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Experimental investigation on the effect of pump incoherence on nonlinear pump spectral broadening and continuous-wave supercontinuum generation

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The development of high-power continuous-wave fiber lasers has triggered a great interest in the phenomena of nonlinear pump spectral broadening and continuous-wave supercontinuum (SC) generation. These effects have very convenient applications in Raman amplification, optical fiber metrology and fiber sensing. In particular, it was recently shown that pump incoherence has a strong impact in these processes. In this paper we study experimentally the effect of pump incoherence in nonlinear pump spectral broadening and continuous-wave supercontinuum generation in optical fibers. We show that**, under certain experimental conditions,** an optimum degree of pump incoherence yields the best performance in the broadening process. We qualitatively explain these results and we point out that these results may have important implications in continuous-wave supercontinuum optimization.

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Nonlinear spectral broadening and supercontinuum (SC) generation in optical fibers have been the subject of many studies in the last years. To date most of the experiments have been performed using high peak power nanosecond, picosecond or femtosecond pulses and/or special fibers such as photonic crystal fibers[1] or dispersion-tapered fibers.[2]

Continuous-wave (CW) SC generation in optical fibers has attracted much attention in the last years for the possibility of developing compact, high-quality sources for ultrahigh resolution optical coherence tomography. Among their good properties, these sources exhibit extremely low coherence lengths (allowing resolutions of only several micrometers), high power spectral densities (normally in the order of several mW/nm) and lower values of relative intensity noise (RIN) than their pulsed counterparts.[3,4] More recently, nonlinear pump spectral broadening of CW beams has been demonstrated as an effective tool to develop spectrally flattened Raman amplifiers.[5]

Previous experiments on CW spectral broadening and supercontinuum generation have been performed both in standard telecommunication fibers[6,7] and in highly nonlinear holey fibers.[8] However, until recently, little effort had been done to clarify the dynamics of the process, and in particular the remarkable smoothness of CW SC spectra. Recent papers have shown that these unique spectral features stem from the fission of the "quasi" continuous-wave input beam into a train of sub-picosecond pulses induced by the modulation instability (MI).[7,9,10] These sub-ps 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. These works showed that the seed that starts the broadening process is the incoherence of the source used as pump. Hence, a certain amount of pump incoherence is necessary to trigger the modulational instability-induced broadening process. However, it has been shown theoretically that the partial coherence of the pump tends to stabilize the growth rate of the instability and, for a certain value of incoherence, the instability is completely quenched.[11] Hence, an experimental investigation on these effects seems necessary to clarify the role of pump incoherence in nonlinear spectral broadening and CW SC generation. In this paper we show experimentally, that **under certain experimental conditions (namely for a given value of the mean input**

power and center wavelength of the pump source used) there is an optimum value of pump incoherence that yields the most efficient spectral broadening.

To investigate on the importance of pump incoherence on CW SC generation, we construct three different experimental setups. The objective is to get three CW pump sources with exactly the same emission wavelength and optical power characteristics but with different spectral widths. We use these sources to pump a cascade of suitable optical fibers (the same for the three cases) where they were effectively broadened to produce three CW SC spectra.

The structure of the sources used is shown in figure 1. Source (a) is based on a fiber ring laser based on erbium-doped fiber amplifiers (EDFAs) and a fiber Bragg grating (FBG) filter. The central wavelength of the laser appears at 1553.5 nm, and the spectral width of the laser is less than 0.02 nm. The optical power obtained at the output of the 1/99 coupler is tuned to 200 mW. Source (b) is essentially similar in structure, except for the fact that the filter used in this situation is a thin film filter whose pass-band spectrum is ten times wider than the spectrum of the FBG. The output power and emission wavelength of this new source are essentially similar to the ones achieved with source (a), but the spectral width is approximately ten times wider (0.22 nm). Source (c) is composed of a light emitting diode whose broadband emission is amplified and filtered by the filter used in source (b). The output of the filter is re-amplified by a chain of EDFAs up to the power level achieved in the previous sources. At the output of the 1/99 coupler, the power and emission wavelength of source (c) are essentially the same as sources (a) and (b), except that the spectral width is that of the filter used, approximately 1 nm. The polarization both inside and outside of the ring is controlled, so as to ensure that the same conditions of light injection apply for the three structures used. **By means of a fast detector and an oscilloscope, we observed that no temporal intensity structure appeared in any of the three sources used.**

To obtain nonlinear pump broadening and SC generation, it is necessary to use a fiber with several kilometers and raise the power of the pump source up to the watt level. To obtain an appropriate pump power to generate SC emission, we use a Raman amplifier that works in a regime of strong depletion. This amplifier consists of a 6 km long standard single-mode fiber (SMF) and a suitable wavelength division multiplexer. The pumping of the Raman amplifier is done by means of a Raman Fiber Laser **(RFL)** tuned at 1455 nm, and whose power is tunable between 0 and 2.1 W. **The amplifier is configured in co-propagation to obtain the highest degree of power transfer between the RFL and the signal at 1550 nm. The RFL exhibits random temporal intensity structures in the order of 100 ps, verified through autocorrelation measurements.[9] However, these structures should not be imprinted in the 1550 nm signal since there is a large walk-off in the SMF between the pump at 1455 nm and the signal at 1550 nm (around 9 ns).** The spectra of the pump signal before and after the SMF are shown in figure 2, both spectra measured with an Optical Spectrum Analyzer (OSA) with a resolution of 10 pm. For these measurements the RFL was switched off, so that there is no amplification of the pump beam along the SMF. Since the propagation along the SMF is done well in the region of anomalous dispersion, modulational instability should occur but with a narrow spectrum. In fact, the signature of modulational instability at the output of the SMF is clear through the presence of two symmetric noise bands in the case of source (a). We can also recognize this feature in source (b), but this is by no means recognizable in the case of source (c). As the RFL power is increased, more power is transferred to the wavelength at 1553.5 nm. At full power (2.1 W), the pump wavelength at 1553.5 nm has a power of 0.9 W, regardless of the actual source used in the experiment (a, b or c).

The output of the SMF is delivered into a dispersion-shifted fiber (DSF) whose zero dispersion wavelength appears at 1553.2 nm. Hence, the propagation of the pump beam in this fiber is performed in the region of small anomalous dispersion. In these conditions one should expect the buildup of broad MI gain bands at each side of the pump spectrum (see figure 3(a)). As the power of the RFL is raised, more power is transferred to the line at 1553.5 nm and the spectral broadening process becomes increasingly efficient. For a RFL pump power of 2.1 W, the spectra of the SC emission obtained in the three cases are depicted in figure 3(b). We can see that the widest spectrum is obtained for source (b), hence the one with intermediate spectral width, whereas pump broadening is strongly inhibited with source (c) due to its large incoherence. As explained above, **for a given mean input power of the pump source,** some incoherence of the pump source used in SC generation is necessary to initiate the spectral broadening, but too much incoherence quenches the MI gain bands and inhibits the broadening process. **For broader bandwidth pumps, which exhibit shorter temporal structures, we can expect that larger powers will be required for the evolution of the MI-amplified noise into solitons. Equivalently, we can expect that for higher pump powers the optimum spectral width will grow since broader bandwidths should yield shorter temporal structures, which require more power to build-up**.

On the other hand, it is interesting to observe the behavior of the shorter wavelength part of the SC spectrum. While shifting their wavelengths, the Raman solitons described above (that compose the longer-wavelength part of the SC spectrum) shed away some blue-shifted radiation in the form of dispersive waves,[9] which explains the generation of the blue-side of the continuum. It is interesting to note that this feature appears to be more developed in the case of the more incoherent pump.

In figure 3(b) we can also observe a spectral peak appearing at a wavelength of 1660 nm. The power of this peak is the same for the three sources, and it is the consequence of the Raman-assisted four wave mixing process among the Raman fiber laser wavelength (tuned at 1455 nm) and the center wavelength of the sources (all of them tuned at 1553.5 nm).

In conclusion, we have demonstrated that the supercontinuum spectra generated with sources of identical **mean output power and center wavelength** but different spectral widths are considerably different in terms of width and morphology. Moreover, we have demonstrated experimentally that **under certain experimental conditions** there exists an optimum value of pump incoherence that leads to the most efficient spectral broadening. We believe that this is an important variable to take into account in the engineering of CW SC sources.

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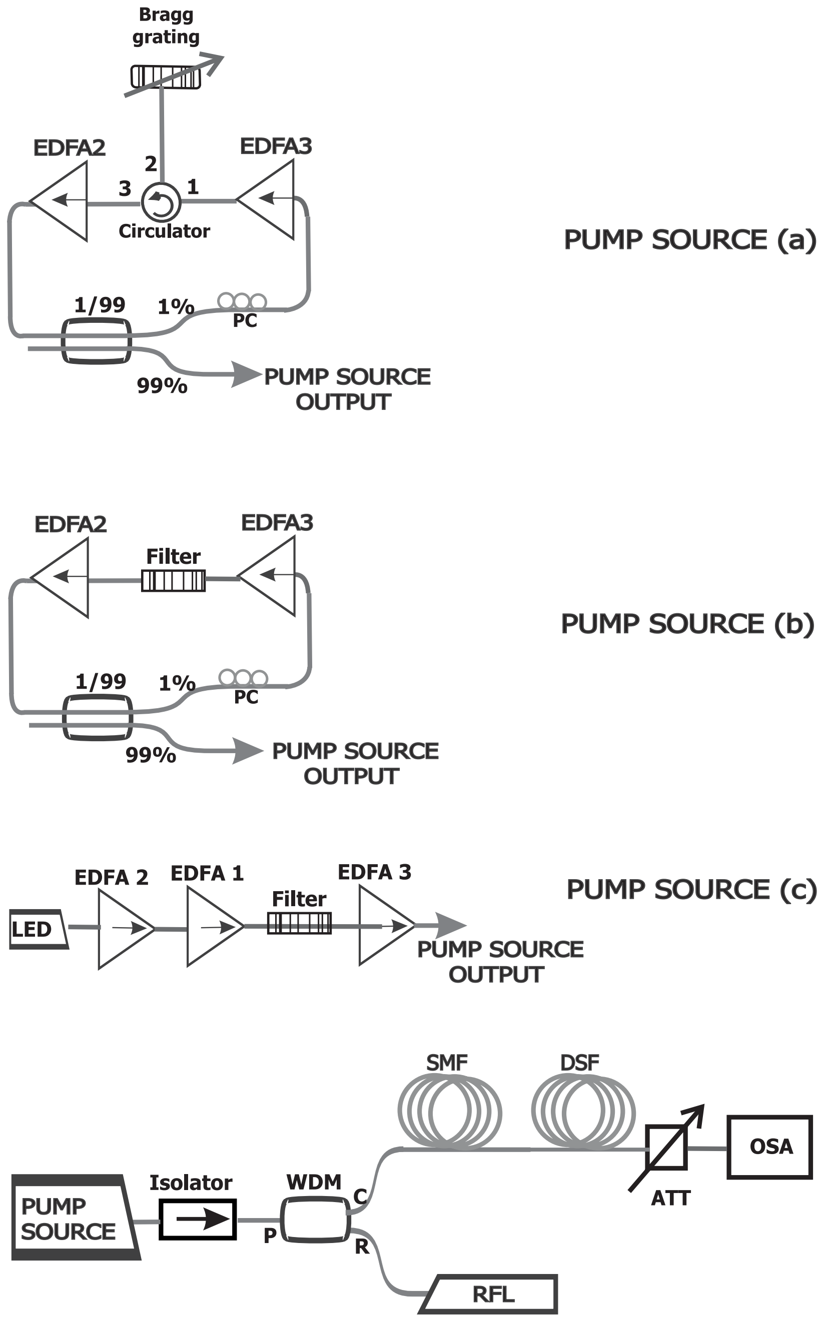
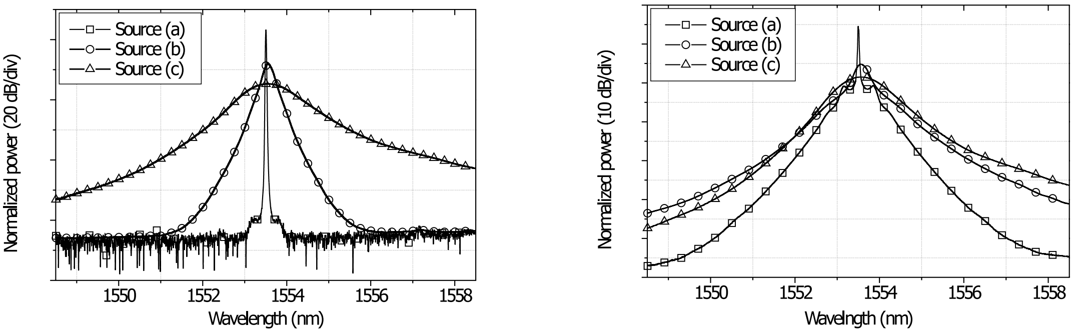
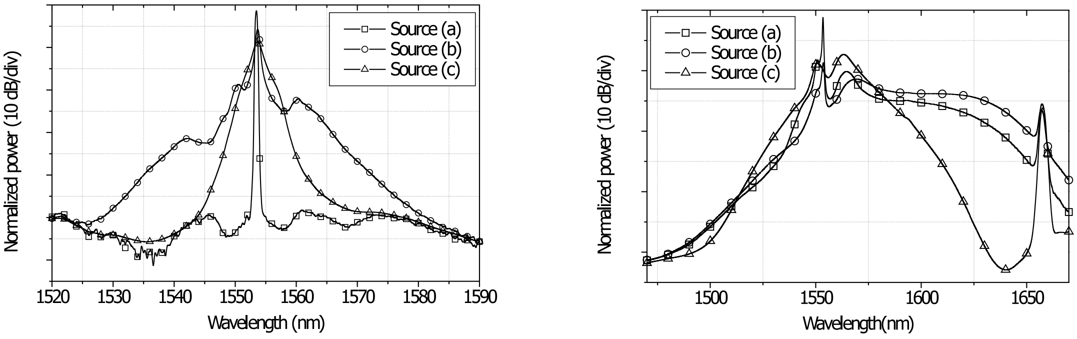


Figure 1. Experimental setup for the generation of CW SC with the following pump sources with different spectral whidths: (a)a ring laser with a linewidth of 0.02 nm; (b)a ring laser with a linewidth of 0.22 nm; and (c)three EDFAs, with a linewidth of 1 nm. PC: Polarization Control; WDM: Wavelength Demultiplexer; ISO: isolator; SMF: fibra estándar; DSF: dispersion shifted fiber; ATT: optical tunable attenuator; OSA: Optical Spectrum Analizer; RFL: Raman Fiber Laser.



(a) (b)

Figure 2. Spectrum of the three pump soures with different coherence, of the experimental setups of figure 1: (a)adquired at the input of SMF, (b)adquired at the output of SMF.



(a) (b)

Figure 3. (a)Spectrum of the three pump soures with different coherence, of the experimental setups of figure 1, adquired at the end of DSF, without Raman amplification. (b)Spectrum of the SC generated with the three pump soures with different coherence, of the experimental setups of figure 1 amplified by Raman (RFL pump power = 2.1W).