Real-time optical spectrum analysis of a light source using a polarimeter

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Abstract: Optical spectrum analysis and polarization analysis are not generally related by conventional wisdom. In this paper, we show that the spectrum of a light beam can be obtained using a polarimeter, with a resolution and a speed that cannot be achieved with traditional spectrum analysis methods. We experimentally demonstrate a novel polarimeter-based optical spectrum analyzer (P-OSA) and show that the high-speed and high-resolution nature of the device enables rapid measurement of the spectrum of swept laser sources at a repetition rate of more than 100 kHz. We show the generation of a unique 3-D plot of the spectral shape of a light source as its center wavelength is swept.

OCIS codes: (260.5430) Polarization; (070.4790) Spectrum Analysis

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References and links

1. B. J. Pernick, D. Yustein, and C. Bartolotta, "An Optical Spectrum Analyzer for Power Spectral Density Measurements," Appl. Opt. **8**, 65-73 (1969)
2. T. K. Gaylord and M. G. Moharam, "Analysis and applications of optical diffraction by gratings," in Proceedings of the IEEE, **73**, 894-937 (1985)
3. M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," J. Opt. Soc. Am. **72**, 156-160 (1982)
4. D. Derickson, *Fiber optic test and measurement*, (Prentice Hall, 1998.), Chap. **3-6**, pp. 12.
5. D. M. Baney, B. Szafraniec, and A. Motamedi, "Coherent Optical Spectrum Analyzer," IEEE Photon. Technol. Lett. **14**, 355-357 (2002).
6. http://generalphotonics.com/POD-101D.htm
7. C. R. S. Fludger, T. Duthel, D. van den Borne, C. Schulien, E. Schmidt, T. Wuth, J. Geyer, E. De Man, G. Khoe, and H. de Waardt, "Coherent Equalization and POLMUX-RZ-DQPSK for Robust 100-GE Transmission," J. Lightwave Technol. **26**, 64-72 (2008)
8. M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light* (7th ed.), (Cambridge University Press, 1999).
9. http://www.lambdaquest.com/products.htm
10. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography," Science **254**, 1178-1181(1991).
11. R. Huber, M. Wojtkowski, and J. G. Fujimoto, "Fourier Domain Mode Locking (FDML): A new laser operating regime and applications for optical coherence tomography," Opt. Express **14**, 3225-3237 (2006).
12. S. Tammela, H. Ludvigsen, T. Kajava, M. Kaivola, "Time-resolved frequency chirp measurement using a silicon-wafer etalon," IEEE Photon. Technol. Lett. **9**, 475-477 (1997)

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1. Introduction

Traditional optical spectrum analyzers (OSAs) are usually realized using one of the following three methods: 1) a spatially dispersive element, such as a diffractive grating, 2) a tunable narrow-band filter, such as a Fabry-Perot (F-P) resonator or a tunable fiber Bragg grating, and 3) path-length-difference varying interferometer (Michelson or Mach-Zehnder) followed by FFT analysis [1-3]. However, design tradeoffs exist among the resolution, the spectral range, and the measurement speed [4], and therefore it is difficult to achieve all three parameters simultaneously. For example, the spectral resolution and the measurement range (free

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spectral range) of an F-P filter based OSA are inversely proportional to each other. In order to achieve fine resolution, the spectral range tends to be sacrificed. Improved resolution and dynamic range are possible with coherent analysis techniques, yet it requires an advanced swept local oscillator with polarization control [5]. Furthermore, for fast swept tunable lasers with a scanning range of > 160 nm and a sweeping rate of tens of kHz, it is desirable to measure the changing wavelength as a function of time. Unfortunately, none of the method described above can simultaneously meet the speed, resolution, and range requirements for characterizing such a swept tunable laser. For example a diffraction grating based spectrum analyzer with a CCD can be sufficiently fast, however, its resolution or range is not sufficient due to limitations imposed by the size of the CCD and the appearance of higher diffraction orders from the grating when the spectrum range is too large or when the grating period is too small.

In this paper, we propose and demonstrate a novel polarimeter-enabled optical spectrum analyzer (P-OSA). Our method is based on analyzing both the state of polarization (SOP) as well as the degree of polarization (DOP) information of the light source after it passes through a variable differential group delay (DGD) module. Thanks to the high-speed polarimeter [5], our proposed P-OSA can readily achieve a measurement speed on the order of MHz, and is therefore capable of measuring the center wavelength of a fast scanning laser as a function of time. The measurement speed is limited only by the bandwidth of the photo-detectors, the RF amplifiers, and digital processing electronics, and can be up to tens of GHz in principle [7].

Another unique and attractive feature of the P-OSA is that it can determine the direction of the frequency change, a capability unobtainable with most of the conventional spectrum analysis methods. Consequently, the P-OSA is capable of having arbitrarily high frequency resolution, yet, with arbitrarily large spectral range, provided that the measurement speed is sufficiently fast compared with the rate of the SOP change caused by the spectral change of the light source and that the signal-to-noise ratio in P-OSA's detection circuit is sufficiently high for accurate SOP measurement. Such a feature opens a wide door for many spectral related measurements not imaginable with conventional spectrum analysis methods.

Finally, the P-OSA can measure the spectral shape (power vs. frequency) of a swept-wavelength light source. With this unique capability, we report the generation of a 3-D plot of the spectral shape of a modulated light signal as a function of center wavelength of a wavelength-scanned light source. This capability enables detailed spectral characterization of a fast swept-wavelength source that cannot be obtained with other conventional methods.

2. Swept-frequency (wavelength) measurement

2.1 Concept

The basic concept of the P-OSA for measuring the instantaneous wavelength of a swept laser source is shown in Fig. 1(a), where the input light source first enters a fixed differential group delay (DGD) element (e.g. a birefringent crystal) before being analyzed by a high-speed polarimeter. It is known that when a tunable light source passes through a DGD element, its SOP will trace a circle on the Poincare sphere when the wavelength of the light source is tuned [4, 8], as shown in Fig. 1(b). The rate of the SOP change as a function of frequency is determined by the value of the DGD element. Therefore, one can obtain the DGD value from the SOP trace on the Poincare Sphere.

If we choose a precisely known DGD element, by using the reverse effect, the frequency of the light source can be determined from the SOP trace on the Poincare sphere. Let τ be the DGD value of the DGD element, the complex amplitude of the electrical field of the light after the DGD element can be expressed as,

$$\vec{E} = (E_x e^{i2\pi f\tau}\hat{e}_x + E_y\hat{e}_y)e^{i\phi_o} \tag{1}$$

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where E_x and E_y are the amplitudes of the electrical field along the x and y directions of the chosen coordinate system, $\hat{e}_x$ and $\hat{e}_y$ are the unit vectors along the x and y directions, and ϕ_o is the common phase term.

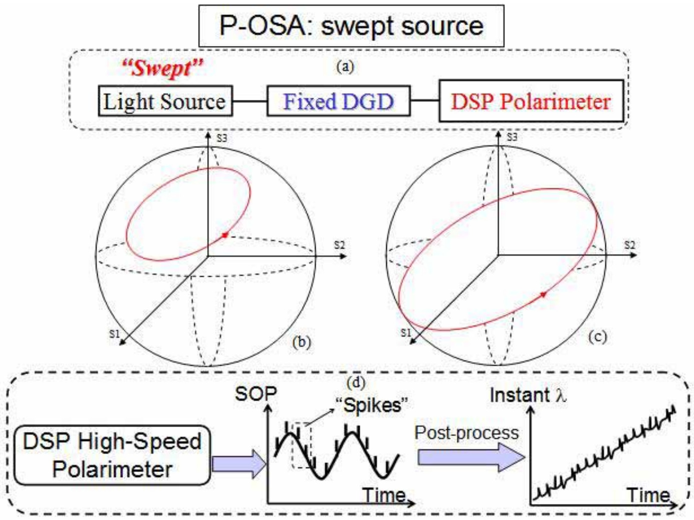

Fig. 1. Concept of the proposed real-time polarimeter-based optical spectrum analyzer used for a swept-wavelength source.

If $E_x = E_y$, the SOP will trace a largest circle on the Poincare sphere, as shown in Fig. 1(c), resulting in the highest frequency measurement resolution or sensitivity. When considering two specific frequency values, f_1 and f_2, during a wavelength sweep , the angular difference, denoted as Δθ, between the two polarization states of these two different frequencies is simply the phase difference in Eq. (1), which can be expressed as,

$$\Delta\theta = 2\pi(f_1 - f_2)\tau \tag{2}$$

For a known differential delay τ, the frequency difference can be calculated from the SOP angular difference on Poincare Sphere as,

$$f_1 - f_2 = \frac{1}{2\pi}\frac{\Delta\theta}{\tau} \tag{3}$$

Figure 1(d) shows the working principle of the swept-wavelength operation mode. The high-speed polarimeter collects the time-resolved SOP traces, which carries the detailed polarization evolution information. Based on the known DGD value, one can translate the SOP traces into the instantaneous wavelength evolution by calculating the polarization rotation angle on the Poincare sphere using Eq. (3).

2.2 Spectral range and resolution

For conventional OSAs, such as those based on F-P interferometer, free spectral range (FSR) is defined as the spacing between the periodic passbands. The FSR usually determines the spectral measurement range of the analyzer. One of the major tradeoffs for the conventional OSAs is that the FSR is always inversely proportional to the spectral resolution. This means that the high spectral resolution will always result in limited measurement range.

For our proposed P-OSA, if we consider that the SOP resolution is 0.36 degree, we can have 360/0.36 = 1000 points resolved in a full circle (one-cycle) on the Poincare Sphere. From

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Eq. (3), we can see that for a given τ, the resolution for measuring the center frequency and the one-cycle measurement range of the polarimeter based spectrum analyzer are,

$$\text{Frequency Resolution:} \quad \delta f = \Delta f / 1000 = 10^{-3} / \tau \tag{4}$$

$$\text{One-Cycle measurement range:} \quad \Delta f = 1/\tau \tag{5}$$

As an example, for a DGD value of 1000 ps, the frequency resolution will be 1 MHz, and the one-cycle measurement range will be 1 GHz. The tradeoff between the resolution and the range still exists if we consider only one-cycle on the Poincare sphere.

However, since the SOP circle will be able to repeat itself on the sphere if the frequency variation range Δf is larger than $1/\tau$, we can utilize the valuable information of the direction of the SOP evolution. By combining Eq. (5) with the SOP direction information, we obtain the following equation as the total measurement range by the multiplication of the SOP cycle number,

$$\text{Total measurement range:} \quad \Delta f = N \times 1/\tau \tag{6}$$

where N can be any arbitrarily large integer number.

This results in the unique feature of arbitrarily large spectral range, without any compromise to the spectral resolution. Since only the value of the fixed DGD element determines the spectral resolution, one can simply improve the resolution by introducing arbitrarily large DGD element without sacrificing the measurement range. The proposed P-OSA is thus not limited by the traditional tradeoff between the spectral range and frequency resolution.

2.3 Experimental setup and results

As shown in Fig. 2, we choose two representatives as the swept input source. The first one is a spectral spliced ASE source using a high speed Fabry-Perot tunable filter [9] (up to 40 KHz sweeping speed). The second swept source is the HP 8164A tunable laser source (TLS) with a sweep step size of 0.05 nm and a dwell time of 0.1 second. A 5.7-ps birefringent crystal is applied as a fixed DGD element, with input adjusted by a polarization controller for equal power splitting between two eigen polarization states. The output port of the DGD element is directed to the General Photonics' high-speed DSP in-line polarimeter (POD-101D) for real-time Poincare sphere display and SOP trace recording at a sampling rate near ~1 MHz [6].

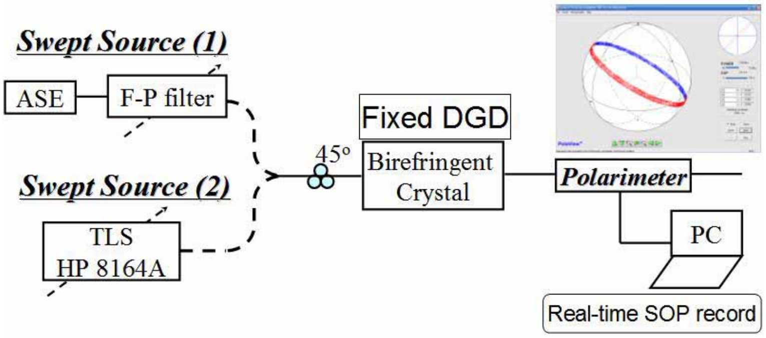
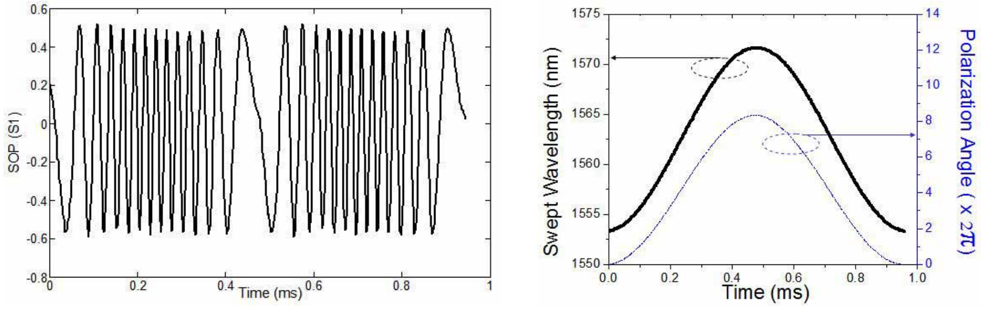


Fig. 2. P-OSA experimental setup for analyzing two types of swept sources. Note that only one source is connected at a time. The SOP of the input light is adjusted to 45 degrees with respect to the birefringent axis of the DGD.

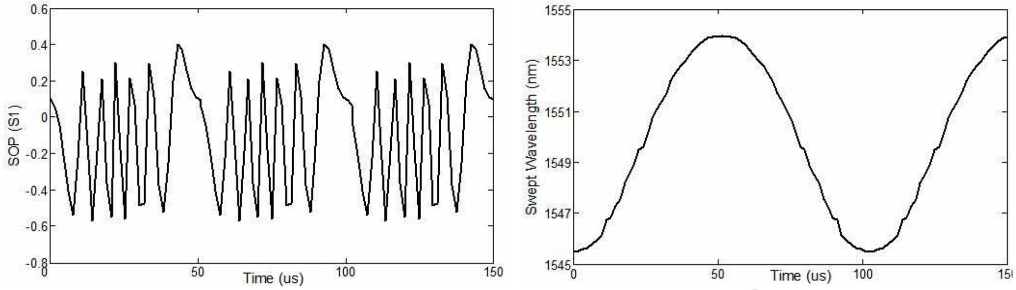
Figures 3 and 4 show the results of the swept-wavelength input using a high speed F-P filter based spectral-slicing source. A high power EDFA with output of ~15 dBm is used as the ASE source. The sweeping wavelength range of the high-speed tunable filter is properly adjusted using a function generator, with frequency, amplitude and offset matched to the EDFA gain bandwidth. Figure 3(a) shows the modulation of one (S1) of the recorded Stokes parameters from the polarimeter when the tunable filter is swept at 1-KHz rate. The amplitude and the offset from the sinusoidal function generator are set to be 10V and 3.5V, respectively. By utilizing the directional SOP evolution, we obtain the accumulated polarization rotation angle, as shown in the right Y axis of Fig. 3(b). Note that the multiple full circle of the SOP modulation can be correctly interpreted to the accumulated rotation angle. From Eq. (3), we further derive the swept wavelength as a function of time (in the left Y axis of Fig. 3(b)) from the accumulated polarization angle. The starting wavelength is determined using a spectrum analyzer. In practice, we can utilize a tunable DGD element and obtain the reference wavelength using the method described in section 3.1. We can see that the swept wavelength curve resembles well with the sinusoidal sweeping function and the time period is determined by the swept frequency of 1-KHz.



(a) **(b)**

Fig. 3. 1-KHz tuning F-P filter (a): SOP (S1) trace. (b): swept wavelength. Note that the starting wavelength is obtained from a commercial spectrum analyzer, although the P-OSA can also determine the absolute starting wavelength directly, as described in the next section.

Figure 4(a) shows one of the recorded Stokes parameters from DSP polarimeter when the tunable filter is swept at a higher rate of 10-KHz. The amplitude and the offset of the function generator are 5V and 4.5V, respectively. Figure 4(b) shows the derived swept wavelength as a function of time. A period of 100 μs proves the swept frequency of 10-KHz. Due to the limited sampling rate of the DSP polarimeter, the recovered SOP trace can not be as smooth as that of the 1-KHz case. Improved results are expected if the sampling rate of the polarimeter is increased. The reduced SOP modulation cycle and thus the reduced swept wavelength range is due to the smaller amplitude swing applied to the F-P filter.



(a) **(b)**

Fig. 4. 10-KHz tuning F-P filter (a). SOP (S1) trace. (b). swept wavelength. Note that the starting wavelength is obtained with a commercial spectrum analyzer, although the P-OSA can also determine the absolute starting wavelength directly, as described in the next section.

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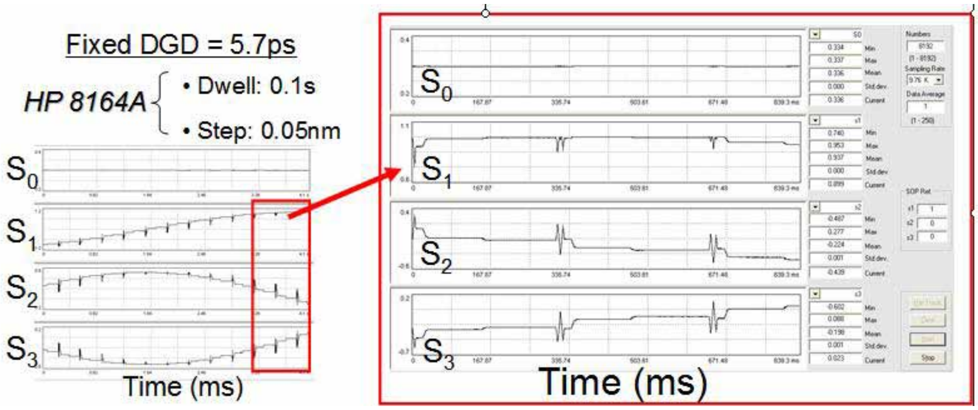

Fig. 5. POD-101D oscilloscope mode. SOP evolutions are recorded when the input is swept at a speed of 0.1 sec.

Figures 5 and 6 show the results of the swept-wavelength input using HP 8164A. Figure 5 shows the screen shots of the oscilloscope mode of the POD-101D, where the SOP traces (S_0, S_1, S_2, S_3) are recorded. Remarkably, the SOPs not only describe the sinusoidal behaviour when the input HP 8164A light source is 0.05 nm step swept, but also the "spiky" details when the wavelength is stepped from one value to the next.

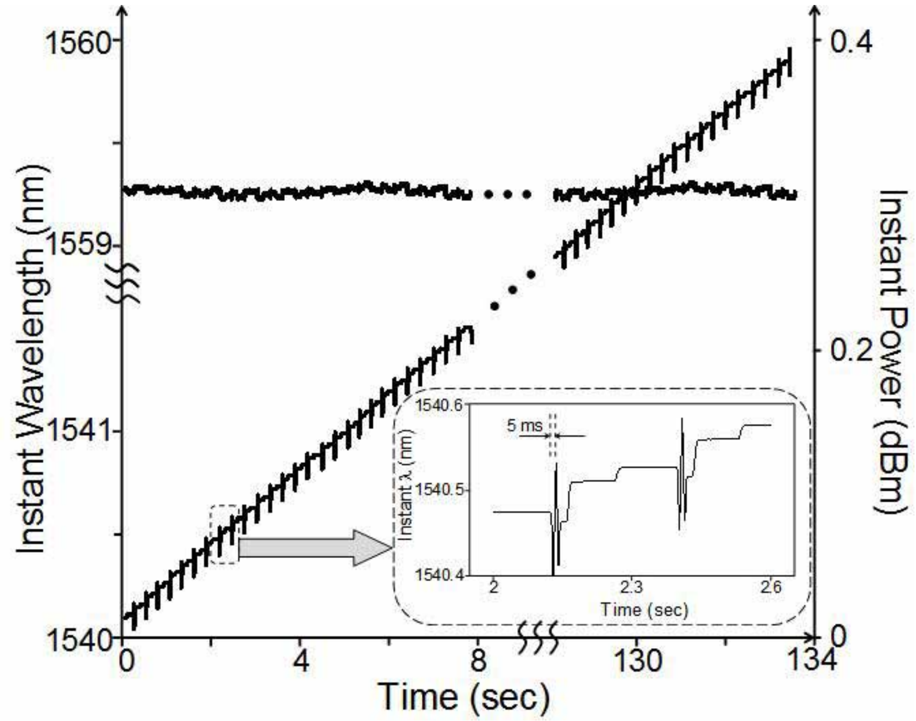

Fig. 6. Instantaneous wavelength and power as the input light source is swept at a speed of 0.1 sec. The starting wavelength is from the setting of the commercial tunable laser. Note that the transient dynamics of the swept laser source can be clearly revealed, as shown in the inset.

Based on the sampled SOP traces, we post-process the recorded SOP data by calculating the accumulated polarization rotation angle, taking into account the direction of the rotation. The polarization rotation angle can be further translated into the time-resolved swept frequency, as shown in Fig. 6, where the instantaneous wavelength is obtained from 1540 to 1560 nm using the periodic nature of the SOP traces in Fig. 5. The starting wavelength is the setting of the tunable laser and its value is not obtained from the analysis, although the P-OSA is capable of determining the absolute wavelength as described in the next section. Note that the range can be further increased by recording more SOP evolution circles. A zoom in of the curve in Fig. 6 proves that a relatively low speed (0.1 second) swept source actually has a fast transition time on the order of millisecond. This reveals that when the light source is stepped from one wavelength to the next, it experiences a fast initialization stage in which the wavelength is oscillating. It then quickly jumps to the desired value within several tens of milliseconds. However, most of the time is then used for wavelength locking and stabilization. From Fig. 5 and Fig. 6, we can see that P-OSA exhibits the powerful capability of capturing the transient dynamics of a swept source. This capability greatly surpasses those of the conventional OSAs. The instantaneous power evolution is also measured from the time-resolved S_0 trace.

The direction of the SOP traces has another interesting usage for determining the direction of the wavelength change. As can be seen from the inset of Fig. 6, the fast oscillation (on the order of millisecond) occurred during wavelength transitioning can be resolved in terms of the direction of the instantaneous frequency changing, which can be well correlated to the SOP evolutions shown in Fig. 5. This unique feature is also unobtainable with traditional OSAs, and can find interesting applications in the field of swept spectral analysis.

3. Spectral shape analysis

3.1 Concept

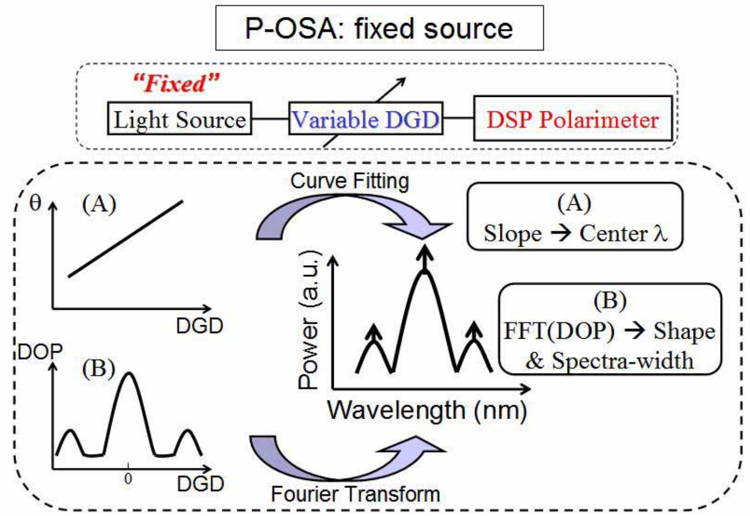

Fig. 7. Concept and principle of the proposed real-time polarimeter-based optical spectrum analyzer used for spectral shape analysis. Curve fitting of (A) determines the center frequency while Fourier transform of (B) yields the spectral shape and width. The spectral resolution is inversely proportional to the range of the variable DGD.

Figure 7 shows the concept and principle of the proposed P-OSA used for analyzing the spectrum of a fixed wavelength source. In this spectrum analysis mode, a variable DGD element is applied and the spectrum of the light source is analyzed by post-processing the recorded SOP and DOP information from the polarimeter as the DGD is tuned. For a fixed wavelength input source, the polarization rotation angle is a linear function of the DGD (τ) value. By curve fitting the measurement data using Eq. (7), one can readily obtain the center frequency of the light source.

$$\theta = \theta_o + 2\pi f \tau \tag{7}$$

In order to determine the spectral shape and width of the input source, we utilize the DOP information of the light as the DGD value is varied from zero to well beyond the coherence length of the source. Since the DOP is well correlated with the self-correlation function of the light source [8], which in turn relates to the power spectrum by the Fourier transform, we obtain the following expression of the power spectrum for the case of equal power splitting between two principle polarization states of the DGD element.

$$P(\omega) = S_o \int_{-\infty}^{\infty} DOP(\tau) e^{i\omega\tau} d\tau \tag{8}$$

where S_0 is the total received power and ω is the relative angular frequency. From Eq. (7) and (8), one can conclude that for a fixed wavelength input, the spectrum of the source can be obtained accurately by measuring both the SOP and the DOP as a function of DGD, as shown in Fig. 7.

3.2 Experimental setup and results

The experimental setup for the spectrum analysis of a fixed wavelength source is shown in Fig. 8. In order to verify the capability of the proposed P-OSA, we generate two interesting spectral features by modulating a narrowband tunable laser using two different on-off-keying (OOK) modulation formats (non-return-to-zero (NRZ) and return-to-zero (RZ)) at 40-Gbit/s. The variable DGD module consists of a 2x2 polarization beam splitter (PBS) for splitting the input light into two orthogonal polarization states (port 1 → port 2 and 3) and combining them again at the output (port 2 and 3 → port 4). One motorized delay line (MDL), with a tuning range of 560 ps, is inserted in one of the arms. Both arms are path length matched when the MDL is set at its origin. Two Faraday rotating mirror (FRM) are placed at the end of both arms for ensuring polarization orthogonality and stability of the light in the two arms when they recombine at the PBS. The output port of the PBS is directed to the DSP in-line Polarimeter [6]. A polarization controller is placed at the input of the polarimetric interferometer to ensure equal power splitting of the two arms when they recombine at the PBS, and thus the largest SOP circle (shown in the inset) on the Poincare sphere, resulting in the highest frequency resolution.

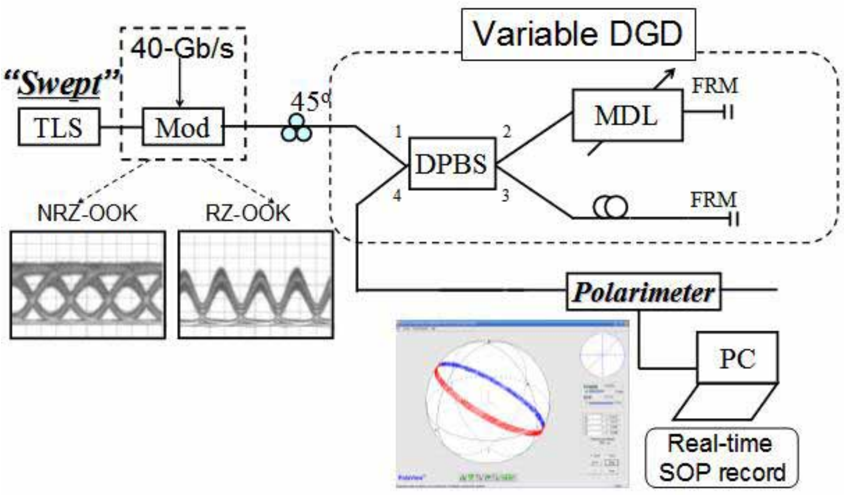

Fig. 8. Experimental setup for spectrum analysis of fixed wavelength source.

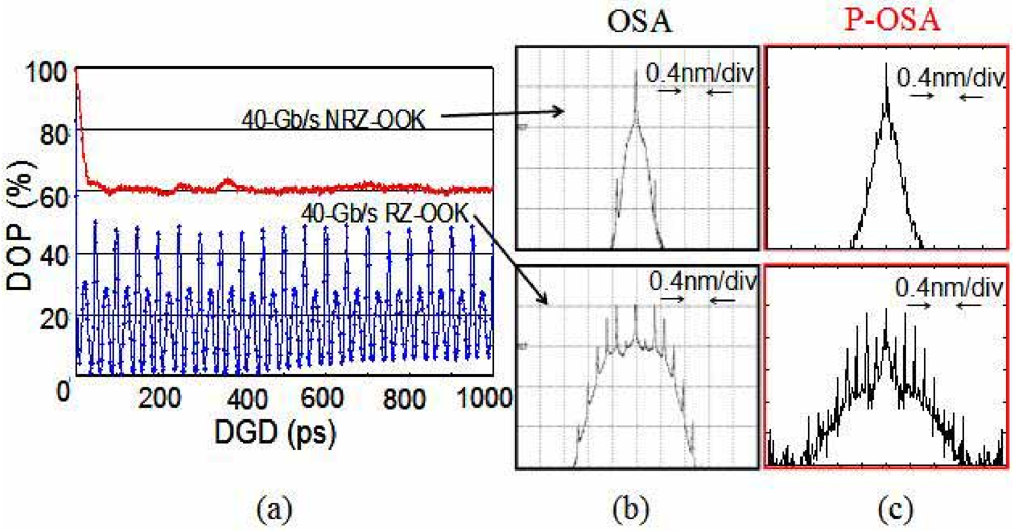

Fig. 9. (a). Experimental results of DOP values when the DGD is changed from 0 to 1000 ps for both 40-Gb/s NRZ-OOK and RZ-OOK signals. (b). The measured OSA spectra. (c). The derived P-OSA spectra for comparison.

Figure 9 shows the experimental results of the spectra analysis operation of the P-OSA. DOP of both the 40-Gb/s NRZ-OOK and RZ-OOK are recorded as the MDL values are increased from 0 to 500 ps. This corresponds to 1000 ps DGD tuning range due to the double pass configuration of the experimental setup. We can see from the DOP vs. DGD curve that the NRZ-OOK curve remains almost constant around 60% when the DGD is beyond 25 ps, while the RZ-OOK curve exhibits periodic DOP natures due to the fact that it has pronounced 40-GHz tones and some residual 20-GHz tones. By using conventional OSAs, Fig. 9(b) shows the measured spectra of both NRZ-OOK and RZ-OOK, which exhibits dominant 40-GHz spaced tones and much wider spectrum width. Based on Eqs. (7) and (8), we obtain the spectra for the two different formats by processing the rotation angle for center frequency as well as the DOP curve for spectral shape and width. Fig. 9(c) shows the derived spectra using our P-OSA method. For the same horizontal and vertical scales, we can see that the P-OSA provides very similar spectra width and shapes, with a much better spectral resolution due to the 1000-ps DGD tuning range, which corresponds to a line-width resolution of less than 1 GHz.

3.3 Spectral shape measurement of swept-wavelength source

The spectral shape and the width of a swept-wavelength source at each wavelength is an important parameter, since it contains the coherence length information of such sources for optical coherence tomography (OCT) applications [10]. However, they cannot be directly measured with conventional OSAs [11]. In this section, we demonstrate that the P-OSA can directly measure the spectral shape of a fast swept-wavelength source, in addition to the measurement of the spectral shape (power vs. frequency) of a fixed wavelength source, as described in section 3.2. With such a capability, we report, for the first time to the best of our knowledge, a unique 3-D plot of the spectral shape of a wavelength-swept light source with feature-rich spectrum as a function of its center wavelength.

Figure 10 shows the unprecedented 3-D display of our proposed P-OSA with an added dimension of the swept wavelength or time. For the swept-frequency input, every time the DGD module is tuned to a specific value, the SOP and DOP information are recorded when the wavelength of the source is swept a full cycle. By tuning the DGD element gradually from minimum to maximum value, we obtain the whole set of SOP and DOP as two dimensional matrices with respect to both swept wavelength values as well as tuned DGD points. By

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rearranging the two dimensional matrices, one can display each spectrum at every swept wavelength using Eqs. (7) and (8). For Fig. 10, during each wavelength scan ranging from 1540 to 1560 nm, we generate alternative 40-Gb/s NRZ-OOK or 40-Gb/s RZ-OOK modulation formats so as to obtain feature-rich yet contrasting spectra. The RZ-OOK spectrum shows a better distinguishable and equally spaced carrier tones, as well as a much wider spectrum. This capability enables detailed spectral characterization of a fast swept-wavelength source that cannot be obtained with any conventional methods.

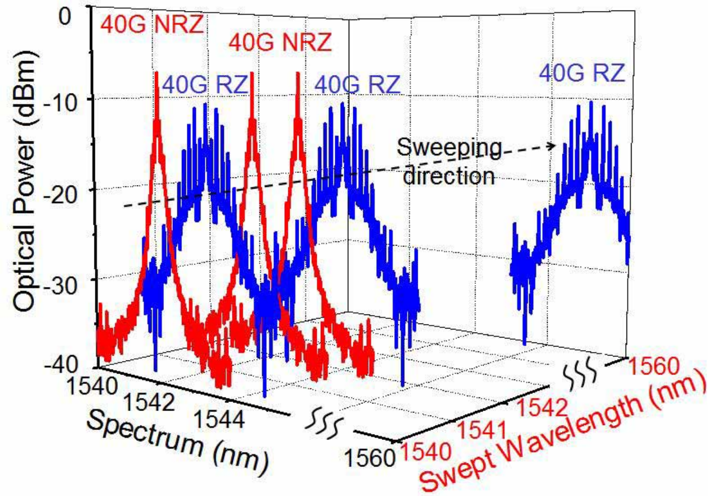

Fig. 10. A 3-D plot using the proposed P-OSA. Swept wavelength is the added dimension compared to the conventional OSAs. Note that the absolute wavelengths are directly obtained with P-OSA via curving fitting.

4. Conclusion

In summary, we have proposed and experimentally demonstrated a novel polarimeter-based optical spectrum analyzer, which utilizes both the state of polarization as well as the degree of polarization information of the light source after it passes through a variable DGD element. The speed, measurement range and the frequency resolution of the proposed P-OSA greatly surpass those of the conventional OSAs. The high speed capability is enabled by the fast sampling polarimeter and is thus ideal for measuring the spectrum of fast sweeping laser sources. This will find broad application in swept-source OCT imaging [11], as well as in the measurement of time-resolved frequency chirping [12]. The large measurement range and high resolution capability are realized by utilizing the unique information of the directional SOP evolution. This will be very useful for measuring the spectra drift of ultra-narrow line width lasers. Finally, we have also demonstrated a unique 3-D plot which displays the spectral shape of a swept-wavelength light source at each instantaneous wavelength.