A low-threshold self-referenced Ti:Sapphire optical frequency comb

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Abstract: We demonstrate an octave-spanning, self-referenced optical frequency comb produced with a high-repetition-rate (*f*rep=585 MHz) femtosecond Ti:Sapphire laser that requires less than 1 W of 532 nm pump power. The frequency comb was stabilized to a CW laser as required for optical clocks and low noise frequency synthesis. These results should be relevant for applications that require more-compact and efficient frequency combs.

OCIS codes: (140.7090) Ultrafast lasers, (320.7090) Ultrafast lasers, (320.7110) Ultrafast nonlinear optics

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1. Introduction

The Ti:Sapphire based femtosecond laser frequency comb (FLFC) has shown tremendous utility for a variety of high precision optical frequency measurements [1-5]. However, because the typical pumping scheme involves a high-power (5-8 W) frequency-doubled Nd:vanadate laser, a complete Ti:Sapphire FLFC remains a costly, heavy, and electrically inefficient device. This is unfortunate because the small footprint of a high repetition rate (500-1000 MHz) Ti:Sapphire laser already lends itself to being the basis of a compact FLFC [6]. Moreover, while FLFCs based on Er-doped fiber lasers have the very compelling advantages of lower cost, small size, good power efficiency and simple/robust operation [7,8], they currently lack the combination of low noise performance and high repetition rate (f_{rep}) that is beneficial for many applications. Given a constant average power, the power per optical mode of the frequency comb increases linearly with repetition rate. Higher power per mode is useful in spectroscopy applications [9,10] as well as applications that require a beat signal with a single frequency laser, such as optical frequency metrology [2]. Photodetection of the optical pulse train produces a microwave frequency comb at f_{rep} and its harmonics. In this case, a high repetition rate results in more power in the microwave harmonics, which is important for the generation of low noise microwave signals at 10 GHz [11].

These issues have motivated us to develop a more efficient high repetition-rate Ti:Sapphire based FLFC that could be pumped with a smaller 532 nm source. Low threshold femtosecond Ti:Sapphire lasers have previously been demonstrated [12,13], with some having repetition rates above 2 GHz [14]. In contrast, the laser presented here operates at a significantly higher repetition rate than the typical 100 MHz system, while still providing sufficient peak power to generate an octave-spanning spectrum in nonlinear microstructure fiber. Specifically, we demonstrate a femtosecond ring Ti:Sapphire laser having f_{rep}=585 MHz and a mode-locking threshold requiring as little as 340 mW of 532 nm pump power. At the typical operating conditions, 830 mW of pump power generates 150 pJ pulses, of which ~55 pJ is coupled into a nonlinear microstructure fiber to produce an octave-spanning continuum extending from below 500 nm to above 1000 nm. This continuum is used in a typical f-$2f$ self-referencing scheme [1] to measure f_o with S/N greater than 40 dB in 300 kHz bandwidth. This system achieves a beat signal (f_{beat}) against a single-frequency 1064 nm source with greater than 30 dB S/N in 300 kHz bandwidth. Both f_0 and f_{beat} are phase-locked as required to generate a phase stable frequency comb. Such low threshold operation should lead to smaller, less expensive and more efficient Ti:Sapphire pumping schemes including either a 1 W Nd-based green sources or an efficient frequency-doubled Yb fiber laser [15].

2. Setup

2.1 Ti:Sapphire laser system

We use a bowtie laser cavity [6], as shown in the inset of Fig. 1, with a 3 mm path length Ti:Sapphire crystal (α=6.35 cm^{-1} at 514 nm). A crystal of this length should introduce approximately 170 fs^2 of group delay dispersion (GDD) at 800 nm. Chirped mirrors were chosen to give a net negative GDD at the center wavelength of 800 nm. Mirror 1 has -60 fs^2 at 800 nm, mirrors 2 and 3 are a chirped pair with a total GDD of –120 fs^2 at 800 nm, and the output coupler has nominally zero GDD around 800 nm. Thus, the cavity should have a net GDD of -10fs^2 at the center wavelength.

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Using a typical gigahertz repetition rate ring laser as a basis for the design, we introduced several modifications that would increase the intracavity pulse power. First, we set the repetition rate close to 600 MHz, yielding an intracavity energy per pulse 66 % higher than previous gigahertz repetition rate lasers at the same power [6]. Second, in conjunction with the more negatively dispersive mirrors, we used a 3mm path length crystal instead of the ~2 mm path length crystals commonly used. This highly doped crystal absorbed 77 % of the incident pump power. Third, a 1 % output coupler was used to increase the power in the cavity. Lastly, we used 30 mm radius of curvature cavity mirrors to give a small beam waist in the crystal, enhancing the peak intensity in the crystal. With this configuration we saw a slope efficiency of 17 % and a stable mode lock down to 400 mW of pump power (340 mW at the crystal) as shown in Fig. 1. At this pump power the laser produced approximately 40 mW of mode-locked output power. This output power was not sufficient to generate an octave spectrum in our microstructure fiber, so we normally operated the laser at around 90 to 100 mW output (0.9 to 1.0 W pump).

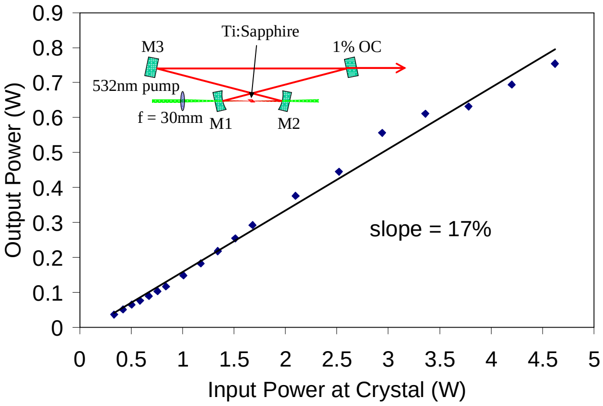

Fig. 1. Laser schematic (inset) and power efficiency curve

At the normal operating conditions of 90 to 100 mW, the output spectrum of the laser has a 35 nm FWHM bandwidth which corresponds to a transform limited pulse width of 14 fs. We extracted the pulse width using the PICASO pulse retrieval algorithm [16], using the measured spectrum and the interferometric autocorrelation shown in Fig. 2 and Fig. 3. A minimum pulse width of 16 fs was found after six bounces off extra-cavity chirped mirrors (-40 fs^2/bounce).

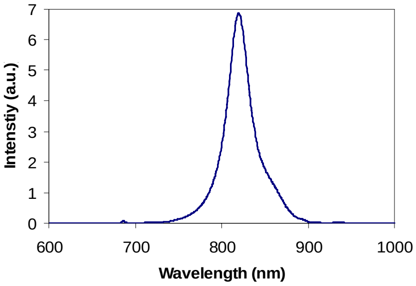

Fig. 2. Optical spectrum of laser at 90 mW output.

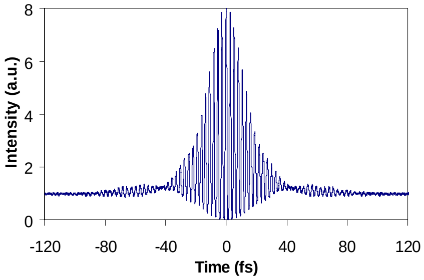

Fig. 3. Interferometric auto-correlation trace leading to a 16 fs pulse width

It might be possible to further reduce the threshold for mode-locking this laser by using smaller radius of curvature mirrors (to decrease w_0 thereby increasing nonlinearity) or by

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increasing the transmission of M1 for 532 nm light. As noted previously, we could not generate the octave spectrum needed for self-referencing at the lowest threshold, so we operated at a higher input power. It is noteworthy, however, that at the lowest threshold this laser provides ultrashort pulses at a repetition rate of 585 MHz with pump powers of only 400 mW.

2.2 Octave generation

We are using an air-silica microstructure (MS) fiber to generate the octave spectrum necessary for self-referencing. We experimented with many fibers and several fiber coupling methods to find a MS fiber that generated an octave at these low powers. The fiber that produced the broadest spectrum at the lowest powers had a 1.5 micron core diameter and zero dispersion at 590 nm. The 92 mW (after compression) from the laser was focused onto the fiber using an aspheric lens, giving approximately 33 mW of continuum light at the output (measured with a broadband power meter). The spectrum has an IR peak around 1015 nm and a blue/green peak around 500 nm, as shown in Fig. 4.

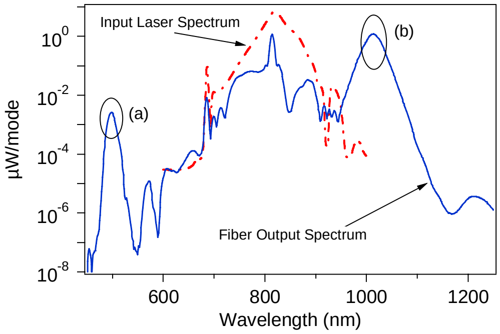

Fig. 4. Optical spectra of laser and fiber outputs (a) 500 nm peak, (b) 1015 nm peak

The spectrum shown is generated with 0.33 m of MS fiber. Increasing the length of the fiber moves the IR peak to longer wavelengths but does not affect the blue/green peak. The longer fibers do not show additional loss compared to the shortest fiber, so we assume that the measured output power corresponds approximately to the coupled power. Improved coupling into this fiber, either through better mode matching or through finding a better focusing element, would further reduce the threshold for generating an octave-spanning frequency comb and allow us to operate the laser at even lower powers.

3. Results

The output of the MS fiber was sent to a f-$2f$ interferometer to obtain the offset frequency of the laser. A 2 mm BBO crystal was used to double the 1000 nm light yielding ~30 µW of second harmonic. This was heterodyned with ~30 µW of 500 nm light to give an f_0 signal with a SNR as high as 45 dB (40 dB typical) in 300 kHz bandwidth as shown in Fig. 5.

We also obtained a beat signal between a single comb element and a single frequency YAG laser operating at 1064 nm using the IR light rejected from the f-$2f$ interferometer. With 5 mW of 1064 nm light, we achieved a beat with a SNR of 30-35 dB shown in Fig. 6. This system could be connected to very stable 1064 nm sources such as demonstrated by Hall and Notcutt [17,18,19], or could easily use the 1070 nm local oscillator for the Al^+ optical frequency standard at NIST [20].

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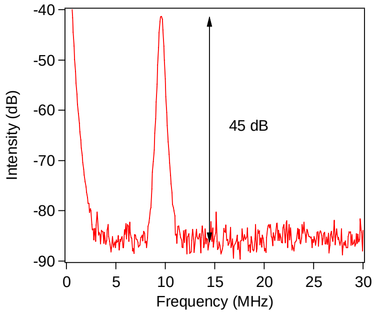

Fig. 5. Carrier envelope offset frequency (f_0) at 300 kHz bandwidth

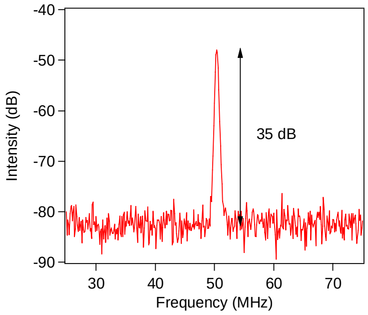

Fig. 6. Optical beat (f_{beat}) with 1064 nm light at 300 kHz bandwidth

The low power of this FLFC reduces some of the undesirable thermal drifts often associated with higher power Ti:Sapphire systems. The result is a stable free-running f_0 beat amenable to long term phase locking. We measured the offset frequency and its SNR over the 15 hour period shown in Fig. 7. The maximum deviations of these values from their averages during this period are 3.2 MHz and 1.5 dB, respectively.

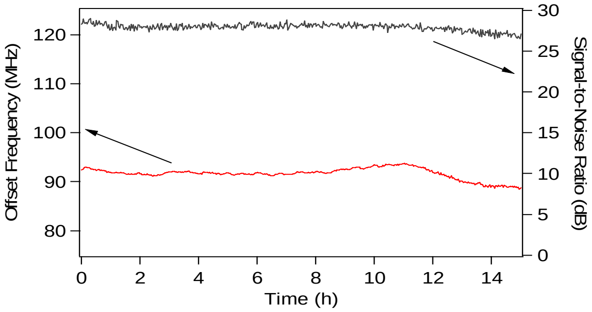

Fig. 7. f_0 frequency and SNR of free-running FLFC sampled every 2 minutes for 15 hours

We phase locked both the offset frequency and the optical reference beat to frequency synthesizers and maintained a lock for more than 3 hours (with 10 glitches over this time). The glitches were mainly caused by noise on the optical table and could be eliminated with better mechanical isolation for the laser and fiber coupling optics. A 1 second integration time yields a standard deviation for f_0 and f_{beat} of 0.4 mHz and 6 mHz, respectively. Fig. 8 shows the counter signals for f_0 and f_{beat} over the 3 hour period. As demonstrated by others [21], with good temperature stability and basic servo control, such microstructure fiber based frequency combs can remain phase locked for extended periods of time (days).

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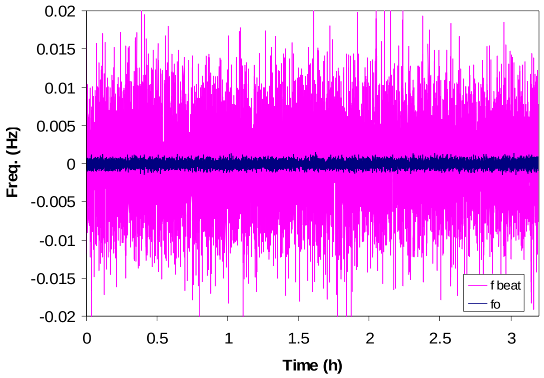

Fig. 8. Counter signals shown as offset from center frequencies of 52.5 MHz (f_{beat}) and 65 MHz (f_0)

4. Conclusion

We have demonstrated a low-threshold self-referenced Ti:Sapphire optical frequency comb with phase locks of both f_0 and f_{rep}. Such a system is a first step towards a more efficient, low-cost Ti:Sapphire FLFC that has some of the advantages of an Er-fiber based FLFC while maintaining a high repetition rate. Low-power, compact femtosecond optical frequency combs will be required for transportable instruments or space-based applications.

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