Abstract. We demonstrate a compact and self-starting fiber-delivered femtosecond Cr:forsterite laser for nonlinear light microscopy. A semiconductor saturable absorber mirror provides the self-starting mechanism and maintains long-term stability in the laser cavity. Four double-chirped mirrors are employed to reduce the size of the cavity and to compensate for group velocity dispersion. Delivered by a large-mode-area photonic crystal fiber, the generated laser pulses can be compressed down to be with a nearly transform-limited pulse width with 2.2-nJ fiber-output pulse energy. Based on this fiber-delivered Cr:forsterite laser source, a compact and reliable two-photon fluorescence microscopy system can thus be realized. © 2005 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2060586]

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Compact fiber-delivered Cr:forsterite laser for nonlinear light microscopy

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Enabled by femtosecond near-infrared (NIR) solid-state light sources,1–6 nonlinear light microscopy such as two-photon fluorescence microscopy (TPFM)7 and higher-harmonic generation microscopy8 has attracted much biological and medical interest in recent years due to its capability to provide molecular and structural information with high 3-D spatial resolution. Compared with single-photon excitation, NIR-based nonlinear light microscopy offers the advantages of deeper penetration, higher sample viability, and much-reduced photodamage and photobleaching effects.9–11 With their output wavelength covering the infrared penetrating window of most biological tissues at 1200–1300 nm,12 femtosecond Cr:forsterite lasers show great promise to serve as excitation sources for nonlinear light microscopy.8,10–14 Our recent in vivo studies in live and untreated wild-type zebrafish embryos with a femtosecond Cr:forsterite laser indicated >1.5-mm penetration capability while maintaining a submicron resolution12 with the third harmonic generation modality. With much-reduced multiphoton absorption in biotissues,13 compared with a femtosecond Ti:sapphire laser, no optical damage in live wild-type zebrafish embryos can be observed even with 100-mW incident average power (1-nJ pulse energy) from a femtosecond Cr:forsterite laser continuously illuminating on the embryos after long-term (12-hour) observations, with a total exposure of over 1000 J applied to one embryo.14 Moreover, the near-1300-nm excitation wavelength provided by Cr:forsterite lasers corresponds to the zero dispersion wavelength in most optical fibers, which makes remote-fiber-delivered microscopic systems possible.

For future biomedical or even clinical application, a compact and fiber-delivered Cr:forsterite laser is desired. Previous studies on Ti:sapphire-based TPFM15 have shown that a fiber-delivered system is a more compact system arrangement and has better isolation from environmental noises than bulk-optics-based systems. Recently, Thomann and his co-workers have demonstrated a compact and fiber-delivered Cr:forsterite laser with a 420-MHz repetition rate and 0.43-nJ output pulse energy from optical fibers.16 With strong spectral broadening in nonlinear fibers leading to octave-spanning spectra, this previously demonstrated highly repetitive light source is ideal for telecommunication and metrology applications.16 For nonlinear light microscopy applications, the fiber-output femtosecond light should provide higher pulse energy (>1 nJ) and a narrower spectral width (<15 nm), to achieve higher nonlinear process efficiency while minimizing dispersion effects in biotissues. Since most fluorophores exhibit a lifetime on the order of several nanoseconds, a laser repetition rate on the order of 100 MHz, but not much higher, is desired.

In this paper, we report a compact and self-starting fiber-delivered Cr:forsterite laser source designed for nonlinear light microscopy. A semiconductor saturable absorber mirror (SESAM)17 is utilized in the laser cavity to maintain long-term stability. Four double-chirped mirrors (DCM),18 instead of prism pairs, are utilized to reduce the size of the cavity and to compensate for group velocity dispersion (GVD) arising from the laser crystal. Without any prechirp units, the generated laser pulses are delivered and could be compressed down to be with a nearly transform-limited pulse width by a large-mode-area photonic crystal fiber with 260-mW average output power. With well-controlled self-phase modulation, negligible spectral broadening effect can be achieved. Based on this compact and self-starting femtosecond all-solid-state laser source, a fiber-delivered Cr:forsterite-based TPFM system is demonstrated for the first time.

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The schematic layout of the compact self-starting fiber-delivered Cr:forsterite laser is shown in Fig. 1. The laser is composed with a single-mode fiber pumping source, a prismless Cr:forsterite laser oscillator, and a single-large-mode photonic crystal fiber for output delivery into a nonlinear light microscope. The pumping source is a cw ytterbium-doped single-mode fiber laser (IPG PYL-10-1064-LP) operating at a 1064-nm wavelength with 10.5-W output power. The pump beam, with a 2.5-mm diameter and 0.35-mm divergence, is focused into the Cr:forsterite laser crystal with ~30-μm beam radius through a pump lens with a 10-cm focal distance. The laser oscillator is composed of one dichroic curved mirror (DC), a Cr:forsterite crystal, a SESAM, two plane DCMs (DCM1, DCM3), two curved DCMs (DCM2, DCM4), and an output coupler (OC). We use a standard z-fold cavity for astigmatism compensation. The repetition rate of the laser oscillator was designed to be 120 MHz to maintain an output pulse energy well above 1 nJ for nonlinear light microscopy. Higher repetition rate is possible for other applications. The radius of curvatures of the focusing mirrors (DC, DCM2, and DCM4) are 10 cm. DC and DCM2 are separated with 10.6 cm and the lengths of both z-folded cavity arms are 62 cm, which result in a 1.24-m total cavity length. The Cr:forsterite crystal is a 5×5×11.4-mm Brewster-cut crystal with an absorption coefficient of 1.5 cm⁻¹. Both the orientations of the pump and the oscillator electric fields are parallel to the b axis of the Cr:forsterite crystal. The crystal is cooled down to −2 °C by a liquid and a TE cooler. The surface of the crystal is purged with dry nitrogen to prevent water condensation. The SESAM with a picosecond transient time is for self-starting and enhancement of the mode-locking force. It consists of 25 periods of a GaAs/AlAs Bragg reflector, followed by an Al₀.₄₈In₀.₅₂As quarter-wave layer with two embedded Ga₀.₄₇In₀.₅₃As quantum wells. To provide the saturable absorber nonlinearity for initiating and stabilizing the Cr:forsterite laser, the quantum-well structure was designed to have the heavy-hole excitonic resonance around 1230 nm at room temperature. The insertion loss of the SESAM is 2.5% with a saturation fluence of ~50 μJ/cm². The laser beam is focused with a curved mirror (DCM4) onto the SESAM. The beam radius of the cavity transverse mode on the SESAM is about 30 μm. The double-pass group velocity dispersion (GVD) of the laser crystal was estimated to be ~568 fs² around 1230 nm. To compensate for positive GVD arising from the laser crystal, four DCMs are adopted in the laser cavity for a compact cavity design. On the surface of each DCM, the period of dielectric coating is chirped, which results in the required negative dispersion. An impedance matching section and antireflection coatings were grown above the chirped region to avoid group delay oscillation and resulted in broadband mirrors with a controlled dispersion, which are important for the further development of a tunable ultrashort pulse laser. In our experiment, each double-chirped mirror was designed with a wavelength from 1200 to 1400 nm and provided ~150-fs² GVD around 1230 nm. By folding the cavity with DCMs, we cannot only reduce the size of the cavity but also accomplish a net cavity GVD of ~632 fs² at 1230 nm for stable mode locking. Due to the prismless cavity design, the optical part of the laser system can be packaged within a box with 20×30×20 cm³ dimension, which is on the order of or smaller than the size of a scanning microscope.

The performance of the Cr:forsterite oscillator can be tuned by changing output couplers with different ratios, by changing intracavity dispersion by replacing DCM3 with a high-reflection mirror, and by fine-tuning cavity length and positions of DCM2 or SESAM with different working points. To generate stable mode-locked pulses, the net cavity dispersion should be in a slightly negative dispersion region. With two double-chirped mirrors (four bounces), the net cavity dispersion is ~24 fs² and the mode-locking behavior is not stable. With three double-chirped mirrors (six bounces), the net cavity dispersion is ~324 fs², which is suitable for generating transform-limited pulses. However, in SESAM-assisted Kerr-lens mode-locking mechanism, too much intracavity dispersion will result in multiple-pulsing effects, which set an upper limit for output power. To increase the upper limit, the net cavity dispersion should be more negative. Thus, four double-chirped mirrors (eight bounces) were utilized in our laser cavity. However, applying even more double-chirped mirrors will increase the size of the laser cavity, which is unsuitable for clinical nonlinear light microscopy.

At 10.5-W pump power, with a 2% to 10% output coupler, the laser oscillator can emit femtosecond pulses with 100 ~350-mW output power, 10 ~20-nm full-width-half-maximum (FWHM) bandwidth, and 85 ~319-fs pulse duration (see Figs. 2 and 3). The threshold pump power for 2% and 10% output couplers are 3.8 W and 4.6 W, respectively. For nonlinear light microscopy applications, we selected a
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We delivered the generated ~1230-nm femtosecond pulses with a 65-cm-long large-mode area PCF (LMA 35, Crystal-Fiber A/S). We choose the large-mode area PCF to output laser pulses not only due to its large effective mode area with diminished nonlinear effects but also due to its slight negative dispersion at 1230 nm so that the chirping of the laser pulses could be compensated during fiber delivery. The incident laser beams were linearly polarized. The polarizations didn’t change during fiber delivery. The LMA-35 PCF is single mode at the 1230-nm wavelength with a mode-field area of 530 µm². The dispersion and its slope at 1550 nm are 25 ps/nm/km and 0.07 ps/nm²/km, respectively. The solid lines in Fig. 3(a) and Fig. 3(b) show the autocorrelation trace and spectrum after optical pulse passing through the PCF. With 260-mW output power, corresponding to an output pulse energy of 2.2 nJ, no significant spectral broadening effect due to self-phase modulation can be observed, in contrast to the previous nonlinear fiber experiment. On the other hand, with negative dispersion compensation provided by the PCF, the width of the chirped pulses from the laser oscillator was successfully compressed down to 200 fs [straight line in Fig. 3(a), assuming a Gaussian pulse shape] with a time-bandwidth product of 0.44, which is transform-limited. The pulse durations and FWHM spectral widths of the delivered pulses were found to be independent of the polarizations of the input laser beams. From an independent calculation, we can also estimate the maximum nonlinear phase shift experienced by the optical pulses inside the PCF to be on the order or less than 0.5°. With a narrow spectral width, a short pulse width, 2-nJ pulse energy, and a central wavelength located at the biopenetration window, this self-started compact Cr:forsterite laser is an ideal light source for nonlinear light microscopy.

We set up a fiber-delivered two-photon-fluorescence microscope (TPFM) system based on the demonstrated Cr:forsterite laser. The PCF fiber is connected to the input end of an Olympus FV300 scanning system combined with an Olympus BX51 upright microscope while all optics were modified to guarantee the collected signals, two-photon fluorescence of chlorophyll, a short wave pass color filter (Lambda Research Optics SWP-1202U-700), and a 40-nm bandwidth interference filter (Lambda Optics 670-F40-12.7), corresponding to the 670-nm two-photon fluorescence wavelength of chlorophyll, are inserted before the photomultiplication tube in the Olympus FV300 scanning unit. The acquired two-photon fluorescence (chlorophyll) images of the mesophyll tissues in a fresh leaf of Rhaphidophora aurea are shown in Fig. 4. The average illumination power on the leaf is decayed down to 5 mW. From Fig. 4, chloroplasts distribution inside the mesophyll cells can be identified with a submicron spatial resolution. This result demonstrates that this fiber-delivered compact Cr:forsterite laser is an ideal source for nonlinear light microscopy. To the best of our knowledge, this is the first fiber-based nonlinear microscope where the fiber can actually increase the excitation efficiency of nonlinear signals through...
compressing the optical pulse width without the help of a dispersion compensation unit.

In conclusion, we have successfully demonstrated a compact, prismless, self-starting, and fiber-delivered femtosecond Cr:forsterite laser for nonlinear light microscopy by employing double-chirped mirrors and a SESAM. Delivered by a large-mode-area photonic crystal fiber, the generated laser pulses can be compressed down to be within a nearly transform-limited pulse width with 2.2-nJ fiber-output pulse energy. Based on this fiber-delivered Cr:forsterite laser source, a compact and reliable two-photon fluorescence microscopy system can thus be realized.

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24. From the published data at http://www.crystal-fibre.com/Products/large_mode_area/datasets/LMA-55.pdf, we can estimate the dispersion zero wavelength to be ~1190 nm. The negative dispersion at 1230 nm is ~2.6 ps/nm/km.