Enhanced two-photon excitation through optical fiber by single-mode propagation in a large core

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Multiphoton excitation through optical fibers is limited by pulse broadening caused by self-phase modulation. We show that for short fiber lengths (approximately 2 m) two-photon excitation efficiency at the fiber output can be substantially improved by single-mode propagation in a large-area multimode fiber (10-μm core diameter) instead of a standard 5.5-μm core fiber. Measurements and numerical simulations of postfiber spectra and pulse widths demonstrate that the increase in efficiency is due to a reduction of nonlinear pulse broadening. Single-mode propagation in a large-core fiber is thus suitable for multiphoton applications for which pulse recompression is not possible at the fiber end. © 2002 Optical Society of America

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1. Introduction

Multiphoton excitation (MPE) of fluorophores has become a well-established method in optical microscopy, especially for imaging living biological tissue.[1,2] For a number of applications efficient MPE through optical fibers is desirable. For example, single-mode fibers (SMFs) can be used to mechanically uncouple microscopes from a laser source.[3] Optical fibers can also be inserted directly into biological tissue to obtain spatially confined fluorescence signals by use of MPE.[4] Because of its nonlinear dependence on laser intensity, efficient MPE depends on the use of subpicosecond laser pulses. On propagation through normally dispersive fibers, such pulses are, however, substantially broadened because of the dispersive and nonlinear properties of the fiber. Although ultrashort pulses can be transmitted through optical fibers even at high pulse energies by use of the principle underlying chirped-pulse amplification,[5] this transmission scheme relies on pulse recompression after the fiber to recover a transform-limited pulse length. Hence, it is not suitable in situations for which short pulses are needed immediately at the end of the fiber, for example, in potential applications such as fiber-optic fluorescence sensors that can be inserted into tissue, or compact, flexibly tethered microscopes suitable for endoscopic use.[6,7] If no postfiber recompression is possible, the shortest achievable pulse length, even with optimized prechirping, increases sharply beyond rather moderate pulse energies.[8,9] This pulse broadening is due to self-phase modulation[5] (SPM) and currently limits the MPE efficiency that can be achieved at the far end of an optical fiber.[10]

Nonlinear pulse propagation through fiber can be described by the nonlinear Schrödinger equation (NLSE), which includes SPM as nonlinearity coefficient γ. For a fundamental fiber mode $\gamma = (4n_2\omega_0)/(c\pi d^2)$, where n_2 is the nonlinear index coefficient (2.67×10^{-20} m^2/W), ω_0 is the carrier frequency, c is the speed of light, and d is the mode-field diameter.[5] The effect of nonlinearity decreases when mode-field diameter d increases as light energy is distributed over a larger area and peak intensities are smaller. Although a reduction of nonlinear pulse broadening can thus be expected for fibers with a larger core, an increase in core size usually conflicts with the requirement of single-mode propagation that is essential for high-resolution microscopy. Larger cores support propagation of several transverse modes that cannot be focused to a single diffraction-limited point. For a limited transmission distance this conflict can

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be solved. Fermann has demonstrated that in relatively stiff multimode fibers (with a large cladding diameter) propagation of the fundamental mode is possible over a distance of several meters with negligible coupling to higher modes.[11] As some applications of MPE through optical fibers require only relatively short fibers,[7] such fundamental-mode propagation through a multimode fiber could be used to improve the efficiency of MPE at the fiber output by the reduction of SPM-induced pulse broadening. Here we test this possibility by comparing two-photon excitation (TPE) through a special large-core (and large-cladding) fiber with a standard SMF using 100-fs laser pulses at a wavelength of 850 nm. Clean fundamental-mode excitation in the special fiber was assured by use of a tapered region at the fiber input. We characterize the propagation of prechirped pulses in both fibers and demonstrate that nonlinear pulse broadening is reduced in the large-core fiber and that the efficiency of TPE at the output of the large-core fiber consequently is enhanced compared with standard SMF.

2. Materials and Methods

Two different fibers were compared: (1) a standard SMF with a 5.5-μm mode-field diameter (FS-SN-4224 from 3M) and (2) a specialty fiber with a 10-μm fundamental mode-field diameter, a 250-μm cladding diameter and 0.09 numerical aperture (INO Company, Quebec, Canada). The relatively stiff large-core fiber was operated well below its single-mode cut-off wavelength (at 850 nm the fiber supports propagation of approximately eight modes) but was preceded by a short segment of small-core fiber. This segment was created near the fiber input by drawing a 4-cm-long region to approximately half-diameter. The tapered region was bathed in index-matching fluid and served as a spatial filter to strip off higher modes. As the power coupled into higher-order modes increases quadratically with length if the higher-order modes are initially unpopulated (with mode coupling length of several meters for sufficiently stiff fibers),[11] power loss to higher-order modes can be kept negligible for short transmission distances. In an approximately 2-m-long fiber, no mode coupling was apparent; single-mode output was confirmed from far-field images taken at the fiber end. No significant SPM is expected in the mode-stripping region in spite of the small core diameter because pulses were negatively prechirped (to compensate for fiber dispersion; see below) and are, therefore, still relatively long at the beginning of the fiber.

Laser pulses from a Tsunami Ti:sapphire laser system with an 80-MHz repetition rate (Spectra Physics) were coupled to 1.7-m-long fiber pieces, and output pulses were analyzed with an SF2000 spectrometer (Ocean Optics) and a custom-built autocorrelator (Fig. 1). Laser pulses were prechirped through a double passing of a pair of diffraction gratings with 400 grooves/mm and a 9.7° blaze angle (Richardson Grating Laboratory) providing negative group-velocity dispersion[12] before they were coupled to the fiber with an $f = 18.4$-mm aspheric lens (Geltech). Pulses at the laser output had an intensity autocorrelation width of approximately 110–120 fs (corresponding to an 80–85-fs pulse width for a Gaussian-shaped pulse) with a spectral width (FWHM) of 13–14 nm at a center wavelength of 850 nm. The time–bandwidth product was approximately 0.45, indicating near-transform-limited pulses. A diffusion-type GaAsP photodiode (Hamamatsu G1115) was used as the nonlinear (two-photon absorption) detector for interferometric measurement of the second-order autocorrelation.[13] The one-photon absorption spectral bandwidth for this photodiode ranges from 300 to 680 nm with a sharp cutoff at 680 nm. The wavelengths used in our experiments (around 850 nm) are well below the bandgap precluding linear, i.e., one-photon absorption. The use of a GaAsP photodiode for second-order autocorrelation measurements is described in detail in Ref. 13. We calculated the intensity autocorrelation traces from the interferometric traces using a rolling average over ten fringes. The FWHM of the intensity autocorrelation trace Δt was used as a measure for the pulse width [Fig. 2(a)]. No pulse-shape correction factor was applied since no information about the detailed pulse shape was available for the high-energy pulses at the fiber output.

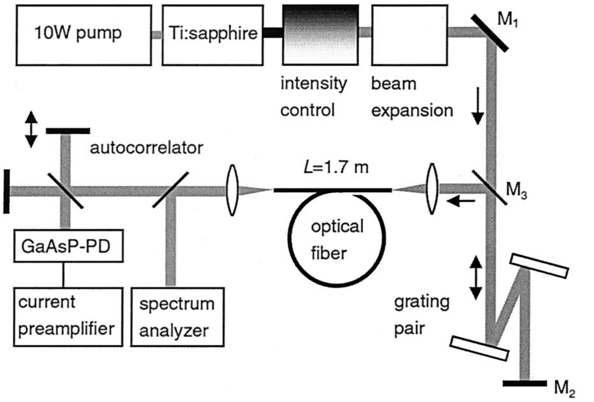

Fig. 1. Optical setup. Ultrashort laser pulses from a Ti:sapphire laser double pass a pair of diffraction gratings before being coupled into the fiber. Output pulses are characterized by use of an interferometric autocorrelator and a spectrum analyzer. PD, photodiode.

Experimental results were compared to numerical simulations of nonlinear pulse propagation performed in the IGOR software environment (WaveMetrics). The NLSE was numerically solved for Gaussian-shaped, negatively prechirped pulses by use of the split-step Fourier method.[5] Second- and third-order dispersion of the grating pair were considered for the prechirp. Only SPM was included in the nonlinear term. The step size was 1 cm (a test at 0.01-cm step size changed results by $<1\%$). Pulse energy was conserved throughout propagation.

3. Results

We first characterized propagation of negatively prechirped laser pulses through the two different fibers

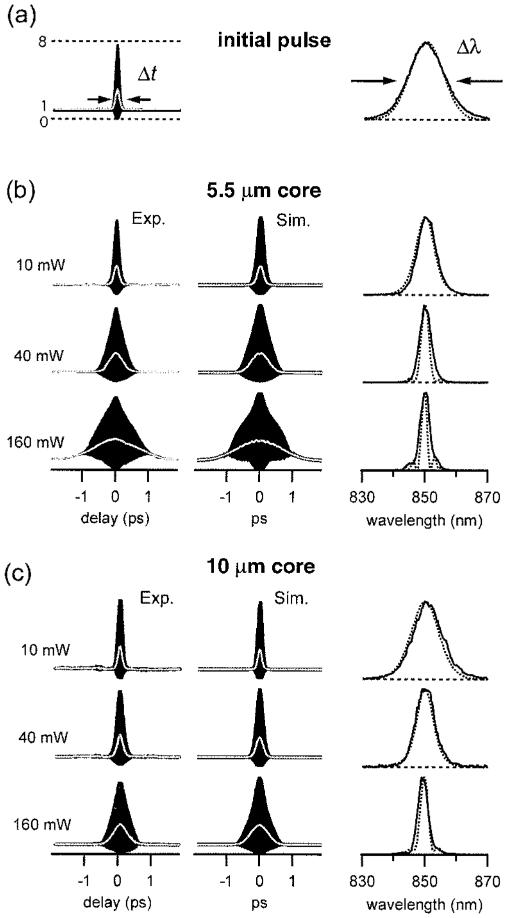

Fig. 2. Pulse propagation in 5.5- and 10-μm core fiber as a function of average transmitted power. (a) Autocorrelation traces (left) and normalized spectrum (right) for the initial pulse. Interferometric traces are bold, derived intensity traces are lightface. Experimental (left) and simulated (middle) autocorrelations, and spectra (right, simulated spectra dashed) for (b) a 5.5-μm and (c) 10-μm core fiber at three different power levels. We adjusted the grating distance to minimize the output pulse width at low power.

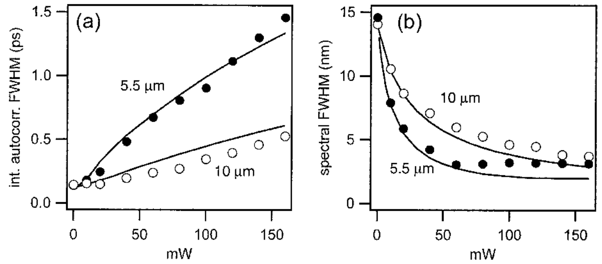

Fig. 3. Pulse broadening and spectral compression as a function of average transmitted power. FWHM of (a) intensity autocorrelation and (b) spectrum for a 5.5-μm core fiber (filled circles) and a 10-μm core fiber (open circles). The solid curves represent the numerical simulations.

as a function of average transmitted power (Fig. 2). At low pulse energies (<0.12 nJ, <10-mW average power), pulses with only slightly increased pulse widths could be obtained at the output of both fibers simply by appropriately prechirping. A negative prechirp of approximately $-60{,}000$ fs^2 was required to compensate for 1.7-m-long fiber corresponding to a fiber dispersion of approximately 350 fs^2/cm (322 fs^2/cm expected for silica). At 10-mW the pulse width could be restored to 131% and 108% of its initial value in the SMF and in the 10-μm core fiber, respectively. We then increased the average power while maintaining the amount of prechirp. Above 10 mW, progressive pulse broadening and spectral compression became apparent in both fibers indicating the onset of intensity-dependent nonlinear effects [Figs. 2(b), 2(c), and 3]. Spectral compression rather than broadening occurred because of the negative prechirp.[8,9] Most notably, the nonlinear effects on pulse length and spectrum were substantially smaller in the large-core fiber. Although the autocorrelation trace broadened to approximately 1.4 ps at 160 mW in the SMF, the width increased to only 0.5 ps in the large-core fiber [Fig. 3(a)]. As expected from the inverse quadratic dependence of nonlinearity coefficient γ on mode-field diameter d in the NLSE, an approximately fourfold higher laser intensity was needed for the 10-μm core fiber to induce pulse broadening comparable with the 5.5-μm core fiber (compare the traces in Fig. 2). In summary, by using single-mode propagation of prechirped pulses through a large-core fiber, we were able to obtain high-energy pulses at the fiber output, which were substantially shorter than the pulses propagated through a standard SMF. The large-core fiber therefore should be advantageous for MPE at high power levels.

Autocorrelation traces and spectra as well as the power dependencies of pulse width and spectral width were well reproduced for both fibers in the numerical simulations (Figs. 2 and 3). The deviation of the measured from the calculated spectral widths for the SMF at high power is probably due to the limited resolution of the spectrometer. The slight discrepancy between the simulated and the experimental data in the case of large-core fiber could be due to some uncertainty in the actual mode-field diameter of the propagated fundamental mode. Nevertheless, the general agreement between experiment and numerical simulation, which assumes only a SPM nonlinearity, indicates that SPM is the predominant cause of the observed effects. Our data furthermore indicate that spectral widths at 160 mW are similar for both fibers although the pulse widths are different [Fig. 3(b)], implying a stronger residual chirp for the small-core fiber. This view is supported by the observation that all interferometric autocorrelation traces in Fig. 2 lack an obvious chirp except the trace for the small-core fiber at 160 mW. These findings suggest that, below a certain peak power threshold, pulses are spectrally compressed but remain nearly transform-limited.[9]

We then proceeded to demonstrate directly the improved TPE through the large-core fiber. The fiber output beam was collimated and then focused on a GaAsP photodiode with an $f = 3.1$-mm aspheric lens (Geltech). The two-photon-induced photocurrent

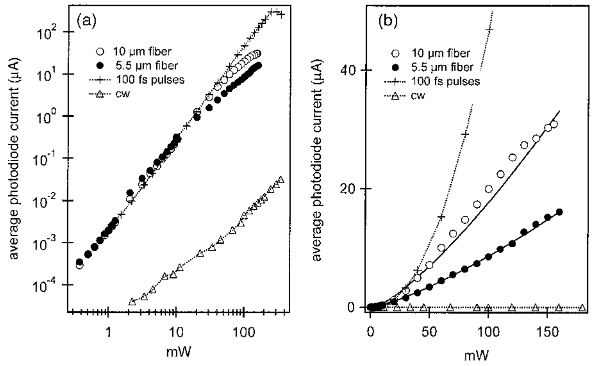

Fig. 4. Two-photon-induced photocurrent in a GaAsP photodiode as a function of average transmitted power for the 5.5-μm (filled circles) and the 10-μm fiber (open circles). (a) Log–log plot including the fiber data as well as photocurrents induced by direct coupling of 100-fs pulses and cw laser light, respectively. Note that photodiode saturation occurs at 300 μA. (b) Same data as in (a) shown as a linear–linear plot. The solid curves represent simulated curves that show the power dependence of two-photon absorption for the two fibers. The simulated curves were scaled to reproduce the data point at 160 mW for the 5.5-μm core fiber.

was measured for both fibers as a function of average fiber output power. Because of the different mode diameters, the output divergence angles from the two fibers differ, resulting in a slight difference in beam diameter. To compare the induced currents directly, we therefore adjusted the beam sizes with an iris aperture so that photocurrents were equal for both fibers at low power (10 mW). As expected for a two-photon process, the induced photocurrent depended quadratically on light intensity as long as the temporal structure of the pulse was unchanged, i.e., for intensities below 10 mW where nonlinear effects in the fiber are negligible (Fig. 4). At higher intensities, however, the power dependence of the photocurrent deviated from the quadratic relationship and became subquadratic. This deviation was not due to photodiode saturation as 100-fs pulses delivered directly from the laser (with beam size adjusted to give the same photocurrent at 10 mW) started to saturate the photodiode only at currents approximately tenfold higher than those maximally observed with the fibers (Fig. 4). Our simulations and pulse width measurements instead suggest that the subquadratic relationship at high power results because the peak pulse intensity increases only moderately above a certain power level while pulses are progressively prolonged. Most importantly, the transition from the quadratic to the subquadratic regime was shifted to higher power values for the 10-μm core fiber. Whereas the SMF data points deviated from the quadratic relationship above 10 mW, this was observed only above 50 mW for the large-core fiber [Fig. 4(a)]. As a consequence, the two-photon-induced photocurrent at high power was approximately twofold larger for the large-core fiber compared with the SMF [Fig. 4(b)]. This directly demonstrates that two-photon excitation through optical fiber at high average power can be enhanced by use of single-mode propagation through a large-core fiber.

4. Conclusion

In summary, we have shown that transmission of negatively prechirped laser pulses through an optical fiber with a large core improves two-photon excitation at the fiber output under circumstances for which no pulse recompression can be used. Such a transmission scheme should therefore prove useful for miniaturized fiber-optic fluorescence probes or microscopes,[7] which are too small to include a postfiber compressor but rely on subpicosecond high-energy pulses to obtain multiphoton-induced fluorescence signals from deep within scattering tissue.[7] Efficient multiphoton excitation in conjunction with fiber optics should make it possible to benefit from the advantages of MPE (such as reduced photobleaching and photodamage as well as inherent optical sectioning properties)[2] in miniaturized and flexible devices. Envisaged applications are endoscopic high-resolution imaging of inner organs, perhaps enabling optical biopsy, as well as *in vivo* fluorescence imaging of animals in motion, which might allow studies on cellular processes in a behavioral context.

The improvement of TPE efficiency in the case of 10-μm core fiber is due to a substantial reduction of nonlinear pulse broadening in the large-area core. Application of an even larger core size should further reduce SPM-induced broadening. However, to enable diffraction-limited focusing of the output beam, it was crucial to ensure single-mode propagation in the low-order multimode fiber. For this purpose we used a relatively stiff fiber in which mode coupling is negligible over a distance of several meters.[11] Coupling into higher modes was prevented by spatial filtering with a short taper near the input of the fiber. In the future, large-area SMFs that exhibit low SPM and would thus be well suited for MPE might also be created by thermal expansion of the core[14] or in the form of all-silica[15] or air–core[16] photonic crystal fibers. In addition, other parameters such as pulse repetition rate[17] and pulse shape[18] could be optimized to further maximize MPE at the output of optical fibers.

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References

1. W. Denk, J. H. Strickler, and W. W. Webb, "Two-photon laser scanning fluorescence microscopy," Science **248,** 73–76 (1990).
2. W. Denk, "Two-photon excitation in functional biological imaging," J. Biomed. Opt. **1,** 296–304 (1996).
3. R. Wolleschensky, T. Feurer, R. Sauerbrey, and U. Simon, "Characterization and optimization of a laser-scanning microscope in the femtosecond regime," Appl. Phys. B **67,** 87–94 (1998).
4. A. Lago, A. T. Obeidat, A. E. Kaplan, J. B. Khurgin, P. L.

Shkolnikov, and M. D. Stern, "Two-photon-induced fluorescence of biological markers based on optical fibers," Opt. Lett. **20,** 2054–2056 (1995).

5. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, San Diego, Calif., 1995).
6. P. M. Delaney and M. R. Harris, "Fiberoptics in confocal microscopy," in *Handbook of Biological Confocal Microscopy,* J. B. Pawley, ed. (Plenum, New York, 1995), pp. 515–523.
7. F. Helmchen, M. S. Fee, D. W. Tank, and W. Denk, "A miniature head-mounted two-photon microscope: high-resolution brain imaging in freely moving animals," Neuron **31,** 903–912 (2001).
8. M. Oberthaler and R. A. Höpfel, "Special narrowing of ultrashort laser pulses by self-phase modulation in optical fibers," Appl. Phys. Lett. **68,** 1017–1019 (1993).
9. B. R. Washburn, J. A. Buck, and S. E. Ralph, "Transform-limited spectral compression due to self-phase modulation in fibers," Opt. Lett. **25,** 445–447 (2000).
10. S. Maiti, J. K. Ranka, A. L. Gaeta, and W. W. Webb, "Multiphoton fluorescence spectroscopy through optical fibers," Biophys. J. **72,** A217 (1997).
11. M. E. Fermann, "Single-mode excitation of multimode fibers with ultrashort pulses," Opt. Lett. **23,** 52–54 (1998).
12. E. B. Treacy, "Optical pulse compression with diffraction gratings," IEEE J. Quantum Electron. **QE-5,** 454–458 (1969).
13. J. K. Ranka, A. L. Gaeta, A. Baltuska, M. S. Pshenichnikov, and D. A. Wiersma, "Autocorrelation measurement of 6-fs pulses based on the two-photon-induced photocurrent in a GaAsP photodiode," Opt. Lett. **22,** 1344–1346 (1997).
14. M. Kihara, M. Matsumoto, T. Haibara, and S. Tomita, "Characteristics of thermally expanded core fiber," J. Lightwave Technol. **14,** 2209–2214 (1996).
15. J. C. Knight, T. A. Birks, R. F. Cregan, P. St. J. Russell, and J.-P. de Sandro, "Large mode area photonic crystal fibre," Electron. Lett. **34,** 1347–1348 (1998).
16. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science **285,** 1537–1539 (1999).
17. M. T. Myaing, J. Urayama, A. Braun, and T. B. Norris, "Nonlinear propagation of negatively chirped pulses: maximizing the peak intensity at the output of a fiber probe," Opt. Express **7,** 210–214 (2000), http://www.opticsexpress.org.
18. C. J. Bardeen, V. V. Yakovlev, J. A. Squier, K. R. Wilson, S. D. Carpenter, and P. M. Weber, "Effect of pulse shape on the efficiency of multiphoton processes: implications for biological microscopy," J. Biomed. Opt. **4,** 362–367 (1999).