A 160-Gb/s Group-Alternating-Phase CSRZ Format

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***Abstract*—We demonstrate a novel 160-Gb/s modulation format that employs phase inversion of every four consecutive bits in a group. This format enables a very simplified clock recovery by optical filtering of 40-GHz spaced tones. The recovered clock shows a low timing jitter of 270 fs. In addition, we investigate its enhanced nonlinear transmission property by comparing it with carrier-suppressed return-to-zero (CSRZ) and pairwise-alternating-phase CSRZ signals through analytical studies and numerical simulations. We experimentally verify its good performance relative to CSRZ through a data transmission over a 38-km single-mode fiber.**

***Index Terms*—Clock recovery, data communication, nonlinear optics, optical modulation, synchronization.**

I. Introduction

In ultrahigh-speed optical transmission systems, clock recovery from a high-rate data stream has been a challenging issue since fast electronics beyond 80 Gb/s are not available yet. The clock recovery schemes for 160-Gb/s optical time-division-multiplexed (OTDM) systems are typically based on optoelectronic injection oscillators [1] or optically phase-locked loops [2]-[4]. In these demonstrations, ultrafast optical-gate devices, such as electroabsorption modulators (EAMs) [1], [2] or nonlinear optical switches [3], [4], are needed to down-convert the input data stream to a low-rate tributary that can be processed by electronics. These configurations become even more complicated than an OTDM demultiplexer.

As alternative to the time-domain approach that requires high-speed optical gating components to switch 160-Gb/s pulses, we realized a simple clock recovery that takes advantage of the spectral characteristics of a novel signal format. Fig. 1(a) shows the conventional 160-Gb/s carrier-suppressed return-to-zero (CSRZ) signal with tones spaced by 160 GHz. A pairwise-alternating-phase (PAP)-CSRZ format was proposed [5] and experimentally demonstrated [6] to possess better nonlinear transmission performance than CSRZ signal at 160 Gb/s. A PAP-CSRZ signal is phase inversed by π for every two bits in a group and, therefore, the resulting frequency spacing of the tones in its spectrum equals 80 GHz, as sketched in Fig. 1(b). This motivated us to further double the period of the π-phase inversion for the signal bits, thus, the tones are even closer spaced to 40 GHz [Fig. 1(c)]. Since in this format the phase modulation of the signal is performed in groups each containing four bits, we term it as group-alternating-phase (GAP)-CSRZ signal. The basic idea for the clock recovery is then to filter the two closely spaced tones that constitute a sinusoidal beat signal clock in time. Thus, a narrow-band optical filter, an optical-to-electrical (OE) conversion, and an electronic 40-GHz high-Q filter would realize the clock recovery. The merit of the proposed scheme, shown in Fig. 2, is its low-complexity design consisting of standard 40-GHz electronic components which supersede the need for high-speed optical gate devices such as EAMs or nonlinear switches.

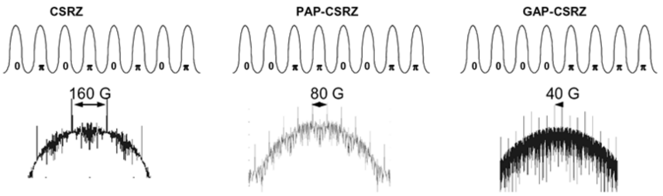

Fig. 1. Modulation schemes of three ON–OFF-keying formats (a pulse represents a bit), and their corresponding spectra.

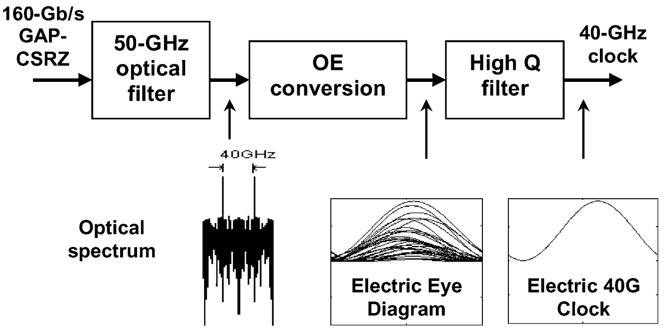

Fig. 2. Schematic of the clock recovery system with GAP-CSRZ signal as the input.

An additional advantage of this format compared to CSRZ signals is that it can effectively suppress intrachannel four-wave mixing (IFWM), which is a major nonlinear transmission impairment at 160 Gb/s. The improvement of the nonlinear performance originates from certain IFWM component cancellations due to the fact of phase inversion in groups rather than in adjacent bits, as will be discussed in the following sections where we investigate its performance and compare it with the one of CSRZ and PAP-CSRZ signals.

II. Signal Generation and Clock Recovery

The transmitter setup for GAP-CSRZ format generation is explained in Fig. 3(a), which primarily consists of an optical fiber Kerr shutter [8] to perform polarization to phase conversion. The Kerr shutter imprints the data pattern of a noncoherent pump to a coherent signal originating from a distributed feedback laser. A 90° polarization-state rotation of the pump pulse (in Jones

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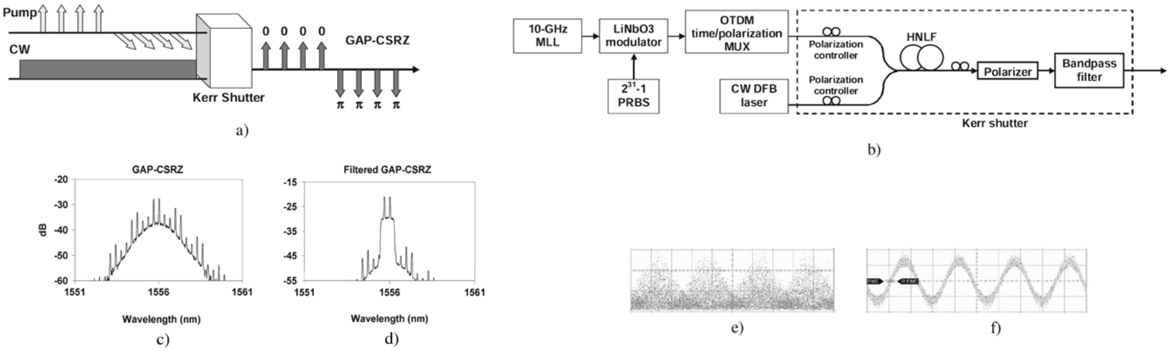

Fig. 3. (a) Illustration of the Kerr shutter, (b) simplified experimental setup, (c) the GAP-CSRZ signal spectrum, (d) spectrally filtered GAP-CSRZ, (e) the eye diagram of the filtered GAP-CSRZ signal, and (f) the recovered clock signal after the high-Q filter.

space) results in a phase flipping of π that is fundamentally attributed to a polarization-dependent cross-phase modulation process [9]. Therefore, a GAP-CSRZ format can be obtained by flipping the polarization of every four pump pulses in a group. The same technique can be applied to generate other phase-correlated formats at ultrahigh speeds, such as PAP-CSRZ [9], vestigial side band (VSB) return-to-zero (RZ) [10], and differential phase-shift keying [11].

The simplified experimental setup is shown in Fig. 3(b). A LiNbO_3 intensity modulator encodes 2.4-ps pulses from a 10-GHz mode-locked laser (MLL) with a pseudorandom bit sequence (PRBS) of $2^{31} - 1$ length. A 160-Gb/s data stream is formed by time multiplexing 10-Gb/s RZ pulses. However, the last stage of the OTDM multiplexer also performs polarization interleaving for the pump pulses organized in groups. Then the pump signal is injected into a section of highly nonlinear fiber (HNLF) together with a continuous-wave (CW)-probe signal. The HNLF has a length of 2.5 km, a Kerr nonlinearity coefficient of 12/W/km, and a dispersion slope of 0.02 ps/km/nm^2. The wavelengths of the pump and the CW-probe are set symmetrically with respect to the zero dispersion wavelength of the HNLF, which are 1546, 1556, and 1551 nm, respectively, to ensure that the group velocities of the pump and the probe signals are equal. Power levels at the input of the HLNF were between 16–19 and 13–16 dBm for the pump and CW-light, respectively. At the HNLF output, a polarizer is set to block the probe signal in absence of the pump. A 5-nm optical filter selects only the probe signal. When the pump is applied, the 160-Gb/s GAP-CSRZ signal is generated with a pulsewidth of 1.8 ps measured by an autocorrelator. The spectrum of the signal is shown in Fig. 3(c).

To recover the clock tone from this signal, a 50-GHz bandwidth optical filter was used to select the two fundamental tones of the data, which are spaced by 40 GHz [Fig. 3(d)]. After OE conversion by a photodetector, the eye diagram of the electric signal is shown in Fig. 3(e), which indicates an intrinsic tone with a periodicity of 40 GHz. An electrical high-Q filter with a Q-value of around 1000 cuts down the data components while selecting the 40-GHz clock tone. The waveform of the recovered clock is shown in Fig. 3(f), exhibiting a measured timing jitter of 330 fs including a 190-fs inherent jitter of the oscilloscope (Agilent 86107A) operated in the precision timing base. Thus, the timing jitter of the clock is deduced to be 270 fs, assuming Gaussian distribution of the jitter. Compared to the ~230-fs jitter of the MLL in the transmitter, the small amount of additional jitter induced by the clock recovery system would not cause receiver sensitivity penalty based on our previous measurements.

III. ENHANCED NONLINEAR TRANSMISSION PERFORMANCE

The GAP-CSRZ format also provides enhanced nonlinear transmission performance relative to conventional CSRZ signals. In particular, it is effective in reducing IFWM-induced ghost pulses on the zero bits due to the phase inversion in groups. Here we investigate this property by an analytical analysis that reveals the fundamental physical mechanism in pulse interaction, and numerical simulations that provide a more quantitative estimation. Experimental studies confirm the theoretical result. We first assume lossless transmission and a symmetric dispersion map that minimizes intrachannel cross-phase modulation. The ghost pulse amplitude generated by IFWM at the zeroth bit slot $(k = 0)$ can be expressed with the following approximation [7]:

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

where l, m, and $l + m$ are the indexes of the interacting pulses relative to the zeroth bit slot, A is the complex amplitude of the corresponding pulse, γ stands for the Kerr nonlinearity coefficient of the transmission fiber, τ denotes a parameter related to the width of the Gaussian pulses, T means the bit period, β'' describes the fiber dispersion, L is the fiber length, and Ci symbolizes the cosine integral function. For a CSRZ signal with alternating signs of fields between adjacent bits, the terms in the form of $A_l A_m A_{l+m}$ always add up constructively since the sign of A_{l+m} is the opposite of $A_l A_m$. Therefore, the IFWM terms can result in an additively enhanced ghost-pulse generation. While for a GAP-CSRZ signal, some IFWM components may cancel out if the signs of two contributing terms are opposite. For example, $A_1 A_2 A_3$ has a different sign from $A_{-1} A_{-2} A_{-3}$, if the phase flipping occurs at the zeroth bit. Similarly, for a PAP-CSRZ signal, it also reduces certain IFWM components due to the phase inversion in pairs.

Next we study the nonlinear transmission performance of the three formats through numerical simulations using $2^{11} - 1$ PRBS, whose length is determined by the limited computing power. The transmission span is a section of 30-km

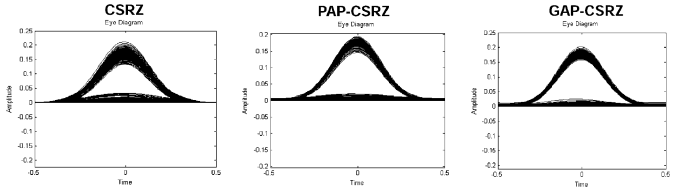

Fig. 4. Eye diagrams of the three formats after nonlinear transmission.

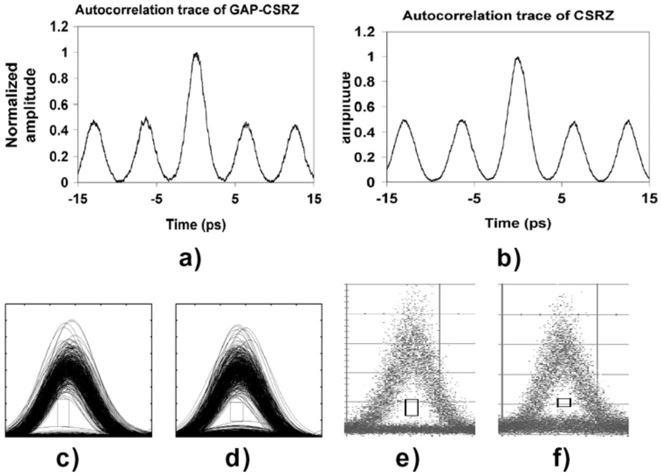

Fig. 5. Autocorrelation traces for the (a) GAP-CSRZ and (b) CSRZ signals before transmission, respectively. (c) and (d) are the corresponding simulated eye diagrams after 38-km transmission in SMF, (e) and (f) experimental results.

single-mode fiber (SMF) using a symmetric dispersion map with equal amount of dispersion precompensation and post-compensation to minimize the intrachannel nonlinear effects. Fig. 4 builds a set of simulations of the three signals with the same duty cycle of 33% and a launch power of 15 dBm. Clearly, PAP-CSRZ and GAP-CSRZ signals show noticeable improvement over the CSRZ signal, while the difference between the PAP-CSRZ and the GAP-CSRZ is small.

Note that at such high rate, each signal pulse can be broadened significantly by fiber chromatic dispersion and overlap with many adjacent pulses even during a short transmission. Therefore, a longer PRBS is needed to generate the worst-case ghost pulse scenario, which is currently only possible by experimental means. To capture these effects in our investigation, we performed an experiment using a 38-km SMF span as described in [6] and long PRBSs. Both GAP-CSRZ and CSRZ signals have the same pulsewidth of 1.8 ps deduced from autocorrelation traces that are shown in Fig. 5(a) and (b), respectively. Thus, the optical phases could cause difference in transmission performance. The launched signal power into the transmission fiber was increased to the level that is large enough to induce significant nonlinear impairment. This can be quantified by eye openings indicated by the windows in the center of the eye diagrams. Fig. 5(c)–(f) shows the simulated and measured eye diagrams of the two formats, respectively, after transmission and dispersion compensation. In the experiment, we monitored the signal eyes with an optical sampling scope having a bandwidth of over 500 GHz. The launched signal power into the transmission fiber was 19 dBm in the simulations and 20 dBm in the experiment, respectively. This discrepancy can be attributed to the losses of the fiber connectors, inaccuracies in the measurements, and the difference in data patterns. By comparing the eyes of the two formats in the simulations and the experiments, the GAP-CSRZ possesses a wider eye opening, showing its effectiveness in combating the intrachannel impairments compared to the CSRZ signal. Furthermore, we characterize the nonlinear performance of the two formats at different launch powers ranging from 14 to 21 dBm. The improvement in eye opening of GAP-CSRZ compared to CSRZ was clearly seen at high launch powers. While we used a simplified dispersion-managed span in our simulations and experiments, we expect the results to apply more generally to conventional dispersion-managed links, since they usually consist of multiple of such spans and the dominating nonlinear penalty, IFWM, simply scales with the number of the spans. In addition, based on the theoretical model presented in this letter, as long as the local dispersion is large enough and pulses strongly overlap, the ghost pulses originated from IFWM would be suppressed in GAP-CSRZ format, which also holds in general in other line configurations.

IV. CONCLUSION

We have demonstrated a 160-Gb/s GAP-CSRZ format, which simplifies clock recovery and provides simultaneous advantage in suppressing intrachannel nonlinear effects. The clock recovery system shows a small timing jitter of 270 fs. We experimentally verified that the eye opening of the GAP-CSRZ signal is larger than the one of a CSRZ signal after a 38-km nonlinear transmission.

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