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Space division multiplexing technology: principles, applications, and future prospects

Xianzhi Lu

School of Information Science and Technology, Fudan University, Shanghai, China

21307130356@m.fudan.edu.cn

Abstract. As demand for fiber-optic communication capacity grows, traditional multiplexing technologies struggle to keep pace, prompting the rise of Optical Space Division Multiplexing (OSDM). By utilizing the spatial dimension of fibers like multi-core and few-mode fibers, OSDM enables parallel data transmission across independent channels. This paper explores its principles and applications in high-capacity networks, mobile backhaul, and microwave photonics. OSDM offers significant advantages, including enhanced transmission capacity and improved energy efficiency over conventional methods like wavelength and time division multiplexing. However, it faces challenges such as high manufacturing costs and complex crosstalk management. Despite these drawbacks, OSDM's scalability and potential for integration with intelligent systems position it as a key technology for future optical communication networks.

Keywords: space division multiplexing, multi-core fiber, high-capacity transmission, energy efficiency optimization, intelligent network management

1. Introduction

In an era of explosive data demand and ever-increasing communication capacity, Space Division Multiplexing (SDM) has emerged as a critical solution to overcome the bandwidth limitations of traditional fiber-optic networks. According to Cisco's predictions, global IP traffic reached 3.3 Zettabytes (ZB) per year in 2023, with an annual growth rate of 29% [1]. Recent advancements in Space-Division Multiplexing (SDM) research have underscored its significant potential. Notably, a study successfully achieved a transmission rate of 1 Petabit per second over a distance of 205.6 kilometers. This was accomplished using a 32-core heterogeneous multi-core fiber, which supported 46 Wavelength-Division Multiplexing (WDM) channels, each employing 96-Gbaud Polarization-Division Multiplexing 16 Quadrature Amplitude Modulation (PDM-16QAM) [2]. The results exemplify outstanding performance in the realm of high-capacity, long-distance optical communication. Another study proposed an energy-efficient SDM architecture for next-generation data center interconnects, significantly reducing system power consumption while maintaining high throughput [3]. Additionally, research on microwave photonic filters based on multi-core fiber SDM explored the integration of SDM with artificial intelligence, demonstrating the feasibility of AI-driven dynamic control in multi-channel systems [4]. These studies collectively highlight the advantages of SDM in enhancing transmission capacity, reducing energy consumption, and enabling intelligent network management. This paper builds on these innovations to explore optimization strategies for SDM and its integration with traditional multiplexing technologies and AI, providing theoretical and practical guidance for the development of future ultra-high-capacity communication systems.

2. Overview and limitations of traditional multiplexing technologies

2.1. Overview of traditional multiplexing technologies

Traditional multiplexing technologies have played a pivotal role in fiber-optic communications by leveraging different physical properties of optical signals to enable parallel transmission of multiple data streams. Common techniques include Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), and Frequency Division Multiplexing (FDM). WDM maps multiple signals to different wavelengths within the optical spectrum, combining them into a single fiber using wavelength multiplexers, enabling high-capacity, long-distance transmission. TDM divides the time axis into fixed slots, allowing multiple signals to share the same transmission channel sequentially, making it suitable for digital communications. FDM modulates signals onto different frequency carriers, which are then separated using filters, and is widely used in wireless communications and telephone systems.

2.2. Limitations of traditional multiplexing technologies

Despite their effectiveness in expanding bandwidth, traditional multiplexing technologies have inherent limitations. WDM systems require expensive, high-precision optical components, and their wavelength allocation schemes are inflexible, limiting dynamic adjustments and scalability. TDM systems require stringent clock synchronization; synchronization errors can result in data packet misalignment or loss. Additionally, the sequential transmission mechanism frequently leads to low channel utilization and heightened latency. FDM systems require guard bands between signals to prevent interference, leading to wasted spectrum resources and high-performance filter requirements, along with susceptibility to noise and interference. These limitations hinder the further application of traditional multiplexing technologies in ultra-high-capacity and energy-efficient communication networks.

3. Space division multiplexing technology

3.1. Principles of optical space division multiplexing

Optical Space Division Multiplexing (SDM) technology significantly enhances optical fiber transmission capacity by fully utilizing the spatial dimension of optical fibers, mapping multiple data streams to different physical channels for parallel transmission. In SDM systems, Multi-Core Fibers (MCF) or Few-Mode Fibers (FMF) are employed to construct multiple independent transmission channels, with each core or mode capable of independently transmitting optical signals. This approach effectively addresses the limitations inherent in traditional multiplexing technologies, which depend solely on wavelength, time, or frequency resources. It achieves linear capacity expansion within a single optical fiber and inherently reduces inter-channel crosstalk. By leveraging SDM technology, overall bandwidth utilization is improved, providing new pathways for ultra-long-distance, high-capacity transmission [6].

3.2. Key components of optical space division multiplexing technology

The implementation of SDM technology primarily depends on the following key components.

3.2.1. Multi-Core Fibers (MCF)

Multi-core fibers integrate multiple independent transmission cores within a single optical fiber, with each core functioning as an independent optical channel. Designing MCFs requires strict control of inter-core crosstalk to ensure the independence and high transmission quality of each channel.

3.2.2. Spatial multiplexers and demultiplexers

Spatial multiplexers are responsible for coupling optical signals from different data streams into their corresponding physical channels, while demultiplexers separate and restore the multiplexed signals at the receiving end. High-precision optical devices such as couplers, splitters, and filters play a crucial role in this process.

3.2.3. Optical amplifiers and modulators

With the increase in transmission channels, SDM systems have higher requirements for signal amplification and modulation. Erbium-Doped Fiber Amplifiers (EDFAs) are frequently employed to mitigate long-distance transmission losses. Meanwhile, high-speed modulators transform electrical signals into optical signals, catering to high data rate demands and ensuring the overall system maintains high performance.

3.3. Advantages of optical space division multiplexing technology

Compared to traditional Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), and Frequency Division Multiplexing (FDM) technologies, SDM technology offers significant advantages in enhancing transmission capacity, reducing power consumption, and improving system scalability.

Firstly, SDM utilizes the spatial dimension of optical fibers for multiplexing, enabling the construction of multiple independent transmission channels within a single fiber, achieving linear capacity expansion. For instance, a study by Kobayashi et al. [2] demonstrated this advantage by transmitting a 1 Pb/s unidirectional data stream over 205.6 kilometers of single-mode heterogeneous multi-core fiber using a combination of 32 SDM channels and 46 WDM channels, each operating at 768 Gb/s, and employing 96-Gbaud PDM-16QAM channels to achieve high spectral efficiency. This research not only broke through the bandwidth limits of traditional single-core systems but also proved the reliability and stability of multi-core fibers in long-distance, high-capacity transmission (see Figure 1).

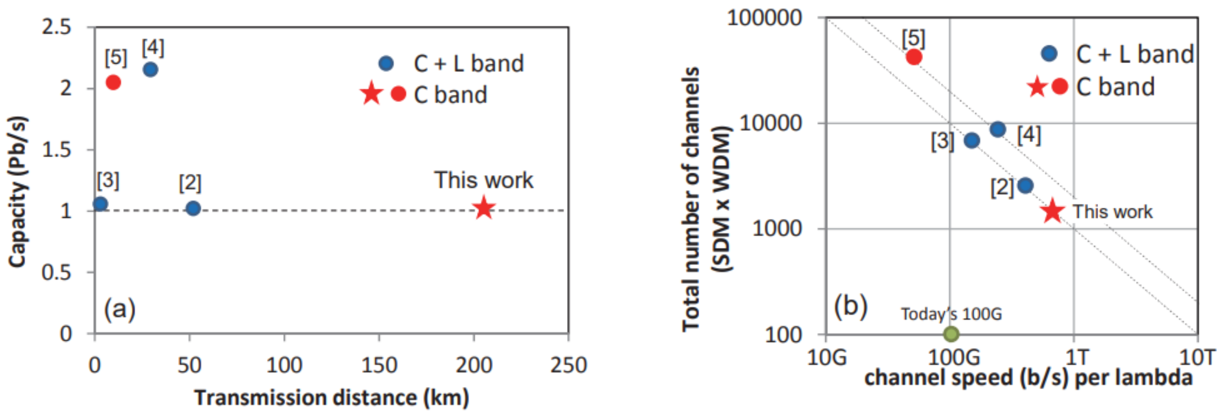

Figure 1. (a) Capacity versus transmission distance; (b) Total number of channels vs channel speed/lambda from recent over-1Pb/s capacity SDM transmission experiments

Secondly, SDM technology also exhibits notable advantages in energy efficiency. Safarnejadian et al. [3] introduced a high-energy-efficiency SDM architecture for next-generation data center interconnects, achieved by optimizing the design of Traveling-Wave Mach-Zehnder Modulators (TW-MZMs) and integrating advanced digital signal processing techniques. This innovation resulted in a substantial decrease in power consumption within multi-channel transmission systems. Experimental results showed that, compared to traditional single-channel schemes, this structure could save up to 59% of energy in practical deployments, which is particularly important for high-density data centers and short-distance interconnect scenarios. The study also explored how to further reduce overall system power consumption while maintaining high throughput by optimizing drive voltage and signal clipping techniques, providing strong support for the development of green communication networks.

Furthermore, SDM technology, by adopting physically independent spatial channels, significantly reduces inter-channel interference, thereby enhancing the transmission stability and signal-to-noise ratio of the system. Its scalability is strong; by simply increasing the number of cores in the optical fiber or utilizing more spatial channels, the system capacity can be further enhanced without significantly increasing system complexity. When integrated with other multiplexing technologies such as WDM, SDM facilitates multi-dimensional multiplexing integration, thereby providing innovative solutions for the development of ultra-high-bandwidth and energy-efficient next-generation communication networks. In summary, SDM technology demonstrates clear advantages over traditional multiplexing technologies in aspects such as transmission capacity, energy efficiency, scalability, and anti-interference capability. These pioneering studies have demonstrated that SDM technology is capable of overcoming traditional bottlenecks, thereby achieving unprecedented performance enhancements in ultra-long-distance transmission and data center interconnect applications. This advancement provides crucial technological pathways for the sustained evolution of future optical networks.

4. Applications and future trends of SDM technology

Space Division Multiplexing (SDM) technology has demonstrated significant application potential across various fields due to its high capacity, low energy consumption, and strong scalability. The following sections outline its core application scenarios, supported by specific research cases.

4.1. Application scenario analysis

4.1.1. Ultra-high-capacity optical fiber communication networks

In long-haul backbone networks and Data Center Interconnects (DCI), SDM achieves parallel transmission of multiple channels over a single fiber using Multi-Core Fibers (MCF), effectively overcoming the capacity limitations of traditional single-mode fibers. For instance, NTT Laboratories [2] in Japan utilized a 32-core MCF to achieve a transmission capacity of 1 Pb/s over a distance of 205.6 kilometers, surpassing single-core Wavelength Division Multiplexing systems by more than seven times. Additionally, Huo demonstrated that microwave photonic filter systems based on MCFs can dynamically reconstruct tap coefficients in both spatial and wavelength dimensions, significantly enhancing signal processing flexibility [4]. By splicing Multi-Core Fibers (MCFs) with Multi-Mode Fibers (MMFs) to create a three-stage all-fiber structure, and leveraging multimode interference effects, the study realized wavelength and spatially tunable filter responses (see Figure 2). This achievement offers novel insights for dynamic resource allocation in future ultra-high-speed optical communication systems.

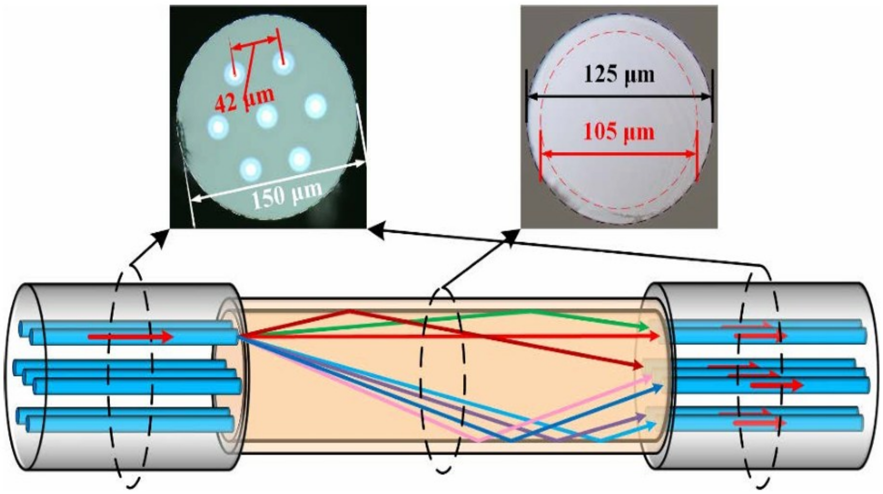

Figure 2. Schematic diagram of multi-core multimode multi-core fiber structure [4]

4.1.2. 5G/6G mobile backhaul networks

With the dense deployment of 5G base stations and the ultra-high throughput demands of 6G, SDM technology supports low-latency, high-capacity fronthaul and backhaul links using Few-Mode Fibers (FMF). Analog and digitized radio-over-fiber are discussed in a scenario featuring parallel fronthaul for different radio access technologies, showcasing their differences and potential when combined with SDM [7]. Furthermore, Huo Liang proposed a neural network-based optimization algorithm for microwave photonic filters, capable of real-time prediction of optimal operating wavelengths and input cores, with a Mean Absolute Error (MAE) of only 0.09 nm and a 100% prediction accuracy for input cores [4]. This technology provides theoretical support for rapid signal reconstruction in dynamic network environments.

4.1.3. High-density optical fiber access networks

In Fiber-to-the-Home (FTTH) and Industrial Internet of Things (IoT) scenarios, SDM utilizes MCFs to spatially separate user signals, alleviating bandwidth bottlenecks on the access side. Morant, M. et. al paper proposes and evaluates experimentally the performance of Single-Carrier QAM (SC-QAM) and OFDM-QAM signals for next-generation backhaul over a deep Fiber-to-the-Home (FTTH) network comprising up to 50 km SSMF combined with in-building transmission over 150 m of 4-core multi-core fiber in order to reach the cellular transmission equipment usually located in the roof [8].

4.1.4. Microwave photonics and integrated optoelectronics

SDM technology is increasingly becoming a research hotspot in the field of microwave photonics. Huo experimentally demonstrated that microwave photonic filter systems based on MCFs can dynamically alter the filter's amplitude-frequency response curve by adjusting input wavelengths and core positions [4]. For example, within the C-band (1530-1565 nm), the system supports independent control of seven tap coefficients, making it suitable for radar signal processing and Radio-over-Fiber (RoF) systems. The study also introduced a fully connected neural network algorithm capable of predicting optimal operating parameters based on target response curves, with excellent generalization performance in simulation tests, laying the foundation for SDM applications in multifunctional Photonic Integrated Circuits (PICs).

4.2. Future trends and research directions

4.2.1. Integration of multi-dimensional multiplexing technologies

Future SDM will deeply integrate with Wavelength Division Multiplexing (WDM) and Polarization Division Multiplexing (PDM) to form a "space-wavelength-polarization" three-dimensional multiplexing architecture. A technique for WDM/SDM transmission with ultra-high aggregated spectral efficiency was demonstrated in Ref (see Figure 3).

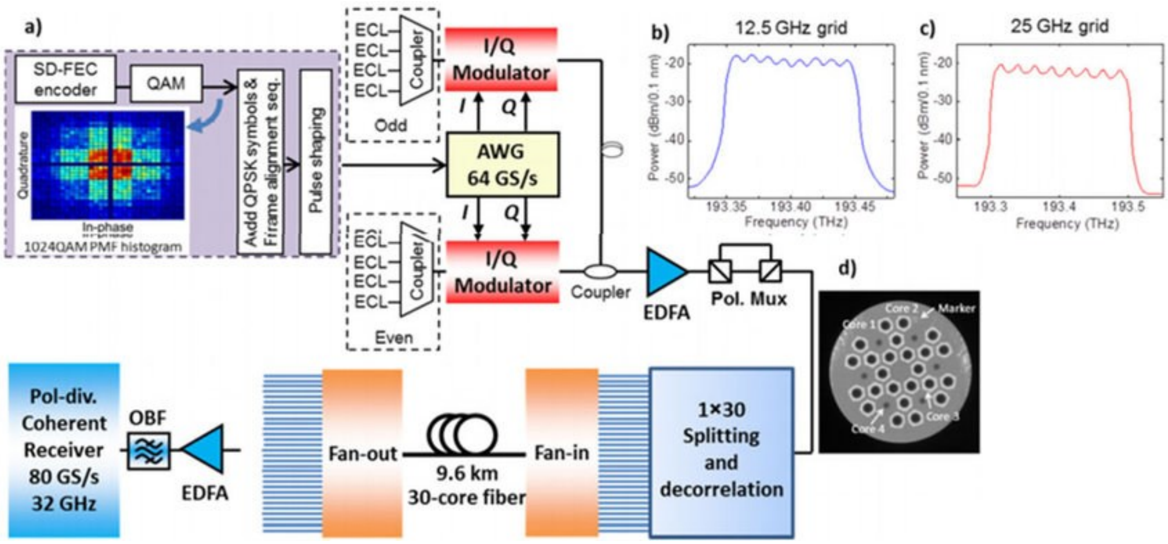

Figure 3. a) Experimental configuration for the WDM/SDM transmission of PS PDM-1024-QAM channels over a 30-core fiber; b) and c) optical spectra of the WDM channels after the 30-core fiber transmission; and d) cross-sectional view of the 30-core fiber [9]

4.2.2. Novel optical fiber materials and manufacturing technologies

The development of bend-resistant MCFs and low-crosstalk MMFs is a future focus. For instance, a company in Jiangsu proposed a scheme of differential inner-cladding structure and identical cores to design a kind of bend-insensitive heterogeneous Multi-Core Fiber (MCF) with high density of cores and ultra-low crosstalk (XT), which have not been previously reported [10].

4.2.3. Artificial intelligence-driven network management

Integrating AI algorithms for adaptive optimization of SDM systems is an important trend. For example, A George Washington University team present a Machine Learning (ML) aided threshold optimization strategy that enhances the performance of any RMCSA algorithm for any network model. They show that their strategy applied to a few algorithms from the literature improves the bandwidth blocking probability by up to three orders of magnitude [11].

4.2.4. Green communication and energy efficiency optimization

SDM's unit bandwidth energy consumption advantage makes it a core technology for green communication. For instance, a TE SubCom team demonstrate the existence of an optimal spectral efficiency that maximizes the power efficiency and/or capacity of a power limited Erbium-Doped Fiber Amplifier (EDFA)-based space division multiplexing transmission system. Optimal spectral efficiency observed experimentally is in good agreement with a theoretical estimate [12].

4.2.5. Expansion applications for quantum communication

The high isolation characteristics of MCFs provide new pathways for quantum communication. For example, Da Lio et al. demonstrate the reliable transmission over a 2-km-long multicore fiber of path-encoded high-dimensional quantum states. Leveraging on a phase-locked loop system, a stable interferometric detection is guaranteed, allowing for low error rates and the generation of 6.3 Mbit/s of a secret key rate [13].

5. Conclusion

This study comprehensively explores the principles, key components, and applications of SDM technology, demonstrating its potential to overcome the capacity limitations of traditional multiplexing technologies. By leveraging the spatial dimensions of fibers through MCF and FMF architectures, SDM enables linear capacity scaling and significant improvements in spectral efficiency and energy consumption. Research has shown that SDM can achieve unprecedented transmission rates over long distances, making it a powerful solution for next-generation backbone networks, data center interconnects, and high-density access networks.

In addition to increasing transmission capacity, SDM's advantages in reducing inter-channel interference and improving signal-to-noise ratio further highlight its superiority over traditional WDM, TDM, and FDM technologies. The integration of intelligent technologies, such as convolutional neural networks for dynamic optimization of microwave photonic filters in MCF, has laid the foundation for intelligent optical network management.

However, challenges remain. The integration of SDM with advanced AI algorithms is still in its early stages, and the robustness and generalization capabilities of neural network models under varying conditions need further improvement. Additionally, the high manufacturing and deployment costs of MCF and FMF may limit their widespread commercial adoption. Effective management of crosstalk and mode coupling in densely packed channels also remains a technical challenge. Nevertheless, ongoing advancements in fiber manufacturing, optical component design, and intelligent control strategies will enhance the practicality and scalability of SDM, ultimately driving the development of high-capacity, energy-efficient next-generation optical communication networks.

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