Over 3 THz Real-Time Optical Vector Oscilloscope

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Abstract: We propose a real-time optical vector oscilloscope to obtain full-field information with over 3-THz acquisition bandwidth. The experiments demonstrate 80 gigabit/s OOK and BPSK signals, and 2×160 gigabit/s QPSK wavelength-division multiplexed signals are simultaneously observed.

1. Introduction

To meet the demand for network capacity [1], various new optical communication technologies have been developed to improve communication capacity. Meanwhile, the rapid increase in communication rate poses significant challenges for data acquisition and optical performance monitoring (OPM). Especially for multiplexed channels system, as each demultiplexed channel is acquired individually, makes synchronization of all channels challenging and measurement latency [2]. Therefore, a large bandwidth optical vector oscilloscope capable of simultaneously measuring high-speed wavelength-division multiplexing (WDM) channels is necessary.

Although a real-time oscilloscope with a high-speed photodetector is the most straightforward approach for observing high-speed signals, it can only achieve an acquisition bandwidth of ~ 100 GHz. On the other hand, the optical pump-probe-based multiple-shot sampling techniques have the potential to achieve terahertz bandwidth [3], but the phase information is significantly distorted. Additionally, the bandwidth limitation can be greatly relaxed by amplifying or compressing the time axis based on the time lens [4,5]. However, the key factors affecting the phase accuracy are the bandwidth limit, phase-shift limit, and imperfect quadratic shape of the time lens.

To overcome the limitations of temporal methods, the Fourier domain of the signal has been researched. According to the properties of the Fourier transform, full-field spectrum technology will be the shortcut solution for large bandwidth oscilloscope [6-8]. The frequency-resolved optical gate method can be applied to obtain the full-field spectrum with a temporal resolution of several femtoseconds in the temporal window of tens of picoseconds [6]. However, mechanical scanning is a ~kHz frame rate, and iterative algorithms are too time-consuming. Alternatively, real-time spectroscopy can be achieved using optical Fourier transforms performed by dispersive Fourier transforms or time-lens systems [9]. Further inverse Fourier can obtain ultrafast temporal waveform transforms [10], but phase information is ignored. The spectral interferometry approach can retrieve the spectral intensity and phase information simultaneously, though there is still less phase ambiguity. In comparison, the phase diversity of the coherent receiver can recover accurate phase information by detecting in-phase (I) and quadrature (Q) components.

This paper proposes an optical vector oscilloscope with a measurement bandwidth over 3 THz based on the combination of dispersive Fourier transforms and spectral interferometry. The proposed system is applied to achieve the high-speed WDM system's real-time observation. This approach provides an effective solution for ultra-large capacity over Tb/s communication in the future network.

2. Principle and experimental setup

Figure 1 depicts the principle and experimental setup of the large bandwidth optical vector oscilloscope. The large bandwidth real-time optical vector oscilloscope in the Fourier domain, and this approach obtains the full-field spectrum through a real-time coherent spectroscopy. As shown in Fig. 1a, the acquisition period of the system is ~50 ns, determined by the repetition rate of the pulsed local oscillator (LO), and the temporal record length ($T = 4\pi f_{BW}\Phi$, ~520 ps) is determined by the acquisition bandwidth (f_{BW}) and the group delay dispersion (GDD, Φ). As illustrated in Fig. 1b, the real-time coherent spectroscopy is performed based on the dispersive Fourier transform, utilizing a time-stretched chirped LO in the coherent detection. The frequency-to-time mapping relationship of the chirped LO is identical to that of the dispersive Fourier transform, enabling the coherent receiver to measure the entire spectrum and significantly exceed the receiver's bandwidth. Therefore, performing a Fourier transform of the full-field spectrum to recover the large bandwidth temporal waveform. Although a single dispersive medium is typically used for implementing the dispersive Fourier transform, its initial condition has a short temporal width (τ_w ~46 ps) to satisfy the Fraunhofer diffraction conditions ($\tau_w^2 << |\Phi|$, where Φ is the group delay dispersion, which is 2115 ps^2 in the configurations). If the temporal window exceeds the initial condition, the time-mapped spectrum $\tilde{E}_{CR}(\omega)$ will distort as an additional quadratic phase profile is introduced to the retrieved temporal waveform $E_{Re\_int}(t)$. To enlarge the temporal record length, a time lens is generally placed before the dispersion to achieve the optical Fourier transform at its temporal focal plane. Nonetheless, the temporal aperture of the time lens is constrained by the maximum phase shift range and imperfect quadratic phase profile.

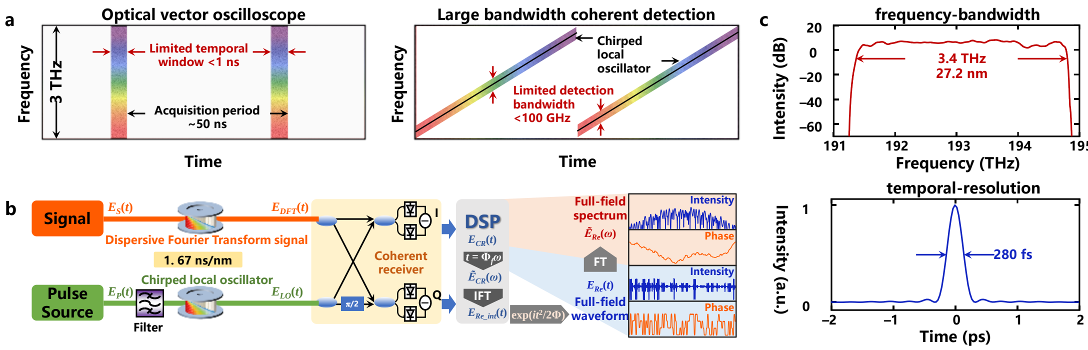

Fig. 1. Schematic of the system principle (a) and experimental setup (b) of the system. (c) Characterization of the frequency bandwidth and temporal resolution.

In our proposed system, the chirped coherent detection method enables us to obtain the full-field spectrum $\tilde{E}_{CR}(\omega)$. Consequently, the extra quadratic phase can be easily removed in the digital signal processing (DSP) process to retrieve the accurate full-field waveform $E_{Re}(t)$ and its full-field spectrum $\tilde{E}_{Re}(\omega)$. The DSP procedure flow is as follows: the initial full-field spectrum is recovered by $\tilde{E}_{CR}(\omega) = I + jQ$. Then, the initial full-field temporal waveform $E_{Re\_int}(t)$ is obtained with an extra quadratic phase profile by performing the inverse Fourier transform. Finally, a complementary quadratic phase shift is applied to eliminate the extra phase profile, resulting in the calibrated full-field temporal waveform $E_{Re}(t)$. Therefore, a Fourier transform is performed to acquire the accurate full-field spectrum $\tilde{E}_{Re}(\omega)$ of the signal under test. Furthermore, the higher-order dispersion can also be compensated during the DSP, leading to significantly less deviation and aberration. We characterize the maximum acquisition bandwidth of the optical vector oscilloscope by employing an ultrashort pulse source. The results indicate a 3.4-THz frequency bandwidth (corresponding to the chirped LO) and a 280-fs temporal resolution, as shown in Fig. 1c.

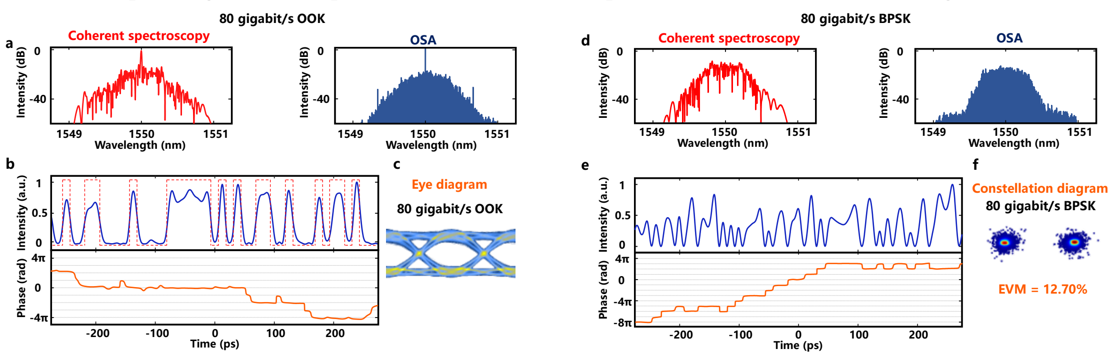

Fig. 2. Observation of 80 gigabit/s OOK and BPSK signals. (a) Spectrum of the 80 gigabit/s OOK signal acquired by the optical vector oscilloscope and OSA respectively. (b) Full-field waveforms of the single-shot OOK signal. (c) Eye diagram of the OOK signal. (d) Spectrum of the 80 gigabit/s BPSK signal acquired by the optical vector oscilloscope and OSA. (e) Full-field waveforms of the single-shot BPSK signal. (f) Constellation diagram of the BPSK signal.

3. Results and discussion

With the advance in ultrafast-data optical communication, the demand for OPM with a hundred gigahertz bandwidth rapidly increases. First, we evaluated the performance of the system for high-speed data measurement. First, the 80 gigabit/s on-off keying (OOK) and binary phase-shift keying (BPSK) signal are applied to be measured, which is far beyond the bandwidth of a 25-GHz coherent receiver and 33-GHz acquisition system. Figure 2a illustrates the time-mapped spectra of the 80 gigabit/s-OOK signal and the typical spectrum obtained by a high-resolution optical spectrum analyzer (OSA). As shown in Fig. 2b, the single-shot acquisition bit patterns of the 80 gigabit/s OOK signal are recorded at the temporal record length of 520 ps. Note that there is apparent intensity noise on the temporal waveform, mainly from the intensity noise of the chirped LO and the quantizing noise. Furthermore, Fig.

2c shows the eye diagram of the OOK signal recovered from the continuously captured hundreds of frames by the optical vector oscilloscope. Similarly, the spectrums and single-shot acquisition bit patterns of the 80 gigabit/s BPSK signal are recorded in Figs. 2d and e, respectively. The constellation diagrams of BPSK obtained from the proposed optical vector oscilloscope are shown in Fig. 2f, achieving an error vector magnitude (EVM) of 12.70%.

Simultaneous observation of multiplexed channels is more challenging than observing a single channel, as WDM and advanced modulation formats are involved. Therefore, a WDM system with 2×160 gigabit/s QPSK channels is introduced to characterize the measurement of multiple synchronized channels with large bandwidths. In the transmitter, two continuous-wave carriers of 1545 and 1560nm are launched into a coherent modulation transmitter. The proposed system obtains the single-shot spectrum, and the typical spectrum of the WDM signal is shown in Fig. 3a.

Figures 3b and d show the channels' intensity fluctuations and phase bit patterns at 1545 and 1560 nm, respectively. Figures 3c and e summarize the measured constellation diagrams of two channels, and the proposed real-time optical vector oscilloscope realizes EVMs of 28.91% (1545 nm) and 30.63% (1560 nm), respectively. The performance indicates that the system can successfully realize real-time optical performance monitoring even if the data rate reaches Tb/s, which greatly exceeds the limitation of electronic bandwidth.

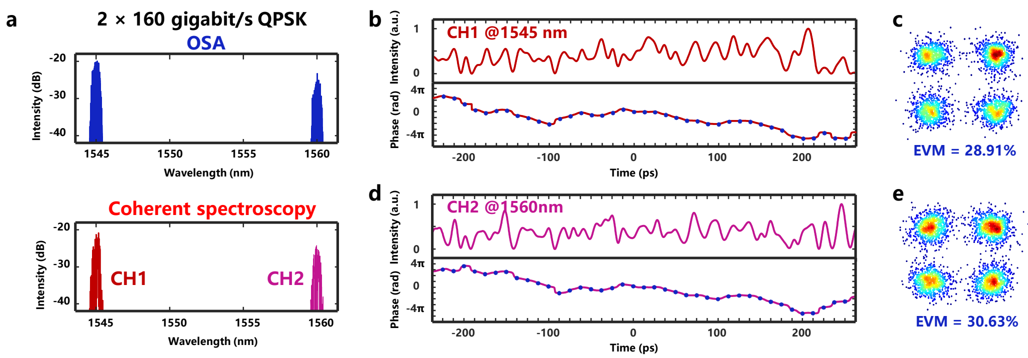

Fig. 3. Simultaneous observation of 2×160 gigabit/s QPSK multiplexed high-speed WDM channels. (a) Spectrum of the 2×160 gigabit/s QPSK signal acquired by the optical vector oscilloscope and OSA. (b) and (d) Full-field waveforms of the single-shot QPSK signal of two channels. (c) and (e) Constellation diagrams of the QPSK signal.

4. Conclusions

The proposed real-time oscilloscope overcomes the WDM system multichannel bandwidth limits and measurement latency and enables full-field characterization of large-bandwidth (>3THz) signals. It can also facilitate the characterization of ultrafast dynamics, such as terahertz waves, soliton generation, and ultrafast optical performance monitoring. Furthermore, the utilization of chirped coherent detection as a unique approach to manipulating arbitrary signals over a wide bandwidth makes it an up-and-coming tool in advanced optical communication systems and ultrafast optical measurement applications.

5. References

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