Up to 20 Mrad/s RSOP monitoring based on FFT and Wavelet Transform in optical domain,

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***Abstract*—An RSOP monitoring technique in optical domain is demonstrated without the help of coherent receiver. Up to 20 Mrad/s RSOP was monitored with CD tolerance of 1360 ps/nm and power sensitivity of -20 dBm.**

***Keywords*—optical fiber communications, rotation of state-of-polarization, FFT, Wavelet Transform**

I. INTRODUCTION

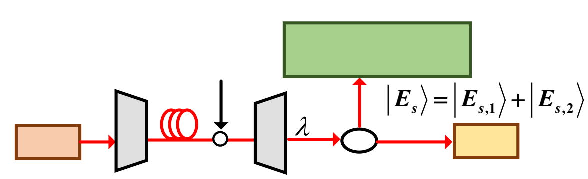
In optical fiber communication system, especially metro WDM networks, the complex environments for optical link come with various risk events, such as fiber squeezing, mechanical vibration, and lightning stroke, which may cause the ultra-fast speed of rotation of state-of-polarization (RSOP) in optical fiber [1-2]. Therefore, accurate monitoring the RSOP's speed (as well as the variation of RSOP's speed) can help us to identify these risk events timely and avoid further damage for signal transmission. Conventional monitoring methods are analyzing the adaptive tap-weights of adaptation algorithms, such as constant module algorithm (CMA), or geometrically analyzing the pilot symbol in Stoke space [3-5]. However, the monitoring performance of the above-mentioned algorithm schemes depends on whether the MIMO tap coefficients in the coherent receiver converge well. This indicates that, in extreme scenarios where the adaptation algorithms cannot converge (e.g., in the case with ultrafast RSOP), the speed of RSOP will not be able to be effectively monitored. In addition, those methods rely on the framework of coherent receiver and cannot monitor arbitrary section of the fiber link that we are interested. Furthermore, the complexity of CMA and geometrically analyzing also limits the speed and accuracy of monitoring. Currently, these monitoring methods can only capture RSOP up to several mega rad/s (Mrad/s), and the relative error is above 5% [3-5].

In this paper, we propose and demonstrate a method for monitoring RSOP that is independent of modulation format and does not require the usage of the coefficients of the converged adaptation algorithm. By directly analyzing the power of optical signal, the proposed method is no longer limited by the framework of coherent receivers. Thus, the proposed monitoring method is applicable to both intensity-modulation direct-detection (IM-DD) system and coherent system. Furthermore, it can monitor the RSOP at any point in the fiber link. Experimental results show that the proposed method can monitor the speed of RSOP up to 20 Mrad/s with the relative error less than 1%. The chromatic dispersion (CD) tolerance is large than 1360 ps/nm (i.e., CD amount of 80 km standard single-mode fiber), and monitoring sensitivity to the input optical power is as low as -20 dBm.

II. PRINCIPLE

Figure 1(a) shows the schematic diagram to verify the proposed RSOP monitoring scheme. The monitoring module is placed before the coherent receiver, and the light to the monitor module is provided by the 5% port of a 95:5 coupler. The signal light to be detected is expressed as $|E_s\rangle$, which includes two polarization tributaries $|E_{s,1}\rangle$ and $|E_{s,2}\rangle$ carrying the polarization division multiplexed signals.

(a)



(b)

(c)

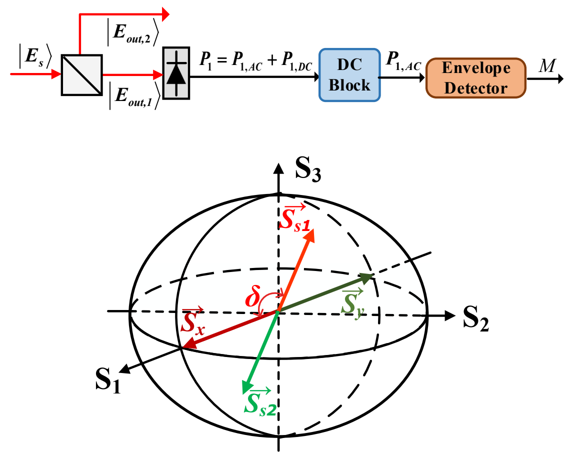


Fig. 1. (a) The schematic diagram to verify our proposed RSOP monitoring scheme; (b) The structure of the monitoring module; (c) Polarization vectors changing in Stokes space.

The structure of the monitoring module is shown in Fig.1(b). The $|E_s\rangle$ is projected by a polarization beam splitter (PBS) onto its two fixed eigenvectors $|E_x\rangle$ and $|E_y\rangle$. The projection results are $|E_{out,1}\rangle = |E_x\rangle\langle E_x|E_s\rangle$ and $|E_{out,2}\rangle = |E_y\rangle\langle E_y|E_s\rangle$. Then two photodetectors convert them into two electrical powers P_1 and P_2, respectively. Both P_1 and P_2 are composed by direct current (DC) parts and alternating current (AC) parts. The DC parts of P_1 and P_2 are equal, and the AC parts are opposite to each other:

$$P_{1,DC} = P_{2,DC},\ P_{1,AC} = -P_{2,AC} = P_0 \sin\delta\cos(\psi) \tag{1}$$

where δ is the angle between two polarization state vectors $\vec{S}_{S1}$ and $\vec{S}_x$ in Stokes space as shown in Fig.1(c). $\vec{S}_{S1}$ and $\vec{S}_x$ in Stokes space correspond to the output signal $|E_{s,1}\rangle$ and the fixed eigenvector $|E_x\rangle$ of the PBS. The change of angle δ reflects the polarization change of fiber link. Therefore, we are only concerned with the AC part and eliminate the DC part. The angle ψ is the phase difference with equal probability between 0-2pi, yielding $\langle \cos^2\psi \rangle = 1/2$. So, after P_1 or P_2 passes through the envelope detector, the expectation value of the electrical power will be proportional to $\sin^2\delta$. Eventually, we get the monitoring signal:

$$M = \langle (P_0 \sin\delta\cos(\psi))^2 \rangle \propto \sin^2\delta \tag{2}$$

Since the variation of the angle δ reflects the polarization rotation of fiber link, we can obtain the speed of RSOP by performing the fast Fourier transform (FFT) on M. For the case with constant RSOP (e.g., considering the RSOP in a short moment), the frequency of M is the speed of RSOP. Considering the noises in the spectrum of M, the peak frequency component (i.e., the frequency component with maximum power) $F_{\max}$ is the speed of RSOP. As a result, the "polarization change" (in radian unit) is:

$$Polarization\ change = 2\pi \times F_{\max} \tag{3}$$

Furthermore, using wavelet transform to time-frequency analysis of M, we can obtain the statistical overview for frequency components of each moment, which allows us to monitor the distribution of the speed of RSOP in fiber link (e.g., the RSOP usually follows the Rayleigh random distributions in practical link).

III. Experimental Results

To verify our proposed monitoring method, we establish a coherent optical communication platform and an RSOP monitoring module. The block diagram of the experimental setup is shown in Fig.2. A 112 GBaud, dual polarization 16QAM signal is generated by the transmitter and then sent to the polarization scrambler (EPS1000), which can emulate the RSOP in the modes of half-waveplate (HWP) and Rayleigh distribution. The speed of RSOP can be set from 0 to 20Mrad/s for the mode of HWP. After scrambler, the signal enters the 80 km standard single-mode fiber which brings the chromatic dispersion of about 1360ps/nm. Then, 5% of the transmission signal is extracted for monitoring. By adjusting the variable optical attenuation (VOA), we can change the input optical of the monitoring circuit in the range of -13 dBm to -20 dBm. The photodetector (PD) module completes opto-electronic conversion and isolates the DC part of the electrical signal (by built-in capacitor). According to Eq. (2), the signal output from envelope detector is only relevant to the angle δ. And the analog to digital converter (ADC) module completes sample and analog-digital conversion. Finally, the digital signal output from the monitoring circuit is sent to a computer for offline processing. The received data does not require any pre-processing, and we can directly perform FFT or wavelet analysis on the data. When the scrambler operates in the HWP mode, the waveform of the monitored signal approximates a sine form, the FFT with low-complexity is sufficient for analysis. For Rayleigh mode of the scrambler, however, due to the random variation of RSOP, it cannot be measured accurately by the FFT spectrum. In this case, we need to use wavelet transform for time-frequency analysis to get more useful information.

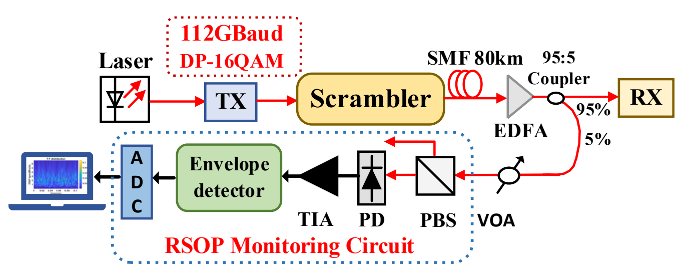
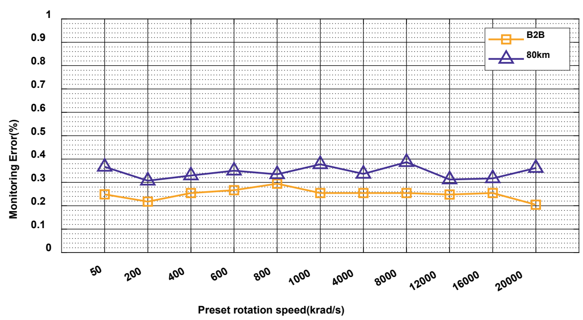


Fig. 2. Experimental setup (PBS: polarization beam splitter; VOA: variable optical attenuator; EDFA: Erbium doped fiber amplifier; PD: photodetector; TIA: trans-impedance amplifier; ADC: analog-to-digital converter)

First, we explored the impact of CD on the monitoring results. When the mode of the scrambler is HWP, we conducted monitoring experiments in the case of back-to-back (BTB) and 80km fiber, respectively, with the same optical power. The results are shown in Fig. 3 (a). In the RSOP's speed range of 50krad/s to 20Mrad/s, the monitoring errors are less than 0.3%

and 0.4% in the cases of BTB and 80 km fiber link, respectively. In addition, Fig.3(b) shows the signal waveform and spectrum of the monitored signal of BTB and 80 km fiber link at 20 Mrad/s RSOP. It can be seen that CD impairment from the 80 km fiber brings power disruptions, such that the monitored frequency has a variety of spurious frequencies. However, it does not impact the primary components of the monitored frequency. Therefore, the proposed monitoring method is fully tolerant of the CD of 1360 ps/nm.

(a)



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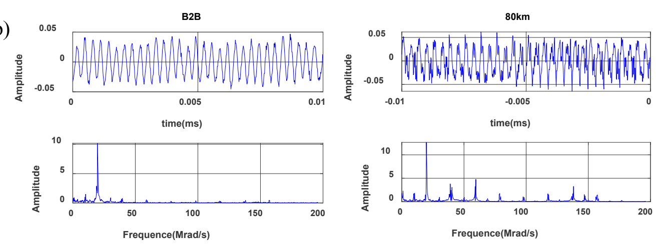
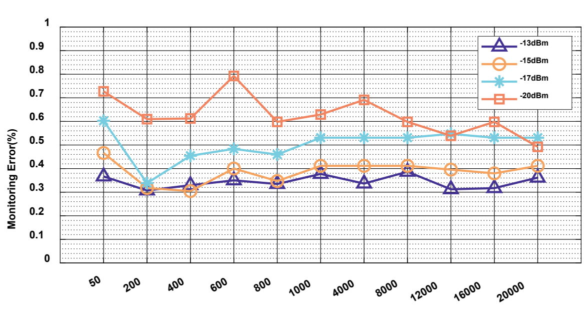


Fig. 3. (a)RSOP monitoring results at BTB and 80km fiber;(b) Time domain waveforms and frequency spectrum of monitoring signal at B2B and 80km fiber.

Fig.4(a) illustrates the sensitivity to input power of the monitoring module, in the case of HWP mode of scrambler and 80 km transmission fiber. The monitoring results of -13 dBm and -15 dBm are basically the same and the monitoring errors of both are less than 0.4%. However, for the input power of -17 dBm to -20 dBm, the relative monitoring error increases to 0.9%. This is because the lower input power makes electrical noise more severely interfering with the monitoring signal, as shown in Fig.4 (b). At -20 dBm, we can hardly get the monitoring signal in sine form due to the noise, and the spectrum becomes very bad compared to the monitored signal at -13 dBm, which leads a poor monitoring result. However, these noises do not change the maximum peak component of the spectrum much, as shown in Fig. 4(b), so the monitoring results remain accurate.

(a)



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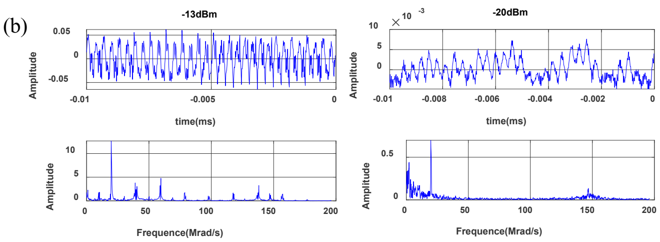
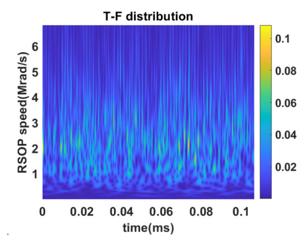


Fig. 4. (a)RSOP monitoring errors at -13 dBm, -15 dBm, -17 dBm and -20 dBm optical power;(b) The time domain waveforms and frequency spectrum of monitoring signal at -13 dBm and -20 dBm optical power.

Furthermore, using the time-frequency analysis of wavelet transform, we can monitor the randomly varying RSOP accurately and obtain the correct statistical distribution. In the case with 80km fiber condition, we switch the scrambling mode to Rayleigh mode and set the maximum rotational speed to 5Mrad/s. Figure 5(a) shows the time-frequency distribution of wavelet transform, and each column represents the frequency distribution at one moment. We count the peak component of each column to get the statistical distribution of Rayleigh mode. As shown in Fig.5(b), the statistical distribution map is basically consistent with the ideal Rayleigh distribution. Therefore, the proposed mothed can monitor and identify some complex and random polarization change events.

(a)



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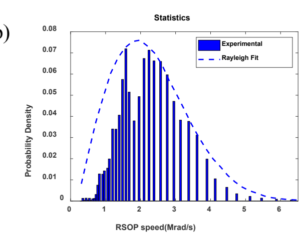

Fig. 5. (a) The time-frequency distribution at 5Mrad/s polarization change with Rayleigh mode; (b) Statistical distribution of the monitored RSOP speed.

In short, the proposed scheme is able to tolerate CD of 1360 ps/nm, has a high sensitivity to the input optical power and can identify the Rayleigh random distribution of RSOP. These capabilities are attributed to the following reasons. By using FFT and Wavelet transform, we get the speed of RSOP which is the peak component in the spectrum, and ignore the other components which mainly caused by the impairments from accumulated CD and low input power. Therefore, the proposed scheme can accurately monitor the RSOP speed as long as the noise is not so large as to completely exceeds the peak frequency component. The experiment is limited by the maximum speed of the scrambler under test and the sampling rate of the ADC, and the monitoring range of the scheme could be larger. Limited by the memory storage depth, the monitoring module cannot sample enough data for wavelet transform for the Rayleigh mode, otherwise the statistical distribution will fit the ideal curve better.

IV. Conclusions

In this paper, we propose an ultra-high speed RSOP monitoring scheme operating in the optical domain and validated it by experiments in a 112 Gbaud-PDM-16QAM coherent system. In the experiment，the monitoring module can completely tolerate the noise caused by accumulated CD of 80 km transmission fiber and the minimum input power can be as low as -20 dBm, with the monitoring error in the range of 0.3% to 0.9%. In the HWP mode, the maximum speed of RSOP monitoring can reach 20 Mrad/s. Furthermore, random RSOP variations in the Rayleigh mode are also accurately identified and monitored.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (62101062, 62071065, 62001040).

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