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Broadband spectrally flat and high power density light source for fiber sensing purposes

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Abstract. We present a new kind of broadband continuous-wave source which outperforms any other broadband superluminescent or amplified spontaneous emission source both in terms of output spectral density and bandwidth. Our source covers the wavelength band of interest for fiber applications (from 1450 to 1625 nm) and has an output power of approximately 1.3 W. The source is obtained by pumping a conventional nonzero dispersion-shifted fiber with a continuous-wave Raman fiber laser tuned to the region of small anomalous dispersion of the fiber. The laser beam undergoes an extreme spectral broadening in the fiber. Our experimental results show clearly that modulation instability (MI)-induced soliton fission is the key element leading to this spectral broadening. Modulation instability is seeded by fast intensity instabilities present in the laser output. We show that this source features a good power stability and we believe it might have very interesting applications in fiber sensing, for instance to avoid the need of amplification in the interrogation of remote Bragg gratings or to improve the resolution and dynamic range of optical coherence tomography setups.

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1. Introduction

White light sources are indispensable in many fiber sensing setups, for instance in low-coherence interferometry [1], interrogation of fiber Bragg grating sensors [2], or fiber-optic gyroscopes [3]. High-power superluminescent light-emitting diodes (SLED) [4] and superfluorescent sources [5] are the main broadband sources used for optical sensing. Typically these sources have bandwidths in the order of 20-80 nm with power spectral densities ranging from -20 to 0 dBm/nm. In this paper we present a new kind of broadband source that outperforms any other superluminescent or superfluorescent light source both in terms of spectral density and bandwidth. This source is based on supercontinuum generation in an optical fiber.

A supercontinuum light source is a broadband source obtained as the result of the broadening of a spectrally narrow source in a non linear medium. Most supercontinuum light sources described in the literature up to now have been built using pulsed lasers of high peak power and short lengths of nonlinear media. Our new light source is based on delivering the ~ 2 W, partially coherent output of a continuous-wave Raman fiber laser (RFL) into a relatively long (6.8 km) non-zero dispersion shifted fiber (NZDSF). The wavelength of the RFL lies in the region of small anomalous dispersion of the fiber, thus triggering a series of processes leading to an extreme broadening of the RFL linewidth [6]. In particular, the main cause of this extreme spectral broadening is the modulation instability (MI) effect, which results from the interplay between the fiber Kerr effect and the anomalous dispersion. The MI effect leads to the fission of the partially-coherent input cw beam into a sequence of Raman-shifted solitons [6, 7].

Extreme broadening of coherent light sources had always been achieved with pulsed lasers of high peak power (see, for instance, ref. [8]). Now, high power RFLs allow to achieve supercontinuum generation using cw pumping. This considerably simplifies the pumping scheme, and many new applications for this source can be thought of. Some very important properties of our broadband source are its extremely wide spectrum (> 200 nm), its large spectral density (> 0 dBm/nm) and its short and long-term stability which are some orders of magnitude better than pulsed-pump supercontinuum sources. Additionally, the spectrum of the source is extremely smooth, a feature that was unobserved in pulsed-pump SCs. These properties make our source suitable for fiber sensing purposes and specially indicated in optical coherence tomography either for ultrahigh-resolution setups or full-field imaging (for a general view of the main challenges in OCT nowadays see ref. [9]).

This paper is divided as follows: in section 2 we will thoroughly explain the experimental construction of our source and we will present its basic spectral and temporal characteristics. In section 3 we will show its main features in terms of stability and noise. We will show, for the first time to our knowledge, a fully detailed experimental study of the noise properties of a cw-pumped SC source. This study shows that the relative intensity noise (RIN) of this kind of sources is thoroughly better than that of pulsed-pump SCs, and that its spectral dependence is smooth. This fact makes the cw

SC source even more appealing for OCT setups in which the low noise of the source is a stringent requirement. Finally, in section 4 we will summarize the conclusions of our work.

2. Continuous-Wave Supercontinuum Source

Continuous-wave supercontinuum generation in fibers results from the fission of a partially coherent cw beam into a sequence of Raman-shifted solitons. For this phenomenon to take place, some intensity oscillations need to be present in the pump. These intensity oscillations are amplified due to the well-known mechanisms of modulational instability [10] and lead to multisoliton generation. Thus, in cw SC generation, the partially coherent nature of the pump is an essential ingredient.

The pump used in our experiment was a continuous-wave Raman Fiber Laser (RFL) tuned at 1455.3 nm. This laser (Keopsys model KPS-BT2-RFL) is a cascaded Raman fiber laser pumped by a 1.1 μm Yb-doped fiber laser. The laser output is depolarized and the maximum output power reaches 2.1 W. We monitor this power with a special integrating sphere radiometer with a 1% uncertainty [11]. A feedback control ensures that the output power of the RFL remains constant and controlled with an accuracy of 10 mW. Figure 1 shows the spectrum of the RFL alone for different power levels. The spectrum of the RFL shows clearly one of the resonances of the laser at 1365 nm. This resonance is effectively suppressed at the laser output (side mode suppression ratio is 20 dB). The temperature of the laser environment is controlled to ensure wavelength stability. As we can see in the inset of fig. 1, the line width of the RFL grows as the power

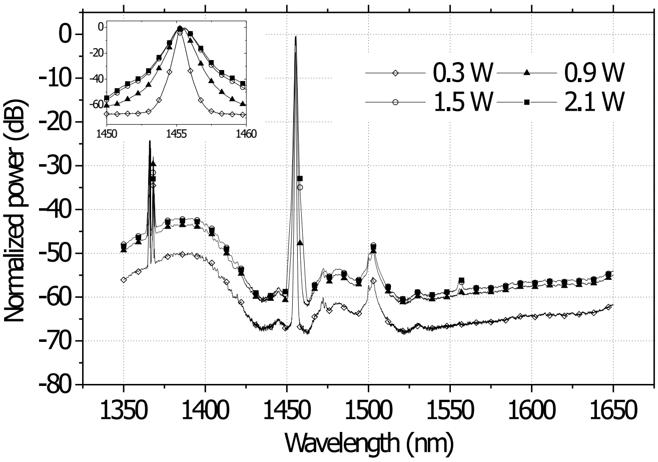

Figure 1. Normalized output spectrum of the RFL. The resolution of the spectrum analyzer used was set to 50 pm, and the sensitivity is better than -70 dBm. The inset shows in detail the spectrum around the pump wavelength. Note that the linewidth of the pump is larger as the power grows.

is increased. For a pump power of 2.1 W, the full width at half maximum (FWHM) of the laser output is 1.1 nm, which means that it has random phase and/or intensity variations in the frequency range of ∼150 GHz. We validate the presence of intensity perturbations at the laser output by measuring the intensity autocorrelation trace of the laser. To perform this measurement we use a home-made non interferometric autocorrelator which uses a BBO sheet as nonlinear medium. The obtained autocorrelation trace is shown in figure 2 for a pump power of 2.1 W. We can see that the autocorrelation signal has a peak that is roughly twice as strong as the cw background, which confirms that the output has intensity perturbations of high contrast and with durations around 100 ps [7, 12]. Furthermore, this is in good agreement with the measured spectral width of the laser.

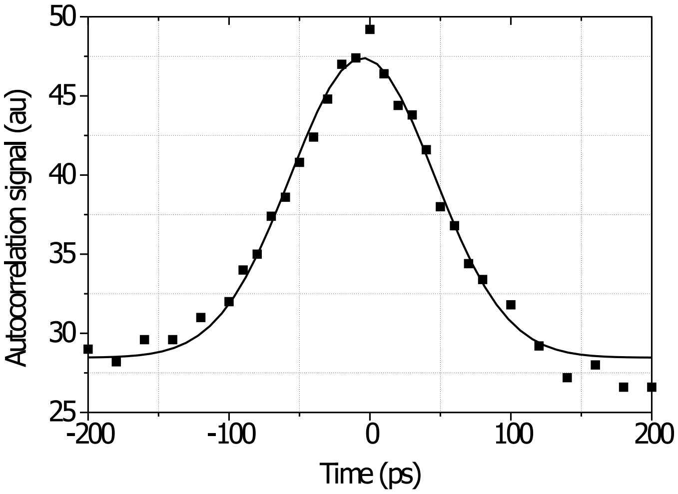

Figure 2. Intensity autocorrelation trace of the Raman Fiber Laser for an output power of 2.1 W. The squares represent the measured points and the solid line is a gaussian fitting. The width of the gaussian is 102 ps.

The Raman Fiber Laser is used to pump a 6.8-km-long spool of Truewave RS non zero dispersion shifted fiber (NZDSF) manufactured by Lucent, with a measured end-to-end zero-dispersion wavelength of approximately 1453.5 nm and a dispersion slope of 0.045 ps$\cdot$nm$^{-2}\cdot$km^{-1} (these measurements were performed using the conventional phase-shift method). Thus, the pump used in our experiment falls in the region of small anomalous dispersion of the fiber, and the expected dispersion coefficient at the wavelength of interest is roughly 0.081 ps$\cdot$nm$^{-1}\cdot$km^{-1}. The mode field diameter of the fiber is 8.4 μm at 1550 nm. In these conditions, modulation instability [6] is expected to arise at power levels in the order of hundreds of milliwatts, leading to a significant broadening of the partially coherent pump spectrum [13]. To ensure that the modulation instability effect is efficient, the spatial uniformity of the chromatic dispersion coefficient has to be preserved. The spatial uniformity of the chromatic dispersion coefficient along the fiber was measured using a method developed by some of us [14] and was found to be better than 0.1 ps·nm^{-1}·km^{-1} at the wavelength of 1555 nm (spatial resolution is 500 m). The fiber loss at the wavelength of 1550 is 0.2 dB/km, and it remains mostly flat in the range from 1450 to 1620 nm.

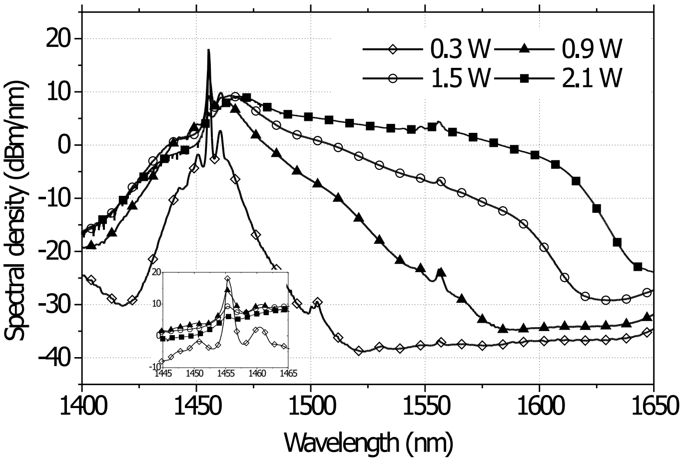

Figure 3. Spectrum of the generated supercontinuum. The settings are the same as in the previous figure. The inset shows how complete pump depletion is achieved for powers higher than 1.5 W.

Figure 3 shows the supercontinuum spectrum at the output of the NZDSF. At 300 mW, the effect of modulation instability (MI) is clearly visible as two nearly symmetric sidebands around the center frequency. The asymmetry between the two sidebands is caused by Raman amplification of the longer wavelengths and attenuation of the shorter ones. As the power at the fiber input grows, the spectrum of the supercontinuum becomes broader. For a power level of 2.1 W, the 20 dB bandwidth of the output supercontinuum is 207 nm (from 1410 nm to 1617 nm), with a peak power spectral density of approximately 7 mW/nm at 1470 nm ($\sim$ 8.5 dBm/nm). This effectively covers the S, C and L bands defined by the International Telecommunications Union. A further increase of the pump power would achieve a broader supercontinuum spectrum. Note that for power levels beyond 1.5 W, nearly complete pump depletion is achieved (the pump power is fully transferred to the supercontinuum). An outstanding feature of the SC spectrum is that it exhibits a very smooth spectral structure at all pump power levels and that it broadens very regularly with increasing pump powers. Such a smooth evolution is observed in all reported cw SC experiments [15, 16, 17, 18]. It is in contrast with what is observed in pico- or femtosecond continua that are usually characterized by the generation, broadening, and merging of individual spectral peaks, which typically leads to SC spectra with complex spectral structures [19, 20, 21, 22, 23].

We can describe the SC generation process as follows: MI is present in the first stages of pump broadening. While the partially coherent cw pump propagates along

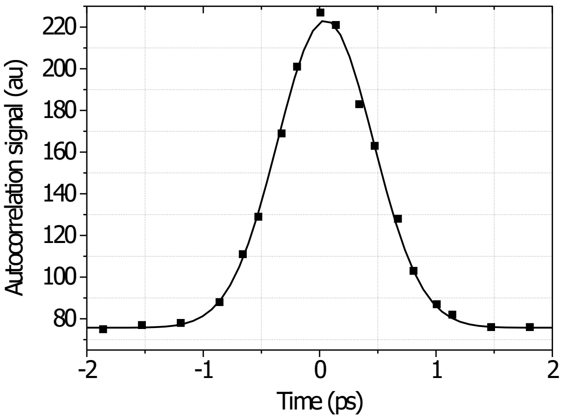

Figure 4. Intensity autocorrelation trace of the supercontinuum for a pump power of 2.1 W. Squares show the measuremed values and the solid line represents a gaussian fitting. The width of the gaussian is 820 fs

the fiber, the MI process amplifies the random temporal instabilities present in the pump intensity and breaks the partially coherent cw pump into a train of short temporal pulses. As the propagation is done in the anomalous dispersion regime, these short pulses might become solitons if their width is sufficiently narrow [6]. The propagation length needed to shape these solitons depends basically on the shape of the random initial fluctuations. If the fluctuations are sharper, the solitons are built earlier [7].

In addition, the Raman process causes a center frequency downshift of these solitons. This center frequency downshift is due to the fact that these ultrashort pulses have a wide spectrum. Raman scattering causes an amplification of the longer wavelengths of the spectrum at the expense of the shorter wavelengths. The amount of frequency downshift suffered by the solitons depends essentially on the fiber length along which they travel. For the solitons that are built earlier, the final frequency shift is larger. Since the intensity fluctuations present in the pump intensity at the fiber input are essentially random, the final spectrum of our supercontinuum source is the superposition of the spectra of many Raman-shifted solitons, each one having undergone a different frequency shift. A detailed numerical study of this process has been presented elsewhere [7].

To support our theory about the generation nature of our source, we acquire the intensity autocorrelation trace of our supercontinuum. Figure 4 shows that trace for a pump power of 2.1 W. We see that the autocorrelation trace shows a peak with much higher contrast and much shorter than the autocorrelation trace of the laser at the fiber input. This trace clearly shows that sub-picosecond solitons are the fundamental element of the output SC. These solitons have an average temporal width of approximately 0.8 ps.

3. Stability and Noise

Ones very important characteristics of our broadband source are its acceptable long-term stability and its very good noise characteristic.

We test the long-term stability of our new source by making repetitive measurements of the supercontinuum spectrum with 40 seconds intervals over approximately one hour (each measurement takes some 15 seconds). The standard deviation of the results from the mean supercontinuum spectrum is computed for each wavelength and normalized to the corresponding mean detected power. We can see the results in linear units in figure 5 (restricted to the wavelength range of the 20 dB SC width). We can see that the stability of the source is relatively flat and better than 1% around the pump wavelength (from 1410 to 1518 nm) while it grows slightly for the wavelengths of the first Raman order (around 1565 nm). Curiously, around these wavelengths there is a strong ripple in the standard deviation of the recorded traces. The origin of this ripple is difficult to explain, but it seems associated with the peak-like feature present in the supercontinuum spectrum around 1560 nm (see figure 3). This peak appears already in the pump spectrum and is possibly originated due to four-wave mixing processes within the RFL (see figure 1). For the longer wavelengths of the supercontinuum (>1600 nm) there is a strong growth of the standard deviation of the spectral density. An explanation of this behavior can be found if we track the evolution of the recorded power spectral density with time.

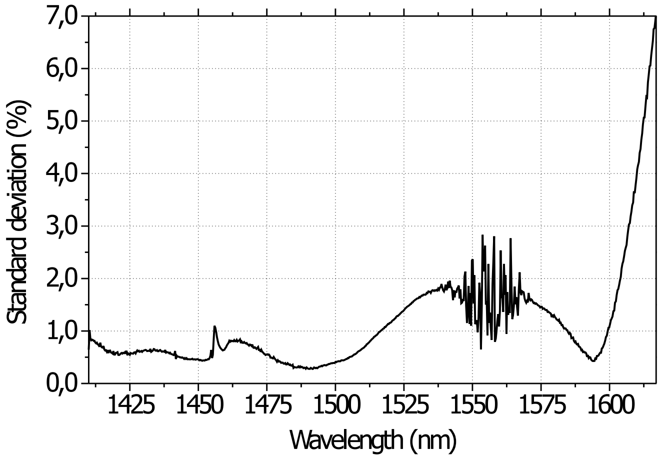

Figure 5. Standard deviation of the power detected for each wavelength, in linear units

In figure 6 we show in detail the evolution of the detected powers for three specific wavelengths over the one hour test. At 1480nm, the detected power remains stable within 0.03 dB. At 1565 nm, there is a positive drift in the detected power with time (+0.2 dB), while at 1615 nm (already in the limit of the 20-dB band) the detected power becomes smaller with time (-0.9 dB). While the overall power contained in the supercontinuum remains unchanged (this is checked by direct numerical integration of the different spectra acquired with time), a spectral redistribution of the power has happened. This gentle drift is not caused by wavelength changes in the RFL and neither by temperature changes of the fiber environment, since the fiber was properly isolated. Additionally, several consecutive tests have shown that the drift is repetitive. The origin of this small drift is unclear, but it might be related to some small intrinsic heating of the fiber due to the 0.6 watts of power lost by Rayleigh scattering in the fiber. This residual heating of the fiber would cause small changes in the fiber parameters (chromatic dispersion and nonlinear coefficient). Due to the special nature of the supercontinuum generation process, the edges of the supercontinuum are strongly sensitive to small changes in the chromatic dispersion coefficient, the nonlinear coefficient and the Raman gain of the fiber [7]. A close look at figure 6 suggests that the drift tends to diminish with time.

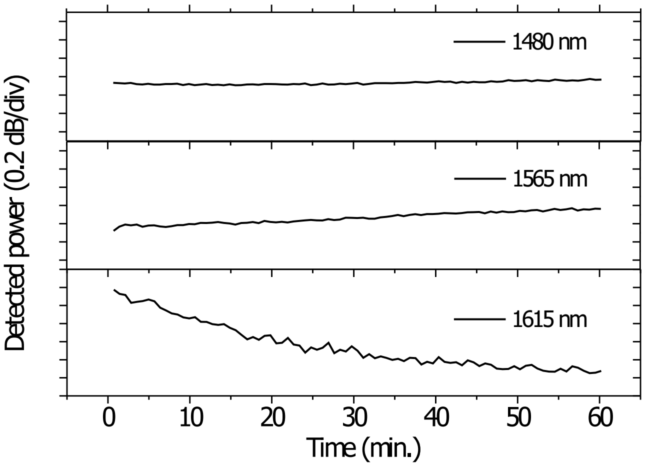

Figure 6. Evolution of the detected power as a function of time for three specific wavelengths.

To test the noise properties of the source, we measured the relative intensity noise (RIN) in our supercontinuum for several conditions. Our first test concerned the RIN of the pump laser itself, which gave a noise value of <-115.5 dBc/Hz for a pump power of 2.1 W (measured in the range 0-200 MHz). After propagation along the non-zero dispersion shifted fiber and subsequent generation of the supercontinuum, the overall RIN of the supercontinuum source was <-113.7 dBc/Hz, which is surprisingly low taking into account previous pulsed supercontinuum experiments reported in the literature [22].

To gain some insight into the origin and characteristics of this noise, we measured its spectral dependence as in [22]. To do this, we used the setup depicted in figure 7. The supercontinuum light was filtered by means of a grating monochromator with 4

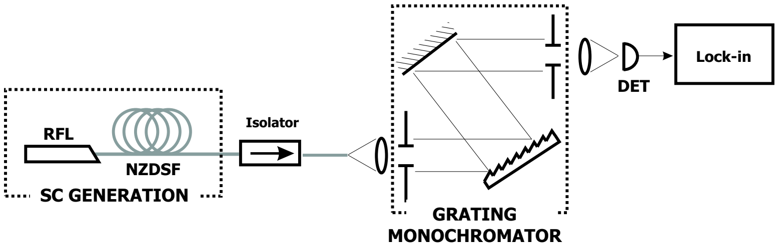

Figure 7. Setup for the characterization of the spectral dependence of the SC noise.

nm resolution. The filtered light was inserted into a fast InGaAs photodetector with 1.5 GHz bandwidth and the noise of the electrical signal was measured by means of a lock-in amplifier which measured the rms value of the noise at a frequency of 100 kHz and with a 10 Hz bandwidth. By use of an RF spectrum analyzer we checked that the spectrum of the noise was quite close to that of white noise all over the wavelength span of the SC, so that the noise density at 100 kHz is representative of the noise density over the 0-1 GHz frequency range. A more suitable characterization of the noise would also require measuring the noise spectral density over a wider frequency span, but this measure is unavailable in our laboratory at the moment. Furthermore, conventional OCT or white-light interferometry applications are basically restricted by the noise density in the kilohertz range rather than in the gigahertz range. The DC component of the signal was also measured by means of a high resolution voltmeter. Additionally, by turning on and off the pumping, we ensured that the essential contribution to the noise measurement was indeed due to the SC. In figure 8 we show the measured spectral evolution of the supercontinuum noise, for a pump power of 2.1 W. Two outstanding

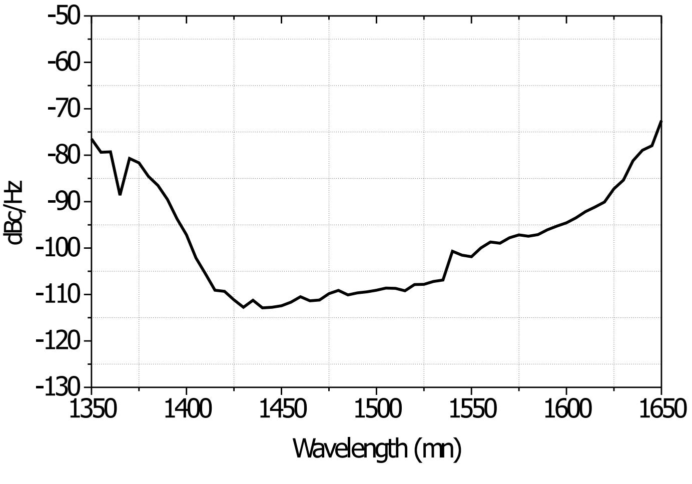

Figure 8. Supercontinuum noise spectrum for a pump power of 2.1 W.

features can be observed: firstly, we can see that the wavelength dependence of this cw

SC noise is much smoother than for the supercontinuums generated with pulsed pumps. Secondly, the longer wavelengths of the supercontinuum appear to suffer from a larger noise than the wavelengths closer to the pump. This can be interpreted by taking into account the lower probability of generating frequency-shifted solitons at wavelengths lying far away from the pump. This also affects the blue side of the SC, since the origin of this side of the SC is related to dispersive waves induced by the soliton fission. Anyway the main conclusion of this study is that the RIN of the SC is surprisingly low, specially taking into account the previous measurements in pulsed SCs [22]. Further theoretical studies should be done to determine the reason of this small RIN, although from the point of view of applications, these cw SC sources seem already adequate for their use in many fiber sensing setups.

4. Conclusions

We have presented a broadband continuous-wave light source spanning more than 200 nm (covering the S, C and L bands defined by the International Telecommunication Union), with a peak power density of approximately 8 dBm/nm. It is based on delivering the ~ 2 W output of a continuous-wave Raman fiber laser (RFL) with a 1.1 nm linewidth into a relatively long (6.8 km) non-zero dispersion-shifted fiber (NZDSF) with small anomalous dispersion at the pump wavelength. We have shown that the supercontinuum results from the modulation instability process induced by fast ($\sim$100 ps correlation length) intensity changes present in the RFL output. The spectral stability of the source was tested over one hour and found to be better than 2% over slightly less than 200 nm, and the noise of the source was found to be better than -113 dBc/Hz. We believe that this source might have a wide range of applications for optical fiber metrology, spectroscopy, fiber sensing and optical coherence tomography.

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