Observation of high-contrast, fast intensity noise of a continuous wave Raman fiber laser

Jochen Schröder [*,†] **and Stéphane Coen**

Physics Department, The University of Auckland, Private Bag 92019, Auckland, New Zealand.
[*] *Now with IPOS, School of Physics, University of Sydney, Sydney, NSW 2006, Australia.*
[†] *j.schroeder@physics.usyd.edu.au*

Abstract: We investigate the intensity noise of a continuous-wave Raman fiber laser based on a novel technique where the noise is sampled with a low repetition rate signal in a low walk-off Raman amplifier configuration. With this method, we experimentally demonstrate that continuous-wave Raman fiber lasers exhibit high contrast intensity fluctuations on a timescale of several tens to hundreds of GHz. In fact, the power of the Raman laser fluctuates between nearly zero and a high multiple of the average power. Numerical simulations are used to study the role of pump depletion on the noise transfer process. Our study validates models of pumps used in some recent continuous wave supercontinuum generation simulations.

OCIS codes: (270.2500) Fluctuations, relaxations, and noise; (320.7100) Ultrafast measurements; (140.3550) Lasers, Raman; (060.2320) Fiber optics amplifiers and oscillators; (320.6629) Supercontinuum generation.

References and links

1. A. V. Avdokhin, S. V. Popov, and J. R. Taylor, “Continuous-wave, high-power, Raman continuum generation in holey fibers,” Opt. Lett. **28**, 1353–1355 (2003).
2. M. González-Herráez, S. Martín-López, P. Corredera, M. L. Hernanz, and P. R. Horche, “Supercontinuum generation using a continuous-wave Raman fiber laser,” Opt. Commun. **226**, 323–328 (2003).
3. F. Vanholsbeeck, S. Martín-López, M. González-Herráez, and S. Coen, “The role of pump incoherence in continuous-wave supercontinuum generation.” Opt. Express **13**, 6615–6625 (2005).
4. M. H. Frosz, O. Bang, and A. Bjarklev, “Soliton collision and Raman gain regimes in continuous-wave pumped supercontinuum generation,” Opt. Express **14**, 9391–9407 (2006).
5. J. C. Travers, S. V. Popov, and J. R. Taylor, “A new model for CW supercontinuum generation,” in *Conference on Lasers and Electro-Optics CLEO’2008* (The Optical Society of America, San Jose, 2008). Paper CMT3.
6. J.-C. Bouteiller, “Spectral modeling of Raman fiber lasers,” IEEE Photon. Technol. Lett. **15**, 1698–1700 (2003).
7. S. A. Babin, D. V. Churkin, A. E. Ismagulov, S. I. Kablukov, and E. V. Podivilov, “Spectral broadening in Raman fiber lasers.” Opt. Lett. **31**, 3007–3009 (2006).
8. S. A. Babin, D. V. Churkin, A. A. Fotiadi, S. I. Kablukov, O. I. Medvedkov, and E. V. Podivilov, “Relative intensity noise in cascaded-Raman fiber lasers,” IEEE Photon. Technol. Lett. **17**, 2553–2555 (2005).
9. S. A. Babin, V. Karalekas, P. Harper, E. V. Podivilov, V. K. Mezentsev, J. D. Ania-Castañón, and S. K. Turitsyn, “Experimental demonstration of mode structure in ultralong Raman fiber lasers,” Opt. Lett. **32**, 1135 (2007).
10. K. Keita, P. Delaye, R. Frey, and G. Roosen, “Relative intensity noise transfer of large-bandwidth pump lasers in Raman fiber amplifiers.” J. Opt. Soc. Am. B. **23**, 2479–2485 (2006).
11. K. Hammani, C. Finot, J. M. Dudley, and G. Millot, “Optical rogue-wave-like extreme value fluctuations in fiber Raman amplifiers,” Opt. Express **16**, 16467–16474 (2008).
12. P. Andrekson and M. Westlund, “Nonlinear optical fiber based high resolution all-optical waveform sampling,” Laser & Photonics Review, **1**, 231-248 (2007).
13. C. R. S. Fludger, V. Handerek, and R. J. Mears, “Pump to signal RIN transfer in Raman fiber amplifiers.” J. Lightwave Technol. **19**, 1140–1148 (2001).

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1. Introduction

Continuous wave (cw) Raman fiber lasers (RFLs) are key application components, e.g., for pumping amplifiers or for cw supercontinuum (SC) generation [1,2]. They are readily available, offer wide tunability, high average output powers, and are generally considered as very stable and reliable. Their low intensity noise characteristics, however, has lately come into question. The present research was prompted by a number of recent publications on cw SC generation. In one of these, Vanholsbeeck et al found that the correct numerical modeling of the generated SC required that the cw RFL pump exhibited ultra-fast, high-contrast temporal intensity fluctuations [3]. These were modeled by considering the finite spectral width of the cw pump and by superimposing a random spectral phase on the measured spectrum. Since then, different strategies for modeling the spectrum of cw SC pump sources have been suggested, from a phase-diffusion model [4] to numerically simulating the actual pump laser [5]. These various models result however in significantly different temporal behavior of the pump source and only provide indirect indications of the true nature of the pump noise. As a matter of fact, even though existing RFL models predict relatively well the linewidth of RFLs [6, 7], little is known about how this affects the temporal behavior of the RFL output. The linewidth of RFLs appears to be caused by four-wave mixing between the longitudinal modes of the laser, an effect similar to the beating between cavity modes in harmonically mode-locked lasers known as supermode noise [7]. Babin et al also experimentally observed mode beating on a megahertz timescale in the power spectra of some RFLs [8, 9]. However it remains unclear if these observations apply to the cascaded cw RFLs used in the above-mentioned SC experiments where no such beating was observed at timescales below 10 GHz (see, e.g., Ref. [2]).

Our aim is to prove the existence of ultra-fast, high-contrast temporal intensity fluctuations in the output of RFLs. Since typical linewidths are in the 100 GHz range, and the Fourier theorem predicts fluctuation timescales of the order of the inverse of the linewidth, a direct measurement of the random intensity fluctuations, although desirable, is extremely difficult. Traditional RF noise measurement techniques fail at these timescales which are beyond the electronic bandwidth. Previous studies have also used 2nd-harmonic autocorrelators but, due to the limited delay range, the true nature of the fluctuations, and whether they are low or high contrast, periodic or random, can be hard to identify. To overcome these limitations, we propose a new intensity noise measurement technique. It is based on transferring the noise of the RFL under test [10] to a low repetition rate signal in a low walk-off forward-pumped Raman amplifier, which is akin to optically sampling the RFL fluctuations. The noise characteristics of the low repetition rate signal are then easily measured by traditional means. We should note that, in a recent experiment, Hammani et al [11] used a similar setup to demonstrate the existence of optical rogue waves. Also, our technique has some similarities with optical sampling oscilloscopes [12]. Our study goes beyond those works, however, in that by varying the pump-to-signal walk-off, we are able to quantitatively measure the timescale of the pump intensity fluctuations. Additional numerical simulations highlight the role of instantaneous pump depletion.

2. Experiments

Our experimental setup is as simple as a fiber Raman amplifier, similar to that described in Ref. [11]. The cw RFL under test acts as the pump of that amplifier and is co-propagated with a weak pulsed signal from a mode-locked laser. When the walk-off between pump and signal is zero (i.e., when they propagate with equal group velocities), the individual signal pulses interact with different parts of the pump beam. If the pump exhibits intensity fluctuations, adjacent signal pulses experience different amount of gain and the pump noise is thus sampled and transferred onto the signal pulse train. By varying the pump-to-signal walk-off, we can measure the timescale of the pump fluctuations since for large velocity differences, the pump

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fluctuations will average out, leading to a measurable decrease in the reduced intensity noise (RIN) of the amplified signal pulses. To reliably sample the pump fluctuations, the signal should be weak enough not to suffer from nonlinear effects. Also, pump depletion must be avoided, i.e, the amplifier must be kept in the small signal gain regime, placing limitations on the signal and pump power as well as the fiber length. Finally, the temporal duration of the signal pulses must be shorter than the pump fluctuations, i.e., shorter than the coherence time of the pump.

In our experiment a passively mode-locked Er-doped fiber laser generated 4 ps signal pulses at 1534 nm with a 3.8 MHz repetition rate. The cw cascaded RFL under test is a commercially available RFL, tunable over 1430–1490 nm with 6 W maximum average power. Signal and pump were coupled together through a wavelength division multiplexer (WDM) into a large effective area fiber (LEAF). This fiber was chosen for its particular dispersion characteristics. With a zero-dispersion wavelength of about 1490 nm, group-velocity matching between pump and signal is obtained with a pump wavelength around 1444 nm. This is well within the tunability of our pump laser and also sets the peak gain of our Raman amplifier right at the signal wavelength. Additionally, the tunability of the RFL enables us to vary the pump-to-signal walk-off (a pump wavelength variation of ± 10 nm induces a pump-signal walk-off of $\simeq 5$ ps per 150 m of fiber length). A second WDM at the fiber output rejects most of the pump and allows for easy reconfiguration of the setup into a counter-propagating pump scheme. Following this, the signal is separated from the remaining pump using a prism in free space and is then measured with a fast photodiode and either an oscilloscope or an RF-spectrum analyzer.

Figures 1(a)–(b) depict the RF spectrum and temporal profile (solid black) of the signal after co-propagating through 150 m of LEAF with a 1444 nm pump, i.e., with no walk-off. Also shown are results without pump and with a counter-propagating pump. The signal had an average power of 1 mW and the pump power was 4 W. Considering a Raman gain coefficient $g_{\mathrm{R}} \approx 0.7\,\mathrm{W}^{-1}\mathrm{km}^{-1}$, the small signal gain is 1.8 dB. The RF-spectra of the amplified signal, both in the co- and counter-propagating configurations, reflect this value: the peak at the 3.8 MHz signal repetition rate is about 2 dB larger than in the non-amplified case. The noise levels in the power spectra differ however markedly. The noise floor observed with a counter-propagating pump (dotted) is identical to that of the non-amplified signal (dashed), i.e., no noise was transferred from the pump to the signal. In contrast, with a co-propagating pump, the noise floor is raised by about 10 dB. Furthermore, apart from the two peaks spaced at ≈ 0.7 MHz around the main peak, which we attribute to relaxation oscillations of the RFL or possibly to spurious reflections, the noise floor has increased uniformly, i.e., the pulse-to-pulse fluctuations are completely random. The high-contrast nature of the fluctuations can be observed in Fig. 1(b) which shows 30 superimposed temporal traces of amplified (black) and non-amplified (grey) signal pulses. The gain of individual pulses varies between nearly 0 dB to > 3 dB. Furthermore, as

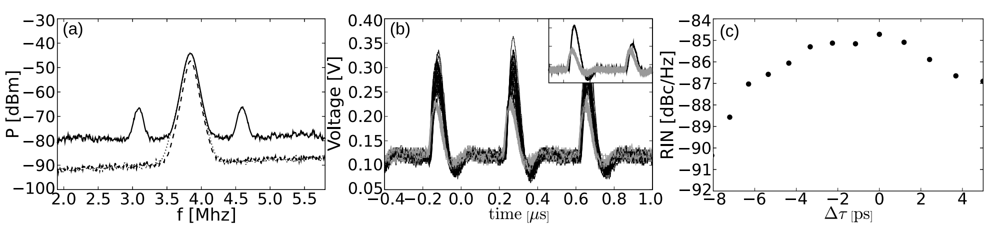

Fig. 1. (a) RF-spectra of the output signal with a co- (solid, zero walk-off) and counter-propagating (dotted) pump. (b) Overlay of 30 oscilloscope traces of pulses amplified with the co-propagating pump (black), with a single trace in inset. The dashed line in (a) and the gray lines in (b) are measured in the absence of pump. (c) Signal noise versus pump-to-signal walk-off. Fiber length is 150 m.

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evidenced by the inset, this variation occurs between subsequent pulses. The RIN of the amplified signal can only be attributed to high-contrast intensity fluctuations of the pump. However, as these fluctuations are not evident when the RFL noise is measured using traditional methods (e.g., Ref. [3] reports a RIN of -110 dBc/Hz in the 0–1 GHz range), they must occur at much higher frequencies and we have to employ a different method to measure their timescale.

To this end, we have taken advantage of the fiber dispersion and of the tunability of our RFL. Varying the pump wavelength effectively changes the walk-off between pump and signal. While the signal pulses experience a gain related to the instantaneous pump power when there is no walk-off, a non-zero walk-off leads to an averaging of the gain over the walk-off time $\Delta\tau$ and to a reduction of the noise transferred to the signal. Figure 1(c) shows the RIN of the co-amplified signal, obtained as the ratio of the RF-spectrum noise level per unit of frequency to the 3.8 MHz peak level, versus the walk-off time $\Delta\tau$. The graph demonstrates the dependence of the transferred noise on the pump-to-signal walk-off. Fludger et al. developed a theory of noise transfer in Raman amplifiers [13]. Although this theory is only strictly valid for small pump intensity fluctuations, applying it to the present case of high-contrast fluctuations still leads to some insights. In the case of a signal co-propagating with the pump, the pump-to-signal walk-off caused by the fiber dispersion acts as a low-pass filter for the pump noise. In an amplifier of length L and pump absorption coefficient α, the -3 dB corner frequency f_c of the filter is [13]:

$$f_c = \frac{1}{2\pi D \Delta\lambda L_{\text{eff}}}, \tag{1}$$

$L_{\text{eff}} = (1-\exp(-\alpha L))/\alpha$ being the effective amplifier length, D the fiber dispersion (in ps/nm/km) and $\Delta\lambda$ the pump-to-signal wavelength separation. Because $D\Delta\lambda L_{\text{eff}}$ corresponds to the walk-off time $\Delta\tau$ between pump and signal, we can use Fig. 1(c) to estimate the timescale of the pump fluctuations. The -3 dB walk-off is about 6 ps (half width) corresponding to a corner frequency and thus an estimate for the timescale of the fluctuations of about 25 GHz.

Care must be taken in interpreting these results. The walk-offs considered in Fig. 1(c) were obtained by varying the pump wavelength over as much as 35 nm. This leads to significant variation of the Raman gain coefficient experienced by the signal. Moreover, the transmittance of the WDM used to combine pump and signal is not uniform over that wavelength range. In addition, with 1 mW average signal power, pump depletion is significant. Also, we would like to investigate the noise transfer process for even larger walk-offs. We therefore conducted a second set of experiments with a longer LEAF of 1000 m. The longer fiber allows for a significantly larger walk-off for the same pump-to-signal separation. It also implies that we have to decrease the pulsed signal power to 6 μW to keep in check detrimental nonlinear effects such as self-phase-modulation. Simultaneously, the power of the cw RFL pump has to be reduced to 0.8 W to avoid spontaneous Raman scattering and keep the amplification in the small signal gain limit. As a matter of fact, increasing the fiber length is a delicate balancing act. It becomes increasingly difficult to avoid pump depletion and the very low signal power increases the influence of secondary noise sources, in particular in the free space pump-signal separation arm. For this experiment, the output signal was measured using a digital sampling oscilloscope with a 1 GHz bandwidth and a 5 GS/s sampling rate. Single traces containing trains of about 400 pulses were stored and later analyzed, allowing us to directly measure the pulse fluctuations.

The RIN measurements obtained with the 1000 m long LEAF are shown in Fig. 2(a). Although they are not immediately comparable with those of Fig. 1(c) because the amplifier has a different gain, the -3 dB walk-off of 7 ps is similar to the 6 ps measured previously. The small discrepancy can be explained by instantaneous depletion of the pump, which will be discussed in more details below. Note that here we have adjusted the pump power when varying the walk-off to keep the output signal power constant, thereby compensating the pump wavelength dependence of the gain coefficient. This compensation is very minor ($<10\%$), however, and the

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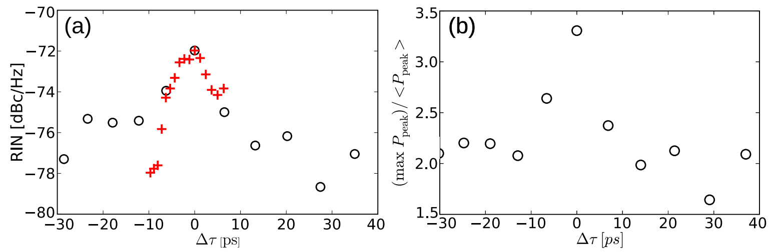

Fig. 2. (a) RIN versus walk-off with 1000 m of LEAF (circles). The result from the 150 m fiber [Fig. 1(c)], translated vertically for comparison, is superimposed (red crosses). (b) Maximum peak power normalized to the average peak power as a function of walk-off.

good agreement between our two measures confirms that our RFL indeed exhibits high-contrast fluctuations over a bandwidth of several tens of GHz. To further illustrate the high-contrast nature of the noise and its dependence on the walk-off, Fig. 2(b) depicts the maximum peak power of our measured 400-pulse long trains normalized to the average peak power of those pulse trains versus walk-off. As expected, the highest peak power is obtained at zero walk-off, where individual pulses are amplified to a level up to 3 times that of the average amplification.

3. Numerical simulations

When the pump-to-signal walk-off is zero, individual signal pulses experience a gain related to the instantaneous pump intensity. However, due to pump noise, the instantaneous intensity can vary widely. When a particular signal pulse interacts with a slot of very low pump intensity, it can easily locally deplete the pump. This can occur even when the average pump power is not markedly depleted since due to the high-contrast nature of the pump fluctuations, there will always be pump slots of very low intensities. This effect becomes more significant for long propagation distances and low average pump powers, because depletion then occurs in more and more pump slots and also for non-zero pump-to-signal walk-offs. It is not immediately clear how this local or instantaneous pump depletion affects the pump-to-signal noise transfer. In order to gain a better understanding of that effect, we performed numerical simulations.

The noise transfer is modeled by two coupled equations taking into account absorption and Raman amplification and that depend on time t and position along the fiber z,

$$\partial_z P_\mathrm{s}(z,t) = -\alpha P_\mathrm{s}(z,t) + g_\mathrm{R} P_\mathrm{s}(z,t) P_\mathrm{p}(z,t)\,, \tag{2}$$

$$[\partial_z - (\Delta\tau/L)\partial_t]\, P_\mathrm{p}(z,t) = -\alpha P_\mathrm{p}(z,t) - g_\mathrm{R} P_\mathrm{s}(z,t) P_\mathrm{p}(z,t)\,. \tag{3}$$

Here we consider that the absorption coefficient α is the same at the pump and signal wavelengths. Both the signal and pump powers, P_s and P_p, are functions of time t. The signal is modeled as a sech^2-shaped pulse with a full-width-at-half-maximum (FWHM) of 4 ps corresponding to the mode-locked laser used in the experiment. The pump laser was modeled as a sech^2-shaped spectral density with a 200 GHz FWHM matching that of our cw RFL (it changes by less than 10 % in the power range we consider here), multiplied by a random phase with a uniform distribution as in Ref. [3]. The simulation time window was chosen to match the largest simulated walk-off time. We simulate the propagation of a single signal pulse at a time. The RIN is obtained by repeating the simulations 2000 times for each value of the walk-off parameter $\Delta\tau$ with different realizations of the random spectral phase.

The simulated signal noise for two different signal input powers is shown in Fig. 3. Because a larger signal input power results in greater pump depletion, we can use these results to analyze the role of pump depletion on the noise transfer. First, we observe that the RIN decreases

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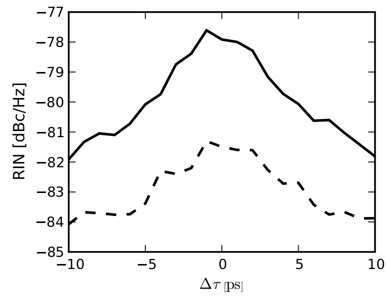

Fig. 3. Signal RIN obtained by simulation of the noise transfer process in a 150 m long LEAF with parameters identical to that of the experiment for an average signal power P_s of 300 μW (solid) and 500 μW (dashed). The pump laser has a 200 GHz FWHM sech^2 spectral linewidth with a random spectral phase.

when the signal power and hence pump depletion are increased. This can easily be understood: a depleted pump does not fluctuate any more, which saturates the noise transfer, thus lowering the RIN. Second, the -3 dB walk-off width increases with pump depletion, from 6 ps (half-width) for the low power signal to > 10 ps for the high power signal. This is due to the reduced influence of depletion for larger walk-offs. Consequently, the previous effect affects more the central part of the curve, which flattens it. The 6 ps simulated -3 dB walk-off width matches very well with our experimental results. The discrepancy in signal power (300 μW numerically versus 1 mW experimentally) may stem from unaccounted losses and from the model assumption that pump and signal are co-polarized while the real pump is unpolarized, which changes the Raman gain coefficient g_R by a factor of 2 at least. Experimental uncertainties also prevent us from comparing the absolute RIN level obtained experimentally and numerically. Note that the -3 dB walk-off width continues to decrease if the signal power is reduced further, as the influence of instantaneous pump depletion keeps diminishing and can never be completely eliminated. The changes become however less and less dramatic with decreasing power. Clearly, the numerical results demonstrate that instantaneous depletion of the pump has to be taken into consideration when deducing the timescale of the pump noise from the signal noise. We can thus conclude that our measured 6 ps -3 dB walk-off half-width is an upper boundary. Our cw RFL therefore exhibits intensity fluctuations faster than the 25 GHz corner frequency calculated earlier and peak powers significantly larger than the average pump power. Another reason for the actual fluctuation timescale to be lower than 6 ps is that this value is very close to the 4 ps signal pulse duration, i.e., close to the temporal resolution of our system. Shortening the signal pulses to improve the resolution is not trivial, however, since dispersion-induced broadening, which is currently negligible, would then quickly set a limit on the fiber length.

4. Conclusion

We have investigated the intensity noise of a cw RFL based on a novel technique which samples the noise of the RFL under test with a low repetition rate signal in a zero walk-off Raman amplifier. Although we cannot draw a definitive conclusion as to the exact nature and timescale of the RFL fluctuations, we have shown that the RFL does exhibit high contrast intensity fluctuations faster than several tens of GHz. Our measurement is somewhat impaired by instantaneous pump depletion, which is unavoidable with high contrast pump fluctuations. Nevertheless, numerical simulations confirm our analysis and indicate that the high contrast intensity noise is probably present over a bandwidth as large as the laser linewidth. Our study further validates the pump laser model used in some recent cw SC generation simulations [3].

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