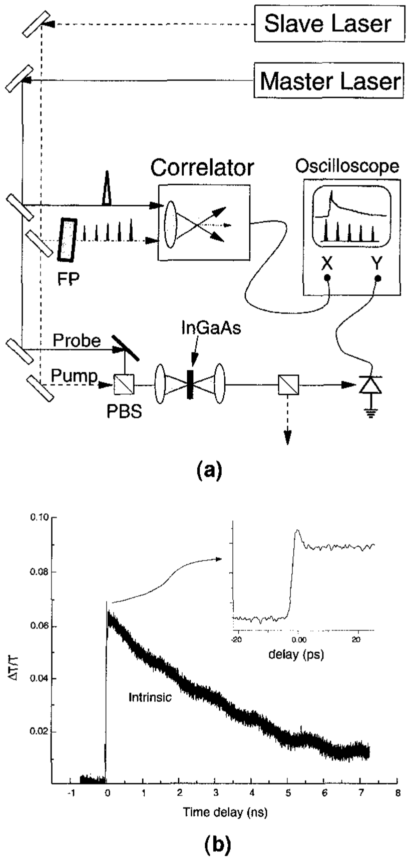

CThH1 Fig. 3 (a) Pump-probe measurement system using scanning, dual laser system, and timing calibration method. A Fabry–Perot étalon (FP) generates the pulse train for timing calibration. (b) Differential transmission near the band edge of intrinsic InGaAs. The 40-ps interval near time-zero (inset) shows an initial fast transient ($\sim$2 ps).

sample of InGaAs]. Timing calibration is accomplished simultaneously by use of background-free optical cross correlation via sum-frequency generation in periodically poled lithium-niobate (PPLN). A train of calibration pulses is produced by inserting a 5-mm-thick Fabry–Perot étalon ($R = 90\%$) into the path of one beam as shown in Fig. 3a. The transmitted beam consists of a decaying train of pulses separated by 50 ps. Any nonuniformity of the pulse spacing in the laboratory time frame indicates that the time delay is being scanned nonlinearly. Figure 3b is a differential transmission scan over a 7-ns time interval, showing a 4-ns decay time. The inset shows a fast ($\sim$2 ps) transient near zero time-delay.

In conclusion, we have demonstrated a new method for scanning the time delay between two lasers that greatly exceeds the performance of conventional scanning delays, and a timing calibration method that gives subpicosecond accuracy. These methods, when combined, comprise a verstile fast-scanning, ultrafast measurement system.

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1. R. F. Fork, F. A. Beisser, Appl. Opt. **17**, 3534 (1978).
2. Z. A. Yasa, N. M. Amer, Opt. Commun. **36**, 406 (1981).
3. D. C. Edelstein *et al.*, Rev. Sci. Instrum. **62**, 579 (1990); K. F. Kwong *et al.*, Opt. Lett. **18**, (7) 558 (1993).
4. K. S. Giboney *et al.*, IEEE Photon. Technol. Lett. **6**, 1353 (1994); J. D. Kafka, J. W. Pieterse, M. L. Watts, Opt. Lett. **17**, 1286 (1992).
5. G. Sucha, M. E. Fermann, D. Harter, M. Hofer, IEEE J. Quantum. Electron. (submitted).
6. G. Sucha, M. Hofer, M. E. Fermann, D. Harter, Opt. Lett. **21**, 1570 (1996).

CThH2 **10:45 am**

Femtosecond short cavity 2.5 GHz fiber laser harmonically modelocked by a saturable Bragg reflector with low temporal jitter

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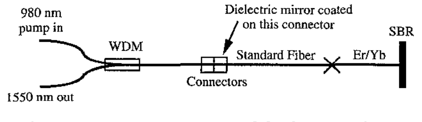
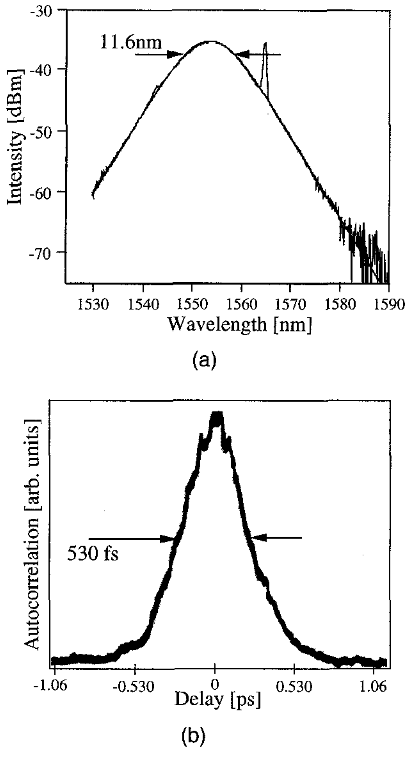
Compact pulsed optical sources about the 1550-nm telecommunications window are becoming increasingly important for high speed fiber optic networks. Both active and passive modelocking methods have been used to modelock erbium fiber lasers but fundamental repetition rates are typically limited to below 50 MHz as a result of the need for lengthy gain fiber. However, in a passive harmonically modelocked laser with no active device to stabilize the intrapulse temporal spacing, unacceptable timing jitter can result. Grundinin *et al.*, proposed that long-range repulsion forces between solitons resulting from index perturbations caused by transverse acoustic wave excitations in the fiber generated by the solitons themselves can lead to reduced temporal jitter.[1]

In this paper we report the observation of stable repetition rates as high as 2.5 GHz from a linear, passively modelocked Er/Yb fiber laser consisting of only 13.2 cm of Er/Yb fiber and 22.5 cm of standard transmission fiber for a fundamental cavity repetition rate of 290 MHz. With an anomalous average cavity dispersion of 7.0 ps/nm/km, the laser is passively modelocked by a saturable Bragg reflector (SBR) and produces near-transform-limited 310-fs pulses.[2] A 980-nm pump diode laser delivers 85 mW through a dielectric high reflector coated directly on the face of the connectorized standard fiber. The opposite end of the fiber cavity is butt-coupled to the SBR.

Harmonic modelocking is achieved with as many as nine pulses circulating in the cavity and an average output power of 20 μW through the high reflector. Figures 2a and 2b show a typical optical spectrum fitted with a sech^2 function and an autocorrelation trace of the modelocked output. The measured average intracavity power, pulsewidth, and cavity dispersion indicates that the pulses in the cavity are fundamental solitons. In the RF spectrum of a fast photodiode measuring the output, the cavity harmonics adjacent to the operating harmonic are suppressed by over 25 dB and analysis of high repetition rate harmonics (shown in Fig. 3) gives an estimated pulse jitter of less than 1 ps over a 1 kHz bandwidth. Reducing the pump power decreases the repetition rate by increments of the cavity fundamental where, at each transition, the pulses temporally rearrange conforming to the frequency of the next lower cavity harmonic and again the low temporal jitter is observed.

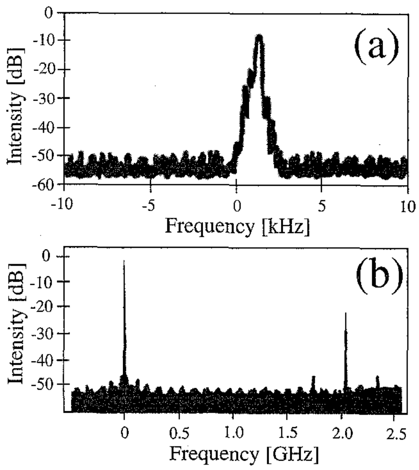


CThH2 Fig. 1 Diagram of the laser cavity.



CThH2 Fig. 2 (a) Optical spectrum of the modelocked output of the laser fitted by a sech^2 function with agreement over four orders of magnitude. The sidebands are due to background cw light shed by the soliton pulses. (b) Autocorrelation trace of the output.

The free carrier relaxation lifetime of the SBR has been measured to be 15 ps, which is significantly less than the 400 ps intrapulse spacing occurring at the highest observed repetition rate, and thus index modulation in the SBR cannot be causing the reduction of the jitter as has been previously observed in other systems with longer carrier relaxation lifetimes.[3,4] The intrapulse spacing may be stabilized by the index perturbation induced by the acoustic wave radiated by the soliton pulses, which is believed to be on the order of 1 ns in duration depending on the fiber.[5,6] Since the duration of this perturbation is on the order of the intrapulse spacing, this suggests that the passive acoustic stabilization may be effective at this repetition rate and the limits of this effect are currently under investigation. To our knowledge, passive harmonic modelocking



CThH2 Fig. 3 (a) Narrow RF spectrum of the tenth repetition rate harmonic centered at 20.5 GHz with the laser operating at 2.05 GHz. (b) Wide RF spectrum showing the suppression of the adjacent cavity harmonics under the same conditions and no activity at the cavity fundamental of 290 MHz.

has not been observed in such a short cavity with these high repetition rates.

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1. A. B. Grudinin, D. J. Richardson, D. N. Payne, Electron. Lett. **29**, 1860 (1993).
2. S. Tsuda, W. H. Knox, J. L. Zyskind, J. E. Cunningham, W. Y. Jan, R. Pathak, Paper CFD2, Conference on Laser and Electro-Optics, Anaheim, Calif. 1996.
3. S. Gray, A. B. Grudinin, Opt. Lett. **21**, 207 (1996).
4. S. Gray, A. B. Grudinin, Paper CFD3, Conference on Laser and Electro-Optics, Anaheim, Calif. 1996.
5. E. M. Dianov, A. V. Luchnikov, A. N. Pilipetskii, A. N. Starodumov, Opt. Lett. **15**, 314 (1990).
6. A. N. Pilipetskii, E. A. Golovchenko, C. R. Menyuk, Opt. Lett. **20**, 907 (1995).

CThH3 (Invited) 11:00 am

Fiber-laser-based femtosecond parametric generators and amplifiers

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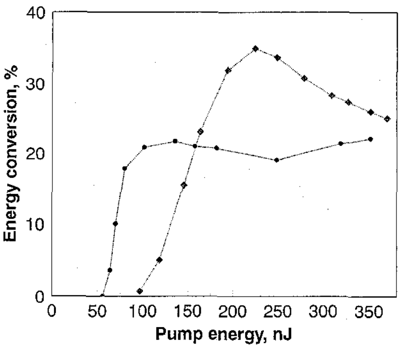
The current advent of commercial femtosecond modelocked fiber lasers is most stimulating for wide practical use of ultrafast technology because of the reliability, robustness, and compactness inherent to optical fiber sources. However, fiber sources, like the majority of other solid-state lasers, operate only at fixed wavelengths. Furthermore, the universal approach for extending the accessible wavelength range from a laser source, which is based on using nonlinear frequency conversion such as parametric frequency conversion, is not applicable directly to modelocked fiber lasers as a result of their insufficiently high output peak-powers. This poses limitations on using fiber oscillators for numerous applications that require ultrashort pulses and wide wavelength-tunability in a variety of spectral regions from visible to mid-infrared.

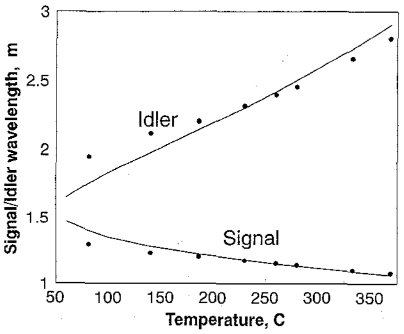
We have demonstrated femtosecond all-diode-pumped fiber systems producing parametrically generated wavelength-tunable pulses in a wide spectral range by employing two recent developments. First, high peak-power ultrashort optical pulses have been obtained with amplified fiber systems by use of a variety of chirped-pulse amplification (CPA) schemes.[1–3] Second, efficient frequency conversion at substantially lower peak-power compared with conventional birefringent phase matching has been reached by use of quasi-phase matching (QPM) in ferroelectric bulk materials such as periodically poled lithium niobate (PPLN).[4,5]

Chirped pulse amplification is essential for amplifying ultrashort pulses in fibers that are due to the small transversal-mode area (typically 50–300 μm^2) and relatively large cavity length (typically several meters) of single-mode fiber amplifiers. We have demonstrated Er-doped-fiber CPA systems by employing conventional diffraction grating based pulse stretchers and compressors or chirped fiber grating arrangements. Diffraction gratings allow us to extract pulse energies up to the saturation-fluence limit of a fiber gain medium, while fiber gratings allow to build very compact and robust all-fiber systems. Currently, we have achieved up to 20 μJ from diffraction-grating based systems. Such a system was first used for the experimental demonstration of parametric wavelength-tunable source,[6] as described below. Fiber-grating based systems have been demonstrated to produce ultrashort pulses with energies in the 10 to 300 nJ range.[2,3] Thus 0.1 to 10 MW peak-power pulses and corresponding focused-beam peak intensities in the range of 10 to 1000 GW/cm^2 are provided by a variety of all-diode-pumped fiber-amplified systems.

A high gain of $\sim 10^9$, sufficient for parametric amplification of vacuum noise to macroscopic levels (optical parametric generation-OPG), is anticipated in PPLN at relatively low around 10 GW/cm^2 peak intensities. This is the result of the large nonlinear coefficient employed ($d_{eff} = 2\ d_{33}/\pi \approx 17$ pm/V) and the absence of beam spatial walkoff at noncritical phasematching. Experiments confirmed the expected low threshold for OPG. Figure 1 shows an example of single-pass parametric-generation efficiency dependence on the pump energy measured in a 3-mm-long PPLN crystal pumped with 500-fs pulses at 777 nm from a frequency-doubled Er-doped-fiber CPA system. The extremely low threshold of 54 nJ indicates approximately two orders of magnitude improvement over the best previous result with birefringence phase-matching.[6] High parametric energy conversion of 38% (internal) has been achieved with only 220 nJ of pump inside the crystal. The low peak intensities required for efficient parametric conversion allow for high repetition-rate operation of OPG: we observed substantial parametric output at up to 200 kHz repetition rate. It is interesting to note that the demonstrated OPG threshold is actually below the continuum-generation threshold for most of the known materials. Because of the availability of microjoule energies from fiber-CPA systems, high parametric-pulse energies are obtainable. We have demonstrated up to 200 nJ of a signal with 1.9 μJ of pump at 777 nm. Figure 2 shows the example of the tuning curve measured with 777 nm pump, demonstrating 1 to 3 μm tuning of 300 fs output pulses from a fiber-based diode-pumped OPG system.



CThH3 Fig. 1 Total energy conversion efficiency in a 3-mm-long single-pass OPG. Focusing the pump at the center of the crystal minimized the OPG threshold (circles); focusing at the back facet of the crystal maximized peak conversion efficiency (diamonds).



CThH3 Fig. 2 Temperature tuning curves for PPLN OPG pumped at 777 nm. Curves are calculated curves, and circles are experimentally measured values.

Femtosecond parametric frequency conversion using OPG rather than a synchronously pumped optical parametric oscillator (OPO) has certain advantages for fiber-amplified pulse sources. The OPG arrangement is simple and robust because it does not require an external cavity, can be operated at variable repetition rate, and can produce high output pulse energies. To eliminate the drawbacks of non-transform-limited pulses and non-Gaussian output beams typical for simple single-pass OPG, we resorted to continuum-seeded optical parametric amplification (OPA) systems.

In summary, the demonstrated all-diode pumped fiber-based systems promise wavelength tunability in different spectral regions of commercial fiber-laser systems for satisfying the requirements of a broad variety of ultrafast applications.

1. A. Galvanauskas, *SPIE OE LASE 95*, San Jose 1995, paper 2377-14.