IFWM Suppression Using APRZ with Optimized Phase-Modulation Parameters

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Abstract—We demonstrate experimentally as well as numerically that the alternate-phase return-to-zero (APRZ) modulation format increases the non-linear tolerance of strongly dispersion-managed 40-Gb/s transmission. An analysis of phase misalignment is also presented.

Index Terms—Fiber optics communications, fibers, nonlinear optics, modulation formats.

I. INTRODUCTION

In strongly dispersion-managed (DM) 40-Gb/s systems, dispersion causes the RZ pulses to broaden before being restored by dispersion-compensating fiber (DCF). During this breathing process, pulses interact nonlinearly with each other, both by attracting or repelling each other through intra-channel cross phase modulation (IXPM) [1,2], and by exchanging energy through intra-channel four-wave mixing (IFWM) [3]. IXPM is a phase-insensitive process giving timing jitter, and can be combated by optimizing the launch position [4]. IFWM is a phase-sensitive process where the pulses interact as groups of two or three, transferring energy to a certain bit-slot. The mixing product has a definite phase relation to its driving pulses. Mixing products appearing in the same bit slot but originating from different groups of interacting pulses interfere coherently, so changing their relative phase will affect the efficiency of the process. In the alternate-phase return-to-zero (APRZ) modulation format, neighboring pulses differ in phase [5-7] and optimizing this phase difference will reduce the IFWM distortion. Other phase-modulated RZ formats have been proposed in [8-14].

In this letter, we demonstrate experimentally that APRZ with optimized amplitude of phase modulation and controlled delay with respect to the pulse centers yields significant improvement in IFWM tolerance, compared to standard RZ. The experimental results are shown to be in excellent agreement with the numerical simulations and with the theoretical predictions [15].

Fig. 1 – The intensity (a) and phase of APRZ signals: in (b) the phase variation for square-APRZ is shown, while in (c) the phase variation for sine-APRZ is shown for the case of pulse-phase alignment (solid line) and misalignment (dashed line).

The key APRZ parameter is indeed \( \Delta \phi \), which determines the relative phase shift of the IFWM contributions [15]. It is noteworthy that in the case of \( \Delta \phi = \pi \), square-APRZ reduces to a generalized carrier-suppressed RZ (CSRZ) [9], in which the duty cycle is a free parameter.

If the signal phase is not constant over the bit slot, as is the case in sine-APRZ, it is useful to introduce an effective phase variation, defined as the weighed average of the phase over the bit slot:

\[ \Delta \phi = \frac{1}{T} \int_{0}^{T} \phi(t) \, dt \]
\[ \Delta \phi_{\text{eff}} = \int_{0}^{T} \phi(t) |A(t)|^2 \, dt - \int_{0}^{T} \phi(t) |A(t)|^2 \, dt \]  

where \( A(t) \) is the normalized field amplitude, \( \phi(t) \) is the periodic phase variation.

Another important parameter is the relative delay, \( \Delta \tau \), between the phase variation and the RZ pulses. Figure 1-c illustrates sine-APRZ with an aligned and a delayed phase variation. If the points of maximum and minimum phase deviation coincide with the bit-slot centers, then the effective phase alternation \( \Delta \phi_{\text{eff}} \) is maximized. If the phase variation is delayed, \( \Delta \phi_{\text{eff}} \) is reduced and the pulses acquire an alternate frequency shift, and therefore a wider spectrum. For \( \Delta \tau = T/2 \), \( \Delta \phi_{\text{eff}} \) becomes zero and the alternate frequency shift is maximized. Numerical simulations in which sine-APRZ is passed through a narrow filter confirm that the spectral width increases with \( \Delta \tau \).

### III. The Transmission System

Sine-APRZ was tested on a dispersion-managed transmission link consisting of four post-compensated spans of length 100km, 100km, 80km, and 80km, respectively. This link was implemented both in an experimental set-up, and as a numerical simulation.

In the experimental set-up (see Fig. 2), a pulse train was obtained by modulating CW light with an electro-absorption modulator (EAM), driven by a 40-GHz sine. The resulting 7-ps-wide pulses were subsequently fed into a Mach-Zender modulator (MZM), driven by a 40-Gb/s PRBS sequence obtained by time-multiplexing four 10-Gb/s PRBS sequences of length \( 2^{21}-1 \). The signal was finally phase-modulated by a 20-GHz sinusoidal clock, aligned with the data (\( \Delta \tau = 0 \)). Alignment was obtained by tuning the delay line in Fig. 2 until the power of the APRZ through a 95-GHz filter was maximized. The \( V_x \) of the phase modulator is approximately 6.5V at 20 GHz. At the receiver side the signal was passed through a 142-GHz Gaussian filter and attenuated to a power level giving BER=10\(^{-9}\). BER was evaluated assuming Gaussian noise in the receiver.

The SMF in the link has dispersion \( D = 16.5 \) ps/nm/km, slope \( S = 0.06 \) ps/nm\(^2\)/km, nonlinearity index \( \gamma = 2.1 \) W\(^{-1}\)/km, and loss \( \alpha = 0.21 \) dB/km. The DCF has \( D = -82.5 \) ps/nm/km, \( S = -0.18 \) ps/nm\(^2\)/km, \( \gamma = 4.3 \) W\(^{-1}\)/km and \( \alpha = 0.7 \) dB/km. The amplifiers had a noise figure of 5dB. In order to emphasize the non-linear effects of the system, relatively high power was launched in the link: 9.5 dBm into the SMF and 3.5 dBm into the DCF.

### IV. Results and Discussion

The system performance was evaluated as the receiver-sensitivity degradation with respect to back-to-back transmission (power penalty). The simulation results are summarized in Fig. 3, which shows the power penalty as a function of the effective phase modulation, for the cases of square and sine modulation, with \( \Delta \tau = 0 \), and the eye diagrams for RZ (\( \Delta \phi_{\text{eff}} = 0 \)) and for optimal phase modulation. In Fig. 4 the experimental results are presented as power penalty versus phase-modulator drive voltage.

Both the simulation and the experimental results show that alternate-phase modulation has a significant impact on the system performance. Reducing the launch power has shown a decreased influence of the phase modulation on the system performance, which confirms that the improvement is indeed due to suppression of non-linear effects. The curves in Fig. 3 show a rough symmetry around \( \Delta \phi_{\text{eff}} = \pi/2 \), in agreement with the theoretical predictions [15]. Moreover, one will notice that square-APRZ and sine-APRZ perform very similarly. This is not surprising since the duty cycle is relatively short (25%), so that the pulses will experience a nearly flat phase, even with a sinusoidal phase modulation. An important observation to be made is that systems with different parameters will in general show different penalty-vs-\( \Delta \phi_{\text{eff}} \) curves and therefore different performance optima. The system studied in reference [5], for example, had shorter spans, and the shape of the penalty-vs-\( \Delta \phi_{\text{eff}} \) curve was consequently different. Pre-compensation, used to reduce the impact of IXPM, was also shown to have a strong impact on the exact shape of this curve, and launch position and phase-modulation amplitude must be optimized simultaneously [5]. Here attention is focused on the IFWM suppression given by phase modulation and therefore launch position was not optimized.

\[ \text{2 We define a 256-bit quasi PRBS as a } (2^8-1) \text{-bit PRBS with an extra zero after the } 7^{th} \text{ consecutive zero in the sequence.} \]
Fig. 3. Performance of sine APRZ (numerical simulations) in terms of power penalty as a function of effective phase-modulation amplitude (a), and eye diagrams for $\Delta \phi_{\text{eff}}=0$ (b), and $\Delta \phi_{\text{eff}}=\pi/2$ (c). Phase modulation suppresses the IFWM-induced ghost pulses. Further improvement in terms of timing-jitter mitigation could be achieved by optimizing the launch position.

Fig. 4. Experimental results showing the performance of sine APRZ in terms of receiver sensitivity as a function of drive voltage in a phase modulator with $V_p=6.5\,\text{V}$ ($\Delta \phi_{\text{eff}}=\pi$ for 6.9V for aligned phase-modulation and 7-ps Gaussian pulses).

Fig. 5 – Numerical simulation of sine-APRZ performance, in the case of phase-modulation alignment (solid line), and quarter-bit-slot delay (dashed line), for which $\Delta \phi_{\text{eff}}=0.67\Delta \phi$.

V. CONCLUSION

We have experimentally demonstrated, by transmitting 40-Gb/s data on a 360-km, strongly dispersion-managed link, that APRZ with optimized phase-modulation amplitude is successful in reducing IFWM. The experiment confirms previous theoretical and numerical predictions. We also observe, through numerical analysis, that the phase-modulation delay on the pulse train has a dramatic impact on the system performance.

REFERENCES