A dispersion zero near 1300 nm of a narrow-diameter tapered fiber is used to generate broadband, near-infrared light. When femtosecond pulses at 1260 nm with 750 pJ of energy are launched in proximity to the second zero-dispersion wavelength, a continuum spanning 1000–1700 nm is produced. © 2002 Optical Society of America

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waist diameters of 1.0 and 1.1 μm should have the second ZDW at 1240 and 1370 nm, respectively (Fig. 1, inset). Therefore, a tapered fiber was prepared with a targeted diameter within this range. The resulting structure consists of a 20-mm-long taper waist with a diameter of ~1 μm, connected to untapered fiber on each side by 35-mm-long transition regions. The tapering process typically produces waist diameters within 10% of the desired size. The GVD of the tapered fiber at 1550 nm is inferred to be +450 ps²/km from the measured broadening of low-energy laser pulses. This value is consistent with the calculated dispersion profiles for waists in the 1.0–1.1-μm-diameter range.

We numerically model the propagation of intense femtosecond pulses centered at 1260 nm through the tapered fiber. The evolution of the amplitude of the pulse is described by an extended nonlinear Schrödinger equation:

\[
\frac{\partial a}{\partial z} + \frac{i}{2} \beta_2 \frac{\partial^2 a}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 a}{\partial t^3} - i \frac{\beta_4}{24} \frac{\partial^4 a}{\partial t^4} \cdots = i \gamma |a|^2 a - i \frac{\gamma}{T_R} \frac{\partial |a|^2}{\partial t} a. \tag{1}
\]

In Eq. (1), the terms that are proportional to \(\beta_i\) describe the \(i\)th-order dispersion, and those proportional to \(\gamma\) and \(\gamma/T_R\) describe the Kerr nonlinearity and the self-frequency shift as a result of Raman scattering, respectively. The important role played by higher-order dispersion for pulse propagation in microstructured fibers was recently shown, and consideration of this role is also necessary for tapered fibers because of their steep dispersion profiles near the ZDW. To this end, the calculated dispersion profile of the tapered fiber was fitted with a third-order polynomial, accounting for up to fifth-order dispersion. As a first approximation, we assume that the mode-field diameter varies as a linear function of distance in the transition regions, and hence the effective nonlinearity changes by a factor of 70.

For a more comprehensive analysis, it is necessary to consider the evolution of the dispersion in the transition regions as well. The dispersion can vary rapidly, and the details of this evolution are not well known. However, the dispersion in the untapered fiber and in the wider part of the transitions is very small (<+5 ps²/km) at 1260 nm (unlike for previous experiments with Ti:sapphire lasers) and changes little for most of the propagation through the transition regions. Therefore, in the transition region, we include only the variation of the nonlinearity and assume a constant average value (+2 ps²/km) for the dispersion, corresponding to that of untapered fiber. We can justify these assumptions by considering that, to first order, the dispersion and nonlinearity can be decoupled, and the dispersion averages to a small value. However, the nonlinear effects are cumulative and cannot be ignored. This approach produces results that are in good agreement with the experiments discussed below.

Given the experimental uncertainty in the waist diameter of the tapered fibers, we consider fiber diameters within the range 1.0–1.1 μm in the simulations. Propagation of 80-fs pulses centered near 1260 nm with varying energy content is considered. For pulse energies less than ~100 pJ, no significant spectral broadening is observed. At higher pulse energies, the spectrum starts to split near the ZDW. For pulse energies above 500 pJ, a broad spectrum is generated, spanning several hundred nanometers (Fig. 2, top). The fine modulations in the spectrum depend sensitively on input pulse energy and width. In actual experiments, these modulations would average out and would not be observed because of rapid, random variations of the input pulse parameters. The details of the resulting spectra depend sensitively on the assumed parameters of the taper; however, the qualitative features remain unchanged.

A mode-locked Cr:forsterite laser provided 1.5-nJ, transform-limited, 80-fs pulses centered at 1.26 μm. Approximately 50% of the available energy was coupled into the taper’s input fiber, which we kept as short as possible to minimize the initial pulse broadening. The spectra of the output pulses were recorded with an optical spectrum analyzer. Although we observe large amplitude fluctuations in the measured continua because of the sensitivity to input pulse parameters, the overall features of the spectra are reproducible. The evolution of the continuum observed in the experiment with launched pulse energy varying from 7 to 750 pJ is presented in Fig. 3. At low energy, no spectral broadening is observed. As the pulse energy is increased, the spectrum splits. For higher pulse energies, most of the energy is shifted to higher and lower frequencies, which leaves the center of the spectrum largely depleted (Fig. 3, 375–750 pJ). The observed features agree qualitatively and semiquantitatively with the numerical simulations and are consistent with nonlinear pulse propagation at the second ZDW. The experimental spectrum corresponding to 750-pJ pulse energy is plotted in Fig. 2 (bottom) for comparison with the

![Fig. 2. Comparison of numerical simulations (top) and experimental results (bottom) for 750-pJ, 80-fs pulses at 1.26 μm (darker curves) and 350-pJ, 100-fs pulses at 1.55 μm (lighter curves). The input spectra are shown as dotted curves.](image-url)
numerical results (Fig. 2, top). The spectrum spans 700 nm at the points 20 dB from the peak of the continuum. Intuitively, the sign of the third-order dispersion at the second dispersion zero reduces the effects of Raman scattering, thereby producing an approximately symmetric spectrum. As a result, the shape and width of the spectrum are roughly as expected from the action of self-phase modulation alone. Numerical simulations show that, with a pulse energy of a few nanojoules, the continuum will span an octave of frequency. In generating self-referenced optical frequency combs, the shape of the spectra observed here is advantageous because maximal energy resides at the ends of the octave.

As a control experiment, 100-fs pulses at 1550 nm from an Er-doped fiber laser were coupled into the same tapered fiber. We observed no significant spectral broadening of the pulses at the highest coupled pulse energy of ~350 pJ, in accordance with the numerical simulations (Fig. 2). This result should be contrasted with propagation at 1260 nm, where a continuum spanning 360 nm (at the ~20-dB points) is generated for similar pulse energy.

In conclusion, we have demonstrated that a tapered fiber is an effective medium for generating broadband light in the near infrared by the use of its second ZDW. Unamplified femtosecond pulses from a Cr:forsterite laser were spectrally broadened to cover 700 nm, from 1000 to 1700 nm. By changing the diameter of the tapered fiber’s waist, this method for continuum generation about the second ZDW should be easily adapted to other wavelengths. We expect continua generated this way to find application in high-resolution biological imaging systems as well as in frequency metrology for telecommunications.

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