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Analysis of self-homodyne detection for 6-mode fiber with low-modal crosstalk

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we present an appropriate analysis on self-homodyne coherent system with $56 \times 5 \times 3$ Gb/s WDM–PDM–MDM quadrature phase-shift keying (QPSK) signals using 6-mode weakly coupled few mode fiber. The mode division technology can effectively improve the spectral efficiency (SE) of self-homodyne detection. Of all the LP modes, LP_{01} mode is used to transmit the pilot tone (PT), while the others for signal channels. The influence of inter-mode crosstalk is analyzed. The proposed frequency domain MMA shows a better BER performance for intra-mode crosstalk elimination. The path-length misalignment's influence caused by mode differential group delay (MDGD) is also investigated. The system tolerance for different laser's line-width is compared as well as the influence of PT filter's bandwidth.

1. Introduction

In recent years, the data business shows explosive growth with the development of mobile internet, cloud computing and the application of things of internet technology [1]. Massive data makes it much more difficult for interconnection in short or medium range. Nowadays, optical communication for short range usually uses the intensity modulation direct detection method (IM/DD). The IM/DD with its simplicity can significantly lower the cost of the system. However IM/DD can only use the light intensity information, resulting in the loss of phase information. Meanwhile the effects of chromatic dispersion (CD) and non-linear noise for IM/DD are also serious making it difficult for 100 Gb/s per carrier. The coherent optical communication with intradyne detection (ID) has been widely used in long distance 100 Gb/s optical network for its high sensitivity, high spectral efficiency and high reliability [2]. However ID technology has complicated high-cost system devices, which makes it difficult to be applied in a low-cost short-distance optical network. Recently, optical communication with self-homodyne detection (SHD) makes a possible way for both low cost and high capacity [3,4]. SHD by using an unmodulated PT transmitting with a polarization-division multiplexed (PDM-SHD) data signal has long been proposed to suppress laser phase noise in coherent system [5–10]. At the receiving end, PT is separated from signal by a polarization beam splitter (PBS) to be as the local oscillator (LO) for coherent reception. Because of PT and signal coming from the same laser and preserving their coherence throughout the optical transmission path, SHD can effectively eliminate optical carrier frequency offset (CFO) and laser phase noise (PN) making it possible for the system to lower the requirements of laser's line-width especially when using phase-noise sensitive quadrature amplitude modulation (QAM) or orthogonal frequency division multiplexing (OFDM) [7,9].The property of phase noise cancellation also reduces the complexity of DSP signal's carrier phase recovery processing algorithm which makes SHD much more energy efficient [11]. However in contrast to ID using PDM, PDM-SHD using one polarization state to transmit PT leads to a trade-off up to 50% of the SE. Another drawback of PDM-SHD is the need of the polarization state control or ultra-narrow band optical filter [12].

Recently, mode-division-multiplexing (MDM) based on few mode fibers (FMF) has been widely investigated for its property of breaking through the capacity crunch in single-mode-fibers (SMF) [13]. MDM utilizing different optical spatial modes in FMF to transmit signals at the same time greatly improves the capacity and SE of one single fiber. Combining the properties of MDM and SHD, MDM-SHD can be a better candidate for optical communication of short range with low system cost, such as the MHz DFB laser, the cancellation of LO, the simplified DSP and high SE (For 6 spatial modes, the SE penalty is only 1/6). Aside MDM-SHD, self-homodyne detection can also be used in multi-core fiber (MCF). MCF is also a promising way for high capacity optical networks. The MCF-SHD has been demonstrated for its high capacity in short-distance optical network. [14,15] Here, we focus on MDM-SHD and explore the mode property to expand system capacity in multimodal

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FMF. The current study on MDM-SHD stays still in two spatial modes, while studies on multimodal MDM-SHD are not yet sufficient [16–18].

In this paper, we make an appropriate analysis about 6-mode MDM-SHD. The scheme utilizes weakly coupled FMF to suppress crosstalks between LP modes of which one LP mode will be used for PT while the others used for signal channels. The SE penalty becomes very small comparable to the 6-mode MDM systems with intradyne detection. In Section 2, we give detailed principles and procedures of establishing the 6-mode MDM-SHD system and the corresponding system parameters. In Section 3, we give an overview on the BER performance of the 6-mode MDM-SHD system, analyze the BER penalty caused by the inter-mode crosstalk and intra-mode crosstalk, compare the BER performance of using CMA and MMA for elimination of intra-mode crosstalk between degenerate modes, such as LP_{11a} and LP_{11b}, LP_{21a} and LP_{21b}. We also research the path-length misalignment's influence on system performance. At last we compare the BER influence of using 20 GHz and 80 GHz PT optical filter and different line-width lasers, including 100 kHz ECL, 1 MHz DFB, 10 MHz DFB lasers. In Section 4, we outline some conclusions about the 6-mode MDM-SHD scheme.

2. Simulation principle

The simulation is established based on VPI. The schematic of proposed 6-mode MDM-SHD scheme is shown in Fig. 1. The light coming from three DFB lasers with respective center wavelength of 1551.7 nm, 1552.5 nm and 1553.3 nm is combined by a wavelength MUX to be the optical source of the system. Then the light goes through a 1:6 optical power splitter and is divided averagely into 6 beams. One of the beams chosen as PT goes through directly to the mode MUX, while the others go through the IQ modulators to generate 56×5 Gb/s PDM-QPSK signals. In this paper, the LP_{01} channel is used for PT transmission. While the other mode channels are used for signal transmission. There are five EDFAs used in signal channels to control the transmission power as well as the PT-signal power ratio. In the modulation area, five different PBRS sources produce different random NRZ signals of length 2^{15}-1. After data mapping, the data is sent to the IQ modulators to produce 28 GBaud×5 PDM-QPSK signals. Then the PT and signals are converted and combined to a 6-mode FMF by a multimodal MUX. The channel modeling of the 6-mode weakly coupled FMF is established according to reference [19]. The main simulation parameters of the 6-mode FMF are on the base of reference [20–23] and are shown in Table 1. We can add CD, PMD, MDGD and other FMF parameters in every piece fiber. We can also set the modal crosstalk values by setting the coefficients in the coupling matrix accurately and changing its values by changing both the matrix coefficient and transmission distance. The inter-mode crosstalk in our paper is determined of -34 dB/km and the intra-mode crosstalk is determined of -28 dB/km.

After transmission in FMF, the spectrum of PT and signals at the receiving end is shown in Fig. 2. The optical signal noise ratio (OSNR) modules are used to control noise power during transmission. As we can see, there exists crosstalk between PT channel and signal channel. Then the PT and signals are separated by the DEMUX. Then five paths of different optical delay lines (ODLs) are used to align the PT and signals between LP_{01} mode and other LP modes due to the existence of mode differential group delay (MDGD). After ODLs, six optical band-pass filters (OBPF) modules are used to suppress the noise as well as choosing signals and PT in certain wavelength. After MDGD compensation and optical filtering, PT is divided into 5 beams by a 1:5 power splitter as the LO for LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b} and LP_{02} signal channels. Polarization controllers (PC) are used in every mode channel to keep the polarization state consistent. Optical signals are converted into electric signals after optical hybrids and balanced detection. Then five analog-to-digital converters (ADCs) with the effective number of bits (ENOB) of 5 bits are used to digitize the electric signal and then going into a digital signal processing (DSP) module. In DSP, the signals are processed including normalization, DC offset elimination, CD compensation, intra-mode crosstalk elimination and bit error ratio (BER) calculation. The carrier phase recovery processing algorithm is ignored, because SHD can eliminate CFO and suppress PN. The MIMO equalization in DSP is also shown in Fig. 1. Different from equalization in strong coupled FMF, the SHD MIMO equalization in weakly coupled FMF is much easier and simpler. Because the equalizers in all the modes are only a combine of 4×4 and 2×2 equalizer. They don't need to cover for the DMGD. The FDE/TDE number of taps decreases significantly, because the TDE part only has to compensate for PMD [24–26]. Here, we use two 40 taps 4×4 and one 40 taps 2×2 CMA or MMA to compensate the intra-mode crosstalk as well as PDM demultiplexing, since the LP_{01}mode channel is used for PT transmission.

Table 1
Simulation parameters of 6-mode weakly coupled FMF.

Item Unit	Chromatic Dispersion ps/nm/km	DMGD Vs.LP01 ns/km	Loss dB/km
LP_{01}	20	/	0.21
LP_{11a}&LP_{11b}	21	4	
LP_{21a}&LP_{21b}	19	8	
LP_{02}	9	7	

3. Simulation results and analysis

3.1. Mode-crosstalk analysis

In 6-mode MDM-SHD, modal crosstalk becomes much complicated compared to 2-mode MDM-SHD, including inter-mode crosstalk caused by the MUX/DEMUE and FMF during transmission, such as crosstalks in LP_{01}, LP_{11}, LP_{21}, LP_{02} and intra-mode crosstalk between two degenerate modes, such as crosstalks in LP_{11a} and LP_{11b}, LP_{21a} and LP_{21b}. The first can make the PT much confused to be the LO and after coherent detection, it will cause beating noises. The second can make signals between two degenerate modes confused. The confusion caused by intra-mode crosstalk can be compensated by MIMO equalization technology. However the beating noises caused by inter-mode crosstalk may be a very difficult problem to solve. Here, we give a brief formula analysis about the beating noises caused by inter-mode crosstalk. For a simple discussion, we only consider three mode groups of which one polarization is included. At the transmitter, the signals S_1, S_2 and PT can be expressed as:

$$E_{S1}(t) = \sqrt{P_{S1}} S_1(t) e^{jwt} \tag{1}$$

$$E_{S2}(t) = \sqrt{P_{S2}} S_2(t) e^{jwt} \tag{2}$$

$$E_{PT}(t) = \sqrt{P_{PT}} e^{jwt} \tag{3}$$

where $E_{S1}(t)$, $E_{S2}(t)$, $E_{PT}(t)$ are the complex amplitudes of signals S_1, S_2 and PT. Their total average power is P_{S1}, P_{S2}, P_{PT} respectively. $S_1(t)$, $S_2(t)$ are the normalized complex signals for data transmitting. The phase noise is neglected, because it can be removed by ODLs. During transmission in FMF, modal crosstalk happens randomly in the entire transmission process. For a simple and clear expression, we only consider one modal crosstalk during the entire transmission process. At the receive side, the PT and signals are separate by the DEMUX. Then after ODLs for MDGD compensation, the signals and PT can be expressed as:

$$E_{PT}(t) = \sqrt{1-2\gamma} E_{PT}(t) + \sqrt{\alpha} E_{S1}\left(t+\tau_1\right) + \sqrt{\beta} E_{S2}\left(t+\tau_2\right) \tag{4}$$

$$E_{S1}(t) = \sqrt{1-2\alpha} E_{S1}(t) + \sqrt{\beta} E_{S2}\left(t+\tau_2-\tau_1\right) + \sqrt{\gamma} E_{PT}\left(t-\tau_1\right) \tag{5}$$

$$E_{S2}(t) = \sqrt{1-2\beta} E_{S2}(t) + \sqrt{\alpha} E_{S1}\left(t+\tau_1-\tau_2\right) + \sqrt{\gamma} E_{PT}\left(t-\tau_2\right) \tag{6}$$

where α, β, γ are the modal crosstalk power ratio of signals S_1, S_2 and PT. τ_1, τ_2 are the MDGD of signals S_1, S_2 compared to the PT, when the modal crosstalk happened in FMF. Then PT is used as LO for