Experimental demonstration of multi-watt CW supercontinuum tailoring in photonic crystal fibers

A. Kudlinski*, G. Bouwmans, Y. Quiquempois and A. Mussot

Université des Sciences et Technologies de Lille,

IRCICA, FR CNRS 3024,

Laboratoire PhLAM, UMR CNRS 8523,

59655 Villeneuve d’Ascq Cedex, France

Abstract

We demonstrate experimentally that the spectral broadening of CW supercontinuum can be controlled by using photonic crystal fibers with two zero-dispersion wavelengths pumped by an Yb fiber laser at 1064 nm. The spectrum is bounded by two dispersive waves whose spectral location depends on the two zero-dispersion wavelengths of the fiber. The bandwidth of the generated spectrum and the spectral power density may thus be tailored for particular applications, such as high-resolution optical coherence tomography or optical spectroscopy.

* Electronic mail address: alexandre.kudlinski@univ-lille1.fr
The continuous-wave (CW) pumping regime has been recently proposed as an interesting alternative to pulsed lasers for the generation of strong supercontinuum (SC) [1, 2, 3, 4, 5]. Sources based on CW SC are characterized by a substantial lower intensity noise, a lower coherence length, a higher stability and a higher spectral power density than their pulsed counterparts. Additionally, photonic crystal fibers (PCFs) can be spliced to recently developed CW fiber lasers, preserving the all-fiber format. These features are of particular interest for ultrahigh resolution optical coherence tomography for instance. SC spectra generated with a PCF pumped by a CW Yb fiber laser were reported in Refs. [1] and [5]. About 700 nm-wide spectra with high spectral power densities (in the order of 10 mW/nm) were obtained. But one drawback of these configurations is that the bandwidth of the SC spectrum is not easily adjustable to the one required for a particular application. As a consequence the pump power budget is not optimized if the application requires a given spectral power density over a particular spectral range, as this is actually the case for many potential applications. Quite recently, it has however been numerically demonstrated that a simple scheme based on a PCF with two-zero dispersion wavelengths allows a tailoring of the SC spectrum extent, and consequently of the spectral power density [6]. These numerical results are of great potential interest for the reasons stated before. In this paper, we provide an experimental proof-of-principle of this novel technique by pumping PCFs with a CW Yb fiber laser. We experimentally show that the generated SC spectrum can be tailored through a suitable design of the group velocity dispersion (GVD) of the fiber, and in particular of the position of its two ZDWs, as predicted numerically [6]. We report the generation of 200 nm and 500 nm wide spectra in two slightly different PCFs with two zero-dispersion wavelengths (ZDWs). The SC is achieved by pumping in the anomalous dispersion region, just between the two ZDWs. We showed that a slight modification of the dispersion curve
allows the control of the SC extension and consequently permits to optimize the pump power budget for particular applications.

For the sake of simplicity and clarity, we recall here only on the basic mechanisms involved in SC generation in CW pumping regime. A detailed theoretical analysis of the SC formation is given in Ref. [6]. In the first stage, modulational instability converts the CW field into a train of quasi-solitonic pulses of a few picoseconds duration [7]. These pulses experience higher-order linear and nonlinear effects so that they become unstable. Consequently, they shed energy away to dispersive waves (DWs) which are phase-matched with the solitonic waves [8, 9]. From this phase-matching condition that depends on the GVD and on the nonlinear phase mismatch of the solitonic waves [9], one can estimate the spectral position of the DWs. On the contrary to fibers with a single ZDW where only one DW is phase-matched with one solitonic pulse, in fibers with two ZDWs there are two wavelengths for which the phase-matching condition is satisfied. Consequently, two DWs are generated: one is located on the blue side of the lower ZDW and the other one is located on the red side of the higher ZDW. Additionally the stimulated Raman scattering shifts the solitons towards longer wavelengths [7]. This so-called soliton self-frequency shift stops just below the second ZDW because a balance is achieved between the red shift due to SRS and the blue shift due to spectral recoil when the dispersion slope of the fiber is negative [10]. It is worth noting that even more complex nonlinear interactions should occur during the propagation of such strong pulses in a low dispersion region, such as soliton collisions that can reinforce the frequency shift towards long wavelengths [11]. Providing that the pump wavelength is located between both ZDWs in a low anomalous dispersion regime, one can simply summarize that the SC extension is roughly limited by the spectral separation between the two DWs.

In order to experimentally demonstrate the numerical results predicted in Ref. [6], we
designed two PCFs with two ZDWs from part to part of the pump wavelength at 1064 nm, and a low anomalous dispersion region at this wavelength. This can be achieved for a relatively small hole-to-hole spacing $\Lambda$ in the order of 1.6 $\mu$m, and a $d/\Lambda$ value of about 0.4, with $d$ being the hole diameter [6, 12]. For a reasonable number of seven air-hole rings, such a small pitch leads to relatively important confinement losses around 1500 nm, where the SC is expected to extend. We numerically evaluated these losses with a finite-elements method (FEM), and we found that they were in the order of 1000 dB/km at 1500 nm. To overcome this problem, we replaced the seventh air-hole period with a ring of larger air holes ($d/\Lambda = 0.8$), as can be seen in the scanning electron micrograph (SEM) represented in the inset of Fig. 1. Confinement losses were thus reduced to about 1 dB/km at 1500 nm, which is an acceptable value for experiments performed in tens of meters long fibers, as required for CW SC generation. Another way to reduce confinement losses without adding such an air-clad structure would be to use a higher number of uniform air-hole rings (typically ten or eleven). However, this would make the fabrication process a lot trickier since this would approximately double the total number of holes in the cladding.

We fabricated two PCFs labeled fiber A and fiber B in what follows. They were designed to exhibit a GVD curve similar to that of PCF1 and PCF2 in Ref. [6]. The GVD curves of the fabricated fibers were calculated from high resolution SEMs with a FEM package. They are represented in Fig. 1 together with an example of SEM for fiber B in inset. They both exhibit a convex shape with two ZDWs located on each side of the pump wavelength (represented by the vertical dashed line in Fig. 1). The basic characteristics of the fabricated PCFs are also summarized in Table I for the sake of clarity. It can be seen from this table that the parameters of fibers A and B are very close to those of PCF1 and PCF2 of Ref. [6] respectively. The nonlinear coefficient $\gamma$ was deduced from the computed effective area at
1064 nm, by taking the typical value of \( n_2 = 2.6 \times 10^{-20} \text{ m}^2.\text{W}^{-1} \) for the nonlinear refractive index of silica [7]. The nonlinear coefficient of both PCFs was in the order of \( 25 \text{ W}^{-1}.\text{km}^{-1} \) at 1064 nm. Note that this value is about twice higher than the nonlinear coefficient of PCFs with a single ZDW around 1064 nm usually designed for SC generation [13]. Since the two ZDWs of fiber A are closer than the ones of fiber B, a broader SC is expected in fiber B according to the theoretical study summarized above and detailed in Ref. [6].

The PCFs were pumped with a linearly polarized CW Yb fiber laser (IPG) delivering 20 W at 1064 nm with a full width half maximum of 0.5 nm. The setup is displayed in Fig. 2(a). The collimated beam with a 5 mm diameter (at \( 1/e^2 \)) was sent through an afocal setup made of two IR-coated lenses in order to reduce the spot size by a factor of 2. About 70% of the pump power was launched into the fibers by using appropriate aspherical lens. However, even though most of the pump power is coupled into the core of the PCFs, there is a small amount of pump power launched and guided in the inner cladding because of the last ring of holes (larger air holes with \( d/\Lambda = 0.8 \)). Consequently the total power of 14 W launched into the fibers does not contribute completely to the SC generation. The output light was butt-coupled to a standard single-mode pigtail in order to record the spectra with an optical spectrum analyzer (OSA). Figure 2 shows the spectra measured for the two PCFs under investigation.

In fiber A (with the ZDWs separated by only 161 nm), we obtained a relatively narrow spectrum ranging from 1000 nm to about 1200 nm. It is important to note that the upper limit of the SC (\( \sim 1200 \text{ nm} \)) is well below the OH absorption peak (1380 nm), which can consequently not be involved to explain the limitation of the SC extension. The total average output power was 9 W. In fiber B (with the ZDWs separated by 285 nm), the SC spectrum is much broader than in fiber A. It spans from 1050 nm to 1550 nm, with an important
dip around 1400 nm due to important losses at this wavelength due to water absorption (measured to be about 300 dB/km at 1380 nm). As a consequence, the average output power is reduced to 6.3 W. Note that the spectrum generated in fiber B is limited by the pump on the low wavelength side rather than by the blue-shifted DW. This is due to the fact that this blue-shifted DW is very weak because its spectral shift with the soliton is very important \[6\]. It is also important to note that the spectral boundaries of both experimental spectra are in very good agreement with the ones predicted by numerical simulations for corresponding PCFs in Ref. \[6\]. Our experimental results thus clearly reveal that the SC spectrum is actually bounded by the presence of two DWs as expected. For both fibers, we checked that the general shape of the output spectrum and especially its upper and lower limits did not change when fibers longer than 60 m were used. In that case, there was only a reduction of the output power due to absorption losses, and more pump power was converted in the SC. On the contrary, by shortening the fiber length to less than 60 m, the bandwidth of the SC was strongly reduced and most of the output power was located in the vicinity of the pump wavelength. We found that a length of 60 m was a good compromise between the output power and the conversion efficiency of the pump power into the SC.

Above the fundamental study and the experimental demonstration reported in the present paper, we believe that SC-based sources with a controllable generated spectrum would be of great interest for numerous applications. However, this would require a very good temporal stability and an improved flatness of the output spectrum. Indeed, in the case of the “free space” injection setup used in our study, the output spectrum was stable just over a few minutes at full pump power. After this duration, the output power and the stability of the spectrum began to decay because of thermal effects at the fiber input. Although the stability over a few minutes is sufficient to record the spectrum with an OSA without any
trouble, it will not be suitable for most of potential applications. This crucial limitation could be overcome by directly splicing the PCF to the fiber laser output. A careful splice would also present the advantage of increasing the amount of pump power launched into the core by limiting the power coupled into the inner cladding. This would consequently improve the conversion of the pump power into the SC, i.e. the spectral power density at the fiber output. Finally, the dip around 1400 nm in the spectrum could be removed by reducing the OH contamination with a suitable cleaning of the stacked PCF preform \[5\].

In conclusion, we have studied CW SC generation in PCFs with two zero-dispersion wavelengths located around the pump wavelength. By a suitable control of the position of both ZDWs and of the dispersion value at the pump wavelength, we evidenced experimentally for the first time to our knowledge the possibility of tailoring the SC spectrum. By this way, the SC extension and the output power can be adjusted over the spectral range of interest required for a particular application in the near IR. This represents an important step towards optimizing the pump power budget for a given application of SC-based sources. Next steps will consist in improving the flatness of the SC by reducing the water contamination and to directly splice the laser source with the PCF. We believe that this all fiber SC light source would become an useful tool for OCT applications for example.

The authors acknowledge Karen Delplace (IRCICA) for assistance in fiber fabrication and Thibault Sylvestre (FEMTO-ST) for fruitful discussions.
[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 (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 (2003).

[3] A. K. Abeeluck, C. Headley, and C. G. Jørgensen, ”High-power supercontinuum generation in highly nonlinear, dispersion-shifted fibers by use of a continuous-wave Raman fiber laser,” Opt. Lett. 29, 2163 (2004).

[4] A. K. Abeeluck, and C. Headley, ”Continuous-wave pumping in the anomalous- and normal-dispersion regimes of nonlinear fibers for supercontinuum generation,” Opt. Lett. 30, 61 (2005).

[5] J. C. Travers, R. E. Kennedy, S. V. Popov, J. R. Taylor, H. Sabert, and B. Mangan, ”Extended continuous-wave supercontinuum generation in a low-water-loss holey fiber,” Opt. Lett. 30, 1938(2005).

[6] A. Mussot, M. Beaugeois, M. Bouazaoui, and T. Sylvestre, ”Tailoring CW supercontinuum generation in microstructured fibers with two-zero dispersion wavelengths,” Opt. Express 15, 11553 (2007).

[7] G. P. Agrawal, Nonlinear Fiber Optics, 3rd ed., (Academic Press, San Diego, CA, USA, 2001).

[8] I. Cristiani, R. Tedioso, L. Tartara, and V. Degiorgio, ”Dispersive wave generation by solitons in microstructured optical fibers,” Opt. Express 12, 124 (2004).

[9] N. Akhmediev and M. Karlsson, ”Cherenkov radiation emitted by solitons in optical fibers,”
Phys. Rev. A 51, 2602 (1995).

[10] D. V. Skryabin, F. Luan, J. C. Knight, and P. St. J. Russell, "Soliton self-frequency shift cancellation in photonic crystal fibers," Science 301, 1705 (2003).

[11] M. H. Frosz, O. Bang, and A. Bjarklev, "Soliton collision and Raman gain regimes in continuous-wave pumped supercontinuum generation," Opt. Express 14, 9391 (2006).

[12] M. L. V. Tse, P. Horak, F. Poletti, N. G. R. Broderick, J. H. V. Price, J. R. Hayes, and D. J. Richardson, "Supercontinuum generation at 1.06 μm in holey fibers with dispersion flattened profiles," Opt. Express 14, 4445 (2006).

[13] W. J. Wadsworth, N. Joly, J. C. Knight, T. A. Birks, F. Biancalana, and P. St. J. Russell, "Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibers," Opt. Express 12, 299 (2004).
TABLE I: Parameters of the fabricated PCFs.
| Parameter          | Fiber A | Fiber B |
|-------------------|---------|---------|
| ZDW1 (nm)         | 1010    | 976     |
| ZDW2 (nm)         | 1181    | 1261    |
| $\gamma$ @ 1064 nm (W$^{-1}$.km$^{-1}$) | 23      | 24      |
| $D$ @ 1064 nm (ps/nm/km) | 3       | 8       |
| Length (m)        | 60      | 60      |
Figure caption

FIG. 1: GVD curves of the fabricated PCFs calculated with a FEM package from high resolution SEMs. Inset: SEM of fiber B. The vertical dashed line represents the pump wavelength (1064 nm).

FIG. 2: (a) Setup used for SC generation experiments. (b) Experimental spectra recorded for 60 m of fiber A (dashed line) and of fiber B (plain line) with a pump power of 14 W launched into the PCFs.
(a)

20 W CW fiber laser
L1 L2 L3
PCF Pigtail OSA

(b)

Fiber A
Fiber B

Power (a.u. - 10 dB/div)

Wavelength (nm)

1000 1100 1200 1300 1400 1500 1600

20 W CW fiber laser
OSA
L1 L2 L3
PCF Pigtail

14