Time-stretch oscilloscope with dual-channel differential detection front end for monitoring of 100 Gb/s return-to-zero differential quadrature phase-shift keying data

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Optical performance monitoring of high-capacity networks is one of the enabling technologies of future reconfigurable optical switch networks. In such networks, rapid performance evaluation of data streams becomes challenging due to the use of advanced modulation formats and high data rates. The time-stretch enhanced recording oscilloscope offers a potential solution to monitoring high-rate data in a practical time scale. Here we demonstrate an architecture with a differential detection front end for simultaneous I/Q data monitoring of a 100 gigabits/s return-to-zero differential quadrature phase-shift keying signal. This demonstration shows the potential of this technology for rapid performance monitoring of high-rate optical data streams that employ advanced modulation formats.

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Optical performance monitoring (OPM) [1–4] is an important function in self-managed and reconfigurable optical switch networks because it provides invaluable information about mean time to repair and mean time to failure. OPM functionality requires rapid measurement and evaluation of the high-data rate signal quality in a very short time scale. Moreover, the need for efficient use of bandwidth has fueled the use of advanced data modulation formats, such as differential quadrature phase-shift keying (DQPSK) and multilevel quadrature amplitude modulation [5–9]. In contrast to conventional binary signaling, where a one-bit quantizer (limiting amplifier) is sufficient to digitize the data, detection and monitoring of such data formats require analog-to-digital converters (ADCs), which are difficult to realize because of the ultrahigh real-time bandwidth that is required.

The photonic time-stretch analog-to-digital converter (TSADC) [10–13] is one of the potential solutions for such applications. By extending the bandwidth of electronic converters, it is capable of digitization of continuous ultrahigh bandwidth electrical signals [14] with high resolution [15]. With the use of single sideband modulation [12] or phase diversity [12], the TSADC has no fundamental bandwidth limitation, although, in practice, the maximum bandwidth is limited by that of the electrooptic modulator. Called the time-stretch enhanced recording (TiSER) oscilloscope [16], the single-channel version of the TSADC has a simple architecture and offers real-time burst sampling (RBS) over repetitive intervals that can span hundreds of sequential bits [for 100 gigabits/s (Gb/s) data]. In addition to the RBS capability, it provides much higher sampling throughput than sampling oscilloscopes, hence reducing the time for bit error rate characterization [16].

The TiSER oscilloscope has demonstrated its capability of capturing an amplitude-modulated signal. However, capture of phase- and amplitude-modulated signals requires simultaneous detection and digitization of in-phase (I) and quadrature-phase (Q) components of the signal in order to enable reconstruction of the original signal in the digital domain. In this Letter, we demonstrate the dual-RF-channel version of TiSER with a differential detection front end for capturing optical DQPSK signals. We also show signal monitoring of 100 Gb/s return-to-zero (RZ)-DQPSK data degraded by different channel impairments. This system holds the potential for rapid performance evaluation in high-capacity optical networks employing phase- and amplitude-modulation formats.

The proposed system uses an optical differential detection front end to demodulate the DQPSK signal into two electrical signals (i.e., denoted by Ch.I and Ch.Q) by means of a pair of one-bit delay-line interferometers and two balanced photodetectors. Consequently, it performs the RBS on two electrical channels simultaneously. The dual-RF-channel TiSER oscilloscope uses only one wavelength channel to capture both I and Q channels. As illustrated in Fig. 1, a train of prechirped broadband pulses is equally split into two paths (i.e., two channels) and guided through two high-speed intensity modulators. In order to phase lock the I and Q channels, the signal paths from the delay-line interferometers to the intensity modulators are tuned so that the corresponding bits of I and Q signals are captured at the same time. The modulated pulse trains are delayed with respect to each other and sent through the second dispersive medium for time stretching. This configuration provides minimal mismatch between the captured I and Q signals.

To demonstrate the performance of the two-RF-channel TiSER oscilloscope, we implemented a 100 Gb/s RZ-DQPSK signal transmitter (Fig. 2). This transmitter consists of a CW laser (1552.524 nm), a >40 GHz nested Mach–Zehnder modulator driven by two 50 Gb/s pseudorandom binary sequences, and finally a 50% RZ pulse

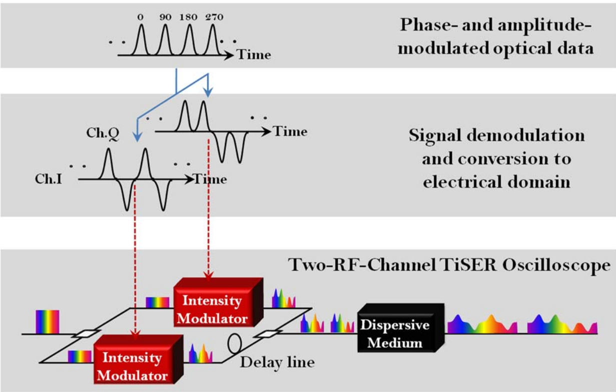

Fig. 1. (Color online) Conceptual diagram of dual-RF-channel TiSER oscilloscope with differential detection front end for 100 Gb/s RZ-DQPSK signal monitoring. This scheme provides minimal mismatch between the captured I/Q data.

carver to create RZ pulses. Two polarization controllers in front of the modulators are adjusted to maximize the signal's output power and extinction ratio. The signal is then boosted by an erbium-doped fiber amplifier (EDFA) and sent through tunable chromatic dispersion (CD) and differential-group-delay (DGD) emulators so as to add different distortions onto the signal. Finally, the 100 Gb/s RZ-DQPSK signal is amplified and filtered by means of an EDFA and a 1.2 nm bandpass filter (BPF). Different types of optical impairments such as CD, DGD, and optical loss are applied to the optical data through the impairment emulator units (Fig. 2).

To capture the 100 Gb/s RZ-DQPSK data using the proposed system, we constructed an experimental apparatus, as shown in Fig. 3. The optical signal to be captured is equally split into two paths and sent to two pairs of 50 GHz delay-line interferometers and 40 GHz balanced photodetectors (u2t Photonics BPDV2020R) for generating I and Q data streams. The average input power into the photodetector is fixed to around 10 dBm, providing differential electrical output ~2 V. This output voltage is sufficient to directly drive the Mach–Zehnder intensity modulator. Also, a mode-locked laser generates a pulse train with ~20 nm bandwidth centered at 1571 nm and a pulse repetition rate of ~37 MHz. The pulse train is split into two paths and sent to two separate 50 GHz

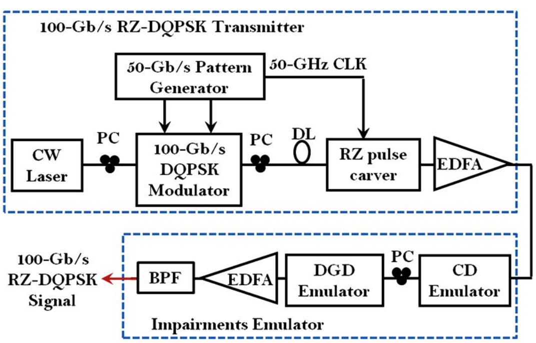

Fig. 2. (Color online) Detailed schematic of the 100 Gb/s RZ-DQPSK signal transmitter and optical impairment emulation units: CW, continuous wave; DGD, differential group delay; CD, chromatic dispersion; DL, delay line; PC, polarization controller; EDFA, erbium-doped fiber amplifier; CLK, clock; BPF, bandpass filter.

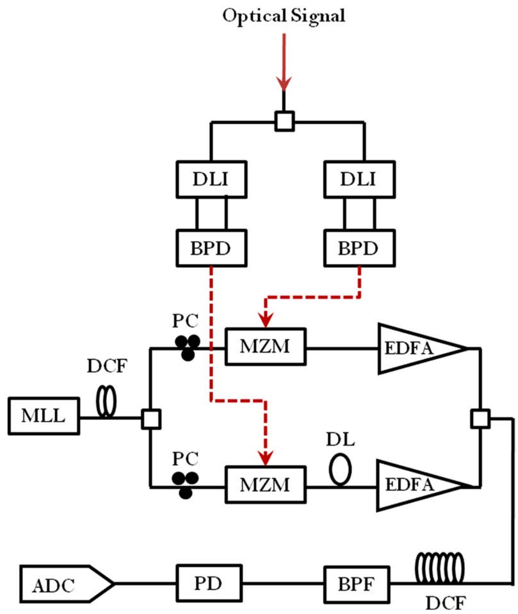

Fig. 3. (Color online) Detailed schematic of the dual-RF-channel TiSER oscilloscope with differential detection front end. Solid (black) and dashed (red) lines represent optical fibers and electrical cables, respectively: DLI, delay line interferometer; BPD, balanced photodetector; MZM, Mach–Zehnder modulator; EDFA, erbium-doped fiber amplifier; MLL, mode-locked laser; DL, delay line; BPF, bandpass filter; PD, photodetector; ADC, analog-to-digital converter; PC, polarization controller; DCF, dispersion compensating fiber.

Mach–Zehnder intensity modulators, where the broadband prechirped pulses are modulated with I and Q data streams. Polarization controllers are used to align the polarizations to the principal axes of the modulators. The modulated pulse trains are delayed with respect to each other, amplified, and sent to the second dispersion compensating fiber (Fig. 3). The dispersion values of the dispersive fibers are chosen such that a stretch factor of ~34 is achieved. After photodetection, the resultant RF signal is a stretched replica of the original signals with a significantly reduced analog bandwidth. A commercial digitizer (Tektronix—DPO71604) with 16 GHz analog bandwidth and 50 GS/s sampling rate is used to digitize the time-stretched signals. Note that digital low-pass filtering with cut-off frequency of 2 GHz is also applied to emulate a monolithic commercial ADC.

The system's time aperture, i.e., the duration of real-time captured segments, is found to be $T_A = D_1 \cdot \Delta\lambda = 400\,\mathrm{ps}$, where $D_1(-20\,\mathrm{ps/nm})$ is the dispersion value of the first dispersive fiber and $\Delta\lambda(20\,\mathrm{nm})$ is the optical bandwidth. As a result, all captured segments consist of 680 sample points that repeat every ~27 ns (the repetition rate of the mode-locked laser is ~37 MHz). Using these segments, the eye diagrams of the 100 Gb/s data are generated in equivalent time, as shown in Fig. 4. Also, because the timings of the prechirped pulses and I/Q data are aligned, the corresponding bits of I and Q signals are found to generate the constellation diagrams of the original data. More importantly, the eye and constellation diagrams shown here are generated from a 400 μs time interval of data, which is 3 to 4 orders of magnitude shorter than conventional methods for capturing these diagrams [16]. This means that the performance of

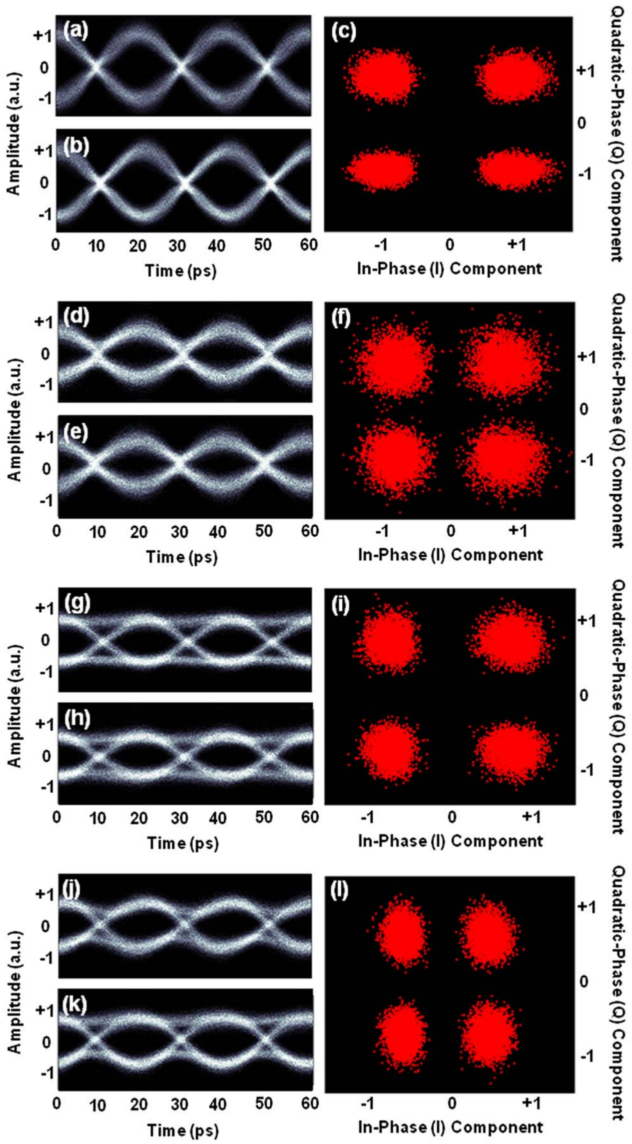

Fig. 4. (Color online) Eye and constellation diagrams of 100 Gb/s RZ-DQPSK data captured by the dual-RF-channel TiSER oscilloscope. I/Q diagrams (a)–(c) without any channel impairments, (d)–(f) with 10 dB optical loss, (g)–(i) with a DGD of 5 ps, (j)–(l) with CD of −20 ps/nm.

the optical channel can potentially be monitored in a very much shorter time scale. Moreover, these real-time segments of the DQPSK signal captured by this system provide useful information about the channel and facilitate equalization algorithm development for the optical network.

In conclusion, we have proposed and demonstrated a dual-RF-channel TiSER oscilloscope with a differential detection front end for 100 Gb/s RZ-DQPSK signal monitoring for advanced high-capacity optical networks. Captured eye and constellation diagrams of 100 Gb/s RZ-DQPSK data having undergone different types of channel impairments are shown. This system provides a useful tool for rapid performance monitoring of high-rate advanced data modulation formats.

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