Continuous-wave, high-power, Raman continuum generation in holey fibers

A. V. Avdokhin*, S. V. Popov, and J. R. Taylor

Femtosecond Optics Group, Department of Physics, Imperial College, Prince Consort Road, London SW7 2 BW, England

Received March 3, 2003

The possibility of using low pump power for cw Raman continuum generation is demonstrated by optimization of the pump peak power and by accounting for the loss-related reduction of the effective length of Raman interaction in holey fibers. A 3.8-W, 324-nm-wide cw Raman continuum with a spectral power density higher than 10 mW/nm is generated in a completely fiber-integrated, single-mode format. © 2003 Optical Society of America

OCIS codes: 140.3510, 060.4370.

In holey fibers peak powers of a few kilowatts are sufficient to initiate Raman and self-phase modulation supported continuum generation in conditions of anomalous dispersion. This has been demonstrated with bulk format picosecond and femtosecond laser sources operating in the visible and near infrared and delivering a few kilowatts of peak power. With such high-intensity optical pulses bulk coupled in a short length of holey fiber, additional continuum components can be generated because of four-wave mixing and harmonic generation with the participation of higher-order modes. In the short-pulse regime additional effects of high-order soliton breakup, multisoliton compression, and self-frequency shift, as originally discovered in anomalously dispersive single-mode fibers, can naturally contribute to continuum generation in holey fibers as well. The alternatives to the high-peak-power requirement are increasing the effective length of nonlinear interaction governed by the optical losses of the fiber and reducing the dispersive walk-off of the pump and continuum pulses. In the case of holey fibers their waveguide losses, possible non-single-mode propagation of continuum components, and water-peak absorption at ~1380 nm will lead to wavelength-dependent losses for continuum components and to an inevitable reduction of the effective nonlinear length $L_{\text{eff}} = [1 - \exp(\alpha L)]/\alpha$, where $\alpha$ is the linear losses of the fiber and $L$ is its physical length. On the other hand, the use of nanosecond-scale pump pulses minimizes the dispersive walk-off effect in the fiber but lowers the peak power under the same average-power pumping conditions. In such a situation stimulated Raman scattering (SRS) can be engaged as a principal nonlinearity for continuum generation in holey fibers. With nanosecond pulses this has been proved by using a microchip and Yb fiber pump sources.

In this Letter we demonstrate the possibility of low-peak-power and even purely cw, multiwatt Raman continuum generation with average powers as high as 4.1 W and present results on the efficiency of Raman continuum generation in holey fibers under the conditions of variable peak power and interaction length. The maximum available spectral power density of the continua is found to be limited by the water-peak-associated absorption of holey fibers and the corresponding reduction of the effective length of the SRS. The direct splicing of a Yb-doped master oscillator power fiber amplifier pump source to the holey fiber also allowed us to avoid excitation of the higher-order modes in the holey fiber and to achieve spectral power densities of tens of milliwatts per nanometer in the single-mode fiber format.

Figure 1 illustrates the experimental schematic. A seeded Yb-doped fiber amplifier in a master oscillator power fiber amplifier configuration similar to that described in Ref. 8 with average output as high as 15 W in a single-mode, isotropic fiber format was employed as the pump. The 10-mW signal of the seed fiber laser at 1065 nm with a linewidth of 0.1 nm was modulated by a LiNbO$_3$ amplitude modulator that allowed the pulse duration and repetition rate at the high-power output to be varied. The source was capable of operating in the cw regime, as well as with duty factors from 1 to ~100, so that the available peak-power budget was as high as 1.5 kW at the maximum average-output-power level of 15 W. The output 6-μm-core-diameter fiber was directly spliced to the high-power optical isolator, which in turn was spliced to the holey fiber under investigation. The polarization-independent isolator had 0.8–1.0-dB losses and provided isolation better than 35 dB.

Two types of holey fiber were used for Raman continuum generation. The first fiber (HF1) was 20 m long and had a core diameter of 2.6 μm, a pitch of $\Lambda = 1.9 \mu m$, an air-hole diameter of $d = 0.67 \mu m$, and an anomalous dispersion of +45 ps nm$^{-1}$ km$^{-1}$ at 1 μm. The second fiber (HF2), with a slightly lower dispersion of +35 ps nm$^{-1}$ km$^{-1}$, was 100 m long and had a 2.3-μm core, $\Lambda = 1.72 \mu m$, and $d = 0.65 \mu m$.

Figure 1. Experimental configuration. SM, single-mode.
The normalized frequency $V$ for HF1 and HF2 was estimated by the method in Ref. 9 and was $-2.1$ at 1065 nm, which implied single-mode propagation for the pump and continuum wavelengths as long as no higher-mode excitation due to the bulk coupling was engaged. By using a filament splicer, we developed a splicing technique that resulted in a significant reduction of the mode mismatch of the output single-mode and holey fibers. This technique allowed us to obtain splices with loss as low as 0.8 dB, whereas the calculated minimal mismatch for 6-, 7- and 2.6-$\mu$m core fibers predicts a loss of 3.6 dB. These splices experienced no damage with average powers as high as 10.5 W and pulse energies as high as 3.5 $\mu$J. Because of the residual losses in the splices and the isolator (Fig. 1), the maximum average power delivered to the core of HF1 and HF2 did not exceed 9 W. This value was below the Brillouin cw threshold power, which was estimated at 59.1 and 9.3 W in HF1 and HF2, respectively. In this estimate we took into account the anisotropy of the holey fiber and the pump laser's linewidth of 0.1 nm. We also point out that the efficiency of the SRS was not restricted in HF1 or HF2 because of the dispersive walk-off. In quasi-cw pumping with 2–3-ns pulses the walk-off length in HF1 and HF2 did not exceed 10% of the pulse duration and could be neglected.

By changing the seed signal's duty factor, the peak power in the holey fibers was varied from a few watts to as high as 400 W. In HF1 the maximum 4.1-W-average-power, a 200-nm-wide continuum (20 mW/nm) was obtained at a 100-W-peak-power level of the pump [Fig. 2(a)] with 3.5-ns pulses at a 25-MHz repetition rate. With an increase in the pump peak power beyond the 100-W level the spectral power density of the continuum starts decreasing because of the reduction of the power of the output continuum [Fig. 2(b)] and the simultaneous leveling off of the generated continuum width at $\sim$290 nm as a result of the water-peak absorption and the long-wavelength waveguide losses.

In the 100-m HF2 a similar dependence of the continuum average power was observed, although the maximum average power was obtained at a peak power of 8.7 W [Fig. 3(a)]. Consequently, the Yb-seeded source was operated in the cw regime with 8.7 W delivered to the core of HF2. A cw continuum with 3.8 W of power and spectral width of 324 nm (20 dB) was generated. Neither temporal soliton shaping nor its precursor, the modulation instability symmetrical spectral wings, were observed at the output of HF2 across the whole range of cw pump powers, which was as high as 8.7 W in the core of the holey fiber. The flatness of the continuum was $\pm3.5$ dB in the spectral range from 1090 to 1375 nm. As expected in the fiber-integrated format, virtually no higher-order modes were excited at the spliced launching end of the holey fiber, and 98% of the continuum power was contained in the fundamental LP$_{01}$ mode. This was verified by spatial filtering of the fundamental mode and measurement of the amount of power in the higher modes. The average spectral power density of the generated cw continuum was 12 mW/nm.

Estimates for the SRS effective length$^{10}$ can be made by taking into account the experimentally measured optical losses of HF1 and HF2. At 1065 nm HF1 and HF2 had losses of 0.21 and 0.018 dB/m, which corresponded to $L_{\text{eff}}$ of 13 and 85 m, respectively. Therefore outside the region of the water-peak absorption the effective length of the SRS in HF1 was not restricted by the fiber's physical length of 20 m. $L_{\text{eff}}$ dramatically shortened as the continuum extended toward the water-peak absorption, where both HF1 and HF2 showed a peak loss of $\sim$0.6 dB/m. This corresponds to the effective length of the SRS of $\sim$6.7 m in both fibers, and it restricts the nonlinear power transfer to the longer wavelengths.

By the method in Ref. 11 we estimated the effective areas of the LP$_{01}$ mode at 1065 nm to be $\sim7.2\mu$m$^2$ in both HF1 and HF2. Assuming a silica Raman gain at 1 $\mu$m of $\sim1.5\times10^{-13}$m/W and taking into account the aforementioned effective SRS lengths and mode field diameters, one can make straightforward estimates$^{10}$ that show that as many as four Raman orders should be generated in HF1 at a 100-W pump peak power, whereas with 8.7 W in HF2 approximately two Raman orders should be excited (normal dispersion propagation assumed). The additional broadening of the continuum caused by the self-phase modulation contribution that occurs in the pulsed pumping regime does not take place in cw operation. The evidence of purely Raman contribution to cw continuum generation can most easily be seen in Fig. 3(b), where residual peaks

---

**Fig. 2.** (a) 4.1-W (thick curve) and 3.2-W (thin curve) continua generated in HF1 (20 m) at 100-W and 140-W peak-power pump levels, respectively. (b) Average power of the continuum within a 1070–1380-nm spectral window (solid circles) and continuum width (open circles) versus pump peak power.

**Fig. 3.** (a) Average power of the continuum in HF2 (100 m) within a 1070–1380-nm spectral window. (b) 3.8-W cw continuum in HF2 at the 8.7-W pump power level.
of the Stokes orders are apparent, compared with the pulsed regime [Fig. 2(a)], where Raman peaks are mostly lost. At the same time we point out that the absence of anti-Stokes Raman components in the continua (Figs. 2 and 3) indicates that under the given pumping conditions no interaction of SRS components via parametric four-wave mixing took place in the holey fibers because of the relatively high dispersions of +35 and +45 ps nm$^{-1}$ km$^{-1}$.

In conclusion, in this Letter we investigated and demonstrated the possibility of low pump peak power, including purely cw, multiwatt, Raman-dominated continuum generation in holey fibers. The 324-nm-wide cw continuum with power as high as 3.8 W was generated in 100 m of holey fiber. The maximum spectral power density of the continua was limited by the water-peak absorption of the fiber at 1380 nm and by the corresponding reduction of the effective SRS length. As a result of this work, the fully fiber-integrated, single-mode, cw white-light source with a 12-mW/nm spectral power density in a 1065–1375-nm wavelength range has been demonstrated. Such a compact source with this relatively high spectral power density could have many applications in interferometry and optical coherence tomography.

The demonstrated technique can be widely applied to any fiber-based pump. We are currently investigating such schemes with power scaling of another order of magnitude.

The support of IPG Photonics is greatly appreciated. Popov's e-mail address is s.popov@ic.ac.uk.

*Also with NTO IRE-Polus, Vvedenskogo Square 1, Fryazino, Moscow 141190, Russia.

References