Pulse delaying using Raman-assisted parametric amplification in polarization-maintaining fibers

Nour Nasser, Gil Fanjoux, Eric Lantz and Thibaut Sylvestre

Institut FEMTO-ST, Département d'Optique, Université de Franche-comté, CNRS-UMR 6174, Besançon, France

gil.fanjoux@univ-fcomte.fr

Abstract: We study both analytically and numerically pulse delaying and advancement through Raman-assisted optical parametric amplification in polarization-maintaining fibers and show that the Raman gain enhances the optical delay up to 35%.

OCIS codes: 060.4370,060.2420,190.4410,350.5500

Slow and fast light (SFL) propagation has been demonstrated over the past few years using Raman-assisted narrowband optical parametric amplification (RA-OPA) in optical fibers [1]. With this technique, large delays and delay tuning ranges up to 160 ps have been achieved in a 2-km standard telecommunication fiber. Recently, we have theoretically demonstrated that large optical delay and advancement can also be obtained by using vector OPA in polarization-maintaining or highly-birefringent (Hi-Bi) fibers [2]. More specifically, we have shown that the optical delay can be one order of magnitude larger than that previously obtained by scalar OPA with similar parameters, which may represent a significant improvement. However, our theory did not account for the Raman gain that plays a crucial role for the optical delay.

The aim of the present work is to give a complete theoretical investigation of the optical delay in Hi-Bi fibers by including both the parametric and Raman gains. With this theory, we demonstrate significant enhancement (35 %) of the optical delay that can be achieved when the vector OPA gain matches the Raman frequency shift. Let us consider the Raman-assisted parametric amplification of a weak signal pulse by a pump pulse polarized at 45° of the birefringence axis of a polarization-maintaining fiber (PMF). The fiber has a birefringence parameter $\delta = \Delta n/c$, a nonlinear coefficient γ, and a anomalous group velocity dispersion (GVD) coefficient $\beta_2 < 0$. To be optically delayed, the signal pulse must be polarized along the slow axis and located in the anti-Stokes gain band because of phase-matching. If we take into account the Raman gain (only the real part of silica Raman susceptibility) in the OPA theory of Ref. [2] as in Ref [1], we can expressed the resulting complex gain in high gain regime as

$$g_s = \left(\frac{\gamma P}{3}\right)^2 \frac{1}{g + \left[i\frac{\kappa}{2} - g_R\frac{P}{2}\right]} - g_R\frac{P}{2} \tag{1}$$

with $g^2 = \left(\frac{\gamma P}{3}\right)^2 - \left(\frac{\kappa}{2}\right)^2 + g_R P\left(\frac{g_R P}{4} - i\frac{\kappa}{2}\right)$, g_R the Raman gain, $\kappa = \delta\Omega + \beta_2\Omega^2 + \gamma P$ the phase mismatch, and P the pump power. The real part of g_s provides the RS-OPA gain while its imaginary part induces a time phase shift on signal pulse that leads to the following group index variation Δn_g and to the time delay Δt_{NL} as

$$\Delta n_g = c\frac{\partial \Im m(g_s)}{\partial \Omega} \qquad \text{and} \qquad \Delta t_{NL} = \int_L^0 \frac{\Delta n_g}{c} dz \tag{2}$$

Fig.(1)(a) compares the theoretical results obtained from Eqs. (1) and (2) for OPA delay (blue curve) and RA-OPA delays (red curve). The parameters used here are $\gamma = 5W^{-1}.km^{-1}$, $\delta = 2ps.m^{-1}$, $P = 4W$. The GVD parameter β_2 is tuned from -15 to -60 ps^2/km to show the optical delay versus the frequency shift. It clearly appears that, whereas 1 ps of delay per meter of propagation can be obtained in the OPA case, 1.35 ps/m can be reach in the RA-OPA case near the Raman gain peak. Moreover, the evolution of the Raman-assisted OPA relative to the OPA one clearly reflects the Raman gain, which proves the strong influence of the Raman effect. Therefore, the RA-OPA allows one to obtain a significant enhancement of the vector OPA optical delays.

To verify our analytical predictions, we performed numerical simulations of the nonlinear Schrödinger equation by taking into account the real and imaginary part of the silica Raman susceptibility [3]. A 10 ns square pump pulse polarized at 45° of the birefringence axes is injected into a 400 m long PMF with a 1 ns signal pulse frequency shifted from the pump to the peak of the parametric gain. The parameters used in simulations are the same as in the previous analytical case. The analytical predictions are obtained from Eqs. (1) and (2) including the weak and strong gain regime. Fig. (1)(b) shows a good agreement between the analytical and numerical results. Furthermore, in case where only vector OPA is taken into account, the pulse signal experiences a frequency independent optical delay of 250 ps. Note that this delay is lower than the expected 400 ps (1 ps/m), the difference being due to the weak gain regime at the beginning of the propagation. On the other hand, the RA-OPA optical delay clearly presents a frequency dependence, as shown in Fig. 1(a). More precisely, near the Raman gain peak, the optical delay reaches 350 ps, i.e. 35 % higher than in the OPA case. It is interesting to mention that, even if the signal is located in the anti-Stokes gain band, i.e. in the Raman absorption band, the optical delay nevertheless increases. It is also interesting to note that the real part of the Raman gain, only included in the numerical simulations, which acts on the phase of the signal does not significantly influence the optical delay.

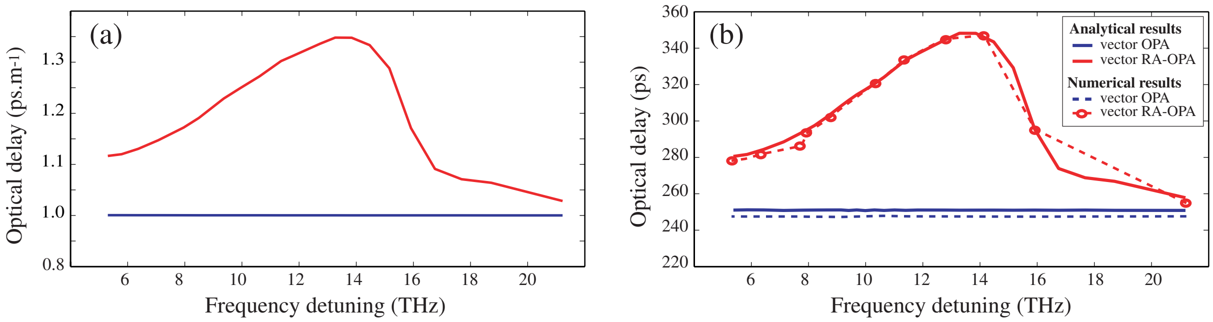

Fig. 1. (a) analytic RA-OPA optical delay versus frequency detuning in high gain regime. (b) Analytic (solid curves) and numeric (dashed curves) optical delays obtained with OPA (blue curves) or RA-OPA (red curves) including the weak gain regime.

To conclude, we theoretically demonstrate that combined effect of Raman gain and vector OPA leads to large optical delays experienced by signal pulse frequency shifted to maximum of parametric gain in Hi-Bi fibers. The Raman gain may improve the optical delay up to 35% at the peak of Raman gain.

References

1. D. Dahan and G. Eisenstein, “Tunable all optical delay via slow and fast light propagation in a Raman assisted fiber optical parametric amplifier: a route to all optical buffering“, Opt. Express,vol 13, 6234–6249 (2005).
2. N. Nasser, G. Fanjoux, E. Lantz, T. Sylvestre, “Tunable optical delay using parametric amplification in highly birefringent optical fibers,”J. Opt. Soc. Am. B **28**, 2352–2357(2011).
3. G.P. Agrawal, *Nonlinear Fiber Optics* ,Academic Press, New York (2001).