Comparing slow-light properties of 10Gbps RZ data in dispersion shifted fibers and highly nonlinear fibers based on Raman-assisted optical parametric amplification

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Comparing Slow-Light Properties of 10Gbps RZ Data in Dispersion Shifted Fibers and Highly Nonlinear Fibers Based on Raman-Assisted Optical Parametric Amplification

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ABSTRACT

We compared experimentally the properties of optically controlled tunable time delay based on a Raman-assisted optical parametric amplifier (OPA) with different gain media of normal dispersion shifted fibers (DSF) and highly nonlinear fibers (HNLF). The Raman-assisted OPA using the DSF has previously been demonstrated to obtain large light delay for one single pulse. Position optimization of pump wavelength according to zero dispersion wavelength of the fibers results in narrow band gain spectrum through a parametric process. Stimulated Raman scattering further modifies the shape of the gain spectrum. The modified gain spectrum with sharper transitions leads to a large group index change so that large time delay can be achieved. In the paper, we experimentally demonstrated propagating 10Gbps return-to-zero (RZ) optical packets through slow-light fiber delay line based on the Raman-assisted OPA with above 100ps time delay. We also experimentally compared the gain, the bandwidth and the time delay versus variable pump powers for the Raman-assisted OPA by using 1km-long DSF and 1km-long HNLF as the gain medium, respectively. While smaller time delay was obtained in the slow-light scheme using HNLF due to its wider gain spectrum, lower pump power threshold was found compared to that using DSF. In the experiment, we found that the slow-light scheme has THz gain bandwidth and indicates that slow light could be achieved at higher bit rates with further optimized system parameters.

1. INTRODUCTION

Optical packet switching network requires optical buffer or tunable optical delay line to control time delays of optical packets for synchronization function or contention resolution. All-optical routers must support routing of variable-length packets that can arrive asynchronously at packet routing nodes. Such routers require all-optical buffering function to control the time delay of optical pulses or optical packets for synchronization function or contention resolution. Slow light has attracted much recent interest since it offers the capability for optically controlling the group velocity of light pulses propagating through different media such as nonlinear fibers and semiconductors [1]. Impressive slow light results have been demonstrated in fibers using stimulated Brillouin scattering (SBS) [2], stimulated Raman scattering (SRS) [3] and Raman-assisted fiber-optic parametric amplification (OPA) [4].

The slow light scheme in [4] is based on two nonlinear effects of optical parametric process and stimulated Raman scattering (SRS) coupling in dispersion shifted fibers (DSF). Propagating in the normal dispersion regime of DSF, the optical pump generates symmetric narrow band gain spectra through a parametric process. Through optimizing the wavelength difference between pump ($\lambda_p$) and...
the zero dispersion wavelength ($\lambda_0$) of the DSF, the generated narrow gain spectra can overlap with the signal wavelength ($\lambda_s$). Further, if adjusting the pump wavelength so as to make $\lambda_p - \lambda_s$ less than 150nm, SRS becomes significant and then modifies the shape of the gain spectra. The modified gain spectrum with sharper transitions leads to a large group index change and then large time delay. In [4], the authors demonstrated large time delay (up to 160ps) for a single pulse with 70ps pulsewidth in 2-km long DSF.

In the paper, we experimentally demonstrated propagating 10Gbps return-to-zero (RZ) optical packets through the Raman-assisted OPA with different gain media of normal DSF and highly nonlinear fibers (HNLF). The HNLF we used in the experiment has three times higher nonlinear coefficient and Raman gain coefficient than the DSF. Hence, the HNLF in the slow light scheme will yield rather different-looking gain spectra from DSF which are likely to greatly impact their slow light properties. Our experiment verified the slow light operation of 10Gbps RZ data propagating through Raman-assisted OPA by using 1km-long HNLF and 1km-long DSF as the gain media, respectively. The gain, the bandwidth and the time delay were compared for using the DSF and the HNLF. Smaller time delay and lower pump power threshold were found in the slow-light scheme using HNLF compared with using DSF. We also observed that self-phase modulation (SPM) of the pump light limits further increasing the pump power for larger time delay and also results in pulse distortion.

2. EXPERIMENTAL SETUP

The experimental setup is described in Figure 1. A tunable laser at $\lambda_p$ serves as the pump and its wavelength range is from 1500nm to 1600nm. The pump is sent to an E/O modulator (EOM) and pulsed-modulated by the electrical frame signal from the 10Gbps pattern generator. The pulsed pump has 3ns pulsewidth and 12% duty cycle. It is amplified by an erbium-doped fiber amplifier (EDFA) and filtered by a 0.4nm optical bandpass filter (OBPF) to remove the amplified spontaneous emission (ASE) noise. Subsequently, it is boosted by a high power EDFA with a maximum average output power of 2W (corresponding to a few watts peak pulse power). The waveform of the amplified pump is shown as the bottom right inset picture in Figure 1 and the spiking in its front is due to the dynamics of the high power EDFA.
A Raman pump laser with the wavelength of 1439nm serves as the signal (\(\lambda_s\)). It goes to an EOM driven by the 10GHz electrical clock from the 10Gbps pattern generator. The generated 10GHz optical pulses with 45ps pulsewidth are modulated by 10Gbps non-return-to-zero (NRZ) data programmed by the 10Gbps pattern generator. In the experiment, we used a fixed pattern “11101101” with 248 “0” bits so that all the “1” bits always fall in the pump pulse. The signal pulses are shown as the up left inset picture in Figure 1. Two polarization controllers (PC) are used to control the polarization state of the signal and pump waves for maximized signal gain.

The signal (\(\lambda_s\)) combined with the pump (\(\lambda_p\)) was fed to 1-km long DSF or 1-km long HNLF through a WDM coupler. The DSF used in our experiment has an average \(\lambda_0 \sim 1553\) nm, nonlinear coefficient \(\gamma = 3.5/W\) km, Raman gain coefficient \(G_R = 2.088\times 10^{-14}m/W\) and dispersion slope \(D = 0.27ps/nm^2km\). The HNLF has an average \(\lambda_0 \sim 1554\) nm, \(\gamma = 10.9/W\) km, \(G_R = 5.03\times 10^{-14}m/W\) and \(D = 0.0167ps/nm^2\) km. At the output of the fibers, two WDM couplers serially connected are used to remove the residual pump and idler waves. The \(\lambda_p\) output ports of the WDM couplers are angled cut to reduce the reflections. An optical spectrum analyzer and a sampling oscilloscope are used to measure the gain spectra and time delay, respectively. A variable optical attenuator (VOA) was placed before them to adjust the power level.

3. MEASURED NARROW BAND GAIN SPECTRA

Firstly we measured narrow band gain spectra of the Raman-assisted OPA with pump only input. Considering a Raman pump laser is used as the signal (\(\lambda_s = 1439\) nm) in our experiment, we focused on the investigation of the narrow band gain spectra around \(\lambda_s\). The narrow band gain spectra are generated through an optical parametric process when the pump wavelength \(\lambda_p\) is appropriately adjusted separated from \(\lambda_0\) of the fibers [5].
Figure 2 The measured ASE spectra at variable pump wavelengths using (a) the DSF with 0.9W average pump power and (b) the HNLF with 0.5W average pump power.

Note that the optical parametric gain spectra of the OPA are similar to its ASE spectra [5]. Figure 2(a) shows the measured ASE spectra using 1km-long DSF at fixed pump power 0.9W but $\lambda_p$ was set to 1550nm, 1551nm, 1552nm, and 1553nm, respectively. Each ASE spectrum according to different $\lambda_p$ consists of a central pump peak and two narrow band peaks on each side of the pump. When decreasing $\lambda_p$ away from $\lambda_0$, we found the gain peaks become further away from $\lambda_p$, but the peak gain dropped. This is an indication that $\lambda_0$ varies along the DSF [5]. Slow light effect happens when the signal $\lambda_s$ falls into the narrow gain peak: it experiences narrow band gain and a change in the group index induced by the spectral resonance, which leads to group velocity change of the signal light as it travels through the fiber.

Similarly, we measured ASE spectra using a 1km-long HNLF with fixed pump power 0.5W and variable pump wavelengths of 1546nm, 1552nm, 1563nm, and 1566nm, respectively. The measured ASE spectra are shown in Figure 2(b). We found the gain spectra using the HNLF are broader than those using DSF. The reason is that larger $\lambda_0$ variation in HNLF rapidly broaden the narrow gain spectra as they move away from $\lambda_0$ [5]. Also, the large $\lambda_0$ variation makes the ASE intensity or gain dropped more in HNLF than in DSF. In the OPA-based slow light scheme, narrow spectral resonance is desired because time delay is proportional to the gain and inversely proportional to the gain bandwidth. So, these measurements indicate larger time delay will be achieved using the DSF than using the HNLF. However, if the HNLF has similar $\lambda_0$ variation to those of the DSF, it would then be possible to have similar time delay but with lower pump power due to its higher nonlinear coefficient.

4. MEASURED GAIN AND BANDWIDTH

We then input signal at $\lambda_s$ with average power of -9dBm to the OPA for the gain measurement. Gain value is calculated through comparing the intensity difference at $\lambda_s$ reading from the optical
spectrum analyzer. Here, we set the pump wavelength $\lambda_p$ to 1549.2nm so that $\lambda_s$ is located at the gain peak. Compared to the parametric gain, the Raman gain induced by the SRS has a small contribution to the total gain, but the Raman absorption/gain modifies the gain spectrum shape which significantly impacts the time delay [4]. We tuned the pump powers to measure the gain at $\lambda_s$ and also recorded 3-dB gain bandwidth at the same time. Figure 3(a) describes the gain and corresponding bandwidth varying with different pump powers using the DSF. We found signal absorption happens first when average pump power is less than 0.8W while the signal starts to experience the gain when increasing the pump power above 0.8W. The threshold-like function comes from the parametric absorption process from the OPA and nonlinear absorption of the Raman amplification. The maximum gain measured is 23dB at an average pump power of 1.8W. When the pump power was further increased, the pump spectrum was significantly broadened due to strong SPM effect so as to make narrow band gain spectra vanished. As shown in Figure 3(a), gain bandwidth is increased from 0.1THz to 0.6THz when increasing the pump power from 0.8W to 1.8W. Although higher gain benefits to larger time delay when increasing the pump power, the gain bandwidth becomes wider and leads to reduced time delay. So, there is a tradeoff between gain and bandwidth for the largest time delay in the slow light scheme.

Similarly, we measured the gain and corresponding bandwidth using the HNLF at different pump powers, as shown in Figure 3(b). The pump wavelength $\lambda_p$ is set to 1545.6nm for adjusting the gain peak to $\lambda_s$. Similar to using the DSF, threshold-like phenomenon was also observed at less than 0.3W. When increasing the pump power from 0.3W to 0.7W, the gain is achieved from 5dB to 14dB while the bandwidth is increased from 1.7THz to 2.9THz. As discussed above, less gain and broader bandwidth compared with using the DSF were believed coming from larger $\lambda_0$ variation in HNLF. Further, the Raman-assisted OPA using HNLF is more vulnerable to the SPM effect due to higher nonlinear coefficient in HNLF so that it is impossible to increase the pump power above 0.7W for higher gain.

![Figure 3](attachment:image.png)

**Figure 3** Measured gain and bandwidth versus variable pump powers using (a) the DSF (b) the HNLF

5. MEASURED SLOW LIGHT
Figure 4 shows the optical spectra measured at the input and output of the Raman-assisted fiber OPA before and after WDM couplers using different gain media of the DSF and the HNLF. The signal at $\lambda_s$ experiences the gain and also a change in the group velocity as it travels through the fibers. At the same time, an idler wave is generated at symmetric position to the pump wavelength $\lambda_p$. The pump and the generated idler were removed by two serially connected WDM couplers with the cutoff wavelength of 1516nm. However, a small part of the broadened pump spectrum due to strong SPM effect still passes through the WDM couplers especially for the Raman-assisted OPA using HNLF. So, it restricts further increasing pump power and thus an optical bandpass filter working at $\lambda_s=1439$nm is desired.

![Figure 4](image-url)

**Figure 4** Optical spectra measured at the Raman-assisted OPA’s input/output before/after WDM couplers using different gain media of (a) the DSF (b) the HNLF.

The time delay is evaluated from the oscilloscope by comparing the temporal position of the pulse peak as turning on/off the pump. Figure 5(a) shows oscilloscope traces of the 10Gbps RZ packet according to different pump powers for the Raman-assisted OPA using DSF. The delay of the pulses is about 100ps when pump power is set to 0.9W or 9dB gain compared to the pump power turned off. When increasing the pump power to 1.75W or 23dB gain, 126ps time delay was achieved. However, when further increasing the pump power above 1.75W, the pulses were drastically distorted partly due to broadened gain bandwidth and partly due to more pump leakage from the much broadened pump spectrum. The delayed pulses have different amplitudes due to the spiking front of the pump waveform and then different gain shown in Figure 1.
Figure 5 The scope traces showing time delay of the signal versus the pump power when using (a) the DSF (b) the HNLF.

Figure 5(b) shows signal pulses’ time delay according to the Raman-assisted OPA using the HNLF. About 70ps and 85ps time delay were obtained when pump power is set to 0.35W or 7dB gain and 0.72W or 14dB gain, respectively. As discussed above, the pump spectrum is more vulnerable to be broadened due to stronger SPM in HNLF so that more pump part passed through the WDM couplers and overlapped with the signal pulses. So, the scope traces of the delayed pulses shown in Figure 5(b) are the addition of the delayed pulses and the leaked part of the broadened pump.

We then investigated the function of the launched pump powers versus the time delay, as shown in Figure 6. The time delay can be conveniently controlled by varying pump powers or the gains. Figure 6(a) shows time delay can be tuned from 100ps to 126ps when increasing the pump power from 0.83W to 1.75W in the Raman-assisted OPA using DSF. And also it has the threshold of 0.83W pump power. The threshold function comes from the absorption of the parametric process and the SRS. Figure 6(b) describes that the slow light scheme using HNLF has time delay tuning from 70ps to 85ps when the pump power is increased from 0.30W to 0.72W. It has the lower pump power threshold of 0.30W due to higher nonlinear coefficient and Raman gain coefficient in the HNLF.
5. CONCLUSIONS

We experimentally verified the slow light operation of 10Gbps RZ optical packets propagating through the Raman-assisted OPA using the DSF or the HNLF as the gain medium. The gain, the bandwidth and the time delay were experimentally compared in the slow light scheme. Lower pump power threshold was found for the scheme using HNLF due to HNLF’s higher nonlinear coefficient and Raman gain coefficient. However, smaller time delay was found in the scheme using the HNLF due to its broad gain spectra compared with using DSF. We also observed that the broadened pump spectrum due to strong SPM effect hinders further increasing the pump power for larger gain and time delay and also results in pulse distortion. The slow light scheme has THz gain bandwidth and indicates its application in higher-speed fiber optical communications systems.

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REFERENCES


