SPM-Based 2R Regenerative 10Gbps Optically Linearly Controlled Delay Line with 0ps to 170ps Tuning Range

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Abstract: We demonstrate a 2R regenerative optical delay line with error-free operation, 1dB negative sensitivity penalty for degraded 10Gbps RZ packets. Its time delay can be linearly tuned from 0ps to 170ps with maintained original wavelength.

OCIS codes: (999.9999) Slow light; (070.6020) Signal processing; (060.4510) Optical communications.

1. Introduction

All-optical routers must support routing of variable-length packets that can arrive asynchronously at packet routing nodes. Such routers require all-optical buffers with low data distortion to control time delays of optical packets for synchronization function or contention resolution [1]. One promising approach using spectral resonant effect has demonstrated slow light results such as achievable delay and bandwidth [2-3]. But the delayed pulse experiences the distortion and its quality is seldom evaluated in a system-level experiment although the distortion may restrict its application in the real system. Another approach uses wavelength conversion and dispersion technique to achieve large time delay based on different wavelength corresponding to different dispersion in a highly dispersive medium [4]. Recently, as large as 4.2ns time delay has been reported for single one pulse using the wavelength conversion and dispersion technique but with more compact configuration: using self-phase modulation (SPM), filtering and dispersion effects [5]. However, the pulsewidth was broadened from 3.5ps to 350ps and thus will result in interpulse interaction and significantly degrade the quality of the data.

Regenerative optical delay lines are desirable for use in real systems to allow cascaded operation for larger delays. In this paper, we report on first time negative power penalty slow light using a 2R regenerative (reshaping and reamplification) optical delay line based on SPM, filtering and dispersion effects for 10Gbps return-to-zero (RZ) packets. Through controlling signal power level and filtering appropriate wavelength, the time delay is linearly and continuously tuned from 0ps to 170ps with output wavelength same as input signal wavelength. The pulsewidth is reshaped from original 25ps to 20ps. System performance measurements of the regenerative delay line demonstrate error-free operations with 0.5dB sensitivity penalty for un-degraded input 10Gbps RZ packets and 1dB negative sensitivity penalty for degraded input packets.

2. Experimental setup and operation principle

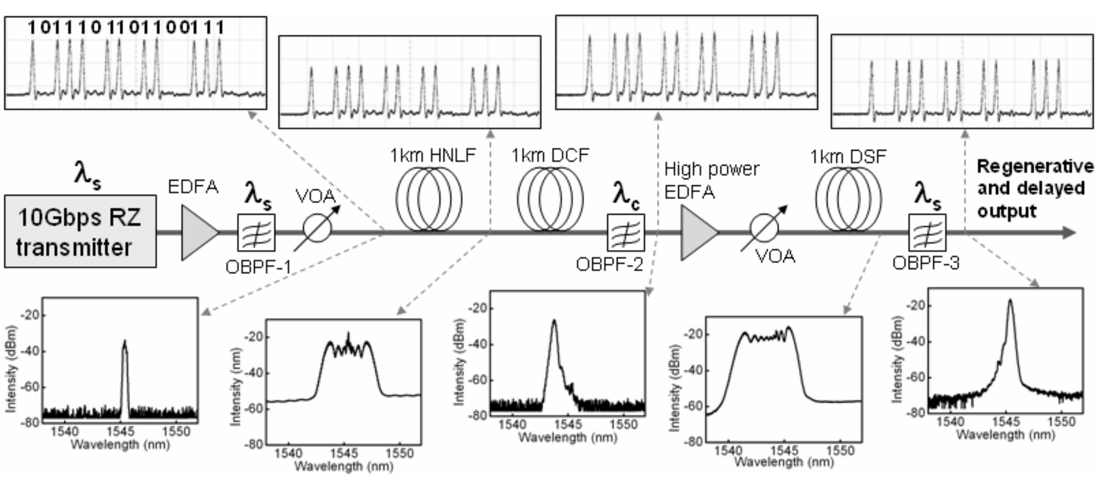

Fig. 1 Experimental setup (OBPF: optical bandpass filter; VOA: variable optical attenuator).

The experimental setup is shown in Fig. 1. A 10Gbps optical RZ transmitter with 1545.4nm wavelength (λ_s) is used to generate 10Gbps optical RZ packets with fixed data pattern of "1011101101100111" and 11.2ns gaps. The RZ

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packets were amplified by an Erbium-doped fiber amplifier (EDFA) and its amplified spontaneous emission (ASE) noise was filtered out by a 0.4nm optical bandpass filter (OBPF-1). The waveform and optical spectrum of the RZ packets are shown as the inset pictures in Fig.1. After passing the RZ packets through a 1km long highly nonlinear fiber (HNLF) with nonlinear coefficient of 10.9/W km, its optical spectrum was broadened from 0.4nm to 4.3nm due to strong SPM effect in the HNLF, shown as the inset picture in Fig.1. Subsequent 1km long dispersion compensation fiber (DCF) with dispersion coefficient of -67ps/nm km at 1545nm is used to provide wavelength-dependent time delay, while the DCF also compensates the negative chirp of the pulses induced by the SPM effect. The OBPF-2 with 0.4nm bandwidth was used to slice the SPM-broadened signal spectrum at a center wavelength (λ_c) offset from λ_s for different time delay, and the inset pictures in Fig.1 show corresponding waveform and optical spectrum. In order to maintain original wavelength λ_s, the delayed RZ packets with center wavelength λ_c were fed to a 1km long standard dispersion shift fiber (DSF) with nonlinear coefficient of 3.5/W km after amplified by a high power EDFA. The SPM effect in the DSF broadened its optical spectrum to 5.5nm bandwidth, shown as the inset picture in Fig.1. Finally OBPF-3 with 0.4nm bandwidth was used to filter out the part centered at λ_s, i.e., delayed RZ packets with λ_s, shown as the inset picture in Fig.1. During the operation of the delay line, the center wavelengths of the OBPF-1 and OBPF-3 were fixed to the original wavelength λ_s, while tuning the center wavelength of the OBPF-2 for different time delays. The power levels of the RZ packets before the HNLF and the DSF were also adjusted by tuning variable optical attenuators (VOA) for optimized signal-noise-ratio (SNR).

3. Tunable optical delay measurement results

Fig.2 depicts measured optical spectra for input 10Gbps RZ packets, after HNLF, after OBPF-2, after DSF and after OBPF-3. The details have been described above. We can see that the central wavelength of output delayed RZ packets is the same as that of the input packets.

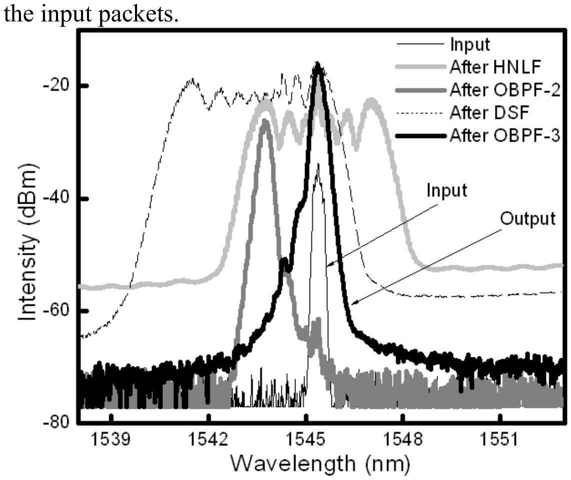


Fig. 2 Measured optical spectra of the 10Gbps RZ packets at different positions in the experimental setup.

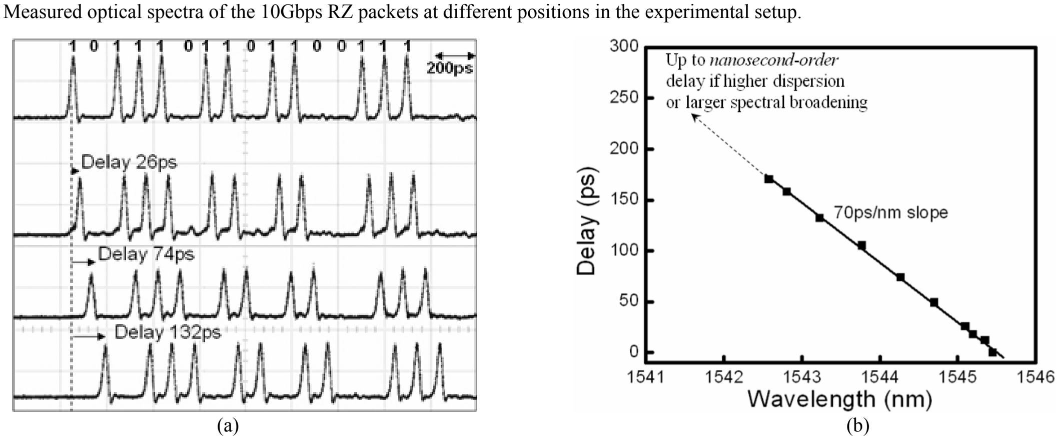


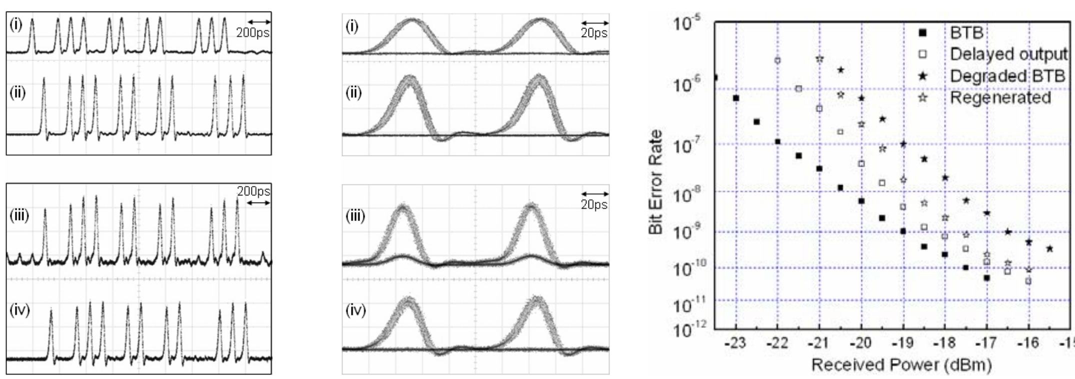
Fig. 3 (a) Oscilloscope traces showing time delay of the RZ packets varying with the center wavelength of the OBPF-2; (b) Linear function between time delay of the RZ packets and the center wavelength of the OBPF-2.

The time delay was measured through comparing the temporal position of the pulse peak on a sampling oscilloscope by tuning the central wavelength of the OBPF-2, as shown in Fig. 3(a). Firstly we marked down the temporal position of the input packets through tuning center wavelength of the OBPF-2 to λ_s and also adjusting VOAs before the HNLF and DSF for no SPM effect happening. And then we increased the power levels into the HNLF and DSF for exciting the SPM and tuned the center wavelength of the OBPF-2 for different time delay. Fig.3 (b) shows the measured delays of the RZ packets versus λ_c of the OBPF-2. We found that the time delay has a linear function with λ_c of the OBPF-2 and its slope is 70ps/nm. The maximum time delay is 170ps corresponding to λ_c=1542.58nm. The slope of the time delay is determined mainly by the dispersion coefficient of the DCF, but also little bit by the dispersion slopes of the HNLF and DSF. Nanosecond-order time delay is possible if employing larger dispersion medium or higher power levels for wider SPM-broadened spectra.

4. System performance

We first evaluated system performance of the optical delay line when input 10Gbps RZ packets were not degraded, whose waveform and eye diagram are shown as (i) in Fig. 4(a) and (b), respectively. After the delay line, the RZ packets was delayed by 90ps and its waveform and eye diagram are shown as (ii) in Fig. 4(a) and (b), respectively. The pulsewidth was reduced from original 25ps to 20ps. Bit-Error-Rate (BER) measurement indicates error-free operation with 0.5dB power penalty in the receiver sensitivity, which is shown in Fig.4 (c).

We then intentionally degraded the extinct ratio of input 10Gbps RZ packets by changing the bias of E/O modulator in the transmitter to increase space level noise, shown as (iii) in Fig.4 (a) and (b), respectively. After the regenerative delay line, the space level noise was removed due to intensity-dependent SPM and filtering effects to discriminate the mark and space levels, shown as (iv) in Fig.4 (a) and (b), respectively. The delay is 46ps due to reduced peak power of the degraded input signal and then narrower SPM-broadened spectrum of the RZ packets compared to the case of un-degraded signal input. A 1.0 dB negative power penalty in the receiver sensitivity is measured due to an increased extinction ratio, as shown in Fig. 4 (c).



(a) (b) (c)

Fig. 4 (a) Waveforms and (b) eye diagrams of (i) input RZ packets and (ii) corresponding delayed RZ packets, (iii) degraded input RZ packets and (iv) corresponding regenerated delayed RZ packets; (c) BER results.

5. Conclusion

We demonstrate a 2R regenerative optical delay line for 10Gbps RZ packets with reshaping the pulsewidth from 25ps to 20ps and tuning the delay from 0ps to 170ps. Nanosecond-order time delay can be expected with further optimized parameters. Error-free operations were demonstrated with 0.5dB and -1dB sensitivity penalty for un-degraded and degraded input 10Gbps RZ packets, respectively. The regenerative delay line allows cascaded operation for larger delay. The potential for higher bit rates is indicated due to ultrafast SPM effect. This work is supported by the DARPA Slow-Light Project #412786-G.

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