

Control of the frequency comb from a mode-locked Erbium-doped fiber laser

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Abstract: We show that a stretched-pulse mode-locked fiber laser produces a well-defined frequency comb, providing a compact source of frequency combs and allowing comb-based optical frequency metrology to be extended into the 1.55 μm region. This is achieved by comparing the frequency doubled output of the fiber laser to that of a mode-locked Ti:Sapphire laser, after the two lasers are synchronized. The offset frequency of the fiber laser frequency comb is found to be highly sensitive to the pump power, which enables the implementation of a feedback loop to control the offset frequency. The resulting RMS frequency jitter of the heterodyne beat signal is 355 kHz (0.5 Hz – 102 kHz BW) for this initial demonstration.

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OCIS codes: (320.7160) Ultrafast technology; (120.3930) Metrological instrumentation

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1. Introduction

Optical frequency metrology and waveform synthesis of ultrashort pulses have recently been revolutionized by the union between ultrafast lasers and laser stabilization [1-5]. This union has allowed for the development of fully characterized optical frequency combs using a single mode-locked Ti:Sapphire (Ti:S) laser oscillator and an absolute microwave frequency reference [3,4]. These combs have become useful absolute optical frequency references to which other lasers may be stabilized [6] or from which optical frequency measurements may be performed. Apart from applications pertaining to optical frequency metrology, phase stabilization of Kerr-lens mode-locked (KLM) Ti:S lasers has also opened the way toward waveform synthesis of few-cycle pulses [2,7,8]. This allows for investigation into time-domain phase-sensitive processes [9-11].

Although Ti:S lasers are tremendously successful at producing optical frequency combs, they suffer from several drawbacks that limit their use outside of the laboratory. This includes size, pump laser requirements and expense. Thus it is desirable to examine other mode-locked lasers as possible sources of stable frequency combs. Mode-locked fiber lasers are particularly attractive, being direct diode-pumped, relatively compact and, in principle, potentially much less expensive. Additionally, they operate at a distinct different wavelength region from existing Ti:S frequency combs and therefore extend coverage across new regions of the spectrum. The wide array of laser and photonic devices associated with telecommunication technology in this region might increase the utility and potential widespread use of mode-locked fiber lasers. However, since fiber lasers use a different mode-locking mechanism than do Ti:S lasers, it is not *a priori* obvious that they will produce a clean frequency comb. Since the frequency comb is sensitive to both the repetition rate and the offset frequency, the demonstration that the timing jitter from modelocked fiber lasers can be nearly quantum limited [12,13] does not guarantee a clean comb as it is insensitive to the offset frequency. Furthermore, fiber lasers present a different set of challenges for controlling the frequency comb, particularly the offset frequency.

Here, we demonstrate a well-behaved comb spectrum around 1.55 μm from a home-built Erbium-doped fiber laser and control of the fiber laser's comb. This is achieved by phase locking the repetition rate and frequency locking the carrier frequency of the fiber laser to those of the comb of a phase-stabilized KLM Ti:S laser. This demonstrated control capability for a fiber laser, in conjunction with the development of continuum generation at 1.5 μm , presents the possibility of a wide bandwidth optical comb, located in the telecommunication spectral window, stabilized in a self-referencing manner similar to that on which phase

stabilization of Ti:S lasers is based [2,14]. Prior work has shown that a fiber laser can produce a comb, although control was not demonstrated [15,16].

With further improvement, it will be possible to use these results to coherently stitch together the frequency comb from a mode-locked fiber laser with that of a Ti:S laser, as has been demonstrated for two Ti:S lasers [17,18]. This can produce a coherently synthesized pulse that is shorter than can be produced by a single oscillator [8].

2. Background

Lasers that emit a periodic train of pulses have a corresponding optical spectrum that consists of a frequency comb of discrete, regularly spaced lines. The spacing of the comb lines is determined by the repetition rate of the laser, f_{rep} , which is one over the round trip cavity time. Apart from the laser repetition rate, the frequency comb of a mode-locked laser is also characterized by the offset frequency, f_o , which causes a frequency shift of the optical comb elements, ν_n , away from exact harmonics of the laser repetition rate, $\nu_n = n f_{rep} + f_o$. Here n is a very large number ($\sim 10^6$) multiplying f_{rep} up into the optical domain. Physically, the offset frequency results from a difference between the group and phase velocities in the laser cavity and is thus related to the phase evolution of the electric field of the light pulse with respect to the envelope [2,14,19]. This relationship defines the connection between time-domain phase control and absolute frequency stabilization of mode-locked lasers.

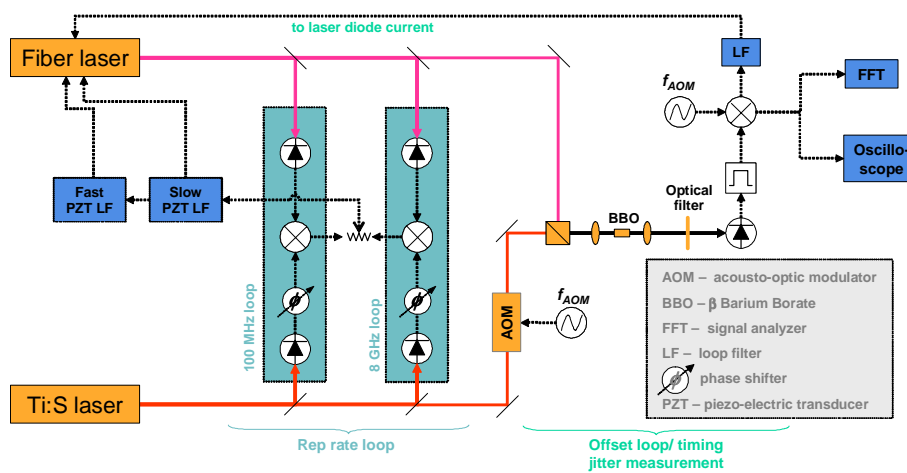


Fig. 1. Schematic of the setup used for synchronizing an Erbium-doped fiber laser to a KLM Ti:Sapphire laser. Measurement of the offset frequency is obtained by angle tuning the BBO crystal such that it is phase matched for second harmonic generation at $1.5 \mu\text{m}$. The optical filter used in the offset frequency measurement is centered at 770 nm . In a similar manner, the measurement of the timing jitter used the BBO crystal for sum frequency generation and an optical filter centered at 520 nm was used to detect the sum frequency mixed light arising from the fiber and Ti:S laser pulses.

3. Experiment

To fully characterize the frequency comb of a mode-locked laser requires that both f_o and f_{rep} be known. The repetition rate can be simply measured using a fast photodetector. The laser offset frequency, however, is more elusive. In these experiments f_o of the mode-locked Ti:S laser is determined independently from a secondary optical reference using a self-referencing technique [5]. The simplest implementation of self-referencing requires an optical octave of bandwidth, which is typically obtained via external broadening of the light pulses in a microstructure fiber [20]. Because continuum generation at the fiber laser wavelength ($\sim 1.55 \mu\text{m}$) is not as of yet readily available, measurement of the fiber laser offset frequency is determined via optical heterodyne with the Ti:S laser as a secondary optical reference. Figure 1 depicts the synchronization scheme [17,18] used in our experiment. In the experiments

presented here, both the laser repetition rate and the offset frequency of the fiber laser are stabilized to those of a phase stabilized KLM Ti:S laser. Synchronization and carrier phase locking of the two pulse trains would not only create a fully characterized frequency comb at 1.5 μm but would also establish coherence between the electric fields of both lasers.

The stretched-pulse mode-locked fiber laser operates at a center wavelength of 1.53 μm and a FWHM-bandwidth of 40 nm as shown in Fig. 2 [21]. Mode-locking is achieved using nonlinear polarization rotation. Gain is provided by an Erbium-doped fiber, which is pumped by a standard 980 nm diode. At the fiber laser's output, (chirped) pulses of 550 fs are observed with an average power of 45 mW at a 33.33 MHz repetition rate, yielding $\sim 0.3 \mu\text{W}$ per comb line. The RF spectrum of the pulse train shows signals at multiple of the repetition rate with a signal to noise ratio in excess of 75 dB (30 kHz bandwidth). The fiber laser is synchronized to a phase-stable Ti:S laser that operates at a center wavelength of 800 nm with an average power of 400 mW at a 100 MHz repetition rate. For ease of stabilization, the Ti:S and the fiber laser are each enclosed in a box to isolate them from air currents and acoustic noise. A full discussion of the stability as well as the stabilization techniques for the Ti:S laser are presented in Ref. [22].

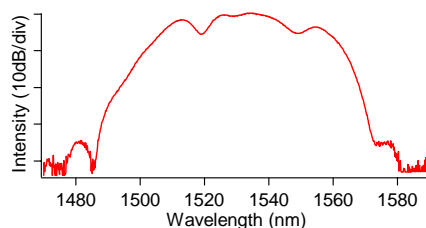


Fig 2. Optical spectrum of the Erbium-doped fiber laser output

Synchronization of the laser repetition rates of the two lasers uses an electronic scheme that is almost identical to that used in previous experiments in which two Ti:S lasers are synchronized [23,24]. The repetition rates of the two lasers are measured independently on fast photodetectors and are then compared using a doubly balanced mixer that provides a phase sensitive error signal to the feedback loop. The repetition rate servo loop to the fiber laser consists of two phase-locked loops. The first loop compares the third harmonic of the fiber laser repetition rate to the fundamental of the Ti:S laser at 100 MHz. Once phase lock is achieved with the 100 MHz loop, the phase lock is shifted to a second, higher phase sensitivity loop that compares higher harmonics of the repetition rates of the two lasers at 8 GHz. In this experiment, negative feedback to the repetition rate of the fiber laser is achieved by changing the cavity fiber length using two fiber-stretching stages. A slow stage (~ 3 kHz) is used to correct for slow drifts in cavity length and a faster stage (~ 6 kHz) is used to correct for the remaining phase error. The slow stage consists of a low voltage, stacked piezo-electric transducer (PZT) with a range of 10 μm . A pre-tensioned section of fiber is glued to ends of this PZT. The fast stage is also constructed by fixing a fiber under tension to two shearing PZTs (with 1 μm travel), oriented in opposite directions.

3.1 Timing jitter measurement

To determine the quality of the synchronization between the two lasers, the timing jitter is measured. The measurement is carried out independently from the synchronization servo loop by optically mixing the fiber and Ti:S laser pulses in a BBO crystal (see offset frequency loop in Fig. 1) for intensity cross-correlation analysis. The mixing product is the sum frequency generated (SFG) signal between the two laser pulses, $\omega_{SFG} = \omega_1 + \omega_2$, where $\omega_{1,2}$ denote the fiber and Ti:S laser frequencies, respectively. Temporal overlap of the pulses from the two lasers is achieved using electronic phase shifters in the 100 MHz and 8 GHz servo loops respectively (see repetition rate loop in Fig. 1). The phase shifter in the 100 MHz loop

introduces a time delay between the two pulse trains that can cover at least 5 ns. This capability ensures pulse overlapping between the two lasers when needed. The phase shifter in the 8 GHz loop is more sensitive and has a range of 334 ps.

By setting the delay between the pulses at the point of steepest slope in the cross-correlation, timing jitter is converted to an amplitude fluctuation of the SFG signal. For small timing jitter, the time to amplitude conversion is linear to good approximation. Calibration of the time to amplitude conversion is obtained by scanning the delay between the pulses and measuring the slope. Figure 3 presents the results of the timing jitter measurement of the repetition rate synchronization. From the time record an RMS timing jitter of 12.4 fs (0.5 Hz – 2.5 kHz BW) is measured. The main limitations to the repetition rate synchronization are due to a relatively small servo bandwidth resulting from mechanical resonance in the fast fiber stretching stage at ~6 kHz. The resonance is believed to arise from coupling between the two piezo-actuators on the stage that resonantly drives the longitudinal vibrational modes in the stretched fiber.

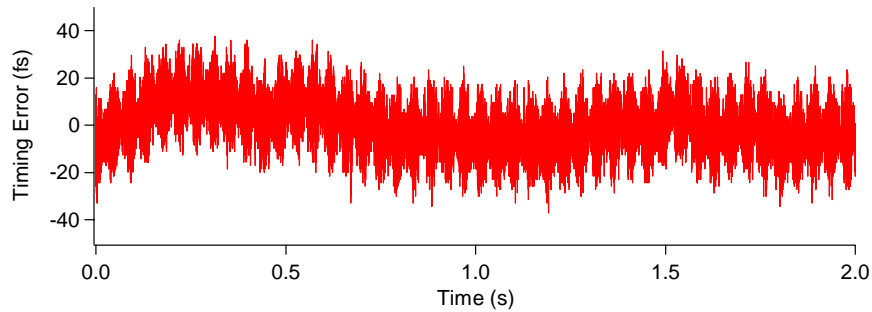


Fig. 3. Timing jitter time record of the synchronization of an Erbium-doped fiber laser to a KLM Ti:S laser. The trace was recorded at 0.4 ms time steps. The RMS timing jitter of 12.4 fs (0.5 Hz – 2.5 kHz BW) was obtained from the standard deviation of this 2 s time record. The modulation seen on the time record at ~20 Hz has not yet been identified. Elimination of this modulation would result in a substantial improvement of the timing measurement.

3.2 Offset frequency measurement and control

Once the pulse streams from the two lasers are synchronized, the difference in offset frequency between their combs can be measured [8,18]. In this experiment, measurement of f_o of the fiber laser is obtained by using the Ti:S laser as an optical reference. This is done by optically heterodyning the second harmonic of the fiber laser (~770 nm) with the fundamental of the Ti:S laser. As seen in Fig. 1, the two laser beams are spatially overlapped at a dichroic beamsplitter before being passed through a BBO crystal. This employs the same setup as was used to measure the timing jitter in Fig. 1. This time, however, the phase matching of the BBO crystal is tuned for frequency doubling of 1.53 μm light from the fiber laser. The light is then passed through a 4 nm bandpass optical filter centered at ~780 nm and the heterodyne beat is detected on a fast Si photodetector. Prior to being combined with the light from the fiber laser, the light from the Ti:S laser is frequency shifted in an acousto-optic modulator (AOM). This shift appears in the heterodyne signal, which allows a frequency lock to be used in addition to circumventing the need to work at DC when the offset frequencies are identical. Given that spectral, spatial and temporal overlap between the two beams are present, a stable heterodyne beat signal between the two laser fields is directly produced in the RF domain, yielding the fiber laser offset frequency:

$$f_{beat} = \pm \left| (m f_{rep1} - 2n f_{rep2}) + (f_{o1} - 2f_{o2}) + f_{AOM} \right|. \quad (1)$$

Here the indices 1 and 2 represent the Ti:S and fiber lasers respectively. From Eq. (1) it can be seen that timing jitter in the repetition rates of the two lasers appears directly as offset frequency phase noise. Therefore to obtain a stable beat signal requires that the repetition rates be first synchronized tightly. In these experiments the offset frequency of the Ti:S laser is locked to 0 Hz ($f_{ol} = 0$).

To stabilize the fiber laser offset frequency, the RF heterodyne signal at $m f_{rep1} = 2n f_{rep2}$ with a signal-to-noise ratio of 35 dB in a 100-kHz bandwidth is detected and filtered. A frequency error signal is derived from this using a digital phase detector. This error signal is used to apply negative feedback to the fiber laser to stabilize its offset frequency. This servo action is made possible by the amplitude-to-phase conversion of the optical field inside the fiber laser. This occurs due to the nonlinear phase shift that the pulse accumulates during a round trip in the laser, effectively making the phase velocity intensity dependent. The offset frequency is proportional to the difference between phase and group velocities, which in turn makes the offset frequency intensity dependent. Changing the pump power does change other characteristics such as the pulse spectrum and group velocity, thus it does not represent an “orthogonal” control variable.

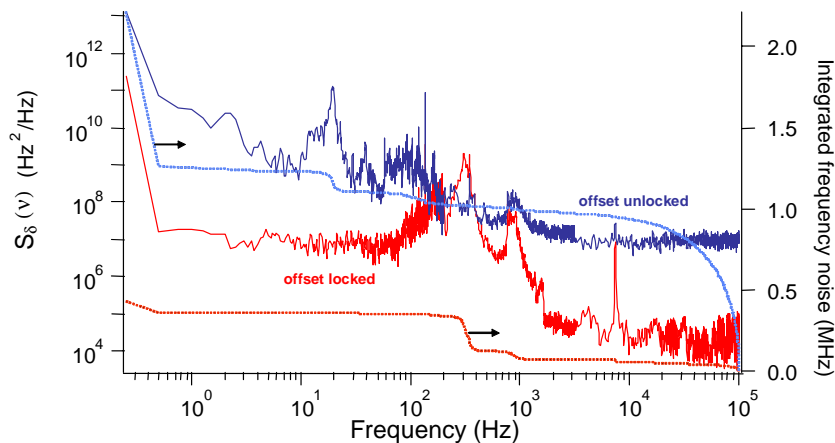


Fig. 4. Fiber laser offset frequency noise PSD, $S_{\delta}(v)$ (solid lines, left axis) and integrated frequency noise (dotted lines, right axis) vs. frequency offset from carrier. The blue (red) solid line is the PSD of the unlocked (locked) offset frequencies, respectively. The unlocked and locked PSD's were compiled from three different spectra of decreasing span (each 800 points) and increasing resolution (span divided by the number of points) to obtain greater resolution close to the carrier (displayed here as zero frequency).

The spectrum of the frequency noise on the offset beat note is used to characterize the instability in the locked comb. A frequency-to-voltage converter, in conjunction with an FFT (fast Fourier transform) analyzer, is used to measure the frequency noise power spectral density (PSD) of the heterodyne beat. Figure 4 shows the in-loop measurement of the frequency PSD, $S_{\delta}(v)$, of the fiber laser offset frequency for both the unlocked and locked cases. To achieve phase lock between the two optical fields, a fast servo bandwidth acting on the fiber laser is necessary. However, at the present stage the amplitude modulation of the pump diode suffers a bandwidth-limiting steep roll-off beyond a few kHz, hence only a frequency locking loop is implemented. Although the optical coherence between the two laser fields is not achieved at long observation times, integration from 102 kHz to 0.5 Hz of the locked frequency PSD in Fig. 4 yields a fiber laser offset frequency RMS jitter of 355 kHz. Several physical mechanisms may underlie the limited servo bandwidth. We hypothesize that it is the phase lag, resulting from the lifetime of the Erbium-doped fiber (~ 1 ms), that may prove to be the limiting factor in using pump amplitude modulation as an actuator. Future work will involve a thorough investigation into the transfer function of the current servo loop and subsequent design of an electronic compensation system for the servo. Another possibility

of circumventing this limiting factor may lie in the modulation of the fiber laser output by an AOM [25].

4. Summary

We have demonstrated that a stretched-pulse mode-locked fiber laser produces a clean frequency comb that can be controlled. The first step is to lock the repetition rate to an external clock, which we are able to do with timing jitter of 12 fs in 2.5 kHz BW. This instability prohibits phase lock of the fiber laser's offset frequency, although a frequency lock is achieved with an RMS frequency jitter of 355 kHz (0.5 Hz – 102 kHz). This demonstrates that the frequency comb of an Erbium-doped fiber laser can in fact be used as an absolute reference at 1.5 μm .

Acknowledgements

Funding for this project was provided by the National Institute of Standards and Technology, Office of Naval Research, the National Science Foundation and DARPA. J.R. acknowledges funding from the Willi Studer-Fonds.