Optimal operating conditions and modulation format for 160 Gb/s signals in a fiber parametric amplifier used as a slow-light delay line element

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Abstract: We study optimal operating conditions for 160-Gb/s signals traversing a slow-light delay line based on parametric amplification. Six phase modulated formats are investigated, including CSRZ, PAP-CSRZ, GAP-CSRZ, RZ duobinary, RZ DPSK and RZ.

OCIS codes: (999.9999) Slow light, Optical buffers;(190.4970) Parametric oscillators and amplifiers.

1. Introduction

Tunable delay lines based on slow light are potential candidates for bit-synchronization and buffer applications in optical packet switched networks. Successful implementation will require the choice of proper operating conditions to achieve the maximum possible delay while simultaneously maintaining reasonable signal quality. Recently, simulations and experiments on this issue have been reported [1]-[5] involving intensity-modulated signals including non-return-to-zero (NRZ) and return-to-zero (RZ) formats at data rates from 10 to 40 Gb/s. Slow light elements cause different phase changes to different spectral components of the signal, therefore the larger spectra of higher rate signals leads to more distortion, potentially causing a larger eye-opening penalty. To the best of our knowledge, however, the impact of the slow-light delay line on high-speed (>40 Gb/s) phase-modulated signals has not yet been investigated.

Previously, we have experimentally investigated the system performance of delayed 10-Gb/s RZ data packets in the telecommunication window [4,5]. In this paper, we study the slow-light delay-line performance of a fiber parametric amplifier (FPA) at 160 Gb/s for recently demonstrated phase-modulated formats including carrier-suppressed return-to-zero (CSRZ), pair-wise-alternating-phase (PAP) CSRZ [6], group-alternating-phase (GAP) CSRZ [7], RZ duobinary, RZ differential-phase-shift-keying (DPSK) as well as RZ on-off keying (OOK). These modulation techniques are attractive for clock recovery and suppression of nonlinear effects at ultra-high data rates and it is important to investigate their employment in slow light settings. We define a new figure of merit, Delay Over Eye opening penalty, (DOE), and use this parameter to identify optimal balance between achievable delay and signal degradation. Finally, we explain the predicted difference in performance between these formats.

2. Transfer function of the FPA and the choice of the pump wavelength and the power

In this study we assume a CW pump for our pulsed signals. The pump wavelength is near the zero dispersion wavelength of the fiber. Then the transfer function of a small-signal FPA based on dispersion shifted fiber (DSF) of length of L for signal E_s can be expressed as [8]:

$$H(j\Omega_s)=\frac{E_s(L)}{E_s(0)}=(\cosh(gL)+j(\gamma P_0+\frac{\Delta\beta}{2})\frac{\sinh(gL)}{g})\exp(j(\frac{-\Delta\beta+2\gamma P_0}{2})L) \qquad (1)$$

where γ is the nonlinear coefficient, P_0 is the pump power and g is the gain coefficient given by $g^2 = -\Delta\beta(\Delta\beta/4+\gamma P_0)$, $\Delta\beta = \beta^{(2)}\Omega^2 + 1/12\beta^{(4)}\Omega^4$ represents the wave-vector mismatch, $\beta^{(2)}$ and $\beta^{(4)}$ are the second and fourth order derivatives of the propagation constant, respectively, and $\Omega = \omega_s - \omega_p$ is the frequency detuning between the signal and the pump. The above equation applies to fibers whose zero dispersion wavelength does not fluctuate appreciably over the fiber length, such as the DSF used in [9].

As discussed in [4], the bandwidth of an FPA depends on the dispersion slope of the fiber, the pump power, and the separation between the zero-dispersion wavelength λ_0 of the fiber and the pump wavelength λ_p. Narrower gain bandwidth means an increased likelihood of signal degradation, implying that the pump power and the pump wavelength will affect the signal quality. Besides the gain bandwidth of the FPA, phase-modulated signal formats may show different properties when propagating through the slow-light delay line where the phases are significantly changed. The narrowest bandwidth of the FOPA used in these simulations is greater than two times the signal bandwidth at 160 Gb/s. The 5-km DSF used in our simulations has a constant dispersion slope of 0.08 ps/(nm^{2}km) at a fixed zero dispersion wavelength λ_0 = 1560 nm with an effective mode area of 54.76 μm^2. Furthermore, we neglect fiber loss, which has a minor effect on the gain profile for our parameters [9].

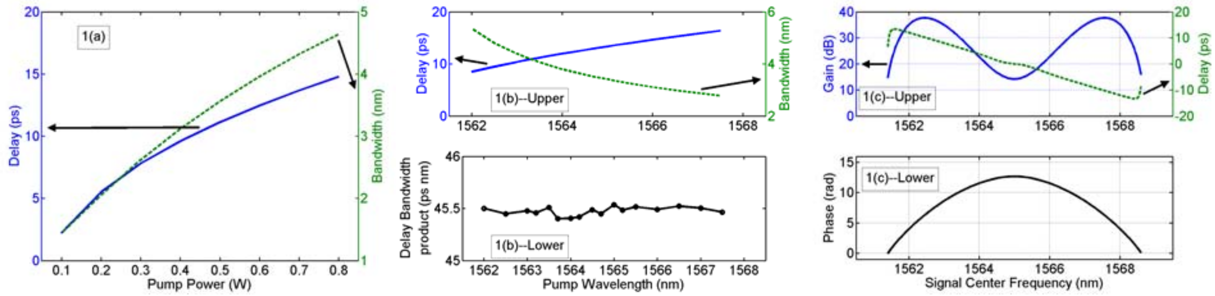

Fig.1(a), maximum delay (solid curve) and bandwidth (dashed curve) vs. λ_p; 1(b)—Upper, bandwidth (dashed curve) and maximum delay (solid curve); 1(b)—Lower, maximum delay bandwidth product vs. λ_p; (c)—Upper, gain spectrum and delay when λ_p=1565nm; (c)—Lower, phase.

To illustrate, Fig.1 (a) shows that both the maximum delay and the bandwidth of the FPA increase as the pump power increases. Note that in the small signal model, gain saturation effects are not included in the simulations. Here we only consider the spectrally dependent phase shifts that cause signal distortion in order to better study intrinsic limitations of our slow light device. We set a fixed pump power, P_0 = 0.56 W as in [4] to ensure no gain saturation occurs for practical input powers. The bandwidth and the maximum delay vary in opposite directions as the pump wavelength changes. It can be seen from Fig.1 (b) that as the separation between λ_0 and λ_p increases, the bandwidth becomes smaller as the maximum delay increases. Furthermore, as illustrated in Figure 1(b)—Lower, the product of the bandwidth and the delay is almost constant and only has a small fluctuation with λ_p, it reaches a peak value at λ_p = 1565 nm, which is a trade-off in the range of pump wavelength of interest. Fig.1(c) shows the gain spectrum with corresponding delay and phase shift of the FPA operating at the chosen pump wavelength.

3. Balance between delay and signal quality

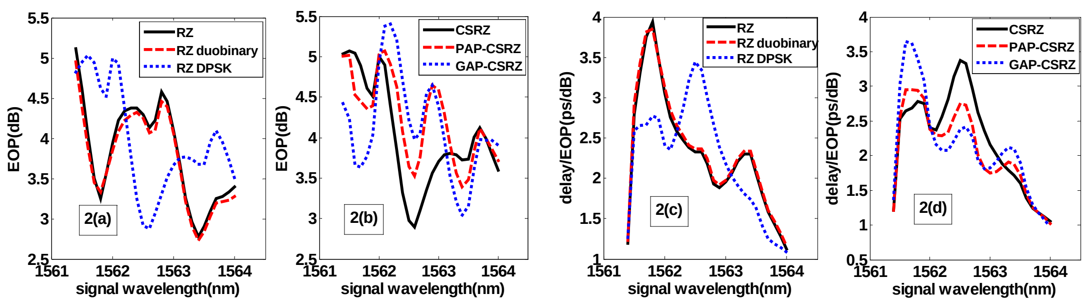

Fig.2(a) and (b): EOP vs. signal wavelength, (c) and (d): delay over EOP vs. signal wavelength

Once the pump wavelength is fixed, the choice of the signal wavelength and the modulation format affects the signal quality. We use Eye Opening Penalty (EOP) to evaluate the output signal quality. The input signal is taken as the reference and EOP = $10\log_{10}\times(EO_{input}\text{-}EO_{output})$ where EO is the maximum eye-opening height normalized to average power. Although EOP may differ from the receiver sensitivity penalty in certain scenarios, it is a convenient measurement of signal quality in many applications. Here we define a new factor DOE = delay / EOP to find optimal conditions so as to achieve small EOP and large delay when we fix the pump power and the pump wavelength with the values discussed in section 2. Fig.2(a-d) show the EOP and DOE curves. In our simulations, the signals are all 33% duty-cycle RZ Gaussian-shaped at 160 Gb/s from a pseudo random bit sequence (PRBS) of length 2^7-1.

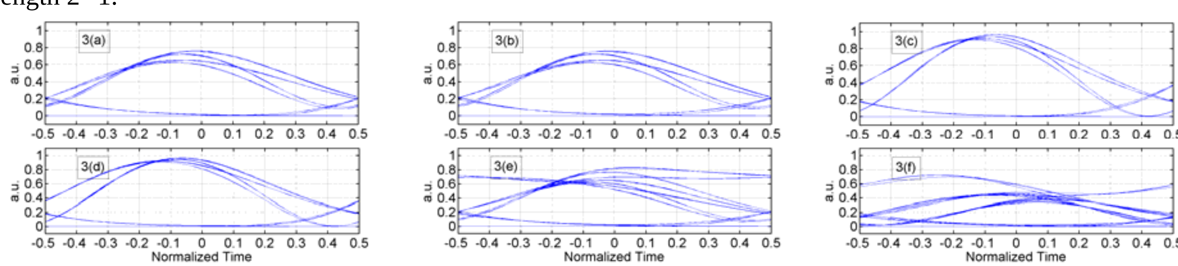

Fig.3 (a) Eye diagram of the output signal for (a) RZ at λ_s=1561.9nm., (b) RZ duobinary at λ_s=1561.9nm, (c) RZ DPSK at λ_s=1562.6nm, (d) CSRZ at λ_s=1562.6nm, (e) PAP-CSRZ at λ_s=1561.9nm, (f) GAP-CSRZ at λ_s=1561.6nm.

From Fig.2, it is clear that RZ and RZ-duobinary have nearly the same EOP and DOE curves while CSRZ and RZ-DPSK behave similarly. The performance of GAP-CSRZ is close to that of RZ. RZ, RZ-duobinary, PAP-CSRZ and GAP-CSRZ show peak DOEs at their first EOP minimum, which are near the peak delays but not the lowest EOPs; CSRZ, RZ-DPSK reach their peak DOEs at their second EOP minimum which are also the lowest EOPs but slightly shifted from the peak delays. Fig.3 also provides the eye diagrams of the six phase-modulated formats at their optimal DOEs.

4. Explanations of the different modulation formats using typical patterns

From the EOP and DOE curves one can obtain a general idea that the signal bandwidth does not affect DOE significantly, rather, the phase-modulation scheme associated with certain data patterns plays a key role. Fig.4 reveals four major degradation factors: 1^{st}), broadening (Fig.4a), which results from the difference in delay between different frequencies of a single pulse. 2^{nd}), level fluctuation for consecutive '1's; 3^{rd}), pulse merging between two neighboring '1' and '-1' (Fig.4c, 4f), meaning that the two pulses with opposite phases strongly interact and merge into a single pulse; and 4^{th}), '0'-level raising (Fig. 4d, 4e), which occurs for two neighboring pulses having the same polarity. The above degradations disappear when smaller delay is experienced. As the broadening is limited to a 3-bit maximum due to the shape of the gain spectrum, a 2^7-1 PRBS length is sufficient to capture all possible interactions.

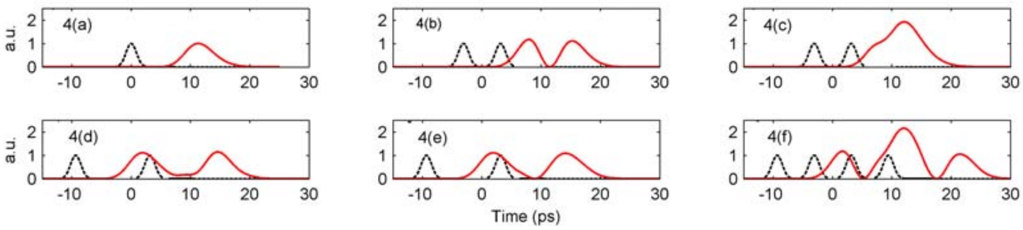

Fig.4. Black dashed curves, input waveform; Red solid curves, output waveform. (a) single RZ input pulse, (b) two consecutive'1's at input, (c) two consecutive'1's at input with opposite phase, (d) two consecutive '1's at input separated by a '0'(101), (e) two '1's at input with opposite phase, separated by a '0'(1 0 -1), (f) typical patterns for PAP-CSRZ(1 1 –1 –1). Output scaled down by factor of 625.

In RZ or RZ-duobinary, there is no such pattern of nearby '1's having opposite phase, so broadening, '1'-level fluctuation and '0'-level raising are the dominant degradation factors. For CSRZ and RZ-DPSK, '1 –1' is a typical pattern, therefore degradation at maximum delay is very large and the optimum DOE is achieved at a smaller delay. While for PAP-CSRZ and GAP-CSRZ, the pattern '1 –1' can also be found but with a much smaller probability, thus GAP-CSRZ shows the EOP and DOE curves close to RZ while PAP-CSRZ is similar to CSRZ.

5. Conclusion

We have investigated the optimal operating conditions for the FPA based slow-light delay line at 160 Gb/s. Six phase-modulated formats are studied using DOE parameter to find balance between the delay and signal quality. We demonstrate that the optimal operating conditions are modulation format dependent. RZ and RZ-duobinary show the highest DOE (thus best performance) followed by RZ-DPSK, CSRZ, GAP-CSRZ and PAP-CSRZ. Explanations have been provided by illustrating with certain typical patterns that pass through the slow-light delay line.

Acknowledgement: This work was supported by the NSFC (60407008), the key project of Ministry of Education (106071), and the Fok Ying Dong Fund (101067).

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