Real-time measurement of full spectrum polarization states in dissipative soliton fiber lasers

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Abstract: There has been tremendous progress in multi-parameter measurement of ultrafast laser, including optical spectrum and waveform. However, real-time measurement of full spectrum polarization state of ultrafast laser has not been reported. We simultaneously measure laser intensities of four channels by utilizing division-of-amplitude. Combining dispersive Fourier transform, dissipative soliton mode-locked by carbon nanotube can be easily detected by high-speed photodetector. By calibrating the system with tunable laser, we reconstruct the system matrix of each wavelength. According to intensity vector of dissipative soliton and the inverse matrix of the system, we get the full spectrum state of polarization in real time.

1. Introduction

Ultrafast laser is involved in industry and human lives, such as, micro-nano fabrication, laser surgery. In past decades, so much efforts have been devoted to investigating the spectrum based on dispersive Fourier transform (DFT) and waveform based on time-lens [1,2]. Besides, shorter pulse duration like attosecond is the frontier in this field. And generation of ultra-intense ultra-short laser pulse also arouses interest among scientists.

However, there has been rare work investigating the real-time measurement of full spectrum state of polarization (SOP) of ultrafast laser [3-4]. Actually, state of polarization is a fundamental parameter, which plays a crucial part in understanding and even controlling the laser. For continuous wave (CW) laser, two methods have been used to measure the state of polarization. One is time-sharing method like rotating wave plate, which is just suitable for constant or slow-varying signals. The other is method of beam splitting, like division-of-amplitude. Four channels can be detected simultaneously by this method. Unfortunately, state of polarization of ultrafast laser still cannot be measured only by division-of-amplitude, due to the insufficient response speed of conventional instrument.

In our work, we measure state of polarization of dissipative soliton based on the division-of-amplitude. By this method, we can detect signals of four channels simultaneously. Furthermore, in order to capture the ultrafast pulses, we utilize DFT technique. So the single-shot optical spectrum can be measured by high-speed photodetector and displayed on oscilloscope.

2. Principle
Firstly, for the theory of DFT technique, impulse response function is

\[ H(\omega - \omega_0) = \exp[i(\omega - \omega_0)^2 \beta_2 L/2] \]  

(1)

where \( \beta_2 \) is the second-order derivative of propagation constant, \( \omega \) and \( \omega_0 \) are angular frequency and center frequency respectively, \( L \) is the fiber length.

From the Fourier transform, the time response function is

\[ h(T) = \exp(iT^2/2\beta_2 L) \]

(2)

where \( T = t - \beta_1 L, t \) is time. For the input pulse signal \( A(0, T) \), the output signal is

\[ A(L, T) = A(0, T) * h(T) \]

(3)

\(*\) denotes convolution. Due to the large dispersion, propagation is under the far-field approximation or condition of Fraunhofer diffraction

\[ \Delta T^2/2\beta_2 L \ll 1 \]

(1)

then the output signal can be rewrote as

\[ A(L, T) = A'(0, \omega)h(T) \]

(3)

where \( A'(0, \omega) \) is the Fourier transform of \( A(0, T) \). So ultrafast pulse signal is projected to temporal domain from spectral domain. Single-shot optical spectrum information is shown in temporal domain by dispersive Fourier transform [5].

Then the state of polarization is described by Stokes vector \( S = (S_0, S_1, S_2, S_3)^T \) and output laser is represented by intensity vector with four parameters \( I = (I_1, I_2, I_3, I_4)^T \) [6]. Because intensity detected by photodetector in each channel can be expressed as the linear combination of four Stokes vector \( I_i = a_{i1}S_0 + a_{i2}S_1 + a_{i3}S_2 + a_{i4}S_3 \). We use a \( 4 \times 4 \) system matrix to express the relationships between the intensities and the Stokes parameters,

\[ I = AS \]

(1)

where determinant of system matrix is not equal to zero,

\[ det(A) \neq 0 \]

(2)

then the inverse matrix exists,

\[ S = A^{-1}I \]

(3)

System matrix \( A \) is determined by the Stokes vector of each wavelength of input CW laser and the output intensity. When the intensities of four channels of ultrafast pulse laser are measured, the SOPs can be calculated by the intensities and the inverse matrix of each wavelength.

Deviation of SOPs is defined as the relative distance between two points on Poincare sphere

\[ \Delta S = \sqrt{(S_1' - S_1)^2 + (S_2' - S_2)^2 + (S_3' - S_3)^2} \]

(4)

3. Experimental setup

As schematically depicted in Fig.1, the dissipative soliton laser ring cavity contains 15 m erbium-doped fiber (EDF) with the dispersion of -12.2 ps/nm/km, forward pumped by a 976 nm diode laser through a 1550/980 nm wavelength division multiplexer (WDM). The saturable absorber (SA) is made from single-wall carbon nanotubes. The rest of the cavity includes an isolator (ISO), a polarization controller (PC), 2.7 m single mode fiber (SMF) with the dispersion of 18 ps/nm/km, and an optical coupler (OC) with a 10% output port. The net normal dispersion is 0.171 ps². The dispersive Fourier transform is achieved by using a 4 km dispersion compensating fiber (DCF) with the dispersion of ps². We adopt erbium-doped fiber amplifier (Amonics, AEDFA-23-B-FA) to get a higher power because of loss of DCF and spatial system.

For the part of division-of-amplitude, we use spatial system containing a collimator to get a collimating beam, which is divided into four paths by three beam splitters with transmission reflection ratio of 5:5. Angles of four analyzers are set as 0°, 45°, 90°, 135°, and the intersection angle between quarter-wave plate and analyzer in the fourth path is 45°. The orientation of 0° is parallel to platform. In this way, any state of polarization can be recognized by this system. In order to input arbitrary state of polarization in calibration process, a polarizer and a quarter-wave plate play the role of polarization state generator (PSG) which is shown inside the brown
box. The four channels of output laser are detected by four photodetectors (PD) of 8 GHz and a real time oscilloscope (Tektronix, DSA 71604B) with the bandwidth of 16 GHz.

![Diagram of the dissipative soliton fiber laser cavity and polarization state measurement system.](image)

**Fig. 1.** Schematic of the dissipative soliton fiber laser cavity and polarization state measurement system.

4. **Results and discussions**

Before measuring the state of polarization of dissipative solitons, the system of division-of-amplitude was calibrated at first. In the calibration process, we use tunable semiconductor laser instead of dissipative soliton laser as source and connected with the first collimator. Then we fixed the polarizer at the angle of 90° and rotated the quarter-wave plate from the intersection angle of 0° to 180°, by the step of 5°. And the 180° is variation period. There are two methods of calibration. One is method of four-points. Four points on Poincare sphere construct a tetrahedron with a nonzero volume, which is equivalent to nonzero determinant or invertible matrix. The other method is equator-poles. We choose four points located at the equator and poles as four known vector to do the calibration because this method can reduce the effect induced by imperfection of optical elements.

Fig. 2 depicts the calibration results of equator-poles. Four known vector of polarization state are \((1,-1,0,0)^T\), \((1,0,1,0)^T\), \((1,0,0,1)^T\), \((1,0,0,-1)^T\). As shown in Fig. 2 (a)-(c), measured \(S_1\), \(S_2\) and \(S_3\) at 1550nm are almost distributed on theoretical curves. In Fig. 2 (f), measured points are located near theoretical points with mean deviation of about 0.03. And the trajectory of points is figure-8, but the pattern and location on Poincare sphere depend on the rotation angle of polarizer and quarter-wave plate. After calibration at 1550nm, we test the division-of-amplitude system at a wide range of wavelength, at least covering the spectrum range of dissipative soliton that to be measured. As displayed in Fig. 2 (d)-(e), wavelengths chose are 1560nm, 1566nm and 1572nm. Deviation of polarization state are all the same at three wavelengths and mean value of deviation for every angle of rotation at three wavelengths is under 0.07. From the calibration process, the constructed division-of-amplitude system can measure the SOPs at least for the range of a dozen nanometers. For a wider range of wavelengths, quarter-wave plate can be replaced by achromatic quarter-wave plate with several hundred nanometers.
As shown in Fig.3(a), the averaged optical spectrum is ranging from 1560nm to 1572nm and the intensity is about -35dB at the pump power of 28mW, which is measured by optical spectrum analyzer (Yokogawa, AQ6370). In Fig.3(b), we measure the autocorrelation trace by using an autocorrelator (APE, Pulse check USB 150) and EDFA for amplified average power of 3mW. The autocorrelation trace is fitted by Gaussian function and full width at half maximum of pulse duration is about 30ps. Fig.3(c) exhibits a normalized single-shot optical spectra with 16 roundtrips based on dispersive Fourier transform. The single-shot spectra of dissipative soliton maintains the rectangular shape when transformed from spectral domain into time domain. Furthermore, as depicted in Fig.3(d), we filtered the dissipative soliton by using a tunable optical filter (Santec, OTF-320). SOPs for various filtered wavelengths are measured by a polarization state analyzer (General Photonics, PGA-101-A). As we can see, there is not a fixed point on Poincare sphere, so SOPs for different wavelength component are different from each other. From the blue side to the red side of the spectrum, a smooth trajectory appears on Poincare sphere.
The intensities of single-shot spectra of dissipative soliton in every channels detected by high speed photodetector are shown in Fig.4(a), plotted with different colors. There are about 30 roundtrips with time period of 130ns and single pulse is stretched to 16ns. We improve the signal-to-noise ratio of every channel by using EDFA before division-of-amplitude to obtain amplified energy. In our measurement system, firstly, all channels are almost the same, and secondly due to the DFT, pulses are stretched to magnitude of nanosecond, so the tiny time difference between pulses of four channels can be ignored. According to the intensities for various wavelengths of four channels and the inverse matrix of the measurement system, we calculate the stokes parameter of them. The 5th, 15th, and 25th pulses are shown in Fig.4(b)-(d). For the stable dissipative solitons, trajectory of SOPs on Poincare sphere are almost the same and slowly varies from short wavelength side to long wavelength side. Minute difference between pulses attributes to the tiny jitter of intensities.
5. Conclusion

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