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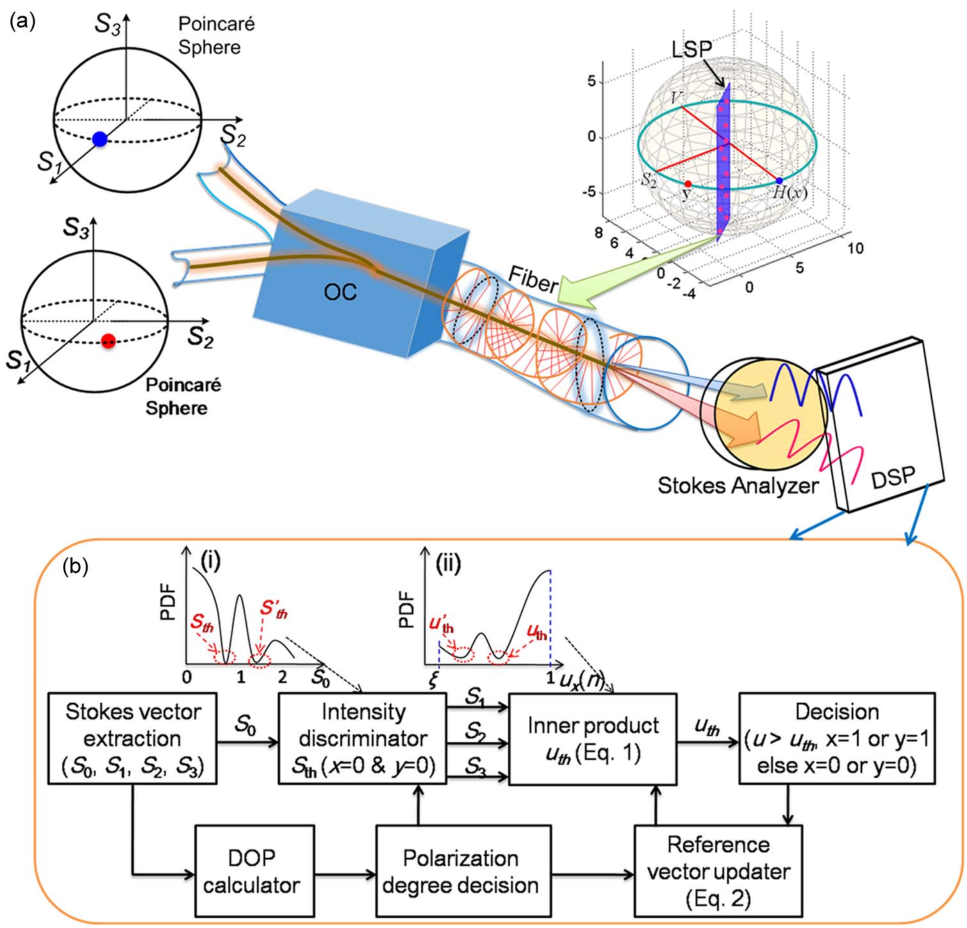

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A Highly Flexible Polarization Demultiplexing Scheme for Short-Reach Transmission

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Abstract: We propose and experimentally demonstrate an effective and highly flexible polarization demultiplexing scheme based on a Stokes analyzer, which could be also applied to the nonorthogonal polarization division multiplexing (NPDM) schemes. Compared with the conventional direct detection, the proposed method has better tolerance to the polarization-dependent loss. Furthermore, such an approach can significantly enhance system flexibility without increasing cost and complexity since the transmitted signals are not required to maintain strict orthogonality, and no additional polarization-tracking feedback circuit is needed. Experimental results show that any polarization multiplexing degree that is larger than 23° can be adaptively demultiplexed after 10-km transmission using optical orthogonality monitoring and digital-signal-processing (DSP) algorithms.

Index Terms: Non-orthogonality, multiplexing, polarization, transmission.

1. Introduction

With the dramatic development of data centers [1], [2], there is currently great interest in short-reach network interconnection with tens of kilometers [3]. Different from the long-haul transmission, such network requires massive numbers of transceivers, which leads to the cost becoming the primary consideration for the short-reach network. Therefore, intensity modulation and direct detection system is considered to be a suitable solution for the short-reach communications.

On the other hand, system capacity increment is the most important demand as well. Generally, the polarization-division-multiplexing (PDM) scheme, which transmits two data streams with orthogonal states of polarization (SOPs) at the same wavelength, is considered to be an imperative technology as it can double the spectral efficiency (SE) directly [4]–[8] with a simple demultiplexing method [9], [10]. The orthogonal polarizations can be directly separated by using a polarization controller (PC) and a polarization beam splitter (PBS). However, such systems are sensitive to polarization-related impairments such as polarization dependent loss (PDL) [11]–[13] and require an additional feedback circuit to realize the polarization tracking. Actually, for the conventional PDM system, the orthogonality itself might become a hurdle to further increase SE as only two polarizations are available. Therefore, a novel transmission technology named as non-orthogonal polarization division multiplexing (NPDM) breaks the orthogonality between two polarization tributaries, and becomes a possible solution since it has high PDL tolerance and capacity potential. Up to now, only a few works have been reported about NPDM, including 45° and 60° multiplexing [14], [15]. However, the first work does not provide the experimental demonstration, while the other one has a limitation for the transmission.

In this paper, we propose a polarization demultiplexing approach for the short-reach applications, which not only can be applied to the PDM system, but also can realize the demultiplexing for NPDM system. Effective and adaptive demultiplexing is achieved using optical orthogonality monitoring (i.e., through degree-of-polarization: DOP) and digital-signal-processing (DSP) algorithms. Such solution can enhance the flexibility of the transceivers without increasing cost and complexity since the transmitted signals are not required to maintain orthogonal to each other strictly and no additional polarization tracking feedback circuit is needed. Furthermore, compared to the conventional direct detection, the proposed demultiplexing approach has a better tolerance to the polarization dependent loss (PDL). Experimental results show that the polarization multiplexing angle as minimum as 23° between two polarization tributaries could be successfully transmitted and demultiplexed after 10-km SMF. To the best of our knowledge, this is the first time that NPDM system with such small degree is experimentally demonstrated over longer distances.

2. Principle of Demultiplexing

For NPDM system, the key technology is the multiplexing and demultiplexing, whose block diagram is shown in Fig. 1. Two signals can be polarization multiplexed to generate a NPDM signal by two polarization controllers (PCs) and an optical combiner (OC). As can be seen from Fig. 1(a), assuming that the coordinate axes x and y represent the polarizations of two incident signals, the SOPs of the combined NPDM have been perpendicular to the $x - y$ direction properly, and hence the signal transmits over SMF with the elliptical polarization.

At the receiver side, the Stokes vector $[S_0, S_1, S_2, S_3]$ is picked up first by employing a Stokes analyzer. Subsequently, a part of the received signal is used to monitor the DOP to determine the polarization multiplexing angle between two incident tributaries. Afterwards, as described in [9], S_0 is used to discriminate intensity while the vector $S = [S_1,\ S_2,\ S_3]$ is used to track one of tributaries. Different from [9], the NPDM demultiplexing should track both tributaries simultaneously in our experiment.

The decision rule of polarization demultiplexing is shown in Fig. 1(b), where the key parameters are two thresholds that are used to determine low logic level (i.e., S_{th}) and high logic level (i.e., u_{th}). In NPDM-OOK system, S_0 means the received total signal intensity. According to the intensity of two input signal, the total intensity of received signal (S_0) can be classified into three groups: (i) S_0 is zero when logic levels of both of the polarization tributaries are low; (ii) S_0 is 1 when one tributary is in high level while the other is in the low level; (iii) S_0 is 2 when both of the tributaries are in the high level. Therefore, the statistical characteristics of S_0 is illustrated as shown in Fig. 1(b-i), where two thresholds S_{th} and S'_{th} are obtained by determining the minimal values of $S_0(n)$. In this case, both logic levels of the tributaries are low when $S_0(n) < S_{th}$, and both logic levels are in high when $S_0(n) > S'_{th}$. However, considering the amplified spontaneous emission (ASE) in the system, cases (ii) and (iii) cannot be separated clearly by using S'_{th} when the noise becomes larger. Therefore, only threshold S_{th} are determined according to the probability density function (PDF) of S_0. Subsequently, in order to track the signal polarization, we introduce two noise-free unit Stokes vectors expressing the SOP of tributaries x and y, represented as $\mathbf{v}_{x,y}$ (if there are three polarizations in the transmission, three reference vectors

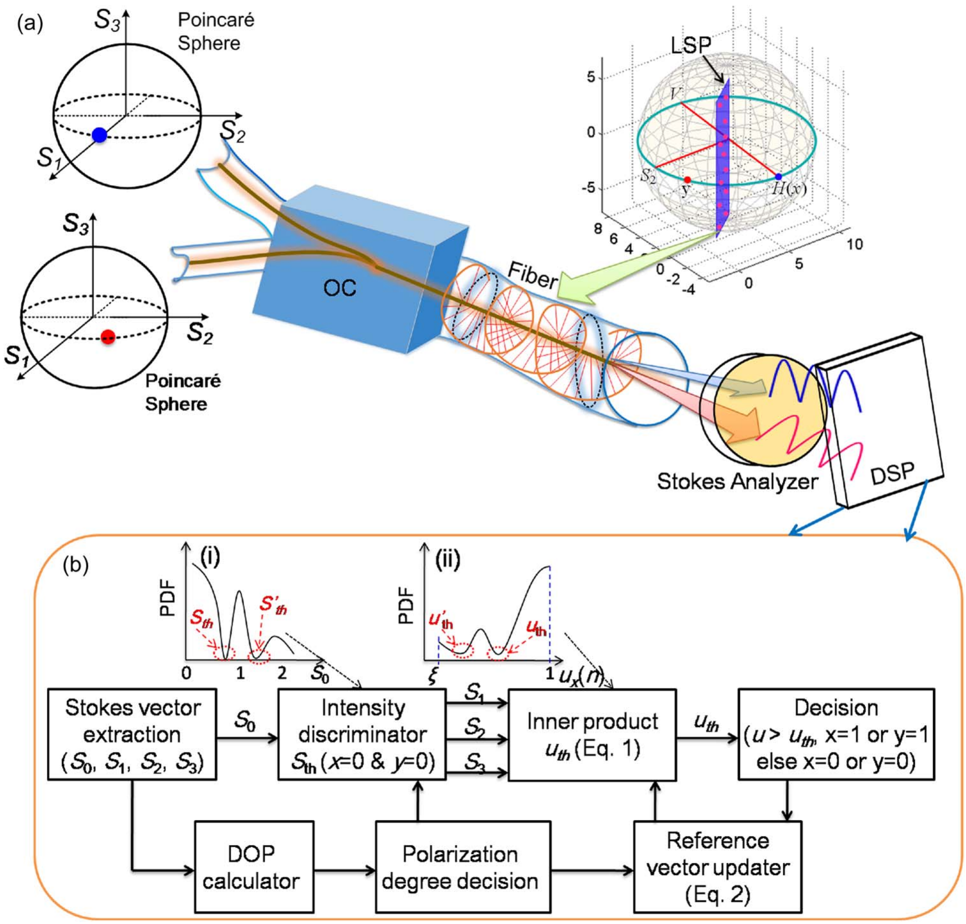

Fig. 1. (a) Conceptual illustration of NPDM system. (b) Polarization demultiplexing of proposed algorithm. H: linear horizontal polarization state; V: linear vertical polarization state; LSP: least squares plane of the Stokes vectors; PDF: probability density function; S_{th} is the threshold to decide the both low levels for NPDM signal; u_{th} is the threshold to decide high level for tributary x or y.

are required). Therefore, the direction offset between the received normalized Stokes vector $\mathbf{S}(n)/S_0(n)$ and reference vector $\mathbf{v}(n)$ can be expressed by an inner product, which is govern by

$$u_{x,y}(n) = [\mathbf{S}(n)/S_0(n)] \cdot \mathbf{v}_{x,y}(n) \tag{1}$$

where n means the nth number of sampled signal. According to (1), if the normalized Stokes vector of received signal is along the direction of the reference vectors $\mathbf{v}_x$ or $\mathbf{v}_y$, the value of $u_x(n)$ equals 1 or ξ, where the value of $\xi(-1 \leq \xi < 1)$ depends on the multiplexing degree. For instance, ξ equals −1 when the multiplexing degree is 90°. On the other hand, if the Stokes vector of the received signal is between the directions of $\mathbf{v}_x$ and $\mathbf{v}_y$, $u_x(n)$ has a value between ξ and 1. The statistical characteristics of $u_x(n)$ is illustrated as in Fig. 1(b-ii), where two thresholds u_{th} and u'_{th} can be determined when the PDF of $u_x(n)$ is minimum. In this case, the x-tributary is in high level when $u_x(n) > u_{th}$, and y-tributary is in high logic when $u_x(n) < u'_{th}$. However, as the multiplexing degree decreases, u'_{th} becomes weak. Therefore, y-tributary should be tracked by using an independent reference vector $\mathbf{v}_y$. The reference vector $\mathbf{v}_{x,y}$ should be updated as

$$\mathbf{v}_{x,y}(n+1) = \frac{\mathbf{v}_{x,y}(n) + \mu[\Delta(n)]}{\left\|\mathbf{v}_{x,y}(n) + \mu[\Delta(n)]\right\|} \tag{2}$$

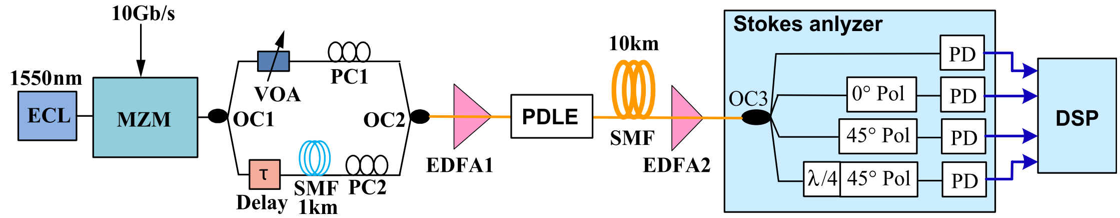

Fig. 2. Experimental setup of NPDM system for the intensity signals. ECL: external cavity laser; MZM: Mach–Zehnder modulator; OC: optical coupler; VOA: variable optical attenuator; PC: polarization controller; PDLE: polarization dependent loss emulator; SMF: single-mode fiber; EDFA: erbium-doped fiber amplifier; PD: photodetector; DSP: digital signal processor.

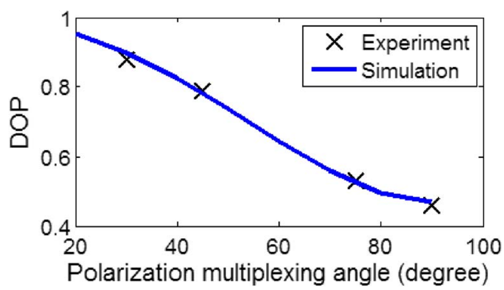

Fig. 3. Comparison of the simulation (solid line) and experimental (cross) orthogonality monitoring results.

where μ is the step-size parameter, $\mathbf{v}_{x,y}$ is the reference Stokes vector for x or y tributary, and $\Delta(n)$ is the error vector, which is expressed as

$$\Delta(n) = \mathbf{S}(n)/S_0(n) - \mathbf{v}_{x,y}(n). \tag{3}$$

On the other hand, when $u_{x,y}(n) \le u_{th}$, the x-tributary (or y-tributary) should be determined to be low level and the reference vector is not updated. Finally, two incident signals with non-orthogonal polarizations can be separated after decision.

3. Experimental Setup and Results

The experimental setup for 20-Gb/s NPDM-OOK optical communication system over 10-km SMF transmission is shown in Fig. 2. At the transmitter, the light from external cavity laser (ECL) oscillating with ~100-kHz line-width at 1550-nm is first modulated by a Mach–Zehnder modulator (MZM). Afterwards, the encoded intensity signal is split into two streams and then are polarization multiplexed to generate a NPDM-OOK signal by employing two optical couplers (OCs) and two polarization controllers (PCs). Here, 1-km SMF is inserted into one branch to decorrelate the data stream, a variable optical attenuator (VOA) is applied in the other branch to balance the optical power of two channels, and an optical delay is used to make the bit sequences of two channels synchronized in the time domain. Subsequently, the NPDM signal launches into a polarization dependent loss emulator (PDLE) or a 10-km SMF whose loss is compensated by an erbium-doped fiber amplifier (EDFA). In the receiver, a stokes analyzer and a digital signal processor (DSP) is used to demultiplex and recover the NPDM signal.

In order to improve the effective and flexibility of the demultiplexing approach, the polarization multiplexing degree monitoring is firstly performed since it could determines the two important parameters S_{th} and u_{th} adaptively. As mentioned above, the angle between two polarizations (i.e., orthogonality) in our experiment could be estimated simply only by calculating the average DOP value of 1024 points as shown in Fig. 3. As can be seen, the experimental results agree well with the simulation performed by using VPI platform.

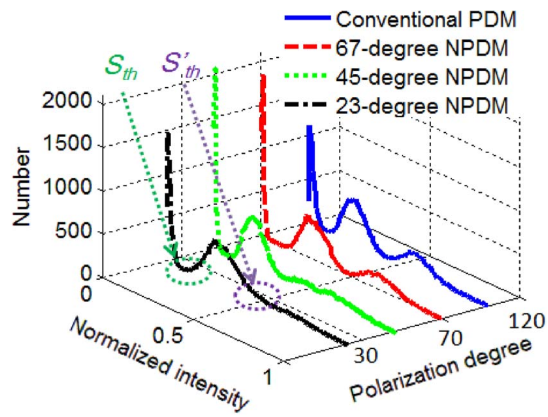

Fig. 4. Histogram of the normalized incident intensity (S_0) for the different polarization multiplexing degree.

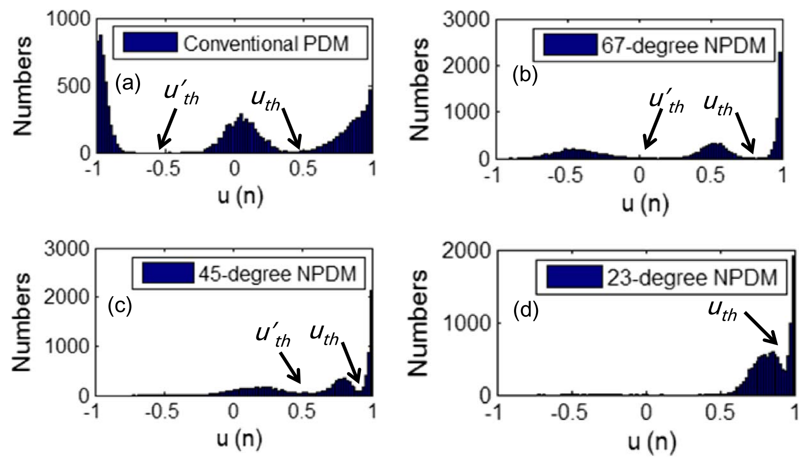

Fig. 5. Histogram of the inner product $u(n)$ for the different polarization multiplexing degree when the totally received power is −14-dBm.

Fig. 4 shows the histogram of the normalized intensity (S_0) for the NPDM-OOK signal with the different polarization multiplexing degrees when total received power is −14-dBm. In all cases, the threshold S_{th} is obvious, and hence the both logic levels of tributaries are decided to be 0 (i.e. $x = 0$ and $y = 0$) when total intensity S_0 is smaller than S_{th}. However, the discrimination ability for the case of both high levels (i.e. $x = 1$ and $y = 1$) becomes more and more poor as the polarization multiplexing degree decreasing since the threshold S'_{th} is hard to be determined.

The histogram of the inner product $u(n)$ given by (1) is shown in Fig. 5, which indicates the ability for separating one tributary from the other one. In Fig. 5(a), the conventional PDM signal can be demultiplexed only using a single reference vector $\mathbf{v}$. The decision rule is that x-tributary is in high logic when $u(n) > u_{th}$. Meanwhile, the y-tributary is in high logic when $u(n) < u'_{th}$. However, in the proposed NPDM scheme, the decision for the threshold u'_{th} becomes weaker as the polarization multiplexing degree deceases, which means that two tributaries should be tracked independently by using different reference vectors $\mathbf{v}_{x,y}$. Taking the x-polarization tracking for example, if $u(n)$ equals 1 (or −1), the direction of the reference vector is considered to be the same (or revise) with the tributary x. Therefore, the high logic level for tributary x can be clearly separated when $u(n)$ is larger than u_{th}. Afterwards, the reference $\mathbf{v}_x$ is updated according to the (2). Nevertheless, the statistical properties of $u(n)$ appear different when the polarization multiplexing degree changes as shown in Fig. 5. Therefore, the optimized thresholds u_{th} is required to be

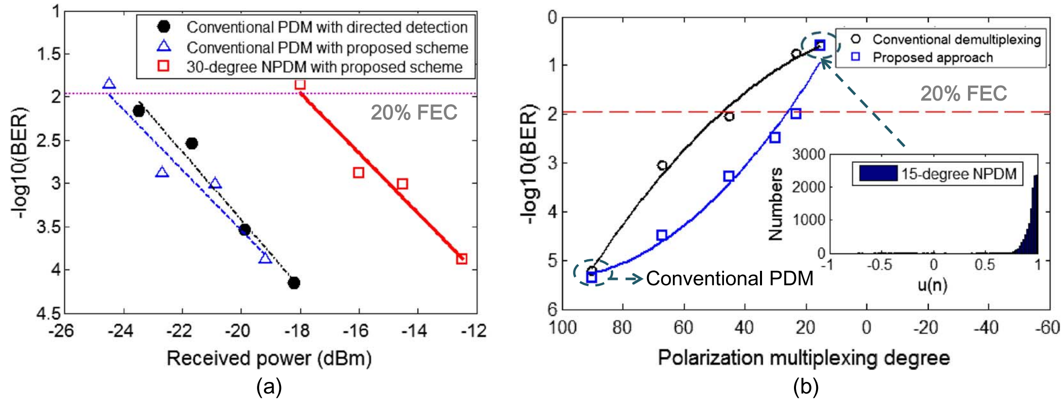

Fig. 6. (a) BER performance of conventional PDM and 30° NPDM systems after 10-km transmission. (b) BER performance versus different polarization multiplexing degree, including 90°, 67°, 45°, 30°, 23°, and 15° NPDM systems after 10-km transmission when the totally receiver intensity is fixed to be −14-dBm.

adjusted according to the different polarization multiplexing degree. Similar to the above steps, the tributary y could be demodulated only by changing the initial reference vector to track the y-polarization signal. In addition, the location of the second peaks of Fig. 5(a)–(d) could provide a potential method to calculate the polarization multiplexing degree.

To further investigate the transmission performance, the 30° NPDM signal is fed into a 10-km SMF. Fig. 6(a) shows the bit-error ratio (BER) for conventional PDM system and 30° NPDM system by employing PBS with direct detection (PBS/DD) and proposed method with Stokes analyzer. Here, the received power is the power of one tributary. Hard-decision 20% FEC threshold are depicted as reference. For the conventional PDM system, the performances of such two demodulation schemes are similar, while for the 30° NPDM system, the receiver sensitivity based on proposed scheme at 20% FEC achieves −18.1 dBm. In this case, although a large power penalty of ~6-dB is obtained compared to the conventional PDM with PBS/DD approach, the measured BER value is still below the FEC threshold. However, when applying the conventional PBS/DD to the 30-degree NPDM, the measured BER is always within the 20% FEC threshold, which indicates that the proposed scheme has a high flexibility for the different multiplexing angles. Fig. 6(b) shows the system performances employing conventional PBS/DD demultiplexing and proposed approach versus the different polarization multiplexing degree when the totally received power is fixed to be −14-dBm (i.e., −17-dBm for each tributary). In this case, the polarization multiplexing angle varies from 90° to 15°. Although the BER performances detected by proposed approach and conventional PBS/DD scheme are very close in 90° multiplexing and 15° multiplexing cases, our approach has the higher demultiplexing performance obviously between 15° and 90°. Furthermore, the NPDM system with the multiplexing angle of small to 23° could still be demultiplexed after 10-km SMF by using proposed algorithm. To the best of our knowledge, it is the first time that NPDM system with such small degree is experimentally demonstrated over longer distance. However, when the multiplexing angle further decreases to 15°, the BER of demultiplexing signal increases to $10^{-0.5}$, which is beyond the FEC threshold. In this case, the NPDM system with the multiplexing angle of 15° cannot be demultiplexed effectively after 10-km transmission. It is because that u_{th} could not be decided according to the histogram of $u(n)$ even increasing the received power.

To assess the PDL tolerance of the proposed algorithm, one channel of the multiplexed signal is launched at 45° relative to the least lossy axis of the PDLE to simulate the worst-case. Fig. 7 shows the OSNR penalties of the 79° and 45° NPDM systems with proposed algorithm and conventional PBS/DD at BER of 10^{-3} as a function of PDL value. Here, OSNR penalty means all of OSNR results are subtracted to the OSNR values when total PDL is 1-dB. In 79° NPDM system, the performance of the proposed scheme after PDL is obviously better than

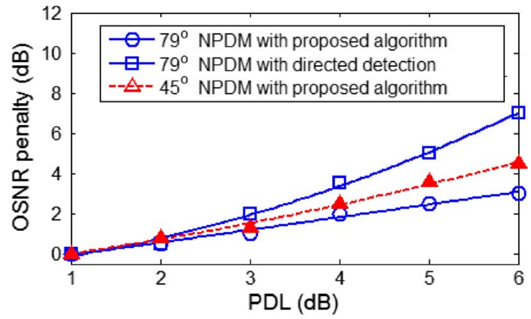

Fig. 7. Simulation results for OSNR penalty of the 79° and 45° NPDM systems with proposed algorithm and directed detection at BER of 10^{-3} as a function of the PDL value.

PBS/DD approach. Especially when PDL value is 6-dB, the OSNR penalty of PBS/DD is 7-dB at the BER of 10^{-3}, while the penalty of proposed algorithm decreases to 3-dB. In order to demonstrate that the proposed scheme is more tolerant towards PDL, 45° NPDM signal is sent to the PDLE as well. In simulation, the OSNR penalty of proposed approach in 45° NPDM system is only 4.5-dB. However, in this case, the signal is even unable to be demodulated by employing DD algorithm. Therefore, it is clearly seen that the proposed NPDM can tolerate a large PDL value.

4. Conclusion and Discussion

We have proposed and experimentally demonstrated a novel polarization demultiplexing algorithm based on Stokes analyzer and DSP, which can be applied to the NPDM system as well. Proposed scheme has a better tolerance to the PDL compared to conventional PBS/DD approach. Experimental results show that the signal with the polarization multiplexing angle of small to 23° is successfully transmitted over 10-km SMF.

This paper does not provide the experimental demonstrations about the cases with more than two polarization tributaries, but it should be noted that the theoretical basis of demultiplexing for multi-polarization division multiplexing (MPDM) signal is similar to that of NPDM signal. For instance, if there are three (or four) polarizations in transmission, three (or four) reference Stokes vectors are required. Furthermore, the updated rule of corresponding reference vector is (2) as well. While we have to admit that there are still some issues worthwhile pursuing when the polarizations are more than two, including algorithm compatibility of NPDM and MPDM systems, how to effectively determine the thresholds S_{th} and u_{th}, etc. We also believe that the MPDM signal transmission would be reported in the near future.

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