Extended continuous-wave supercontinuum generation in a low-water-loss holey fiber

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We report on the development of a 2.5 μm core photonic crystal fiber with a substantially reduced water-peak loss around 1.38 μm, which allows extended Raman-soliton supercontinuum generation up to 1.55 μm with a cw ytterbium fiber laser pump source. The resulting broadband, high-spectral-power-density, low-coherence light source can be employed for advanced, submicrometer resolution optical coherence tomography. © 2005 Optical Society of America

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Continuous-wave pumping of anomalously dispersive, highly nonlinear holey fibers with fiber lasers leading to the generation of Raman-soliton continua is an efficient and practical approach to creating broadband optical sources with high spectral power density. High-resolution optical coherence tomography (OCT) is poised to benefit from such an all-fiber low-coherence white-light source. The relative intensity noise of such sources can be substantially lower than configurations where short lengths of holey fibers are pumped by ultrafast lasers. Additionally, the spectrum of an all-fiber cw-pumped continuum can be naturally shaped to a near-Gaussian form, for example, by using a fused fiber coupler or long-period fiber Bragg gratings, both of which preserve the all-fiber integrated format. However, the majority of silica-based holey fibers developed to date exhibit strong absorption around 1.38 μm associated with the presence of OH− at the air–glass interfaces of the fiber. Peak absorption of 500–600 dB/km is typical for most currently available holey fibers with anomalous dispersion at 1 μm and micrometer-scale cores. Recently we showed that this limits the effective Raman interaction length to just a few meters around the loss peak and imposes severe spectral restrictions on the generation of supercontinua beyond 1.38 μm with cw-format pumping.

Here we present results on the development of a highly nonlinear, anomalously dispersive holey fiber with a near-sixfold reduction in water loss compared to previously developed fibers with the same geometry. We also demonstrate the potential of this fiber to allow generation of a supercontinuum that spans the entire spectral range up to 1.55 μm by using a 50 W cw single-mode Yb fiber laser at 1.07 μm as the pump source.

The holey fiber used in these experiments had a core diameter of 2.5 μm, a mode field diameter of 1.75 μm at a 1.07 μm wavelength, and an air-fill factor of 91%. It had a zero-dispersion wavelength of 0.81 μm and an anomalous dispersion of about 100 ps/nm/km at 1.07 μm. The fiber was fabricated by using a conventional stack and draw method; however, special care was taken to reduce water contamination during all process steps. The capillaries forming the stack were drawn in a high-purity nitrogen atmosphere from the highest grade of fused silica commercially available. The completed preform stack was then subjected to chemical cleaning and drying in a halogenic atmosphere at over 1000 °C to reduce surface contamination and to lower OH− content in the stack assembly. The resulting fused preforms were again purged with high-purity nitrogen before being drawn to a fiber, and additional care was taken not to reintroduce contaminating water during the fiber draw. The loss spectrum, measured with a supercontinuum generated by picosecond pumping a holey fiber with a Yb fiber laser, is shown in Fig. 1. The measured loss of the fiber was 11 dB/km at 1.07 μm and 73.2 dB/km at the peak of the overtone of the water absorption at 1.38 μm. This value is dramatically lower than the 500–600 dB/km found in typical holey fibers of similar structure.

We used a 100 m length of this low-water-loss fiber for most of the Raman continuum generation experiments. The effective Raman length was 88 m at the pump wavelength of 1.07 μm and was reduced only to 48 m around 1.38 μm. In contrast, the effective Raman length of conventional holey fibers at 1.38 μm is less than a tenth of that at 1.07 μm, which results in
in a sharp roll-off of the Raman gain, confining the continuum to the range of 1–1.38 \( \mu \text{m} \).

A 50 W cw ytterbium fiber laser (IPG Photonics) with a single-mode, randomly polarized 1.07 \( \mu \text{m} \) output and a linewidth of \( \sim 1 \text{ nm} \) (FWHM) was used as the pump. The laser’s free-space output delivered a TEM\(_{00} \), 1.5 mm diameter (1/e\(^2\) level) collimated beam with \( M^2 \leq 1.03 \) and was coupled into a standard single-mode Flexcore fiber. The Flexcore fiber was fusion spliced to the holey fiber via an intermediate thermally expanding fiber (Nufern), which allowed us to match the mode field diameters with a total loss of 0.8 dB. Although the holey fiber could have been spliced directly to the output of the laser, thus achieving complete fiber integration, we chose the free-space configuration to control possible feedback into the laser at high pump powers. Up to 80\% of the 1.07 \( \mu \text{m} \) pump radiation was coupled into the Flexcore fiber delivering up to 32 W of the pump power into the core of the holey fiber.

Figure 2(b) shows the continuum at 32 W cw pump power. This extends over 450 nm, and the total output power reaches 12 W. Figure 2(a) shows the evolution of the total output power at the output of the holey fiber (residual pump and continuum) as well as the percentage of the power in the continuum beyond 1.2 \( \mu \text{m} \) as a function of the cw pump power. No roll-off of the output power, as seen with cw pumping in standard water-loss holey fibers,\(^1\) was observed in our fiber. At approximately 15 W of pump power the continuum extends to the water-peak region of 1.38 \( \mu \text{m} \). With further increases of the pump power the continuum power increases monotonically.

As a result of the high dispersion in the region of the pump, soliton formation was inhibited since the power for soliton formation is proportional to the dispersion value. Consequently, over the extended gain length, gain processes competing with soliton formation and soliton self-frequency shift can become significant. This is confirmed by the spectrum in Fig. 2(b), where transfer of power to the first and second Stokes components at 1.13 and 1.19 \( \mu \text{m} \) through stimulated Raman scattering is significant. Such behavior is distinct from conventional Raman-soliton generation in regimes of low anomalous dispersion. Regardless of this, 50\% of the pump power was converted into the continuum in the region beyond 1.2 \( \mu \text{m} \). The Raman Stokes peaks could be suppressed by using low-water-loss holey fiber designs with reduced anomalous dispersion.

Autocorrelation measurements of the spectrally sliced continuum at 1.3 \( \mu \text{m} \) showed a soliton of about 280 fs duration with a pedestal of 7\%. The pedestal reflects the stochastic nature of the soliton formation process under cw pumping conditions, initiated by the quantum noise and residual intensity fluctuations of the pump, which give rise to randomly spaced cross-correlating solitons as well as to the presence of nonsolitonic dispersive wave components.

For comparison, Fig. 3 shows the output power of 350 m of the holey fiber while varying the cw pump power. Increasing the length of the fiber to 350 m lowered the threshold of supercontinuum generation but also affected the flatness of the output spectrum (inset in Fig. 3). This is because both the total loss and Raman gain increase exponentially with length, leading to increased water-peak absorption and enhanced Stokes generation in the longer fiber. It is worth noting that the effective Raman length at the water-loss peak (1.38 \( \mu \text{m} \)) only halved compared to its value at the pump wavelength in the 100 m long

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**Fig. 2.** (a) Output power from 100 m of the holey fiber (HF), and the percentage of the output power in the continuum beyond 1.2 \( \mu \text{m} \), as a function of the cw pump power. (b) Spectra at the holey fiber output for 32 W cw pumping.

**Fig. 3.** Output power of the 350 m long holey fiber versus cw pump power. Inset, output spectrum of 350 m of the holey fiber with 19 W cw pump power.
fiber, whereas in the 350 m long fiber it was reduced to just a quarter of its value at 1.07 μm.

In both the 100 and 350 m lengths of holey fiber tested we observed a change in the slope efficiency of the continuum generation at around the 15 W pump power level [Figs. 2(a) and 3]. This is because the residual water loss at 1.38 μm prevents the Raman gain from supporting the soliton self-frequency shift under the conditions of high anomalous dispersion at this wavelength. Lower values of dispersion and water loss would reduce this change in efficiency and lead to lower power requirements for extension of the continuum beyond 1.38 μm.

To overcome the high dispersion limit to the Raman-soliton continuum, we compared the cw pumping of the low-water-loss holey fiber with a quasi-cw pumping regime. We used 2 ns pulses from a seeded Yb fiber source similar to that described in Ref. 1 to provide higher, up to 100 W, peak power pumping. Figure 4(a) shows that there is no change in the slope efficiency of the continuum generation, which is the result of enhanced soliton formation at these peak power levels despite the high anomalous dispersion of the fiber. Figure 4(b) shows the continuum generated by pumping 100 m of the holey fiber with ~50 W peak power. The dip in the continuum at the water-loss peak has been reduced compared to cw-format pumping. The overall spectral width in this case was over 700 nm with an average output power of ~0.2 W in the continuum.

Taking the broadest Gaussian fit for the continuum generated in the low-water-loss holey fiber, one can see that a 256–300 nm (3 dB level) ~1.3–1.35 μm centered Gaussian profile can be readily produced, which corresponds to an ~2.5 μm coherence length in air. Further reduction of the coherence length to the submicrometer level should be possible with a low-water-loss holey fiber with a reduced anomalous-dispersion value. Such short-coherence-length, compact, all-fiber sources are well suited to OCT applications.

In conclusion, we have reported on the development of a 2.5 μm core holey fiber with a significantly reduced water loss that enabled cw-pumped supercontinuum generation beyond the water-loss peak at 1.38 μm. We achieved a considerable increase in bandwidth compared to previously reported cw-pumped Raman-soliton continua. This will be of particular benefit to micrometer-resolution, low-noise OCT.

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