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Time domain multiplexed spatial division multiplexing receiver

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Abstract: A novel time domain multiplexed (TDM) spatial division multiplexing (SDM) receiver which allows for the reception of >1 dual polarization mode with a single coherent receiver, and corresponding 4-port oscilloscope, is experimentally demonstrated. Received by two coherent receivers and respective 4-port oscilloscopes, a 3 mode transmission of 28GBaud QPSK, 8, 16, and 32QAM over 41.7km of few-mode fiber demonstrates the performance of the TDM-SDM receiver with respect to back-to-back. In addition, by using carrier phase estimation employing one digital phase locked loop per output, the frequency offset between the transmitter laser and local oscillator is shown to perform similar to previous work which employs 3 coherent receivers and 4-port oscilloscopes which are dedicated to the reception of each the three modes.

OCIS codes: (030.4070) Modes; (060.4230) Multiplexing; (060.1660) Coherent communications.

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1. Introduction

It is undisputed that the demand for capacity in optical transmission systems has been growing in the past, and will continue to do so in the next decade. Although, the continuous annual growth rate (CAGR) of traffic over time is slowing down, it is expected to converge to approximately 30-40% in 2020 [1]. Therefore, it is a clear indication that carriers are to provide for this exponential capacity growth, to avoid an upcoming capacity crunch. This creates a challenging goal for research: increase the capacity limits of optical transmission systems.

In the past, first the serial baud rate was increased, before adding parallel wavelengths carrying information in wavelength division multiplexed (WDM) optical transmission systems. Around 1998, polarization division multiplexing (PDM) started to attract attention [2]. The following decade, enabled by coherent transmission and 2 × 2 multiple-input multiple-output (MIMO) digital signal processing (DSP), the capacity of coherent optical dual polarization (DP) transmission systems annually increased by approximately 25% [3]. This however, was clearly not sufficient to meet the CAGR. Therefore, a new way of substantially increasing the transmission capacity had to be investigated.

One method to substantially increase the transmission capacity is mode group diversity multiplexing, also known as spatial division multiplexing (SDM). In 2005, the main impact in SDM was made using direct detection in multimode fiber [4], and interest in coherent SDM systems increased in 2010 [5,6]. Within one year, the first DP 3 linearly polarized (LP) mode coherent SDM transmission system was demonstrated [7], which required three 4-port oscilloscopes and corresponding optical coherent receiver front-ends. The 4 ports are used to receive the in-phase (real) and quadrature (imaginary) components of the complex transmitted constellations, for each of the two polarizations. Within a year, the number of simultaneously transmitted modes was increased to 6 DP spatial LP modes [8]. However, the work in [8] required six 4-port oscilloscopes and corresponding optical coherent receiver front-ends. Currently only one research group in the world has been able to invest in the resources required for such experimental demonstrations, other SDM research groups continue to work on 3 spatial LP mode transmission [9,10]. Due to this limitation, more recently, SDM research is focusing on the integrations of 3 and 6 spatial LP mode transmission components, such as amplifiers [11], wavelength selective switches [12]. It is important that required SDM components are developed further, however note that without the required receiver systems, these components cannot be validated. In addition, to meet CAGR, further increment in the number of simultaneously transmitted spatial LP modes should continue to be investigated.

In support of the scaling to more modes, we propose a time domain multiplexed (TDM) SDM receiver to extend the number of simultaneously received DP modes, which allows for the reception of >1 mode per 4-port oscilloscope, and hence additional 4-port oscilloscope and corresponding coherent receivers are not necessary. Employing a 41.7 km 3 mode FMF transmission experiment, the proposed receiver is successfully demonstrated with quadrature phase shift keying (QPSK), 8, 16, and 32 quadrature amplitude modulation (QAM) transmitted constellations. Therefore, the number of transmitted modes can be increased, whilst minimizing the financial investment required. Employing this method, the predominant 3-mode setups can easily be expanded to higher number of modes. In addition, a potentially larger number of research groups can work on SDM systems.

To this end, this paper is structured as follows: first, the proposed TDM-SDM receiver is described in section 2. In section 3 the experimental setup, which is used to verify the performance of the proposed receiver is described, and in section 4 the experimental measurement results are shown and discussed.

2. Proposed TDM-SDM receiver

To alleviate the requirement for more 4-port oscilloscopes for receiving an increased number of DP spatial LP modes, the time domain multiplexed spatial division multiplexing receiver, depicted in Fig. 1(a), is proposed. Using the proposed TDM-SDM receiver, we show that both dimensions for increasing the received number of modes can be simultaneously exploited by

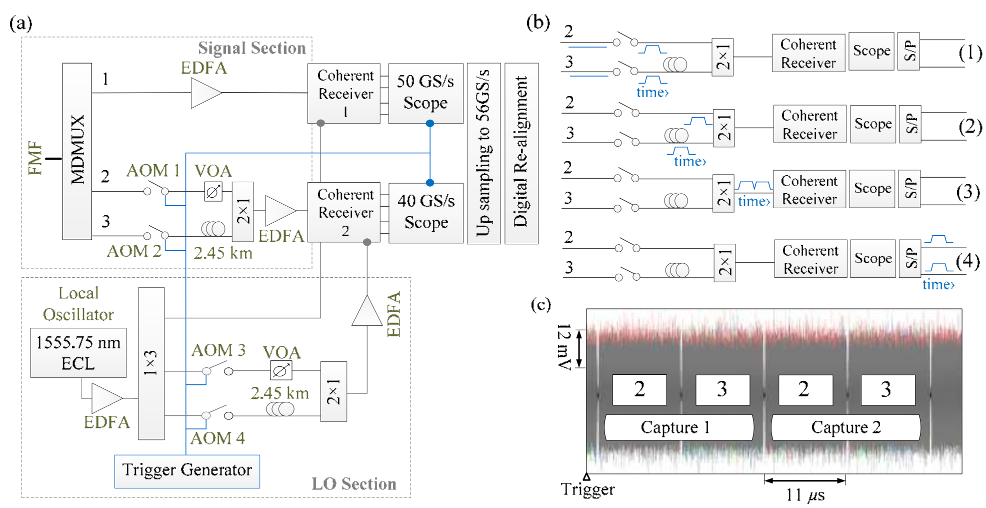

Fig. 1. (a) Proposed TDM-SDM receiver setup. (b) The four time alignment steps comprising both the optical and digital domain. (c) The 40GS/s oscilloscope screen capture.

using two 4-port oscilloscopes, whilst receiving three DP LP modes. Coherent receiver 1 receives one DP mode (input 1), and Coherent receiver 2 acquires 2 modes (inputs 2 and 3). In this section, we focus on the signal alignment of inputs 2 and 3 received by Coherent

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receiver 2. Note that the local oscillator (LO) section is a copy of the Coherent receiver 2 signal path.

For MIMO systems, it is mandatory that the received modes are correctly aligned in time at the input of the MIMO DSP block, which is further detailed in section 3. At the output of the mode demultiplexer (MDMUX), also further detailed in section 3, the transmitted signals are always aligned in time. Therefore, the most obvious choice is to use one DP coherent receiver per input to directly connect the mode demultiplexer to the MIMO DSP input. However, in between the mode demultiplexer output, and MIMO DSP input, the timing alignment can be freely rearranged, as long as the timing boundary conditions are satisfied. By employing the following four steps, the timing boundary conditions can be satisfied, and the number of required 4-port oscilloscopes can be reduced. These steps are, depicted in Fig. 1(b): In step (1) each received input signal passes through a shutter or switch, where the (continuous) signal is allowed to pass at selected time slots. The shutters, or switches, open and close simultaneously to create a windowing function. In this work, an acoustic optical modulator (AOM) is used as shutter, where AOM1 and AOM2 act as shutters for inputs 2 and 3, respectively. The AOMs are driven by a 27MHz sinusoidal RF signal. Consequently, this adds a 27MHz frequency offset to the signal. At step (2): one input is delayed in time with respect to the other in the optical domain. In this work, a 2.45km single mode fiber is used to delay the input 3, which results in an 11 μs time delay. To keep the optical power equal for both inputs, the input 2 path is attenuated by a variable optical attenuator (VOA). At Step (3): both the separate received inputs are then combined by a 2 × 1 combiner, amplified, and received by Coherent receiver 2. Amplifying after the combiner reduces the number of erbium doped fiber amplifiers (EDFAs) required. However, each input can also be separately amplified in step (1). The input signal of the Coherent receiver 2 is depicted in Fig. 1(c). Finally at step (4), after the time slotted signal is coherently received by Coherent receiver 2, and digitized by the 40GS/s 4-port oscilloscope, the time slotted signal is up sampled to 56GS/s. This allows for sample rate alignment between the employed oscilloscopes, which is the alignment in the parallel coherent receiver dimension. In the digital domain, the signal is serial to parallel block (S/P) converted to parallelize the incoming serial data blocks in time. Of course, this structure can be further up scaled to receive >2 inputs with a single 4-port oscilloscope.

In Fig. 1(a), in the LO path, the signal section previously described is replicated. However, where LP modes are used as inputs in the signal section, one LO acts as source for all the inputs in the LO section. The used LO is an external cavity laser (ECL), and is a different laser than the transmitter laser. It is critical to match the LO phase such that input 2 and 3 beat with the LO phase, well within its coherence length. Therefore, the 2.45km single mode delay fibers in the signal and LO section were measured to be within 2 meters (approximately 245 symbols) difference of each other using delay estimation by channel state estimation [13]. In Fig. 1(a) AOM3 and AOM4 are used as switches. These AOMs are also driven by a 27MHz sinusoidal RF signal, which shifts the LO frequency by 27MHz. Hence, the frequency offset of the LO with respect to the signal is cancelled. The proposed SDM receiver performance is evaluated in an experimental transmission system.

3. Experimental setup

The proposed TDM-SDM receiver is used in the experimental system depicted in Fig. 2. This section describes the experimental setup in detail, where the transmitter is described in section 3.1. In section 3.2 the mode multiplexer, few mode fiber, and mode demultiplexer characteristics are detailed. Finally, in section 3.3 the receiver side is described, mainly

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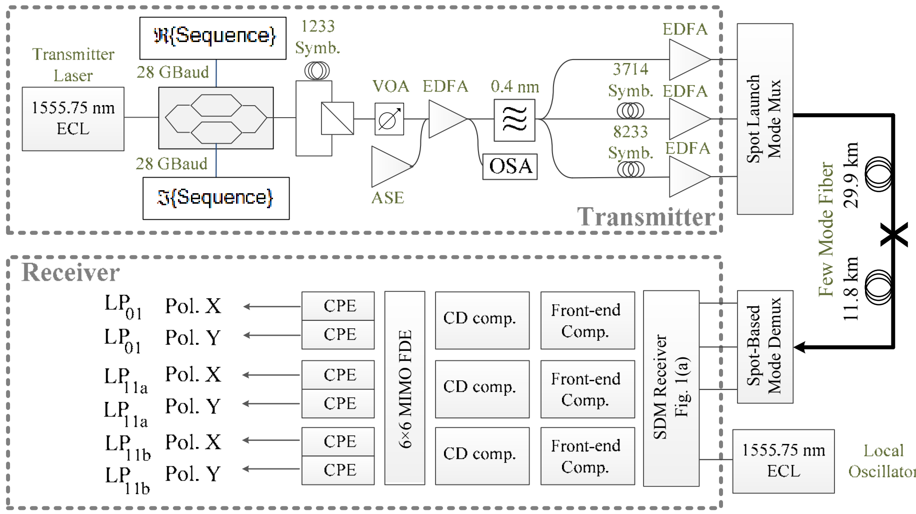

Fig. 2. Three mode few-mode fiber experimental setup.

focusing on the digital signal processing, which employs the proposed TDM-SDM optical front-end already detailed in section 2.

3.1 Transmitter

At the transmitter, a 1555.75 nm ECL is used which has a linewidth of <100kHz. The output is guided through a Lithium Niobate IQ-modulator, where the laser light is modulated by the output of two digital to analog converters (DACs). Each DAC represents one component of the 2 dimensional transmitted constellations, the inphase (real) or quadrature (imaginary) component. The DACs are running on a baud rate of 28GBaud, and a sequence coming from a field programmable gate array (FPGA) is fed to each DAC separately. In section 2 was noted that the single mode fiber time delay T_{SMF} is 11 μs, and hence the capture time is 11 μs. The capture time can be converted to the number of symbols per transmitted polarization S_{pol} as

$$S_{\mathrm{POL}} = \frac{T_{\mathrm{SMF}}}{T_{\mathrm{S}}} [\text{symbols}], \tag{1}$$

where T_{s} represents the symbol time. Therefore, the 2.45km single mode delay fiber results in a capture window of approximately 310,000 symbols per polarization. The transmitted constellation sequences are offline generated in Matlab before being loaded into the FPGA, and have a length of 2^{15} symbols. The constellations used in this work are QPSK, 8, 16, and 32QAM. As each constellation carries a different number of bits per symbol, N pseudo random bit sequences (PRBSs) with length 2^{15} are generated, which are then combined to form the constellation sequences. The bit allocation and autocorrelation of each constellation is depicted in Fig. 3. The corresponding sequence autocorrelation plot indicates that there is no correlation within the generated sequences, with exception of the correlation with itself. Note that the correlation values have different heights due to the absolute value differences within the constellations. The plots depicted in Fig. 3 are of utmost importance for the accuracy of the transmission experiment, as the modulated output of the IQ-modulator is used to emulate the separate tributaries for the transmitted polarization mode channels. Accordingly, the output of the modulator is split into two equal tributaries; one tributary is delayed by 1233 symbols with respect to the other for polarization decorrelation, before being recombined. This gives an uncorrelated DP signal, which is noise loaded using an attenuator and an amplified spontaneous emission noise source to characterize the optical signal to noise

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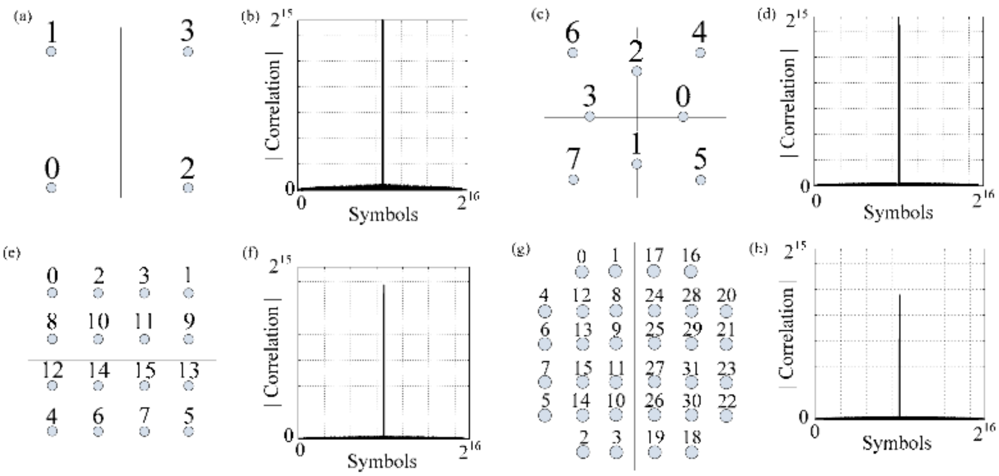

Fig. 3. Bit allocation represented by decimal numbers for (a) QPSK, (c) 8, (e) 16, and (g) 32QAM, and transmitted sequence autocorrelation for (b) QPSK, (d) 8, (f) 16, and (h) 32QAM.

ratio (OSNR) system performance with respect to theoretical performance [14]. The OSNR is determined by an optical spectrum analyzer (OSA). Then, the noise loaded DP signal is split into three equal tributaries. Two DP tributaries are delayed for mode decorrelation by 2458 and 5236 symbols, respectively, which again indicates that having no correlation in the transmitted sequence is very important. Therefore, the 3 × 2 transmitted polarization channels have delays of 1233, 2458, 3691, 5236, and 6469 symbols, respectively. The delays are estimated using least-squares frequency domain correlation [13]. The three single mode DP signals are then fed to the mode multiplexer (MMUX) with a 10dBm launch power.

3.2 Mode multiplexer, few mode fiber, and mode demultiplexer

The mode multiplexer is a single stage spot launcher, depicted in Fig. 4(a), and has been reported in [15]. Three collimated DP single mode inputs are guided onto a three facet mirror, where each facet represents one input as depicted in Fig. 4(b). The mirror combines and aligns the three inputs in free-space to allow excitation of certain areas of the few-mode fiber. Finally, two telecentric lenses with focal length f_1 = 150mm and f_2 = 2.7mm are used to image the free-space three spots onto the few mode fiber, as depicted in Fig. 4(c), which then results in the equal, and thus fully mixed, excitation of the 6 transmitted polarization modes. The difference between the maximum and minimum excitation of the polarization modes is the mode dependent loss (MDL), which is within 1dB for the MMUX. The insertion loss of the MMUX is approximately 4.5 dB. The three LP modes propagate along the 41.7km few mode fiber [16], after being excited at the transmitter side. The few mode fiber consists of two fiber spans, which have respective lengths of 29.9km and 11.8km. The differential mode delay

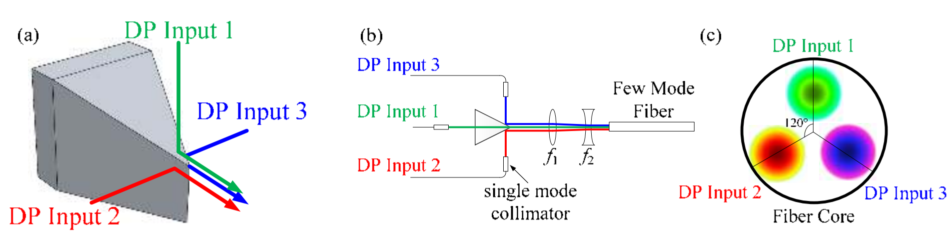

Fig. 4. (a) 3 facet mirror (b) aligning the DP single mode inputs (c) to the few mode fiber core.

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Table 1. Fiber properties at 1550nm wavelength.

	Few Mode Fiber 1	Few Mode Fiber 2	Unit
Length	29.9	11.8	km
Fiber diameter	125	124.9	μm
LP_{01}-LP_{11} group velocity	0.067	0.154	ps/m
Differential Mode Delay	2	1.82	ns
LP_{01} Chromatic dispersion	19.8	19.9	ps/(nm·km)
LP_{11} Chromatic dispersion	20	20.1	ps/(nm·km)
Mode field diameter LP_{01}	11	11	μm
Mode field diameter LP_{11}	11	11	μm
Effective Area LP_{01}	95	96	μm^2
Effective Area LP_{11}	95	95	μm^2

(DMD) is defined as the $LP_{01} - LP_{11}$ group velocity difference in seconds/meter multiplied by the fiber length, and is 2 ns and 1.82 ns, respectively. The few mode fiber properties are shown in Table 1, where A_{eff} is the effective area of the spatial LP mode.

The MDMUX at the receiver side is the reciprocal setup of the mode multiplexer, where the fully mixed modes after transmission are split into three DP single mode outputs. Therefore, each DP single mode MDMUX output contains all 6 transmitted polarization modes, and is guided to the receiver. The MDMUX insertion loss is 4.5 dB, and the MDL is within 2 dB.

3.3 Receiver

From the MDMUX, three DP single modes fiber inputs come into the optical front-end of the SDM receiver. The optical front-end, analog to digital conversion, and digital up sampling to 2 times the baud rate have been detailed in section 2. In the digital domain, there are now three aligned mixed received modes, and the key processing steps in the receiver DSP have been depicted in Fig. 2. First, the optical front-end is compensated [17]. Then, chromatic dispersion estimation and compensation is performed [18]. The next key processing stage is the heart of the DSP, the MIMO equalizer. In this work, an adaptive step size minimum mean squared error (MMSE) frequency domain equalizer (FDE) is used [19]. It unravels the received signal to separate outputs by performing a convolution between the incoming signal and a weight matrix. This weight matrix is updated heuristically by the data-aided least mean squares (LMS) algorithm during convergence and decision-directed least mean squares (DD-LMS) during data transmission. The convergence time is set to be 25,000 symbols. The MIMO FDE employs the 50% overlap-save scheme, combined with radix-4 256-point Fast-Fourier transforms (FFTs). Note that in FDEs the even and odd samples are separated and are symbol spaced due to 2-fold (Nyquist) oversampling. The total impulse response taken into account in the MIMO equalizer therefore is 128 symbols (4.57 ns), which is larger than the combined FMF's DMD of 3.82 ns. Each MIMO equalizer output is fed to a carrier phase estimation (CPE) stage [20], where the phase noise is estimated and the carrier phase offset between the transmitter laser and local oscillator laser is estimated and compensated. After the carrier offset has been removed, the MIMO output error is determined, which provides feedback for updating the FDE weights. The outputs of this stage are then used for bit error rate (BER) measurement. The presented BER in the results section is the average over 2 captures, where each capture is 310,000 symbols. Note that Fig. 1(c) shows the two captures for the two DP inputs received by the single oscilloscope under the proposed receiver scheme. The first 25,000 symbols are used for initial convergence, resulting in BER averaging over 3.42 million symbols per system OSNR value.

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4. Measurement results

The proposed TDM-SDM receiver detailed in section 2 has been verified using the experimental setup described in section 3, and the experimental transmission results are shown in Fig. 5. Through this experimental result, we demonstrate that two DP coherent receivers and corresponding 4-port oscilloscopes can successfully show the transmission of three DP modes. All 6 transmitted polarization channels carry a 28GBaud QPSK, 8, 16, or 32QAM signal, yielding a total transmitted gross bit rate of 336Gb/s, 504Gb/s, 672Gb/s, and 840Gb/s, respectively, on a single wavelength.

To fully verify the transmission system performance, including TDM-SDM receiver, three cases are investigated. The performance is shown in Fig. 5 for all four transmitted constellation types. First, a single mode DP back-to-back (BTB) transmission is performed to provide a primary benchmark result with respect to the theoretical performance. The BTB result gives an indication on the error-floor limitations of the transmitter and DP receiver. Then secondly, a 6 × 6 BTB result shows the transmission performance penalty over the MMUX, 2 meters of few mode fiber, MDMUX, and SDM-TDM. In addition, it corroborates that the TDM-SDM receiver performs as a conventional 3-mode receiver. Figure 5 shows that the 6 × 6 BTB OSNR penalties at the 20% soft-decision (SD) forward error correcting (FEC) limit with a BER of $2.8 \cdot 10^{-2}$ are 0.4dB, 0.4dB, 0.5dB, and 2dB for QPSK, 8, 16, and 32QAM with respect to BTB, respectively. We dedicate this OSNR increase to the TDM-SDM LO alignment tolerance becoming increasingly important as the constellation size scales up, and to losses in the mode multiplexers and TDM-SDM receiver. Furthermore in Fig. 5 the 41.7km FMF transmission system results are shown to be 0.5dB, 0.7dB, 1.3dB, and 6.2dB for QPSK, 8, 16, and 32QAM with respect to BTB, respectively. In this case, the increased OSNR penalty is not only caused by the alignment tolerances, but also by the transmission system losses. The transmission fiber has an 8.3 dB loss, and the multiplexers have a 4.5 dB loss each. Taking the 10 dBm launch power into account, the receiver side EDFA increasingly generates more noise due to amplification. This results in an increased OSNR penalty for the higher order constellations. These FMF BTB OSNR penalties are similar to previous work [21]. Note that in [21], binary phase plate mode multiplexers were used. These have an insertion loss of approximately 8.5 dB, whereas the spot launch mode multiplexers have an insertion loss of approximately 4.5 dB. By combining the DP channels in the TDM-SDM

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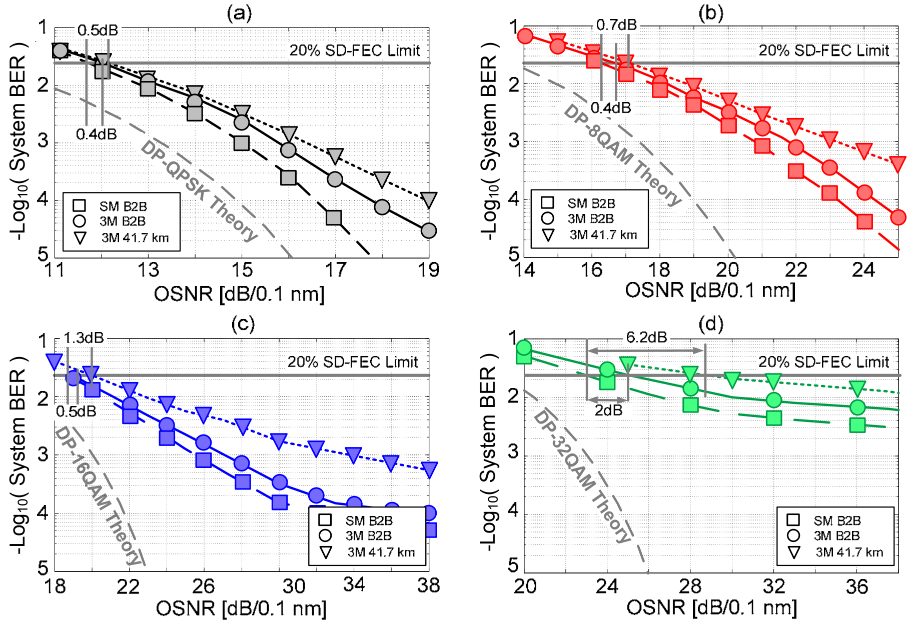

Fig. 5. Experimental transmission results for 28GBaud BTB, 6 × 6 BTB, and 6 × 6 41.7 km transmission. (a) QPSK. (b) 8QAM. (c) 16QAM. (d) 32QAM.

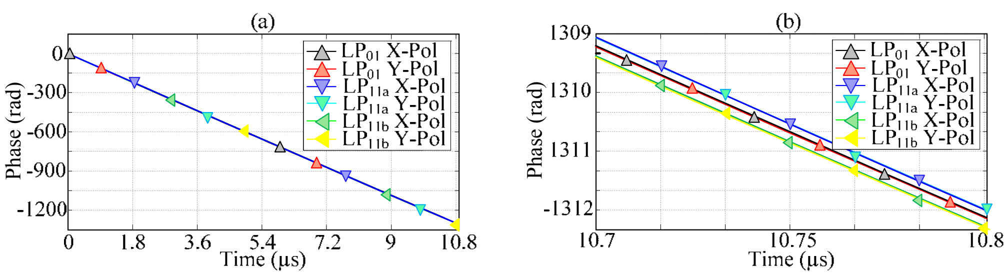

Fig. 6. (a) DPLL phase output for 10.8µs. (b) DPLL phase output from 10.7µs to 10.8µs indicating that the two corresponding polarizations correlate, and a small difference is noticed between received LP modes.

receiver, and taking the AOM insertion loss into account, the total BTB setup attenuation difference is <3 dB. This result fully substantiates the transmission performance of the TDM-SDM receiver in a full experimental transmission setup.

As the TDM-SDM receiver receives the DP LP modes in time slots, it is crucial to match the phase of the LO well within the coherence length of the laser. In this case, 2 spatial LP modes are time domain multiplexed. When increasing this number, we suspect these tolerances become more stringent. This is accomplished by replicating the signal path of the TDM-SDM receiver, as described in section 2. However, the frequency offset between the transmitter laser and LO for the various transmitted polarization channels is of interest for further observation. Note that the CPE stage tracks and mitigates the frequency offset and phase noise, the DPLL output over time is expected to exhibit similar trends for all polarization mode channels as depicted in Fig. 6. This result is similar as observed in previous work [20], where three 4-port oscilloscopes were used to acquire three DP LP modes. Therefore, we can conclude that the TDM-SDM receiver shows very similar performance to using a number of 4-port oscilloscopes to process individual modes in a few-mode transmission setup.

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5. Conclusion

The proposed TDM-SDM receiver has been exploited to reduce the number of 4-port oscilloscopes and respective DP coherent receivers. Successful transmission of 28 GBaud 3 spatial LP modes QPSK, 8, 16, and 32QAM over 41.7 km few-mode fiber demonstrates that the TDM-SDM receiver can reduce the number of 4-port oscilloscopes and DP coherent receivers without adding a penalty to the measurement result. A second key contribution of this work is the demonstration of the scaling of the number of received DP mode channels in a second dimension in addition to the conventional method of adding 4-port oscilloscopes. Through carrier phase estimation, it is shown that the TDM-SDM receiver performs similarly as adding additional 4-port oscilloscopes. Key to this performance is the phase matching between the LO and signal paths particularly when AOM switches are employed to gate the modes into the receiver. Particularly as the ongoing challenge in few-mode systems is to increase the number of transmitted modes, it is highlighted that this proposed method is an order of magnitude cheaper than scaling conventionally by adding oscilloscopes. This method potentially allows a greater level of output on spatial division multiplexed systems research.

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