Broadly tunable, low timing jitter, high repetition rate optoelectronic comb generator

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We investigate the low timing jitter properties of a tunable single-pass optoelectronic frequency comb generator. The scheme is flexible in that both the repetition rate and center frequency can be continuously tuned. When operated with 10 GHz comb spacing, the integrated residual pulse-to-pulse timing jitter is 11.35 fs (1 Hz to 10 MHz) with no feedback stabilization. The corresponding phase noise at 1 Hz offset from the photodetected 10 GHz carrier is -100 dBc/Hz.

Introduction: Since their advent around the turn of the century, frequency combs produced from phase-stabilized mode-locked lasers have revolutionized the field of spectroscopy and permitted stable frequency synthesis to unprecedented levels. Applications such as optical clocks [1] and metrology [2] now make extensive use of the phase stable frequency grid these combs provide. However, the mode spacing of most mode-locked frequency combs is too narrow for the individual lines to be spectrally resolved. In this high frequency regime (>5GHz), optoelectronic comb generators (OECG) have proven to be advantageous [3], with applications including terahertz signal generation [4], coherent communications [5], optical arbitrary waveform generation (OAWG) [6], and generation of low-noise millimeter wave signals [7]. In the most basic of these schemes, a continuous wave (CW) laser is sent though an electro-optic (EO) modulator driven by a stable radio-frequency (RF) source. The modulation creates side-bands around the CW laser frequency which are spaced by the repetition rate of the RF oscillator. In additon to large mode spacing, OECGs offer the advantages of simplicity, robustness, and flexibility in terms of center frequency and repetition rate. If one can leverage these attributes to create a flexible pulsed source with good timing accuracy, OECGs could enable new applications in high-resolution radar and precise high-speed sampling.

A recent OECG scheme utilizing a narrow-linewidth ($\sim$10 kHz) laser locked to a modulator in a resonant cavity yielded a timing jitter as low as 6.4 fs when paired ultra-stable RF source [8]. The use of a resonant configuration enhances the bandwidth of the OFC, facilitating shorter pulse durations, but it also demands greater stability of the CW source and restricts repetition rate tuning to integer multiples of the cavity free-spectral-range (FSR). An alternative approach to increasing bandwidth is to simply concatenate multiple modulators in a single-pass configuration, a process which preserves continuous tuning of both the repetition rate and center frequency. A particularly useful derivative of this configuration combines an intensity modulator (IM) in series with multiple phase modulators (PM) producing a comb with a flat spectral envelope, a desirable property in optical communications and OAWG.

Utilizing the aforementioned single-pass configuration comprised of multiple PMs and an IM, we recently reported an OECG which allows for continuous tuning of the repetition rate (6-18 GHz) while exhibiting a flat spectral profile over 50-70 lines in a -10dB bandwidth [9]. Investigation into the overall timing jitter and microwave phase noise properties of a flexible single-pass EO comb generation scheme has not yet been demonstrated. Previously, we reported basic single-sideband (SSB) phase noise measurement on the OECG in [9], but were limited by a relatively noisy RF oscillator. Another noise measurement utilizing a similar generation scheme was performed in [5], but here the focus was on the accumulation of noise for individual comb modes as one moves further from the CW carrier. Additionally, this measurement was performed optically and the close-to-carrier noise was cloaked by the drift of the CW laser, pinning the phase noise below 10 MHz at a level of -70 dBc/Hz. In this contribution, we will investigate for the first time the pulse-to-pulse timing jitter by examining the low close-to-carrier residual phase noise properties of a non-resonant OECG utilizing an ultra-stable RF source. Achieving a tunable high repetition rate source with a high degree of phase stability is beneficial for applications including stable OAWG [6], the transmission of precise frequency and time signals [10], and coherent communications [5].

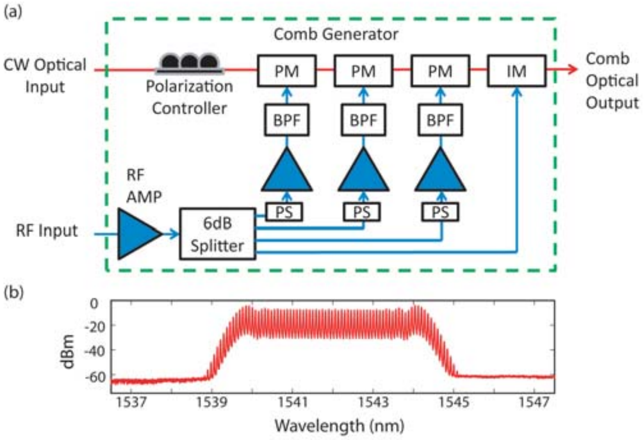

Fig. 1 *(a) Layout of optical frequency comb generator. PM-phase modulator, BPF-band pass filter, PS-RF phase shifter, IM-intensity modulator. (b) Example output spectrum at 10 GHz repetition rate*

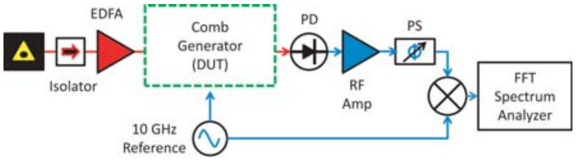

Fig. 2 *Residual phase noise measurment setup. FFT-Fast Fourier Transform spectrum analyzer, EDFA-erbium doped fiber amplifier, PD-photodiode, PS-RF phase shifter*

Experimental Results: Our OFC generation scheme is detailed in Fig 1a. A narrow linewidth (10kHz) CW laser is passed through three PMs and an IM all driven by the same low-noise RF source. The IM is biased to carve out a flat-top 50% duty cycle pulse train from the CW input. RF phase shifters (PS) are utilized to align the peak of the pulse with the cusp of the applied phase modulation –the point where the imposed chirp is most linear– mapping the flat top pulse profile to the spectrum in a process known as time-to-frequency mapping [11]. Three phase modulators are used to increase the modulation index, each contributing roughly 20 lines. Besides the benefit of a flat top profile, which is ideal for applications requiring pulse shaping or channel equalization, the line spacing of this comb can be continuously tuned from 6-18 GHz, limited by the bandwidth of the RF amplifiers. An example of the spectrum at 10 GHz repetition rate is given in Fig. 1b. The slight peaking in the spectral amplitude that appears near the edge of the spectrum arise because the PMs act as an imperfect time-lens [12]. For more demanding applications the spectral flatness can be improved by adding an additional IM at the cost of increased insertion loss. Further information on this general scheme can be found in [9].

The residual phase noise measurement setup is detailed in Fig.2. The narrow linewidth CW laser is amplified by an erbium-doped-fiber-amplifier (EDFA) before seeding the OECG. The output optical signal is sent directly to a photodiode (PD) with 12 GHz bandwidth to produce the 10 GHz RF beat signal. The RF signal then gets amplified and passes through a phase-shifter before going to the signal arm of the microwave mixer. The reference RF signal is split with a 3dB splitter, one arm goes to the OECG and the other is sent to the reference arm of the microwave mixer. The PS in the signal arm is used to align the two RF mixing signals at quadrature (0V DC), the point where the relative phase noise is converted to amplitude fluctuations, allowing measurement by a Fast-Fourier-Transform FFT spectrum analyzer. The FFT records voltage fluctuations from 1 Hz to 10 MHz during the measurement. The 10 GHz source used is generated via optical frequency division, with absolute phase noise of -100 dBc/Hz at 1 Hz offset, and -177 dBc/Hz at 10 MHz offset [14]. This low noise source was used to prevent any frequency discriminator effects from corrupting the residual phase noise measurement.

Fig.3 shows the measured residual SSB phase-noise power spectral density (PSD) in dBc/Hz for our OECG along with the recorded noise floor. The measurement noise floor was determined by removing the

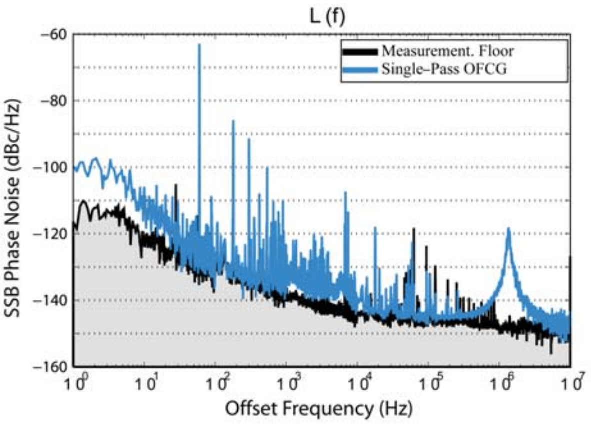

Fig. 3 *SSB residual phase noise results at 10 GHz repetition rate. (Black) measurment noise floor. (Blue) current results.*

OECG and PD from the reference path and instead directly connecting the RF source used to drive the OECG to the microwave mixer. The results show the residual phase noise is as low as -100 dBc/Hz at 1 Hz offset which drops to -140 dBc/Hz at 100 kHz, limited by the measurement noise floor. The observed spectral peak around 1 MHz corresponds to the relative intensity noise (RIN) peak from the relaxation oscillation from of the CW laser, suggesting either imperfect rejection of amplitude noise in the mixer, or amplitude-to-phase conversion by the photodetector. Other noise spurs at lower frequencies can be attributed to active components, such as optical and RF amplifiers, modulators, and pick-up from surrounding electronics. The high power RF amplifiers which drive the PMs generate 30-33 dBm of output power which likely make the spurs more prevalent. This deterministic noise can be reduced by paying better attention to ground loops, using low-noise RF amplifiers, and providing better shielding of the system.

We can further examine the stability by calculating the RMS timing jitter τ_{rms} from the measured phase noise using the relation in (1), where f_m is the comb repetition rate, $\mathcal{S}_\phi(f) = 2\mathcal{L}(f)$ and $\mathcal{L}(f)$ represents the SSB phase noise PSD.

$$\tau_{rms} = \frac{1}{2\pi f_m}\sqrt{\int \mathcal{S}_\phi(f) df} \tag{1}$$

Integrating the SSB phase-noise for Fourier frequencies from 1 Hz - 10 MHz, results in a timing jitter of 11.35 fs. A major portion of the jitter can be attributed to the high peak from the RIN of the CW laser. If we instead integrate our signal's phase noise with the RIN peak removed, by assuming the background noise floor for Fourier frequencies above 600 kHz, we achieve a very low timing jitter of 3.17 fs.

Our jitter numbers are comparable to other sources relying on resonant structures employing feedback servos [8, 15]. However, we want to point out that using a single-pass scheme garners two additional benefits in terms of flexibility. 1) The repetition rate can be continuously tuned and is not limited to integer multiples of the cavity FSR. And 2) there is no requirement that the CW laser frequency be precisely aligned with that of the resonant cavity. In the case of the resonant OECG, slight fluctuations in the CW laser frequency with respect to the cavity resonance will negatively affect the timing jitter [13]. This imposes strict requirements on the linewidth of the CW laser.

Because the choice of CW input frequency is de-coupled from the rest of the comb generation process in the single-pass case, the requirements on linewidth are less stringent and a servo is no longer needed to align the CW laser to the resonant cavity. This lends itself well for on-chip integration where an array of inexpensive lasers could be sent to a single OECG to produce multiple independent low-jitter sources. In addition, broadly tunable laser sources, which typically have MHz-class linewidth's, could be used to seed the OECG.

Conclusion: We have experimentally demonstrated the low phase noise properties of a flexible and robust OECG. Phase noise was shown to be as low as -100 dBc/Hz at 1 Hz offset with a corresponding integrated timing jitter 11.35 fs from 1 Hz to 10 MHz. A major benefit of our single-pass configuration is the ability to continuously tune the repetition rate and center frequency. In addition, because our scheme does not utilize a resonant cavity, stabilization requirements of the CW seed laser are less demanding. Applications which can benefit from such a flexible high frequency phase-stable source include low-noise synthesis of microwave signals, OAWG, and coherent communications.

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