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Cavity dispersion management in continuous-wave supercontinuum generation

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Abstract: Supercontinuum generation using continuous-wave pumping is usually obtained by pumping a suitable fiber with a high-power fiber laser. Whereas many studies have concentrated in optimizing the dispersion characteristics of the nonlinear medium (the fiber) used to obtain the spectral broadening, very few have actually concentrated in optimizing the pump laser characteristics, and in particular, the dispersion in the cavity. In this paper we experimentally demonstrate that the fiber laser cavity dispersion has a strong influence in Raman fiber laser-pumped continuous-wave supercontinuum generation. We show that anomalous dispersion in the cavity favors spectral broadening over normal dispersion, since large, high-contrast intensity noise appears at the output of the laser. Additionally, we find that there is an optimum value of chromatic dispersion coefficient to obtain the most efficient broadening.

OCIS codes: codes: (190.4370) Nonlinear optics, fibers ; (190.4380) Nonlinear Optics, Four-wave mixing ; (190.5530) Pulse propagation and solitons ; (060.3510) Lasers, fiber .

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1. Introduction

Continuous-wave supercontinuum (CW-SC) generation in optical fibers has attracted much attention in the past few years for the possibility of developing compact, high-quality sources for ultrahigh resolution optical coherence tomography [1]. Among their good properties, these sources exhibit very low coherence lengths (allowing resolutions of only several micrometers), high-power spectral densities (normally in the order of several milliwatts per nanometer), and lower values of relative intensity noise than their pulsed counterparts. Additionally, nonlinear pump spectral broadening of continuous-wave (CW) beams has been demonstrated as an effective tool to develop spectrally flattened Raman amplifiers[2].

The seed that starts the broadening process of the CW beam is the incoherence of the source used as the pump [3, 4]. The quasi-CW input beam develops into a train of subpicosecond pulses induced by the modulation instability (MI). These subpicosecond pulses lead to the formation of optical solitons with inherently random parameters, which self-frequency shift differently depending on their characteristics. The resulting supercontinuum spectrum is hence the average of many different soliton spectra, which have suffered different frequency shifts.

Two obvious ingredients are therefore important in the generation of a CW-pumped supercontinuum source: the pump laser incoherence and the chromatic dispersion of the fiber. While many studies have concentrated in optimizing the chromatic dispersion of the fiber from several viewpoints [5, 6, 7], only few studies have actually concentrated in searching the best pump laser characteristics. In a previous study [8], it was shown that an optimum degree of pump incoherence yields the best performance in the broadening process: for a given mean input power of the pump source, some incoherence is necessary to initiate the spectral broadening, but too much incoherence quenches the MI gain bands and inhibits the broadening process.

In this paper we investigate experimentally the dependence of the supercontinuum spectrum on the dispersion in the fiber laser cavity. We show that the cavity dispersion plays potentially a key role in enhancing CW-SC development. In particular, we show that having anomalous dispersion in the cavity favors the appeareance of fast intensity instabilities with high contrast, which in turn favor the broadening process. Additionally, we show that there is an optimum value of anomalous dispersion coefficient that yields the most efficient broadening.

2. Experimental setup

The experimental setup used in this work is depicted in Fig. 1. The setup is basically comprised of a home-made Raman fiber laser and a dispersion-shifted fiber that acts as the nonlinear medium. The output of both the laser and the supercontinuum are characterized temporally by means of an autocorrelator and spectrally by means of an optical spectrum analyzer (OSA). The power of the laser and the supercontinuum is also monitored in all the cases by means of an integrating sphere radiometer.

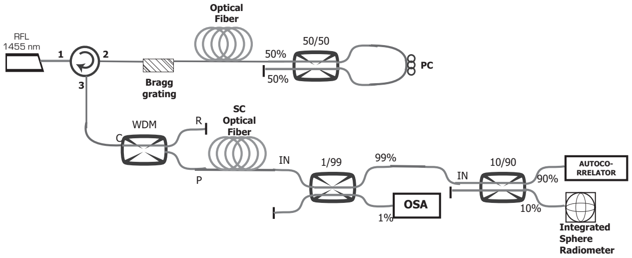

Fig. 1. Experimental setup for the SC generation in a 11 km of DSF fiber, pumped by a Raman Cavity Laser. RFL: Raman fiber laser, WDM: wavelength division multiplexer (port R: 1450-1480 nm, port P: 1528-1563 nm, port C: all wavelengths), PC: polarization control, OSA: optical spectrum analizer.

A typical design of a Raman fiber laser consists on a pump laser and a nested linear cavity of fiber Bragg gratings [9, 10, 11]. In our case, the design of the cavity is slightly modified to optimize the laser efficiency. One end of the cavity consists on a loop mirror designed with a $50/50$ optical coupler and a polarization controller. Due to the short length of the fiber coupler arms (less than 1 m) and the identical coupler relation, this mirror works as a perfect mirror with 100% reflectivity. In the other end of the cavity we introduce a conventional fiber Bragg grating. The grating has the maximum reflectivity at 1554.28 nm, with a spectral width at half maximum of $\sim$1 nm. The maximum reflectivity of the grating is 80%. Between the fiber Bragg grating and the fiber loop we introduce some kilometers optical fiber which act as the Raman gain medium. The fiber in the cavity is changed in the different tests, but the rest of the experimental setup remains the same.

To pump this cavity we use a commercial continuous-wave Raman fiber laser, with the center wavelength at 1455 nm and a maximum output power of 2.4 W. The spectral width at 20 dB from the peak is $\sim$1 nm. This laser is fed into the cavity through an optical circulator. The value of relative intensity noise (RIN) of the laser is -110 dBc/Hz.

To generate the supercontinuum, we use 11 km of dispersion-shifted fiber after the Raman laser. The zero-dispersion wavelength of this fiber is at 1553.2 nm, and the dispersion slope is 0.056 ps/nm/km. Since the laser emission is centered in 1555 nm, the propagation is, in all cases, in the region of small anomalous dispersion of the fiber.

3. Results

3.1. Normal or anomalous dispersion regime in the cavity

First of all we choose two different fibers (F1 and F2) which are tested in the Raman laser cavity. Their characteristics appear in table 1.

Fibers F1 and F2 are chosen so as to have the same product γL_{eff} (within the uncertainty of our measurement of γ). This ensures that (1) the nonlinear phase shift is equal for the same input pump powers (2) the threshold is very similar for both fibers and (3) very similar values of P_{Stokes} are obtained for the same input pump power. The main difference between them is that they exhibit a different dispersion regime at the lasing wavelength (1555 nm). F1 exhibits anomalous dispersion at 1555 nm while F2 shows normal dispersion. In Figs. 2(a) and (b) we depict the spectra at cavity output for these two fibers. In Figs. 2(c) and (d) we depict the

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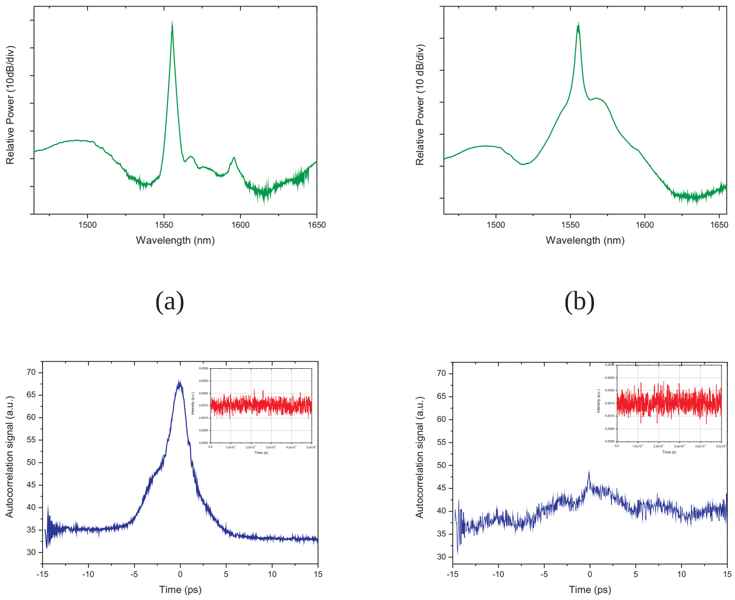
Table 1. Characteristics of the different fibers used in the experiments. D is the dispersion coefficient at the lasing wavelength

Fiber	**F1**	**F2**
L(km)	19	11
λ_0 **(nm)**	1315	1559.6
D **(ps/nm/km)**	16.9	-0.55
γ **($W^{-1}km^{-1}$)**	1.3	2.2
γL_{eff} **(W^{-1})**	24.7	24.2

autocorrelation traces at the cavity output for these two fibers. The insets 2(c) and (d) are a representation of the typical intensity output obtained for these two cases. These traces have been acquired with a digital oscilloscope with 2.5 GHz bandwidth and a fast InGaAs detector with a bandwidth of 1.5 GHz. The output power of the cavity is around 400 mW for all the cases.



(a) (b)

(c) (d)

Fig. 2. Spectra (a) and autocorrelation traces (b) of the output of the Raman cavity for Fiber F1 and Fiber F2.

We can observe that for Fiber F1 the output spectrum is relatively narrow ($\sim$ 4.8 nm at 20 dB from the peak), but the autocorrelation trace shows high-contrast intensity oscillations with a duration of several ps. On the contrary, for F2 the spectrum is broadened considerably with respect to the previous case (7.3 nm spectral width at 20 dB) but the autocorrelation trace appears reasonably flat. The higher efficiency in spectral broadening in F2 is due to the higher efficiency of the four-wave mixing processes between the lasing modes in this fiber (which has a dispersion very close to zero) [10, 12]. However, the most relevant fact for supercontinuum generation is that for F2 the autocorrelation trace does not record significant intensity oscillations, while for F1 these oscillations exhibit high contrast (the peak is twice the background, consistent with 100% contrast intensity oscillations). We attribute this intensity noise to modulation instability inside the cavity. Previous models of Raman fiber laser dynamics [12, 13] mainly attributed the spectral broadening to pure four-wave mixing, dependent basically on the strength of dispersion, without explicitly highlighting the importance of the sign of the dispersion. Our experimental results seem to indicate, however, that the sign of the dispersion is very relevant. When the power of the CW wave in the cavity reaches a certain value, modulation instability appears and breaks the CW train into short picosecond pulses. Under the adequate pumping conditions, one can obtain solitons, as in the Raman soliton ring laser [14]. These lasers were widely investigated in the 80's and early 90's, normally using synchronous pulsed pumping. The only difference between our laser and the lasers described previously is the type of cavity and that our laser is pumped with a purely CW laser. However, the underlying physical principle to obtain the self-pulsing remains the same.

Additionally, one may wonder if the cavity output is somehow mode-locked, or if some kind of passive mode-locking is at the origin of the intensity oscillations. As we can see in the insets of Fig. 2, for both cases (F1 and F2) we can observe no periodic intensity structure in the oscilloscope trace. Additionally, if the oscillations were of higher frequency than the detector bandwidth, the spectrum in the OSA would appear discretized (the resolution of the OSA is set to 10 pm, roughly 1.14 GHz at 1550 nm). Since this is not the case, we can conclude that our laser output is not mode-locked, and that the intensity oscillations at the output are basically chaotic. Interestingly, the relative intensity noise of the laser with Fiber F2 seems larger, since the quotient of the rms noise with the mean value appears to be higher for F2. This indicates that the laser with F2 in the cavity does exhibit intensity instabilities, but in a much longer time scale (therefore not visible to our autocorrelator) and probably with less contrast. Possibly in this case the oscillations are strictly related to dissipative four-wave mixing in the cavity, but not MI.

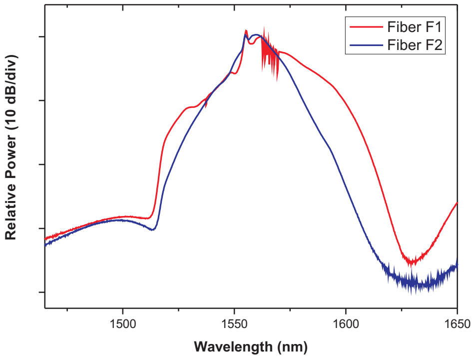


Fig. 3. Output spectra of the supercontinuum generated by pumping 11 km of DSF with the output of the Raman cavities built with Fibers F1 and F2.

Considering that fast, high-contrast intensity oscillations appear at the output of the laser for F1 and not for F2, we should expect that the supercontinuum generated with F1 in the cavity would be much broader than with F2 in the cavity for the same laser power. The results of supercontinuum generation with F1 and F2 in the cavity are plotted in Fig. 3, both for 400 mW of Stokes power and 2.1 W of pump power. As expected, the supercontinuum obtained with

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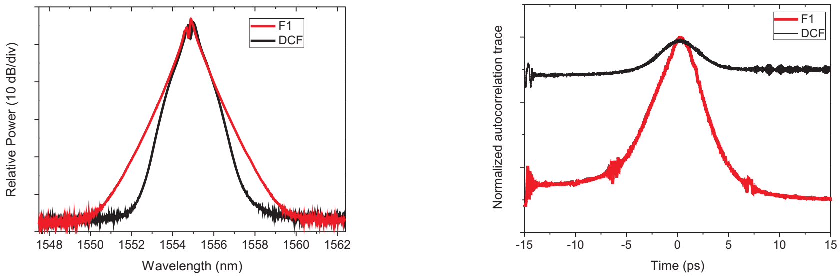
F1 in the cavity is much broader, both on the red and blue-shifted parts. We may distinguish which is the main driving process behind the supercontinuum by estimating the soliton order of the pulses injected in the fiber. Considering a peak power of the intensity oscillations of 800 mW (twice the mean, consistent with the autocorrelation trace), and the duration of the pulses estimated from the autocorrelation trace, we can conclude that we are injecting in the fiber pulses with soliton order well over 1, and therefore soliton fission is the main motor of the supercontinuum in this case. On the contrary, for F2 the main driving force must be plain MI, since the intensity noise is not of high-contrast.

To further verify our arguments, we inserted a 5.7 km-long dispersion compensating fiber with much larger normal dispersion coefficient (D=-100 ps/nm/km@1550 nm). The losses in this fiber are 0.28 dB/km and the γL_{eff} product is around 20 W^{-1}. In terms of efficiency, the results are not very comparable to the previous ones obtained with fibers F1 and F2 given above since the slope efficiency of the laser with the DCF in the cavity turns out to be quite reduced (the threshold is also reduced). Thus, at the pumping power of 2.1 W we obtain only 190 mW at the output, which is comparable to the output power that we obtain with fiber F1 for only 1.8 W. However, if we effectively do this comparison (same output power in both cases, set to 190 mW), we can register the results seen in Figs. 4(a) and 4(b). As it is visible, the output spectra obtained with the DCF and with F1 in the cavity closely resemble in terms of spectral width at 3 and 10 dB from the peak. The only difference in the spectrum is that with F1 the spectrum shows a somewhat broader pedestal. However, the autocorrelation traces change much more dramatically. As it can be seen in Fig. 4(b), the intensity oscillations at the output are of much higher contrast with F1 than with the DCF in the cavity. This reinforces the arguments given above, claiming that anomalous dispersion seems to favour the appeareance of high-contrast oscillations at the laser output.



(a) (b)

Fig. 4. Spectra (a) and autocorrelation traces (b) of the output of the Raman cavity for Fiber F1 and Fiber DCF.

3.2. *Optimization of the dispersion value*

It seems clear that the efficiency in SC generation is considerably higher when the cavity dispersion is anomalous. This is due to the appearance of intensity oscillations in the laser output. There is a second question to solve now, which is whether we can optimize the value of the cavity dispersion so as to maximize the broadening efficiency. The reason is clear: by varying the cavity dispersion in the anomalous dispersion regime we can modify the parameters of the output intensity oscillations. If the dispersion coefficient is small, the cavity should deliver shorter oscillations with higher mean frequency, while for larger dispersion, the oscillations should be longer and with lower mean frequency.

To see what values of dispersion make the optimum broadening, we perform the same supercontinuum experiment with Fibers F3, F4 and F5 in the cavity. The characteristics are shown in table 2.

Table 2. Characteristics of the different fibers used in the experiments. D is the dispersion coefficient at the lasing wavelength

Fiber	**F3**	**F4**	**F5**
L(km)	8.6	4.5	4.9
λ_0 **(nm)**	1313	1503.9	1540.9
D **(ps/nm/km)**	20.38	4.29	0.51
γ **(**$W^{-1}km^{-1}$**)**	1.3	1.9	2.1
γL_{eff} **(**W^{-1}**)**	9.1	9	9.3

Again, they are chosen so as to have roughly the same product γL_{eff} and different dispersion coefficients at 1550 nm. For the experiments with these three fibers the output power of the cavity is ∼400 mW too. The spectra at the laser output are shown in Fig. 5.

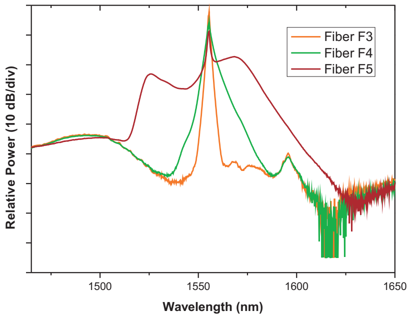


Fig. 5. Output spectra of the fiber laser with fibers F3, F4 and F5 in the cavity

We can see that, as the dispersion in the cavity is smaller, the spectral width of the laser becomes larger (again, consistent with intracavity four-wave mixing). At 20 dB from the peak, the spectral widths of the laser for fibers F3, F4 and F5 in the cavity are 1.8 nm, 5.8 nm and 61.8 nm, respectively. The autocorrelation traces are also shown in Fig. 6. As it can be seen, the intensity fluctuations become shorter as the dispersion is smaller. The temporal width of the intensity fluctuations at full width at half maximum (FWHM) is around 3.2 ps for the Fiber F3, 2.2 ps for the Fiber F4 and 213 fs for the Fiber F5. The insets show the oscilloscope traces obtained as in the previous case for fibers F1 and F2. Considering the above reasoning, we can again say that the laser that we develop is not a mode-locked laser.

The results of supercontinuum generation with these sources are plotted in Fig. 7. The results seem surprising because the broadest spectrum does not correspond to the shorter intensity fluctuations at the input. The best broadening results are obtained with Fiber F4, which has an intermediate value of dispersion. Using the same reasoning with the soliton order used in the previous section, we can conclude that soliton fission is the main driving force behind SC generation in the cases of Fiber F3 and F4 (N>>1). On the contrary, for F5 we are very close to N=1 or even below, and therefore we can not expect soliton fission in this case.

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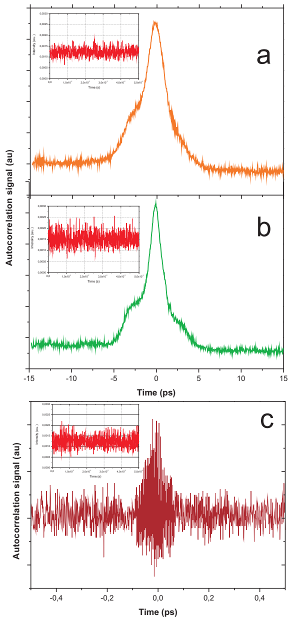

Fig. 6. Autocorrelation traces of the fiber laser with fibers F3 (trace a), F4 (trace b) and F5 (trace c) in the cavity.

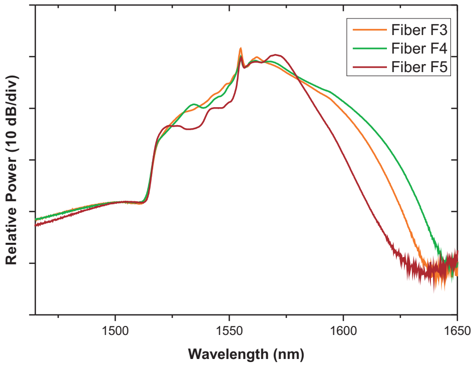

Fig. 7. Output spectra of the supercontina generated pumping 11 km of DSF with fibers F3, F4 and F5 in the Raman fiber laser cavity

To get some more insight into this result, we measure the autocorrelation traces of the supercontinua obtained with F3, F4 and F5 in the cavity. The temporal widths at full width at half maximum (FWHM) obtained with F3, F4 and F5 in the cavity are 176 fs, 164 fs and 288 fs respectively. As we can see, the shortest feature corresponds to the wider supercontinuum, but this shortest feature does not correspond to the shortest trace at the fiber input.

The results can be explained by the CW supercontinuum dynamics [3, 4]. When the light signal from a partially coherent beam propagates in an optical fiber in the anomalous dispersion regime, the intensity instabilities of the pump lead (normally through modulation instability) to soliton fission if they are energetic enough. However, if they are not powerful enough, the instabilities simply suffer dispersion. In our case, the intensity fluctuations at the output of the lasers built with F3 and F4 in the cavity are relatively long (several ps), but energetic enough to lead to soliton fission. For Fiber F5, the laser fluctuations are shorter and the peak power is the same, and therefore the fluctuations are less energetic, so they cannot lead to further soliton fission and pulse compression in the supercontinuum fiber. Thus, in this case, the intensity fluctuations are simply broadened because of dispersion at the fiber output, while they were strongly shortened for the cases of F3 and F4.

Qualitatively speaking, the rule to optimize the cavity dispersion seems to be roughly the same rule as in conventional dispersion management for supercontinuum generation [5]: overall, the dispersion should be decreasing all along the propagation (including the cavity), and the dispersion steps should not be too high. This should ease soliton fission and also favor pulse compression along the fiber.

4. Conclusion

In conclusion, we have shown the importance of the cavity dispersion in continuous-wave Raman fiber laser-pumped supercontinuum generation. It is shown that anomalous dispersion in the cavity favors the broadening over normal dispersion, since the intensity oscillations at the output of the laser are considerably larger. Additionally, we find that there is an optimum dispersion to obtain the most efficient broadening.

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