Demonstration of a 160-Gb/s Group-Alternating Phase CSRZ format Featuring Simplified Clock Recovery and Improved Nonlinear Performance

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Abstract: We propose and demonstrate a new 160-Gb/s signal format employing phase inversion of every four consecutive bits in a group. This format enables simple clock recovery by spectral filtering, and increases the nonlinear tolerance compared to CSRZ signals.
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1. Introduction

In 160-Gb/s optical transmission systems, clock tone recovery from a high-rate data stream is a challenging issue due to the unavailability of ultra-high-speed electronics. The clock recovery at the receiver side is typically based on optically phase-locked loops [1] or opto-electronic injection oscillators [2]. A typical solution employs an ultra-fast optical gate device that de-multiplexes one tributary of the 160-Gb/s data stream, the low-rate optical pulses (e.g. 10 Gb/s) are then converted to an electrical signal and sent to a phase locked loop or an electronic high-Q filter. The extracted clock tone in turn provides timing for the optical gate. This architecture becomes even more complicated than an OTDM demultiplexer, and the ultra-fast optical gate device has to be capable of handling 160-Gb/s signals. Here we propose and demonstrate a new modulation format to realize a simple clock recovery. In this format, the phase modulation of the signal is performed in groups. Each group contains four bits; the phases of the bits in adjacent groups are altered by π. Therefore we term this format as group-alternating phase (GAP)-CSRZ. Fig. 1a-d show the coding schemes and the resulting optical spectra for the GAP-CSRZ and conventional CSRZ signals, respectively. This new format possesses some attractive features: the spectral spacing of the clock tones is 40 GHz, thus clock recovery can be easily implemented by filtering the fundamental tones using standard 40-GHz components without the need for high-speed switching devices such as electro-absorption modulators. In addition, compared to CSRZ signals, this format can effectively suppress intra-channel four-wave mixing (IFWM), which is a major nonlinear impairment at 160 Gb/s. The improvement of the nonlinear performance originates from certain IFWM component cancellation due to the fact of phase inversion in groups rather than in adjacent bits, as will be explained in the subsequent section.

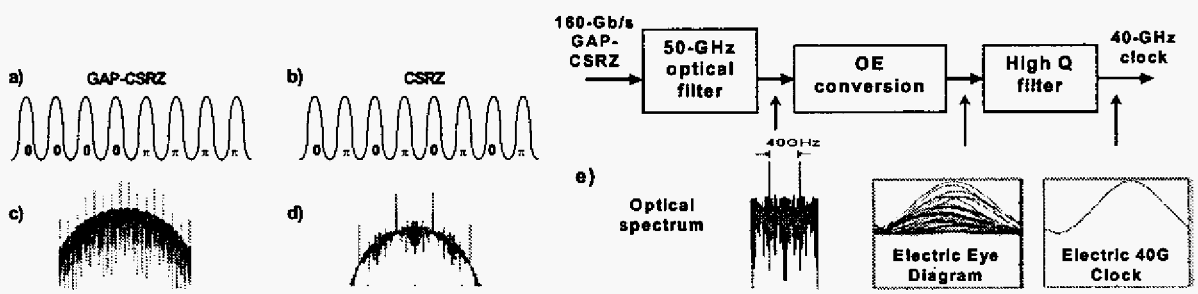

Fig. 1: Illustration of phase modulation for a) GAP-CSRZ, and b) CSRZ, respectively. A pulse represents a bit. c) and d) are the resulting spectra for the two formats, respectively. e) The schematic of the clock recovery.

2. Clock recovery and nonlinear transmission performance of the GAP-CSRZ format

A simple clock recovery schematic is sketched in Fig. 1e. A 50-GHz bandwidth optical filter selects the two fundamental tones of the GAP-CSRZ signal, which are spaced by 40 GHz. After optical-to-electrical (OE) conversion, the 40-GHz clock tone of the signal is filtered by an electric high-Q filter with a Q-value of 1000. This scheme employs standard 40-GHz components to provide a simple and reliable solution for a 160-Gb/s clock recovery. The timing jitter performance depends largely on the Q-value of the high-Q filter, which has been widely used in telecom systems to satisfy the transmission standard requirement.

Compared to conventional CSRZ signals, the GAP-CSRZ format also provides improved performance in suppressing IFWM-induced ghost pulses on the ZERO bits due to the phase inversion in groups. The advantage of the higher nonlinear tolerance can be explained by analytical means as such: Assuming a symmetric dispersion map and loss-less transmission, the ghost pulse amplitude generated at the 0-*th* bit slot (k=0) can be expressed with the following approximation [3]:

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

where l, m, and $l+m$ are the indices of the interacting pulses, A is the complex amplitude of the corresponding pulse, γ is the fibre nonlinear coefficient of the transmission fibre, τ is related to the width of the Gaussian pulses, T is the bit period, β'' is the fibre dispersion, L is the fibre length, and Ci is the cosine integral function. For a CSRZ signal with alternating phase 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 $A_l A_m$. Hence, the IFWM terms can result in a 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 0-th bit. In the following we experimentally verify the nonlinear transmission perofrmance of the GAP-CSRZ and CSRZ formats.

3. Generation of the GAP-CSRZ signal

The generation principle of the GAP-CSRZ format is illustrated in Fig. 2a, mainly based on an optical fiber Kerr shutter [4] that imprints the data pattern of a non-coherent pump to a coherent signal originating from a DFB laser. Phase modulation of the signal can be realized by controlling the polarization of the pump pulses, i.e., the phase of the converted signal flips by π if the polarization of the pump pulse is rotated by 90°, which results from the polarization dependent cross phase modulation process. Through this approach, a GAP-CSRZ format can be generated by flipping the polarization of every four pump pulses as sketched in Fig. 2. The same scheme can be used to generate other phase-correlated formats at ultra-high speeds, such as pairwise-alternating phase CSRZ [5], vestigial side band (VSB) RZ [6], and differential phase shift keying [7].

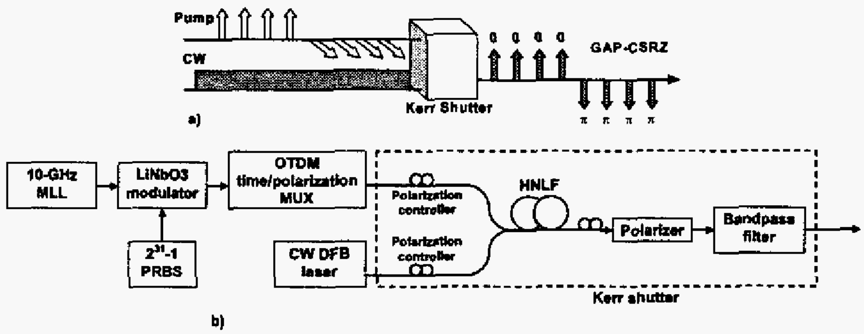

Fig. 2: a) Phase coding through the Kerr shutter by controlling pump polarization, and b) experimental setup

The main components of the experimental setup are shown in Fig. 2b, a 10-GHz mode-locked laser (MLL) outputs 2.4-ps pulses. 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 in a way as shown in Fig. 2a. The OTDM pump signal and a CW probe signal are injected into the HNLF having a length of 2.5 km, and a Kerr non-linearity 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 of the HNLF, which are 1546 nm, 1556 nm, and 1551 nm, respectively to ensure zero walk-off between the pump and the probe signals. At the HNLF output, a polarizer that is adjusted by a polarization controller, blocks the probe signal in absence of the pump. A 3-nm optical filter selects only the probe signal. Power levels at the input of the HLNF were 16-19dBm and 13-16dBm for the pump and CW-light, respectively.

4. Experimental results

Fig. 3a shows the optical spectrum of the generated GAP-CSRZ signal at the output of the Kerr shutter. The auto-correlation trace indicates a pulse width of 1.8 ps. The signal is then passed through a narrowband filter with a rectangular shape. The filter selects two tones spaced by 40 GHz as shown in Fig. 3b, and the corresponding electrical signal after the photo detection is provided in Fig. 3c showing a repetition rate of 40 GHz. The high-Q electric filter cuts down the data components while selecting the 40-GHz clock tone. The recovered clock is shown in Fig. 3d, with a measured timing jitter of 330 fs including a 190-fs inherent jitter of the oscilloscope (Agilent 86107A) operated in the precision timing mode. Compared with the ~300-fs jitter of the MLL in the transmitter, the clock recovery system only adds a very small amount of additional jitter, which would not cause receiver sensitivity penalty based on our previous measurements.

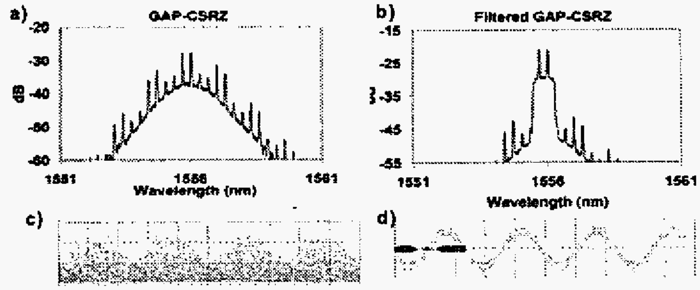

Fig. 3: a) The optical spectrum of the GAP-CSRZ signal, b) the filtered spectrum, c) the eye diagram of the resulting signal after photo detection, and d) the recovered 40-GHz clock signal.

We also investigate the nonlinear performance of the GAP-CSRZ signal in transmission, relative to a CSRZ signal with the same pulse width of 1.8 ps as evidenced in Fig. 4a and 4b. Thus only the optical phases could cause difference in transmission performance. We first perform simulations of the two formats using a transmission span as reported in [5]. The launched signal power into the transmission fiber is 19 dBm, which is large enough to induce significant nonlinear impairments that can be quantified by eye openings indicated by the windows in the center of the eye diagrams shown in Fig. 4c and 4d, respectively. Then we carry out an experiment to compare the transmission performance of the two formats. We use the same 38-km transmission span and monitor the signal eyes with an optical sampling scope having a bandwidth of over 500 GHz. The launched signal power into the transmission fiber was 20 dBm so the nonlinear impairments are clearly visible on the oscilloscope. The signal power at the DCF input is limited to 0 dBm. Fig. 4e and 4f show the experimental results. By comparing the eye diagrams of the two formats obtained from the simulation and the experiment, the GAP-CSRZ possesses a wider eye opening, showing its effectiveness in combating the intra-channel impairments compared to the CSRZ signal.

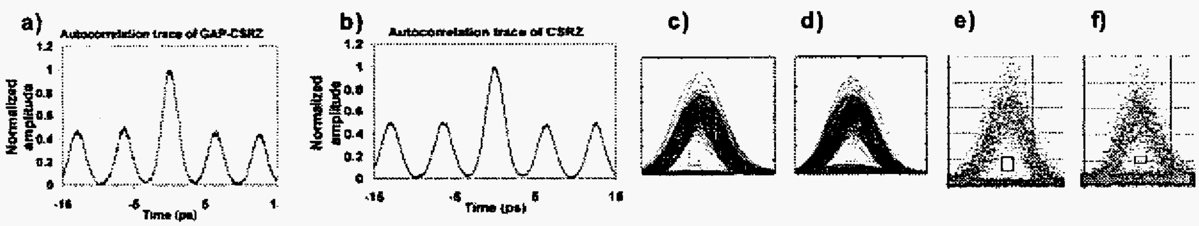

Fig. 4: Auto-correlation traces for the a) GAP-CSRZ and b) CSRZ signals before transmission, respectively. c) and d) are the corresponding simulated eye diagrams after 38-km transmission in SMF, e) and f) are the experimental results for GAP-CSRZ and CSRZ, respectively.

5. Conclusion

We demonstrate a new GAP-CSRZ format at 160 Gb/s, which enables simple clock recovery and provides simultaneous advantage in suppressing intra-channel effects. The clock recovery system shows a timing jitter of 330 fs. In addition, the group-alternating-phase property of the GAP-CSRZ signal shows improvement in nonlinear transmission relative to a CSRZ signal.

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