

基于外差相干探测的极化复用 16QAM 信号双模式 1000 km 少模光纤传输系统

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摘要 为了解决通信容量不足以及非线性损伤问题,基于正交相位(IQ)调制外差相干探测,利用极化复用技术、模分复用技术以及先进的数字处理算法,搭建了单通道模分复用少模光纤传输系统,并成功实现了波特率为 32 Gbaud 的 16 正交振幅调制(QAM)信号在两个兼并模 LP11a 和 LP11b 模式下的 1000 km 传输。使用时域和频域多输入多输出最小均方(MIMO-LMS)算法进行均衡处理后,误码率(BER)低于软判决前向纠错(SD-FEC)的阈值(5.2×10^{-2})。

关键词 光通信; 光纤通信; 模分复用; 少模光纤; 极化复用; 长距离传输

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1 引言

随着光纤通信的发展,光纤传输系统的容量一直在增长。然而,由于互联网流量的快速增长,人们对大传输容量的需求也急剧增加。而目前光纤传输系统中单模光纤(SMF)的传输容量受制于香农极限定理,正在迅速接近极限,如何解决传输容量问题成为当务之急,新技术的发展迫在眉睫。解决此问题的一种方法是应用空分复用(SDM)技术,例如使用多芯光纤(MCF)或使用多输入多输出(MIMO)技术。然而,为了在传输系统中使用多芯光纤,需要利用精确的耦合技术耦合进入和离开多芯光纤的每个通道的功率。此外,紧密分布的纤芯产生的串扰也限制了多芯光纤的性能。应用 SDM 技术的另一种方法是在多模光纤(MMF)中进行 MIMO 信号处理。多模光纤可以支持数十甚至上百种传输模式,但是模式之间的色散严重,非线性损伤较大,长距离传输时效果较差。少模光纤(FMF)支持的模式数目介于单模光纤和多模光纤之间,少模光纤与单模光纤相比有较多的传输信道,与多模光纤相比有较小的模间色散,少模光纤在长距离光纤通信中更有应用潜力^[1-3]。

2017 年,日本大阪大学演示了一个 10 模多路传输实验,成功在长度为 81 km 的弱耦合少模光纤上传输了波特率为 10 Gbaud 的差分正交相移键控(DP-

QPSK)波分复用(WDM)信号,使用多输入多输出(MIMO)均衡器,降低了接收机数字信号处理(DSP)的复杂度^[4]。2018 年,日本 KDDI 电信公司采用 19 芯 6 模多芯少模光纤(19C-6M-FM-MCF),实现了单信道接近 100 Tbit·s⁻¹ 的传输速率,不过传输距离仅为 11.3 km^[5]。2019 年,日本国家信息与通信研究院采用 38 芯 3 模多芯少模光纤(38C-3M-FM-MCF),实现了单根光纤大于 10 Pbit·s⁻¹ 的通信传输速率,传输距离为 3.37 km^[6]。2021 年,日本国家信息与通信研究院与贝尔实验室采用少模光纤,实现了空分复用的高容量和长距离传输^[7];次年,该研究团队基于之前的研究,采用 3 模少模光纤,实现了波特率为 8.575 Tbaud 的 16 正交振幅调制(QAM)信号在 C 和 L 波段的传输,传输距离为 1100 km^[8]。

国内研究机构也对模分复用技术进行了研究。2017 年,吉林大学采用强度调制-直接检测的方式,在长度为 10 km 的少模光纤中实现了 3 个模式传输速率为 4.25 Gbit·s⁻¹ 的复用传输^[9];2018 年,上海大学采用正交频分复用强度调制-直接检测的方式,在长度为 50 m 的光模式(OM)多模光纤中实现了传输速率为 7.2 Gbit·s⁻¹ 的信号复用传输^[10];2018 年,北京大学采用强度调制-直接检测的方式,在长度为 10 km 的少模光纤中实现了 4 个模式传输速率为 10 Gbit·s⁻¹ 的复用传输^[11];2021 年,上海大学在强度调制-直接检测场景

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中引入基于神经网络的 MIMO 均衡技术,实现了传输速率为 200 Gbit·s⁻¹ 的模分复用传输,单通道速率为 100 Gbit·s⁻¹[12];2022 年,北京邮电大学研究了概率成型与交织编码对信号传输性能的影响,经过 50 km 长的六模光纤传输,传输距离得到延长[13]。可以看出,目前国内在模分复用领域中仍处于追赶的阶段,主要采用强度调制-直接检测方式搭建系统,无法满足高速度、超长距离的使用需求,且目前所研究的模分复用系统利用的模式数量较少,对通信系统容量的提升效果有限。

本文使用先进的数字信号处理技术作为信道均衡和色散补偿的方法,采用正交相位(IQ)调制/外差相干探测的方式,使用极化复用和空分模式(两模)复用技术,进行了单通道双模式极化复用 16QAM 信号 1000 km 传输实验,净速率为 400 Gbit·s⁻¹。据我们所知,这是国内传输距离最长的极化复用少模光纤传输系统。同时,采用外差相干探测减少了模数转换器(ADC)或示波器通道数,对于 2 个模式的外差相干接收,只需要采用 4 个通道就能够实现信号的同时相干接收[14-17]。

2 实验装置

单通道 1000 km 少模光纤传输系统装置图如图 1 所示,使用外腔激光器(ECL)生产光信号(线宽小于 100 kHz,输出光功率为 13 dBm),然后将产生的连续光波通过 IQ 调制器(3 dB 带宽为 30 GHz,插入损耗小于 8 dB),利用 16QAM 信号进行调制。加载到任意波

形发生器(AWG)上的 16QAM 信号由 MATLAB 离线产生,AWG 的取样速率为 64 GSa·s⁻¹。在 MATLAB 中生成一段长度为 2¹³ 的伪随机二进制码,将其调制为 16QAM 格式,对调制后的 16QAM 信号进行两倍上采样后,通过根升余弦(RRC)滤波器完成基带成型,然后分为 I 路和 Q 路驱动 IQ 调制器。调制信号通过偏振光分束器(PBS)等分成偏振正交的两路,并在保偏光纤中传输,其中一路经过一段长度为 1 m、延时 5 ns 的延时线进行解相关,并与另一路通过偏振合束器(PBC)合路,完成极化复用。极化复用后的信号在掺铒光纤放大器(EDFA)中放大,并通过 1×2 耦合器等分成两路,其中一路经过长度为 3 m、延时 15 ns 的延时线进行解相关,然后注入到光纤链路中进行传输。光纤链路采用环路系统,环路开关由两个声光调制器(AOM)控制,通过设置 AOM 的通断时间,控制复用信号在环路或环形器(LOOP)中的传输圈数,实现目标传输距离。信号通过模式复用模块分别被调制成 LP11a 和 LP11b 模式,两种模式的信号共同在少模光纤中传输。少模光纤的损耗为 0.202 dB·km⁻¹,在两种模式中的色散系数都为 21.01 ps·(nm·km)⁻¹,LP11 模式下的有效面积为 121 nm²,由于传输的是简并模,因此没有差分群时延的影响。每个模式在各自 LOOP 中的传输距离控制在 0.1 m 范围内。信号通过少模光纤后进入模分解复用模块进行解模式复用,解复用后的两种模式信号分别通过 EDFA 进行补偿放大,同时每一个模式信号的光功率得到平衡。由于 AOM 开关以及耦合器存在插入损耗,因此信号进入光纤环路后

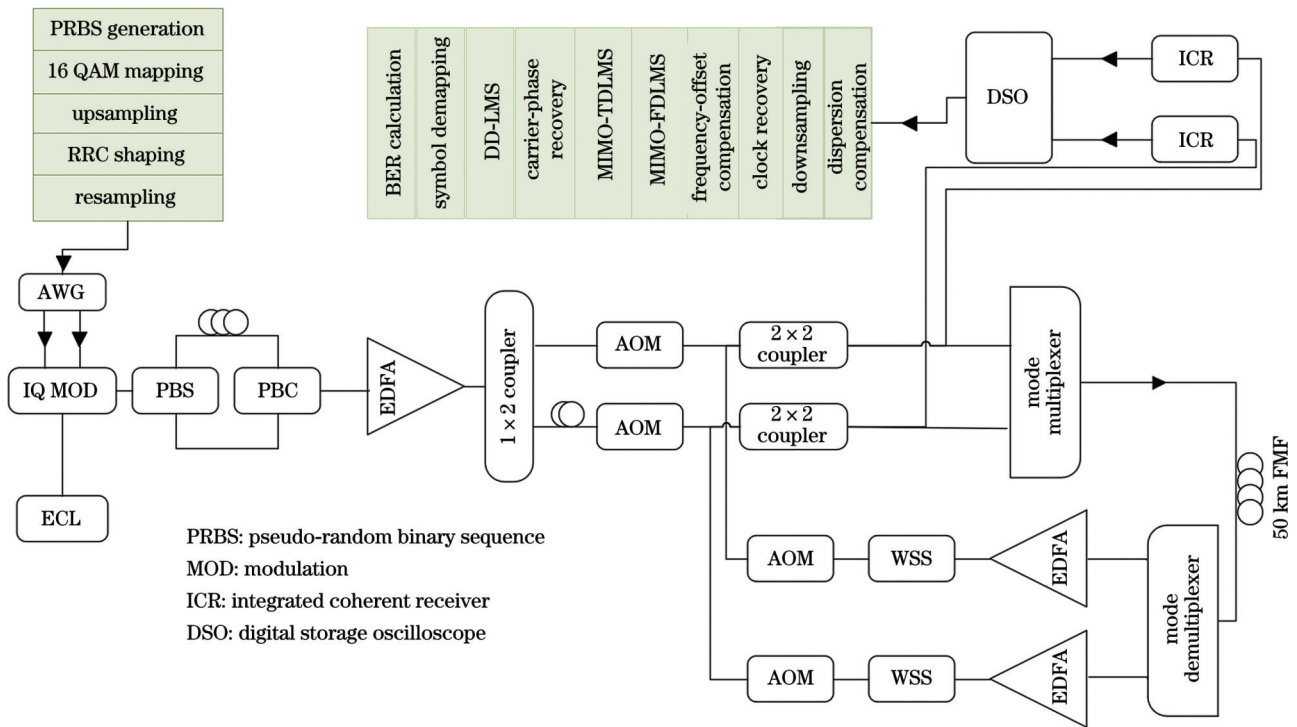


图 1 实验装置及 DSP 流程
 Fig. 1 Experimental setup and DSP process

需要通过 EDFA 进行放大。波长选择开关(WSS,最大插入损耗为 5 dB)用于滤除带外放大器自发辐射噪声(ASE),防止能量在波长通道中泄漏,并对增益谱进行整形。通过声光调制器完成一个跨段的传输,之后信号进入下一个 LOOP,信号在每个 LOOP 中通过一段长度为 50 km 的少模光纤,通过不同的圈数后相干接收机对调制信号进行外差检测,相干接收机的接收功率控制在 -5 dBm 左右,以防止非线性的产生。最后通过采样率为 80 GSa·s⁻¹、带宽为 32 GHz 的示波器捕获检测基带电信号,并进行 DSP。

接收信号的 DSP 流程如图 1 所示,首先对接收信号进行频域色散补偿,然后对补偿信号进行下采样,下采样时保留四倍信号速率,在信号时钟恢复之后再次进行下采样,并依次通过 MIMO-时域最小均方(TDLMS)、MIMO-频域最小均方(FDLMS)、载波相位恢复和面向判决的最小均方(DDLMS)算法恢复出原始信号,最后对信号进行 QAM 解映射和误码率计算。少模光纤参数如表 1 所示。

表 1 少模光纤参数

Table 1 Few mode fiber parameters

Parameter	Value
Loss / (dB·km ⁻¹)	0.208 for LP01
	0.202 for LP11
	0.207 for LP21
Differential group delay / (ps·m ⁻¹)	0.40 for LP01-LP11
	0.11 for LP11-LP21
Length of single FMF / km	50
Coefficient of dispersion / [ps·(nm·km) ⁻¹]	21.25 for LP01
	21.01 for LP11
	19.50 for LP21
	20.29 for LP02
Effective area / nm ²	90 for LP01
	121 for LP11
	159 for LP21
	161 for LP02

由于少模光纤传输相比于单模光纤传输信号间串扰更大,加上信号本身的偏振态引起的串扰,在经过多个器件以及 1000 km 传输后,需要在接收端对 2 个模式 2 个偏振态的四路调制信号进行信道均衡处理以恢复出每一路信号,本文在信道均衡处理中使用 MIMO-LMS 算法。在两模式模分复用系统中,对每个模式的输入信号进行两倍符号速率采样后,得到对应的奇次序和偶次序数据,通过快速傅里叶变换得到频域信号,然后初始化滤波器抽头,计算输出信号,产生期望输出,接着计算误差信号,更新抽头权向量。

3 实验结果与分析

我们将实验测试的两种模式(LP11a 和 LP11b)在

不同光信噪比(OSNR)下的误码性能与加性高斯白噪声(AWGN)信道仿真结果作对比,结果如图 2 所示,实验中低信噪比条件下的误码率接近理论信道结果,高信噪比(约 20.5 dB)条件下的 BER 为 1×10⁻²,与理论值相差 2.5 dB。

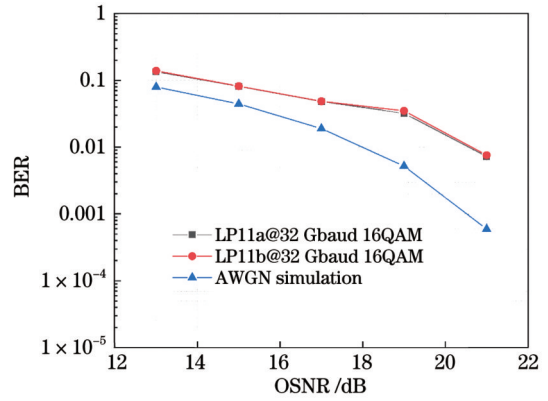


图 2 在不同 OSNR 条件下测量得到的误码率与 AWGN 信道仿真结果的对比

Fig. 2 Comparison of measured BERs and AWGN channel simulation results under different OSNR conditions

图 3 展示了不同输入光纤功率下传输 1000 km 后两个模式的误码性能,在 1000 km 传输前,设置不同的输入光纤功率,在 1000 km 传输后接收端的误码率均处于 5.2×10⁻² 软判决前向纠错(SD-FEC)门限以下。由于 LP11a 和 LP11b 两种模式的有效折射率非常接近,可以发现两种情况下两种模式均表现出相近的性能。可以看出,误码率并不是随着输入光纤功率的增加而增加,当输入光纤功率在一定范围内时,噪声功率不变,有效信号功率增加,信噪比升高,误码率降低;在功率到达一定程度后,信号在光纤中传输,引起较大的非线性效应,增加了损耗,接收信号发生显著的非线性损伤,现有的算法无法完全补偿这些非线性损伤,最终导致误码率下降。当输入光纤功率为 -2 dBm 时性能

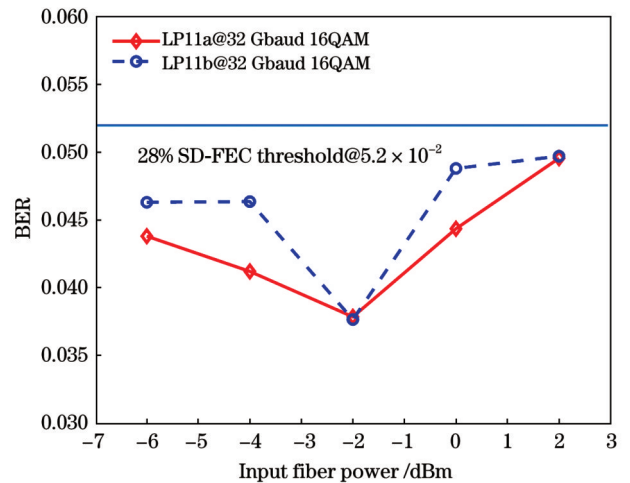


图 3 不同输入光纤功率下传输 1000 km 后两个模式的误码率

Fig. 3 BERs of two modes after transmission for 1000 km under different input fiber powers

最佳。

最后我们分别测试了输入光纤功率为 -2 dB 时两种模式的误码率,并对多次测量的结果取平均值,如图 4 所示,两种模式在传输中同样表现出相似的性能,且在所有传输距离下误码率均小于 5.2×10^{-2} 软判决前向纠错门限。实验产生误差的原因:为了调整光谱平坦度,我们根据光谱仪显示的光谱控制 EDFA 的输出功率,人工校准的方法对最终结果会产生一定的影响;ECL 工作时间较长时输出不稳定,发射功率会有轻微浮动,频率漂移,产生微小的误差;调制器由于温度变化,可能轻微地偏移最佳工作点。

图 5(a)、(b)分别为传输 1000 km 后 LP11a 模式下的两种偏振星座图。图 5(c)为传输 1000 km 后的光谱图,利用 WSS 滤除带外放大器的自发辐射噪声,信号的光信噪比曲线相对平坦。图 5(d)为 1000 km 传输实验图。实验中传输 1000 km 后两种模式下两种极化复用信号的误码率均处于 SD-FEC 门限以下,

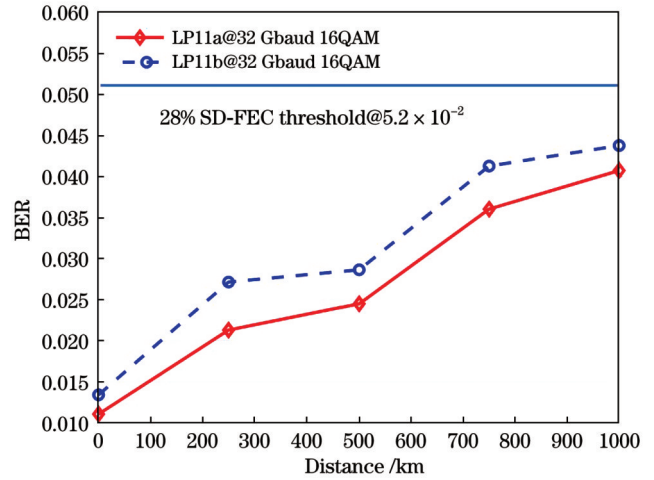


图 4 不同传输距离下的误码率

Fig. 4 BERs under different transmission distances

由此可得到总传输速率为 $512 \text{ Gbit} \cdot \text{s}^{-1}$,有效传输速率是 $400 \text{ Gbit} \cdot \text{s}^{-1}$ 。

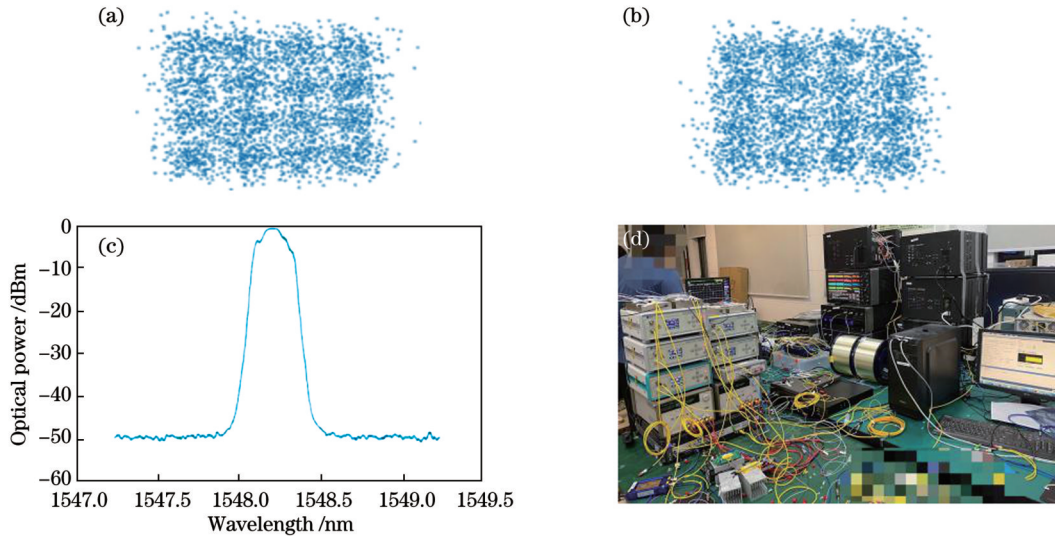


图 5 传输 1000 km 后的结果。(a) X 偏振星座图;(b) Y 偏振星座图;(c) 光谱图;(d) 传输实验图

Fig. 5 Results after 1000 km transmission. (a) X-polarization constellation diagram; (b) Y-polarization constellation diagram; (c) optical spectrum; (d) transmission experiment diagram

4 结 论

展示了单通道模分复用-偏振复用 16QAM 双模信号传输 1000 km 的实验系统。利用 WSS 滤除带外放大器的自发辐射噪声,防止能量在波长通道中泄漏,在接收端使用 MIMO-TDLMS 和 MIMO-FDLMS 两级 MIMO 算法进行信道均衡处理,并最终实现单通道两模两偏振总计 $512 \text{ Gbit} \cdot \text{s}^{-1}$ 的传输速率,且误码率低于软判决前向纠错的阈值 (5.2×10^{-2}),前向误差校正开销为 28%,净速率为 $400 \text{ Gbit} \cdot \text{s}^{-1}$ 。虽然实现更长的传输距离需要改进链路的模式相关损耗,但研究结果证实了少模光纤在未来大容量长途传输系统中的应用潜力。

参 考 文 献

- [1] Sillard P, Benyahya K, et al. Few-mode fiber technology, deployments, and systems[J]. Proceedings of the IEEE 2022, 110 (11):1804-1820.
- [2] Khonina S N, Kazanskiy N L, MButtet al. Optical multiplexing techniques and their combination for on-chip and optical fiber communication: a review[J]. Opto-Electronic Advances, 2022, 5 (8):210127.
- [3] Du J B, Shen W H, Liu J C, et al. Mode division multiplexing: from photonic integration to optical fiber transmission[J]. Chinese Optics Letters. 2021, 19(9):091301.
- [4] Kobayashi T, Nakamura M, Hamaoka F, et al. 1-Pb/s (32 SDM/46 WDM/768 Gb/s) C-band dense SDM transmission over 205.6-km of single-mode heterogeneous multicore fiber using 96-gbaud PDM-16QAM channels[C]//Optical Fiber Communication Conference, March 19-23, 2017, Los Angeles, California. New York: IEEE Press, 2017.

- [5] Soma D, Wakayama Y, Beppu S, et al. 10.16-peta-B/s dense SDM/WDM transmission over 6-mode 19-core fiber across the C+L band[J]. *Journal of Lightwave Technology*, 2018, 36(6): 1362-1368.
- [6] Luis R S, Rademacher G, Puttnam B J, et al. 1.2 Pb/s throughput transmission using a 160 μm cladding, 4-core, 3-mode fiber[J]. *Journal of Lightwave Technology*, 2019, 37(8):1798-1804.
- [7] Rademacher G, Luis R S, Puttnam B J, et al. High-capacity and long-haul transmission with space-division multiplexing[C] // *Optical Fiber Communication Conference (OFC) 2021*, June 6-10, 2021, Washington, DC. Washington, D.C.: Optica Publishing Group, 2021: W7D. 1.
- [8] Rademacher G, Luis R S, Puttnam B J, et al. Comparative study of few-mode and coupled-core multicore fiber transmissions [J]. *Journal of Lightwave Technology*, 2022, 40(6): 1590-1596.
- [9] 陈嘉轲, 胡贵军, 韩悦羽. 基于光子灯笼的 3×3 模分复用通信实验系统[J]. *中国激光*, 2017, 44(11): 1106009.
Chen J K, Hu G J, Han Y Y. Communication experimental system with 3×3 mode division multiplexing based on photonic lanterns [J]. *Chinese Journal of Lasers*, 2017, 44(11):1106009.
- [10] 陈健, 黄青青, 张倩武, 等. 基于光子灯笼的正交频分/模分复用 IM-DD 多模光纤传输系统[J]. *光学学报*, 2018, 38(6): 0606008.
Chen J, Huang Q Q, Zhang Q W, et al. Orthogonal frequency division/mode division multiplexing IM-DD multimode fiber transmission system based on photonic lanterns[J]. *Acta Optica Sinica*, 2018, 38(6): 0606008.
- [11] Hu T, Li J H, Ge D W, et al. Weakly-coupled 4-mode step-index FMF and demonstration of IM/DD MDM transmission[J]. *Optics Express*, 2018, 26(7): 8356-8363.
- [12] 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 is based on neural networks in a high-speed IM-DD mode-division multiplexing transmission system[J]. *Acta Optica Sinica*, 2021, 41(14): 1406003.
- [13] 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.
- [14] 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, Chi N, Chen L. Coherent optical communication technology based on digital signal processing[M]. Beijing: Posts and Telecom Press, 2013.
- [15] Kong M, Li X Y, Zhang J, et al. High spectral efficiency of 400 Gb/s transmission using different modulation formats and advanced DSP[J]. *Journal of Lightwave Technology*, 2019, 37(20):5317-5325.
- [16] 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): 单载波调制技术[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.
- [17] 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.

Dual-Mode Polarization-Multiplexed 16QAM Signal 1000 km Few-Mode Fiber Transmission System Based on Heterodyne Coherent Detection

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Abstract

Objective With the rapid growth of internet traffic, the demand for large transmission capacities from all walks of life has grown dramatically. The current transmission capacity of a single-mode fiber (SMF) in a fiber optic transmission system is rapidly approaching the Shannon limit. Solving the transmission capacity problem has become a top priority. One method to solve this problem is to apply mode-division multiplexing (MDM). In MDM, multi-mode fibers have severe intermodal dispersion and large nonlinear impairment; this is less effective for long-haul transmission. Few-mode fibers have less intermodal dispersion and more potential for long-haul fiber optic communications. Currently, China is catching up in the field of MDM and mainly adopts the intensity modulation direct detection (IMDD) method for experiments that is not suitable for long-distance transmission. The number of modes used in the studied MDM system is small; this has a limited effect on improving the capacity of the communication system. This study adopts polarization multiplexing and advanced digital signal processing technologies to construct a single-channel mode division multiplexing optical fiber transmission system based on an in-phase quadrature (IQ) modulation heterodyne coherent detection system. We successfully realize a 1000 km transmission of 32 Gbaud 16 quadrature amplitude modulation (QAM) signals in two degenerate modes, LP11a and LP11b. After equalization using the time-domain and frequency-domain multiple-input multiple-output least mean square (MIMO-LMS) algorithms, the bit error rate (BER) is lower than the soft-decision forward error correction (SD-FEC) threshold (5.2×10^{-2}).

Methods At the transmitter side, external cavity lasers (ECL) generate light wave. The generated continuous light wave is modulated by a 16QAM signal through an IQ modulator. The 16QAM signal loaded into an arbitrary waveform generator (AWG) is generated offline using MATLAB. The modulated signal is divided into two paths by a polarization beam splitter (PBS) and transmitted in the polarization-maintaining fiber. One path passes through the delay line and is then combined with the other path by a polarization beam combiner (PBC) to complete polarization multiplexing. The polarization-multiplexed signal is amplified in the erbium-doped fiber amplifier (EDFA) and divided into two paths together through a 1×2 coupler equal. One path is decorrelated through a delay line with a length of 3 m and delay time of 15 ns and then injected into the fiber for transmission. The fiber optic link adopts a loop structure in which the loop switch is controlled by two acousto-optic modulators (AOM). Long-distance transmission is achieved by setting the AOM to control the number of transmission turns of the multiplexed signal in the loop. The signals are modulated into the LP11a and LP11b modes by the mode-multiplexing module, and the signals under the two modes are jointly transmitted in the few-mode fiber (FMF). The signals enter the mode-demultiplexing module through a few-mode fiber and are boosted using an EDFA. Owing to the insertion loss of the AOM switch and coupler, the signals must be amplified by the EDFA after entering the optical fiber loop. We solve the problem of the uneven gain of EDFAs by adopting a wavelength selective switch (WSS). The output of the WSS is sent back to the mode multiplexer to conduct MDM and 50 km FMF transmissions again until the total transmission distance can meet our requirement. On the receiver side, a coherent optical receiver conducts heterodyne detection on the output signal and performs digital signal processing (DSP). In offline DSP, the received electrical signal is first processed by frequency-domain dispersion compensation, and the compensated signal is then downsampled. Quadruple signal rate is preserved for clock recovery during downsampling. After clock recovery, the signal is downsampled again and the original signal is recovered by the MIMO-time domain (TD) LMS, MIMO-frequency domain (FD) LMS, carrier phase recovery, detection-directed LMS (DDLMS) algorithms. Finally, the BER calculation is performed for the signal.

Results and Discussions Figure 2 shows the BERs of the two modes measured under different OSNR conditions compared with the additive white Gaussian noise (AWGN) channel simulation results. In the case of a low signal to noise ratio (SNR), the BER is close to the theoretical channel result, whereas in the case of a high SNR (about 20.5 dB), the BER is 1×10^{-2} that is 2.5 dB away from the theoretical value. Figure 3 shows the BERs of the two modes after 1000 km transmission under different input fiber powers. In the case of different input fiber powers, after 1000 km transmission, the BERs of both the LP11a and LP11b modes can meet the SD-FEC threshold (5.2×10^{-2}). Because the indices of refraction of LP11a and LP11b are close, the BERs of the different modes show little difference. As shown in Fig. 4, the two modes exhibit similar performance at all transmission distances and both can meet the SD-FEC threshold (5.2×10^{-2}).

Conclusions In this study, we experimentally build a dual-mode polarization-multiplexed 16QAM signal 1000 km few-mode fiber transmission system based on heterodyne coherent detection. At the receiving end, the MIMO-TDLMS and MIMO-FDLMS algorithms are used for channel equalization, and a single-channel 512 Gbit/s transmission rate is achieved. The BER can meet the SD-FEC threshold (5.2×10^{-2}), and the corresponding net data rate is 400 Gbit/s. Although achieving longer transmission distances requires improved mode-dependent losses in the links, the results confirm the potential of few-mode fibers for future high-capacity long-distance transmission systems.

Key words optical communications; optical fiber communications; modular division multiplexing; few-mode fiber; polarization multiplexing; long-haul transmission