Simultaneous Slow-Light Delay and Pulse Reshaping of 10Gbps RZ Data in Highly Nonlinear Fiber-based Optical Parametric Amplifier with Clock-Modulated Pump

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Abstract: We demonstrate 25ps slow-light delay of 10Gbps RZ data simultaneously with pulsewidth reshaping from 50ps to 20ps using optical parametric amplifier. Error-free operations are achieved for both 10Gbps RZ packets and PRBS data.

OCIS codes: (999.9999) Slow light; (060.4370) Nonlinear optics, fibers; (190.4970) Parametric oscillators and amplifiers.

1. Introduction

Slow-light techniques have attracted great interest for the development of optically controlled delay lines compatible with future optical fiber communication systems. Early slow-light scheme employed electromagnetically induced transparency (EIT) in different media [1]. Recent research focuses on slow-light scheme based on optical resonances in fibers and semiconductors, such as stimulated Brillouin scattering (SBS) [2], stimulated Raman scattering (SRS) [3] and optical parametric amplification [4]. These methods are suitable for optical fiber communication systems and intense research has been carried out recently to improve slow light performance to meet system-level requirements, such as delay time, bandwidth, and pulse distortion [5]. The scheme based on resonant effect increases the group index and thus reduces the group velocity of optical pulses by causing large normal dispersion in a narrow gain or absorption spectral region. However, the pulses propagating through slow-light media could be broadened and distorted. The need for larger delay results in greater distortion and ultimately degrades the quality of pulses.

In this paper, we demonstrate for the first time a slow-light delay line with simultaneously pulse reshaping function based on an optical parametric amplifier (OPA) with clock-modulated pump. Through exponential parametric gain, the OPA is able to reshape the signal pulses and minimize the distortion of the delayed pulses since the clock-modulated pump determines the quality of delayed pulses. Time delay of signal pulses is controlled by the OPA's parametric gain and bandwidth. We propagated 10Gbps optical return-to-zero (RZ) packets and pseudorandom binary sequence (PRBS) data through the OPA and error-free operations were achieved. We characterized the OPA and measured its slow light properties, including gain, transfer function and time delays.

2. Principle of operation

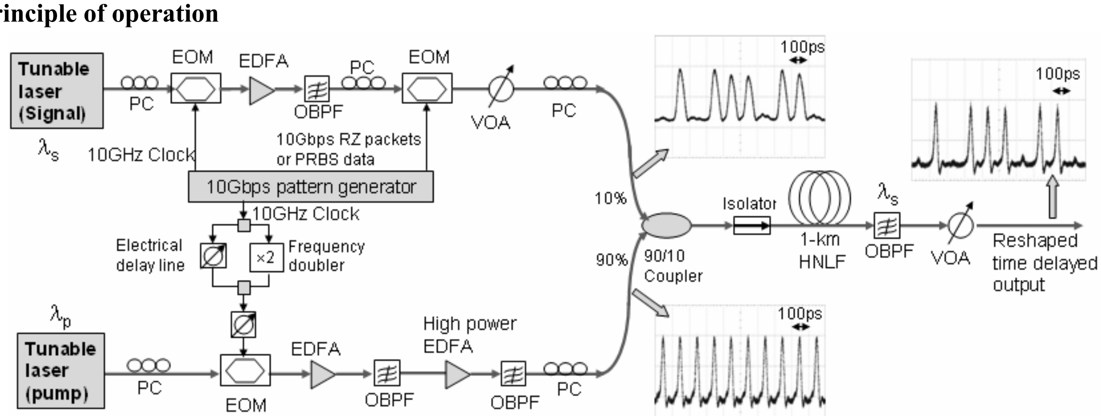

Fig. 1 Experimental setup (PC: polarization controller; EOM: E/O modulator; OBPF: optical bandpass filter; VOA: variable optical attenuator).

As shown in Fig.1, the OPA is constructed using 1-km long highly nonlinear fiber (HNLF) as the slow-light medium. When the signal pulse travels through the fiber, it experiences a narrowband parametric gain and an increase in the group index induced by the spectral resonance, which leads to a reduced group velocity of the signal pulse. However, the delayed signal pulse becomes broadened and gets distorted somewhat due to large normal dispersion and saturation effect [4]. Using a clock-modulated pump in the OPA, the signal pulse is reshaped simultaneously during the slow-light propagation due to nonlinear transfer function of the OPA's parametric gain versus the pump power.

In the experimental setup described in Fig. 1, a tunable laser at λ_p was used as the pump and an E/O modulator (EOM) was used to generate 10GHz clock-modulated pump. A 20GHz electrical clock signal generated by a frequency doubler was mixed with the 10GHz electrical clock signal to drive the EOM in order to compress the pulsed pump for higher peak power and also broaden the pump optical spectrum to increase SBS threshold for better pump-signal power transfer in the OPA [6]. The pulsed pump is 20ps pulsewidth and boosted by two erbium-doped fiber amplifiers (EDFA). A tunable laser at λ_s serves as the signal and is injected into an EOM driven by the 10GHz electrical clock from the 10Gbps pattern generator. The generated 10GHz RZ optical pulses with 50ps pulsewidth are carved by 10Gbps non-return-to-zero (NRZ) data from the 10Gbps pattern generator. In the experiment, we used two kinds of data pattern: 1) packets consisting of a fixed pattern “10111011” with 24.8ns gaps and 2) 2^7-1 PRBS data. The signal pulses are shown as up left inset picture in Fig. 1. Two polarization controllers (PC) were used to control the polarization state of the signal and pump waves for maximized signal gain. The signal combined with the pump was then fed to 1-km long HNLF through a 90/10 optical fiber coupler. The HNLF used in our experiment has an average zero dispersion wavelength λ_0 ~1554 nm, nonlinear coefficient γ=10.9/W km, and dispersion slope D=0.0167ps/nm^2 km. At the output of the fiber, a 0.4nm optical bandpass filter (OBPF) was used to remove the residual pump and idler waves.

3. Characteristics measurement of optical parametric process in HNLF

We measured the narrowband gain spectra of the OPA with only pump input generated through an optical parametric process. Note that the parametric gain spectra of the OPA are similar to its amplified spontaneous emission (ASE) spectra. Fig. 2(a) shows measured ASE spectra of the OPA at fixed pump wavelength 1558.37nm but with different average pump powers. Each ASE spectrum consists of a central pump peak and two narrowband peaks on each side of the pump. As the pump power increases, the OPA’s narrowband gain increases and its peak wavelength slightly shifts. When the pump power was further increased, the pump spectrum was significantly broadened due to self-phase modulation (SPM) effect. Fig. 2(b) shows the optical spectra measured at the input and output of the OPA before and after the coupler when the signal pulses at wavelength of 1553.25nm entered the OPA.

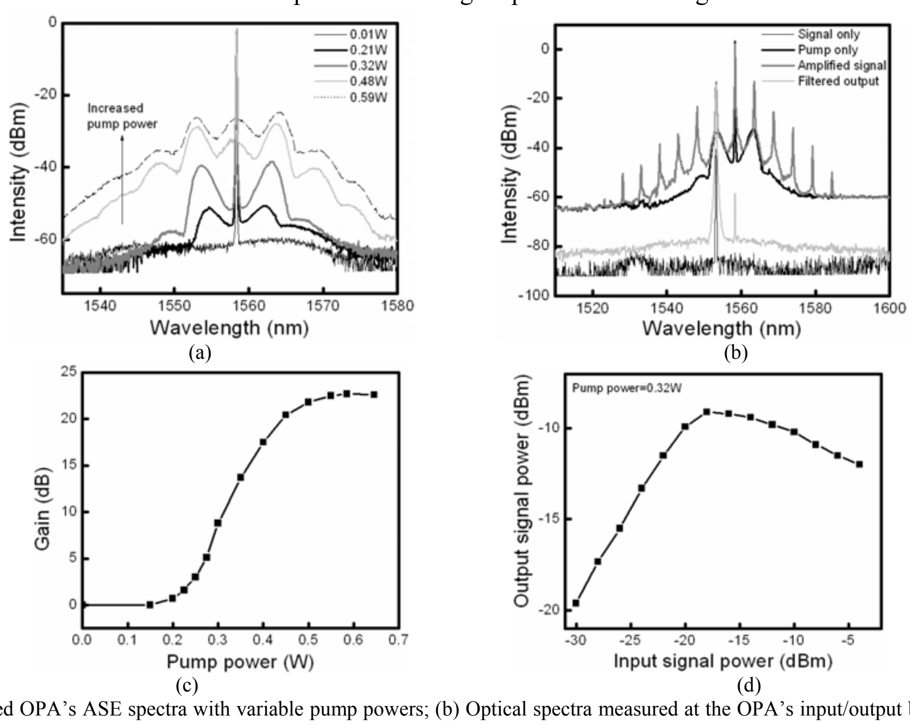

Fig. 2 (a) Measured OPA’s ASE spectra with variable pump powers; (b) Optical spectra measured at the OPA’s input/output before/after OBPF; (c) Measured gain versus variable pump powers; (d) Measured transfer function of the OPA.

We then measured the OPA’s gain when the input signal pulses have -20dBm average power. Gain value is calculated through comparing the intensity difference at 1553.25nm reading from an optical spectrum analyzer. Fig.2 (c) describes the gain varying with different pump powers. The maximum gain measured is 23dB at an average pump power of 0.6W. The transfer function of the OPA is described in Fig. 2(d), which shows the output signal power of the OPA varying with the input signal power at 0.32W pump power. We can deduce from the nonlinear transfer function that amplitude noise of the signal pulses could be significantly suppressed in the OPA.

4. Slow light results

We first evaluated the time delay of 10Gbps RZ packets with fixed data pattern of "10111011" and 24.8ns gaps on an oscilloscope by comparing the temporal position of the pulse peak as tuning the pump power, as shown in Fig. 3(a). The delay of the RZ packets becomes larger as increasing the pump powers. It reaches 25ps time delay at 0.56W average pump power. However, when further increasing the pump power, the extinction ratio of the RZ packets is drastically degraded due to SPM-induced pump spectrum broadening. Fig. 3(b) shows error-free operations for the OPA with different pump powers of 0.2W, 0.27W and 0.36W corresponding to the time delays of 12.8ps, 15ps and 20ps, respectively. Their BER results show 2~3dB power penalties due to instability of the pump intensity (high-power EDFA) and ASE noise from the OPA. Fig. 3(c) shows oscilloscope traces of time delayed 2^7-1 PRBS data with different pump powers and inset pictures are their corresponding eye diagrams. When increasing the pump power to 0.39W, 13.5ps time delay was achieved. Less time delay for PRBS data compared to RZ packets is believed due to larger gain depletion experienced by the former. Fig. 3(d) shows its BER result and error-free operation was also achieved. For both RZ packets and PRBS data, the signal pulsewidth was reshaped from 50ps to 20ps by the OPA.

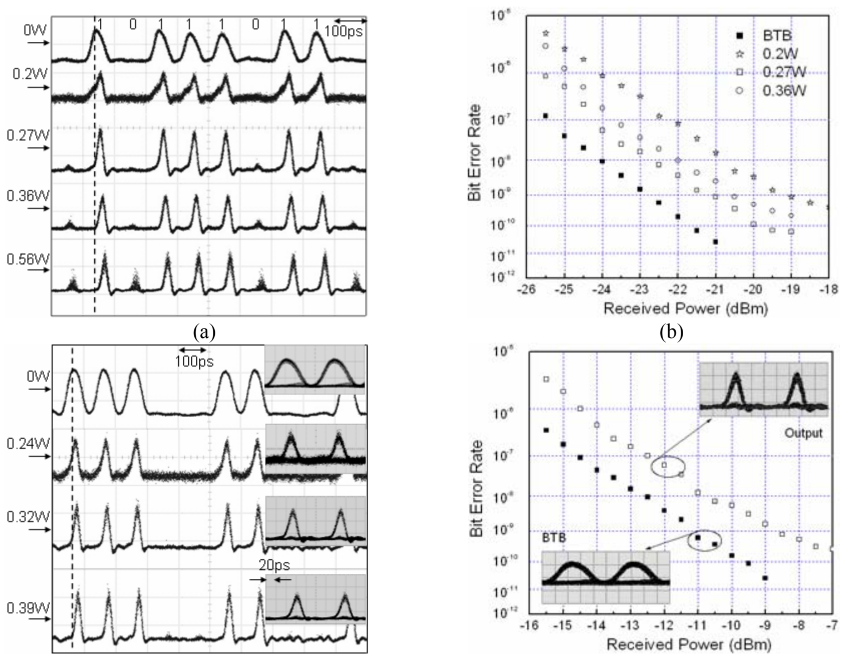

Fig. 3 Scope traces showing time delay of the signal varying with the pump powers when the signal is (a) RZ packet and (c) PRBS data; Corresponding BER results for (b) RZ packet and (d) PRBS data, respectively. Inset: corresponding eye diagrams.

5. Conclusion

We have demonstrated for the first time a slow-light delay line based on an OPA with clock-modulated pump to achieve simultaneously slow-light delay and pulse reshaping functions. The signal pulses were reshaped from 50ps to 20ps in the OPA. Measured maximum delay is 25ps at 0.56W average pump power. Error-free operation is achieved for both 10Gbps RZ packets and PRBS data. The OPA is potential to provide both slow-light time delay and 3R (reshaping, retiming, and reamplification) regeneration functions for the data if using pulsed recovered optical clock as the pump. This work is supported by the DARPA Slow-Light Project #412786-G.

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