Tunable all optical delay via slow and fast light propagation in a narrow band Raman assisted optical fiber parametric amplifier

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Abstract *:* We report the first demonstration of slow and fast light in optical fiber using narrow band Raman assisted optical parametric amplification. A tunable delay of up to 162 ps was obtained for a 70 ps pulse.

Facing the exponential growth of the Internet traffic, next generation of Internet routers will be based on all optical technologies to scale their capacity to the traffic demand. Such routers will require the development of all optical buffers via the velocity control of optical pulses propagating through a dispersive medium [1]. The concept of slow and fast light has recently initiated intense research efforts through the use compact media such as semiconductors [2] and optical fibers [3]. Early demonstrations of slow light made use of electro magnetic induced transparency [4] or population pulsations [2], both of which introduce some optical loss. Nonlinearities in optical fibers may, on the other hand, offer optical gain in addition to other advantages such as a broad range of operating wavelengths, operation at room temperature and flexible length. The first demonstration of slow and fast light in optical fibers used the narrow gain bandwidth associated with Stimulated Brillouin Scattering (SBS) and achieved impressive results [3]. The disadvantage of SBS is of course its extremely narrow band width which does not allow for narrow pulses to be delayed.

This paper reports on the first demonstration of slow and fast light in optical fibers based on tunable, narrow band Raman assisted optical parametric amplification (Raman assisted OPA). The system uses controllable narrow band parametric gain spectra, previously used as tunable amplifying filters in multi channel communication systems [5]. The pump power and its spectral placement relative to the zero dispersion wavelength tailor the OPA gain spectral shape and hence the group delay of a pulse being amplified. We demonstrate here controllable tuning of the delay experienced by a 70 ps wide pulse propagating in several lengths of Dispersion Shifted Fiber (DSF). Using a 2000 m long DSF, we demonstrate tunable delay up to 162 ps. Its dynamic range is limited by the fiber length and the variation of the zero dispersion wavelength along the imperfect fiber. Negative delays which amount to fast light are also demonstrated

The system we report is described schematically in Fig. 1. A pulsed tunable laser source at λ_p, (2 ns pulses at a duty cycle of 0.7 to 2.5%) serves as a pump source. It is pre-amplified and filtered before being further amplified by a high power amplifier with a maximum output average power of +27 dBm which amounts to a peak pulse power of a few W. A weak signal at λ_s is modulated to provide 70 ps pulses at 500 MHz and is combined with the pump wave through a WDM coupler. The two signals feed different lengths of Dispersion Shifted Fiber (DSF) with an average zero dispersion wavelength λ_0=1539 nm and a negative fourth order dispersion coefficient β_4. Since the pump wave propagates in the normal dispersion regime of the fiber, it generates, through a parametric process, symmetric narrow band gain spectra far from the pump wavelength [5]. The spectral separation between this narrow gain spectrum and λ_p increases while its width decreases as the spectral separation λ_0-λ_p increases. The parametric process is coupled to Stimulated Raman Scattering (SRS) for λ_p-λ_s up to 150 nm. The shape of the gain spectrum can be tailored with the pump power. Once λ_s falls within the narrow gain spectrum, it experiences gain and a change in the group index leading to a propagation delay. At the same time, an idler wave is generated at λ_i. A WDM coupler separates the waves at the DSF output but for better temporal separation during the analysis, we use a 1 km Dispersion Compensating Fiber (DCF). A Variable Optical Attenuator (VOA) was put before the DCF to prevent nonlinear effects. An optical spectrum analyzer was used to map out the parametric gain spectra while a 10 GHz receiver followed by a sampling oscilloscope was employed for the characterization of the delay. The delay is obtained by comparing the temporal position of the pulse peak for various pump powers.

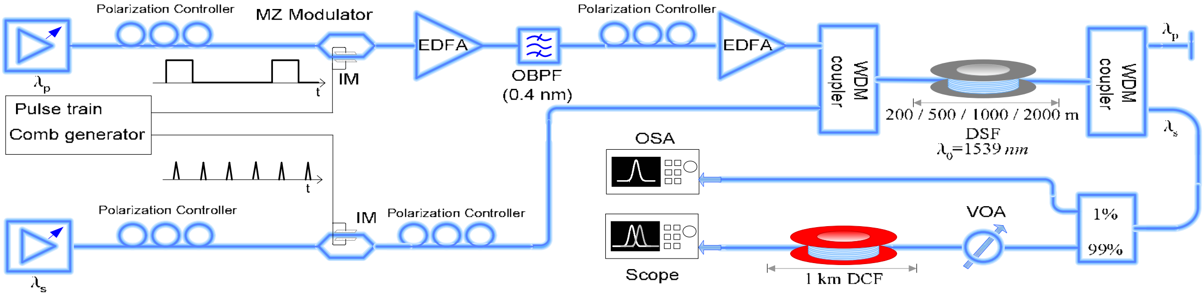

Fig 1: System set up

$$\begin{cases} \dfrac{\partial A_s}{\partial z} = j2\gamma P_0 A_s + j\gamma P_0 A_i^* \exp\left(j\left(2\gamma P_0 - \Delta k\right)z\right) - \dfrac{g_R}{2} P_0 A_s = j2\gamma P_0 A_s + \tilde{g}_s A_s & (1) \\ \dfrac{\partial A_i}{\partial z} = j2\gamma P_0 A_i + j\gamma P_0 A_s^* \exp\left(j\left(2\gamma P_0 - \Delta k\right)z\right) + \dfrac{g_R}{2} P_0 A_i = j2\gamma P_0 A_i + \tilde{g}_i A_i & (2) \end{cases}$$

Under the simplifying assumptions of a non depleted pump, a lossless fiber and negligible dispersion induced broadening, The evolutions of the signal (A_s) and idler (A_i) waves is governed by Eqs (1)-(2), where P_0 is the pump power, γ is the fiber nonlinear coefficient, $\Delta k=k_i+k_s-2k_p$, is the mismatch between the relevant propagation constants and g_s is the Raman gain coefficient. Eqs (1) and (2) can be rewritten using complex equivalent parameters $\tilde{g}_s$ and $\tilde{g}_i$. The real parts of theses parameters are related to the gain while their imaginary parts cause additional phase shifts in both waves leading to a change in the group index:

$$\Delta n_g = c\left(d\,\mathrm{Im}\left(\tilde{g}\right)/d\omega\right) \qquad (3)$$

For large gain and negligible SRS ($|\lambda_p-\lambda_s|>150$ nm), this change is given by :

$$\Delta n_g \approx -\frac{c}{2}\frac{d\Delta k}{d\omega} = \frac{\pi c^2}{\omega^2}\frac{d\Delta k}{d\lambda} \qquad (4)$$

Fig. 2 shows the phase mismatch as function of the wavelength when the pump propagates in the normal dispersion regime ($\beta_2>0$) with $\beta_4<0$.

For P_0=10W and λ_p=1530nm phase matching conditions are satisfied for frequencies corresponding to Δk values between the two horizontal lines. Two narrow gain spectra, both located far from the pump frequency, are obtained: at 1377 nm and at 1721.5 nm.

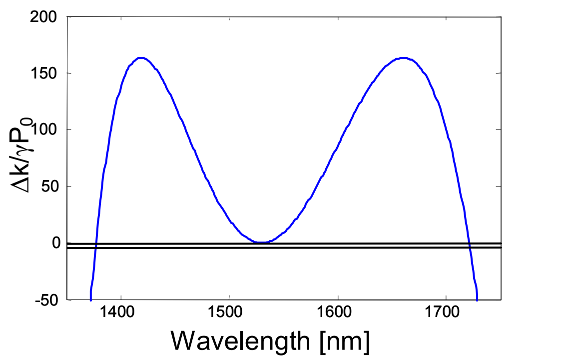

Fig 2: Phase mismatching as function of the wavelength with λ_p=1530 nm for β_2=8.7 10^{-28} s^2/m and β_4=-5.6 10^{-55} s^4/m at λ_p

According to Eq. 4, the narrow gain spectra induce an increase of the group index (designated as slow light) for wavelengths shorter than the pump wavelength whereas it decreases the group index (designated as fast light) for wavelengths longer than the pump wavelength.

Fig. 3 shows calculated gain spectra and the resulting timing delay for wavelengths around 1337 nm (Fig.3a) and 1721.5 nm (Fig 3b) with the pumping conditions that were used to calculate Fig. 2. In both spectral regimes, the gain reaches the same maximum value of 34 dB and the maximum absolute value of the induced timing delay is 19 ps. As explained previously, the timing delay is positive for the spectrum centered near 1377 nm while it is negative for the one at 1721 nm. Both delay spectra are large and quite flat over some 40 GHz where the gain exceeds 25 dB.

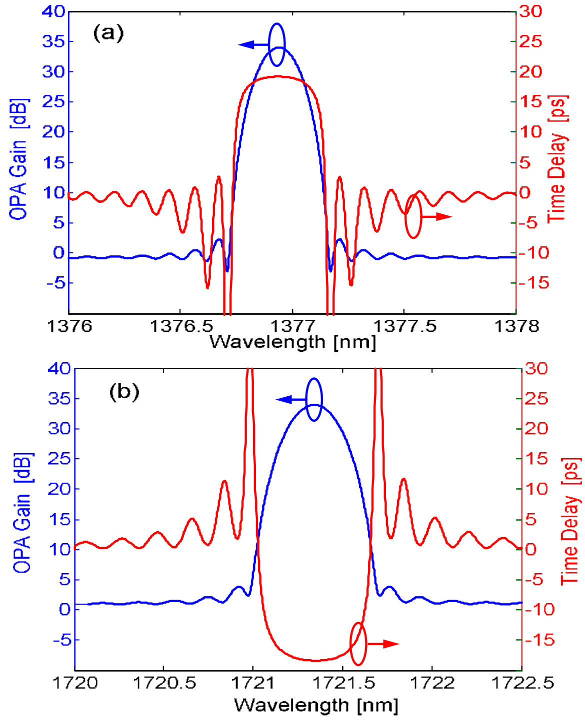

Fig. 3 : OPA gain and induced delay spectra at (a) the short and (b) long wavelength region using a 200 m long DSF with the same parameter as in Fig. 2

When the wavelength separation between the signal and the pump is less than 150 nm, SRS enhances the parametric amplification process. The derivation of the group index change becomes more complicated since SRS introduces an asymmetry between the short and long wavelength local gain parameters.

When the phase matching conditions are not satisfied, a signal whose frequency is lower than that of the pump experiences attenuation and a signal whose frequency is higher than the pump frequency is amplified. When phase matching is satisfied, the same maximum gain is obtained in both wavelength regions. However, since for short wavelengths OPA gain occurs in an absorptive environment, the complex parameter $\tilde{g}_s$ has sharper transitions, leading to a larger group index change and to an enhancement of the time delay. On the other hand, with a signal wavelength longer than the pump wavelength, the OPA gain adds to an already amplifying region which softens the transition of $\tilde{g}_s$, leading to a lower group index change and therefore a smaller time delay.

This is illustrated in Fig. 4 which exhibits calculated gain spectra and the resulting timing delay in a 200 m long DSF for wavelengths around 1428 nm (Fig.4a) and 1659 nm (Fig 4b). The pump wavelength is λ_p=1535 nm and the fiber parameters are β_2=3.95 10^{-28} s^2/m and β_4=-5.7 10^{-55} s^4/m at λ_p. In comparison with the previous case where SRS was absent (shown in Fig. 3), the gain spectra are broader due to the smaller wavelength separations and consequently the time delay is reduced.

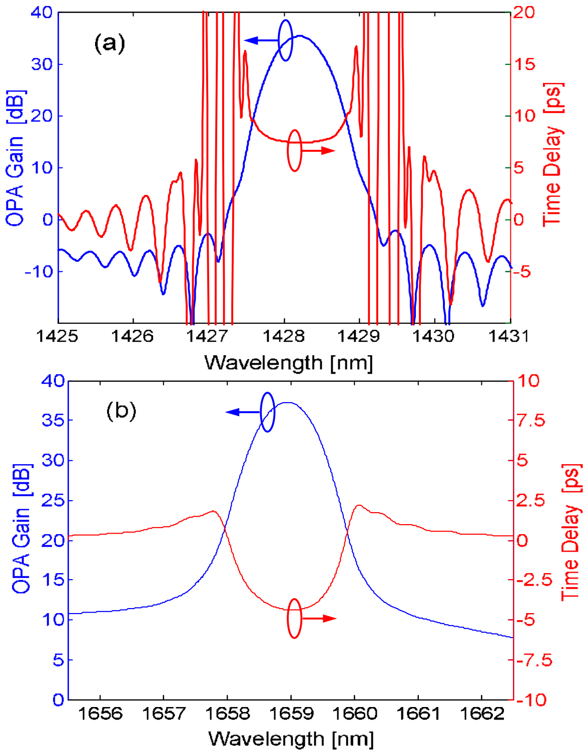

Fig. 4 :Raman assisted OPA gain and induced delay spectra at the (a) short and (b) long wavelength region using a 200 m long DSF with λ_p=1535 nm for β_2=3.9 10^{-28} s^2/m and β_4=-5.7 10^{-55} s^4/m at λ_p

The gain spectra present an asymmetry in the short and long wavelength regimes, where the peak gain is 33 dB and 37 dB respectively. The time delay is larger in the short wavelength region however, especially at the edges of the gain spectrum. The delay spectrum exhibits a delay of 7.5 ps over a fairly flat region for gain values larger than 25 dB, which represents an operational bandwidth of 150 GHz. In the long wavelength region, the time delay within the gain spectrum is negative. Since in this case SRS reduces the efficiency of the group index variations, the delay is smaller, -4.5 ps, for a gain higher than 30 dB, which represent an operational bandwidth of 110 GHz.

Fig. 5a describes measured ASE spectra of the narrow band OPA using a 200 m long DSF with different values of λ_p. Shown are spectra on the short wavelength side of λ_p but a symmetric duplication exists at long wavelengths. Each narrow gain spectrum induces a group index change leading to a delay which can be increased by sharpening the gain spectrum by increasing λ_0-λ_p. Figure 2b shows the experimental ASE power obtained around λ_s using 200 m of DSF for different pump power levels with a fixed λ_p at 1535 nm. The spectra width varies from 1 nm to 5 nm when the gain measured at λ_s=1428.6 nm varies from 25 to 49 dB. The spectra broaden and shift their maxima in direction of the shorter wavelengths as predicted by the numerical gain spectra shown in Fig. 3c since β_4<0. The coupling between the parametric process and SRS widens the gain spectra while it slightly decreases the peak gain value. However the larger experimental spectra can be attributed to the longitudinal variation of λ_0 along the fiber.

Fig. 6a shows variable delay measured for 70 ps pulses in a 200 m long DSF. Shown are the cases of no amplification and several gain values. The delay varies from 10 to 16 ps when the parametric amplifier operates in the linear regime whereas in saturation, the delay still increases but the pulse broadens. By using a 2000 m long DSF, the delays are strongly increases from 122 to 162 ps for comparable gain levels. The larger delays are attributed to the longer fiber and to a larger SRS efficiency which enhances the delay at the gain spectrum edges. Figure 3c exhibits the delay as a function of the parametric gain for different fiber lengths. For a fixed gain, the delay increases with the fiber length but the dynamic delay range is limited by the enhancement of the OPA saturated power when using long fiber. The optimal tunability range, obtained for 500 m long DSF represents 150 % of the minimum achievable delay.

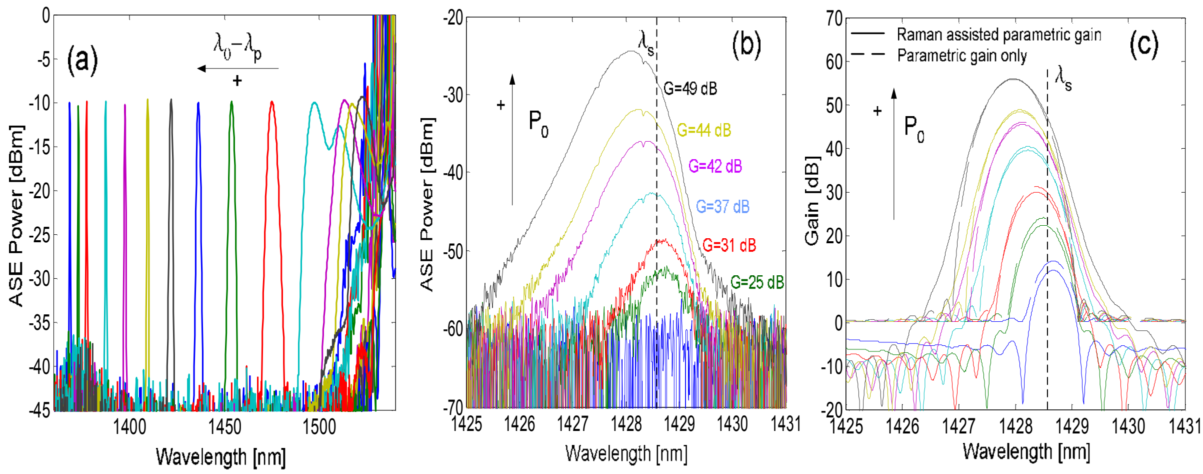

Figure 5 : Using 200 m long DSF : (a) Experimental ASE power for several pump wavelengths, (b) experimental ASE power and (c) numerical gain spectra around 1428 nm for several pump powers

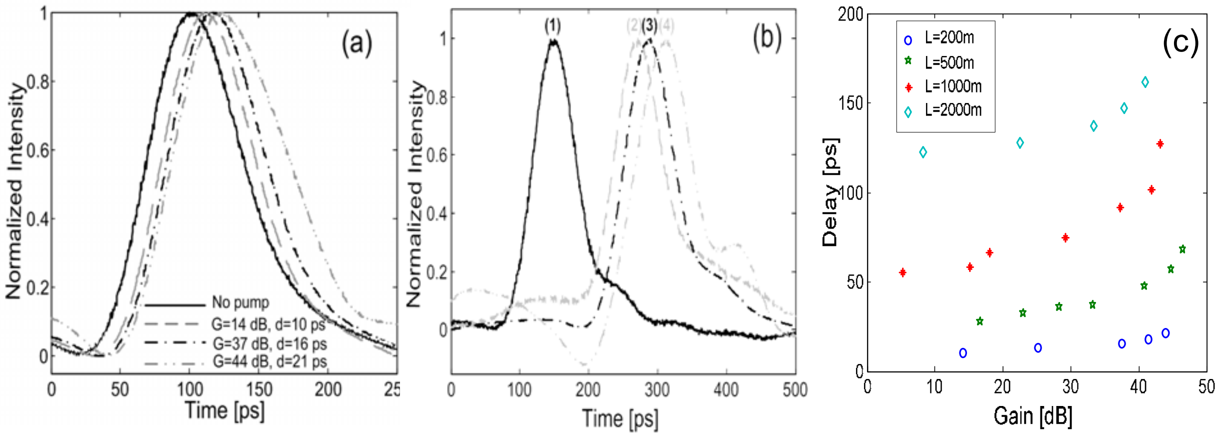

Figure 6 : Experimental traces for different gain values using (a) 200 m long DSF, (b) 2000 m long DSF (1 : no gain, 2: G=8dB, d=122ps, 3: G=33dB, d=137ps, 4: G=41dB, d=162ps) and. (c) delay as a function of the gain for different fiber length

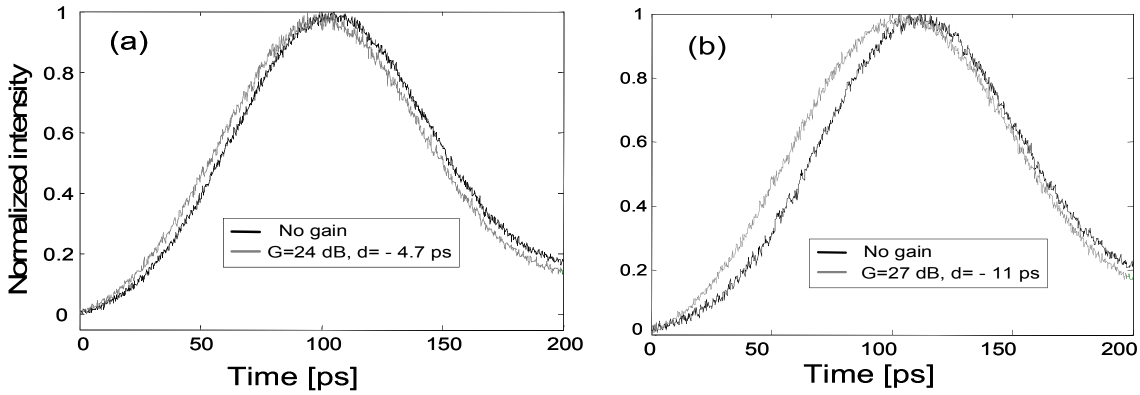

Fig. 7 : Fast light observation at λ_s=1600 nm using (a) 2000 m long DSF (b) 3000 m long DSF

Fast light (negative delay) occurs at wavelengths longer than the pump as explained previously. The longest available wavelength from a single mode laser was λ_s=1600 nm where the induced negative delay per unit length is very small. In order to demonstrate the principle of fast light we used 2000 m and 3000 m long DSF where Raman assisted OPA enabled observable pulse advancement. In order to provide gain at λ_s=1600 nm, we set the pump wavelength at λ_p=1537.6 nm. The results are presented in Fig. 7.

For a 2000 m long DSF, we obtained a pulse advancement of 4.7 ps for a gain of 24 dB and by using 3000 m long DSF, the advancement increased to 11 ps for a gain of 27 dB. However, for this latter case, the pulse undergoes some broadening which may result from a combination of pump saturation and dispersion induced by the strong variation of the group index induces at the gain spectral edges. For longer wavelength signals (if these would be available), pulse velocity enhancement would have equaled the velocity slow down observed at short wavelength.

In conclusion, we have demonstrated a Raman assisted optical fiber parametric amplifier with a controllable narrow gain spectrum which enables tunable slow and fast light. Delays up to 162 ps were demonstrated for 70 ps pulse using a 2000 m long DSF. The delays increase with the amplifier gain and the fiber length but optimal operation requires a constant zero dispersion wavelength along the fiber.

The proposed system has several advantages. First, it offers a bandwidth of larger than 100 GHz and is therefore suitable for delaying high speed digital data streams as well as picosecond pulses. Second, it offers large gain levels and therefore allows for the use of long fibers, in contrast to systems based on absorption resonance where the device length is limited by severe signal amplitude attenuation. The long fibers yield large delays together with large tuning ranges even though the group index change is moderate. Finally, the delay is easily controlled by the pump power and there is flexibility in choosing the wavelength of operation.

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