Ghost-Pulse Suppression in Phase-Modulated RZ Formats using Data-Pattern-Assisted Phase Modulator

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Abstract *We study the nonlinear performance of phase-modulated formats where phase inversion occurs for every group of bits ranging from 2 to 5. A novel data-pattern-assisted phase modulator is proposed to minimize ghost pulse generation.*

1. Introduction

The intra-channel effects are the dominating impairments in high-speed systems of 40 Gb/s and above. Although timing and amplitude jitters originating from intra-channel cross phase modulation and intra-channel four-wave mixing (IFWM) can be greatly reduced using symmetric dispersion maps [1, 2], the IFWM induced ghost pulses cannot be cancelled. Previous research has addressed return-to-zero (RZ) formats with different phase modulation schemes, such as alternate-phase RZ (APRZ) [3], pairwise-alternating-phase (PAP)-CSRZ [4, 5] and group-alternating-phase (GAP)-CSRZ [6], showing their effectiveness in suppressing nonlinear impairments especially for ghost-pulse generation. Recently, ref. [7] revealed the mechanics of ghost-pulse cancellation for phase-modulated formats. In [4-6], π-phase inversions are performed for every two and four bits in a group for PAP-CSRZ and GAP-CSRZ, respectively. An extension for the GAP-CSRZ format would be GAP(*n*)-CSRZ signals, where *n* could be any integer greater than 2. However, the performance of GAP(*n*) signals and their comparison with PAP-CSRZ have not been examined.

In this paper, we first study the ghost-pulse generation in four modulation formats including PAP-CSRZ and GAP(*n*)-CSRZ signals where *n* ranges from 3 to 5. We then investigate the phase-inversion position in the data pattern and its impact on ghost pulse generation. The histograms of ghost-pulse amplitudes show that the ghost pulses can be greatly suppressed by properly adjusting the phase-inversion positions. Based on the observations, we propose a novel transmitter employing a data-pattern-assisted (DPA) phase modulator. In this transmitter, a monitoring module is used to identify the "0" bits of importance, where significant ghost pulses could appear. The start point of the DPA phase modulator is then adjusted to ensure that the phase inversions occur at those "0" bits. Our simulation shows that the transmitter employing DPA phase modulator can effectively suppress the ghost pulses.

2. Impact of Phase Inversion Position

We investigate the ghost-pulse generation of four phase-modulated RZ formats in a 40-km standard single-mode fiber (SMF) with a dispersion of D=17 ps/nm/km. The four formats are shown in Fig.1. When assuming a symmetric dispersion map and lossless transmission, the ghost pulse amplitude generated at *k*-th bit slot can be approximately expressed as follow [1, 5, 7]:

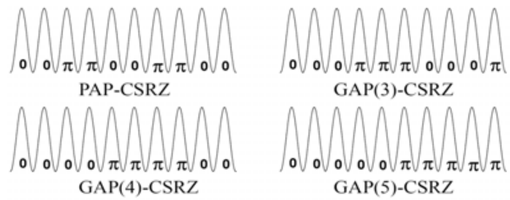

Fig.1 Four phase modulated RZ format

$$\Delta u_k = -j\frac{2\gamma\tau^2}{\sqrt{3}|\beta_2|}\sum_{l,m} A_l A_m A^*_{l+m-k}\, Ci\left[\frac{2(l-k)(m-k)}{|\beta_2|L}\right] \qquad (1)$$

where *l, m* and *l*+*m* are the indices of the interacting pulses, *A* is the complex amplitude, γ is the fiber nonlinear coefficient, τ is the half-width of the Gaussian pulses, *T* is the period, *L* is the fiber length and *Ci* is the cosine integral function. We use the above equation to compute the ghost pulse amplitudes. The pulse width is set to be 5 ps at 40 Gb/s. The launch power is set to 13 dBm so the ghost pulses are clearly identifiable. The sequence length in the analysis is 15 bits as determined by the criteria in [8], with a "0" bit at the center (*k*=8). We evaluated all the possible combinations of the 14 bits with different phase inversion positions. The best- and worst-case histograms of ghost-pulse amplitudes

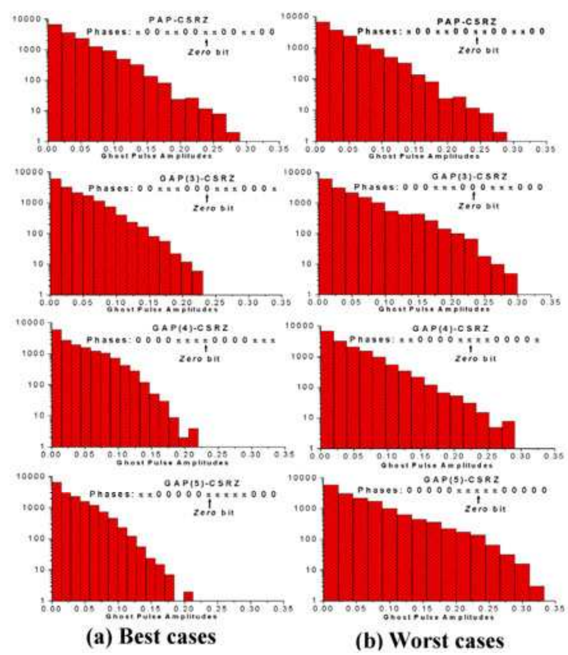

Fig.2 Histograms of ghost-pulse amplitudes for four formats with 2^{14} possible bit combinations. (a) Best cases (b) Worst Cases.

are shown in Fig.2. Note that for PAP-CSRZ the ghost-pulse histogram is independent of the phase-modulation position due to its inherent symmetry.

Clearly, the phase-inversion position has important impact on ghost-pulse generation, particularly for large *n* of GAP(*n*)-CSRZ formats. From Fig.2 we can see that if the "0" bit of concern is at the phase-inversion position, which indicates an odd-symmetric phase-modulation, the best cases are achieved (Fig. 2a). While if the "0" bit is in the middle of a block with the same phase showing an even symmetric phase modulation, the worst cases are encountered (Fig. 2b). The underlying reason is that in the first case most IFWM components cancel out while the second modulation-scenario causes most of the IFWM components to add up. This can be evidenced if the terms of Eq.(1) are checked. We also observed that in the best cases, the larger the *n* the more effective the ghost-pulse suppression is, while the discrepancy between the best and worst cases becomes more significant.

The above observations motivated us to use GAP(*n*) formats with large *n* values with an automatic instrument to monitor and adjust the phase-modulation positions.

3. Data-Pattern-Assisted Phase Modulator

The schematic of our proposed DPA phase modulator is shown in Fig.3. The monitoring module is used to store the

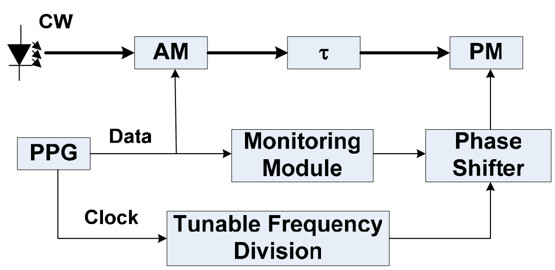

Fig.3 Schematic of data-pattern-assisted phase modulator

bits stream within an *m*-bits-length time window, where *m* is determined by the criteria in [8]. A broadband phase shifter is used to delay the phase-modulating signal based on the monitoring-circuit output to ensure the maximum suppression of ghost pulses. When changing the divide ratio of the tunable frequency-divider, PAP-CSRZ or other GAP(*n*)-CSRZ signal with different *n* values can be generated.

The monitoring module has to identify the worst pattern to suppress the largest ghost pulse. This can be realized as follows: the monitoring module stores *m*-bits-length data stream and identify the "0" bits, counting the number of "1"s around each side of the "0" bit. The sequence which has the maximum number of "1"s is selected as the phase inversion position. Then the phase shifter delays the phase-modulating signal according to the monitoring result, until the selected "0" bit aligns with the phase inversion position.

To evaluate the performance of the proposed transmitter, we performed simulations using a 2^9-1 length PRBS in a 40-km SMF fiber with symmetric dispersion mapping. The pulse width is set to be 5 ps at 40 Gb/s and the launch power

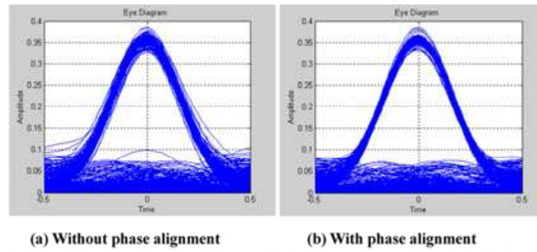

Fig.4 Eye diagrams of GAP(5)-CSRZ signal after transmission of 40 km SMF fiber (a) without phase alignment (b) with phase alignment.

is 13 dBm. The results for GAP(5)-CSRZ are shown in Fig.4. It can be clearly seen that after phase alignment the worst ghost pulses have been effectively suppressed.

4. Conclusions

We have investigated the ghost-pulse generation of PAP-CSRZ and GAP(*n*)-CSRZ signals (*n*=3, 4 and 5) at 40 Gb/s. The impacts of phase modulation position on ghost pulse suppression for these phase-modulated RZ formats are analyzed and numerically simulated. It is shown that GAP(*n*)-CSRZ with large *n* is effective in suppressing ghost pulses if the phase inversion can be properly controlled at the right position. A novel DPA phase modulator is proposed to properly adjust the relative position of phase inversions. The simulation results show that our proposed transmitter effectively suppresses the ghost pulses.

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