# Raman cascade suppression by using wide band parametric conversion in large normal dispersion regime

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**Abstract:** We present experimental results on the suppression of a complete Raman cascade in a holey fiber by using gain competition with parametric processes. The modulation instabilities which strongly affect the stimulated Raman scattering (SRS) gain are induced by two pump wavelengths (532 nm, 1064 nm) placed far and quasi symmetrically on each side of the zero dispersion wavelength (ZDW) of the fiber (790 nm). The competition between these two nonlinear effects takes place in large normal dispersion regime. We experimentally determinate the quantity of energy needed at each pump wavelength to obtain total suppression of the SRS and we evaluate the sensitivity of this effect with respect to the ZDW position.



**OCIS codes:** (190.4370) Nonlinear optics, fibers; (190.5650) Raman effect; (190.4410) nonlinear optics, parametric processes; (190.3270) Kerr effect.

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## References and links

1. R. H. Stolen, M. A. Bösch and C. Lin, "Phase matching in birefringent fibers," Opt. Lett. **6**, 213-215 (1981).
2. M. Nakazawa, T. Nakashima and S. Seikai, "Raman amplification in 1.4-1.5-µm spectral region in polarization-preserving optical fibers," J. Opt. Soc. Am. B **2**, 515-521 (1985).
3. J. K. Chee and J. M. Liu, "Raman-assisted parametric frequency and polarization conversion in a birefringent fiber," Opt. Lett. **14**, 820-822 (1989).
4. J. K. Chee and J. M. Liu, "Polarization-dependent parametric and Raman processes in a birefringent optical fiber," IEEE J. Quantum Electron. **26**, 541-549 (1990).
5. T. Yang and P. Gao, "Stimulated four-photon mixing with crossed pump dividing in an optical fiber," Opt. Lett. **15**, 1002-1004 (1990).
6. S. Trillo and S. Wabnitz, "Parametric and Raman amplification in birefringent fibers," J. Opt. Soc. Am. B **9**, 1061-1082 (1992).
7. P. Tchofo Dinda, G. Millot and S. Wabnitz, "Polarization switching and suppression of stimulated Raman scattering in birefringent optical fibers," J. Opt. Soc. Am. B **15**, 1433-1441 (1998).
8. P. V. Mamyshev, A. P. Vertikov and A. M. Prokhorov, "Switching of the frequency shift of stimulated Raman scattering caused by parametric interaction in optical fibres," Sov. Lightwave Commun. **2**, 73-77 (1992).
9. A. P. Vertikov and P. V. Mamyshev, "Mixed-mode and single-mode types of parametric suppression of stimulated Raman scattering in birefringent fibres," Sov. Lightwave Commun. **2**, 119-124 (1992).
10. Y. R. Shen and N. Bloembergen, "Theory of stimulated Brillouin and Raman scattering," Phys. Rev. **137**, A1787-A1805 (1965).
11. E. Golovchenko, P. V. Mamyshev, A. N. Pilipetskii and E. M. Dianov, "Mutual influence of the parametric effects and stimulated Raman scattering in optical fibers," IEEE J. Quantum Electron. **26**, 1815-1820 (1990).
12. S. Pitois, G. Millot and P. Tchofo Dinda, "Influence of parametric four-wave mixing effects on stimulated Raman scattering in bimodal optical fibers," Opt. Lett. **23**, 1456-1458 (1998).
13. P. Tchofo Dinda, G. Millot and S. Wabnitz, "Polarization switching of stimulated Raman scattering in optical fibers by dual-frequency pumping," Opt. Lett. **22**, 1595-1597 (1997).

14. T. Sylvestre, H. Maillotte and E. Lantz, “Stimulatted Raman suppression under dual frequency pumping in singlemode fibres,” Electron. Lett. **34**, 1417-1418 (1998).
15. T. Sylvestre, H. Maillotte, P. Tchofo Dinda and E. Coquet, “Suppression of stimulated Raman scattering in optical fibres by power-controlled multifrequency pumping,” Opt. Comm. **156**, 32-36 (1999).
16. P. Tchofo Dinda, S. Wabnitz, E. Coquet, T. Sylvestre, H. Maillotte and E. Lantz, “Demonstration of stimulated-Raman-scattering suppression in optical fibers in a multifrequency pumping configuration,” J. Opt. Soc. Am. B **16**, 757-767 (1999).
17. P. A. Champert, V. Couderc, P. Leproux, S. Février, V. Tombelaine, L. Labonté, P. Roy, C. Froehly and P. Nérin, “White-light supercontinuum generation in normally dispersive optical fiber using original multi-wavelength pumping system,” Opt. Express **12**, 4366-4371 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-19-4366.

## 1. Introduction

Stimulated Raman Scattering is a nonlinear process induced by the propagation of intense laser beams in nonlinear media. This effect can be understood as an energy transfer from a pump field toward another field whose frequency is downshifted by an amount determinated by the vibrational modes of the medium. Combined with other processes, this nonlinear phenomenon is exploited in holey fibers for continuum generation, in which it largely participates to the spectral enlargement. Nevertheless its contribution in the nonlinear propagation induces non homogeneous spectral broadening with large modulations which limit the use of the generated broadband signal. It is known that SRS can be strongly affected by parametric processes as four-wave-mixing (FWM) or modulation instabilities (MI) [1-9]. After the first investigation by Shen and Bloembergen [10], many papers have shown the interplay between Raman effect and nonlinear mixing processes [5-7]. For example, it was already demonstrated that the effective Raman gain may be suppressed through the coupling between Stokes and anti-Stokes waves, which occurs for relatively small value of the linear wave vector mismatch with the pump [6-7][11]. Moreover we can note that the influence of parametric gain was analyzed and observed in bimodal fibers under single frequency pumping conditions in normal dispersion regime [12]. In this study, modal phase matching between the fundamental and the first high order transverse mode of the fiber could induce MI effect causing strong perturbation in SRS growing.

Finally, Raman annihilation was demonstrated using double pumping scheme. First, the two non degenerate frequencies were orthogonally polarized. SRS was then suppressed in one axe of a highly birefringent fiber through the orthogonal components of the Raman nonlinearity [13]. Later, pure non parametric SRS suppression was demonstrated by using the combined effect of Raman Stokes gain and Raman anti-Stokes absorption processes with parallel polarization of the two input waves [14-16]. Nevertheless, among all these published papers, no suppression of a complete Raman cascade in large normal dispersion regime was, to our knowledge, already observed.

We present in this paper an experimental investigation showing the total suppression of Raman cascade by using gain competition with MI process. This effect is observed in a singlemode microstructured silica fiber longitudinally pumped by two radiations placed quasi symmetrically on each side of the ZDW of the fiber [17]. The gain competition takes place in large normal dispersion regime with a large evolution of the chromatic dispersion. We determinate the experimental conditions in term of pump power leading to SRS suppression.

## 2. Experimental set-up; characteristics of the optical fiber

The setup used in the experiment is shown in Fig. 1. The pump source consists of a passively Q-switched Nd:YAG microchip laser delivering 600 ps duration pulses at $\lambda_1 = 1064$ nm with a repetition rate of 5.4 kHz. The free space radiation of the laser is frequency doubled in a 20 mm long type-II KTP crystal, with 30 % conversion efficiency, yielding to pulses of 420 ps at $\lambda_2 = 532$ nm. A polarizer placed between the fiber and the nonlinear crystal selects a linear polarization state. The infrared and green radiations are coupled into a 3 m long air-silica microstructured optical fiber (MOF). The insertion of two filters (named "RG 850" and "BG 18") permits to select either the infrared or the visible pump with more than 40 dB of attenuation. This permits to have less than 20 mW of peak power at 532 nm and less than 60 mW (peak power) at the fundamental wavelength in single-pump configuration.

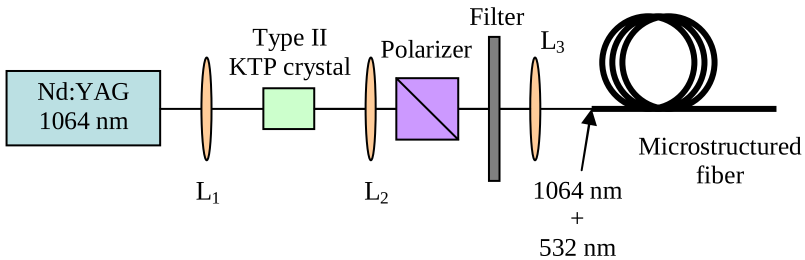


Fig. 1. Experimental setup.

The MOF used in these experiments has been fabricated by using the conventional stack and draw process. A cross sectional scanning electron microscope image of the fiber is shown in Fig. 2. The hole-to-hole spacing $\Lambda$ is around 2.5 µm, the average hole diameter d is 1.5 µm, leading to a core diameter approximately equal to 3.5 µm. After coiling the fiber on a 1.5 cm roller, we observed singlemode propagation from blue to infrared region. Moreover this fiber has been specially designed for exhibiting low OH- absorption at 1.4 µm.

The chromatic dispersion and the effective area of the fundamental mode have been computed from 400 to 1600 nm using a full vectorial finite element algorithm and taking into account the actual cross section of the fiber (see Fig. 2). The ZDW is located at $\lambda_{ZDW}$ ~ 790 nm between the two pump wavelengths $\lambda_2$ and $\lambda_1$. The chromatic dispersion of the fundamental transverse mode is respectively -350 ps/nm/km and +95 ps/nm/km at these wavelengths. The small effective area $A_{eff}$ is equal to 2.4 µm² and 2.9 µm² at 532 and 1064 nm respectively. The nonlinear coefficient $\gamma = 2\pi.n_2/\lambda.A_{eff}$ is then 0.15 $W^{-1}.m^{-1}$ for the second harmonic wave and 0.06 $W^{-1}.m^{-1}$ for the fundamental ($n_2$ being the nonlinear refractive index, $n_2 \sim 3\times10^{-20}$ $m^2.W^{-1}$ for silica fibers).

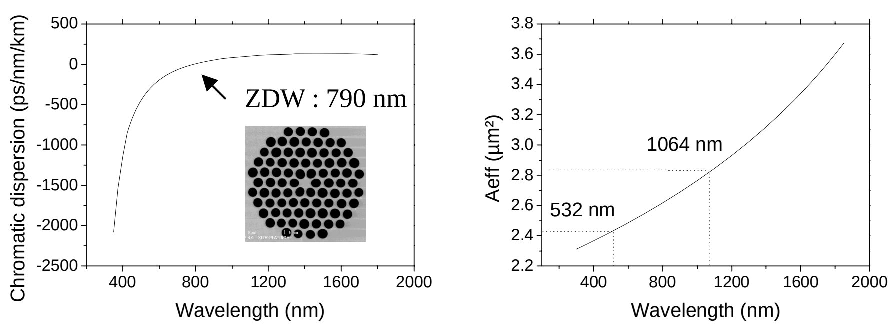


Fig 2. Chromatic dispersion curve (left) and effective area (right) of the fundamental transverse mode of the fiber versus wavelength. Inset: cross sectional scanning electron microscope image of the microstructured air-silica fiber.

## 3. Raman cascade generation

In a first step, we launched the green pump into the waveguide. We observed successively the apparition of a weak anti-Stokes and several energetic Stokes waves. For a peak power of ~ 300 W and an average power of 1 mW measured at the output end of the fiber, we obtained six Stokes orders (see Fig. 3). The spectral shift of each ray is equal to the silica shift

#8401 - $15.00 USD Received 8 August 2005; Revised 1 October 2005; Accepted 7 October 2005

(~ 13.5 THz). Due to the strong normal dispersion at 532 nm, SRS is the dominating nonlinear process. The SRS threshold was experimentally determined and is close to ~ 100 W (peak power of the green light).

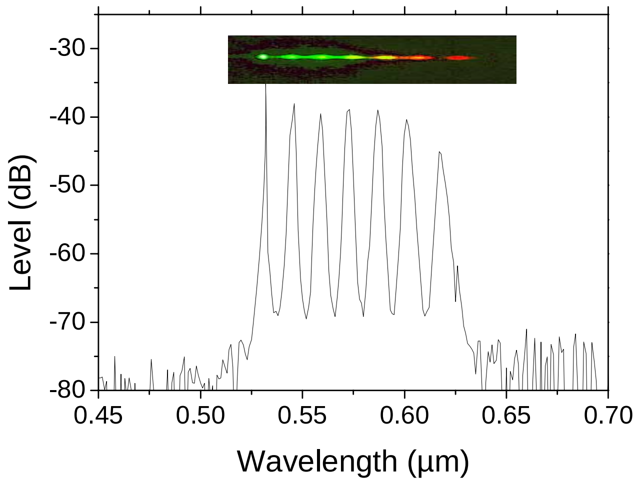


Fig. 3. Photograph and profile of the generated output spectrum. Six Stokes components are visible with an input peak power of ~ 300 W at 532 nm.

## 4. Raman cascade suppression

In a second step, by removing BG 18 filter, we added the fundamental wavelength of the Nd:YAG laser and we coupled it into the holey fiber without modification of the precedent step. The addition of pump power at 1064 nm permits to obtain significant spectral broadening both in infrared and visible regions. First, the spectral enlargement in infrared domain (between 1064 and 1800 nm) is the result of the combination of Raman effect, Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and parametric mixing. Higher is the infrared pump power, larger is the spectrum. The evolution of this continuum versus the input power is shown in Fig. 4(c).

The second continuum takes place in the visible region around the first pump at 532 nm and extends from ultraviolet (350 nm) to near infrared region (700 nm) (Fig. 4(a) and 4(b)). For a low input power at 1064 nm, the nonlinear generation remains weak and is visible 20 dB below the Stokes components. This effect is due to MI induced by the double pumping system. For a sufficiently low infrared input power, no modification of the Raman cascade is observed. Then, we can see superimposition of the two spectral broadening effects.

By increasing the infrared pump level, without any change on the green pump level, we observe the growth of infrared and visible continua. Simultaneously we obtain the gradual disappearing of Stokes rays (Fig. 4(a) and 4(b)). The decrease of the Raman contribution is realized progressively, Stokes ray by Stokes ray, with the increase of the infrared pump power. This effect is equivalent to a progressive decrease of the pump level which is directly responsible for the SRS effect (532 nm). We observed this phenomenon up to the complete removing of the Stokes components. The modulated spectral broadening is then replaced by a smooth continuum between ultraviolet and red wavelengths. The required infrared peak power to obtain total suppression of the Raman cascade is close to 1.8 times the green input peak power. The calculated intensity ratio between the two input wavelengths leading to a total suppression of the Raman contribution is $I_{2\omega} / I_{\omega} = 0.7 \pm 0.1$.

#8401 - $15.00 USD Received 8 August 2005; Revised 1 October 2005; Accepted 7 October 2005

It is worth to note that the output level of the generated smooth continuum is at least 15 dB lower than the Raman cascade level. This fact proves that the Raman contribution decreases without being masked by MI process. Furthermore, Raman cascade suppression is a completely reversible process, i.e. for a fixed infrared pump power, the Raman cascade reappears when increasing the green power above the 0.7 ratio.

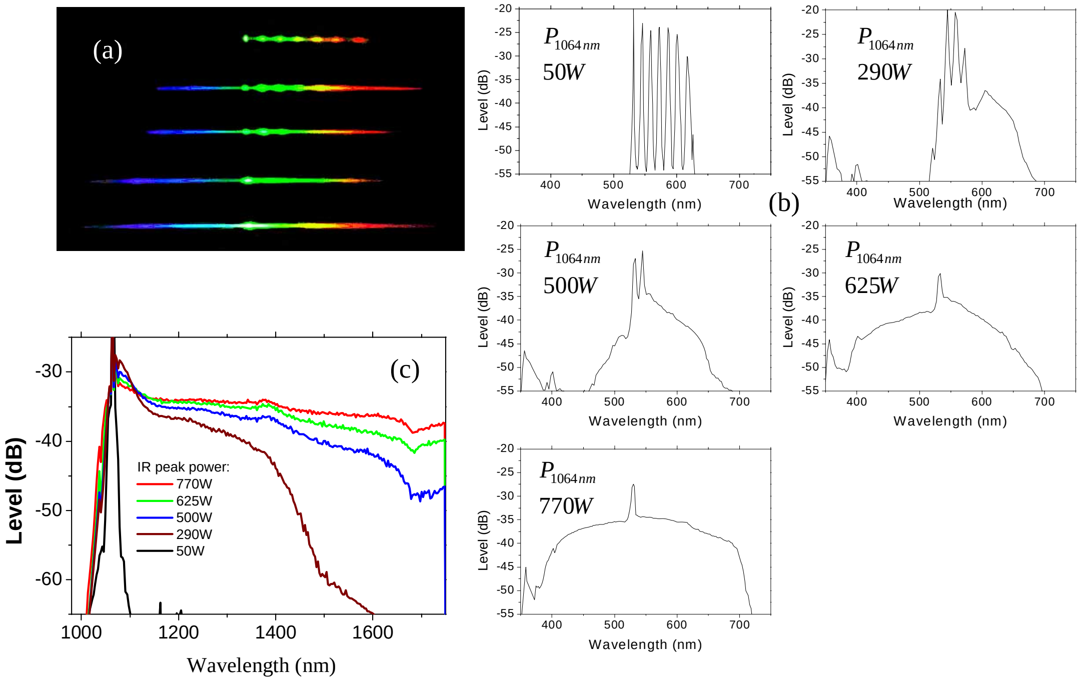


Fig. 4. Experimental results showing the Raman cascade suppression according to the increase of the infrared pump peak power (1064 nm) for a fixed input level at 532 nm (300 W peak power). Photograph of the phenomenon (diffracted output beam) (a); Spectrum profile of the visible continuum (b); Spectrum evolution of the infrared continuum (c).

It is clear that Raman effect and MI grow using green pump but are not directly linked. The Raman cascade does not participate to the MI phenomenon. To prove this fact, we realized the same operation as previously but with a low amount of energy at 532 nm. We sent an energetic fundamental pump at 1064 nm (~ 1000 W peak power) with a weak pump in the visible region (peak power: 15 W). In these conditions, we observed spontaneously a smooth continuum between 400 and 580 nm. Because of the low pump power at 532 nm, the output power spectral density is weak. Increasing the green pump level, no modification of the nonlinear behavior is observed while the intensity ratio between the two pump powers remains lower than ~ 0.7. The increase of the 532 nm pump power permits to obtain higher power spectral density of the visible continuum with a larger spectrum (Fig. 5). This double pumping system which induces MI blocks the expansion of the Raman phenomenon. It is known that MI appears at lower power threshold than SRS. In our case, the SRS growth is only due to the green pump power whereas the MI effect is induced both by the infrared and the green powers. In these conditions, an appropriate adjustment of the power ratio between the two pumps permits to maintain Raman gain lower than MI gain.

Moreover, we can note in Fig. 5 the presence of spectral broadening due to third harmonic generation from the strong infrared pump. This third harmonic generation process extends the bandwidth of the continuum. The non evolution of the ultraviolet-blue part of the spectrum proves the non modification of the infrared pump power during the process.

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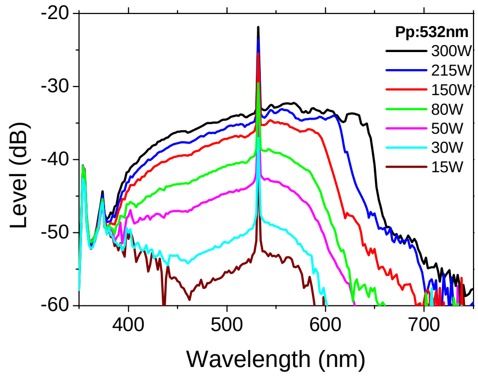


Fig. 5. Evolution of the visible spectrum versus the green (532 nm) pump peak power for a fixed input peak power of the infrared pump (~ 1000 W).

SRS suppression has also been observed in several other singlemode microstructured fibers with core diameters as high as 4 µm. It seems that MI developing is not extremely sensitive to the ZDW position of the fundamental transverse mode with respect to the two pump wavelengths. Indeed Raman suppression was observed with ZDW position varying from 790 to 860 nm.

The length of the used fiber is another important parameter as well. No modification of the nonlinear process is observed for fiber lengths between 0.7 and 30 m. Only the intrinsic losses of the fiber may modify the pump power ratio needed for total suppression of the SRS process. The use of shorter fibers requires higher input power in order to observe significant suppression of several Stokes components. A more complete study with ultra short microstructured fibers is currently under investigation.

In addition, Raman cascade annihilation was observed in a germanium-doped multimode microstructured fiber using the same double pumping system. All the Stokes components on all transverse modes were removed thanks to the MI process. As a matter of fact, the multimode transverse structure of the waveguide permits modal phase matching and consequently favors the growth of parametric processes. Besides it seems that germanium-doping permitted to exacerbate the efficiency of both SRS and MI effects, as the same SRS suppression phenomenon as previously was observed.

At last, according to our measurements, it is clear that the different microstructured fibers used in the experiments exhibit a large birefringence. Furthermore the infrared and visible pump radiations are linearly polarized at the input end of the fiber. Maintaining the polarization of the second harmonic wave fixed, we modified the orientation of the linear polarization of the fundamental radiation by using a 1064 nm half wave plate at the zero order. We then observed low evolution of the spectrum width versus the polarization orientation. Moreover no significant change in the nonlinear behavior was obtained for each orientation. This experiment proves that vectorial FWM phenomenon takes place in the spectral broadening. At this point, numerical investigation is then required for a better understanding of vectorial FWM impact.

## 5. Conclusion

We experimentally demonstrated Raman cascade suppression by using competition with MI process in a microstructured singlemode optical fiber. The parametric process was induced by a double pumping system in large normal dispersion regime with a strong evolution of the chromatic dispersion. The total suppression of the six Stokes components was obtained for a proper peak power ratio between the two input pump waves. This effect was observed in

#8401 - $15.00 USD Received 8 August 2005; Revised 1 October 2005; Accepted 7 October 2005

several microstructured fibers with different characteristics and also in a multimode germanium-doped fiber. Theoretical description of this phenomenon is currently under investigation.

**Acknowledgments**

The authors thank G. Millot, F. Van Holsbeeck, T. Sylvestre, H. Maillotte for fruitful discussions and ABX Diagnostics (HORIBA group) for its financial support.

#8401 - $15.00 USD Received 8 August 2005; Revised 1 October 2005; Accepted 7 October 2005