Ultra High-Speed Data Signals With Alternating and Pairwise Alternating Optical Phases

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***Abstract*—We demonstrate two 160-Gb/s modulation formats that posses the same intensity pulse profile but differ regarding their phase coding. We analyze the nonlinear transmission properties of both coherent modulation formats by experimental and analytical investigations. The results show that the pairwise alternating phase coded carrier suppressed return-to-zero (PAP-CSRZ) signal outperforms the conventional CSRZ format. Our modulation technique is even applicable at higher speed as demonstrated with the generation of the first CSRZ signal at a record rate of 320 Gb/s.**

***Index Terms*—Nonlinear optics, phase coding, polarization, ultrafast optics.**

I. Introduction

PHASE-CODED signals from ultrafast laser transmitters can provide many advantages. For example, by manipulating the phase relation between adjacent bits, some attractive modulation formats for telecom applications have been demonstrated such as carrier suppressed return-to-zero (CSRZ), differential phase shifted keying (DPSK), and duobinary. Transform-limited short pulses with high extinction ratio can be obtained from actively mode-locked fiber lasers [1] or solid-state lasers [2], however the data rates of the systems based on these lasers are limited by the speed of electronics, typically to 10 Gb/s. To further increase the data rate of a system, optical time-division multiplexing (OTDM) is a commonly used technique. In a typical OTDM experiment, replicas of a signal are combined in time domain to form a high-rate data stream. However, such approach loses the phase coherence of the adjacent bits due to the length drift of the fiber delay lines in the OTDM multiplexer. Therefore, it is difficult to generate stable phase-coded signal formats at ultra high-speeds based on OTDM approaches.

Here we demonstrate a novel all-optical method to obtain stable phase-coherent short pulses of OTDM signals stemming from fiber lasers by reconstructing the optical phases of the pulse train. The scheme is based on an optical fiber Kerr shutter. The high-speed data stream is formed from low-rate data by multiplexing them in time, as well as in polarization as necessitated by the phase coding requirement in the later stage. This time- and polarization-multiplexed signal acts as the control of the optical Kerr shutter, which translates the polarization state of the control pulses to the phase of a probe signal. The probe signal is generated from a highly phase-coherent distributed feedback (DFB) laser, therefore, a phase-coded ultra high-speed signal can be obtained. Since the optical Kerr shutter is all-fiber based, it is ultrafast, the fundamental speed is only limited on the order of femtosecond. Such an all-optical device is very attractive for research purpose on next generation of high-speed systems above 100 Gb/s and extending to Tb/s range.

We use this method to generate two different 160-Gb/s signal formats and investigate their nonlinear propagation features [3]. The two formats are 160-Gb/s conventional CSRZ with alternating phase between adjacent bits, and 160-Gb/s PAP CSRZ with pairwise alternating phases. They consist of the same pulse intensity profile but differ regarding the optical phase shift between adjacent pulses. Generation of 320-Gb/s CSRZ signal is also demonstrated; we believe this is the highest rate of CSRZ reported to date. We also provide an analytical explanation on the improved nonlinear tolerance of the pairwise alternating phase coded carrier suppressed return-to-zero (PAP-CSRZ) signal compared with a CSRZ signal.

II. Phase Construction of the Pulses From a Fiber Laser

The modulation scheme is based on an optical fiber Kerr shutter [4]. A noncoherent data signal acts as the pump in a nonlinear polarization rotation (NLPR) process with a CW-light in a highly nonlinear fiber (HNLF) as the probe. Due to the NLPR process, the polarization state of the probe wave is flipped in those wave sections that sufficiently experience cross phase modulation effects. A polarizer at the HNLF output blocks all nonscattered probe wave light. Therefore, a data pattern is carved out of the original CW-light with a similar intensity profile as the pump wave has but it is phase-coherent since it stems from a highly coherent DFB laser. Furthermore, phase coding can be realized by controlling the polarization state of the pump signal. For example, if the polarization of a pump pulse is flipped by 90°, the resulting phase shifts of 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

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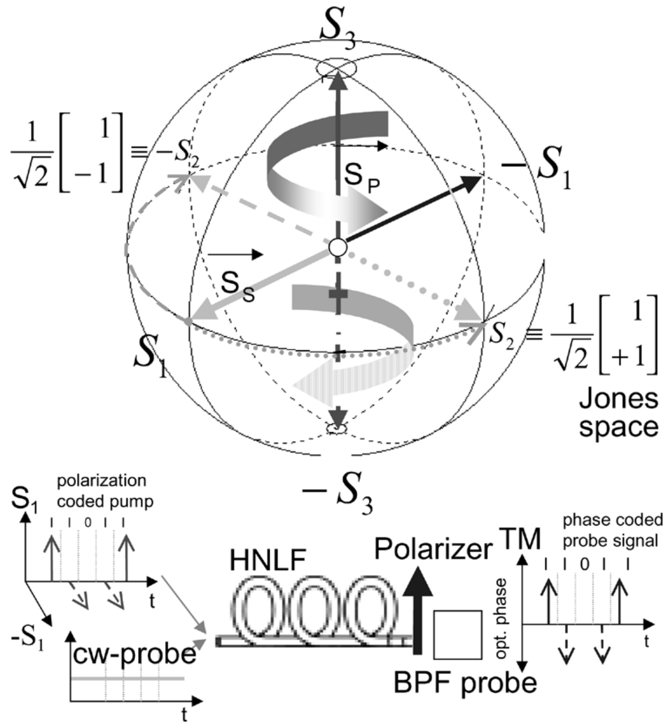

Fig. 1. Poincaré sphere and Jones space representations of the NLPR. Depending on the pump SOP (S_P) the probe SOP (S_S) is rotated clockwise or counter clockwise along the equator. A polarizer with orientation ($-S_1$) selects the field component of the probe signal that possesses a pump SOP dependent sign.

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.

Note the given picture of NLPR shows the basic modulation principle but is simplified regarding the SOP traces of the pump and probe on the Poincare sphere.

We first study the effect of phase construction using the Kerr shutter at a low rate of 10 GHz. The phase coherence of an ordinary fiber ring laser output is not sufficient for direct phase-coded data signal generation. 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. 2(a) and (b)], indicating 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. The spectrum of the fiber laser signal [Fig. 2(e)] however shows a clear comb. When performing the same test with the converted probe signal, the waveforms appear clean and stable [Fig. 2(c) and (d)].

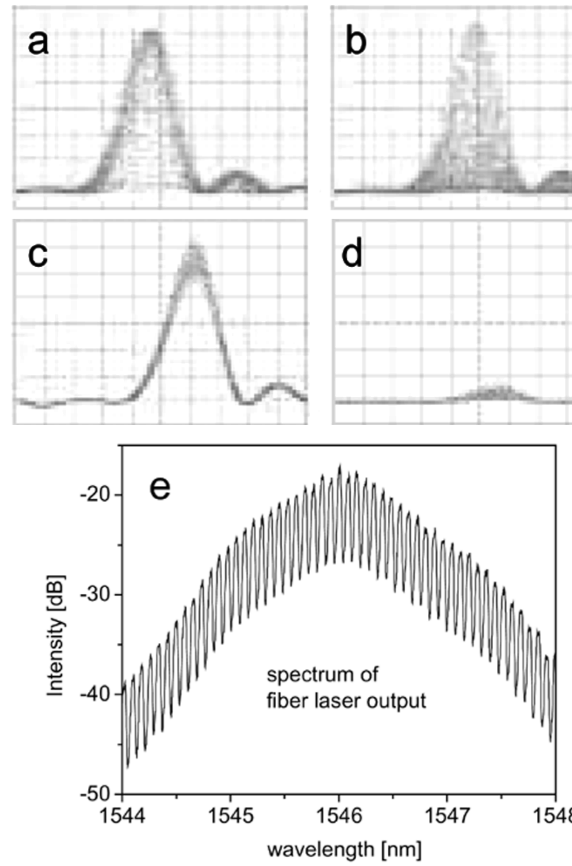

Fig. 2. (a) and (b) Interfered pulses from the fiber laser at the MZI constructive and destructive ports, respectively. (c) and (d) Corresponding pulse waveform for the converted probe signal (5 ps/div). (e) Pump signal spectrum (0.01 nm res.).

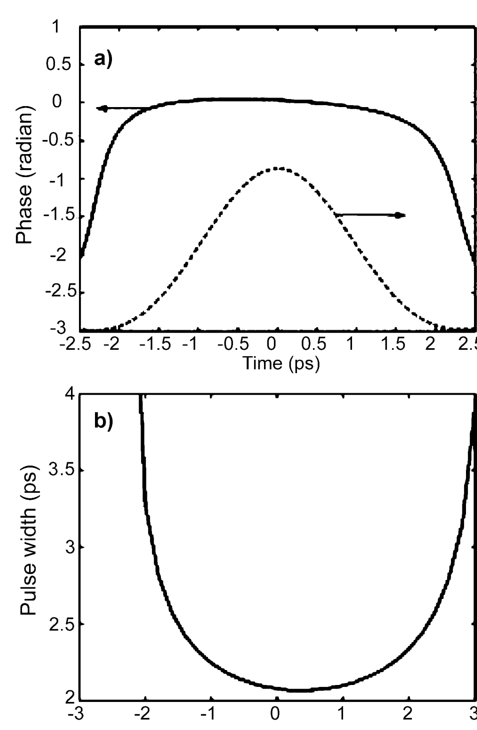

Fig. 3. (a) Optical phase across the probe pulse after the polarizer. (b) Pulse compression due to chromatic dispersion. Pump (pulse width 2 ps) and probe signal power is 16 dBm. All other parameters are similar to those given in Section III.

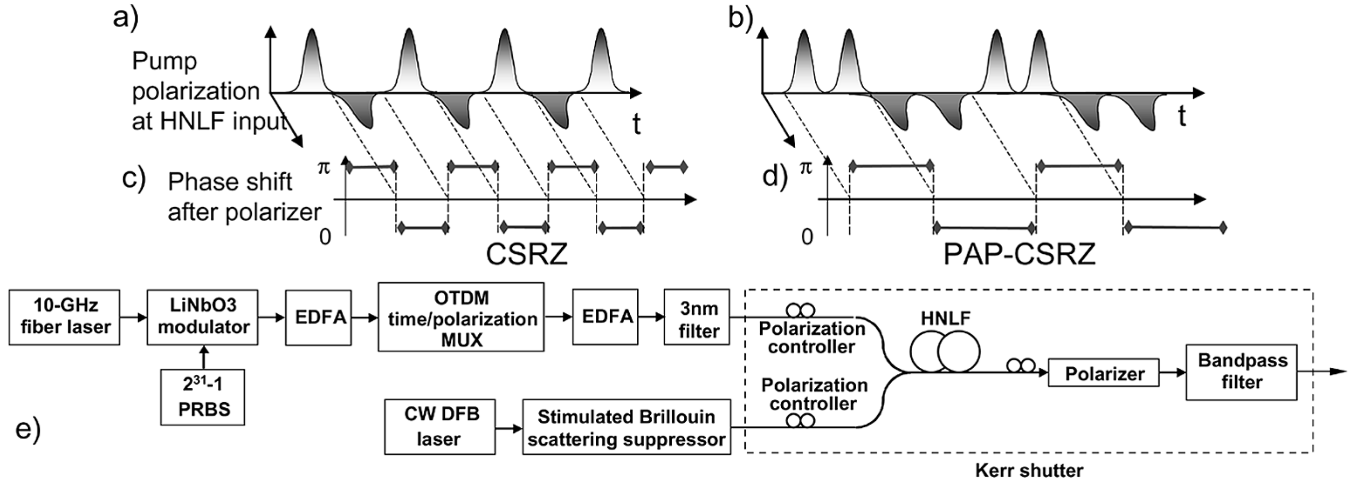

Fig. 4. Illustration of phase coding through polarization control of the pump pulses. (a) Alternating polarization of noncoherent pump pulses. (c) The resulting periodic phase shifts for CSRZ. (b) Pairwise alternating polarization state. (d) PAP-CSRZ. (e) Setup of the all-fiber based Kerr shutter.

To investigate the phase homogeneity (chirp) within the width of the probe pulse we simulated the NLPR process by numerically solving the coupled NL Schrödinger equations [4]. For typical parameters the phase modulation in comparison to the pulse envelope is shown in Fig. 3. Over a large fraction of the pulsewidth the phase stays almost constant. Applying a small amount of chromatic dispersion ($\sim 0.5\ \mathrm{ps/nm}$) to the signal reduces its pulse width only about a few negligible fs indicating that the chirp is really small.

The two schemes depicted in Fig. 4 show pump polarization state alignments and the corresponding phase shifts of the probe signal that are required for the modulation formats we are investigating. When every other pump pulse is orthogonally polarized the probe signal becomes $0\ \pi\ 0\ \pi$ phase modulated, which results in a CSRZ signal. If the pump pulses are pairwise orthogonally polarized the probe signal is $0\ 0\ \pi\ \pi$ phase modulated, which leads also to a carrier suppression [5]. But the spectra of both formats differ by the frequency spacing of their line components. While for CSRZ signal the line spacing is equivalent to the data rate, in the case of PAP-CSRZ the spacing is equal only to half of the rate [see, i.e., Fig. 5(a)–(c)]. The frequency of the phase coding equals the one of the signal's first subharmonic.

III. Experimental Setup for Generation of CSRZ and PAP-CSRZ Signals at 160 and 320 Gb/s

Fig. 4(e) shows the key components of 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. A $\mathrm{LiNbO_3}$ intensity modulator encodes the pulses with a pseudorandom 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 sketched in Fig. 4(a)–(d). 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, 1556, 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 $\mathrm{ps/km/nm^2}$. 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 signal.

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. A 3-nm optical filter blocks the noise from EDFAs that are used to compensate for the OTDM unit's insertion loss, thus ensuring a high optical signal-to-noise ratio for the probe signal ($> 43\ \mathrm{dB}$, 0.1 nm res). Power levels at the input of the HLNF were 16–19 dBm and 15–16 dBm for pump and CW-light, respectively. The autocorrelation trace of the CSRZ [Fig. 5(d)] signal, which looks identical to that of the PAP-CSRZ, indicates a pulsewidth of $\sim 1.4\ \mathrm{ps}$. The reduced pulsewidth, 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 pulsewidth of the converted signal of 1.2 ps. The receiver design consists of an EDFA preamplifier, a 3-nm filter to block ASE noise, an electroabsorption modulatior for demultiplexing the 160-Gb/s signal to 40 Gb/s, and an electronic 40-Gb/s receiver. The modulator has an extinction ratio of better than 20 dB, and is driven at 40 GHz to provide a switching window of 3.5 ps, which is sufficinetly short for demultiplexing 160-Gb/s data signals. In the experiment we achieved almost identical sensitivities of $-26.7 \pm 0.25\ \mathrm{dBm}$ for the best and worst tributaries of the CSRZ and the PAP-CSRZ signals.

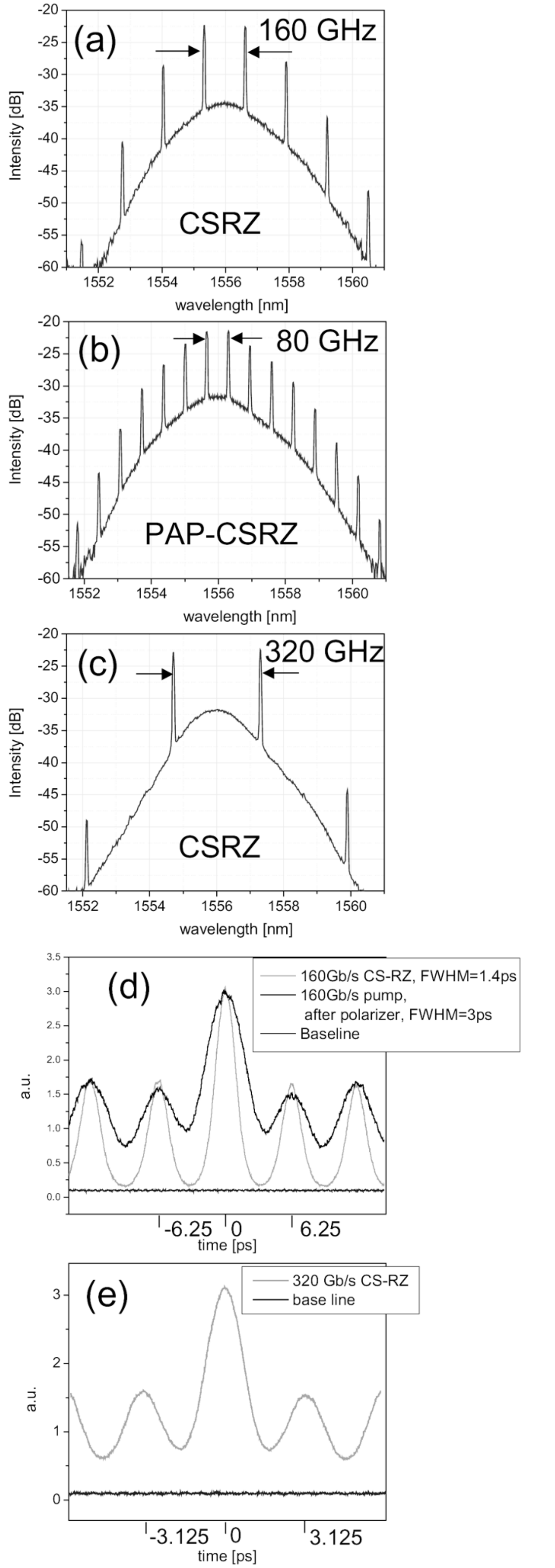

Fig. 5. Spectra of (a) 160-Gb/s CSRZ. (b) 160-Gb/s PAP-CSRZ. (c) 320-Gb/s CSRZ. Autocorrelation traces of (d) 160-Gb/s signals. (e) 320-Gb/s signals.

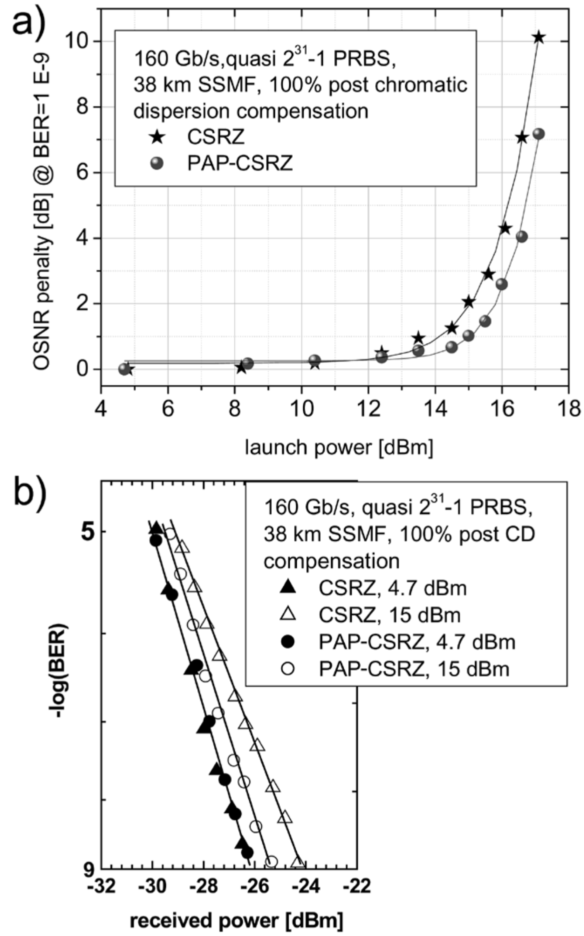

Fig. 6. (a) Sensitivity penalty due to NL propagation versus launch power in SMF. (b) BER curves for both formats at launch powers of 4.7 and 15 dBm in SMF.

IV. 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 study 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 chromatic dispersion is 100% postcompensated. The signal power at the DCF input was always lower than $-4\ \mathrm{dBm}$. Conventional clock recovery was performed at the receiver side. Fig. 6 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. The advantage of a higher nonlinear tolerance was studied by Petermann's group through numerical simulations [5]. It can also be explained as such by analytical means: in quasi-linear transmission systems, the pulses are highly dispersed and overlap strongly even after short propagating distance; therefore, the intrachannel effects become the dominant impairments. The IFWM-induced ghost pulses on the zeros remain an impairing factor, even though a symmetric dispersion map can minimize these intrachannel effects. Under some simple assumptions, the ghost pulse amplitude generated at the zeroth bit slot $(k = 0)$ can be expressed with the following approximation [6]

$$\Delta u_0 \cong -i\frac{2\gamma\tau^2}{\sqrt{3}|\beta''|}\sum_{l,m} A_l A_m A^*_{l+m} \times Ci\left(\frac{2lmT^2}{|\beta''|L}\right) \quad (1)$$

where l, m, and $l+m$ are the indices of the interacting pulses, A is the complex amplitude of the corresponding pulse, γ is the fiber nonlinear coefficient of the transmission fiber, $2^*\sqrt{\ln 2}\,0.5\tau$ corresponds to the FWHM of the Gassian pulse, T is the bit period, β'' is the fiber dispersion, L is the fiber length, and Ci is the cosine integral function. Clearly, for a CSRZ signal the terms in the form of $A_l A_m A_{l+m}$ are always negative, since the sign of A_{l+m} is the opposite of $A_l A_m$. Consequently, the IFWM contributing terms add up. While for a PAP-CSRZ signal, some IFWM components may cancel out if the signs of two contributing terms are the opposite. For example, $A_1 A_2 A_3$ has a different sign from $A_1 A_1 A_2$, therefore they cancel out to some extent. This would effectively suppress a ghost pulse at the bit '0' surrounded by many "1"s.

V. Conclusion

We discussed a novel method to generate phase-coherent data signals based on incoherent emitting pulsed fiber lasers. An ultrafast optical fiber Kerr shutter imprints phase coding on the generate signal. As one application, we demonstrated for the first time the novel 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.

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