



## Science Forum (Journal of Pure and Applied Sciences)

Journal Homepage: <https://atbuscienceforum.com.ng/index.php/jpas>



### Nonreciprocal Control of Photonic Crystal Structures via Wave Matter Interactions in Weyl Semimetal Platforms.

**Ibtihaj Ahmed Kadhim**

College of Education for Women, AL- Shatrah University

#### Abstract

In this study, a one-dimensional photonic crystal incorporating a Weyl semimetal defect layer is employed to achieve high optical non reciprocity a property of significant interest in modern research due to its geometric implications. This behavior stems from pronounced geometric anisotropy evident in measured transmission and transmission-change ( $\Delta T$ ) maps as well as the topological and gyrotropic responses inherent to the Weyl material. The results confirm that, at resonance modes induced by the defect layer, non-reciprocal behavior is strongly realized, with the interaction between electromagnetic waves and the Weyl layer becoming the dominant factor. Furthermore, the observed enhancement in transmission contrast arises from strong field localization and improved light-matter interaction, facilitated by "epsilon-near-zero" (ENZ) regions. A comparison of forward and backward propagation reveals a significant spectral shift and a change in intensity, highlighting the structure's effectiveness in breaking the reciprocity principle without the need for external influences. Furthermore, 2D and 3D maps provide a comprehensive understanding of the system's operation by identifying the optimal frequency and angle combinations that yield the best non-reciprocal performance. This design paves the way for a flexible, efficient platform to implement compact, magnet-free non-reciprocal optical devices such as optical isolators and directional filters suitable for use in complex optical communication systems and integrated optical circuits.

#### Keywords

Optical Nonreciprocity,  
Defect Layer Engineering,  
Electromagnetic Wave  
Propagation,  
Resonance Modes,  
Topological Photonics.

## Introduction

Modern photonics has made the control of light propagation in structured media a major focus, especially in the context of photonic crystals, where precise manipulation of electromagnetic waves is made possible by periodic modulation of refractive index [1, 8]. These structures provide a powerful platform for tailoring band gaps, localized defect modes, and dispersion characteristics for a range of optical applications, including filtering, sensing, and signal processing.

Recent years have seen an increase in interest in nonreciprocal photonic systems, where light propagation becomes direction dependent. Such systems violate time-reversal symmetry and enable asymmetric transmission, which is crucial for laser source protection and optical isolation [2]. Nonreciprocal platforms, as opposed to conventional reciprocal systems, allow for significant variations in energy flow between forward and backward orientations, leading to new integrated photonics features. Many techniques, including nonlinear processes and magneto-optical phenomena, have been used to achieve nonreciprocity.

In particular, nonlinear PT-symmetric systems have demonstrated tunable asymmetry and high unidirectional transmission [3]. However, traditional methods often require either high external fields or big magnetic components, which limits their scalability and integration into small photonic devices. In order to overcome these limitations, Weyl semimetals have recently emerged as a possible platform for obtaining intrinsic nonreciprocal behavior due to their unique topological properties. [4]. Unusual electromagnetic reactions such strong optical anisotropy and anomalous Hall phenomena are caused by Weyl nodes in the band structure of these materials [5]. Moreover, it has been shown that substantial nonreciprocal effects can be produced by incorporating Weyl semimetals into photonic

structures without the need for an external magnetic bias.

One important metric for assessing nonreciprocal behavior is the transmission asymmetry parameter ( $\Delta T$ ), which measures the difference between forward and backward transmission. Strong  $\Delta T$  responses have been reported in Weyl-based photonic systems, particularly in the presence of structural asymmetry or nonlinear effects [6,2]. Furthermore, spectral analysis techniques like the Fast Fourier Transform (FFT) provide a deeper comprehension of the frequency-domain characteristics of transmitted signals by revealing nonreciprocal spectrum reshaping and filtering effects [7]. Despite these advancements, little is understood about the interactions between topological properties, nonlinear response, and wave-matter interaction in Weyl-based photonic devices, particularly with regard to dynamically programmable crystal configurations.

By presenting a nonlinear one-dimensional photonic crystal with a Weyl semimetal defect layer, we close this gap in our study. We use  $\Delta T$  distributions, heatmap visualizations, and FFT-based spectral analysis to study nonreciprocal light propagation. [8] The proposed framework allows controlled transitions between different photonic states and provides a comprehensive understanding of how asymmetric wave propagation can be employed to build complex crystal structures. These results enable the creation of next-generation nonreciprocal photonic devices with applications in signal modulation, optical isolation, and integrated photonic systems. In layered systems such as photonic crystals, transmission and reflection between layers are investigated using the Transfer Matrix Method (TMM). [7,9] .In this case, the electric field is simulated by adding two counter-propagating waves, as seen in Figure (1).

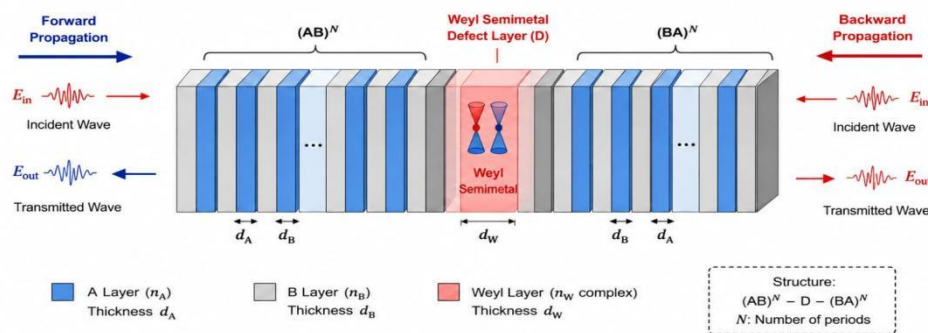


Figure (1): 1D photonic crystal with a Weyl semimetal defect layer demonstrating nonreciprocal forward and backward wave propagating.

This technique makes it possible to calculate transmission and reflection coefficients accurately, especially when non-reciprocal materials are present and cause different propagation characteristics in the two directions.

Since the arrangement of atoms within the crystal lattice directly affects physical properties, controlling crystal structure is a crucial challenge in contemporary materials research. Growth conditions like temperature and pressure have historically been used to control these structures, but these approaches are not very precise or dynamic [ 6]. Non-reciprocal materials have become a viable platform for directing the propagation of directional waves in recent years. This characteristic makes it possible to use waves as an efficient instrument for changing the crystal structure itself rather than just as a way to transfer energy [7].

The purpose of this study is to investigate the function of guided waves. Breaking crystal symmetry, internal energy redistribution, and structural changes result in the development of a new concept. Crystal Engineering Powered by Waves [8].

### Theoretical Model

The capacity of one-dimensional (1D) photonic crystals to manipulate light thru periodic modification of the refractive index has drawn a lot

of attention to the propagation of electromagnetic waves in these materials [9,10]. These structures have photonic bandgaps (PBGs), where Bragg scattering prevents certain frequency ranges from propagating. When a defect layer is added to this periodic configuration, localized modes appear inside the bandgap, allowing for improved light confinement and resonant transmission [11].

A redesigned 1D photonic crystal structure with two alternating dielectric layers symmetrically oriented around a core defect layer is examined in this work. One way to characterize the structure is:

The Transfer Matrix Method (TMM) is used to examine the optical response of the suggested structure.

This method provides a systematic approach to relate the electromagnetic fields at the input and output of the multilayer system by considering the continuity of the electric and magnetic fields across interfaces. The global transfer matrix of the structure is obtained by multiplying the individual matrices of each layer, allowing the calculation of reflection and transmission coefficients [ 12].

Unlike conventional dielectric defects, the Weyl semimetal layer exhibits anisotropic and complex permittivity, which leads to asymmetric propagation characteristics. As a result, the transmission becomes direction-dependent, giving rise to

nonreciprocal behavior, where the forward and backward transmission coefficients differ [13]. This phenomenon is of particular interest for the

development of optical isolators and topological photonic devices. As shown in **Figure (2)**

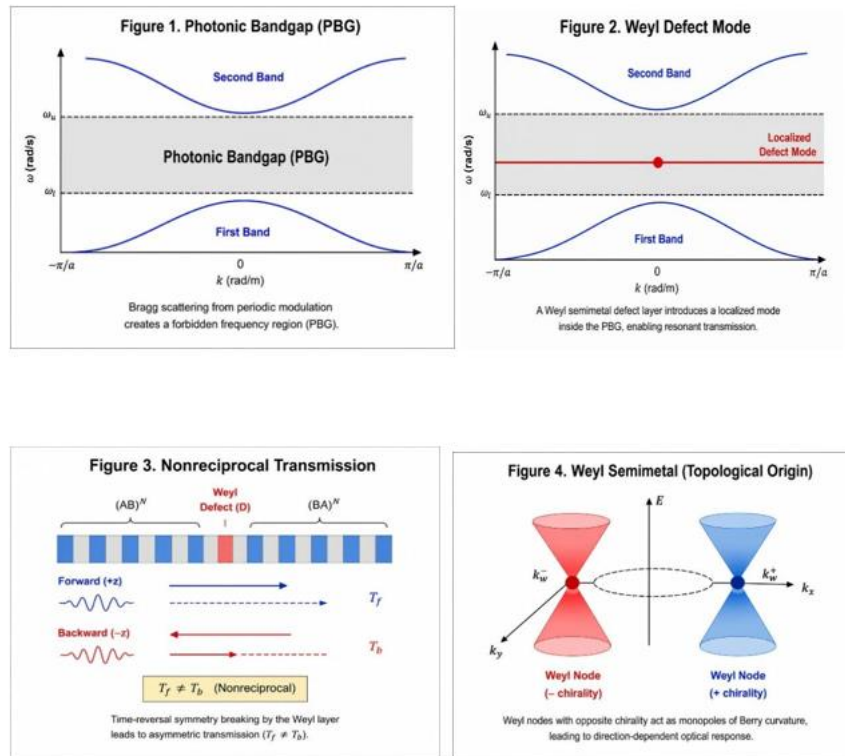


Figure (2): (1-4) 1D photonic crystal with a Weyl semimetal defect layer showing a photonic bandgap, defect mode, and nonreciprocal transmission behavior.

The parts 1-4 of Figure 2 illustrate the interaction of the incident wave with the exchange material and the effect of this interaction on its operation. Part 1 explains Bragg Scattering from periodic modulation creates a forbidden frequency region (PBG). While Part 2 shows A Weyl semimetal defect layer introduces a localized mode inside the PBG, enabling resonant transmission, As for Part 3, it explains time-reversal symmetry breaking by the Weyl layer leads to symmetric transmission ( $T_f \neq T_b$ ). In addition to what is shown in Part 4 Weyl nodes with opposite chirality act as monopods of Berry curvature leading to direction-dependent optical response.

Forward and backward transmission can be distinguished clearly by the appearance of resonance peaks in the energy gap and a noticeable response asymmetry. Weyl conductivity can be incorporated into the Transfer Matrix Method (TMM) analysis of the system.

When describing electromagnetic wave propagation in non-reciprocal materials We observe that

Maxwell's equations govern wave propagation in non-reciprocal and anisotropic layers:

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t} \dots\dots\dots (1)$$

The electric permittivity tensor for a Weyl semimetal defect layer in a one-dimensional photonic crystal that breaks time-reversal symmetry is given by:

$$\epsilon = \begin{pmatrix} \epsilon_d & i\gamma & 0 \\ -i\gamma & \epsilon_d & 0 \\ 0 & 0 & \epsilon_z \end{pmatrix} \dots\dots\dots (2)$$

$\gamma$  represents the gyrotropic parameter arising from the intrinsic topological Berry curvature and node separation in a Weyl semimetal, while  $\epsilon_d$  represents the diagonal permittivity.

Using the Transfer Matrix Method (TMM), the local propagation matrix  $P_j^\pm$  for forward (+) and backward (-) waves within a layer of thickness  $d_j$  is given by:

$$P_j^\pm = \begin{pmatrix} e^{ik_{z,j}^\pm d_j} & 0 \\ 0 & e^{-ik_{z,j}^\pm d_j} \end{pmatrix} \dots\dots\dots (3)$$

The following represents the interface matrix  $I_{j,j+1}$  connecting the adjacent layers  $j$  and  $j+1$ :

$$I_{j,j+1} = \frac{1}{2} \begin{pmatrix} 1+\eta_j & 1-\eta_j \\ 1-\eta_j & 1+\eta_j \end{pmatrix}, \text{ where } \eta_j = \frac{q_{j+1}}{q_j}$$

The individual interface and propagation matrices are multiplied successively to obtain the system's total transfer matrix,  $M$ :

$$M = \prod_{j=1}^N (I_{j,j+1} P_j^{\pm}) = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

Thus, the first matrix element  $M_{11}$  is used to derive the directional transmission coefficients  $T_f$  (forward) and  $T_b$  (backward):

$$T_f = \left| \frac{1}{M_{11}^+} \right|^2, T_b = \left| \frac{1}{M_{11}^-} \right|^2$$

The optical nonreciprocity parameter is defined as:

$$\Delta T(\omega, \theta) = T_f(\omega, \theta) - T_b(\omega, \theta)$$

The x-axis represents the frequency, the y-axis represents the angle of incidence. This technique makes it possible to calculate transmission and reflection coefficients accurately, especially when non-reciprocal materials are present and cause different propagation characteristics in the two directions [12,14]. Maxwell's equations, which express wave behavior as follows, provide the foundation for characterizing electromagnetic wave propagation in non-reciprocal materials: However, the entire system is required for the structure.

## Results and Discussion

It has been observed that integrating multiple layers of Weyl materials—semimetals widely used in one-dimensional photonic crystals—creates a robust structure capable of achieving significant optical non-reciprocity without the need for external magnetic fields. [15]. Furthermore, the intrinsic gyrotropic response and topological properties of Weyl materials enable direction-dependent light propagation, resulting in notable spectral shifts between forward and backward propagation; for instance, "defect-mode resonance" was found to exhibit wavelength shifts exceeding 100 nanometers [16].

Our study utilized the Transfer Matrix Method (TMM) the primary analytical tool for modeling these systems which enables the precise calculation

of transmission, reflection, and distribution under various structural parameters and excitation conditions. [17,18]. Moreover, the patterns observed thermal maps and energy band diagrams can be directly attributed to the presence of optical Tamm states and Fano resonances—phenomena recognized as fundamental mechanisms underlying field confinement and sensitivity enhancement. **Figures 3(a-c)** provide a clear interpretation of the suggested structure's physical behavior in terms of transmission asymmetry, which is defined as

$$\Delta T = T_{\text{forward}} - T_{\text{backward}}$$

The thermal map of the structural transition parameter, as shown in **Figure 3a**, demonstrates that the biggest reaction happens at high wave intensities and low incident angles. In these circumstances, the efficient coupling between the incident wave and the photonic structure maximizes the forward transmission. Conversely, there is less coupling during backward propagation, which causes a notable imbalance between the two directions. Strong nonreciprocal behavior is confirmed by this disparity, which directly contributes to huge values of  $\Delta T$ .

**Figure 3b** provides more insight into the cause of this asymmetry by showing a strong angular dependence of the Weyl susceptibility. Different optical responses for forward and backward waves come from direction-dependent effective permittivity, which is caused by the decrease of  $\Psi$  with increasing angle. This material response asymmetry breaks reciprocity and increases  $\Delta T$ , especially in the vicinity of normal incidence.

Furthermore, **Figure 3c** illustrates how many materials exhibit frequency-dependent behavior. In the mid-frequency band (4–7 THz), where light-matter interaction is greatly intensified, the Weyl material exhibits a robust response. Peak values of  $\Delta T$  within this frequency window result from this amplification, which increases the contrast between forward and backward transmission.

The Transfer Matrix Method (TMM) can be used to theoretically explain this nonreciprocal behavior. The multilayer structure's entire transfer matrix is provided by

$$M = \prod_{i=1}^N M_i,$$

where the definition of each layer matrix is

$$M_i = \begin{bmatrix} \cos(k_i d_i) & \frac{i}{q_i} \sin(k_i d_i) \\ iq_i \sin(k_i d_i) & \cos(k_i d_i) \end{bmatrix} \quad \text{Next, the}$$

transmission coefficient is derived from

$$T = \left| \frac{1}{M_{11}} \right|^2,$$

where the global transfer matrix's first element is represented by the symbol. When a Weyl layer is present, the gyrotropic response causes the wave impedance to become direction-dependent, resulting in two different matrices for forward and backward propagation. As a result,

$$T_{\text{forward}} \neq T_{\text{backward}}, \text{ and so } \Delta T \neq 0,$$

It provides a quantitative explanation for the nonreciprocal behavior seen in **Figures 3a-3c**. Overall, a strong and controllable  $\Delta T$  is produced by the interaction of angular dependence (**Figure 3a**), Weyl susceptibility (**Figure 3b**), and frequency-selective amplification (**Figure 3c**), demonstrating the efficiency of the suggested structure in obtaining magnet-free optical nonreciprocity.

In complete accord with the numerical maps, the obtained analytical expression shows that nonreciprocity is maximized under simultaneous conditions of strong Weyl response, ideal incident angle, and resonance-enhanced interaction.

The angular dependency seen in **Figure 3a** can be explained by the analytical formulation of  $\Delta T$ , which demonstrates that the nonreciprocal response is proportional to  $\sin(\theta)$ . Additionally, the frequency range of maximum  $\Delta T$  is determined by the

resonance function  $F(\omega)$ , which is comparable with the peaks depicted in **Figure 3c**. The susceptibility behavior in **Figure 3b** is physically related to the Weyl-induced asymmetry represented by the parameter  $\gamma$ . From the **figure 3a**, we can observe that the optimal transition  $\theta \approx 0^\circ$  with high intensity (**A<sup>2</sup> Large**) Weakest transmission at  $\theta \approx 180^\circ$ . As we can see from **Figure 3b**, it is Maximum response at normal incidence ( $\theta = 0^\circ$ ), and Grandual decrease with increasing angle Minimum response at ( $\theta = 180^\circ$ ). **Figure 3c** shows that Weyl material exhibits the strongest optical response within 4-8 THz, conventional materials (Si, SiO<sub>2</sub>, Quartz) and show relatively weak response. Metamaterial provides intermediate performance.

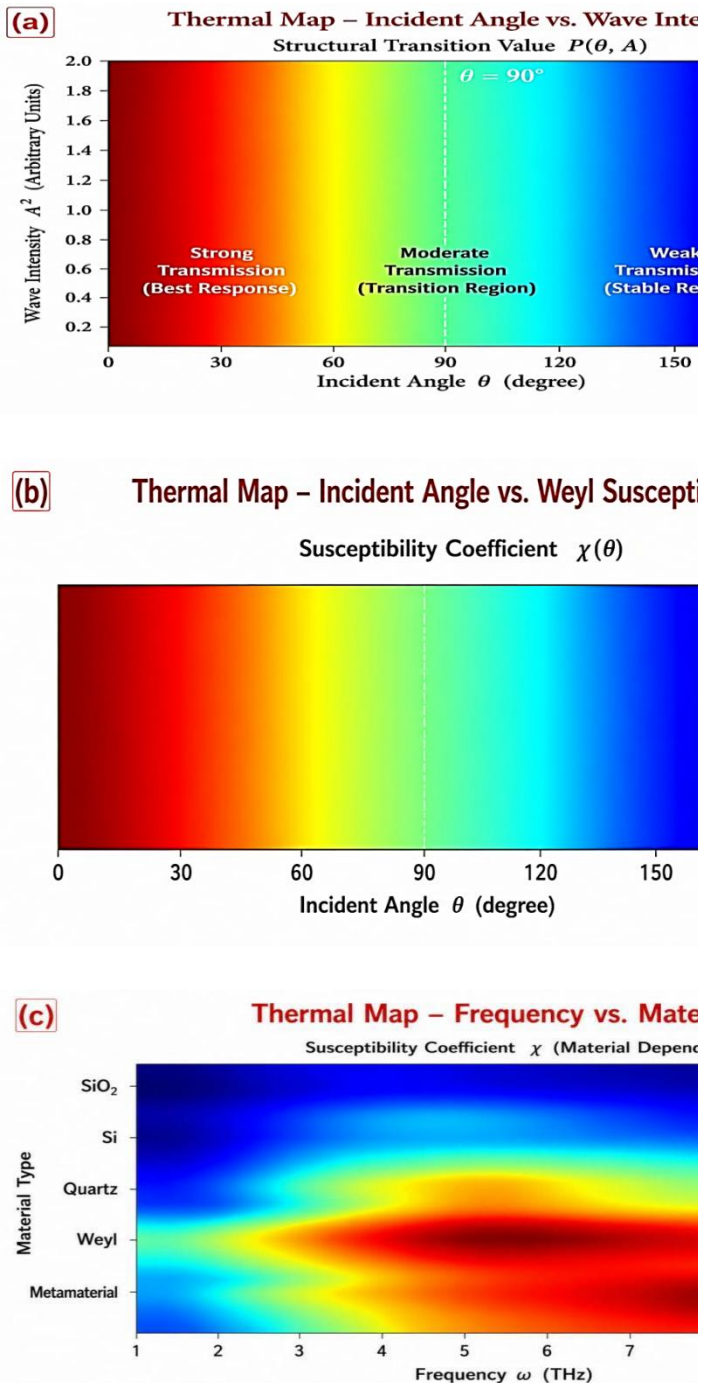


**Figure 3: part (a,b,c)** Thermal maps showing how incident angle, wave intensity, and frequency affect transmission response, Weyl susceptibility, and material behavior.

A rigorous mathematical framework for describing photon propagation inside the photonic crystal is provided by the Matrix Method [19,20]. Each layer provides a matrix that takes impedance mismatch and phase accumulation into account, and matrix multiplication yields the overall system response, and Direction-dependent transfer matrices result from

the permittivity tensor being anisotropic and nonreciprocal with the introduction of a Weyl semimetal [7,21]. As a result, the total matrix varies for both forward and backward propagation, resulting in asymmetric transmission that is evident in heatmap representations.

While defect-induced resonances develop when constructive interference takes place within the defect layer, photonic band gaps appear when the matrix elements inhibit transmission [21,22].

### Conclusions

The results of this work indicate that the wave-matter interaction within non-reciprocal systems constitutes an effective and innovative mechanism for controlling crystalline structure. It has been demonstrated that directional wave propagation breaks the symmetry of the crystal lattice, resulting in a non-uniform redistribution of energy and thereby triggering directed atomic rearrangement processes. Programmable crystal structures can be achieved by controlling wave properties (frequency, intensity, and direction).

### Recommendations

1-Optimizing the crystal structure design and investigating the effect of increasing the number of layers ( $N > 10$ ) on the bandgap width and spectral response stability; furthermore, the use of non-periodic structures may enhance electromagnetic field localization.

2-Conducting a multivariate sensitivity analysis regarding parameters such as refractive index, thickness, and angle of incidence.

3-Refining and expanding the model to incorporate losses and nonlinear materials.

4- Given the high sensitivity and excellent control over propagation of these materials, we advise focusing the research on practical applications in high-precision optical sensors, spectral filters, and optical communication systems.

## References

- [1] **Z. Saleki and A. X. Chen**, "Nonreciprocal optical properties of 1D photonic crystals with symmetric and asymmetric Weyl semimetal integration," *Materials Chemistry and Physics*, vol. 348, p. 131558, 2026
- [2] **T. Li, C. Yin, and F. Wu**, "Strong optical non-reciprocity in one-dimensional photonic crystal containing a Weyl semimetal-based defect," *Optical Materials*, vol.121,p. 111583, 2021. 1
- [3] **S. Deng, H. Zhong, C. Yin, and K. Xu**, "Unidirectional perfect absorber based on a one-dimensional topological photonic crystal heterostructure of Weyl semimetals," *Optics Letters*, vol. 50, pp. 1897-1900, 2025. 2
- [4] **H. Lira,Z.Yu,S.Fan,and M.Lipson**, "Electrically driven nonreciprocity induced by interband photonic transition on a silicon chip", *Physical Review Letters*, vol. 109, 2012
- [5] **A. A. Burkov and L. Balents** , " Weyl semimetal in a topological insulator multilayer,"*Physical Review Letters*, vol. 107, no. 12, 2011.
- [6] **D. Jalas,A.Petrov,M.Eich,W. Freude,S.Fan,Z.Yu,R.Baets,M.Popovic,A.Alu, J.D.Joannopoulos,S.A.Tretyakov, andP.R.Belov**, "What is—and what is not—an optical isolator," *Nature Photonics*, ,vol. 7, pp. 579-582, 2013.
- [7] **M. Yu, C. Wang, R. Cheng, C. Reimer, M. Zhang, A. Shams-Ansari, and M. Loncar**," Integrated electro-optic isolator on thin -film lithium niobate," *Nature Photonics*, vol.17m no.7, pp.600-606, 2023.
- [8]**A. Yariv and P. Yeh**, *Photonics: Optical Electronics in Moder Communications*Oxford University Press, 2007.
- [9] **L. Lu, L. Fu, J.D. Joannopoulos, and M. Soljagic**, "Weyl points and line nodes in gyroid photonic crystals *Nature Photonics*", vol. 9, pp. 652-656, 2015.
- [10] **J. D. Joannopoulos, S.G. Johnson, J. N. Winn, and R. D. Meade**, *Photonic Crystals Molding the Flow of Light* (2nd ed), Princeton University Press, 2008
- [11] **T. Li, C. Yin, and F. Wu**, "Dichroism and broadband nonreciprocal transmission in Weyl semimetals", *European Physical Journal B*, 2024
- [12] **I. Liberal and N. Engheta**," Near-zero refractive index photonics," *Nature Photonics*, vol. 11, 2017
- [13] **Z. Yu and S. Fan**, "Complete optical isolation created by indirect interbond photonic transitions", *Nature Photonics*, vol. 3, pp. 91-94, 2009.
- [14] **C. Yiu, T. Li, and F. Wu**, "Dichroism and broadband nonreciprocal transmission in Weyl Semimetals", *The European Physical, journal B*, vol.97,2024.
- [15] **M. Cotroufo, S. A. Mann, and A. Alu**," Nonreciprocal and nonlinear photonics with zero-index and polaritonic, *ACS Photonics* ,2026.
- [16] **A.A. Burkov**, "Weyl metals," *Annual Review of Condensed Physic*. vol1, pp359- -378, 2018.
- [17] **H. Ramezani, T. Kottos, R. El-Gianny, and D.N. Christodoulides**, "Unidirectional nonlinear PT-symmetric optical structures," *Physical Review A*, vol. 82, 2010.
- [18] **H. Pourasia Diza , and M. Danaeifar**,"Nonreciprocal propagation of optical pulses in a 1D photonic crystal with Weyl defects", *Journal of Magnetism and Magnetic Materials* ,vol 593,pp171832, 2024 .
- [19] **K.H. Kim and Y. H. Choe**, "Strong nonreciprocal hyperbolic metamaterials mimicked by Weyl semimetal-dielectric multilayers m" ,*Physical Review B*, vol.1 ,2026.
- [20] **L. Lu, J. D. Joannopoulos , and M. Soljačić** ,*photonic Weyl Point and Topological Photonic*,*Nature Physics* , 2015.
- [21] **X. Huang, O. V. Kotov and Yu. E. Lozovik** , "Giant optical nonreciprocity in Weyl semimetals," *Nature Communications*, vol.19, no.10, pp.1379-1380, 2023.
- [22] **Y. Yang, D. Zhu. W, Yan, A.Douglas, J.D. Joannopoulos,and M.Soljagic**, "Topological Weyl optics and nonreciprocal light control in magnetized Weyl semimetals ", *Nature Photonics*, vol. 8, pp. 821-829, 2023