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# Extended blue side of flat supercontinuum generation in PCFs with a cw Yb fiber laser

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**Abstract—We report the generation of a broadband supercontinuum with a CW Yb fiber laser and a PCF. The spectrum extends toward short wavelengths through efficient dispersive wave generation.**

## I. INTRODUCTION

Supercontinuum (SC) based sources with continuous wave (CW) pumping have a wide range of potential applications because of their low temporal coherence and because of the high spectral power density (SPD) available at the fiber output. Furthermore, these all-fiber light sources are compact, robust and can easily be implemented in an experimental setup. In first experiments, Raman fiber lasers emitting around 1500 nm were used, the pump wavelength being in the vicinity of the zero dispersion wavelength (ZDW) of dispersion shifted fibers or of highly nonlinear fibers [1]. By pumping around the ZDW of optical fibers, the spectral broadening on the Stokes side of the pump is mainly due to the Soliton Self-Frequency Shift (SSFS) process while the one on the anti-Stokes side originates from the generation of dispersive waves (DW). More recently, with the aim of further increasing the SPD of CW-SCs, Travers *et al.* have taken advantage of powerful CW Ytterbium (Yb) fiber lasers and of the high nonlinearity of photonic crystal fibers (PCFs) [2]. In their experiment, the pump wavelength is far away from the ZDW of the fiber and as a consequence the SC is only generated on the Stokes side of the pump. A SC ranging from 1070 nm to 1600 nm with 12 W output average power has been reported by pumping a PCF with a 50 W CW Yb-fiber laser.

In this paper we report the generation of a flat and strong SC by pumping a PCF around the ZDW with a CW Yb fiber laser. This is the first time to our knowledge that a spectral broadening on both sides of the pump is reported in a CW pumping configuration. We obtained a SC ranging from 1 m to 1.3 m with 1 W output power by launching 6 W of pump power inside the fiber.

## II. EXPERIMENTS AND RESULTS

In order to extend the SC on the anti-Stokes side of the pump we designed and fabricated a PCF with a ZDW just below the pump wavelength to enhance the generation of DWs. The linear properties of the fabricated PCF were calculated

from the Scanning Electron Micrograph (SEM) of the fiber cross-section (inset of Fig. 1(b)) with a finite-elements method. The dispersion curve represented in Fig. 1(b) exhibits a ZDW of 1064 nm. The linear attenuation was measured to be about 15 dB/km at 1064 nm, and the nonlinear coefficient  $\gamma$  is  $11 \text{ W}^{-1} \cdot \text{km}^{-1}$ .

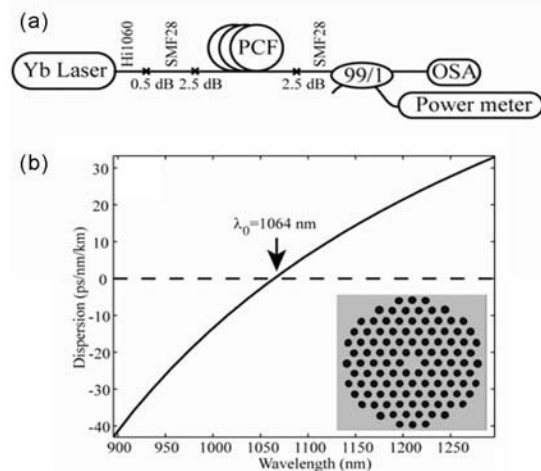


Fig. 1. : (a) Experimental setup. (b) Dispersion curve of the PCF calculated from a SEM of the fiber cross-section (inset).

The experimental setup used for SC generation is displayed in Fig. 1(a). We used a randomly polarized CW Yb fiber laser with 12 W output power at 1066 nm (just above the ZDW of the PCF) and a spectral width of 1 nm. The laser is spliced to the PCF under test which output is also spliced to a 99/1 coupler to reduce the power before recording the output spectrum with an optical spectrum analyzer. To ensure a better mode matching between the Hi1060 optical fiber at the output of the laser and the PCF we introduced a piece of SMF28, leading to a total splicing losses value of 3 dB between the pump laser and the PCF. By launching 6 W of pump power inside 500 m of the PCF we obtained a SC ranging from 1 m to 1.3 m with 1 W output power (Fig. 2(a)). The SC is quite flat and it is worth noting that most of the

pump power is converted into the SC. Moreover, a blue-side extension of nearly 50 nm is observed due to DW generation. This is in good agreement with the value given by the theory of DW generation. Two physical processes may be invoked to explain the limitation of the SC extension on the Stokes side of the pump at 1300 nm : the OH absorption (around 1380 nm) and/or the maximum spectral red shift of the SSFS process. Indeed, on one hand, no special attention has been paid to reduce the OH content during the drawing process, so that a large value of a few hundreds of dB/km is expected for the water peak. On the other hand, the rate of the spectral red-shift of the soliton is proportional to  $\beta_2/T_0^4$  or  $\beta_2/T_0$ , depending on the soliton duration ( $T_0$ ) [3]. Since  $\beta_2$  increases from  $-2.3 \times 10^{-28}$  s<sup>2</sup>/m at 1066 nm to  $-3 \times 10^{-26}$  s<sup>2</sup>/m at 1300 nm, the rate of the spectral shift should be strongly reduced at this longer wavelength. To find the reason to the stop of long wavelength generation, we performed numerical simulations by neglecting the OH absorption.

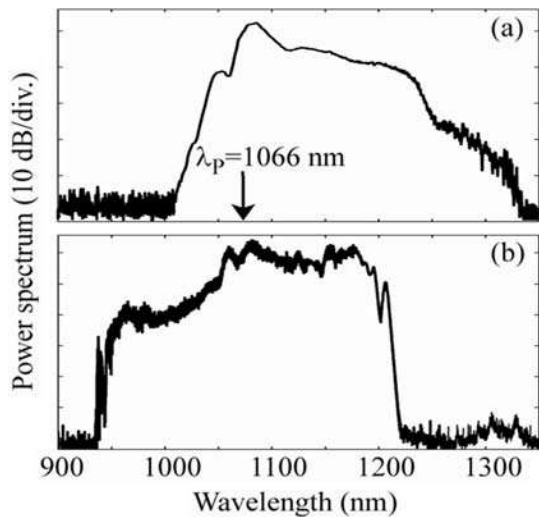


Fig. 2. Spectra of the output of the PCF. (a) experiments and (b) numerical simulations.

### III. SIMULATIONS

The numerical procedure is detailed in Ref. [4]. We assumed that the power spectrum of the pump is Gaussian with a full width at half maximum of 1 nm and that the phase of the longitudinal mode is random [3], [5]. We used the dispersion curve represented in Fig. 1 and constant linear attenuation of 15 dB/km (losses at the pump wavelength) on the whole spectral range. Figure 2(b) represents the output spectrum obtained with an averaging on 35 numerical simulations (averaging required because of the random nature of the pump model [5]). A good qualitative agreement is reached between numerical simulations and experimental results. The SC obtained numerically stops at 1220 nm despite the fact that no OH absorption has been included in the model. It demonstrates that the increase of the dispersion value with

wavelength at this pump power is responsible for the upper limit of the SC, as assumed above. Note that the slight discrepancies between numerical simulations and experimental results can be due to uncertainties of the dispersion curve obtained from the SEM of the fiber, to dispersion fluctuation along the fiber length and/or to the random nature of our laser model.

### IV. CONCLUSION

In conclusion, we report the generation of a flat and strong SC by pumping around the ZDW of a PCF with a CW Yb fiber laser. DWs generation is at the origin of a spectral broadening on the anti-Stokes side. We demonstrate that the SC extension at this pump power is limited by the increase of the dispersion value at long wavelengths. To enhance the broadening on the red side of the SC, one have to shorten the duration of soliton like pulses which originate from modulation instability during the first stage of the SC formation. It can be achieved either by increasing the pump power or by reducing the spectral shift between the pump wavelength and the ZDW of the fiber.

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