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A frequency-stabilized Yb:KYW femtosecond laser frequency comb and its application to low-phase-noise microwave generation

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Abstract We present an optically stabilized Yb:KYW fs-laser frequency comb. We use an *f*–2*f* nonlinear interferometer to measure the carrier envelope offset frequency (f_0) and the heterodyne beatnote between the comb and a stable CW laser at 1068 nm to detect fluctuations in the comb repetition rate (f_{rep}). Both of these degrees of freedom of the comb are then controlled using phase-locked loops. As a demonstration of the frequency-stabilized comb, we generate low-phase-noise 10 GHz microwaves through detection of the pulse train on a high bandwidth photodiode. The phase noise of the resulting 10 GHz microwaves was −99 dBc/Hz at 1 Hz and the corresponding Allen deviation was $<2.6 \times 10^{-15}$ at 1 s, measured by comparison to an independently stabilized Ti:sapphire frequency comb. This room-temperature, optically based source of microwaves has close-to-carrier phase noise comparable to the very best cryogenic microwave oscillators.

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1 Introduction

The optical frequency comb has brought about a revolution in optical frequency metrology over the last decade [1, 2]. The underlying comb in the output spectrum of a femtosecond (fs)-laser can be used in many applications if stabilized in its two degrees of freedom: the optical comb spacing, f_{rep}, and offset frequency, f_0. When stabilized, the output provides a frequency ruler across hundreds of terahertz in the optical domain. It can be used to measure other optical frequencies with straightforward RF frequency metrology techniques or as a light source for spectroscopy. This frequency comb technology has enabled the measurement and comparison of state of the art optical atomic clocks to unprecedented accuracy [3]. The optical frequency comb has been applied to a variety of scientific and technological problems, such as breath-analysis [4], astronomical spectrograph calibration [5], atomic and molecular spectroscopy [6] and attosecond pulse generation in the XUV domain [7].

Many applications will require compact, efficient, reliable and inexpensive comb sources at application-dependent optical frequencies. Also, higher repetition-rate combs approaching 10's of GHz are preferred for use in microwave photonics, communications and astronomical spectrograph calibration. To date, the majority of work in this field has employed frequency combs based on Ti:sapphire or Er: and Yb:fiber femtosecond lasers. The Yb:KYW laser (and the related Yb:KGW) used in our work has some distinct advantages relative to these other sources. For example, the Yb:KYW/KGW laser has some of

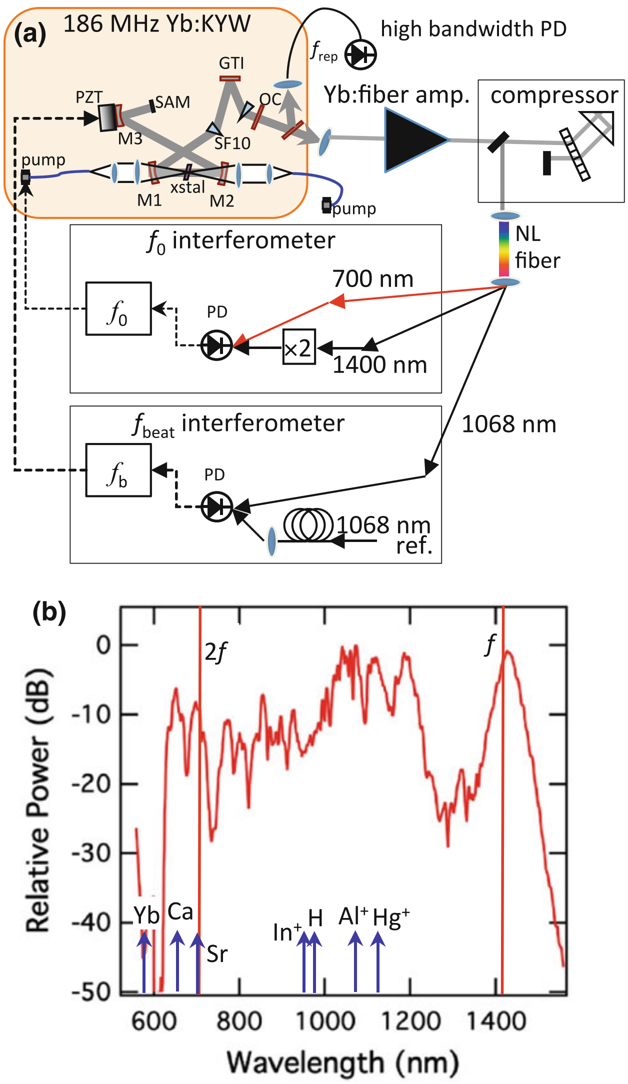

Fig. 1 **a** A schematic representation of the Yb:KYW comb system. The pump diodes were PM fiber coupled and fiber Bragg grating stabilized at 980 nm. The 10-at. % doped Yb:KYW crystal was Brewster cut for E||a with 1-mm optical path length. M1 and M2 are chirped mirrors with radii $R = 5$ cm. The SF10 prisms and a -375 fs^2 Gires-Tournois-Interferometer (GTI) mirror provided negative dispersion. M3, an $R = 20$ cm chirped mirror, focussed the laser light onto a semiconductor saturable absorbing mirror (SAM) to initiate and stabilize mode-locking. The output coupler (OC) of 5 % provided the output beam for amplification with a Yb:fiber amplifier, followed by compression with a volume phase hologram and roof prism and nonlinear broadening in a microstructured fiber. f_{rep} and its higher harmonics were detected with a fiber-coupled high bandwidth photodiode (PD). **b** Octave-spanning spectrum generated in microstructured fiber. Also shown are f and $2f$ used for the nonlinear interferometer and the wavelengths of a variety of optical references under research at various institutions that overlap with the broadened spectrum

the same desirable properties of Ti:sapphire, such as high average power [8], multi-gigahertz repetition rates [9–12] and low cavity losses. It also benefits from direct diode pumping and is one of the most efficient femtosecond-solid-state lasers, with pump-to-output efficiency of >60 % [13]. While diode-pumped Yb: and Er:fiber lasers have been reported with gigahertz repetition rates, they typically have longer pulse widths, lower powers [15, 16] and higher cavity losses; many of these factors can contribute to a comb with intrinsically greater timing-jitter noise when compared to lower-loss solid-state femtosecond lasers, such as the one demonstrated here [17]. Finally, the broadened output spectrum of Yb-based combs overlaps well with many of the optical standards under development in the clock community, as can be seen in Fig. 1b. These features make the Yb:KYW fs-laser an interesting and worthwhile system to explore for precision frequency comb applications.

In previous work, we demonstrated the generation of the octave-spanning spectrum necessary to measure f_0 using f– $2f$ interferometry and then detected and stabilized f_0 with subradian in-loop integrated phase noise [18]. In this paper, we build upon previous work by stabilizing the second degree of freedom of the comb, f_{rep}, to obtain the first optically stabilized Yb:KYW frequency comb. We locked f_{rep} to a cavity-stabilized CW laser. The resulting frequency-stabilized comb was used to generate a 10 GHz microwave signal with high stability and exceptionally low close-to-carrier phase noise [19–21]. This type of low-phase-noise 10 GHz signal is useful for many scientific and technical applications, but it is also a particularly stringent test of the comb's performance.

2 The Yb:KYW comb

The Yb:KYW fs-laser and its f_0 stabilization have been described in detail elsewhere [18]; we give a brief overview and highlight any differences here. Figure 1a shows the schematic for the laser and stabilization. The fs-laser has an X-fold cavity which uses a SESAM in one arm to initiate and stabilize soliton mode-locking and SF10 prisms for dispersion control in the second arm, along with the output coupler. When mode-locked the laser emits 250 mW of power at 1030 nm using a total pump power of 830 mW from PM fiber coupled diode lasers at 980 nm. The pulses are $\sim$300 fs, with a corresponding optical bandwidth of $\sim$4 nm and thus a time-bandwidth product of 0.34. The pulses are at a repetition rate of 160–190 MHz (scalable without changing the properties of the output), with 186 MHz being used for the results presented herein. Since the previous reports we added optical isolators between the fiber-coupled pump diodes and the femtosecond laser (not shown in figure), eliminating optical feedback between pump lasers and permitting better alignment and overlap of these beams in the Yb:KYW crystal. In addition, we improved the 980-nm transmission of the two $R = 5$ cm mirrors around the Yb:KYW crystal, resulting in a pump-to-laser output efficiency of 25 % in mode-locked operation.

Self-referencing via an f–$2f$ scheme requires an octave-spanning spectrum. To that end, a Yb:fiber amplifier increased the average power while the optical spectrum was simultaneously broadened via self-phase modulation in the fiber. The pulses were re-compressed with a single volume phase hologram combined with roof prisms [22, 23] down to 113 fs, i.e. shorter than the input pulses due to the extra spectral bandwidth. The compressed 300 mW of average power generated the octave-spanning spectrum shown in Fig. 1b in a 75-cm long microstructured fiber with 945-nm zero dispersion wavelength and a core diameter of 3.2 µm. The fiber was end-sealed and terminated with FC/APC connectors to allow long-term use. The resulting spectrum from 650 nm to 1450 nm allowed detection of f_0 using an f–$2f$ interferometer with a signal-to-noise ratio (SNR) of 40 dB in 100 kHz resolution bandwidth (BW). A phase-locked loop (PLL) locked f_0 to a reference frequency with feedback to the input modulation port on the current controller of one of the pump diodes as an actuator. The modulation of the pump power had ~180 kHz bandwidth. However, the resulting servo bandwidth for f_0 was limited by the Yb:KYW crystal's upper state lifetime to ~45 kHz. To counteract this effect, a phase lead pushed the servo bandwidth out to 100 kHz, as indicated by the servo bumps on the RF spectrum of the f_0 beatnote shown in Fig. 2a. The increased servo bandwidth led to the in-loop phase noise profile shown in Fig. 2b, with an integrated phase noise of 0.3 rad (0.1 Hz–1 MHz), which is about a factor of three above what was measured in a 200 MHz Ti:sapphire system [24] and lower than what has been reported for typical Er:Fiber systems with comparable repetition rate and integration bounds [25].

With f_0 controlled, we needed to measure and lock f_{rep} to a reference frequency to fully stabilize the optical comb. A locked comb reproduces the stability of the reference, so we chose to leverage the excellent short-term stability and low phase noise of a cavity-stabilized CW laser as the comb's reference. Technically, when we lock the comb to a CW reference we are locking one comb mode to the reference. However, since all modes of the comb are tightly locked in phase by the mode-locking process, controlling one mode of the comb effectively controls all the modes. This results in the stabilization of the second degree of freedom in the comb, which is f_{rep}. In our case, the Yb:KYW comb was referenced to CW light at 1068 nm that also serves as the local oscillator for the Al^+ optical clock at NIST [3, 26]. For our measurements, the light was not stabilized to the ion's clock transition. Nonetheless, the fractional frequency instability of this light is $\frac{\delta f}{f} < 1 \times 10^{-15}$ at 1 s of integration. The reference light came from another lab to the Yb:KYW comb through ~300 m of noise-cancelled optical fiber [27]. A simple interferometer overlapped the 1068 nm light with a 4-nm wide portion of the comb. We detected the heterodyne beat, f_{beat} with an SNR of 35 dB in 100 kHz resolution BW.

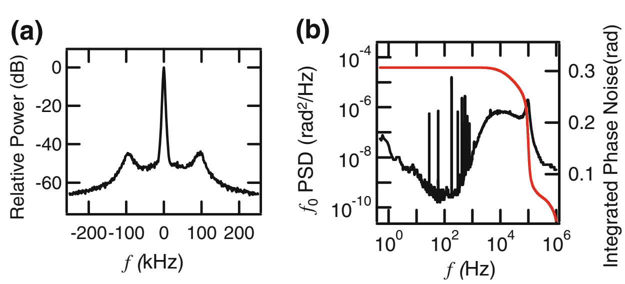

Fig. 2 **a** RF spectrum at 3-kHz resolution bandwidth and **b** residual phase noise and integrated phase noise of the locked f_0 beatnote

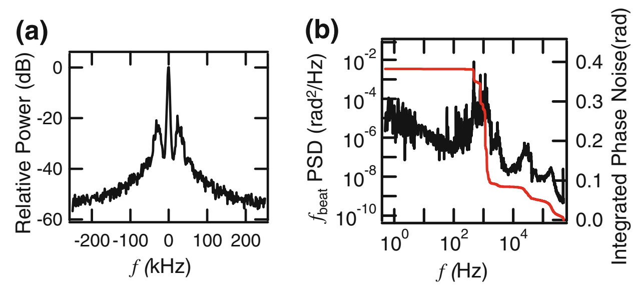

Fig. 3 **a** RF spectrum at 3-kHz resolution bandwidth and **b** residual phase noise and integrated phase noise of the locked f_{beat} beatnote

The detected f_{beat} signal was locked to an RF reference by using a piezo electric transducer element mounted behind one of the cavity mirrors as an actuator within a PLL. The microwave spectrum of the locked f_{beat} is shown in Fig. 3a. Figure 3b shows the measured residual phase noise on f_{beat}. The integrated phase noise was 0.4 radians (0.1 Hz–0.5 MHz). With the two comb parameters locked, we focussed on the application of the stabilized comb to low phase noise microwave generation.

3 Low-phase-noise microwave generation and characterization

With the Yb:KYW comb now frequency-stabilized, several applications are possible. As a first demonstration, we use the comb to generate 10-GHz microwaves with phase noise comparable to that achieved with the lowest noise microwave oscillators of any type. Such low-phase-noise microwaves have a variety of scientific and technical applications. These include serving as local oscillators for Cesium fountain clocks [28], remote synchronization for X-ray free electron laser facilities [29], low noise waveform synthesis [30], high speed analog to digital conversion [31] and very long baseline interferometry radio astronomy [32]. To generate low-phase-noise microwaves, the comb serves as an optical-to-microwave frequency divider. As already described, the comb is locked to a stable optical reference, the stability of which is reproduced in the repetition rate of the optical pulse train, with some added noise sources as discussed below. This stable optical signal is converted to an electronic signal with a high bandwidth photodetector. The RF spectrum of the photocurrent contains harmonics of the repetition rate, any of which has the same $\frac{\delta f}{f}$ of the CW laser reference. Here, we focus on the 54th harmonic of the Yb:KYW laser repetition rate to provide a low noise signal near 10 GHz.

The potential stability of the repetition rate of the stabilized Yb:KYW laser is evident from simple analysis of the equation governing the optically stabilized comb. The m-th comb element is locked to the optical reference frequency, ν_{opt}, with an offset beat frequency f_{beat}, such that:

$$\nu_{opt} + f_{beat} = m f_{rep} + f_0. \tag{1}$$

Solving for the repetition rate gives

$$f_{rep} = \frac{\nu_{opt} + f_{beat} - f_0}{m}. \tag{2}$$

For the optical lock at 1,068 nm, m is $\sim$1.6 million, which provides significant leverage in dividing down the optical-domain frequency noise. Here, we focus on long timescales of >1 s. Consider the effect of frequency fluctuation of ν_{opt}, f_{beat} and f_0 on the repetition rate. The fluctuations of the cavity-stabilized laser are δf <0.3 Hz in 1 s averaging, corresponding to a fractional instability of <1 $\times$ 10^{-15}. For the locked parameters, we have measured δf_0 and δf_{beat} to be few mHz in 1 s averaging. So, the frequency fluctuations on the locked comb's f_{rep} should be dominated by the optical reference. Thus, δf_{rep} should be less than 1 μHz and the fractional frequency fluctuations should mimic the optical reference at these longer timescales. A corresponding reduction is realized when one considers the phase fluctuations, where the optical-to-microwave division ideally reduces the phase noise power spectral density by a factor of m^2. In our generation of 10-GHz microwaves, we measure the phase noise of the 54th harmonic of the repetition rate, so the noise in our measurement is larger by that factor.

The optically referenced Yb:KYW comb was anticipated to produce microwave signals with significantly lower phase noise than can be measured with standard techniques. Therefore, we required a second 10-GHz source with comparable or better phase noise, which in this case was provided by a 1 GHz Ti:sapphire comb that was frequency-stabilized by an independent optical frequency reference at 578 nm [42]. The stabilization and

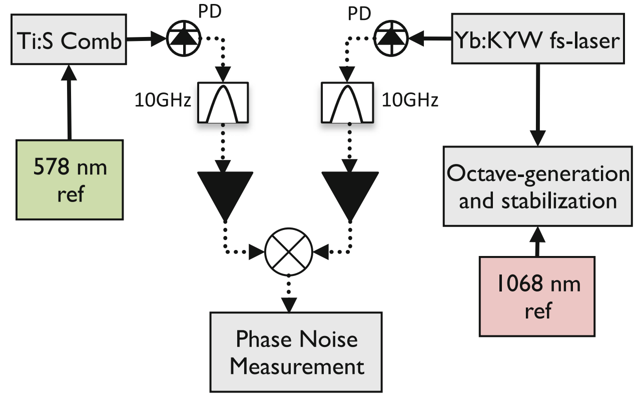

Fig. 4 A schematic representation for the microwave measurement *PD* photodiode

characterization of the Ti:sapphire (Ti:S) laser has been described elsewhere [34]. The set-up for these measurements is shown in Fig. 4. The Yb:KYW and Ti:S frequency combs were on different optical tables with the microwave detection on the same (floating) table as the Ti:sapphire comb; the Yb:KYW comb's table was not floating. The light from the Yb:KYW comb was transported to the photodiode in 5 m of single mode fiber. Each comb was detected using a fiber-coupled InGaAs top-illuminated photodiode. An integrated GRIN lens shaped the optical beam to illuminate the diode uniformly [35, 36]. The photodiode bandwidth was 22 GHz at 1550 nm and the responsively was 0.26 A/W at 900 nm.

In the photodetection process, relative intensity noise (RIN) on the optical pulse train can be converted to phase noise on the electrical microwave signal via amplitude modulation to phase modulation (AM–PM) conversion [36, 37]. We measured an increase in the laser RIN after the nonlinear fiber, thus we chose to place the photodetector for the microwave generation directly at the output of the Yb:KYW laser.

The signals from the photodiodes at 10 GHz were isolated with bandpass filters, amplified and mixed down to an intermediate frequency of 23 MHz. The phase noise of the 23-MHz signal, which contained the combined noise of both 10-GHz sources, was input into a digital phase noise measurement system referenced to a low-noise 10-MHz quartz oscillator. The results are shown in Fig. 5. Using this 10-GHz phase noise, the Allan deviation was calculated as 2.6 $\times$ 10^{-15} at 1 s averaging, a promising result. For comparison, we show the 10-GHz phase noise of the Ti:S comb as well as the projected noise contribution from the 1068-and 578-nm optical references, as determined from recent measurements [34]. Compared to a previous result, scaled from 2 to 10 GHz, we had $\sim$20 dB noise suppression throughout the frequency range by using light before the microstructured fiber to detect the f_{rep} harmonic [38, 39].

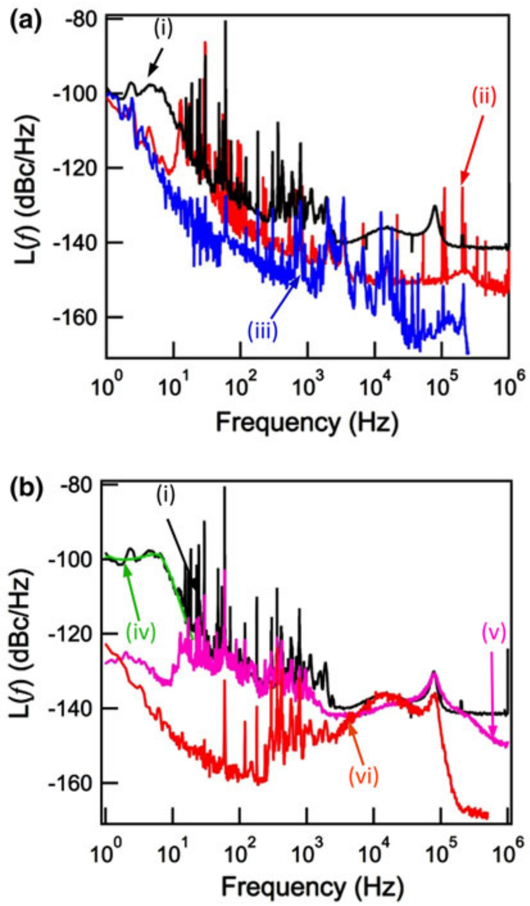

Fig. 5 **a** The phase noise of the 10-GHz signal generated with the Yb:KYW and Ti:sapphire combs (*i*), along with the limit of the Ti:sapphire reference (*ii*) and the optical references (*iii*). **b** The phase noise limitations at various frequencies, including the noise on the RF reference used for the phase noise measurement (*iv*), the relative intensity noise (*v*) and the residual comb noise (*vi*)

We investigated which noise sources dominated the measured phase noise at various frequency offsets from the 10-GHz carrier. Above 100 kHz, we are limited by shot and thermal noise. Due to saturation [40], the photodiode provides only –25 dBm of microwave power in the 10-GHz harmonic with 7.1 mA of average photocurrent. Near 10 kHz the contribution due to the residual comb phase noise limited the measurement, as shown in Fig. 5b. This limitation was 10 dB above what is possible with optimization of the f_0 PLL. Using the measured RIN and scaling it to match the 10 GHz phase noise data, we see that RIN noise via AM–PM conversion was likely contributing to noise in the 10–1000 Hz range and near 100 kHz. The phase noise at frequencies less than 100 Hz nearly follows the Ti:S 10-GHz phase noise, except for the bump in the 1–10 Hz range. This bump was the result of the 10-MHz RF reference used by the phase noise measurement system, as shown in Fig. 5b. Since the RIN and residual comb noise in the 1–10 Hz range are 30 and 40 dB (respectively) below the currently measured limit, we expect much lower phase noise to be detected in this range once the 10-MHz reference limitation is lowered.

4 Conclusions and outlook

In this paper, we demonstrate a frequency-stabilized Yb-doped crystal frequency comb. The resulting comb should be a low-noise, compact, efficient and high repetition rate source for many present and future comb applications. As a first demonstration, we applied this comb to the generation of low-phase-noise microwaves. Our first results at 10 GHz are promising and can be improved in the future by making a few straightforward changes to the system and measurement. For example, the low-frequency noise (1–10 Hz) is impacted by the measurement system itself, and is therefore not fully representative of the phase noise of the 10 GHz signal itself. This can be improved by using a lower phase noise RF reference to improve the measurement sensitivity. At frequencies >10 kHz, improvements to the f_0 servo would reduce both the impact of the residual noise and the AM-PM via reductions in the RIN. In addition, the shot and thermal noise floor can be improved by using cavity filtering [40] or pulse interleaving techniques [41, 42]. With the demonstration of mode-locked Yb:KYW(KGW) lasers at multi-GHz repetition rates [9–12], including a self-referenceable Yb:KGW laser at 1 GHz [43], we anticipate fully stabilized Yb-doped crystal combs at even higher repetition rates in the near future, which could improve on these 10 GHz microwave results even further.

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