

2025 International Conference on Advanced Mechatronics and Intelligent Energy Systems

Analysis and Research on the Progress of Wavelength Division Multiplexing Technology in Optical Communication

AIPCP25-CF-AMIES2025-00046 | Article

PDF auto-generated using **ReView**



Analysis and Research on the Progress of Wavelength Division Multiplexing Technology in Optical Communication

Haidong Wen

International College, Chongqing University of Posts and Telecommunications, Chongqing, China

2279315@brunel.ac.uk

Abstract. With the commercial maturity of 5G mobile communication technology, the research on 6G mobile communication technology, the rapid growth of Internet traffic, and the development of the Internet of Things, big data, and cloud computing, the demand for the capacity and rate of communication systems is still increasing rapidly. The transmission capacity of traditional single-mode optical fibers has approached the theoretical nonlinear Shannon limit (100 Tbit/s), so upgrading the existing technology is urgently needed. As a light-space multiplexing scheme to break the capacity bottleneck of single-mode optical fibers, the asymmetric demultiplexing multiplexing (MDM) technology has become a research hotspot in the field of optical communication in recent years. The research on MDM technology covers the improvement and exploration of various components in communication systems. According to the published research results, this paper summarizes the development progress of key components, including the LP mode dispersion in weakly coupled single-mode fibers (MF), erbium-doped ring-core fibers supporting four groups of modes, single-mode fiber amplifiers, integrated devices related to MDM multiplexers, and a review of the transmission system. These contents provide references for researchers of MDM technology.

INTRODUCTION

With the rapid growth of Internet traffic and the development of Internet of Things, big data and cloud computing, the demand for transmission capacity of communication networks has been continuously rising. The transmission capacity of traditional single-mode optical fibers has already approached the theoretical nonlinear Shannon limit (100 Tbit/s), and the development of the next-generation 6G mobile communication services has even raised higher requirements for the capacity and speed of communication networks[1][2]. Therefore, it is urgent to develop new large-capacity optical transmission technologies to break through the current transmission capacity limitations. Against this background, the mode multiplexing technology has attracted the attention of scholars worldwide[3].

The research on MDM technology encompasses the updates and iterations of key components in communication systems, including the most fundamental laser, optical amplifier, and several modulation modules, etc. Moreover, the research also involves the evolution of MDM multiplexers, integrated devices, and even the entire transmission system.

This article aims to provide researchers with an overview of the development of multimode dispersion management (MDM) technology by reviewing existing studies. This will facilitate their more effective conduct of related research. Firstly, the article introduces the dispersion characteristics of LP modes within weakly coupled single-mode fibers (MFs) and the situation of erbium-doped ring-core fibers supporting four modes. Subsequently, it reviews the research progress of single-mode fiber amplifiers. Then, it summarizes the research status of two types of devices integrating MDM multiplexers. Finally, it presents a three-mode system that achieves 3060-kilometer transmission within the full C-band and does not require management of differential mode delay (DMD).

RESEARCH PROGRESS OF SINGLE-MODE FIBER

Research on Dispersion Inside Modes

A detailed analysis and measurement experiment on the intramode dispersion (IMD) of LP modes in a weakly coupled multimode fiber (MF) were conducted to study the dispersion characteristics of LP modes in this type of fiber[4]. Firstly, the generation mechanism of ILMD (internal mode dispersion) was discussed, and the average ILMD values of different LP modes in typical step-index circular-core single-mode fibers (MF) were calculated. Based on this, the impact of ILMD on the performance degradation of IM/DD MDM systems was further evaluated through numerical simulation. Subsequently, an improved fixed analyzer method (IFAM) was proposed for precise measurement of ILMD in weakly coupled MFs. To this end, a set of ILMD measurement experimental devices for dual-core weakly coupled fiber MFs was constructed. It was found that the dispersion within different LP modes (such as LP01, LP11a, LP11b, etc.) varies significantly, with the dispersion of LP11 mode being approximately four times that of LP01 mode. Experiments proved that the dispersion coefficient of LP01 mode is approximately 0.05 ps/(nm·km), while that of LP11 mode is around 0.2 ps/(nm·km). As the transmission distance increases, the cumulative effect of mode internal dispersion becomes more obvious, which may lead to signal distortion and an increase in bit error rate. For higher-order non-circular core LP modes (such as LP31 and LP12), their ILMD values are larger. Therefore, between higher-order non-circular core LP modes, the differences between characteristic modes become more significant, resulting in larger ILMD values.

The research outcome provides a theoretical basis for the design optimization of single-mode optical fibers and the enhancement of the transmission performance of mode multiplexing systems. It is suggested to reduce the influence of intramode dispersion by further optimizing the fiber structure and adopting advanced signal processing techniques.

Erbium-ion layered-doped core fiber

In order to achieve gain balance among different modes in FM-EDFA, a layered erbium-doped core fiber with four modules is proposed[5], which works under the condition of cladding pumping. During the design process, the influence of the pumping mode was not considered. Instead, the refractive index variation caused by the central depression of the core and the external grooves was controlled, and the doping radius and concentration of erbium ions were reasonably set to reduce the differential mode gain (DMG). The study shows that when erbium ions are doped in the core with a double-layer structure, the maximum DMG decreases from 0.8 dB in the case of uniform doping in a single layer to 0.44 dB. The performance of this cladding-pumped erbium-doped fiber amplifier supporting four modules was investigated. The gain balance among LP01, LP11, LP21 and LP31 modes was achieved by using the layered erbium-doped core. In this erbium-doped fiber, erbium ions are doped in a ring-shaped double-layer distribution, effectively reducing the DMG. When the input power of each signal mode is -10 dBm, a flat gain of more than 22 dB can be obtained in the C-band, and the DMG is less than 0.45 dB, with a noise figure lower than 5.3 dB.

OPTIMIZATION OF SINGLE-MODE FIBER AMPLIFIERS

Long-distance transmission single-mode fiber amplifiers

This paper introduces a high-gain integrated single-mode fiber amplifier that supports long-distance transmission up to 3840 kilometers[6]. We have demonstrated for the first time in a long-distance MDM transmission system the online high-gain integrated 3M-EDFA > 3000km 3MF. By integrating 3M isolators and 3M power combiners, a system with an insertion loss of < 0.6 dB and an MDL structure of 0.3 dB was constructed, thereby achieving the integration of 3M-EDFA similar to that of the widely used single-mode EDFA. Importantly, the average mode gain reached 25 dB, the DMG was approximately 1.1 dB, and through the proposed 3M-EDFA, a low noise figure of 5-7 dB can be achieved simultaneously in the C band. In erbium-doped fibers, erbium ions are doped in a ring-shaped double-layer distribution, which effectively reduces the DMG of FM-EDFA. When the input power of each mode is -10 dBm, 28 Gbaud QPSK transmission across 3840 kilometers can be achieved. After 3840 kilometers of transmission, the average bit error rates of the three modes are 6.33×10^{-3} , and the MDL value is < 10 dB. The overall output signal power of the proposed FM-EDFA can be further increased by a larger pump power, indicating

its potential application in integrated MDM systems supporting more linear polarization modes and longer transmission distances.

Design of single-mode fiber amplifiers based on genetic algorithm optimization

Subsequently, a design scheme for a single-mode fiber amplifier based on genetic algorithm optimization was introduced[7]. For the four-mode group and the five-mode group, three-layer and four-layer erbium-ion-doped structures were respectively designed. The erbium-ion-doped structures in the fiber were optimized through a binary-coded genetic algorithm, and the gain performance evaluation function was updated, thereby achieving low mode gain difference (DMG) and high gain uniformity, significantly improving the overall performance of the amplifier. The simulation optimization results showed that when using 980nm dual-mode multiplexed pump and adopting the forward pumping mode to amplify 1550nm four-mode multiplexed signals, the average gain of each mode of the obtained signal reached 24.48 dB, while the mode gain difference was only 0.103 dB; when using 980nm three-mode multiplexed pump to enhance the five-mode multiplexed signal, the average gain of each mode was 23.31 dB, and the mode gain difference was reduced to 0.016 dB. Through the optimization of the pump mode combination and the fiber doping structure, the gain characteristics of the single-mode fiber amplifiers in the C-band four-mode group and five-mode group were significantly improved.

RESEARCH PROGRESS OF INTEGRATED DEVICES

Integrated Devices of Silicon-Based Electro-optic Modulation and Mode Division Multiplexing

This paper introduces a device that integrates the functions of electro-optic modulation based on silicon materials and mode multiplexing[8]. The electro-optic modulation part of this integrated device consists of a photonic crystal waveguide based on silicon materials and a width modulation (WM) type resonator, while the mode multiplexing part adopts an asymmetric parallel nanowire waveguide structure based on silicon materials. To reduce the inter-wavelength coupling loss between the two waveguides, a conical transition structure is designed at the connection point of the photonic crystal waveguide and the nanowire waveguide. By using the time-domain coupling theory and the plasma dispersion effect, the effective control of the TE0 mode is achieved through the WM type resonator and the PN doped structure. Meanwhile, according to the lateral coupling theory, the asymmetric parallel nanowire waveguide can realize the conversion from TE0 mode to TE1 mode. The integrated device is simulated and analyzed using the two-dimensional finite-difference time-domain method (2D-FDTD). The results show that at a modulation voltage of 1.24V, the device can achieve narrowband passband modulation and multiplexing functions for the TE0 mode and TE1 mode when the central wavelength is 1553.91nm. Within the working wavelength range of 1550~1560nm, its insertion loss is less than 0.46dB, the extinction ratio is 19.73dB, the modulation degree is up to 0.9894, the quality factor Q value can reach 1.5×10^4 , and the inter-channel interference is lower than -14.66dB.

Integrated Devices of Electro-optic Modulation and Mode Division Multiplexing

Subsequently, a silicon-based electro-optic modulation and mode multiplexing integrated device based on photonic crystal WM cavities and nanowire waveguides was introduced[9]. In this device, the electro-optic modulator adopted an improved WM cavity design, which belongs to the point-like cavity type. The side-coupled structure was formed by removing one row of air holes from the photonic crystal waveguide. The mode multiplexing part employed an asymmetric directional coupling module composed of single-mode waveguides and multimode waveguides. When the working wavelength was set at 1550 nanometers, this integrated system could first perform electro-optic modulation operation and then complete the multiplexing between TE0 mode and TE1 mode; the insertion losses of the two modes were 0.186 decibels and 0.18 decibels respectively, the extinction ratio reached 29.6 decibels and 24.5 decibels, the inter-channel interference was controlled within the range of -49.57 decibels to -49.12 decibels, and the modulation depth was all 0.999.

THREE-MODE MULTIPLEXED FULL C-BAND TRANSMISSION SYSTEM

Finally, this paper presents the longest case of three-mode multiplexed all-C-band transmission to date, with a transmission distance exceeding 3060 kilometers[10]. This achievement is based on a previously proposed mode arrangement strategy, which can significantly alleviate the modal dispersion effect even in weak-coupling single-mode fiber transmission lines. The paper elaborates on how to utilize the cyclic mode arrangement (CMP) technology to achieve broadband long-distance single-mode fiber transmission. Within each span, the spatial channels are cyclically exchanged to suppress the pulse broadening caused by differential modal delay (DMD). Through CMP technology, DMD-unmanaged long-distance transmission across a 4.4 THz optical bandwidth with DMD unmanagement was achieved on dual-mode single-mode fibers. By using CMP transmission, DMD-induced pulse propagation was suppressed throughout the wavelength/spatial channel range, with a DMD variation range of 33.7 - 44.3 ps/km, thus achieving a 3060-kilometer single-mode fiber transmission with a net capacity of 40.2 Tb/s. Introducing a transmission mode with a strong multimode transmission hybrid mechanism is one method to achieve DMD-unmanaged long-distance mode division multiplexing transmission. This can basically be achieved by using coupled-core multi-core fibers or applying mode mixing technologies (such as long-period grating technology) to single-mode fibers.

OUTLOOK

As the transmission capacity of traditional single-mode optical fibers is gradually approaching the Shannon limit, the development of mode multiplexing (MDM) technology for few-mode fibers has become an important direction in the industry. Currently, the key hardware research on strong-coupling few-mode fiber multiplexing transmission is becoming a hot topic and has achieved significant progress. Advanced strong-coupling mode multiplexing technology has increased the optical fiber transmission capacity by several orders of magnitude. Future research needs to make breakthroughs in the following key areas: developing mode multiplexers and demultiplexers with low insertion loss, high integration, and support for multimode transmission to further enhance the capacity of mode multiplexed optical transmission systems; optimizing the performance of few-mode fiber amplifiers, such as reducing differential mode gain by improving erbium ion doping or adjusting the pump light mode field distribution to achieve uniform amplification of multiple modes; reducing the differential mode group delay of strong-coupling few-mode fibers to ensure simultaneous transmission and efficient reception of all LP modes. In addition, in the field of optical communication system integration, further improvements in the integration level of silicon-based electro-optic modulation mode multiplexing integrated devices are needed to enhance the overall capacity of the entire optical communication network. Through continuous technological innovation, multiplexing technology will play a more important role in future optical communications.

CONCLUSION

This paper reviews the research progress of space division multiplexing technology in the field of optical communication, and demonstrates the key roles played by few-mode fibers, few-mode fiber amplifiers, mode division multiplexers, optical modulators, and some integrated devices in enhancing the transmission performance of optical fibers. The future research directions should focus on developing low insertion loss and highly integrated mode division multiplexing and demultiplexing devices, optimizing the working efficiency of few-mode fiber amplifiers, and improving the overall integration of optical communication systems, thereby further enhancing the capacity and efficiency of the systems.

REFERENCES

1. Pei Li, Li Zhiqi, Wang Jianshuai, etc. Research progress on gain equalisation technology of air division multiplexing optical fibre amplifier [J]. Journal of Optics, 2021, 41(1): 0106001.
2. Wang Manzhuo. Research on key devices of modular multiplexing systems based on PLC platform.
3. Wang Xiao, Zheng Hongjun, Li Xin, Liu Yang, Yu Ruyuan, Bai Chenglin, Hu Jian. New progress in the research of low-mode optical fibre in the modular multiplexing system. Journal of Liaocheng University (Natural Science Edition) 1672-6634 (2019) 02-0069-11
4. Ge D, Zuo M, Zhu J, et al. Analysis and measurement of intra-LP-mode dispersion for weakly-coupled FMF. Journal of Lightwave Technology, 2021, 39(22): 7238-7245

5. Ruan Jiangran, Pei Li, Zheng Jingjing, etc. Gain equalisation of 4-mode erbium-doped optical fibre amplifier based on cladding pump [J]. Journal of Optics, 2022, 42(4): 0406001
6. Xu T, Gao T Y, Wang Y Z, et al. High-gain integrated in-line few-mode amplifier enabling 3840-km long-haul transmission[J]. Photonics Research, 2022, 10(12): 2794-2801
7. Wang Wensheng, Ning Tigang, Pei Li, etc. Low-mode optical fibre amplifier gain equalisation based on genetic algorithm [J]. Journal of Optics, 2021, 41(9): 0906001
8. Xiang Tong, Chen Heming, Hu Yuchen. Silicon-based electro-optical modulation and modularisation multiplexing integrated devices [J]. China Laser, 2021, 48(11): 1106001
9. Li Qi, Chen Heming. Electro-optical modulation and modularisation multiplexing integrated device based on photonic crystal WM cavity and nanowire waveguide [J]. Optical Communication Technology, 2022, 46(6): 10-17
10. Shibahara K, Mizuno T, Kawakami H, et al. Full C-band 3060-km DMD-unmanaged 3-mode transmission with 40.2-Tb/s capacity using cyclic mode permutation[J]. Journal of Lightwave Technology, 2020, 38(2): 514-521