

Slow light on Gbit/s differential-phase-shift-keying signals

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Abstract: We demonstrate, via simulation and experiment, slowing down of a phase-modulated optical signal. A 10.7-Gb/s NRZ-DPSK signal can be delayed by as much as 42 ps while still achieving error free via broadband SBS-based slow light. We further analyze the impact of slow-light-induced data-pattern dependence on both constructive and destructive demodulated ports. By detuning the SBS gain profile, we achieve 3-dB Q-factor improvement by the reduction of pattern dependence. Performance comparison between NRZ-DPSK and RZ-DPSK shows that robustness to slow-light-induced pattern dependence is modulation format dependent.

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1. Introduction

Slow light techniques have enjoyed much recent interest due to the potential systems applications involving tunable delay lines, such as bit-level synchronizers, equalizers, and signal processors. In general, slow light is achieved by tailoring an enhanced group-index resonance within a given medium [1]. Unfortunately, a high group index accompanied by a narrow resonance bandwidth tends to also distort a high-bit-rate data signal and cause data-pattern dependence [2]. Recent publications have described the quality of a data stream that

has passed through the slow light element, including results for data-pattern dependence, limited data bandwidth, and bit-error-rate (BER) measurements. Promising slow light techniques to achieve tunable delay lines for Gbit/s data include the use of: (i) stimulated Brillouin scattering (SBS) in fiber [3], (ii) stimulated Raman scattering (SRS) on silicon chip [4], (iii) optical parametric amplification (OPA) in fiber [5], and (iv) four-wave-mixing (FWM) in semiconductor optical amplifiers (SOAs) [6].

We emphasize that all previously published slow light system results were for intensity-modulated signals. However, phase-encoded formats, such as differential-phase-shift-keying (DPSK), have not been explored in a slow light element before. DPSK is becoming ever-more important in the optical communications community due to its potential for increased receiver sensitivity, tolerance to various fiber impairments, and better spectral efficiency [7]. It is highly desirable to understand how the phase information of the DPSK signal could be preserved and how much fractional delay it could experience. Furthermore, it is important to explore how slow light nonlinearities could affect differently the demodulated two ports of a delay interferometer-based DPSK receiver. A laudable goal would thus be to examine critical system limitations on Gbit/s DPSK data as it traverses a tunable slow light element.

In this paper, we demonstrate experimentally and via simulation slowing down of a phase-modulated signal. A 10.7-Gb/s NRZ-DPSK signal can be delayed by as much as 42 ps (45% fractional delay) while still achieving error free via broadband SBS-based slow-light element. We further analyze slow-light-induced data-pattern dependence on demodulated output ports. By detuning the SBS gain profile, 3-dB Q factor improvement is achieved by reducing the data-pattern dependence. Performance comparison between 2.5-Gb/s and 10-Gb/s with the same fractional delay shows that data-pattern dependence is bit-rate specific. Finally, system level comparisons of 2.5-Gb/s NRZ-DPSK with RZ-DPSK under the same 5-GHz SBS bandwidth show different robustness to slow-light-induced data-pattern dependence.

2. Concept of slow light on phase-encoded optical signals

The concept of slowing down phase-modulated optical signals is shown in Fig. 1 (Left). When a DPSK signal passes through the slow light element, one expects that its phase patterns get delayed according to the slow light gain and bandwidth. Meanwhile, phase preservation should also be expected for information integrity. However, commonly-generated DPSK signals feature unavoidable residual intensity modulation, which also experiences slow-light nonlinearities. Demodulation of such delayed DPSK signal encounters the problem of data-pattern dependence on both the constructive “DB” (Duo-binary) and the destructive “AMI” (Alternate-Mark-Inversion) ports after the one-bit delay interferometer (DI), as shown in Fig. 1 (Left). It is thus crucial to analyze critical system limitations on Gbit/s DPSK signals transmitted through a narrowband tunable slow-light element.

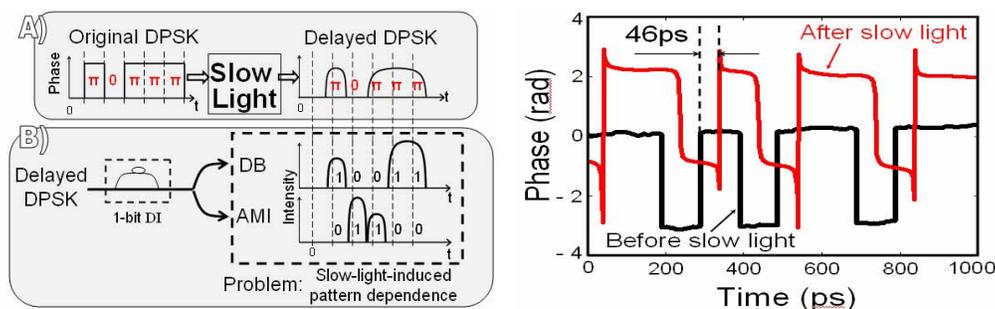


Fig. 1. Left: A) Concept of slow light on phase-modulated optical signals. B) Slow-light-induced data-pattern dependence on demodulated two output ports. Right: Simulation result of phase patterns of a 10-Gb/s DPSK signal before and after 8GHz BW slow light element. Phase is preserved and delayed by 46 ps.

Figure 1 (Right) shows the simulation result of slow light on the phase patterns of a 10-Gb/s DPSK signal. The slow-light element is analytically modeled to have a Lorentzian-

shaped imaginary part of the refractive index, with controllable bandwidth and gain. Kramers–Kronig relationship determines the real part of the refractive index, whose derivative gives the slow-light delay profile. A 10-Gb/s NRZ-DPSK signal is simulated using a Mach-Zehnder modulator with proper bias and driving voltage. The phase patterns of the DPSK signal are shown both before and after an 8-GHz slow-light element. We show that phase patterns can be delayed by up to 46-ps and the differential ‘ π ’ phase relationship preserves quite well. This confirms the concept of slow light delays on phase information.

3. Experimental results of slow light on 10-Gb/s NRZ-DPSK signals

We further carry out DPSK slow-light experiment and the setup is shown in Fig. 2 (Left). The slow-light mechanism is based on broadband SBS [3] in a piece of highly nonlinear fiber (HNLF). Broadband SBS pump is used to accommodate Gbit/s optical signals. We use a Gaussian noise source driven by 400-MHz clock to modulate the injection current of a commercial directly-modulated laser (DML). The pump spectral-width is adjusted by an RF attenuator. The broadband pump is then amplified by a high-power EDFA and enters a 2-km HNLF, with the measured Brillouin shift to be 10.3-GHz. An NRZ-DPSK probe data stream is generated by externally modulating the tunable laser source (TLS) using a Mach-Zehnder modulator (MZM), which is biased at its transmission null and driven by approximately 2V. A sinusoidally-driven second pulse carver modulator is used to generate 50% RZ-DPSK signals. The amplified and attenuated DPSK signal with controllable power counter-propagates with the pump in the HNLF. One polarization controller is used on the signal path to maximize the SBS interaction. The amplified and delayed DPSK signal is finally demodulated using a one-bit DI and both DB and AMI ports are detected. An optical attenuator is adjusted accordingly to the SBS gain so as to keep the input power into the EDFA fixed. BER measurements are taken on both the DB and AMI demodulated signals.

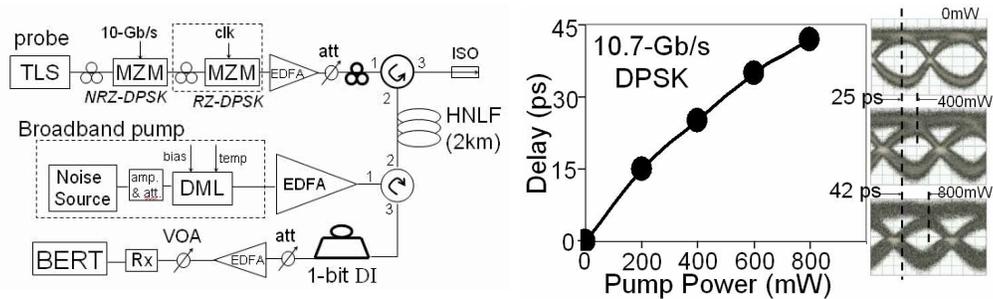


Fig. 2. Left: Experimental Setup for DPSK slow-light based on broadband SBS. Right: Observation of DPSK slow-light: continuous delay of up to 42 ps for a 10.7Gb/s DPSK signal.

Figure 2 (Right) shows the measured delay of a 10.7-Gb/s NRZ-DPSK signal with 0dBm power under an 8-GHz SBS gain bandwidth. The measured delay scales fairly linearly with the increased pump power, demonstrating the ability to continuously control the delay of the DPSK phase pattern. The detected balanced DPSK eyes are shown for three different pump powers, with a maximum of 42 ps delay at a pump power of 800 mW. The achieved 42 ps delay of a 10.7-Gb/s NRZ-DPSK signal corresponds to a fractional delay of 45%.

4. DPSK data-pattern dependence

As shown in Fig. 2 (Right), delayed DPSK eyes exhibit severe signal distortion with the increased slow light delay. In order to assess the signal quality, we analyze both the constructive and destructive ports of the DI after demodulation individually. Figure 3 shows the 10.7-Gb/s NRZ-DPSK intensity patterns before and after passing through the slow light element, with positions recorded right before demodulation (NRZ-DPSK) and right after demodulation (DB and AMI), respectively.

The typical and well recognized method for generating an NRZ-DPSK signal, using an MZM, has several advantages: (i) exact ‘ π ’ phase modulation, (ii) insignificant frequency chirping, and (iii) increased tolerance to driving voltage imperfections [7]. However, residual intensity modulation occurs unavoidably during phase transitions. We can categorize these “intensity dips” as isolated “1”s (between two consecutive dips) and consecutive “1”s (between two long separated dips). Isolated “1”s occupy higher frequency components compared to consecutive “1”s, and will therefore experience much less gain after passing through a narrowband slow-light resonance. This effect can be clearly seen for the distorted NRZ-DPSK intensity patterns after slow light.

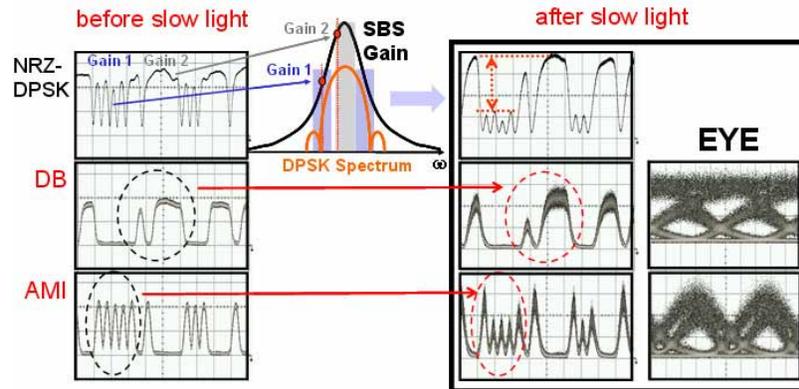


Fig. 3. Slow-light-induced data-pattern dependence: 10.7-Gb/s NRZ-DPSK through an 8-GHz slow light element. Bit patterns before (NRZ-DPSK) and after (DB and AMI) demodulation are shown before and after slow light.

The pattern-dependent gain NRZ-DPSK experiences will translate into two different types of data-pattern dependence on demodulated two signals. In the DB port, the peak power is much higher for long “1”s, compared with single “1”s. This can be explained from the fact that single “1”s are only demodulated from two consecutive “1”s in NRZ-DPSK which has a much slower rising time due to slow-light third-order dispersion [8]. This leads to an insufficient constructive interference for the generation of single “1”s. The AMI port exhibits strong pattern dependence within a group of “1” pulses. Compared with the “1”s in the middle, the leading and the trailing “1”s always have much higher peak powers in that they both experience unequal-power constructive interference from the edge pulses in a group of “isolated dips” in delayed NRZ-DPSK pattern. Both DB and AMI eye diagrams exhibit vertical data-pattern dependence. Furthermore, the AMI port also features non-negligible pulse walk-off, which can be attributed to the slower rising and falling times of the two edge pulses compared with fast-transitioned middle pulses, in a group of “1” pulses.

BER measurements on the DB port of a demodulated 10.7-Gb/s NRZ-DPSK signal under different delay conditions are shown in Fig. 4 (Left). We emphasize that we could still achieve error free at a delay of up to 42 ps with a power penalty of 9.5dB. The clear tradeoff between signal fidelity and delay can be explained by the following two main reasons. Data-pattern dependence due to limited slow-light bandwidth is one major factor for signal degradation, as confirmed by the vertically closed eyes. Not only the gain but also the phase (delay) spectrum of the broadband SBS [9] will affect the delayed PRBS data quality. Spectra in Fig. 4 (Left) show that crosstalk from Rayleigh backscattering of the broadband pump is another contributor to the power penalty, especially when the bit-rate is comparable to the Brillouin shift. The performance of the demodulated AMI port from 10.7-Gb/s DPSK signals is worse than that of the DB port because of severe pulse-walkoff and increased Rayleigh spectral overlapping due to much wider AMI bandwidth. Figure 4 (Right) shows the performance comparison of 10.7-Gb/s and 2.5-Gb/s NRZ-DPSK data with a fixed SBS gain bandwidth of 7-GHz. System performance of 2.5-Gb/s NRZ-DPSK exhibits 6.5dB better performance at

800 mW pump power, the main reason being lower bit-rate signals see much less data-pattern dependence and much smaller Rayleigh crosstalk, as can be confirmed by the two DB eyes.

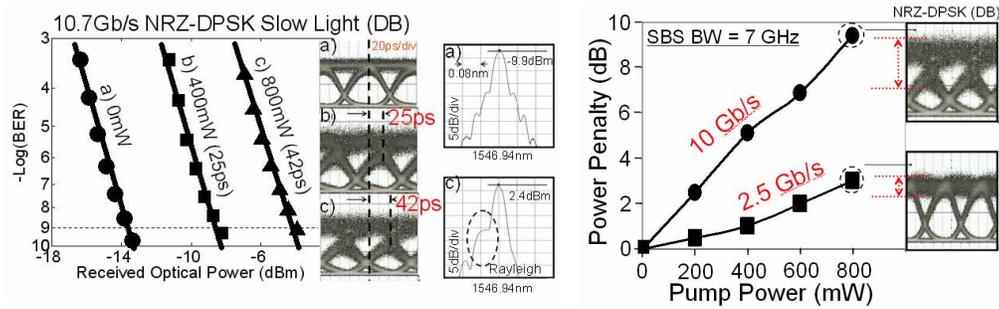


Fig. 4. Left: BER measurement of DB port from 10.7-Gb/s DPSK signals after SBS slow light element. Data-pattern dependence and Rayleigh crosstalk (shown in the spectrum) are the two main reasons for DPSK signal degradation. Right: Power penalty comparison between 2.5-Gb/s and 10-Gb/s NRZ-DPSK shows that data-pattern dependence is bit-rate specific.

5. Reduction of DPSK data-pattern dependence

Realizing that the slow-light-induced data-pattern dependence mainly comes from the pattern-dependent gain, we red-detune the peak of the SBS gain profile by 0.016nm from the channel center, resulting in gain equalization and thus pattern-dependence reduction between isolated “1”s and consecutive “1”s within NRZ-DPSK “intensity dips”, shown in Fig. 5. Bit-patterns and eye diagrams with and without detuning for both demodulated DB and AMI ports are also recorded for comparison. The optimum 3-dB Q factor (determined from BER measurement) improvement (from 12 to 15dB) for the AMI eyes confirms the effectiveness of this detuning method. The detuning not only resolves vertical data-pattern dependence, but also reshapes the rising and falling times of the edge pulses in a group of “1” pulses, such that pulse walk-off is also alleviated, as can be seen from the AMI eye diagram after detuning.

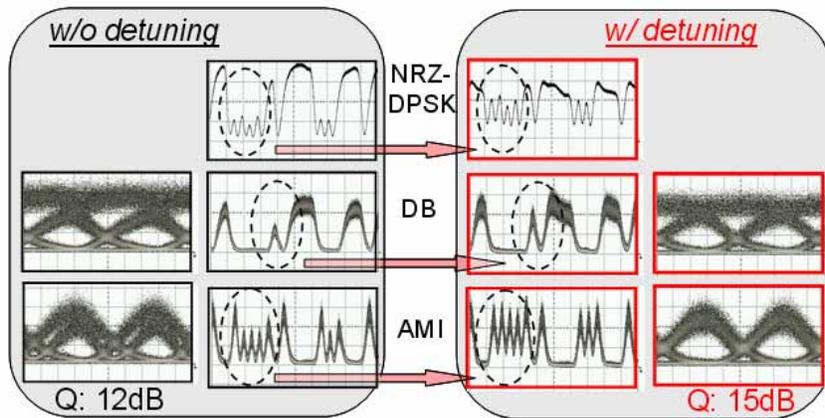


Fig. 5. Reduction of DPSK data-pattern dependence by detuning the SBS gain peak: 3-dB Q factor improvement on the AMI port demodulated from 10.7-Gb/s DPSK signals is achieved.

6. System performance comparison between 2.5-Gb/s NRZ-DPSK and RZ-DPSK

Motivated by the fact that RZ-DPSK is also another popular modulation format thanks to the increased tolerance to fiber nonlinearities, we conduct performance comparison of NRZ-DPSK with RZ-DPSK at a bit rate of 2.5-Gb/s. The reason we are not comparing them at 10-Gb/s is that RZ-DPSK bandwidth exceeds the 10-GHz Brillouin shift. Figure 6 shows delay and power penalty comparison as a function of increased pump power. Under a fixed 5-GHz

SBS gain bandwidth, the fractional delay (absolute delay divided by pulse-width) of RZ-DPSK is comparable with that of NRZ-DPSK. In terms of signal quality, RZ-DPSK outperforms NRZ-DPSK by as much as 2dB at 700 mW pump power. The inset AMI eye diagrams show that RZ-DPSK is much more tolerant than NRZ-DPSK in terms of slow-light-induced data-pattern dependence. The main reason can be understood from the fact that pulse carver modulator used in RZ-DPSK extracts only the amplitude-modulation-free center portions of the bits, thus largely eliminating any residual dips, which is the main cause of data-pattern dependence in NRZ-DPSK.

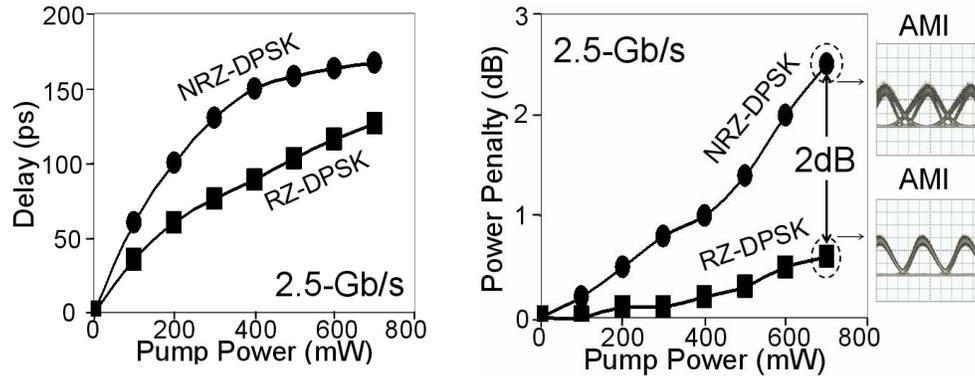


Fig. 6. Left: Delay for 2.5-Gb/s NRZ and RZ-DPSK with the same 5-GHz SBS BW. The fractional delays for both NRZ and RZ-DPSK are comparable. Right: RZ-DPSK outperforms NRZ-DPSK by as much as 2dB, which shows its robustness to data-pattern dependence.

7. Conclusion

We experimentally demonstrate slow light effect on a phase-encoded optical signal. By utilizing broadband SBS-base slow light in HNLFF, 10.7-Gb/s NRZ-DPSK signals can be continuously delayed by as much as 42 ps while still achieving error free. Slow-light-induced DPSK data-pattern dependence on demodulated output ports are systematically analyzed and reduction of data-pattern dependence is achieved by detuning the SBS gain peak away from the channel center frequency, resulting in 3-dB Q factor improvement for the AMI port. Future research directions as to slow down >10-Gb/s phase-modulated signals would involve the use of narrow band parametric amplification [10] in optical fibers, which proves to maintain signal fidelity while still achieving reasonable slow-light delay.

Acknowledgment

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