Propagation of 10-Gb/s RZ data through a slow-light fiber delay-line based on parametric process

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Abstract: We experimentally demonstrate fine-tuning of a slow-light delay line by propagating 10-Gb/s RZ data packets through a parametric amplifier, and for the first time investigate the system performance of such a delay line.

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1. Introduction

In optical packet switching (OPS) networks, controlling the propagation velocity of the optical pulses in delay lines is important for buffering and synchronizing functions. Previous scheme employed electromagnetic induced transparency [1] in an ultracold atomic gas, which requires extreme conditions and is difficult to implement on a day-to-day basis. Recently, experiments have been carried out to delay the optical pulses utilizing semiconductors [2], as well as fiber nonlinearity, such as stimulated Brillouin scattering (SBS) [3,4], stimulated Raman scattering (SRS) [5] and Raman assisted fiber-optic parametric amplification (FOPA) [6]. These methods are suitable for room temperature operation and are relatively easy to realize and control. Particularly, the ones based on fiber nonlinearity are compatible with fiber-optic communication systems. Among them, the SBS based scheme can achieve large delay but does not work at high data rates because of the very narrow bandwidth of SBS. The delay time induced by the SRS method is very short owing to the wide bandwidth of the process. Raman assisted FOPA scheme can work at tens of Gb/s rate and has achieved delay of several bits. However, in [6] the signal wavelength was far from the pump wavelength and was therefore out of the 1.55μm telecommunication window. We further note that none of the proposed slow-light schemes has been evaluated at the system level by measuring the bit error rate (BER) of delayed optical packets.

In this paper, we investigate, for the first time to the best of our knowledge, the system performance of delayed 10-Gb/s return-to-zero (RZ) data packets in the 1.55μm telecommunication window. The time delay is achieved through the process of FOPA, and can be conveniently controlled by varying the parametric gain. We also investigate the pulse distortion due to saturated parametric gain to understand the limitation in our method. Our experiment verifies the feasibility of fine-tuning the time delay for 10-Gb/s packets, and indicates that higher-speed data can be supported by the FOPA based slow-light delay line.

2. Experimental setup

The experimental setup is shown in Fig.1. Two tunable laser sources (TLSs) with a tuning range from 1500 nm to 1600 nm serve as the pump and the signal source, respectively. The pump is sent to an intensity modulator (IM) driven by an electrical pulse source with 1.28-ns pulse width and 10% duty cycle. Polarization controllers (PC) are used to control the polarization state of the light. The modulated pump is pre-amplified by an erbium-doped fiber amplifier (EDFA) before being boosted by a second high-power EDFA with a maximal output power of 30 dBm. A tunable filter (TF) is inserted after EDFA2 for removing the strong

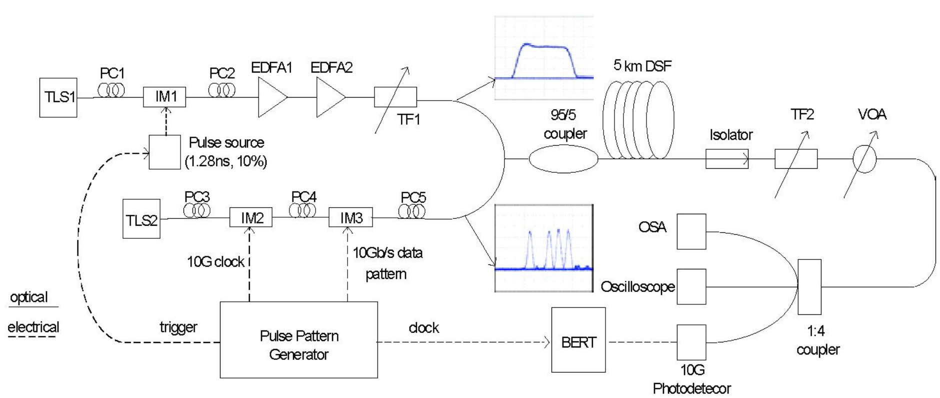

Fig.1. Experimental setup

amplification spontaneous emission (ASE) to effectively measure the gain spectrum of the FOPA. The signal is intensity-modulated by a 10-GHz clock to generate a RZ pulse train, and subsequently encoded by a 10-Gb/s NRZ data pattern. The pump and the signal are then combined through a 95/5 coupler and launched into a spool of 5-km dispersion shifted fiber (DSF) to achieve amplification and delay. Note that the pump pulse and the signal pattern must be kept synchronous before entering the DSF, which is achieved by tuning the delay of the electrical pump pulse. The signal data packet is a fixed pattern "10111" followed by 123 '0'-bits so that all the "1" bits are always within the wide pump pulse. The waveforms of the pump and the signal pulses are shown as the insets in Fig.1. The zero dispersion wavelength of the DSF is ~1558 nm and the dispersion slope is 0.08ps/(nm^2.km). By tuning PC2 and PC5, maximal signal gain can be obtained. After amplification and delay process in the DSF, the signal is separated from the pump power by TF2. A variable optical attenuator (VOA) is used to control the amplified signal power before measurement. We use an optical spectrum analyzer (OSA), an oscilloscope, and a bit error rate tester (BERT) to measure the optical spectra, signal waveforms, and BER, respectively.

3. The system design for slow-light

In slow-light schemes, a narrow spectral resonance is needed to achieve significant amount of delay. The spectral resonance induces a narrowband gain/absorption peak in the medium, which leads to a change of the group velocity based on Kramers-Kronig relationship [5]. In the slow-light methods based on stimulated scattering, the delay time is proportional to the gain and inversely proportional to the gain bandwidth [4]. To achieve considerable time delay, high gain and narrow gain peak in the FOPA are necessary. Firstly we measure the ASE spectra of the FOPA with a 22-dBm average pump power and at different pump wavelengths, as depicted in Fig. 2 (a). When the pump wavelength is larger than the zero dispersion wavelength of the DSF, the parametric process produces two gain peaks, one on each side of the pump wavelength [7]. As the pump wavelength increases, the two gain peaks become narrower and closer to the pump wavelength, and the peak gain becomes higher. Signals falling into the narrow gain peak experience time delay. We chose 1564.1nm as the pump wavelength because of the relatively narrow gain spectrum and the left gain peak being close to ITU-T CH 40 (1561.419nm). Then we show the ASE spectra at different pump powers in Fig. 2(b) to illustrate the impact of the pump power on the gain spectra. When the pump power exceeds 23dBm, the gain bandwidth is significantly broadened. To achieve good delay performance, it is necessary to balance between the gain value and the gain bandwidth.

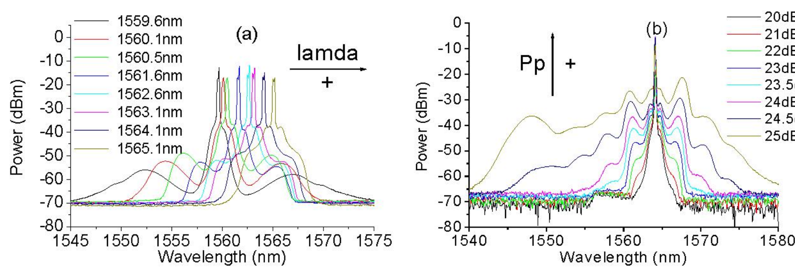

Fig.2 The measured ASE spectra with 0.2nm resolution. (a) The ASE spectra at 22dBm average pump power and variable pump wavelengths; (b) the ASE spectra at 1564.1nm pump wavelength and variable pump powers.

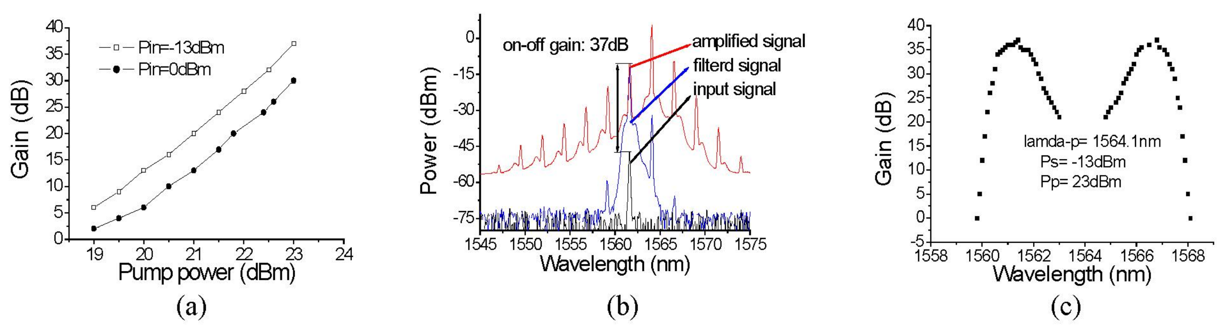

Fig.3 (a) The signal gain versus the average pump power at different input signal powers; (b) the optical spectra of the input signal, the amplified signal, and the amplified signal after the filter; (c) the measured signal gain spectrum.

We set the pump wavelength to be 1564.1nm and the signal wavelength to be 1561.4nm, which is at the left gain peak. The gain varies with the pump and the signal powers as shown in Fig.3 (a). For an average pump power of 23 dBm and a signal input power of -13 dBm, measured before the 95/5 coupler, the on-off gain is as high as

37dB. Higher signal power saturates the FOPA, leading to lower gain and therefore smaller delay. The optical spectra of the input signal, the amplified signal and the filtered signal are shown in Fig. 3 (b), respectively. Since the signal and pump wavelengths are close to the zero dispersion wavelength of the DSF, the four-wave mixing is very strong, which produces high-order frequency components. With -13-dBm signal power and 23-dBm pump power at 1564.1nm, the gain spectrum is shown in Fig.3 (c). In the parametric amplification process, the gain peak at the shorter wavelength corresponds to the slow light and the one at the longer wavelength leads to the fast light [6]. Due to the lack of the longer wavelength filters, we only choose the wavelength lying in the left gain peak at 1561.4nm and demonstrate the time delay.

4. The system performance

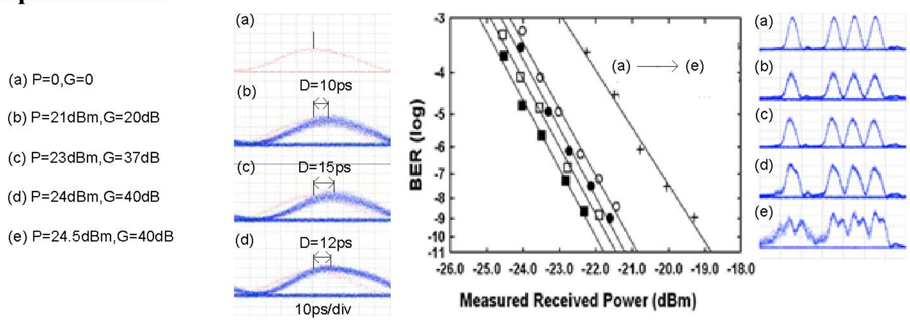

Fig.4 The delay time, BER and waveforms of the signal versus the pump power.

We investigate the impact of the pump power on the delay time, the BER, and the signal waveforms respectively, as shown in Fig. 4. When the pump power is 21dBm, corresponding to a 20-dB gain, the delay of the pulse is about 10ps. BER measurement indicates 0.3-dB power penalty in the receiver sensitivity, and pulse distortion is not observed. This is different from the delay induced by SBS, where the SBS amplification filters out the high frequency components of the data and leads to pulse distortion [8]. When the pump power is increased to 23 dBm and the corresponding gain goes to 37 dB, the delay is increased to 15ps, and the sensitivity penalty is 0.6 dB. Meanwhile no noticeable distortion of the signal pulses is observed. However, once the pump power exceeds 23 dBm, the gain bandwidth is significantly broadened, leading to shorter delay time even though the gain is a little bit enhanced. A 24-dBm pump power results in only 12-ps delay, while the pulses are broadened and distorted because of the parametric gain saturation. If the pump power is further increased, the signal pulses are drastically distorted, and the sensitivity penalty is as high as 3 dB.

In this demonstration, 15-ps delay is achieved with 10-Gb/s RZ data, which could be used in finely tuned delay lines for traffic synchronization purpose. It is expected that higher speed (e.g.160-Gb/s) data can also be delayed owning to the sufficient gain bandwidth of 1.6 nm. We believe that the ratio of the delay to the pulse width can be increased if system parameters are further optimized.

5. Conclusion

We demonstrate the first system testing of delayed 10-Gb/s RZ data packets based on parametric process in the telecommunication band. The measured maximal delay is 15 ps at a pumping level of 23 dBm, and the sensitivity penalty is only 0.6 dB, with no pulse distortion observed. The potential for higher bit rates is implied. Better results can be expected with further optimized system parameters.

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