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Study of Electromagnetic Wave Polarization and Its Applications in Optical Communication Systems

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Abstract- The rapid increase in data traffic and the demand for high transmission efficiency have intensified the need for effective polarization management in modern optical communication systems. Polarization of electromagnetic waves is influenced by birefringence and polarization mode dispersion (PMD), yet it also serves as an essential resource for enhancing system capacity through techniques such as polarization-division multiplexing (PDM) and dual-polarization transmission. This study employs a systematic literature review of reputable publications from the past decade, selected based on topical relevance, quantitative data availability, mathematical modeling, and experimental validation.

The analysis of five key studies demonstrates that polarization control plays a fundamental role in improving optical transmission performance. Dual-polarization nonlinear Fourier transform (NFT) techniques have shown superior efficiency in mitigating nonlinear impairments, while graphene-based photonic devices offer strong polarization selectivity for high-speed modulation. Furthermore, advancements in silicon photonics enable precise polarization control through waveguide engineering, and integrated MDM–PDM architectures contribute to increased channel capacity with minimal crosstalk. The implementation of PDM-MZM structures also improves signal stability in both fiber and hybrid SMF–FSO links, supporting high-order modulation formats essential for 5G and 6G networks.

Overall, the findings indicate that the integration of polarization management, advanced photonic materials, and digital signal processing forms a critical foundation for future high-capacity, low-distortion optical communication systems.

Keywords: *Polarization; optical communication; polarization-division multiplexing (PDM); nonlinear Fourier transform (NFT); silicon photonics; graphene photonics; PMD; high-capacity transmission.*

1 Introduction

The development of optical communication technology over the past few decades has been largely driven by the increasing demand for extremely high data capacity, low latency, and improved energy efficiency to support broadband services, cloud computing, data centers, and emerging 5G/6G networks (Hasan, 2025). As these demands continue to grow, optical fiber systems remain essential as the backbone of global telecommunication networks due to their exceptionally low transmission losses and extremely large bandwidth, enabling the stable delivery of massive amounts of data (Fadila et al., 2024). However, the surge in connectivity requirements is not limited to core networks; it also extends to backhaul and last-mile

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segments, thereby encouraging the adoption of more flexible alternatives. One emerging technology receiving increasing attention is free-space optical (FSO) communication, which offers high-capacity links without the need for complex physical cable infrastructure (Taher & Majumder, 2018). The rise of FSO as a complement to fiber-optic systems has consequently intensified the need for a deeper understanding of light behavior, particularly its polarization characteristics, to maintain transmission quality. In this context, light polarization is no longer viewed merely as a parameter to be controlled to avoid interference, but rather as an additional dimension that can enhance transmission capacity through techniques such as polarization multiplexing (Sandi, 2025).

Polarization is an intrinsic property of light waves that defines the orientation of the electric-field oscillation as the wave propagates (Antunes & Varum, 2024) . This concept can be described mathematically using the Jones and Stokes formalisms, and visualized through a specialized representation known as the Poincaré sphere (Alonso, 2022). n an ideal optical fiber, the fundamental mode exhibits two orthogonal and degenerate polarization states; however, fabrication imperfections, material inconsistencies, mechanical stresses, and temperature fluctuations introduce birefringence, causing the two polarization states to propagate at different velocities and thereby generating polarization mode dispersion (PMD) (Ilori & Arena, 2019). PMD leads to pulse broadening and inter-symbol interference, effects that become increasingly pronounced as data rates reach tens to hundreds of gigabits per second, ultimately making PMD one of the key performance-limiting factors in long-haul fiber-optic communication systems (Dafe et al., 2025).

Various strategies for controlling and compensating polarization mode dispersion (PMD) have been developed, ranging from the use of polarization-maintaining fibers and adaptive optical compensators to digital signal processing (DSP) techniques that enable impairment correction in coherent receivers (Wu et al., 2022). In addition to mitigating transmission distortions, polarization is also exploited to enhance system capacity through polarization-division multiplexing (PDM). In this technique, two distinct signals are transmitted on two orthogonal polarization states, allowing the channel capacity to be doubled without increasing the spectral bandwidth (Han et al., 2022). The implementation of PDM in advanced modulation formats, such as PDM-QPSK, has become a key solution for high-capacity dense wavelength-division multiplexing (DWDM) systems operating at 100–200 Gb/s (X. Chen et al., 2018). However, the success of PDM requires stable control of the polarization state along the transmission link, as well as accurate polarization demultiplexing techniques at the receiver.

Beyond optical fibers, polarization plays a crucial role in free-space optical (FSO) systems and wireless optical channels, where atmospheric turbulence, intensity fluctuations, and beam wandering significantly affect propagation performance (Savino et al., 2024). Interestingly, several studies have shown that the state of polarization (SOP) tends to remain stable even when the signal intensity undergoes strong fluctuations, allowing polarization to be utilized for polarization diversity or multiplexing to enhance the reliability and capacity of wireless optical systems (Z. Chen et al., 2017) Advances in material technology and integrated photonics have also enabled the development of polarization-sensitive devices such as polarizing beam splitters, modulators, and polarization-sensitive photodetectors that can be embedded directly into photonic integrated circuits (PICs), thereby opening opportunities for integrating polarization-management functionalities into compact next-generation optical systems (Liu et al., 2025).

Although research on polarization and its applications in optical communications has advanced rapidly, a comprehensive review is still needed to bridge theoretical polarization concepts with their practical implementations in optical fibers, FSO systems, and modern polarization-based photonic devices. Based on this need, this article aims to present a systematic literature review on electromagnetic wave polarization and its applications in modern optical communication systems, covering the theoretical foundations and representations of polarization, the utilization of polarization to enhance the capacity and reliability of fiber-optic transmission, the role of polarization in FSO systems and unguided optical channels, as well as the identification of technical challenges and future research directions. Accordingly, this article is expected to serve as a reference for students and researchers in the fields of Electrodynamics and Optical

Communications, and as an initial framework for formulating advanced research topics related to polarization management and exploitation in high-capacity communication systems.

2 Research Methodology

The research method employed in this article is a literature review conducted through an in-depth examination of scientific publications from reputable journals such as IEEE Xplore, Optica, SPIE, MDPI, and *Nature Photonics*. The systematic literature review was carried out using a structured pattern and sequential steps based on established scientific principles. This process includes searching, critically evaluating, and comprehensively synthesizing various studies related to the selected topic (Kiraga, 2023). The selection criteria include:

1. Articles that discuss polarization as a primary focus within optical communication systems.
2. Publications from the last ten years, with several classical works included as theoretical foundations.
3. Studies that contain quantitative data, mathematical models, or experimental evaluations relevant to optical transmission systems.

3 Results and Discussion

Based on the established selection criteria—including topic relevance, methodological appropriateness, data completeness, and publication quality—five articles were ultimately selected after an initial screening process and a more in-depth review. These five articles were deemed to best meet the required standards and subsequently served as the primary foundation for the analysis, forming the basis of the discussion presented in this study, as summarized in Table 1

Table 1. Article Findings

No.	Judul	Penulis (Tahun)	Nama Jurnal
1.	Dual-polarization nonlinear Fourier transform-based optical communication system	Porto et al. (2018)	OPTICA
2.	Review of Polarization Optical Devices Based on Graphene Materials	Zhang & Li (2020)	MDPI
3	Polarization management in silicon photonics	Hahn & Tul (2025)	npj Nanophotonics
4.	Spatial and Polarization Division Multiplexing Harnessing On-Chip Optical Beam Forming	González-andrade et al., (2023)	Laser & Photonics Reviews (LPR)
5.	Polarization Division Multiplexing-Based Hybrid Microwave Photonic Links for Simultaneous mmW and Sub-6 GHz Wireless Polarization Division Multiplexing-Based Hybrid Microwave Photonic Links for Simultaneous mmW and Sub-6 GHz	Nguyen et al. (2020)	IEEE

Research conducted by Porto et al., (2018) demonstrates that the utilization of two polarization modes of light can enhance both the capacity and stability of transmission in optical communication systems based on the nonlinear Fourier transform (NFT). By employing the Manakov equations as the propagation model for the two polarization components and applying modulation to the scattering coefficients in the nonlinear spectral domain, the study shows that information can be transmitted more efficiently and with greater resilience to the nonlinear effects of optical fibers. Experimentally, the dual-polarization NFT system achieved transmission distances of up to 373.5 km with a bit-error rate (BER) below the HD-FEC threshold, indicating that dual polarization can serve effectively as independent channels without significant signal instability. These findings affirm that managing electromagnetic-wave polarization in the nonlinear domain has strong potential as a solution for overcoming capacity limitations imposed by fiber nonlinearity in conventional optical systems.

Research by Zhang & Li (2020) emphasizes that graphene exhibits exceptionally strong electromagnetic-wave polarization characteristics, making it highly promising for enhancing the performance of optical communication devices. Using the Kubo model, the conductivity of graphene is shown to depend on its chemical potential, which determines whether it supports TE or TM modes. Various experiments demonstrate its superior performance: graphene-based fiber polarizers achieve extinction ratios of 27–37.5 dB, waveguide modulators offer bandwidths exceeding 100 GHz, and TIR-based polarization sensors exhibit sensitivities up to 1.9 times higher than those of gold films. The combination of polarization effects, evanescent-field gain, and electrically tunable properties positions graphene as a highly potential material for future optical transmission systems.

Research by Hahn & Tul (2025) highlights that polarization management on silicon photonics platforms plays a crucial role in improving the stability and performance of optical communication systems, particularly in polarization-sensitive applications such as coherent detection, polarization-division multiplexing (PDM), and high-speed transmission. The article shows that birefringence arising from waveguide geometry and material stress is the primary cause of phase differences between TE and TM modes, which can lead to losses, increased PMD, and signal instability during propagation. Through mathematical modeling of phase evolution and refractive-index variation, waveguide engineering can be optimized to minimize polarization sensitivity, including achieving zero-birefringence conditions in specific structures. Experimentally, various polarization-management components such as polarization beam splitters (PBS), polarization rotators (PR), isolators, and circulators have demonstrated high performance; for instance, directional-coupler-based PBS devices achieve extinction ratios up to 36 dB with a footprint of only 14 μm, while photonic-crystal-based devices provide broad bandwidths of up to 111 nm to support WDM systems. In addition, integrated isolators based on magneto-optic materials such as Ce:YIG, as well as non-magnetic approaches like Brillouin scattering, offer effective solutions for suppressing back-reflections in on-chip lasers. Overall, the development of integrated polarization components strongly supports improvements in the capacity and reliability of modern optical transmission systems, although challenges such as fabrication sensitivity in submicron waveguides, limited efficiency of magneto-optic materials, and the need for further device miniaturization still require refinement to achieve full large-scale photonic integration.

Research by González-andrade et al., (2023) demonstrates that evanescent-coupling-based beam-forming techniques can efficiently separate electromagnetic wave modes and polarizations within silicon chips. The three-mode MDM device exhibits an insertion loss of 0.3–1.7 dB and crosstalk levels down to −31 dB, with an effective bandwidth of 195 nm. The two-polarization PDM system achieves extremely low crosstalk (−35 to −61 dB) across a 180-nm range. Transmission tests at 40 Gbps yield a BER below 10^{-9} with low power penalties (0.03–1.5 dB), confirming stable performance in high-speed optical communication applications. These findings indicate that MDM–PDM architectures based on beam-forming provide a promising solution for enhancing the capacity and scalability of integrated optical transmission systems.

Research by Nguyen et al., (2020) shows that the use of a polarization-division multiplexing Mach–Zehnder modulator (PDM-MZM) can enhance the efficiency and stability of simultaneous transmission of 25-GHz mmWave and 2.6-GHz sub-6-GHz signals through both optical fiber and hybrid SMF–FSO channels. Polarization-angle adjustment using a polarization controller (PC) is proven effective in optimizing system performance, particularly in suppressing chromatic dispersion (CD) effects that induce power fading in double-sideband (DSB) modulation schemes. Quantitatively, mmWave transmission over 15–20 km of SMF without optimization exhibits power degradation exceeding 20 dB and distorted constellations, whereas polarization optimization enables RF power recovery and stabilizes the EVM at 5–13%, remaining below standard limits for 4-, 16-, and 64-QAM. Meanwhile, the 2.6-GHz signal is more tolerant to CD, with EVM maintained below 8%, indicating that the second polarization channel performs more stably at lower frequencies. In the hybrid SMF–FSO configuration, atmospheric turbulence leads to intensity fluctuations and degrades mmWave signal quality, increasing EVM up to 17%. However, polarization-based compensation effectively reduces EVM to around 5%, with BER remaining below the FEC threshold ($<10^{-6}$). These findings indicate that polarization control functions not only as a multiplexing technique but also as a mitigation strategy against linear and nonlinear impairments in optical channels. Overall, the simulation and experimental results demonstrate that PDM-MZM-based systems offer advantages in maintaining transmission quality, enabling higher-order modulation formats, and providing a promising solution for efficient wireless–optical transport in 5G and 6G networks.

In addition, a graph illustrating Electromagnetic Wave Polarization and its applications in Optical Communication Systems is also presented as shown below.

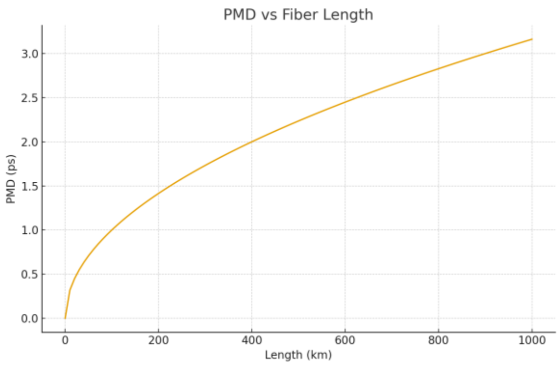

Figure 1. PMD vs. Fiber Length

Figure 1 illustrates the relationship between Polarization Mode Dispersion (PMD) and optical fiber length. It can be observed that the PMD value increases as the fiber length becomes longer, following a square-root growth pattern (√L). At shorter fiber lengths, the PMD rises rapidly, but the rate of increase gradually decreases over longer distances. This behavior is consistent with the physical characteristics of PMD, in which polarization-mode dispersion accumulates randomly along the fiber, causing the total PMD to be proportional to the square root of the fiber length. In the graph, the PMD reaches approximately 3 ps at a length of 1000 km, indicating that longer transmission paths result in greater differential group delay between the two polarization modes, which can ultimately limit the performance of high-speed optical communication systems. The graph highlights the importance of controlling PMD in long-distance systems to maintain optimal optical signal quality.

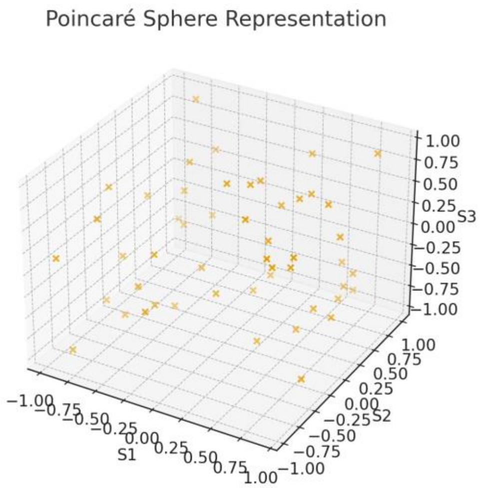

Figure 2. Poincaré Sphere Representation

Figure 2 presents a representation of light polarization states on the Poincaré Sphere, a three-dimensional model that depicts polarization conditions based on the Stokes parameters (S1, S2, and S3). Each orange cross mark corresponds to a specific polarization state projected into a three-axis coordinate space. The S1 axis represents the intensity difference between horizontal and vertical polarizations, S2 indicates the difference between diagonal polarizations (+45° and –45°), and S3 represents the components of right-hand and left-hand circular polarization. The distribution of points across all regions of the sphere illustrates various polarization states, including linear, elliptical, and circular. Overall, this graph demonstrates how different polarization conditions can be visually mapped within the geometric structure of the Poincaré Sphere, thereby facilitating the analysis of polarization characteristics in optical systems.

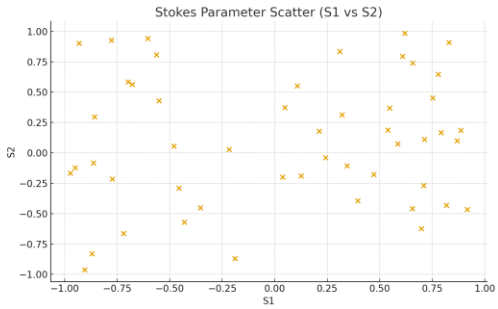

Figure 3. Stokes Parameter Scatter Plot

Figure 3 presents a scatter plot illustrating the relationship between the Stokes parameters S1 and S2, which represents variations in light polarization states within a two-dimensional coordinate plane. The data points are randomly distributed across all quadrants, ranging from approximately –1 to 1 for both S1 and S2. This distribution indicates that the observed polarization states vary widely, encompassing different combinations of dominant horizontal–vertical components (S1) and diagonal components (S2). The absence of a specific pattern suggests that the optical source or signal exhibits significant fluctuations in polarization state, rather than being concentrated in a single type of polarization. Overall, this graph represents the dynamic and varying polarization states of light as reflected by changes in the Stokes parameters S1 and S2.

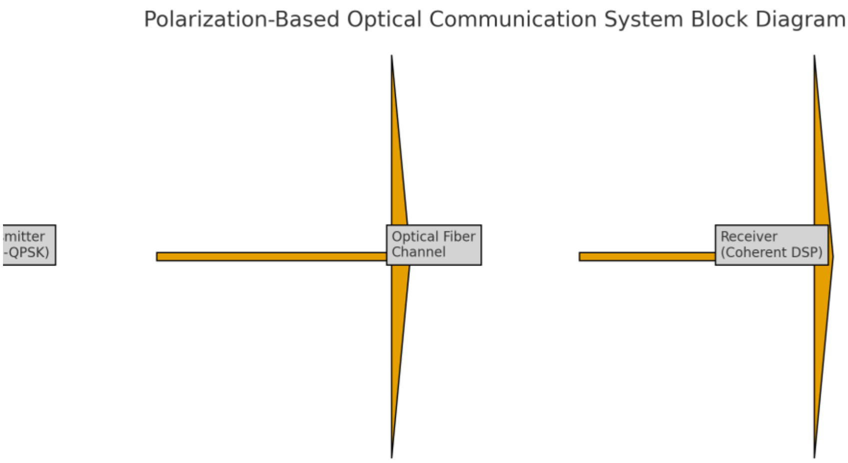

Figure 4. Polarization-Based Communication System Diagram

Figure 4 shows a block diagram of a polarization-based optical communication system. On the left side is the transmitter block, which generates a polarized optical signal, for example through PDM-QPSK modulation. This polarized signal is then transmitted through the optical fiber channel illustrated in the center. The middle section also depicts the polarization changes or distortions that may occur along the fiber due to birefringence, Polarization Mode Dispersion (PMD), or other environmental effects. After propagating through the fiber, the signal is received by the coherent DSP-based receiver, which functions to detect the signal, compensate for polarization impairments, and reconstruct the transmitted information. Overall, this diagram illustrates the signal flow from the transmitter to the receiver through an optical fiber medium, emphasizing the role of polarization in modern coherent optical communication systems.

The research findings described in the previous paragraphs demonstrate that the management and utilization of polarization play a fundamental role in enhancing the capacity, stability, and efficiency of modern optical communication systems. The studies by Porto et al. (2018) on dual-polarization NFT-based transmission, Zhang and Li (2020) on strongly polarized graphene materials, and Hahn and Tul (2025) on polarization optimization in silicon photonics platforms all confirm that polarization characteristics must be precisely controlled, as each polarization mode carries information that can be affected by dispersion, birefringence, and other optical channel impairments. This correlation is clearly reflected in Figure 1, which shows that Polarization Mode Dispersion (PMD) increases according to the square-root dependence on fiber length ($\sqrt{L}$). This cumulative phenomenon aligns with the challenges identified in high-speed transmission research, in which polarization instability and differential group delay between modes can limit performance, particularly in NFT systems, PDM architectures, or silicon photonics devices.

Furthermore, Figures 2 and 3, which present polarization distributions on the Poincaré Sphere and the scatter plot of the Stokes parameters S1–S2, are closely related to various research approaches that emphasize the importance of mapping polarization states in the optical domain. The broad distribution of points in both visualizations indicates that polarization states can vary dynamically, as also observed in experimental systems such as the PDM-MZM configuration reported by Nguyen et al. (2020), which demonstrated the sensitivity of mmWave and sub-6 GHz signals to polarization variations. These graphical representations reinforce the view that polarization analysis based on Stokes parameters or the Poincaré Sphere is crucial for understanding distortions and facilitating polarization compensation in modern optical devices whether in graphene-based photonics, silicon photonics, or NFT-based systems.

This connection becomes even more evident in Figure 4, which presents a block diagram of a polarization-based optical communication system illustrating the flow of polarized signals from the transmitter to the receiver through an optical fiber. The polarization distortions along the optical channel shown in the diagram directly correlate with the findings of González-Andrade et al. (2023), who employed beam-forming techniques to efficiently separate modes and polarization states, as well as the study by Nguyen et al. (2020), which demonstrated that polarization compensation can mitigate dispersion effects and enhance signal quality. The diagram highlights the essential roles of components such as PBS, PR, and coherent DSP in overcoming PMD, birefringence, and other impairments—consistent with the technological developments occurring in silicon photonics platforms and graphene-based materials. Collectively, the four figures provide a visual representation of the polarization phenomena discussed in the referenced research, ranging from PMD accumulation, variations in polarization states, PDM modulation characteristics, to polarization-control components in high-speed optical systems, thereby demonstrating the coherence between theoretical models, experimental data, and graphical representations of light polarization behavior.

Overall, the interrelation between the five studies reviewed and the four figures analyzed indicates that polarization is a key parameter determining the ability of optical communication systems to operate at high capacity, long distances, and under complex impairment conditions. The increase in PMD with fiber length (Figure 1), the variations in polarization states within the Stokes domain (Figures 2 and 3), and the polarization-based system flow diagram (Figure 4) all confirm the importance of polarization-management techniques developed in current research—from dual-polarization NFT, graphene-based modulation, and waveguide engineering in silicon photonics, to MDM–PDM architectures and PDM-MZM-based compensation. These studies demonstrate that effective polarization control can enhance signal stability, suppress dispersion effects, support higher-order modulation formats, and expand transmission capacity. Thus, the integration of polarization modeling, material engineering, and digital compensation systems forms a fundamental framework for addressing nonlinear and dispersive limitations in next-generation optical communication systems, including large-scale integrated photonics and future 5G/6G networks.

4 Conclusion

Based on the conducted literature review, it can be concluded that the polarization of electromagnetic waves plays a crucial role in enhancing the performance of modern optical communication systems, both in fiber-optic transmission and in wireless optical channels such as free-space optics (FSO). From a theoretical perspective, understanding polarization properties its representation through Stokes parameters and the Poincaré Sphere, as well as phenomena such as birefringence and polarization mode dispersion (PMD)—forms the fundamental basis for designing stable and high-capacity optical systems. Through a methodological literature-based approach focused on reputable journals, this study successfully identifies five key works that provide significant contributions to the development of polarization management and utilization techniques.

The analysis demonstrates that polarization management is not only essential for mitigating impairments such as PMD but also serves as an effective strategy for increasing channel capacity through techniques such as polarization-division multiplexing (PDM), nonlinear Fourier transform (NFT), integrated beam-forming, and the use of polarization devices based on advanced materials such as graphene and silicon photonics platforms. Experimental findings across various studies further confirm that these methods improve signal stability, expand bandwidth, reduce crosstalk, and support higher-order modulation formats in 5G/6G networks and integrated photonic systems.

The diagrams, plots, and visual representations analyzed in this review reinforce these findings by illustrating the cumulative growth of PMD, the dynamic behavior of polarization states within the Stokes space, and the operational flow of polarization-based transmission in modern coherent optical systems. Overall, this review affirms that the integration of polarization management, material engineering, and digital signal processing constitutes an essential foundation for improving the efficiency, capacity, and reliability of next-generation optical communication systems. Further research is required to address challenges in fabricating nanometer-scale polarization devices, optimizing high-performance materials such as graphene, and developing more efficient integrated photonic architectures for future network applications.

5 Reference

Alonso, M. A. (2022). Geometric descriptions for the polarization of nonparaxial light : a tutorial. *preprint arXiv*.

Antunes, F., & Varum, T. (2024). Concept and Design of a Multi-Polarization Reconfigurable Microstrip Antenna with Symmetrical Biasing Control. *Sensors (MDPI)*.

Chen, X., Macho, A., & Horche, P. R. (2018). Performance evaluation of 100 and 200-Gb / s WDM PM-QPSK transmission systems : tolerance analysis to the optical link impairments according to the optical carrier shape. *Optical Review*, *0*(0), 0. https://doi.org/10.1007/s10043-018-0463-y

Chen, Z., Yan, L., Pan, Y., Jiang, L., Yi, A., Pan, W., & Luo, B. (2017). Use of polarization freedom beyond polarization- division multiplexing to support high-speed and spectral-efficient data transmission. *Light: Science & Applications*, *6*(2). https://doi.org/10.1038/lsa.2016.207

Dafe, O., Oghenemega, S., Tobore, A., & Olisenekwu, C. (2025). Experimental Evaluation of PMD Effects in NRZ and QAM-modulated High-speed Optical Systems in Abuja ,Nigeria. *Physical Science*

International Journal, *29*(5), 16–28.

Fadila, W. A., Aini, Q., Wahyudi, F. A., & Fisika, P. (2024). Perkembangan teknologi pemanfaatan fiber optik dalam industri telekomunikasi untuk koneksi jaringan. *Jurnal Pendidikan Fisika*, *8*(2), 309–320.

González-andrade, David, Roux, L., Le, X., Aubin, G., Amar, F., Hao, T., Nguyen, N., Ruano, P. N., Thuy, T., Dinh, D., Oser, D., Pérez-galacho, D., Cassan, E., Marris-morini, D., Vivien, L., Alonso-ramos, C., Nhi, T. H., Ruano, N., & Duong, T. T. (2023). Spatial and Polarization Division Multiplexing Harnessing On-Chip Optical Beam Forming. *Laser & Photonics Reviews (LPR)*. https://doi.org/10.1002/lpor.202300298

Hahn, H., & Tul, S. (2025). Polarization management in silicon photonics. *npj Nanophotonics*. https://doi.org/10.1038/s44310-024-00033-6

Han, X., Jiang, Y., Frigg, A., & Xiao, H. (2022). Mode and Polarization-Division Multiplexing Based on Silicon Nitride Loaded Lithium Niobate on Insulator Platform. *Laser & Photonics Reviews (LPR)*.

Hasan, N. A. (2025). Advancing Optical Communicating 6G Network Infrastructures. *International Journal of Optical Communication (IJOC)*, *6*(1), 1–5.

Ilori, D. A. P., & Arena, A. N. C. (2019). Observing the effect of polarization mode dispersion on nonlinear interference generation in wide-band optical links. *Osa Continuum*, *2*(10), 2856–2863. https://doi.org/10.1364/OSAC.2.002856

Kiraga, F. (2023). *Literature Review : Efforts To Improve Creative Thinking Ability In Science Learning*. *4*(2). https://doi.org/10.37251/isej.v4i2.330

Liu, Z., Liu, M., Qi, L., Li, S., Zhang, N., Wang, B., Sun, X., & Zhang, R. (2025). Versatile on-chip polarization-sensitive detection system for optical communication and artificial vision. *Light: Science & Applications*. https://doi.org/10.1038/s41377-025-01744-x

Nguyen, D., Dat, P. T., Nguyen, D., Bohata, J., & Spacil, J. (2020). Polarization Division Multiplexing-Based Hybrid Microwave Photonic Links for Simultaneous mmW and Sub-6 GHz Wireless Polarization Division Multiplexing-Based Hybrid Microwave Photonic Links for Simultaneous mmW and Sub-6 GHz. *IEEE*. https://doi.org/10.1109/JPHOT.2020.3036440

Porto, E., Ros, D., & Aiarin, S. G. (2018). Dual-polarization nonlinear Fourier transform-based optical communication system. *OPTICA*. https://doi.org/10.1364/OPTICA.5.000263

Sandi, E. (2025). *Teknologi Antena Mimo*. Nasmedia.

Savino, N., Leamer, J., Saripalli, R., Zhang, W., Bondar, D., & Glasser, R. (2024). Robust Free-Space Optical Communication Utilizing Polarization for the Advancement of Quantum Communication. *Entropy (MDPI)*, 1–13.

Taher, K. A., & Majumder, S. P. (2018). BER Performance of PDM 4-QAM Optical Transmission System Considering the Effects of PMD and GVD Using Exact Probability Density Function. *American Journal of Optics and Photonics*, *6*(1), 14–19. https://doi.org/10.11648/j.ajop.20180601.13

Wu, Q., Zhu, Y., Jiang, H., Zhuge, Q., Member, S., & Hu, W. (2022). Optical Field Recovery in Jones Space. *arXiv*.

Zhang, S., & Li, Z. (2020). Review of Polarization Optical Devices Based on Graphene Materials. *MPDI*, *2*.