Stabilization of the Offset Frequency of an All Polarization-Maintaining Fiber Erbium Frequency Comb

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Abstract: We demonstrate a completely polarization-maintaining fiber frequency comb operating at a 200 MHz repetition rate and show initial phase-locking of the carrier-envelope offset frequency. This design is compatible with a robust, fieldable frequency comb.

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The compactness and relative simplicity of erbium-doped fiber combs makes them an ideal choice for a system to move beyond the optical table into the field. However polarization wander induced by strain, temperature or humidity is a significant environmental challenge for fiber combs. The recent availability of telecom grade polarization-maintaining (PM) components, highly doped PM fibers and highly non-linear PM fibers offers a cost effective and promising solution to this problem. Semiconductor saturable absorber mirrors (SESAMs) offer polarization independent mode-locking that is robust, compact and compatible with all-fiber femtosecond fiber lasers [1-7]. SESAMs have enabled frequency combs with low noise [2-4] and high repetition rates [5-7], although all these lasers have included free-space sections increasing vulnerability to vibrations. Recent results have shown that low timing-jitter can be achieved for soliton fiber lasers using SESAMs based on carbon nanotubes [8]. Finally, an all-PM-fiber, figure-8 femtosecond fiber laser has demonstrated robust mode-locking even in the presence of strong vibrations, although at relatively low repetition rates [9]. Here, as a step towards a compact, robust, fieldable fiber frequency comb, we construct an Erbium fiber frequency comb at 200 MHz that uses only PM fiber and we demonstrate carrier-envelope frequency phase-locking.

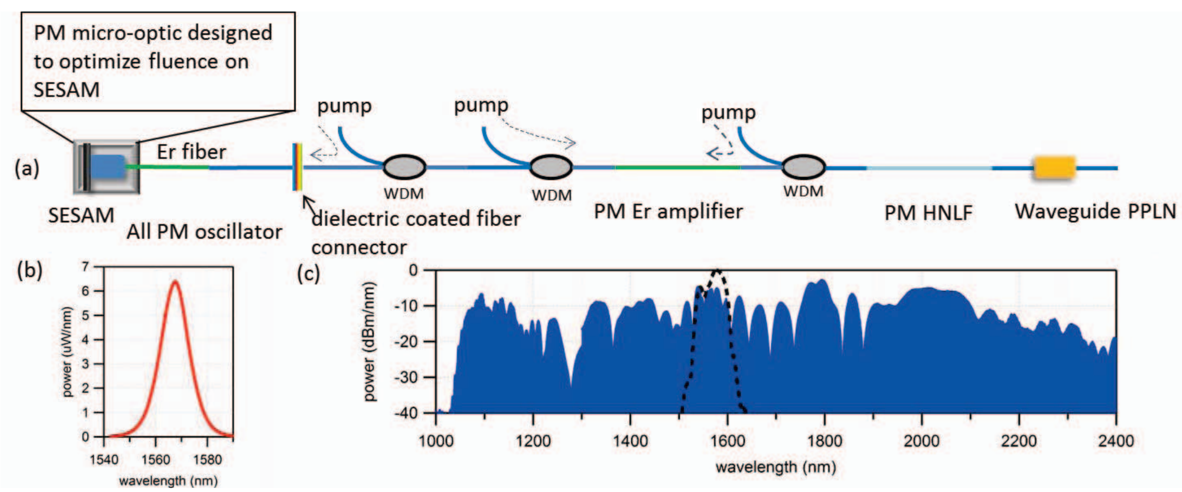

Figure 1: (a) Monolithic Laser Design. A custom PM micro-optic is used to optimize the fluence on the SESAM. A dielectric coated fiber connector serves as the input/output coupler for the oscillator. All fiber is PM, all components are telecom grade and no free space alignment is required anywhere. (b) Oscillator output spectrum. (c) Input Spectrum from Amplifier (black dashed) and Continuum Generated by HNLF (solid blue).
SESAM: Semiconductor Saturable Absorber Mirror, WDM: Wavelength-Division Multiplexing, HNLF: Highly Non-Linear Fiber, PPLN: Periodically Poled Lithium Niobate

The fiber comb design is given in Figure 1 (a). The femtosecond fiber laser consists of a 50 cm linear cavity with a dielectric coating between two fc/pc connectors to form the output coupler and a custom micro-optic containing a SESAM for mode-locking and fast axis blocking. The micro-optic is necessary to optimize the fluence on the SESAM for the largest oscillator spectral-bandwidth. All fiber in the cavity has anomalous dispersion for a net cavity dispersion of ~ -0.01 ps^2, which supports soliton mode-locking. The femtosecond fiber laser produces a relatively modest 10 nm of bandwidth and an output power of 5 mW (25 pJ/pulse). This output is amplified in a PM fiber amplifier to 1.5 nJ pulses that is then compressed to 70 fs. The output of the amplifier is directly spliced to a

PM highly non-linear fiber (HNLF) from Sumitomo [9]. The output of the PM HNLF is an octave-spanning spectrum, as shown in Figure 1 (c). In order to detect the carrier-envelope offset frequency, the supercontinuum is fiber-coupled to a waveguide PPLN [11] that doubles the supercontinuum light at 2120 nm to ~1060 nm. This doubled light is heterodyned against the supercontinuum light at 1060 nm and detected on a 100-MHz photodetector to yield the carrier-envelope offset frequency, f_{ceo}.

To stabilize f_{ceo}, the filtered heterodyne signal is mixed with a 1 GHz signal and then divided by 256 before phase-locking to an rf reference signal via feedback to the pump diode current. The phase-locked rf power spectrum and divided rf power-spectrum are shown in Figure 2(a) and (b), respectively. The free-running and phase-locked frequency noise is shown in Figure 2(c). The phase-lock bandwidth is limited by the laser response to about 10 kHz, but is still preliminary. The deviation of the carrier-envelope offset frequency was recorded for an hour without phase slips as shown in Figure 2(c). It should be possible to increase the feedback bandwidth through phase-lead compensation to improve the locked phase noise.

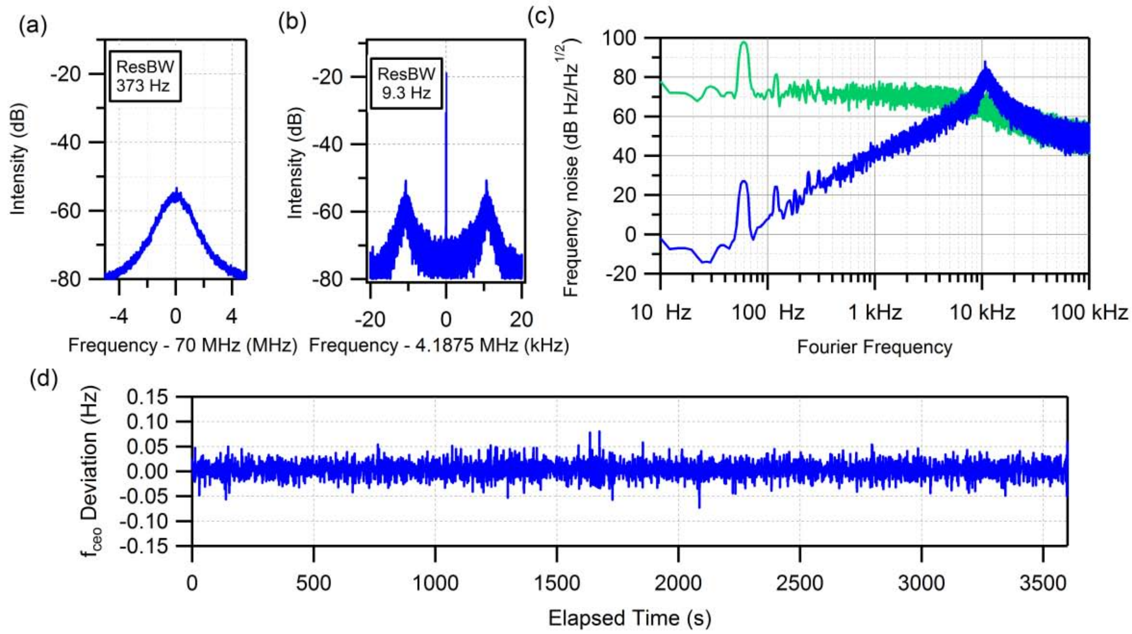

Figure 2: (a) Rf power spectrum of the phase-locked, undivided f_{ceo} signal. (b) Rf power spectrum of the phase-locked, divided f_{ceo} signal. (b) Frequency noise of the f_{ceo} signal with the laser free-running (green) and with it phase locked to an RF reference (blue). (c) Stability of phase-lock. Frequency of f_{ceo} beatnote recorded for 1 hour at a 1 second gate time. The standard deviation is 15 mHz.

We have shown that a 200 MHz PM fiber design that makes use of a SESAM for mode-locking can produce an octave-spanning spectrum. The resulting f_{ceo} beatnote has a sufficient signal-to-noise ratio to be phase-locked for an hour without phase slips. In the future, additional actuators will be added to stabilize the repetition rate as well, leading to an all PM self-referenced frequency comb that is robust and compact.

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