State-of-Polarization Monitoring Employing Optical Supervisory Channel with Modulated Light

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***Abstract*— We demonstrate a state-of-polarization monitoring method employing an optical supervisory channel is effective in practical situations. The polarization rotation speed was estimated even when the light was modulated and received power was low.**

Keywords—Polarization, state of polarization, optical fiber transmission, optical supervisory channel

I. Introduction

Digital coherent transmission technology with digital signal processing (DSP) has been widely used to cope with the increase in internet traffic. Polarization division multiplexing (PDM) technology enables twice the capacity increase in one single-mode fiber (SMF). In PDM, signals in each polarization are mixed through the fiber transmission; therefore, compensation for crosstalk and separation of signals at the receiver side are required. A multiple-input multiple-output (MIMO) equalizer is used for this processing. Estimation of the state of polarization (SOP) at the receiver side is necessary for MIMO. If there is a steep and abrupt SOP change in the transmission line, it causes tracking errors of MIMO. This leads to signal-quality degradation and penalties in transmission systems [1]. It is important to constantly monitor SOP changes to detect any failure of the optical transmission link and repair it to maintain transmission performance. The causes of SOP change are, for example, fiber squeezing, mechanical vibration, temperature fluctuation, heavy equipment digging near a fiber, and earthquakes. A lighting strike near a fiber line results in fast polarization rotation up to several hundred krad/s in a short time, e.g., less than 500 μs [2]. Methods have been proposed for SOP monitoring. One method is employing finite impulse response filter coefficients of MIMO equalizer to derive the SOP in the Stokes coordinates [3]. This is an attractive method because it does not require extra hardware. However, the monitoring speed is intrinsically limited by the polarization-tracking performance of the MIMO equalizer since it uses the equalized signal. Fast SOP transients may also cause loss-of-signal and make calculating the polarization rotation rate impossible. Another method estimates the SOP by trans-impedance amplifier gain using a convolutional neural network [4]. This method has a limitation of instantaneous short-time SOP fluctuation monitoring because it requires time for calculation. An SOP monitor using an optical supervisory channel (OSC) with polarization beam splitters and two photodiodes has been proposed [5]. This method enables real-time high-speed SOP monitoring. However, its effectiveness was demonstrated only on continuous wave (CW). It is unclear whether this method is effective if the light is modulated and the received power level is low which is common in the practical situations.

In this paper, we demonstrate that the SOP-monitoring method employing optical supervisory channel is effective in practical situations. We compared its SOP-monitoring performance with CW and modulated light (ML) in a back-to-back configuration. The results indicate that our proposed method can be used even with ML. Assuming a more practical use case, we found that the same results can be obtained with fiber spans and when the received signal level is very low, i.e., −40 dBm.

II. Concept of the Proposed Method

Commercial optical transmission systems with wavelength division multiplexing (WDM) typically include an OSC for monitoring and maintaining the transmission line and remotely controlling EDFAs. This OSC also carries information about the main signal such as wavelength channel number and condition of EDFA sites. The signal power of an OSC is controlled to be low to suppress interference with main signals in the C-band. For an OSC, on-off-keying modulation with an OC-3 156 Mb/s signal at 1510 nm is typically used [6]. Fig. 1 shows an example of a transponder-system configuration employing the OSC. The OSCs are inserted into each EDFA node. The single-wavelength OSC optical signal outside the C-band is removed from and added to the optical in-line EDFA system with couplers or filters. Adding SOP monitoring capability to the OSC enables localization of the span where the SOP changes because of the optical-span isolation of the OSC.

III. Back-to-Back Measurement

Fig. 2 shows the measurement setup for our evaluation. The operating wavelength of the laser diode (LD) was 1510 nm, and a modulator with on-off no-return-zero (NRZ) imitating the OC-3 was implemented [7]. We used a polarization scrambler that can rotate electro-magnetic type six quarter wave plates (QWPs) and a half-wave plate (HWP) inside the scrambler at various speeds. The rotation of the

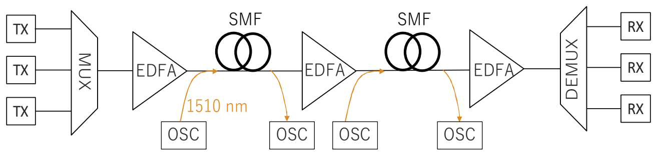

Fig. 1. Configuration of a transponder system employing OSC.

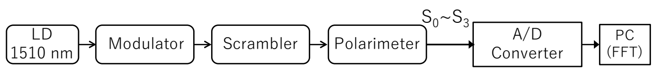

Fig. 2. Back-to-Back measurement setup.

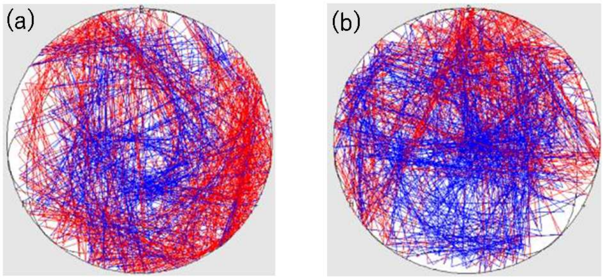

Fig. 3. Traces on the Poincare sphere of (a) CW and (b) ML.

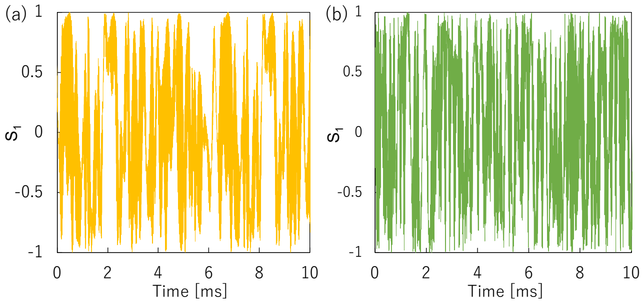

Fig. 4. Time evolution of S_1 for (a) CW and (b) ML.

wave plates causes SOP change, and the HWP-rotation speed (ν) determines the SOP change speed [8]. The ν in this experiment was set from 100 Hz to 1 MHz. The 1-MHz rotation can mostly cover the fast SOP rotation due to lightning strikes [2]. The QWP-rotation speeds were independently set to be sufficiently slower than the HWP-rotation speed to change the SOP randomly. Fig. 3 and 4 illustrate traces of the Stokes parameters on the Poincare sphere and time evolution of S_1 when ν was set to 100 kHz for light without modulation and ML. This light without modulation indicates the light is a CW. The SOP traces were rotated on the Poincare sphere sufficiently and the SOP changed with a random waveform. The rotation was kept continuously to simplify the experiment. The light was received using a polarimeter, which derived the Stokes parameters of the received light, and outputted as analog electrical signals proportional to the Stokes parameters. We used a digital oscilloscope as an analog-to-digital (A/D) converter to convert the input analog signals to digital signals. The SOP-change speed is defined by the Stokes-parameter speed change. This change was analyzed through fast Fourier transform (FFT) in the PC. The SOP-rotation speed was derived from the peak of the FFT waveform.

The Stokes parameter has four elements, S_0, S_1, S_2, and S_3. When a light is traveling along the z-axis, and the x- and y-axes are in a plane perpendicular to the z-axis, then the oscillation vector E of the electric field of the light is written with two components (E_x and E_y) projected onto the x- and the y-axes as follows:

$$E_x = E_{0x}\exp(-ikz) \tag{1}$$

$$E_y = E_{0y}\exp(-ikz + \phi) \tag{2}$$

where E_{0x} and E_{0y} are the maximum amplitude values along the x- and the y-axes, respectively, and ϕ is the phase difference between E_x and E_y. The Stokes parameters S_0–S_3 are then described using (1) and (2), as follows,

$$S_0 = E_{0x}^2 + E_{0y}^2 \tag{3}$$

$$S_1 = E_{0x}^2 - E_{0y}^2 \tag{4}$$

$$S_2 = 2E_{0x}E_{0y}\cos\phi \tag{5}$$

$$S_3 = 2E_{0x}E_{0y}\sin\phi \tag{6}$$

Fig. 5 shows the measured S_1, S_2, and S_3 after FFT when ν was 100 kHz for the CW. The S_0 denotes the total power of the received light, as seen in (3). Because S_0 was constant in this experiment, it could not be used for polarization analysis. The S_1, S_2, and S_3 were similar waveforms that had peaks around 100 kHz; thus, we focused only on S_1 for the following measurements.

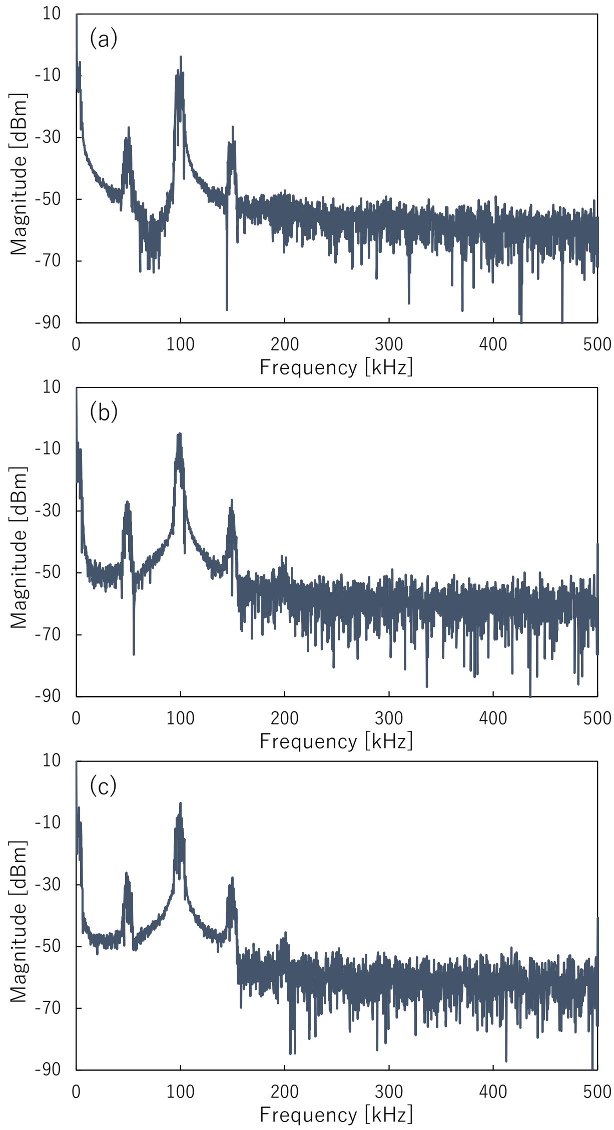

Fig. 5. Measured (a) S_1, (b) S_2, and (c) S_3 after FFT when ν was 100 kHz.

Fig. 6 shows the measured S_1 after FFT for CW and ML when ν was set to 5 kHz and 500 kHz. The peak frequency was almost the same between CW and ML. The peak frequencies also agreed well with ν at each ν. This confirmed that the proposed method is effective for ML and that the SOP-rotation speed can be estimated from the peak frequency.

IV. Measurement Assuming a Practical Situations

We then rearranged the measurement setup to include 50-km and 25-km SMF spans before and after the polarization scrambler. This arrangement enabled us to observe the impact of polarization mode dispersion (PMD) and chromatic dispersion on the proposed method after fiber transmission. For the assumption of further practical conditions, the received power level at the polarimeter was controlled to be low enough, i.e., –40 dBm with a variable attenuator. Fig. 7 shows the rearranged measurement setup.

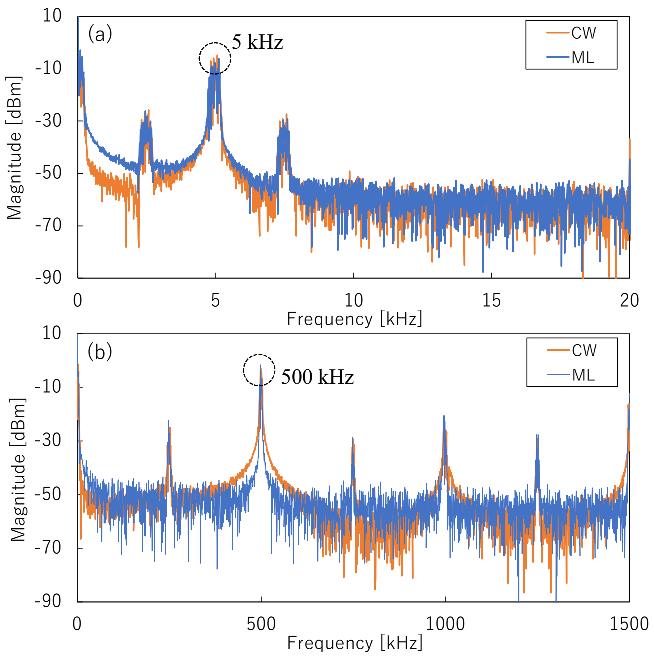

Fig. 6. Measured S_1 after FFT for CW and ML (back-to-back) when ν was set to (a) ν: 5 kHz and (b) ν: 500 kHz.

Fig. 8 shows FFT waveforms for CW and ML when ν was set to 5 kHz and 500 kHz. As ν increased, the difference between the peak and bottom became smaller due to the increase in the noise floor. Although the low received power, peaks at each SOP-change speed were clearly observed as the previous back-to-back configuration.

Table 1 summarizes the correlation coefficients between the FFT waveforms of CW and that of ML at each ν from 100 Hz to 1 MHz. Peak frequencies in each condition are also summarized in table 1. High correlation was achieved, which indicates that SOP-change speed can be evaluated as CW even if the light is modulated in a practical situation. Peak frequencies well matched with ν for both CW and ML. When ν was 1 MHz, the peak was observed by setting the received power up to −30 dBm for both CW and ML but difficult at −40 dBm. We believe this is due to the operation lower-power-limit of the polarimeter, which was around −40 dBm in our experiment, and the sampling time was short to take the high-speed change. The results indicate that the proposed method can be useful in practical situations in which there are fiber transmission lines and the received power is low.

V. Conclusion

We demonstrated the effectiveness of an SOP-monitoring method that uses an OSC by comparing its performance with CW and ML. The results indicate that the proposed method can be used with ML and when the transmission power is low, as assumed in practical situations.

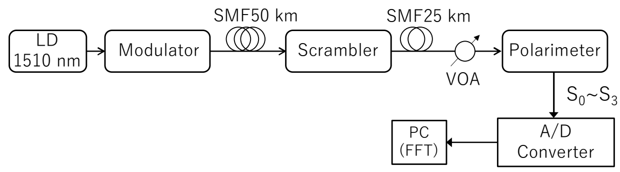

Fig. 7. Measurement setup with SMF spans.

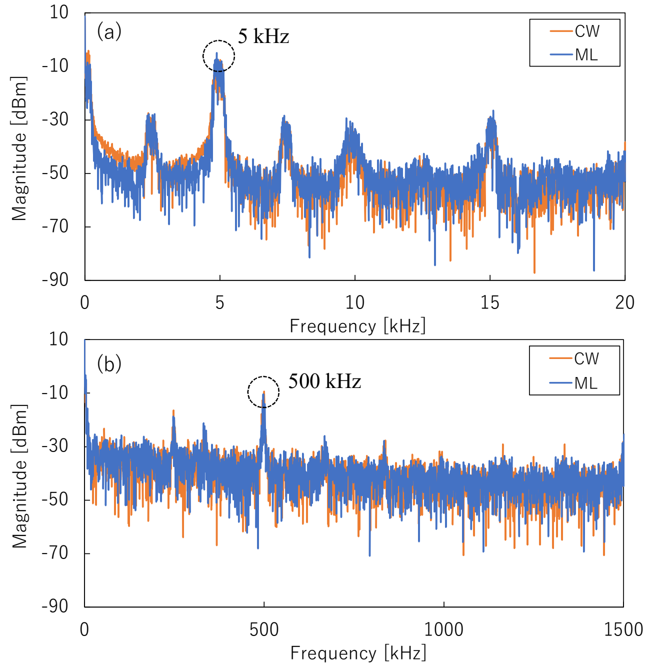

Fig. 8. Measured S_1 after FFT for CW and ML (with SMF spans and low received power) when ν was set to (a) ν: 5 kHz (b) ν: 500 kHz.

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TABLE I. Correlation coefficients between CW and ML and peak frequencies

ν [Hz]		100	500	1k	5k	10k	50k	100k	500k	1M
Correlation efficient		0.92	0.91	0.96	0.93	0.93	0.93	0.93	0.96	0.92
Peak frequency	CW[Hz]	98.4	505	1.02k	4.98k	9.89k	49.4k	101k	500k	0.984M
	ML[Hz]	98.6	502	1.00k	5.01k	9.84k	49.6k	101k	499k	0.986M