior of electric and magnetic fields, are the foundation of electromagnetism and provide the mathematical framework for simulating wave propagation in materials. In particular, FDTD solves these equations on a grid by discretizing both the spatial and temporal components.

Maxwell's equations consist of four key equations: Gauss's law for electricity, Gauss's law for magnetism, Faraday's law of induction, and Ampère's law with Maxwell's correction. These equations describe the generation of electric fields from charges, the absence of magnetic monopoles, how time-varying magnetic fields induce electric fields, and how electric currents and changing electric fields generate magnetic fields. The FDTD method discretizes these differential equations to calculate the evolving electric (E) and magnetic (B) fields at each point in space and each time step.

2.2 Analytical insights

Band structure analysis: The band structure analysis determines the allowed and forbidden frequency ranges for electromagnetic wave propagation in the hybrid DG. Using the FDTD method, we calculate the eigenfrequencies and eigenmodes for various wave vectors within the first Brillouin zone, revealing the following:

Polarization band gaps: The hybrid DG exhibits distinct band gaps for right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) modes. The size and location of these band gaps depend on the dielectric refractive index and the volume fraction of the gyroid structure, indicating tunable optical properties.

Circular dichroism (CD) and coupling indices: The CD and coupling indices provide insights into the polarization-dependent behavior of the gyroid modes:

- Circular dichroism (CD) Index: The CD index measures the difference in absorption of RCP and LCP light. A high CD index indicates strong circular polarization dependence, crucial for applications that require specific polarization states.

- Coupling index: The coupling index quantifies the interaction between an incident plane wave and the gyroid modes. High coupling indices indicate efficient coupling of light into the gyroid structure, essential for effective light manipulation.

Anomalous dispersion and negative refraction: The hybrid DG also exhibits anomalous dispersion properties, such as negative refraction, which are analyzed through equi-frequency contour (EFC) analysis and beam propagation simulations:

Equi-frequency contour (EFC) analysis: EFC analysis visualizes the dispersion characteristics at specific frequencies, showing the loci of wave vectors with constant frequency. This helps determine the direction of group velocity and the potential for negative refraction.

Negative refraction: Simulations of Gaussian beam propagation demonstrate negative refraction within the hybrid DG slab, where the refracted wave vector bends opposite to the expected direction. This phenomenon is indicative of the gyroid's potential for unconventional light manipulation

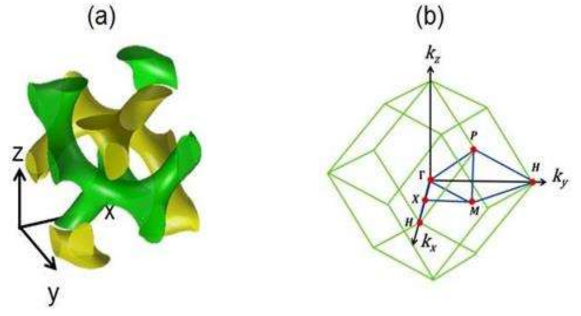

Figure. 1 (a) The perspective view of a unit cell of metal/ dielectric DG with volume fraction = 20%. (b) The first Brillouin zone of DG (Chernow et al. 2021).

3. RESULTS

- The band structure of the hybrid DG is shown in Figure 2(a), which presents the distribution of modes and their polarization characteristics. The colors of the points represent the circular dichroism (CD) index, where right-handed circularly polarized (RCP) modes are indicated in red, and left-handed circularly polarized (LCP) modes are in blue. The size of each point represents the coupling index, illustrating the strength of interaction between the incident light and the gyroid modes.

- In this representative band structure, distinct band gaps for both RCP and LCP modes can be identified. These polarization-specific band gaps demonstrate the gyroid's capability to selectively filter light based on its polarization state, a property essential for advanced photonic applications such as polarization-sensitive sensors and filters.

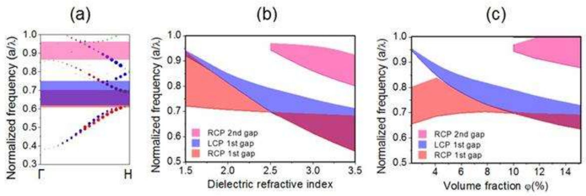

Figure 2: Band Structure and Gap Analysis of the Hybrid Metal-Dielectric Double Gyroid

Figure 2(b) reveals the gap frequencies of the hybrid DG when the dielectric refractive indices vary from 1.5 to 3.5. As the dielectric index increases, the LCP band gap broadens, indicating enhanced confinement of LCP modes within the band gap. On the other hand, the RCP band gap is initially wide at a refractive index of 1.5 but gradually narrows as the refractive index increases. The RCP gap disappears at a refractive index of 2.5 and reappears at higher indices. Additionally, a second RCP band gap emerges at higher frequencies when the refractive index is 2.5, which broadens as the refractive index continues to rise.

Figure 2(c) illustrates the relationship between the gap position and volume fraction (ϕ). The LCP and RCP gaps exhibit similar trends to those in Figure 2(a). However, when the volume fraction is below 4.1%, the RCP gap shifts to lower frequencies (red-shifts) as the volume fraction decreases. These results highlight the significant influence of the refractive index and volume fraction on the optical properties of the hybrid DG, allowing for precise tuning of photonic band gaps based on design requirements.

Anomalous Dispersion and Negative Refraction

The hybrid DG structure also exhibits anomalous dispersion, as demonstrated by the equi frequency contour (EFC) analysis. According to electromagnetic theory, the group velocity of light is determined by the gradient of the dispersion surface, which represents the orientation of the Poynting vector. In addition to the polarization-dependent band gaps, the hybrid DG structure also exhibits anomalous dispersion, including negative refraction. An equi-frequency contour (EFC) analysis was conducted at a normalized frequency of 0.71 to investigate this phenomenon. The results are shown in Figure 3(a).

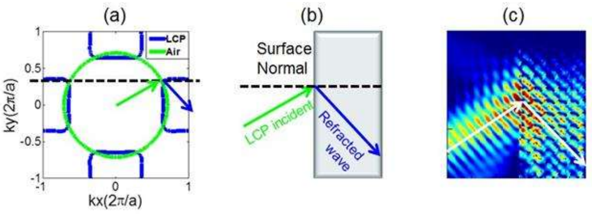

Figure 3: Anomalous Dispersion and Negative Refraction in the Hybrid DG

Figure 3(a) shows the EFC analysis at a normalized frequency of 0.71. The group velocity of refracted light is shown in blue, while the incident light's group velocity is depicted in green. At an incidence angle of 30°, the incident beam encounters a convex EFC, causing the beam to refract in a direction normal to the surface, which is characteristic of negative refraction. This analysis demonstrates the potential for the hybrid DG structure to achieve negative refraction, a property that can be leveraged for advanced optical applications like superlenses and cloaking devices.

Figure 3 (b) provides an illustration of the negative refraction at the input interface of the hybrid DG. This diagram visualizes the refracted rays in the actual crystal, further validating the occurrence of negative refraction in the hybrid structure.

Figure 3 (c) shows the distribution of the electric field of a Gaussian beam incident at 30° with LCP light at a frequency of 426 THz. The arrows indicate the direction of energy flow, illustrating that the wave refracts negatively within the hybrid DG slab. The observed negative refraction highlights the gyroid's ability to bend light in unconventional ways, opening new avenues for optical device engineering.

4. DISCUSSION

The results of this study demonstrate the unique optical properties of the hybrid metal-dielectric double gyroid structure. The ability to control photonic band gaps through dielectric refractive index and volume fraction adjustments underscores the versatility and tunability of the hybrid DG. This tunability is crucial for designing photonic devices with specific polarization and dispersion characteristics, enhancing their applicability in various technological domains. The observation of anomalous dispersion and negative refraction suggests the hybrid DG's potential for use in creating metamaterials with exotic optical properties. Negative refraction, in particular, offers exciting possibilities for super-resolution imaging and cloaking applications, where conventional optics are limited.

While the results are promising, further research is needed to explore the practical implementation of hybrid DG structures. This includes experimental validation of theoretical predictions, exploration of material losses, and integration into existing photonic platforms. Additionally, investigating active tuning mechanisms, such as using external fields or mechanical deformation, could further expand the versatility and functionality of these structures. The hybrid metal-dielectric double gyroid structure presents a promising avenue for advancing photonic technologies. Its unique polarization-dependent characteristics and ability to exhibit anomalous dispersion and negative refraction make it a valuable platform for developing next-generation photonic devices. The insights gained from this study provide a foundation for further exploration and development of gyroid-based materials in sophisticated optical systems.

5. CONCLUSIONS

This study has explored the optical properties of a hybrid metal-dielectric double gyroid (DG) structure through theoretical insights and finite-difference time-domain (FDTD) simulations. The results highlight the structure's unique polarization-dependent behavior and its potential applications in photonics, particularly in areas requiring precise light manipulation.

The hybrid DG structure exhibits distinct polarization-dependent band gaps for right-handed (RCP) and left-handed circularly polarized (LCP) modes. These findings demonstrate the structure's capability to filter and manipulate light based on polarization, which is crucial for applications such as optical communications and polarization-sensitive devices, like circularly polarized light sources and detectors.

The optical properties of the DG can be tuned by adjusting the dielectric refractive index and volume fraction, making it highly versatile. This tunability enables the design of photonic devices that can be customized for specific functions, offering greater control over light propagation and enhancing the flexibility of gyroid-based materials for various technological applications.

The hybrid DG structure shows efficient light-matter interaction, as indicated by high coupling indices, and exhibits anomalous dispersion properties, including negative refraction. These characteristics suggest potential applications in advanced optical systems such as supersenses and invisibility cloaks, where precise control over light paths is essential.

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PHÂN TÍCH VỀ KHOẢNG TRỐNG DẢI PHÂN CỰC VÀ HIỆN TƯỢNG TÁN SẮC BẤT THƯỜNG TRONG CẤU TRÚC GYROID KÉP LAI ĐIỆN MÔI KIM LOẠI

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TỪ KHOÁ

Khoảng cách dải phân cực;

Phân tán dị thường;

Khúc xạ âm.

TÓM TẮT

Bài báo này trình bày một nghiên cứu toàn diện về các tính chất quang học của cấu trúc gyroid kép điện môi kim loại lai (DG), Nghiên cứu tập trung vào các đặc điểm phụ thuộc vào phân cực và hiện tượng tán sắc bất thường. Thông qua việc sử dụng các mô phỏng theo thời gian dựa trên chênh lệch phần tử hữu hạn (FDTD). Bài báo đã trình bày kết quả nghiên cứu cấu trúc dải, chỉ số lưỡng sắc tròn (CD), và chỉ số ghép nối của các DG lai để khám phá sự tồn tại của các khoảng trống dải phụ thuộc phân cực cụ thể cũng như các khoảng trống dải hoàn chỉnh. Các thông số từ kết quả nghiên cứu này cho thấy rằng DG lai biểu hiện các khoảng trống dải phân cực tròn phải (RCP) và phân cực tròn trái (LCP) riêng biệt. Hơn nữa, những khoảng trống này có thể được điều chỉnh một cách chính xác thông qua việc điều chỉnh chiết suất điện môi và tỷ lệ thể tích của cấu trúc. Nghiên cứu này cũng đã làm rõ các chỉ số ghép nối cao đối với các chế độ khác nhau. Qua đó cho thấy khả năng tương tác ánh sáng và vật hiệu quả, điều này rất quan trọng đối với sự phát triển của các thiết bị quang tử tiên tiến như cảm biến và bộ lọc quang học. Ngoài ra, Bài báo còn phân tích các tính chất tán sắc bất thường của DG lai, bao gồm khúc xạ âm, mở ra tiềm năng cho các ứng dụng sáng tạo như siêu thấu kính và thiết bị tàng hình. Những kết quả này nhấn mạnh tính linh hoạt và tiềm năng của các cấu trúc gyroid điện môi kim loại lai trong việc phát triển các ứng dụng quang tử thế hệ tiếp theo, cũng như cung cấp các tính chất quang học có thể tùy chỉnh và điều chỉnh, phù hợp với nhu cầu của nhiều lĩnh vực công nghệ khác nhau. Kết quả mô phỏng này đã đóng góp quan trọng vào việc nâng cao hiểu biết về vật liệu dựa trên gyroid, và tạo ra một hướng nghiên cứu trong việc ứng dụng thực tế của chúng trong các hệ thống quang học phức tạp.