Harmonic mode locking in a sliding-frequency fiber laser

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We demonstrate a sliding-frequency mode-locked (SFM) erbium fiber laser generating 20 ps pulses with center wavelengths rapidly sweeping across a spectral range of 50 nm. Excess optical nonlinearity in the laser cavity leads to multipulsing, with a tendency to tight pulse bunching (<3 ns) at the fundamental cavity frequency of 25 MHz. The addition of a parallel optical delay line, with a path difference equal to a rational fraction of the cavity length, distributes the pulses uniformly across the entire cavity and achieves a harmonic SFM up to 1 GHz. The result establishes cavity nonlinearity as a critical design parameter for picosecond wavelength-swept lasers.

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Sliding-frequency mode locking (SFM) is a technique for generating wavelength-swept pulses directly from laser oscillation via the interplay between spectral filtering and nonlinear broadening [1]. Optical nonlinearity, such as that within a fiber laser cavity, allows short optical pulses to reshape their spectra via self-phase modulation and traverse the shifting passband of an intracavity sweeping filter with less loss than CW radiation. A pulse train thus becomes the preferred mode of oscillation. While similar mechanisms have been studied in the context of frequency-shifted feedback lasers [2,3] and optical transmission lines [4], the particular principle in swept lasers was first recognized [5] and demonstrated in an Er^{3+}-doped fiber (EDF) laser employing a scanning Fabry–Perot filter [1]. Rapidly sweeping a 0.27 nm bandwidth filter generated self-starting pulses with about 100 ps pulse widths over a spectral sweep range of 27 nm at a center wavelength of 1550 nm.

The potential utility of SFM lasers can be greatly enhanced, particularly for time-resolved spectroscopy or nonlinear imaging applications [6,7], if shorter and more broadly tuned pulses are generated. Broader filter bandwidth is a direct way to produce shorter pulses in an SFM laser. However, as we report in this Letter, excess optical nonlinearity associated with high pulse peak intensity leads to problematic multipulsing. We then demonstrate how an SFM pulse train can be timing stabilized in the picosecond regime via harmonic mode locking with an optical delay line.

Figure 1 depicts a schematic of our laser setup. A 300 mW, 980 nm pump diode was coupled to 2.4 m of EDF (LSL, OFS) with a 5 μm mode-field diameter and nominal absorption of 17.5 dB/m. Emission from the EDF was routed through standard single-mode fiber to a scanning filter within a ring cavity. In the scanning filter, a fiber collimator (CL1) directed light toward a scanning galvanometer mirror (GM) and a diffraction grating (GR) close to the Littrow configuration. A second collimator (CL2) captures the diffracted beam after descanning by the same galvanometer. The grating density (300 lines/mm) and incident beam width (3 mm) determined the Gaussian filter bandwidth to 3.3 nm. The wavelength sweep range and repetition rate were controlled with the voltage and frequency of a triangular-waveform signal driving the galvanometer. The cavity length was approximately 7.7 m. Cavity birefringence was adjusted with a pair of polarization controllers (PCs) to minimize polarization-dependent losses in the cavity elements, and to optimize pulse train stability. An optical isolator (ISO) ensured unidirectional oscillation in the cavity. Laser operation was monitored through a 20% output coupler.

Later, an optical delay line was appended parallel to the cavity to induce harmonic mode locking [8] by forming a Mach–Zehnder interferometer (MZI) between two 50:50 fiber couplers. The order of harmonic generation, m, is defined as $m = L/|\Delta L|$, where L is the cavity length and ΔL is the path length difference. ΔL is adjusted by varying the free-space distance between two collimators (CLs) in the delay line. In general, for both the cw and pulses, the MZI is a lossy element with 50% of light exiting the cavity via the rejection port. However, a coherent pulse train with interpulse spacing equal to ΔL can traverse the MZI with very little loss if pulses overlapping at the second coupler interfere constructively. Thus, this arrangement renders harmonic mode locking the preferred mode of oscillation. For this to occur, ΔL must be an integer fraction of the cavity length L; that is, m is an integer.

We initially characterized laser emission without the optical delay line. With the galvanometer held fixed by

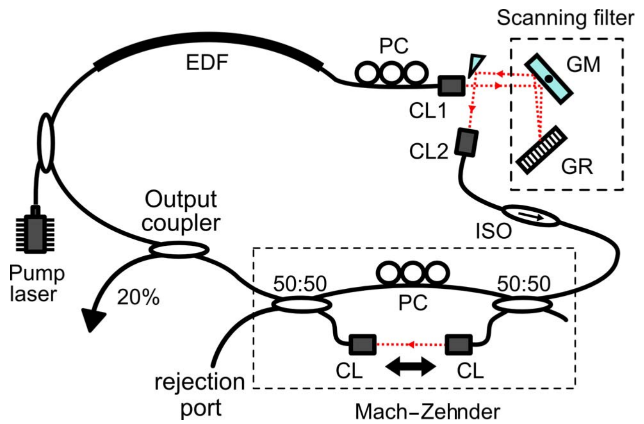

Fig. 1. (Color online) Schematic of a harmonic SFM fiber laser.

a DC signal, the laser produced narrowband cw emission with a maximum spectral width of 0.2 nm. During rapid scanning, 100 Hz to 2 kHz sweeps, mode locking occurred across a tuning range of 50 nm from 1520 to 1570 nm [Fig. 2(a)] with an average output power of 10 mW. Corresponding temporal peak-hold profiles measured with an InGaAs photodiode (Model 1811, New Focus) are shown in Fig. 2(b), in context with the position feedback signal from the galvanometer. Positive slopes in the sawtooth represent tuning toward longer wavelengths. At 1 kHz driving frequency, the tuning slope was 0.24 nm/μs or a 8.6 pm shift per round trip. At a higher temporal resolution, we saw a 25 MHz pulse train with a detection-limited pulse width [3 ns rise time—Fig. 2(c)]. We also observed pulse trains at the second up to the fourth harmonic by fine-tuning the PCs, with some compromise in polarization-dependent losses.

An intensity autocorrelator (PulseCheck 1200, APE) revealed unexpectedly complex structure at the subnanosecond time scale [Fig. 3(a)]. The autocorrelation prominently featured a large extended (>600 ps) pedestal. This suggested that each "pulse" in Fig. 2(a) was actually an unresolved bunch of randomly spaced pulses. Meanwhile, the central lobe of the autocorrelation indicated a characteristic pulse width of 20 ps. Although there is nearly always some ambiguity in inferring temporal features from an autocorrelation, our computer simulations of the SFM laser strongly corroborate the above interpretation.

We applied a standard split-step Fourier algorithm to a numerical model that considers gain saturation, spectral filtering, self-phase modulation, and dispersion [1]. Results showed that the SFM laser favors multipulsing when there is excessive optical nonlinearity in the laser cavity. Distributing energy across multiple pulses allows the laser to reduce the peak nonlinear phase shift per cavity round trip. Essentially, the total cavity nonlinearity limits the peak power of SFM pulses. Figure 3(b) shows the intensity autocorrelation from an SFM simulation that yielded 36 pulses, each with a 20 ps pulse width. Note the excellent agreement with experimental results in Fig. 3(a).

Multipulsing is ubiquitous in passively mode-locked lasers. It is generally attributed to the conflict between the broader spectral bandwidth demands of high-power mode-locked pulses and the finite gain bandwidth or filter bandwidth. Thus, a laser favors multiple lower power pulses over a single pulse above some threshold power [9]. In SFM, it is the rapid spectral broadening due to self-phase modulation and associated with the high peak nonlinear phase shift that makes multipulse operation energetically favorable.

Pulse bunching has also been widely observed, particularly in passively mode-locked fiber lasers. In fact, very similar dynamics to what we see in our SFM laser, i.e., multiple bunches occurring at cavity harmonics selected by tuning cavity birefringence, have been reported for EDF lasers mode locked by nonlinear polarization rotation [10,11]. While electrostriction and acoustic interactions, cited as the mechanism for pulse bunching, may also lead to regular pulse spacing [12], we were unable to achieve the latter state by birefringence tuning in our SFM laser.

We varied the net dispersion in the SFM laser cavity between $-0.1\ \mathrm{ps}^2$ and $+0.1\ \mathrm{ps}^2$ by adding lengths of single-mode or dispersion-compensating fiber, but we did not find any noticeable differences in output characteristics. Corresponding simulations predicted less than 10% variation of the pulse width for 20 ps pulses. Dispersion caused more significant broadening and narrowing in the simulation results as the pulse width approached 1 ps.

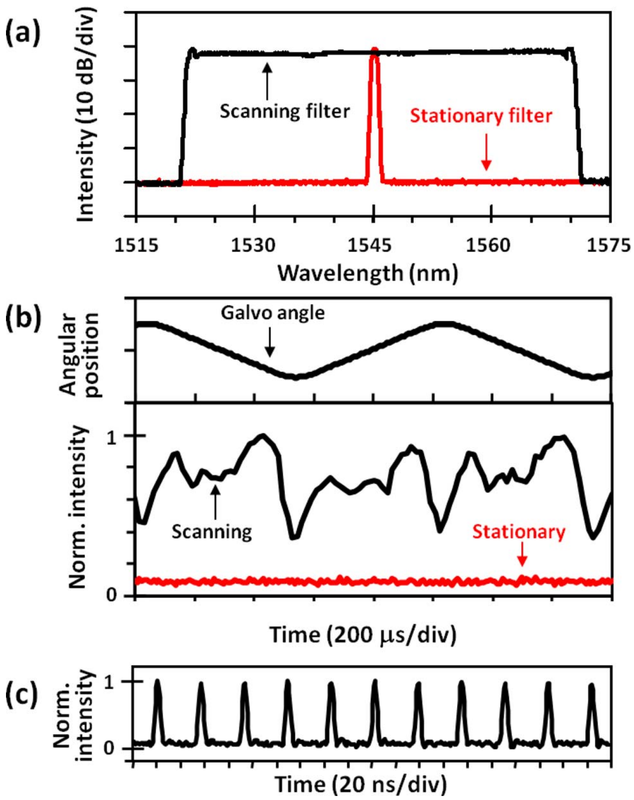

Fig. 2. (Color online) (a) Peak-hold spectrum of laser with scanning and stationary filters. (b) Peak intensity of laser emission versus position of galvanometer mirror. (c) Laser emission as measured with a 125 MHz bandwidth photodiode.

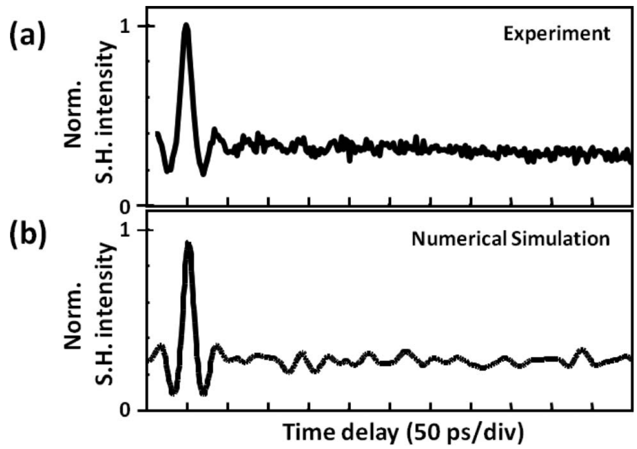

Fig. 3. Comparison of intensity autocorrelation for (a) experiment and (b) simulation. Simulation shows that the extended pedestal is consistent with multiple (e.g., 36) pulses with approximately the same amplitude and pulse width but distributed at random intervals.

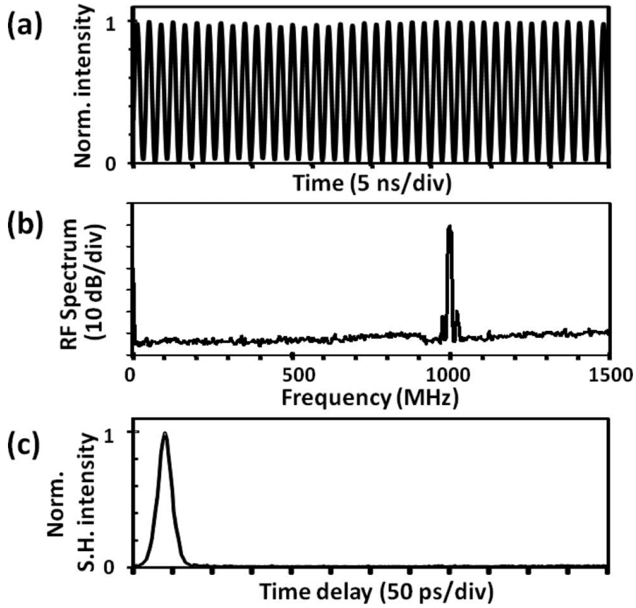

Fig. 4. (a) Pulse train from SFM laser operating at the fortieth harmonic. (b) Corresponding rf spectrum shows 1 GHz pulse repetition rate. (c) Autocorrelation shows a single peak, without the extended pedestal, indicating well-separated pulses.

Bunched-pulse operation might be useful for applications that respond to energy delivered within a few nanoseconds, such as photoacoustic spectroscopy. But in general, the random distribution of pulses within each bunch remains less than desirable. Strategies for stabilizing laser output to a single pulse per cavity round trip would primarily involve reducing the total optical nonlinearity in the laser. Indeed, we observed reduced multipulsing in our SFM EDF laser by limiting the pulse intensity via reduced pump power, but the spectral tuning range was also reduced. Shortening the nonlinear interaction length by reducing the optical fiber in the laser cavity, particularly the EDF where light intensity was greatest, also improved stability, but again it reduced gain.

An alternative approach is to harness the multipulse tendency into harmonic mode locking. To this end, we appended an optical delay line parallel to the laser cavity as described above [Fig. 1]. For the integral harmonic order, m pulses are organized into the corresponding harmonic of the fundamental cavity frequency. Figure 4(a), for example, shows a pulse train at the fortieth harmonic ($\Delta L = 19.25$ cm) as measured with a 10 Gbits/s photoreceiver (PP-10GC58J, Bookham) on a 500 MHz oscilloscope (TDS 620B, Tektronix). A 1.5 GHz rf spectrum analyzer (E4411B, Agilent) confirmed mode locking at 1 GHz [Fig. 4(b)]. At the maximum pump power of 300 mW, optimum stability was achieved at the thirtieth to fortieth harmonics, with 35 mW average power circulating in the laser cavity and 7 mW extracted by the 20% coupler. The SPM-induced nonlinear phase shift on each pulse per round trip in the cavity was estimated to be about 0.05 ± 0.01 rad. Figure 4(c) shows how the large pedestal observed previously in the intensity autocorrelation was fully suppressed, indicating well-separated pulses. Harmonic mode locking successfully defeated the tendency to pulse bunching. Similar stability was also achieved at lower harmonics after an appropriate reduction of pump power. For $m > 40$, harmonic mode locking is no longer sustained due to the lack of available energy in the laser cavity, resulting in less than m circulating pulses, and, for much higher m, the operation returned to a bunched-pulse train modulated at the fundamental frequency.

Although the relatively low peak power of the output pulses currently limits practical applications for our EDF laser, there are many possible strategies for increasing power. With stable harmonic SFM, pulse-picking with an electro-optic modulator becomes feasible and facilitates peak power scaling with fiber amplifiers for nonlinear applications. Utilization of short, high-gain, large-mode-area EDF could also increase laser power while still limiting cavity nonlinearity. Notably, design principles learned here may be applicable to other laser platforms. Ti:sapphire is a particularly interesting target, as SFM could provide a means of generating high-energy picosecond pulses with a broad sweep range, even without Kerr lens mode locking. A free-space cavity provides flexible control over total nonlinearity by gain crystal position or additional nonlinear elements within the laser [13].

In summary, we introduced harmonic SFM to generate timing-stabilized wavelength-swept picosecond pulses. Our results demonstrated the critical role of total cavity nonlinearity in limiting peak power by causing multipulsing in the SFM laser. We employed a simple optical delay line in a mode-locked fiber swept laser to leverage an inherent multipulsing tendency and produce 20 ps pulses at up to 1 GHz repetition while sweeping across a 50 nm spectral range.

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