Long-wavelength continuum generation about the second dispersion zero of a tapered fiber

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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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Much attention has been paid to the spectral broadening of femtosecond pulses that occurs in microstructured and tapered fibers.[1–3] To date, experiments in this area have been performed at pump wavelengths near 800 nm. A number of applications motivate the development of similar broadband light sources at longer wavelengths. For example, such a light source centered around 1300 nm would allow optical Doppler tomography that would provide micrometer-resolution imaging of blood circulation and tissue structures *in vivo*.[4] In a separate application, octave-spanning continua near 1300 and 1550 nm are desired to establish time and frequency standards for telecommunications by use of self-referenced optical combs that are directly linked to atomic transition frequencies.[5]

A requirement for the generation of broadband continua is small group-velocity dispersion (GVD) at the propagating wavelengths. In addition to reducing dispersive spreading of the input pulse, propagation near the zero-dispersion wavelength (ZDW) allows phase matching and group-velocity matching of four-wave mixing processes. The propagation of intense femtosecond pulses near the ZDW of ordinary single-mode fiber leads to spectral splitting through self-phase modulation, four-wave mixing, and stimulated Raman scattering, but substantial spectral broadening is not observed.[6] In a tapered fiber designed to maximize nonlinear effects, Dumais *et al.* observed enhanced spectral broadening of 350-fs pulses.[7] The small mode area in microstructured and tapered fibers increases the effective nonlinearity and produces strong waveguide dispersion. The latter shifts the ZDW from ~1300 nm in fused silica to ~800 nm, coincident with the center wavelength of Ti:sapphire lasers. In principle, one can exploit waveguide dispersion to move the ZDW to wavelengths longer than 1300 nm, but only at the expense of reduced effective nonlinearity: A larger mode area would be required.

It is known that higher-order dispersion produces a second ZDW at longer wavelengths in microstructured and tapered fibers (Fig. 1), and Gaeta has suggested using these zeros for continuum generation at infrared wavelengths.[8] When the short-wavelength ZDW is pushed to visible wavelengths through tight mode confinement, the second ZDW moves into the 1–2-μm range. In this Letter we show that this second ZDW can be exploited to generate continua centered on ~1300 nm. Femtosecond pulses from a mode-locked Cr:forsterite laser are launched into a tapered fiber designed to have the second ZDW at the center laser wavelength, ~1260 nm. For pulse energies of ~1 nJ, continua spanning 700 nm (>100 THz) are produced.

We calculated the GVD of the waist of the tapered fiber by assuming a step-index waveguide with a pure silica core and a free-space cladding. The propagation constant of the fundamental mode was calculated as a function of wavelength from the characteristic equation for the vector wave equation, with the index of silica given by a Sellmeier formula. The propagation constant was then numerically differentiated to yield the GVD. For continuum generation near 1300 nm, this calculation indicates that tapered fibers with

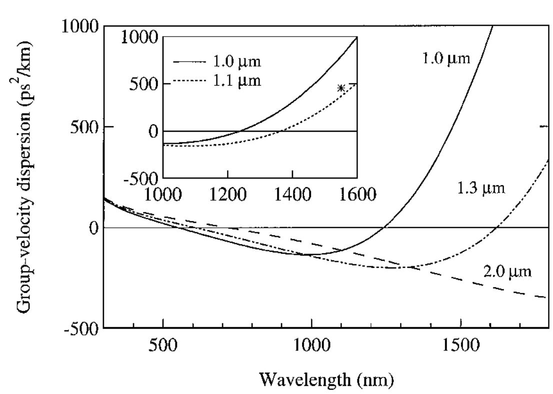

Fig. 1. Calculated GVD for 1.0-, 1.3-, and 2.0-μm-diameter waist tapered fibers. The inset shows the GVD of the 1.0- and 1.1-μm waist tapers in proximity to their second ZDWs, and the asterisk shows the dispersion value measured at 1550 nm.

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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.[2] 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 $+450$ ps^2/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:

$$\frac{\partial a}{\partial z} + i\,\frac{\beta_2}{2}\,\frac{\partial^2 a}{\partial t^2} - \frac{\beta_3}{6}\,\frac{\partial^3 a}{\partial t^3} - i\,\frac{\beta_4}{24}\,\frac{\partial^4 a}{\partial t^4}\cdots = i\gamma|a|^2 a - i\,\frac{\gamma}{T_R}\,\frac{\partial |a|^2}{\partial t}\,a\,. \quad (1)$$

In Eq. (1), the terms that are proportional to β_i describe the ith-order dispersion, and those proportional to γ and γ/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,[8] 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 ($<+5$ ps^2/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 ($+2$ ps^2/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.[2] 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.[9] 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

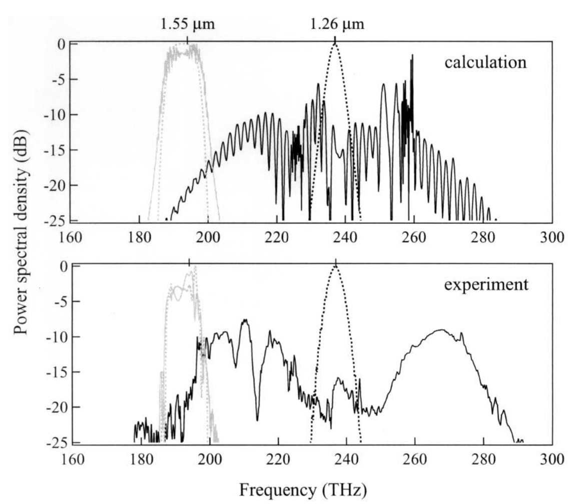

Fig. 2. Comparison of numerical simulations (top) and experimental results (bottom) for 750-pJ, 80-fs pulses at 1.26 μm (darker curves) and 350-pJ, 100-fs pulses at 1.55 μm (lighter curves). The input spectra are shown as dotted curves.

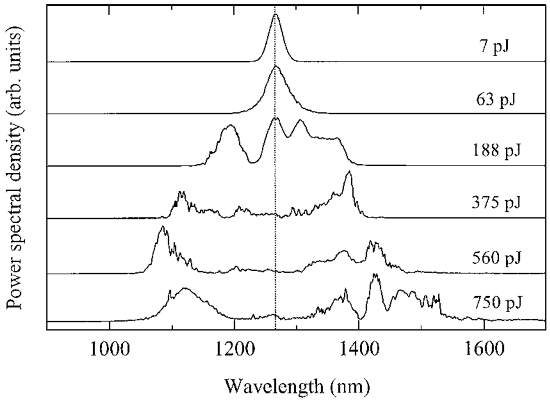

Fig. 3. Experimentally observed evolution of the continuum with pulse energy. The dotted line indicates the center of the input spectrum.

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 $\sim$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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