光学学报

32.768 Tbit/s净速率1000 km长少模光纤波分复用系统

雎洲[1]，王晨[1]，王凯辉[1]，丁俊杰[1]，朱博文[1]，沈磊[2]，张磊[2]，王瑞春[2]，闫长鹍[2]，刘博[3]，余建军[1*]

[1]复旦大学信息科学与工程学院，上海 200433；
[2]长飞光纤光缆股份有限公司，湖北 武汉 430073；
[3]南京信息工程大学，江苏 南京 210044

摘要 为了满足日益增长的数据需求，实现“超大容量、超长距离”通信，结合波分复用、偏振复用、模式复用3种复用技术，演示了一个少模光纤传输系统。实验生成符合ITU-T标准的80个通道，利用两个正交偏振及LP11a、LP11b两个模式，在最长达1000 km的少模光纤上传输32 GBaud的16QAM信号。为了减少色散效应和严重的偏振间、模间串扰产生的影响，在接收端数字信号处理(DSP)中，采用基于时域和频域的多输入多输出(MIMO)均衡解复用技术，显著提升系统性能。实验结果表明，经500/1000 km的少模光纤传输，系统的比特误码率(BER)分别能满足7%低密度奇偶校验码(LDPC)硬判决门限(3.8×10^{-3})和25% LDPC软判决门限(4.2×10^{-2})。当少模光纤传输距离为1000 km时，系统实现的净速率为32.768 Tbit/s，属于国内领先水平。

关键词 光通信；少模光纤；波分复用；MIMO均衡；大容量传输；长距离通信

中图分类号 O436 **文献标志码** A **DOI：** 10.3788/AOS222174

1 引言

随着互联网、大数据、人工智能等技术的飞速发展，各行业对信息的需求量呈指数级上升的趋势。与此同时，光纤通信由于高带宽、低损耗等特点，已成为长距离传输的首选技术。然而，传统单模光纤(SMF)的容量日益逼近理论香农极限，即100 Tbit/s，如何进一步提升系统容量以满足逐渐增长的需求成为近年来的研究热点[1-2]。

上述问题的一种解决方案是利用复用技术，包括波分复用(WDM)、偏振复用(PDM)和模式复用(MDM)等。前两者已有较为广泛、成熟的研究，而MDM则是一种基于少模光纤(FMF)或多模光纤(MMF)，以模式为自由度同时独立传输多路信号的技术。尽管FMF比MMF能支持的模式要少，但其各个模式更易于激发，且非线性损伤也比MMF小。因此，在长距离MDM传输时往往采用FMF，更具性价比[3-7]。2011年，Randel等[8]在33 km长FMF中实现了3个模式的同时传输，这使能够提升系统容量的MDM技术开始被学者们关注。2018年，Wakayama等[9]借助少模掺铒光纤放大器(EDFA)实现了6个模式的90.4 km传输，系统总容量达266.1 Tbit/s。2020年，Shibahara等[10]采用循环模式置换技术，在3060 km长的FMF上进行3个模式的长距离传输，速率达40.2 Tbit/s。2021年，Rademacher等[11]实现了13 km长的多芯少模光纤(38核3模)传输，速率可达10.66 Pbit/s，已远远超过SMF的速率极限。近年来，国内也充分关注模式复用光传输系统的研究。2020年，吉林大学相关团队[12]采用光子灯笼技术搭建了具有6个模式的MDM系统，该系统在10 km的FMF上实现了6×8.5 Gbit/s的信号传输。2018年，Wu等[13]用强度调制-直接检测(IMDD)的方式，在WDM的多通道上实现了3×4×10 Gbit/s速率的21 km长OM3光纤传输。中山大学相关团队[14]同样使用WDM-IMDD架构，结合查找表算法，在20 m标准OM2光纤上以1.6 Tbit/s的速率传输了3个模式。2022年，张强等[15]结合PDM技术，用相位调制-相干接收实现了3个模式3×34 Gbit/s速率的FMF传输。可以看出，目前我国在MDM传输领域相较于国外仍处于追赶阶段，原因如下：国内进行的相关实验中能有效利用的模式较少，且光纤长度往往不超过几百千米，难以满足骨干网“超大容量、超长距离”的通信需求；IMDD-MDM系统虽然成本效益较高，但只适配短距离传输的场景，难以有广泛的应用。

收稿日期： 2022-12-23；**修回日期：** 2023-01-13；**录用日期：** 2023-01-29；**网络首发日期：** 2023-02-07

基金项目： 国家科技部重点研发项目(2018YFB1800905)、国家自然科学基金(61935005，61720106015，61835002，62127802)

通信作者： *E-mail：jianjun@fudan.edu.cn

另一方面，尽管采用MDM技术后系统容量可以得到成倍提升，但模式间群速度的差异会使系统中存在差分模式群时延（DMGD），这会导致脉冲的叠加从而形成码间串扰，严重影响通信质量，故需要在接收端用先进的数字信号处理（DSP）技术进行补偿[16]。2011年，Koebele等[17]首次尝试用最小均方误差（LMS）算法代替传统的恒模算法，提升了少模光纤传输的性能。龚思雨等[18]研究了MDM系统中的模式依赖损耗，采用自适应算法进行快速信道补偿以降低系统的误码率。2021年，朱子岳等[19]更是尝试将基于神经网络的均衡技术引入FMF传输系统，这为未来发展提供了可能的方向[20-21]。

本文利用先进DSP算法，演示了一个长距离、大容量的少模光纤传输实验。该SMF-MDM系统结合了WDM和PDM技术，在80个波长通道的两个偏振方向上传输了具有LP11a和LP11b两个模式的32 GBaud 16QAM信号，并进行零差相干接收。接收端DSP中的核心是基于时域（TD）和频域（FD）的多输入多输出（MIMO）均衡解复用技术，该技术能够有效补偿信道间的多种串扰，提升系统性能。实验结果表明，在经过500/1000 km的FMF传输后，系统的比特误码率（BER）能分别满足3.8×10^{-3}的低密度奇偶校验码（LDPC）硬判决门限和4.2×10^{-2}的LDPC软判决门限要求。在FMF传输总长为1000 km时，系统的净速率可达32.768 Tbit/s，无论是传输距离还是系统容量均属于目前国内领先水平。

2 实验系统

本实验采用能传输6个模式的强耦合渐变型FMF，其具体参数和折射率分布分别如表1和图1所示。由于LP11的损耗最低，选择传输LP11a和LP11b两个简并模式。

表1 实验所用的少模光纤参数

Table 1 Parameters of the FMF used in the experiment

Parameter	Value
Loss / (dB·km^{-1})	LP01：0.208 LP11：0.202 LP21：0.207
Differential group delay / (ps·m^{-1})	LP01-LP11：0.40 LP11-LP21：0.11
Length of single roll / km	50
Dispersion coefficient / (ps·nm^{-1}·km^{-1})	LP01：21.25 LP11：21.01 LP21：19.50 LP02：20.29
Effective area / nm^2	LP01：90 LP11：121 LP21：159 LP02：161

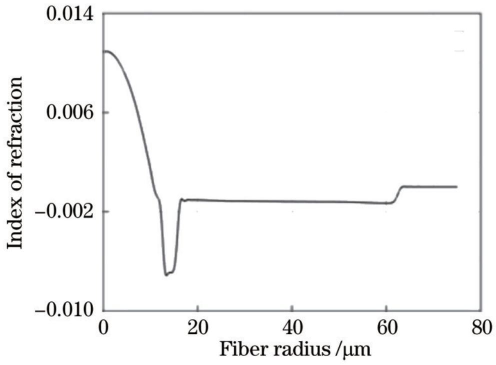

图1 FMF的折射率分布

Fig. 1 Refractive index distribution of the FMF

所采用的长距离大容量少模光纤传输实验装置和DSP算法的流程如图2所示。在发射端，首先通过Matlab软件生成码长为2^{13}的伪随机二进制序列，将其每4比特映射成一个16QAM符号，并在两倍上采样之后，通过根升余弦（RRC）滤波器来实现基带成型。两组（奇数路和偶数路各为一组）40个频率间隔为100 GHz的外腔激光器（ECL）输出共80路50 GHz间隔的光载波，波长范围为1530～1562 nm，符合ITU-T标准C20～C59与H20～H59信道的要求，每个波长通道输出的光功率为13 dBm。之后，将Matlab软件生成的数字基带信号重采样后加载至采样率为64 GSa/s的任意波形发生器（AWG），转换为两路电信号，用于驱动IQ调制器对两组光载波进行调制，该IQ调制器的3 dB带宽为29 GHz。调制后的光信号经偏振光分束器（PBS）分成正交的X、Y偏振两路，在保偏光纤中传输。同时，为了复用时去除不同偏振间的相关性，其中一路信号会额外经过一段1 m长的延迟线。偏振光合束器（PBC）将两个偏振光合为一路；而1×2耦合器耦合奇数路和偶数路的信号，使它们能够一起被一个EDFA放大；另一个1×2耦合器将经EDFA放大后的光信号分成不同的两路，以分别进行模式复用。同样地，为了复用时去除不同模式间的相关性，其中一路光在复用前会额外经过一段3 m长的延迟线。声光调制器（AOM）在此起到了光开关的作用，用于控制光学循环器的输入信号。两路独立的双偏振信号在模式复用器内被分别调制成LP11a和LP11b模式，即共有LP11a. X、LP11b. X、LP11a. Y、LP11b. Y四路数据，它们共同在50 km长的少模光纤中进行传输。需要指出，本实验采取循环跨段的环路结构来实现长距离（1000 km）的少模光纤传输，上述50 km光纤即为循环基元。每经过一次50 km传输系统都将进行模式解复用，以便各模式独立用单模EDFA来补偿传输损耗，EDFA的输出功率皆为23 dBm。另外，本实验采用波长选择开关（WSS）来尝试抑制EDFA高输出功率下产生的非线性功率转移与增益不平坦。WSS有5 dB的插入损耗，最小可调间距为50 GHz，其输出的两路

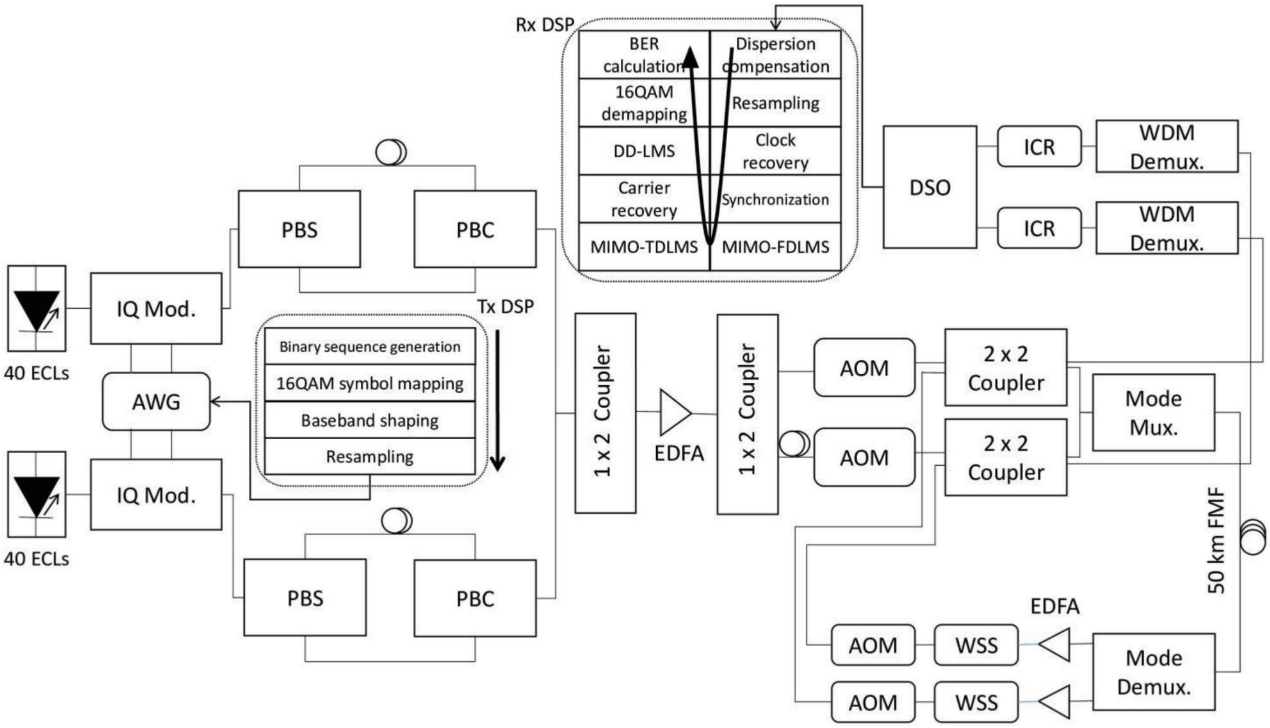

图2 实验装置及DSP流程

Fig. 2 Experimental setup and DSP block diagram

信号将重新进行模式复用，进入下一次循环，直至光纤传输距离满足要求。

在接收端，相干光接收机将对波分解复用后选出的光信号进行零差检测（接收功率控制在−5 dBm左右，以防止非线性），产生的基带电信号被采样率为80 GSa/s的同步8通道示波器捕获，以进行离线DSP处理，示波器的带宽为33 GHz。

接收端DSP的流程如下：首先，在频域内对接收信号进行色散补偿；在经过重采样后，再进行时钟恢复以消除定时误差，本实验采取的是平方定时估计算法，故重采样时保留了四倍信号速率；之后便是整个流程的核心，即数据辅助的MIMO-T/2-FDLMS（802抽头）和MIMO-TDLMS（401抽头）均衡解复用。为了得到训练用的数据及其对应的标签，需要先进行信号的同步。MIMO均衡解复用的输出在依次经过盲相位搜索、判决辅助最小均方（DDLMS）算法（401抽头）后，即可进行16QAM符号解映射与最后的BER计算[22-23]。

3 核心算法——MIMO均衡解复用

3.1 必要性

在所提出的实验系统中，由于结合了三种复合方式，即WDM、PDM和MDM，串扰十分严重且种类繁多，每一路接收信号都会包含其他路上的信息。经1000 km光纤传输后，色散与不同模式和偏振态间的串扰将会严重影响信号的恢复，降低接收灵敏度。因此，需要将两个模式的两个偏振态上的数据，即$2\times2=4$路信号放在一起进行信道均衡，进而恢复出每一路上的数据，完成解复用，故称MIMO均衡解复用。

值得注意的是，MIMO均衡解复用算法是需要训练数据的，虽然引入了额外开销，但相比盲均衡算法，能取得较大的性能提升。为了能有更好的训练效果，在进行MIMO-TDLMS与MIMO-FDLMS算法前先完成了频域色散补偿、时钟恢复等操作，以提升同步出来的训练帧的质量。

3.2 MIMO-TDLMS

MIMO-TDLMS算法的具体流程如图3所示。

MIMO-TDLMS算法是基于时域模型的。在本实验中，四路输入信号通过一滤波器组后产生对应的四路输出信号，该滤波器组共包含$4\times4=16$个FIR（finite impulse response）滤波器，其抽头系数由LMS算法训练产生。每一路输入和每一路输出之间都会训练一个FIR滤波器，使最终四路输入信号的某种加和形式能去逼近一路应有的输出，这非常符合本实验系统中串扰的模型。在训练过程中，用于计算误差的训练标签是事先准备好的；在测试过程中，标签则直接使用距离当前输出最近的那个16QAM星座点。

3.3 MIMO-FDLMS

MIMO-FDLMS与MIMO-TDLMS的主要思路相同，但它是基于频域的。与TDLMS相比，FDLMS的算法复杂度较低，且运行速度更快。算法首先将输入的待均衡信号分块，并进行快速傅里叶变换（FFT）从而转换到频域上进行操作，该分块的窗长及其滑动步长需要根据实际效果进行调整与选择。为了提高计

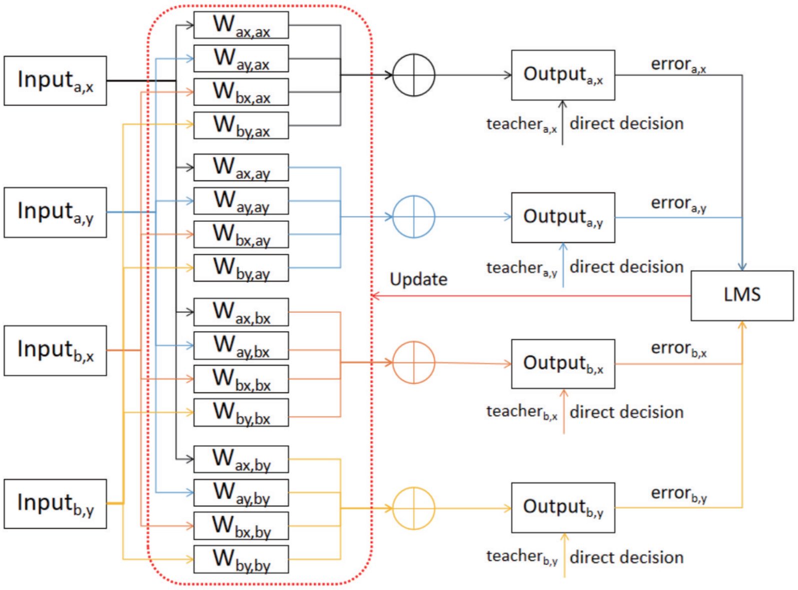

图 3　MIMO-TDLMS 算法的流程

Fig. 3　Flowchart of MIMO-TDLMS algorithm

算的精度，本实验对输入数据先进行了两倍上采样，拆成奇数路和偶数路分别进行后续的块操作，因此该算法也称为 MIMO-T/2-FDLMS。滤波器的抽头数与分块长度适配，相关的计算也转换到频域进行。算法的频域输出是对应的 8 组输入与滤波器系数（两个模式×两个偏振态×奇偶两路）相乘求和得到的，而时域输出则是对上述频域结果进行快速傅里叶逆变换（IFFT）得到的，共 4 路。至于权重的训练，仍采用 LMS 算法，标签的选取原则与误差的计算也与 MIMO-TDLMS 相同，只不过均需转变到频域上进行块处理。MIMO-T/2-FDLMS 算法的具体流程如图 4 所示。

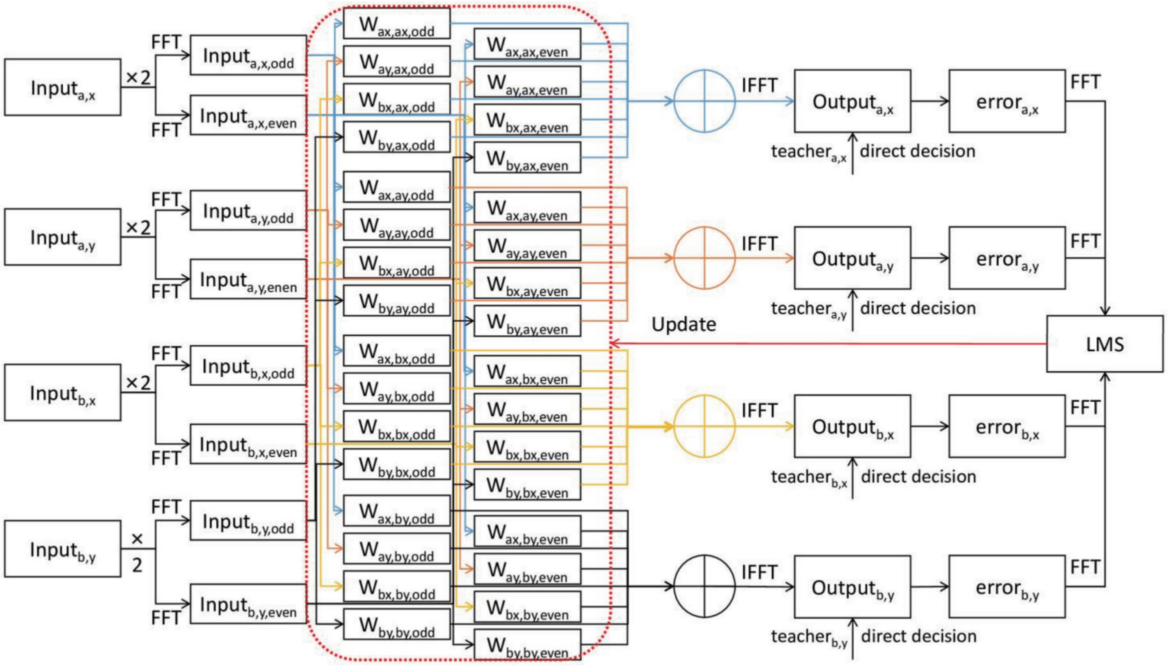

图 4　MIMO-T/2-FDLMS 算法的流程

Fig. 4　Flowchart of MIMO-T/2-FDLMS algorithm

4　实验结果与分析

需要注意，若给出某一模式的 BER 而没有说明是哪个偏振时，则指的是该模式在 *X*、*Y* 两个偏振态上 BER 的平均值。

图 5 给出了背靠背（BTB）情形下接收信号的光

谱。可以看到，实验共产生了80个间距为50 GHz的WDM信道，且相邻信道的光信噪比（OSNR）之差小于1 dB，平坦度较好。然而，随着FMF传输距离的增加，串扰不断累计，信道OSNR的平坦度将会逐渐变差。

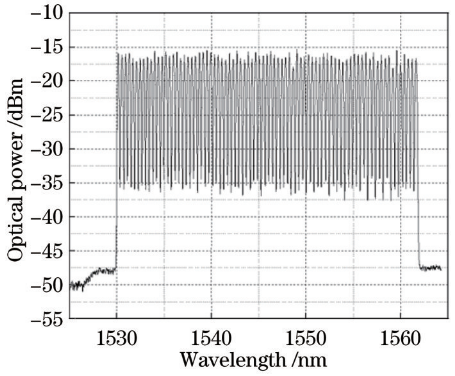

图5 BTB情形下接收信号的光谱

Fig. 5 Optical spectrum of the received signal under BTB circumstance

图6给出了实验传输的LP11a和LP11b模式在不同OSNR下的BER曲线，并给出了加性高斯白噪声（AWGN）信道下的性能以供参考。随着OSNR的增加，偏振串扰和模式串扰逐渐成为噪声中的主导因素，若不能有效解除，便会出现如图6所示BER与理论值的差距越来越大的情况。若取BER为0.01作参考，实验信道与AWGN信道有约2.5 dB的灵敏度差异，可见系统还有一定提升空间。

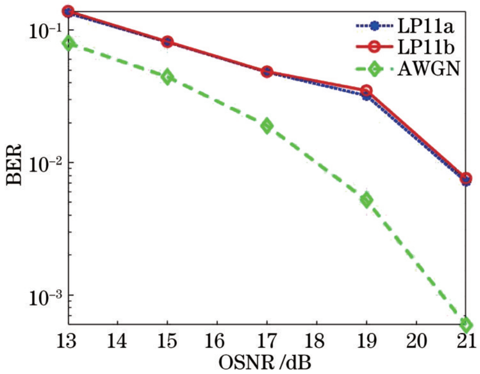

图6 不同OSNR下LP11a和LP11b模式的误码率

Fig. 6 BER of LP11a and LP11b under different OSNR

实验还测量了经过1000 km少模光纤传输后，所有80个信道的误码性能（所有信道的BER均低于2×10^{-2}），图7具体给出了其中13个信道（C25～C37）上两个模式的BER曲线。可以发现，信道间的BER有所起伏，这主要是经多次环路传输和EDFA放大后光谱具有不平坦性导致的。另一方面，同一信道不同模式的BER相差不大，这是由于LP11a和LP11b模式的有效折射率很接近，在同一条件下性能差距不大。

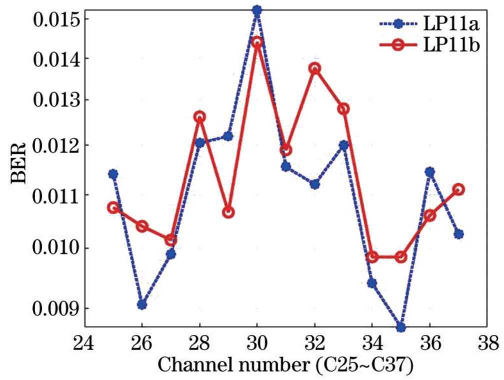

图7 C25～C37通道经1000 km FMF传输后的误码性能

Fig. 7 BER performance of channel C25-C37 after 1000 km FMF transmission

最后，分别测试了C30通道在BTB、光纤传输距离为250，500，750，1000 km的情形下，两种模式的BER（E）性能，如图8所示。图9为传输距离为1000 km时C30信道最终恢复出的4路数据的星座图。随着传输距离的提升，LP11a和LP11b模式的BER逐渐增大，但模式间的差异很小。当传输距离达500 km时，两个模式的BER都能满足LDPC硬判决门限（3.8×10^{-3}@7% HD-FEC）；当传输距离达1000 km时，BER则远远低于软判决门限（4.2×10^{-2}@25% SD-FEC）。由此，所提系统可以通过编码实现80通道两模式双偏振32 GBaud 16QAM信号的无误码传输，总净速率为传输500 km时的$32\times4\times2\times2\times80/(1+0.07)=38.28$ Tbit/s，传输1000 km时的$32\times4\times2\times2\times80/(1+0.25)=32.768$ Tbit/s。

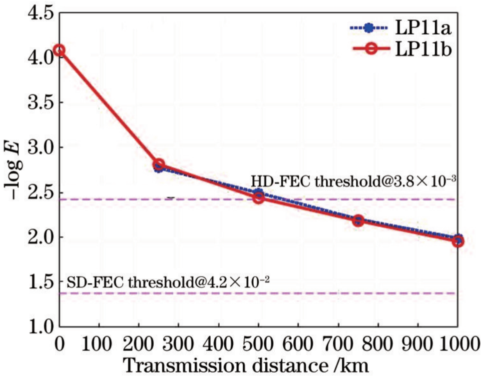

图8 不同传输距离下的BER性能

Fig. 8 BER performance at different transmission distances

5 结论

结合了波分复用、模式复用和偏振复用3种复用技术，并在接收端采用MIMO-TDLMS与MIMO-FDLMS均衡解复用算法，最终实现了80通道两模式双偏振32 GBaud 16QAM信号的后FEC无误码传输。所提WDM-PDM-MDM系统在FMF传输总长为1000 km时可实现的总净速率为32.768 Tbit/s，无论

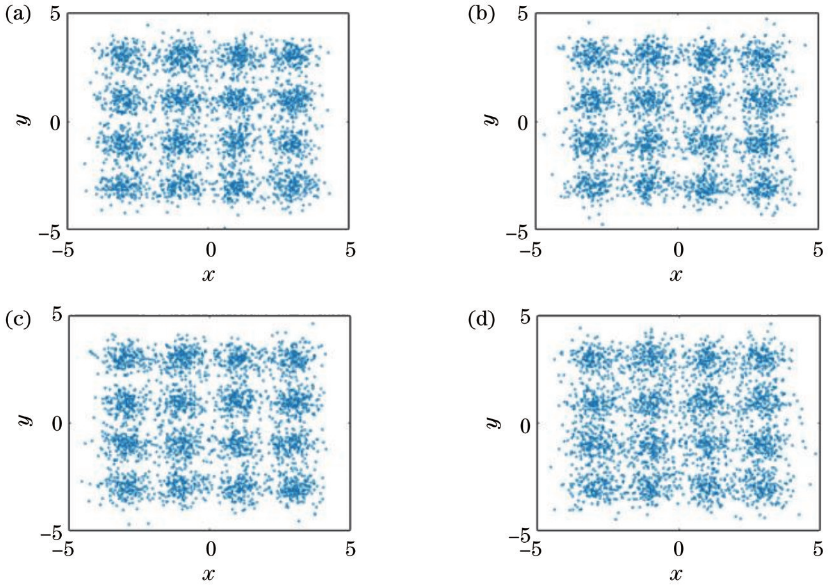

图9　经1000 km FMF传输后C30信道恢复出的星座图。(a) LP11a. X；(b) LP11a. Y；(c) LP11b. X；(d) LP11b. Y

Fig. 9　Constellation diagrams recovered from C30 channel after 1000-km FMF transmission. (a) LP11a. X; (b) LP11a. Y; (c) LP11b. X; (d) LP11b. Y

是传输距离还是系统容量，在国内少模光纤领域均属于领先水平。

参 考 文 献

[1] 余建军，迟楠．高速光纤通信中数字信号处理算法原理与应用：第一卷：I：单载波调制技术（著）[M]．北京：清华大学出版社，2017.
Yu J J, Chi N. Digital signal processing in high-speed optical fiber communication principle and application (I): single carrier modulation[M]. Beijing: Tsinghua University Press, 2017.

[2] Yu J J, Wu Y. High-speed optical fiber communication in China [J]. ACS Photonics, 2022: 01480.

[3] 王芳璧．少模光纤模分复用系统均衡技术的研究[D]．成都：电子科技大学，2020.
Wang F B. Research on equalization technology of mode division multiplexing system based on few mode fiber[D]. Chengdu: University of Electronic Science and Technology of China, 2020.

[4] Gnauck A H, Tkach R W, Chraplyvy A R, et al. High-capacity optical transmission systems[J]. Journal of Lightwave Technology, 2008, 26(9): 1032-1045.

[5] Rademacher G F, Puttnam B J, Luis R S, et al. Ultra-wide band transmission in few-mode fibers[C]//2021 European Conference on Optical Communication (ECOC), September 13-16, 2021, Bordeaux, France. New York: IEEE Press, 2021.

[6] 涂佳静，李朝晖．空分复用光纤研究综述[J]．光学学报，2021，41(1): 0106003.
Tu J J, Li Z H. Review of space division multiplexing fibers[J]. Acta Optica Sinica, 2021, 41(1): 0106003.

[7] 毋桐，田凤，杨雷静．基于概率成形和交织编码的少模光纤传输系统[J]．光学学报，2022，42(7): 0706006.
Wu T, Tian F, Yang L J. Few-mode fiber transmission system based on probability shaping and interleaved encoding[J]. Acta Optica Sinica, 2022, 42(7): 0706006.

[8] Randel S, Ryf R, Sierra A, et al. 6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization[J]. Optics Express, 2011, 19(17): 16697-16707.

[9] Wakayama Y, Soma D, Beppu S, et al. 266.1-Tbit/s repeatered transmission over 90.4-km 6-mode fiber using dual C+L-band 6-mode EDFA[C]//2018 Optical Fiber Communications Conference and Exposition (OFC), March 11-15, 2018, San Diego, CA, USA. New York: IEEE Press, 2018.

[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.

[11] Rademacher G, Puttnam B J, Luís R S, et al. Highly spectral efficient C L-band transmission over a 38-core-3-mode fiber[J]. Journal of Lightwave Technology, 2021, 39(4): 1048-1055.

[12] 张强，郭玉彬，陈嘉轲，等．基于相位调制-相干检测的模分复用通信实验[J]．中国激光，2020，47(3): 0306001.
Zhang Q, Guo Y B, Chen J K, et al. A communication experiment using mode division multiplexing with phase modulation-coherent detection[J]. Chinese Journal of Lasers, 2020, 47(3): 0306001.

[13] Wu Z Y, Li J H, Tian Y, et al. 3×4×10-Gb/s MDM-WDM transmission over 21-km OM3 MMF with OOK modulation and direct detection[C]//Optical Fiber Communications Conference and Exposition, March 11-15, 2018, San Diego, California, USA. Washington, D. C.: Optica Publishing Group, 2018: W4J.3.

[14] Zou D D, Li F, Wang W, et al. Beyond 1.6 Tb/s net rate PAM signal transmission for rack-rack optical interconnects with mode and wavelength division multiplexing[J]. Journal of Lightwave Technology, 2021, 39(2): 340-346.

[15] 张强，韩伟，熊振，等．基于少模光纤的3×34 Gb/s PDM-QPSK信号模分复用实验[J]．光通信技术，2022，46(1): 77-80.
Zhang Q, Han W, Xiong Z, et al. 3×34 Gb/s PDM-QPSK signal mode division multiplexing experiment based on few-mode fiber[J]. Optical Communication Technology, 2022, 46(1): 77-80.

[16] 谢意维，付松年，张海亮，等．少模光纤模式差分群时延的设计与优化[J]．光学学报，2013，33(9): 0906010.
Xie Y W, Fu S N, Zhang H L, et al. Design and optimization of mode differential group delay for few-mode fiber[J]. Acta Optica Sinica, 2013, 33(9): 0906010.

[17] Koebele C, Salsi M, Sperti D, et al. Two mode transmission at 2×100 Gb/s, over 40 km-long prototype few-mode fiber, using LCOS-based programmable mode multiplexer and demultiplexer

[J]. Optics Express, 2011, 19(17): 16593-16600.

[18] 龚思雨, 张建勇. 具有模式依赖损耗的模分复用系统的动态信道补偿特性[J]. 光学学报, 2020, 40(23): 2306006.
Gong S Y, Zhang J Y. Dynamic channel-compensation characteristics of MDM system with mode-dependent loss[J]. Acta Optica Sinica, 2020, 40(23): 2306006.

[19] 朱子岳, 赵梦鑫, 张一尘, 等. 高速IM-DD模分复用通信系统中基于神经网络的MIMO均衡技术[J]. 光学学报, 2021, 41(14): 1406003.
Zhu Z Y, Zhao M X, Zhang Y C, et al. MIMO equalization technology based on neural network in high-speed IM-DD mode division multiplexing transmission system[J]. Acta Optica Sinica, 2021, 41(14): 1406003.

[20] Sang B H, Zhang J, Wang C, et al. Multi-symbol output long short-term memory neural network equalizer for 200 gbps IM/DD system[C]//2021 European Conference on Optical Communication (ECOC), September 13-16, 2021, Bordeaux, France. New York: IEEE Press, 2021.

[21] 余建军, 迟楠. 高速光纤通信中数字信号处理算法原理与应用(第二卷): 多载波调制和人工智能新技术[M]. 北京: 清华大学出版社, 2018.
Yu J J, Chi N. Digital signal processing in high-speed optical fiber communication principle and application (II): multi-carrier modulation and artificial intelligence[M]. Beijing: Tsinghua University Press, 2018.

[22] 余建军, 迟楠, 陈林. 基于数字信号处理的相干光通信技术[M]. 北京: 人民邮电出版社, 2013.
Yu J J, Chi N, Chen L. Coherent optical communication technology based on digital signal processing[M]. Beijing: Posts & Telecom Press, 2013.

[23] Kong M, Li X Y, Zhang J, et al. High spectral efficiency 400 Gb/s transmission by different modulation formats and advanced DSP[J]. Journal of Lightwave Technology, 2019, 37(20): 5317-5325.

1000-km-Long Few-Mode Fiber Wavelength Division Multiplexing Transmission System with Net Rate of 32.768 Tbit/s

Ju Zhou[1], Wang Chen[1], Wang Kaihui[1], Ding Junjie[1], Zhu Bowen[1], Shen Lei[2], Zhang Lei[2], Wang Ruichun[2], Yan Changkun[2], Liu Bo[3], Yu Jianjun[1*]

[1]*School of Information Science and Technology, Fudan University, Shanghai* 200433, *China*;
[2]*Changfei Optical Fiber and Cable Joint Stock Limited Company, Wuhan* 430073, *Hubei, China*;
[3]*Nanjing University of Information Science & Technology, Nanjing* 210044, *Jiangsu, China*

Abstract

Objective With the rapid development of technologies, such as the Internet and artificial intelligence, there has been an exponential increase in the demand for data from all areas of life. However, the capacity of traditional single-mode fiber (SMF) networks is approaching the Shannon limit. Consequently, several multiplexing technologies, including wavelength division multiplexing (WDM), polarization division multiplexing (PDM), and mode division multiplexing (MDM), have been explored to meet the growing data demand. In MDM, using few-mode fiber (FMF) for long-distance transmission is more cost effective than using multimode fiber (MMF) because of the lower nonlinear impairment. Moreover, MDM introduces severe crosstalk between different modes, which must be compensated for by advanced DSP algorithms on the receiver side. In China, most ongoing studies on MDM transmission employ the intensity modulation direct detection (IMDD) method, which is suitable for only short-distance transmissions. The number of modes that can be effectively exploited is also too small, making it difficult to achieve "ultrahigh-capacity" communication. In this study, we developed a high-capacity long-distance FMF transmission system that combines WDM, PDM, and MDM technologies. Eighty channels that satisfy the ITU-T standard are generated, and 32-GBaud 16QAM signals are transmitted up to 1000-km FMF on dual polarization and two modes (LP11a and LP11b). Multiple input multiple output(MIMO) equalization demultiplexing algorithms based on time domain (TD) and frequency domain (FD) are adopted, which can greatly improve system performance. For a transmission distance of 1000 km, the net data rate reaches 32.768 Tbit/s, which is the highest recorded rate in China.

Methods In this experiment, we used strong coupling graded-index FMF that can support the transmission of six modes and we chose two degenerate modes, including LP11a and LP11b. At the transmitter side, 80 external cavity lasers generate 1530-1562 nm light waves with a 50-GHz frequency spacing. The digital baseband signal is generated with Matlab and then loaded into an arbitrary waveform generator to modulate the optical carriers through an IQ modulator. Polarization-beam splitters and combiners are used to conduct PDM so that the signal can be divided into two parts with orthogonal polarization of *X* and *Y*. After being boosted by an erbium-doped optical fiber amplifier (EDFA), two independent dual polarization signals are modulated into LP11a and LP11b modes through a mode multiplexer and then transmitted over a reel of 50-km FMF. Thereafter, mode demultiplexing is performed so that single-mode EDFAs can compensate for the transmission loss for each mode. Wavelength selective switches (WSS) are employed to solve the problem of the uneven gain of EDFAs. We adopted a loop structure to realize long-distance transmission. Thus, the output of WSS is sent back into the mode multiplexer to perform MDM and 50-km FMF transmission again until the total transmission distance meets our requirement. At the Rx side, the coherent optical receiver conducts homodyne detection on the selected signal after wavelength division demultiplexing. In the offline DSP, the captured electrical signal is mainly processed by dispersion compensation, clock recovery, MIMO equalization demultiplexing based on the least mean square (LMS) algorithm, carrier recovery, detection-directed least mean square algorithm, and, finally, BER calculation. Among them, MIMO-TDLMS and MIMO-FDLMS are the core parts. MIMO equalization creates a filter between each input and output. Since our proposed system uses three multiplexing technologies, every path of the received signal can contain information from other paths due to the crosstalk between different polarizations and modes, which well fits the characteristics of the MIMO model. The coefficients of the filters are trained using the LMS algorithm. For MIMO-FDLMS, fast Fourier transform is applied to the TD signal so that the algorithm can perform block processing in the FD, which is more efficient.

Results and Discussions Fig. 5 shows the optical spectrum of the received signal in BTB circumstance. It shows that 80 channels with a 50-GHz frequency spacing were successfully generated, and the optical signal-to-noise ratio (OSNR) difference between the adjacent channels is below 1 dB. The BER performance of the LP11a and LP11b modes under different OSNR values was evaluated, as shown in Fig. 6. With an increase in OSNR, the crosstalk between different polarization and modes became the dominant factor of noise, and the performance of our system still differs from that of theoretical AWGN channels. Furthermore, we calculated the BER of the 80 WDM channels after 1000-km FMF transmission, and all of them are below 2×10^{-2}. Due to the uneven spectrum after several times of loop transmissions and EDFA amplification, the BER of different channels was unstable. Meanwhile, the BER values of different modes in the same channel were slightly different. This is because the refraction indices of LP11a and LP11b are comparable. Finally, Fig. 8 shows the BER performance under different FMF transmission distances. The BER increased with an increase in fiber length. After 500/1000-km FMF transmission, the BER of the LP11a and LP11b modes can meet the 7% HD-FEC threshold of 3.8×10^{-3} and the 25% SD-FEC threshold of 4.2×10^{-2}, respectively.

Conclusions In this study, we developed a WDM-PDM-MDM transmission system, in which 32-GBaud 16QAM signals can be transmitted over 1000-km FMF on dual polarization and LP11a and LP11b modes in 80 WDM channels. Using MIMO-TDLMS and MIMO-FDLMS algorithms in the offline DSP, the dispersion effect and the crosstalk between different polarizations and modes can be effectively compensated for. At an FMF transmission distance of 500 km, the BER can meet the 7% HD-FEC threshold of 3.8×10^{-3}, and the corresponding net data rate is $32\times4\times2\times2\times80/(1+0.07)=38.28$ Tbit/s. At an FMF transmission distance of 1000 km, the BER can meet the 25% SD-FEC threshold of 4.2×10^{-2}, and the corresponding net data rate is $32\times4\times2\times2\times80/(1+0.25)=32.768$ Tbit/s. This is a record-breaking result in China for both the net data rate and the transmission distance in an FMF MDM system. The proposed system is, thus, a promising candidate for future "ultrahigh-capacity, ultralong-distance" communication.

Key words optical communication; few-mode fiber; wavelength division multiplexing; MIMO equalization; ultrahigh-capacity transmission; ultralong-distance communication