PDP20

All-optical Phase Construction of ps-Pulses from Fiber Lasers for Coherent Signaling at Ultra-high Data Rates (≥160 Gb/s)

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Abstract: A novel method to reconstruct the optical phase of fiber laser data pulses allows for generating phase-coded signal formats at record high speed (up to 320 Gb/s). This enables the first-time analysis of nonlinear transmission properties of different coherent modulation formats at 160-Gb/s.
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1. Introduction

Mode-locked fiber lasers[1]-[3] are preferred candidates for generating transform-limited short pulses with high extinction ratio in high-speed telecommunication applications. However the optical phases of the output pulses from practical actively mode-locked fiber lasers show insufficient phase correlation between adjacent pulses, even when a laser-cavity length control is applied, as experimentally shown in the following section. The weak phase coherence of the pulse trains make them unsuitable for phase-correlated modulation formats such as carrier suppressed return-to-zero (CSRZ), differential phase shifted keying (DPSK), and duobinary signals, which have shown many important applications in optical telecommunications. Furthermore, a phase-stable pulsed laser source is highly desired for novel devices such as low-noise amplifiers with a noise figure below the 3-dB quantum limit [4] and their applications in picosecond all-optical processing systems [5], where coherent pump pulses are needed in the parametric process [6].

Here we demonstrate a novel all-optical method to obtain stable phase-coherent short pulses from fiber lasers by reconstructing the optical phases of the pulse train. The method is also suitable for optical time division multiplexing (OTDM) applications, where the precise phase relation between neighboring pulses is difficult to control due to the length drift of the fiber delay lines. This problem exists in OTDM signals even when diode [7] or solid-state lasers [8], which possess a better phase coherence of the output pulses, are used as the sources for the fundamental pulse train. The method is suitable for generating 320-Gb/s CSRZ signals, which is the highest data rate of a phase-coded signal reported so far. We also reveal the method's potential by investigating the nonlinear propagation features of two different 160-Gb/s signal formats.

2. Phase construction of the pulses from a fiber laser

The scheme is based on an optical fiber Kerr shutter [6]. A non-coherent data signal acts as the pump in a nonlinear polarization rotation (NLPR) process with a CW-light in a highly nonlinear fiber (HNLF). Due to the NLPR, the polarization state of the probe wave is flipped in those wave sections that sufficiently experienced cross phase modulation. A polarizer at the HNLF output blocks all non-scattered probe wave light. Thus, a data pattern is carved out of the original CW-light that has a similar intensity profile as the pump wave but is phase-coherent since it stems from a highly-coherent DFB laser. Furthermore, phase-coding can be realized by controlling the polarization of the pump signals. For example, if the polarization of a pump pulse is flipped by 90º, the resulting phase on the CW-light differs by π due to the corresponding cross phase modulation process. This process of polarization state and phase conversion can be conveniently visualized on the Poincare sphere. At the HNLF input the pump is polarized in either north or south direction whereas the CW-light polarization points to S1. Then NLPR forces the CW-light polarization state vector to walk along the equator of the Poincare sphere either clock- or counter-clock wise as sketched in Fig.1. When properly adjusted the CW-light polarization at the HNLF output resides at the points S2 or –S2, respectively. These two polarization states are associated in Jones space with two E-fields that are proportional to the vectors {1, 1}, {1, -1}. Thus after separating the field component, described by the second vector element, a phase-modulated signal appears. Hence, ultra-high-speed phase-coded signals can be constructed by utilizing a polarization-coded OTDM data signal as the pump in the Kerr shutter. The intensity driven NLPR process requires only an incoherent high-speed pump signal that is formed from low-rate data streams by multiplexing them in time, as well as in polarization as necessitated by the phase coding requirement in the later stage. Since the optical

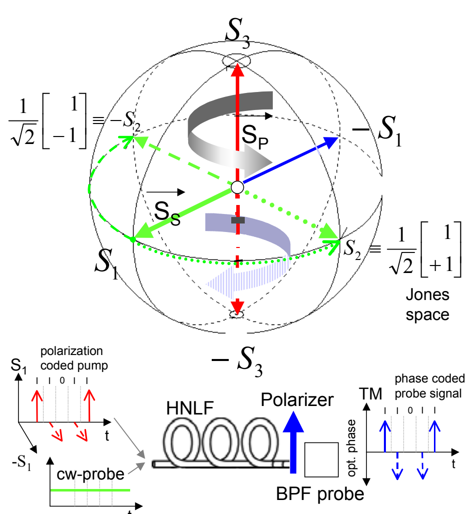

Fig. 1: Poincare sphere and Jones space representations of the NLPR.

Kerr shutter is all-fiber based, it is ultra-fast to process data rates extending into the Tb/s range. The fundamental speed limit is on the order of a femtosecond.

We visualize the insufficient phase coherence of the pump signal by launching periodic 10-GHz pulses from a commercial actively mode-locked fiber laser through a Mach-Zehnder interferometer (MZI) with a 100-ps delay between the two arms. It can be clearly seen that the unstable phases of the optical pulses cause significant amplitude fluctuations of the interfered pulses (Fig.2a,b). The spectrum of the fiber laser signal (Fig.2e) however shows a clear comb. When performing the same test with the converted probe signal, the waveforms appear clean and stable (Fig.2c,d).

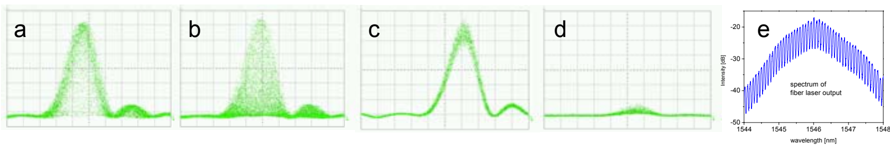

Fig.2: a) and b) interfered pulses from the fiber laser at the MZI constructive and destructive ports, respectively, c) and d) are the corresponding pulse waveform for the converted probe signal (5ps/div), and e) pump signal spectrum (0.01nm res.).

Two examples in Fig.3 show pump polarization state alignments and the corresponding phase modulation of the probe signal. When every other pump pulse is orthogonally polarized the probe signal becomes 0 π 0 π phase modulated, which results in a CSRZ signal. If the pump pulses are pair wise orthogonally polarized the probe signal is 0 0 π π phase modulated, which leads also to a carrier suppression but a pair-wise alternating phase (PAP)[9]. The spectra of both formats differ by the frequency spacing of their line components. While for CSRZ signals the line spacing is equivalent to the data rate, in the case of PAP-CSRZ phase coding it is only half of the data rate since the coding method represents a fraction of the data rate (see i.e. Fig.4a-c).

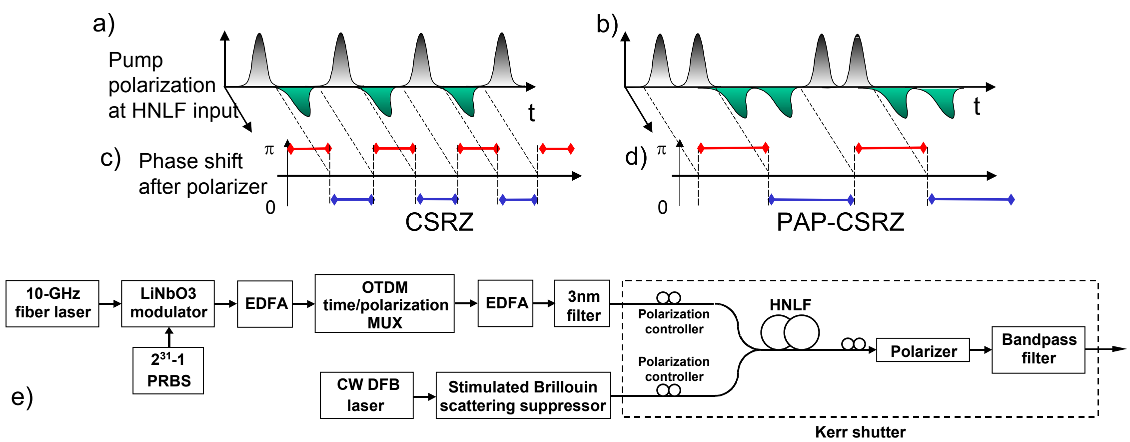

Fig. 3: Illustration of phase coding through polarization control of the pump pulses. a) alternating-polarization of non-coherent pump pulses, b) the resulting periodic phase shifts for CSRZ, c) pair-wise alternating polarization state, d) PAP-CSRZ, e) setup of the all-fiber based Kerr shutter.

3. Experimental setup for generation of CSRZ and PAP-CSRZ signals at 160 and 320 Gb/s

Fig.3e shows the experimental setup for generating ultra-high-speed phase-coded signals using an all-fiber based Kerr shutter. The 10-GHz actively mode-locked fiber laser outputs 2.2-ps pulses, which show low phase correlation that can be attributed to the vibration and temperature changes in the dispersion shifted fiber (DSF) of the laser cavity even when the cavity-length control is applied (Fig.2a,b). A $LiNbO_3$ intensity modulator encodes the pulses with a pseudo-random bit sequence (PRBS) of $2^{31}-1$ length. The 10-Gb/s RZ pulses are then multiplexed by OTDM means to form an ultra-high-speed data stream. However, at the last stage of the OTDM multiplexer the polarization of the pump pulses are controlled such that the desired probe signal formats can be obtained as shown in Fig.3. The OTDM pump signal and a CW probe signal are injected into the HNLF having a length of 2.0 km, and a Kerr nonlinearity coefficient of 12/W/km. The wavelengths of the pump, the CW probe, and the zero dispersion of the HNLF are chosen to be 1546 nm, 1556 nm, and 1551 nm, respectively to ensure that no walk-off between the pump and the probe signals occurs. The HNLF's dispersion slope is 0.02 ps/km/nm^2. At the HNLF output a polarizer is adjusted by a polarization controller thus it blocks the probe signal in absence of the pump. A band-pass filter selects only the probe wavelength.

For generating the 160 Gb/s (PAP)-CSRZ signal the 10-Gb/s pulse train passes three OTDM stages before finally entering the polarization multiplexer stage. In the case of the 320-Gb/s CSRZ signal a fourth OTDM stage was passed before the polarization multiplexing. Noise generated in EDFAs, used to compensate for the OTDM unit's insertion loss, was blocked by a 3-nm optical filter in order to ensure a high optical signal-to-noise-ratio for the probe signal (>43dB, 0.1nm

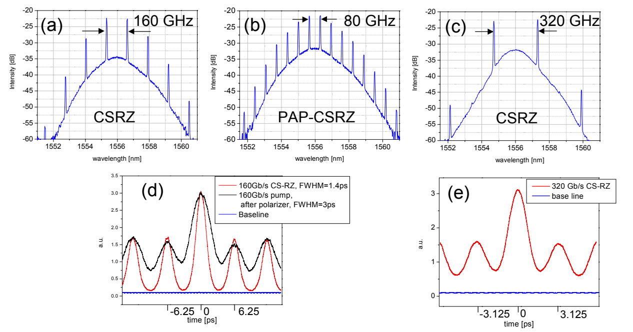

Fig. 4: spectra of a) 160-Gb/s CSRZ, b) 160-Gb/s PAP CSRZ, c) 320-Gb/s CSRZ, and autocorrelation traces of d) 160-Gb/s and e) 320-Gb/s signals.

res.). Power levels at the input of the HLNF were 16-19dBm and 15-16dBm for pump and CW-light, respectively. The autocorrelation trace of the CSRZ (Fig.4d) signal, which looks identical to that of the PAP-CSRZ, indicates a pulse width of ~1.4ps. The reduced pulse width, compared to the original pump pulses, is a reshaping effect stemming from the NLPR process in the HNLF. This can be explained by the intensity driven NLPR process that is only strong enough in sectors close to the center of the pump pulse. For the generation of the 320-Gb/s CSRZ signal we carefully compensated the chromatic dispersion of the OTDM unit and the involved EDFAs thus even shorter pump pulses at the HNLF input were obtained, which resulted in a pulse width of the converted signal of 1.2 ps. The receiver design mainly consists of an electro-absorption modulator driven at 40 GHz, which provides a switching window of 3.5 ps, short for de-multiplexing 160-Gb/s data signals. We achieved almost identical sensitivities of -26.7 ±0.25dBm for the best and worst tributaries of the CSRZ and the PAP-CSRZ signals.

4. Transmission performance of 160-Gb/s PAP-CSRZ and CSRZ signals

We demonstrate the applicability and the stability of our source with an experimental investigation of the nonlinear transmission properties of PAP-CSRZ and CSRZ at 160 Gb/s. Such an experiment is yet the only approach to studying the nonlinear propagation of ultra-high-speed data signals that would be difficult to predict with sufficient accuracy by computer simulations. At such high data rates the pulses strongly overlap already after short transmission sections due to the fiber chromatic dispersion. An accurate simulation by means of solving the NL Schrödinger equation would require long PRBSs ($>2^{15}$-1) in order to capture these effects and would need tens of days computation time. To investigate the nonlinear tolerance of the PAP-CSRZ and CSRZ formats, we used a 38-km single-mode fiber (SMF) transmission span whose dispersion is 100% post-compensated. The signal power at the DCF input was always lower than –4dBm. Conventional clock recovery was performed at the receiver side. Fig.5 shows the receiver sensitivity penalties versus the signal launch power in the SMF for both formats. Compared to the CSRZ signal, the PAP-CSRZ signal possesses a certain improvement in a reduced sensitivity penalty at high launch powers. This proves the advantage of a higher nonlinear tolerance of this new format at ultra-high-speed.

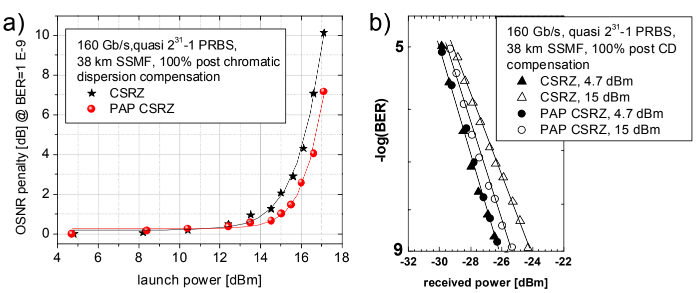

Fig.5: a) Sensitivity penalty due to NL propagation vs. launch power in SMF, b) BER curves for both formats at launch powers of 4.7 and 15 dm in SMF.

5. Conclusion

We discussed a novel method to generate phase-coherent data signals based on incoherent emitting pulsed fiber lasers. An ultra-fast optical fiber Kerr shutter imprints phase coding on short pulses. As one application we demonstrated for the first time a new PAP-CSRZ signal format at 160 Gb/s and compared its performance with CSRZ in the nonlinear transmission regime. We also generate 320-Gb/s CSRZ, which is the phase-coherent signal with the highest data rate reported so far.

6. References:

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