# Supercontinuum generation with picosecond ultraviolet pulses in a solid-core photonic crystal fiber

**T. Sylvestre[1], M. W. Lee[1], A. R. Ragueh[1], B. Stiller[1], G. Fanjoux[1],**
**B. Barviau[2], A. Mussot[2] and A. Kudlinski[2]**
*1: Institut FEMTO-ST, Département d'Optique, Université de Franche-Comté, CNRS UMR 6174, F-25000 Besançon, France*
*2: Laboratoire PhLAM, Université de Lille 1, CNRS UMR 8523, IRCICA, 59655 Villeneuve d'Ascq, France*

**Abstract:** Black light supercontinuum generation is demonstrated as a result of picosecond pumping a solid-core photonic crystal fiber at 355~nm through the combined effects of intermodal four-wave mixing and cascaded Raman scattering.

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The study of supercontinuum (SC) generation in photonic crystal fibers (PCF) continues to be an area of active research, motivated by many applications in bio-photonics, optical metrology, spectroscopy, and imaging. Although many previous reports on SC generation have used PCFs pumped with near infrared or visible lasers [1–5], studies of SC generation using UV laser have not yet been investigated.

In this work, we report the observation of a broadband continuum spanning from 350 to 470 nm, i.e., in the black-light region of the electromagnetic spectrum, as a result of picosecond pumping a solid-core silica photonic crystal fiber at 355 nm. This was achieved despite both the strong absorption and large normal group-velocity dispersion (GVD) of silica glass in the UV. Further investigations reveal that the continuum generation results from the interplay of intermodally phase-matched four-wave mixing and cascaded Raman scattering.

In our experiment, we used a standard solid-core silica PCF similar to those usually used for SC generation when pumping at 1064 nm in the small anomalous dispersion regime [4]. It has a triangular lattice with pitch and holes diameters of 3.88 µm and 2.73 µm, respectively. Its zero-dispersion wavelength is 1044 nm. At 355 nm, our PCF exhibits a large normal GVD dominated by material dispersion (D=-1720 ps/nm/km). In addition, the PCF carries several propagation modes at 355 nm that have been numerically identified as the $LP_{01}$, $LP_{11}$ and $LP_{31}$ modes using a finite element method.

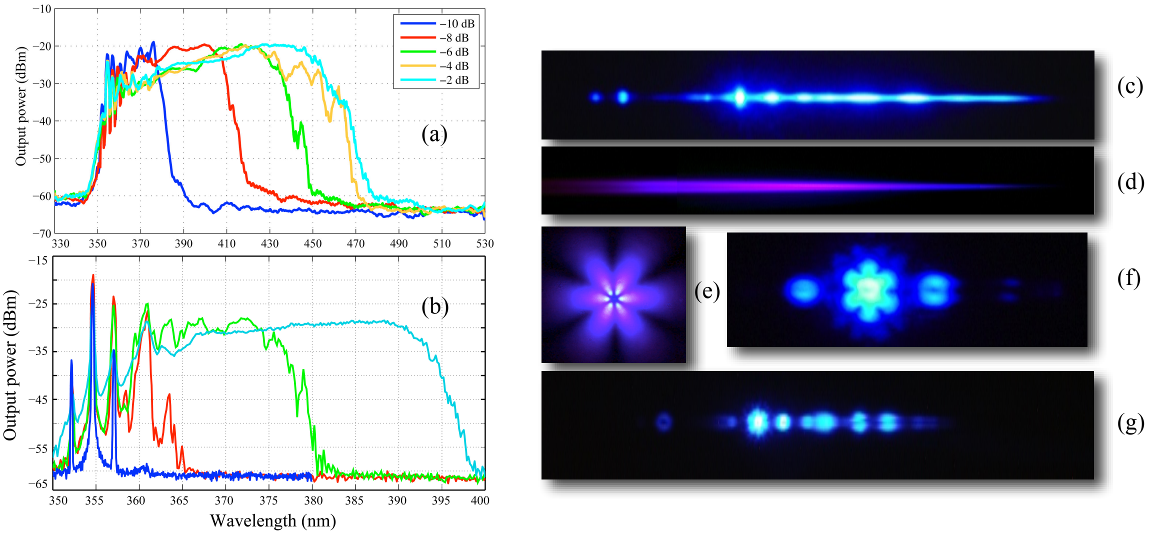

**Fig. 1**. Left Top : (a) Output spectra for increasing input power from 0.5 to 4 mW showing black-light continuum generation in the UV-A-visible from 350 nm up to the blue at 470 nm in a 30 m-long silica PCF pumped at 355-nm with 300-ps Q-switched pulses. Left bottom : (b) Output spectra in shorter fiber samples showing the FWM sidebands (blue) and cascaded Raman scattering (red and green) responsibles for SC generation. Right images show respectively the UV (c) and visible (d) parts of the continuum, the optical mode output (e), and the modal distribution of the continuum showing the FWM sidebands (f) generated in the fundamental $LP_{01}$ and in the higher-order $LP_{11}$ mode for phase-matching reasons, and all the FWM and Raman sidebands (g).

As a pump laser, we used a passively Q-switched frequency-tripled Nd :YAG microchip laser emitting 300-ps pulses at a repetition rate of 1~kHz. The output was coupled into our PCF with an 10x microscope objective. The output spectra were recorded using an optical spectrum analyzer (OSA) and the continuum formation was analyzed by means of a variable attenuator. We also used a grating spectrometer (2400 lines/mm) and a CCD color camera for modal and spectral analysis.

Figure 1(a) shows the output spectra for an increasing coupled pump power ranging from 0.5 mW to 4 mW. We can clearly see SC generation that starts from the pump wavelength at 355 nm and broadens up to the blue. The widest continuum spans 120 nm (third of an octave), from 350 nm to 470 nm, with an output power of 120 μm. This corresponds to a low spectral power density of only 1μW/nm. Figures 1 (c) and (d) show the UV and visible parts of the continuum, respectively. Fig. 1 (e) shows the optical mode output of the widest continuum recorded by the color camera. The UV light appears as white whereas the visible light is in true color. This image shows that the continuum is mainly carried by the LP31 mode.

Figure 1(b) details the beginning of the continuum generation by cutting the fiber back to 1 m and 4 m, respectively, keeping the same injection conditions. We can readily identify an intermodal four-wave mixing (FWM) process involving the pump at 355nm in a mixed-mode distribution (see image (g) for modal distribution), an anti-Stokes sideband in the $LP_{01}$ mode and a Stokes one in the $LP_{11}$ mode, respectively. At higher pump power, cascaded Raman scattering takes place in the PCF and, because of the large Raman gain bandwidth, this combined FWM and CRS evolves towards a smooth continuum, as those shown in Figs. 1 (a-b). It is important to emphasize that this spectral broadening dynamics is equivalent to the one previously reported using visible 532-nm pump pulses propagating in a dispersion-shifted fiber [5].

Let us now discuss the main limitations of UV-pumped SC generation in PCF. The most important ones are fiber absorption and photodarkening effect caused by UV radiation that could be mitigated by using specialty high-OH or solarization-resistant optical fiber. The third drawback is the large normal dispersion of silica that induces a strong pulse walk-off among the Raman pulses and thus limits the continuum extension towards longer wavelength. This can however be overcome by using longer nanosecond pulses.

Finally, this broadband fiber-format black-light source could find potential applications to biomedical sciences (e.g., multi-color excitation of fluroescent proteins in medecine and molecular biology) and spectrocopy [6]. Further progress should however be pursued in near future to improve the continuum bandwidth and spectral power density by using solarization-resistant silica optical fibers.

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