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# Near-infrared supercontinuum source by intracavity silica-based highly-nonlinear fiber

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**Near-infrared supercontinuum generation by using silica-based highly-nonlinear fiber placed inside of the ring-cavity of an erbium-doped fiber laser pulsed by mode-locking is experimentally demonstrated. Only one erbium-doped fiber amplifier is employed to generate supercontinuum with a spectral width as long as 830 nm (from 1205 to 2035 nm) and a spectral power higher than −30 dBm/nm. To generate supercontinuum, it is not necessary a second amplifier to raise the power of the laser pulses coupled into the nonlinear fiber. Moreover, all the devices employed are commercial and available at any photonics laboratory. To the best of our knowledge, this is the first demonstration of this kind of device by pumping the nonlinear fiber in the third window of communications.**

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Supercontinuum generation (SCG) can be broadly understood as a great widening of the spectrum due to the interaction between very high optical intensity beams and matter. This interaction induces nonlinear effects (self-phase modulation, four-wave mixing, stimulated Raman scattering, Kerr effect, etc.), generating new optical frequencies. It is possible to develop very wide optical sources based on SCG, which find immediate usefulness in different fields like biology, chemistry or spectroscopy, and can be used in different applications, such as spectral calibration of photonic elements, optical coherence tomography, optical frequency metrology, fiber gyroscopes, networks of optical sensors, optical measurements in biological tissues, spectroscopic analysis of air and water pollutants, or explosive detection [1,2].

Although SCG can be achieved using continuous-wave lasers, the pumping by means of pulsed lasers is usually more efficient, since the energy is restricted in very short intervals of time and, consequently, the optical intensity is extremely raised. Therefore, nonlinear effects are exhibited in a very much stronger way and SCG is greatly enhanced. In this sense, mode-locked lasers are particularly suitable for SCG since they emit a train of pulses with a time width usually shorter than 1 ps. Moreover, the optical intensity of our system can be boosted by using optical fiber because the light is practically confined in a very small area ($<30\ \mu\text{m}^2$), even more if it is employed some type of fiber with a high Raman gain coefficient, which strengthens nonlinear effects. Usually, photonic-crystal fibers (PCF) pumped at 800 nm (Ti:sapphire laser) are employed for SCG from ultraviolet up to near-infrared (NIR); highly-nonlinear silica fibers (HNLF) achieve SCG from NIR up to 2.2 μm (due to the high attenuation of the silica at longer wavelengths); zirconium fluoride ($ZrF_4$, ZBLAN) fibers, and indium fluoride ($InF_3$) fibers can extend the spectrum until 4 μm and 5 μm, respectively; and chalcogenide ($As_2S_3$, $As_2Se_3$) optical fibers [3] extend from 2 μm up to 10 μm. Some of the widest supercontinuum reported are the following: Buczynski *et al.* [4] generated a two octaves spectrum widening from 700 nm up to 3000 nm by using PCF; Rifin *et al.* [5] achieved a widening from 1130 nm up to 2220 nm by employing HNLF; Swidersky and Michalska [6] expanded the spectrum from 900 nm up to 3600 nm with ZBLAN fibers; and Xia [7] developed a SCG source based on ZBLAN fiber pumped by means of nanosecond pulses from 800 nm up to 4500 nm and, moreover, its usefulness in some biomedical applications was demonstrated.

The silica HNLFs are a very suitable choice to SCG since they can provide high spectral powers (>1 mW/nm along several hundreds of nanometer) and can be pumped in a really effective way by means of mode-locked lasers based on commercial erbium-doped fiber amplifiers (EDFAs), which makes possible the development of simple, stable, compact, and reliable supercontinuum sources. For example, SCG from 1100 nm up to 2300 nm by using this method was reported in a previous paper [8]; although, it was necessary to employ two EDFAs: one of them to build the mode-locked laser, and the other one to amplify the pump pulses since the pulses emitted by the mode-locked laser have not enough optical intensity to generate supercontinuum.

Of course, if these sources could operate with only one amplifier, then it would be a great improvement, so this aim will guide the present work. Considering that the energy of the pulses inside the laser cavity is higher than the energy of the pulses emitted, the arrangement explored in this work is based on placing a HNLF sample inside the laser ring, exactly at the amplifier output rather than outside the laser. This idea is inspired by the layout of a frequency-doubled solid-state laser, which improves its efficiency by including the nonlinear crystal inside the laser cavity instead of placing it outside. The typical example is the Nd:YAG laser, whose power is emitted at 1064 nm and can be doubled to 532 nm by placing a KTP (Potassium-Titanyl-Phosphate)

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nonlinear crystal inside the cavity. In spite of the simplicity of this idea, only a few papers related with our proposal have been reported. In fact, to the best of our knowledge, only Lin *et al.* [9] reported the employment of a pulsed erbium-doped fiber laser in order to expand the output spectrum. However, they did not include nonlinear fiber but standard single-mode fiber, and in consequence, spectral widths did not exceed 165 nm. Nevertheless, it is worth to mention the results of Cheng *et al.* [10] and Cascante *et al.* [11], which reported supercontinuum spectra extended from 570 nm up to 1760 nm by placing PCF inside the linear cavity of ytterbium lasers (1064 nm). However, as these lasers are pulsed by Q-switching, the time width of their pulses is larger than 1 ns, which is very far from our proposal, since mode-locked pulses have time widths lower than 1 ps. In addition, other kinds of cavity have been also proposed for generating supercontinuum by using only one optical amplifier. Recently, Guo *et al.* [12] have obtained supercontinuum generation with a width of 410 nm (1315–1725 nm) by means of a 4 ns mode-locked fiber laser with a figure-eight cavity, which it is formed by standard fiber and it does not include any HNLF fiber.

In this paper, it is experimentally demonstrated that a supercontinuum source with a spectral width as long as 830 nm (its spectrum is extended from 1205 nm up to 2035 nm) and a spectral power higher than $-30$ dBm/nm can be achieved by including a HNLF sample inside the ring cavity of a mode-locked erbium-doped fiber laser, which employs only one commercial EDFA. Thus, it is not necessary a second amplifier to raise the power of the laser pulses in order to obtain supercontinuum.

The scheme of the experimental set-up is shown in Fig. 1. It consists roughly in a passive mode-locked laser with a ring cavity including a nonlinear medium inside. As amplifier medium we used an EDFA operating in L-band (henceforward, EDFA-L20) with 20 dBm saturation output power (Keopsys, model KPS-BT2-L-20-PB-FA). The ring cavity was made of standard single-mode optical fiber (Corning, model SMF-28; step-index profile; numerical aperture 0.11 at 1550 nm, core radius 4.1 µm and modal field diameter (MFD) of 10.4 µm at 1550 nm). A sample of 21 m length of HNLF (YOFC, type NL-1550-Zero, model NL1016-B, numerical aperture 0.35, MFD = 4.9 µm, Raman gain coefficient higher than 4.8 $\mathrm{W}^{-1}\,\mathrm{Km}^{-1}$ and zero-dispersion wavelength at 1550 nm) was placed inside the laser cavity at the output of the EDFA because this is the place where the power is highest. This length was carefully determined to optimize the width of the supercontinuum.

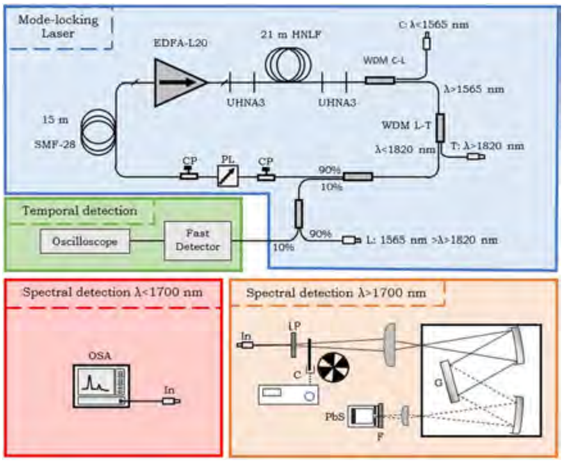

**Fig. 1.** Scheme of the experimental setup employed to generate and measure supercontinuum.

In order to improve the power coupled into the HNLF sample and to diminish cavity losses (both effects raise the input power into the HNLF and therefore enhance the nonlinear effects), the splices between SMF-28 and HNLF were avoided. A bridge fiber with a high numerical aperture (Nufern, model UHNA3, numerical aperture 0.35, core radius 0.9 µm, MFD 6.7 µm) was inserted between both fibers in order to improve losses, which were reduced from 2.3 dB to 1.4 dB in each joint.

As the EDFA-L20 operates in L-band (amplification range from 1565 to 1645 nm), the ring cavity also includes two wavelength division multiplexers (WDM). The cutoff wavelength of the first one (WDM C-L, Lightstar Technologies) is 1565 nm, and it allows to output the spectral power at wavelengths lower than 1565 nm. The cutoff wavelength of the second one (WDM L-T, Optizone Technology Limited) is 1820 nm and it extracts the spectral power at wavelengths longer than 1820 nm. The spectral power at wavelengths from 1565 up to 1820 nm remains travelling into ring cavity, and it is partially extracted by means of a 10/90 coupler. Therefore, the full spectrum is divided in three different outputs, named C ($\lambda < 1565$ nm), L ($1565\ \mathrm{nm} < \lambda < 1820$ nm) and T ($\lambda > 1820$ nm).

Finally, 15 m length of SMF-28 fiber was placed before the EDFA-L20 in order to facilitate the nonlinear polarization rotation effect, which induces a rotation of the polarization state depending on the optical intensity and the propagation length. It is commonly used in ring-cavity fiber lasers as a passive technique to achieve the mode-locking because of the large length of the fiber cavities [13,14]. The modulator was formed by a linear polarizer (Thorlabs, model ILP1550SM) placed between two polarization controllers (General Photonics, model Polarite).

The spectral power below 1700 nm was measured by an optical spectrum analyzer (OSA, Agilent, model 86142B) with 5 nm of resolution. On the other hand, the spectral power above 1700 nm was analyzed with a resolution of 4 nm by using a monochromator (SPEX, model 340E) equipped with a diffraction grating of 300 grooves/mm and a Blaze wavelength of 2000 nm (Horiba Scientific) and was detected by means of a PbS photoconductor (spectral sensitivity from 1000 nm up to 2750 nm, Thorlabs, model FDPS3X3). In order to remove the influence of the second order of diffraction, a long-pass spectral filter (cut-on wavelength of 1500 nm, Thorlabs, model FEL1500) was placed in front of the photoconductor. The input beam was modulated by a chopper to use synchronous detection (lock-in amplifier). As the spectral efficiency of the diffraction grating depends on the polarization state, a linear polarizer (model LPMIRO50-MP2, Thorlabs, wavelength range from 1.5 to 5.0 µm) was added to the setup. Thus, each optical spectrum was measured for two orthogonal polarization states (vertical and horizontal). Both measurements were corrected considering the losses of the setup, which had been previously calibrated. The addition of both measurements provides the shape of the supercontinuum spectrum. At last, its spectral power was assigned given that it must coincide with the spectral power measured by the OSA along the spectral region common to both systems (from 1500 nm up to 1700 nm).

Laser output spectrum without a HNLF sample is shown in Fig. 2. Its peak is at 1594 nm and its spectral width is around 20 nm at $-3$ dB and 80 nm at $-30$ dB. After the optimization

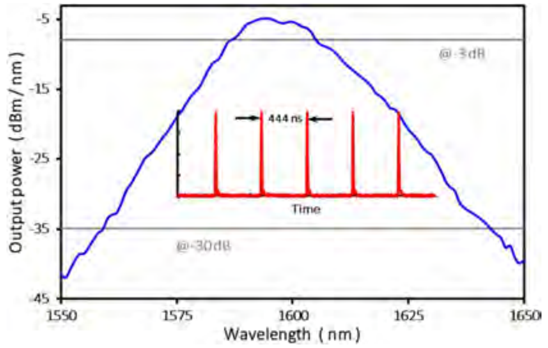

**Fig. 2.** Laser output spectrum without the HNLF sample. Its peak is at 1594 nm, and its spectral width is around 20 nm at −3 dB and 80 nm at −30 dB. The inset shows the train of pulses of the mode-locked laser with 21 m of HNLF (2.25 MHz).

of the HNLF length, a supercontinuum source with a spectral width of 830 nm (at −30 dB) was achieved, from 1205 nm up to 2035 nm. However, due to the sensitivity of the detection system, the output power cannot be measured in a range of 80 nm (from 1700 to 1780 nm). Of course, the spectral improvement is significant in spite of the fact that the intracavity sample of the HNLF generates a very low power along this 80 nm spectral range. The output spectrum is shown in Fig. 3. It was measured in three parts, one by each cavity output. Thus, the spectral power from 1205 to 1565 nm belongs to the C output, from 1565 to 1700 nm to the L output, and from 1780 to 2035 nm to the T output. It must be noted that the L output extracts only a 10% of the confined power.

The spectral power generated by HNLF is shown in Fig. 4, and it has been determined by keeping in mind spectral losses of all the couplers (including the 10/90 coupler of the L-band). This would be the optimal output of our system, which could be extracted by means of a suitable coupler. It can be assumed as a reference in order to compare our results with the results obtained from other experimental setups based also on nonlinear effects. The temporal evolution of the mode-locked laser was monitored by splitting 10% from the L-output power towards a fast photodetector (BCP, model 310A). The frequency of the train of pulses obtained with 21 m of HNLF is 2.25 MHz (inset in Fig. 2), corresponding to a ring-cavity of 91 m length. The response time of the detector is too long (around 3 ns) to measure the temporal width of the pulses. If they were transform-limited pulses, then its duration would be 0.22 ps because their spectral FWHM is 20 nm. However, the temporal width of the supercontinuum pulses will be significantly longer [15]. Unfortunately, we could not measure its duration due to its too low energy.

As it can be appreciated in Figs. 3 and 4, a supercontinuum spectrum with a spectral width as wide as 830 nm has been obtained by using only one EDFA with a mean output power as low as 100 mW and without the need to amplify the power of the pulses by means of a second EDFA. In comparison with other experiments, this source produces a wider spectrum than those obtained using CW regime [9,16,17]. Although it is far from the spectral width reported by Cheng *et al.* [10], whose spectral width reached 1450 nm, it is necessary to underline that Cheng *et al.* needed a pump power of 450 mW, and they did not observe any widening by employing a pump power as low as 100 mW. Therefore, we think that we could improve our supercontinuum spectrum by making use of a more powerful pump source, because it would allow us to insert longer nonlinear fiber samples in the ring cavity. The other important difference between both experiments is the pump wavelength, since Cheng *et al.* pumped at 1.06 μm.

We can also compare these results with a previous source developed by the authors and reported in Ref. [6]. This source consisted of a passive mode-locked ring laser, which used an EDFA as active medium and whose output pulses were amplified by means of a second EDFA in order to achieve more powerful pulses to pump a HNLF sample, which was also placed outside the ring cavity. Although this source was originally optimized using 63 m of HNLF, it was newly tested with 25 m of HNLF, which is similar to the optimum length found for the source developed in this work. As it is shown in Fig. 4, the spectral width of the supercontinuum source with external HNLF is around 250 nm wider (at −30 dBm/nm) and its output power is around 7 dB higher. However, this source needs two EDFAs and the spectrum cannot be widened without employing the second EDFA, while the supercontinuum source with intracavity HNLF only requires one EDFA. Therefore, it can be concluded that both experiments provide equivalent results. In any case, the output spectrum of our source offers clearly a better performance than the wide sources usually used for spectroscopy applications (such as SLED, ELED, semiconductor optical

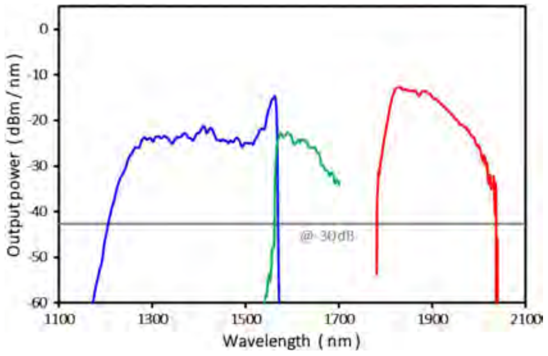

**Fig. 3.** Supercontinuum spectrum from the three outputs of the cavity: C (blue), L (green), and T (red). The spectral width is 830 nm at −30 dB.

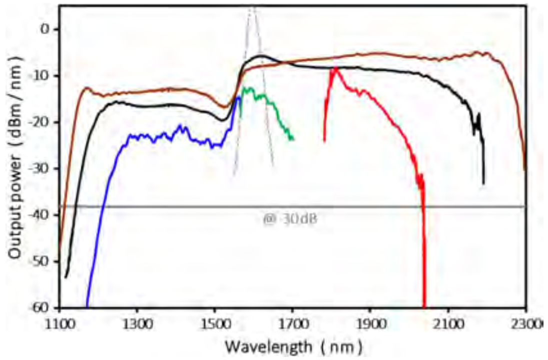

**Fig. 4.** Intracavity spectral power in the three outputs of the cavity: C (blue line), L (green line), and T (red line). Supercontinuum spectra obtained by the source with 21 m of intracavity HNLF and only one EDFA and the source with external HNLF and two EDFAs (25 m of HNLF, black line; 63 m of HNLF, brown line). Dashed gray line represents the spectral power of the pump pulse inside the cavity (before the HNLF).

amplifiers, etc.), because their spectral width only reaches around 200 nm and their spectral power is very low in mostly all the spectrum.

In order to achieve these positive results, the experimental setup had to be carefully optimized. This optimization process allows us to verify some hypothesis for this cavity type. Notice that there are two opposed behaviors because a nonlinear medium is inside the laser cavity. On the one hand, the higher pump power inside the cavity, the higher supercontinuum generation. Thus, the cavity losses must be minimized to enhance the confined pump power. Moreover, it is necessary to select the most suitable place for the nonlinear medium to favor supercontinuum generation. In the other hand, a stronger supercontinuum generation implies more cavity losses and, consequently, the confined pump power inside the cavity is diminished. Therefore, there is a HNLF length that optimizes the supercontinuum spectrum.

The optimization was performed according to the following reasoning. First, all devices inside the cavity laser were connected by splicing so that fiber connectors were avoided. Moreover, the splice losses between the nonlinear fiber and the cavity fiber were minimized by inserting a bridge fiber between both of them. Second, it was verified that the best result is obtained by placing the HNLF sample at the output of the EDFA because this is the point of the ring with the highest power. Besides, it was determined that the supercontinuum spectrum is always enhanced as the pump power is raised. Furthermore, supercontinuum generation by placing a HNLF sample outside the ring cavity was also explored, but the obtained results were always negative due to the low power coupled into HNLF sample since there was not a second EDFA. Finally, the optimal length of HNLF was determined by inserting samples from 10 m up to 30 m in length. In Fig. 5, the width and the power of the supercontinuum are shown as a function of the HNLF length placed inside the ring cavity. As it can be appreciated, the optimal HNLF length for our setup is near 21 m. By placing short samples, the longer HNLF is, the wider supercontinuum spectrum is obtained since nonlinear effects are increased. However, HNLF lengths that are too long produce cavity losses so high that the laser does not operate. Therefore, it can be found an optimal length that provides the maximum width without inducing a shutdown of the laser. In fact, if the HNLF length was longer than 30 m, then the pulsed laser was unable to run.

In conclusion, it has been experimentally demonstrated that the insertion of a silica HNLF sample inside the ring cavity of a passive mode-locked fiber laser can generate a supercontinuum spectrum. If the nonlinear fiber is placed outside the ring cavity, then supercontinuum is not generated. This technique has allowed for the development of a supercontinuum source by using only one EDFA, without the need to use a second EDFA in order to amplify the power of the pulses. To the best of our knowledge, this is the first experimental device based on this technique. Furthermore, all the devices employed are commercial and are usually available in every photonic laboratory. Therefore, our technique is easy to implement, and it simplifies other experimental sources reported in the literature, which use more than one amplifier.

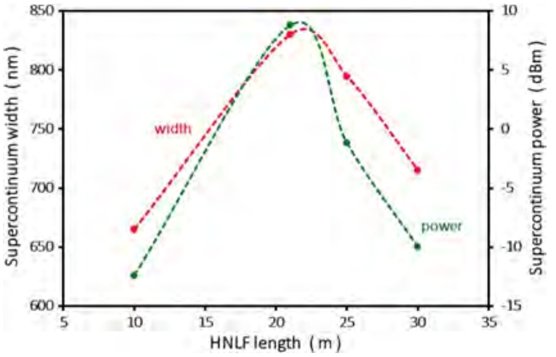

**Fig. 5.** Width and power of the supercontinuum generated in function of the HNLF length placed inside the ring cavity.

A compact supercontinuum source with a spectral width of 830 nm, from 1205 nm up to 2035 nm, has been developed with enough spectral power for many supercontinuum applications in the NIR region, which is competitive with most commercial proposals for such purposes. In fact, it is the widest supercontinuum achieved by employing a mean pump power of only 100 mW. However, it is necessary to point out that the output power is too low in a spectral range of 80 nm (1700–1780 nm). This problem could be solved including positive or negative dispersion fiber or changing the EDFA-L20 by another EDFA operating in the C-band, as long as these changes shift the pulse peak towards the zero-dispersion wavelength (ZDW) of the HNLF (around 1550 nm).

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