

# A high coherence supercontinuum source at 1550 nm

J. W. Nicholson, M. F. Yan, A. Yablon, P. Wisk, J. Fleming,  
F. DiMarcello and E. Monberg

*jwn@ofsoptics.com*

*OFS Labs, 600-700 Mountain Avenue, Murray Hill, NJ 07974*

**Abstract:** We present a low noise supercontinuum source based on a femtosecond fiber laser. Varying the dispersion along the fiber length generates a flat, symmetrically broadened continuum. No degradation in coherence is observed.

© 2003 Optical Society of America

**OCIS codes:**

Spectral slicing of supercontinua has been proposed as a means of generating many different WDM signals from a single laser source [1]. Previous work has used picosecond pulse sources launched into kilometer lengths of continuum generating fiber. Anomalous dispersion fiber is capable of generating the broadest continuum but the coherence of a supercontinuum generated with ps pulses in anomalous dispersion is not maintained [2]. Dispersion decreasing fiber (DDF) generates a broader, flatter continuum than anomalous or negative dispersion fiber, but even with DDF, coherence is not maintained over the full width of the continuum. Since coherence degradation corresponds to increased timing jitter and amplitude fluctuations, it is critical that coherence be maintained for the supercontinuum to be used in many applications.

Recent simulations have modeled the loss of coherence in continuum generation in cm long lengths of small core microstructure fibers pumped by 800 nm, Ti:sapphire pulses [3]. These numerical simulations show that coherence is better maintained as the launched pulse becomes shorter. For pulses shorter than 100 fs, no loss of coherence was observed over the entire length of the continuum, while for launched pulses longer than 150 fs coherence was severely degraded. Therefore one expects that using shorter pump pulses at 1550 nm should also help to better maintain the coherence of the supercontinuum.

Recently, low dispersion slope, dispersion shifted highly nonlinear fibers (HNLF) have been developed [4]. In this work, we show that significant supercontinuum generation can be obtained at low powers with femtosecond pulses in short (few meter) lengths of HNLF. By altering the dispersion along the length, the generated supercontinuum is significantly broader and flatter than HNLF with constant dispersion. Finally, we show that coherence is not degraded in the supercontinuum generating process.

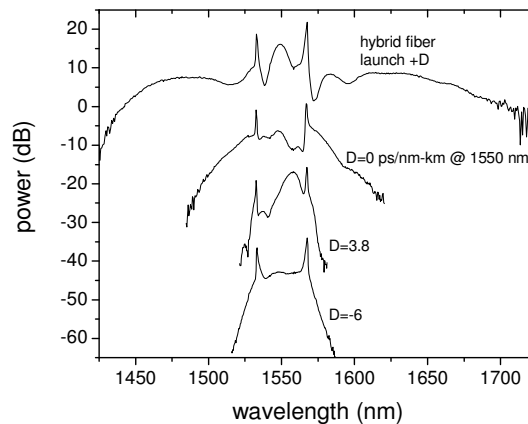


Fig. 1. Supercontinuum for different fiber dispersions at 0 dBm launch power.

Lengths of HNLF with different dispersion were drawn from the same preform by varying the diameter slightly during the draw. Measured attenuation was 1.1 dB/km at 1550 nm. The dispersion slope was 0.024 ps/nm<sup>2</sup>-km at 1550 nm. The effective area of the HNLF,  $A_{eff} \approx 13.9 \mu\text{m}^2$  at 1550 nm, and the nonlinear coefficient,  $\gamma \approx 8.5 \text{ W}^{-1}\text{km}^{-1}$ , were calculated from the measured index profile. We found that the HNLF could be fusion spliced to itself with 0.02 dB loss. Therefore, we could create an arbitrary variation of the dispersion map along the length of the continuum generating fiber by splicing together sections of

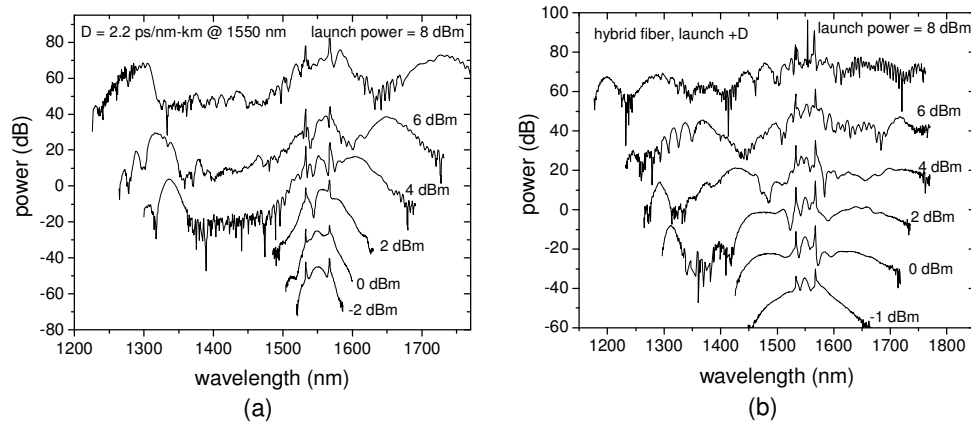


Fig. 2. Supercontinuum as a function of launch power for (a) 10 m of  $D=2.2$  ps/nm-km (b) 6 m hybrid fiber.

different dispersion HNLF. We created a 6 m long hybrid HNLF consisting of 4 sections of 1.5 m lengths of HNLF with dispersion, in order,  $D=3.8$  ps/nm-km at 1550 nm, 2.2, 0, and -6.

A passively modelocked Erbium laser was used as a pulse source for these experiments. The laser operated with a fundamental repetition rate of 33 MHz and an average power of up to 7 mW, and a pulse width of 188 fs. The continuum produced by fibers of different dispersion is shown in Fig. 1 for a launch power of 1 mW. The constant dispersion HNLFs were 10 m long; the hybrid fiber length was 6m. The sharp peaks seen in the spectra are soliton sidebands from the laser oscillator itself [5]. The spectrum from the hybrid fiber, in addition to being very flat, is much broader than the spectra from the other fibers. The 3.8 ps/nm-km fiber shows the beginnings of a soliton pulse breaking off, whereas the negative dispersion fiber shows very little spectrum generation at this power level. The zero dispersion fiber also has a symmetrically broadened spectrum, although much narrower than that from the hybrid fiber. Dispersion decreasing fiber has been shown to generate a broader, flatter continuum with picosecond pulses through adiabatic compression of solitons [6], and we expect the same mechanism is responsible for the substantially increased broadening in the hybrid fiber.

The continuum generation as a function of launch power is shown for 10 m of the  $D=2.2$  ps/nm-km in Fig. 2a and for the hybrid HNLF fiber in Fig. 2b. Measurement of the spectra was limited to wavelengths less than 1770 nm by the OSA detector. The spectra have been offset vertically for clarity. As the launch power is increased, the positive dispersion HNLF shows the same sequence of events as continuum generated at 800 nm in high delta microstructured fiber. A soliton pulse breaks off and self Raman shifts to longer wavelengths as four wave mixing components are generated at wavelengths shorter than dispersion zero.

In contrast, the spectrum in the hybrid HNLF fiber is generated more symmetrically around the launched pulse wavelength. At high powers, the spectrum is flatter and more filled in at wavelengths shorter than the launched pulse wavelength. Although there is significant structure in the spectra at high launch power, this structure showed excellent long term stability. In general, at a given launch power, the spectrum generated in the hybrid fiber was always broader than the spectra generated in constant dispersion HNLF, even though the hybrid fiber was 4 m shorter.

A quantitative measure of the coherence of a light source is the fringe visibility measured in an interferometer. In order to measure whether the continuum generating process introduces timing jitter or amplitude fluctuations, two independently generated continua must be interfered together. To do this, consecutive pulses in the pulse train were interfered in an interferometer with an additional delay in one arm of the interferometer equal to the repetition rate of the laser. The fiber interferometer, depicted schematically in Fig. 3, was made with a 1550 nm, 3 dB coupler. One arm of the interferometer used a metal plated fiber for a reflector. In the other arm, additional fiber was used to achieve a delay equal to the round trip time of the fiber laser. A fiber polarizer ensured parallel polarization at the output of the interferometer.

The interference spectrum of two continua generated in the hybrid fiber from consecutive pulses in the pulse

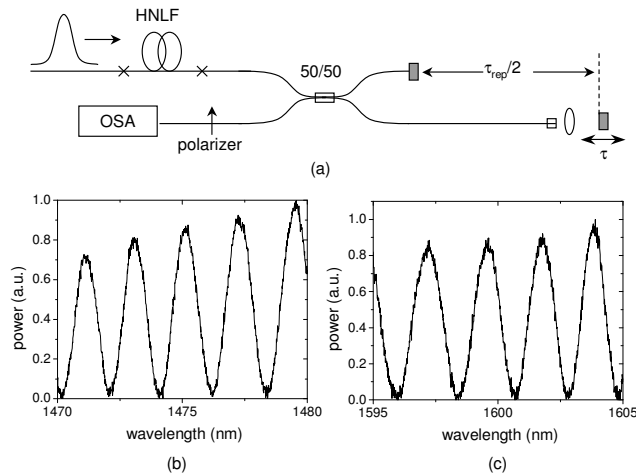


Fig. 3. (a) Interferometer with one arm delayed by the repetition rate of the laser oscillator (b)&(c) Interference fringes at two difference wavelengths in the continuum.

train at 1 mW input power for two different wavelength ranges are shown in Fig. 3b and c. The fringe contrast is a maximum; that is, the fringes go to zero showing complete destructive interference. In fact, a fringe visibility of one was observed over the entire length of the continuum for spectra generated in both the hybrid fiber and the constant dispersion HNLf fiber. A fringe visibility of one was also observed in continuum generated in 10 m of  $D=3.8$  ps/nm-km fiber. In contrast, when amplified 1.5 ps pulses were used to generate a 100 nm broad continuum in 1 km of  $D=3.8$  ps/nm-km fiber, the interference between independently generated continua showed a fringe contrast of less than 0.1. Therefore, the coherence was significantly degraded when the continuum was generated when picosecond pulses.

In conclusion, continuum generation was observed in short lengths of HNLf pumped by 188 fs pulses from a passively modelocked Er fiber laser. By fusion splicing together HNLfs of different diameter, we created a hybrid fiber where the dispersion varied along its length. In contrast to the continuum generated in positive dispersion HNLf, the continuum from the hybrid fiber was flat, and generated symmetrically around the pump wavelength. Finally, coherence was maintained when the continuum was pumped with 188 fs pulses, indicating the continuum generating process did not introduce extra timing or amplitude jitter. Coherence was lost, however, when the continuum was generated with 1.5 ps pulses. It is possible that optimization of the dispersion map through nonlinear Schrödinger equation modeling, could further enhance the bandwidth over which a flat continuum is obtained. Because this is an all fiber, diode pumped device, it can potentially be made very compact and stable.

The authors would like to thank S. Diddams, N. Newbury, K. Corwin, J. Jasapara, and T. Her for many helpful discussions and suggestions.

## References

1. T. Morioka, S. Kawanishi, K. Mori, and M. Saruwatari. Transform-limited, femtosecond WDM pulse generation by spectral filtering of gigahertz supercontinuum. *Electronics Letters*, 30:1166, 1994.
2. M. Nakazawa, K. Tamura, H. Kubota, and E. Yoshida. Coherence degradation in the process of supercontinuum generation in an optical fiber. *Optical Fiber Technology*, 4:215–223, 1998.
3. J. M. Dudley and S. Coen. Coherence properties of supercontinuum spectra generated in photonic crystal and tapered optical fibers. *Optics letters*, 27(13):1180–1182, 2002.
4. T. Okuno, M. Onishi, T. Kashiwada, S. Ishikawa, and M. Nichimura. Silica-based functional fibers with enhanced nonlinearity and their applications. *IEEE Journal of Selected Topics in Quantum Electronics*, 5(5):1385–1391, 1999.
5. M. L. Dennis and I. N. Duling III. Role of dispersion in limiting pulse width in fiber lasers. *Applied Physics Letters*, 62(23):2911–2913, 1993.
6. K. Mori, H. Takara, S. Kawanishi, M. Saruwatari, and T. Morioka. Flatly broadened supercontinuum spectrum generated in a dispersion decreasing fibre with convex dispersion profile. *Electronics Letters*, 33:1806–1808, 1997.