Widely tunable femtosecond pulses from a tapered fiber for ultrafast microscopy and multiphoton applications

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Abstract. Sub-50fs transform limited pulses are produced in the 670-1050nm range by compressing sections of the ultrabroadband supercontinuum generated in a tapered fiber injected with pulses from a cavity dumped Ti:Sapphire laser. 2-Photon imaging of fluorescent beads is demonstrated. Biological and chemical applications are discussed.

1. Introduction

The recent introduction of new types of optical fibers with novel nonlinear properties has caused much excitement in part because of their ability to generate an ultrabroadband continuum spanning the visible to the near IR. Most of the attention has been focused on microstructured, so called “holey,” photonic crystal fibers (PCF’s) that consist of a 2-D hexagonal array of airholes surrounding a central 1-2µm diameter fused silica core.[1] Through an effective index of refraction model, the airholes act as an air cladding and shift the zero GVD-wavelength of the fiber into the visible, thereby allowing very long nonlinear interaction lengths for propagating pulses of the appropriate wavelength. Unamplified Ti:Sapphire (Ti:S) lasers operating around 800nm have been used as the primary sources to demonstrate continuum generation as well as other nonlinear processes and optical meteorologies.[2-4] Tapered fibers, or standard single-mode fibers that have had a length of their midsection uniformly reduced to 1-2µm in diameter, have been used in a similar manner to generate broad continua.[5] Tapered fibers are superior to PCF’s as stable continuum sources because of their more robust coupling conditions as well as their higher damage threshold. Even though the spectral output of both types of fibers have been well documented, the time domain output still remains relatively uninvestigated. Furthermore, few applications that utilize short duration pulses from microstructured fiber sources have been reported.

2. Experimental Methods

Experiments were conducted with a home-built cavity dumped Ti:S laser that delivered 30nJ, 16fs pulses centered at 800nm at a 125kHz repetition rate.[6] 10nJ of this light was sent through a prism-pair precompensation line and then focused into the tapered fiber through a 10x plan-achromat objective. The remaining light was diverted and used as a gate pulse for cross-correlation analyses of the continuum performed by sum frequency generation in a thin Type I BBO crystal. The tapered fiber was 17.5cm overall in length with a midsection uniformly narrowed to a diameter of 2.5µm (zero GVD point ~800nm) that was approximately 9cm in length. The output of the fiber was recollimated with a 20x plan-achromat objective or aspheric lens and recompressed in a prism-pair postcompensation line. Spectral selection was achieved with an adjustable pair of razor blades on the back mirror plane of the prism line, and the pulses then sent either to the cross-correlation apparatus or directly to the 2-photon microscope.

The 2-photon microscope consisted of a 100x oil immersion objective (Zeiss) mounted horizontally on a piezo actuated XYZ stage. Epi-detected fluorescence was separated from the excitation pulses with a dichroic mirror (Chroma), detected with a fiber-coupled PMT, and acquired with a photon counter.

3. Results and Discussion

Figure 1 shows the cross-correlation of a 35nm FWHM continuum slice centered at 930nm. The gate-deconvoluted near-IR pulse is a 38fs FWHM nearly transform limited Gaussian. Pulses of comparable duration (<50fs) have been obtained at other wavelengths in the 670-1050nm range. Since the full continuum extends beyond our detector range (650-1250nm), various applications beyond the spectral coverage of Ti:S lasers are envisioned.

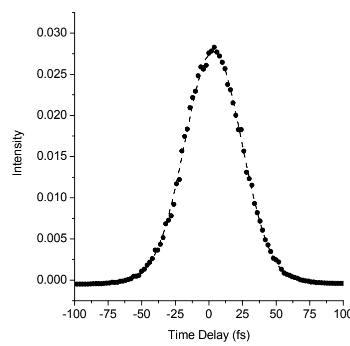

Fig. 1. Cross-correlation of imaging pulse

2-photon imaging was demonstrated with yellow-green fluorescent beads (Molecular Probes) with a 1-photon absorption maximum at 500nm and emission maximum at 510nm. Bead samples were placed between coverslips and mounted on an XY piezo scanstage (Queensgate) that was raster scanned to acquire an image. 2-photon excitation was achieved with the 38fs transform limited 930nm pulses characterized in Figure 1. Fig. 2(b) shows the image obtained from raster scanning a roughly 13µm x 13µm area. Individual beads are well resolved. Fig. 2(a) shows a cross-sectional slice of one 500nm bead with a fitted FWHM of 380nm, implying some bead sectioning.

These short duration tunable pulses are intended for microscopy applications that allow novel functional imaging and study of dynamics from sub-micron regions and nanostructures. Extension of 2-photon interferometry measurements of individual particles [7] are in progress. The multi-spectral potential of the tapered

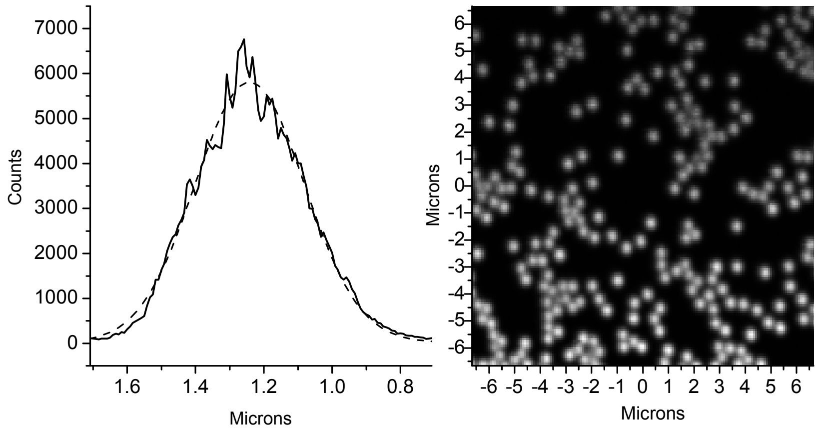

Fig. 1. (a) Cross-section of a 500nm diameter bead (solid) with a Gaussian fit (dotted). (b) 13µm x 13µm 2-photon image of 500nm diameter fluorescent beads.

fiber source can be employed for sub-diffractive imaging of molecular relaxation by 2-color stimulated emission depletion (STED).[8] The time-resolved chemical dynamics of processes like solvation can be studied within 100 attoliter focal volumes in heterogeneous systems like argarose gels and intracellular environments. Similarly, the extension of 2-photon microscopy [9] to a 2-color 2-photon variant for the ratiometric study of multiple (indigenous or exogenous) fluorophores becomes more straightforward.

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References

1 T.A. Birks, J.C. Knight, and P. St. J. Russell, *Opt. Lett*. 22, 961-963 (1997).
2 J.K. Ranka, R.S. Windeler, and A.J. Stentz, *Opt. Lett*. 25, 25-27 (2000).
3 J.E. Sharping, M. Fiorentino, A. Coker, P. Kumar, and R. Windeler, *Opt. Lett.* 26, 1048-1050 (2001).
4 S.A. Diddams, et al, *Phys. Rev. Lett.* 84, 5102-5105 (2000).
5 T.A. Birks, W.J. Wadsworth, and P. St. J. Russell, *Opt. Lett.* 25, 1415-1417 (2000).
6 Y.-H. Liau, A.N. Unterreiner, D.C. Arnett, and N.F. Scherer, *Appl. Opt*. 38, 7386-7392 (1999).
7 Y.-H. Liau, A.N. Unterreiner, Q. Chang, and N.F. Scherer, *J. Phys. Chem. B.* 105, 2135-2142 (2001).

8 M. Dyba, T.A. Klar, S. Jakobs, and S. W. Hell, *Appl. Phys. Lett*. 77, 597-599 (2000).
9 W. Denk, J.H. Strickler, W.W. Webb, *Science* 248, 73-76 (1990).