Long-Term Stable Balanced Optical-Microwave Phase Detector with Sub-Femtosecond Residual Timing Jitter Capability for Optical-to-RF Extraction

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***Abstract*—Balanced optical-microwave phase detectors (BOMPD) based on fiber Sagnac interferometers and single-ended heterodyne detection are capable of optical-to-RF conversion with sub-femtosecond residual timing jitter. By increasing the BOMPD phase sensitivity and reducing its internal noise down to the thermal noise limit, we achieve an integrated noise floor in the sub-fs regime. Second, we demonstrate long-term stable optical-RF conversion by phase-locking an RF oscillator to a mode-locked laser using a BOMPD with <1 fs RMS drift and <7 fs pk-pk for over 10 hours.**

***Keywords*—timing, synchronization, optical pulses, phase-locked loop, femtosecond, optical-RF, phase detector, ultrafast, mode-locked lasers**

I. INTRODUCTION

Sub-femtosecond synchronization between several optical and radio-frequency (RF) sources is desirable for realizing a new regime of light and electron bunch control in next-generation light sources [1]. While recent developments in optical timing distribution systems [2] are enabling sub-fs timing precision for kilometer-scale beamlines, it remains equally important to develop techniques to preserve the ultralow noise properties of optical signals into the microwave domain for RF synchronization.

Conventional optical-to-RF extraction techniques, e.g. direct detection, are subject to amplitude-to-phase (AM-PM) conversion and excess phase noise during detection [3], which may degrade the signal by orders of magnitude. An alternative technique is to use a balanced optical-microwave phase detector (BOMPD) [4] to extract the timing information prior to detection. Based on electro-optic sampling in a fiber Sagnac interferometer (SGI), the BOMPD converts the relative phase error between the pulse positions of an optical pulse train and the zero-crossings of an RF signal into an amplitude modulated signal, thus circumventing phase noise issues upon detection.

Few groups have improved upon the basic BOMPD scheme (with nonreciprocal loop biasing and balanced detection) to suppress the BOMPD noise floor down to -154 dBc/Hz to realize RF extraction with sub-fs absolute timing jitter [5] and verified AM-PM suppression up to 60 dB [6]. However, this scheme requires additional components that break the inherent symmetry and robustness of the Sagnac loop, thus degrading its long-term performance.

For this reason, we have continued improving upon our previous work on the basic BOMPD scheme with heterodyne detection [7]. First, we demonstrate that even without balanced detection, our BOMPDs are capable of optical-RF locking with sub-fs residual timing jitter; by increasing the BOMPD phase sensitivity and reducing its internal noise down to the thermal noise limit, we can achieve an integrated noise floor in the sub-fs regime. Second, using a BOMPD to phase-lock a commercial RF oscillator to a mode-locked laser, we achieved long-term stable optical-RF extraction with <1 fs RMS drift and <7 fs pk-pk for over 10 hours, easily covering a full shift at a light source facility.

II. EXPERIMENTAL SET-UP

To perform optical-RF extraction, we operate the BOMPD in an optoelectronic phase-locked loop (PLL) to lock a voltage-controlled oscillator (VCO) to an incoming optical pulse train. The input pulse train is generated from a free-running Er-doped mode-locked laser (Menlo Systems; M-comb-custom) that outputs 170-fs pulses centered at 1558 nm with a 200.392 MHz fundamental repetition rate. The input pulse train is first divided into the main SGI path and reference path. The reference path is used to generate a RF modulation signal at a half-repetition-rate frequency to: 1) bias the SGI at quadrature

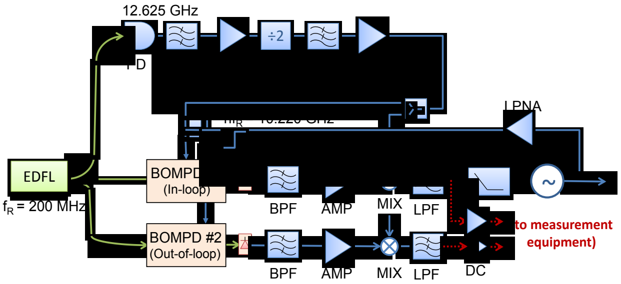

Fig. 1: Experimental set-up for optical-to-RF extraction using a BOMPD in an opto-electronic PLL. Second BOMPD is for an out-of-loop residual phase error measurement; EDFL, Er-doped laser; PD, detector; BPF, bandpass filter; AMP, amplifier; DIV, frequency divider; LPF, low pass filter, MIX, mixer; PI, proportional integral controller; LPNA, low phase noise amplifier

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for maximum phase sensitivity and 2) impart alternating ±π/2 phase shifts between consecutive pulses. The alternating phase flips the SGI between two different quadrature points while maintaining a constant amplitude pulse train at the SGI output. Contrary to our previous work, the modulation frequency is increased into the multi-GHz regime so that the phase modulator in the SGI operates uni-directionally; this relaxes the repetition rate dependence of the Sagnac loop and renders the SGI robust against imperfect loop lengths and environmental noise.

With the BOMPD properly biased, the VCO (PSI; DRO-10.225-FR), whose frequency is to be locked to the 51st harmonic (10.220 GHz) of the pulse train, is then added to the phase modulator. Any phase error between the VCO and input pulse train will perturb the BOMPD from quadrature and modulate the amplitude of the output pulse train. The modulated pulse train is then detected and down-converted to baseband using the modulation signal as the local oscillator. A proportional-integral controller feeds the error signal back to the VCO to close the PLL with a 100-kHz locking bandwidth. The VCO output serves as the regenerated RF signal. To maximize the BOMPD phase sensitivity, the VCO signal is amplified to just below the damage threshold of the modulator. A low-noise DC preamp is used to amplify the signal above the measurement noise floor. The in-loop BOMPD sensitivity, as measured from the input to the measurement equipment, is 4.4 mV/fs referenced to 10 GHz.

To characterize the PLL performance, a second nearly identical BOMPD was implemented for an out-of-loop measurement. The out-of-loop BOMPD sensitivity was 4.8 mV/fs referenced to 10 GHz. For long-term drift measurements, the out-of-loop error signal is low-pass filtered at 1 Hz and sampled at 1 Hz with an analog-to-digital converter. For short-term jitter measurements, the in-loop and out-of-loop error signals are analyzed with a vector signal analyzer in the frequency range 1 Hz to 1 MHz.

III. RESULTS AND DISCUSSION

Note that the purpose of the short-term jitter measurements is not to regenerate the best possible RF signal, which can be achieved easily by replacing our current VCO with an ultralow-noise one and implementing a loose lock. We prefer here to use a "noisy" oscillator to demonstrate how effectively the BOMPD suppresses relative phase error within a large locking bandwidth and, more importantly, to characterize its intrinsic noise floor.

Improving upon our previous work [7], we show for the first time that optical-RF extraction is dominated by the thermal noise limit in the in-loop BOMPD (see Fig. 2 – out-of-loop curve), with exceptions due to noise spurs from particular RF components (200-600 Hz) and low frequency noise possibly from vibrations and acoustics (near 6 Hz). The measured BOMPD noise floor integrated from 1 Hz to 10 kHz including the noise spurs is only 0.6 fs (see red curve), and the extrapolated BOMPD noise floor from 10 kHz to the 100-kHz loop bandwidth using the thermal noise limit is 0.4 fs (see green curve), totaling a conservative estimate of 1 fs for the integrated noise floor. We justify using the thermal noise for the latter frequency range because the measured spectrum near the loop bandwidth represents signal power, i.e. residual phase error between the locked VCO and the pulse train, and does not represent the intrinsic noise of the BOMPD. If we optimize the system further to eliminate the noise spurs, the thermal noise limit alone integrated over the same frequency range from 1 Hz to 100 kHz would be only ~0.6 fs.

Despite observing the thermal noise floor, this does not imply that the BOMPD is performing at its fundamental limit. The key system parameter is the signal-to-noise ratio at detection. The BOMPD noise floor can be effectively suppressed further by increasing the signal power (i.e. BOMPD phase sensitivity) to increase the signal-to-noise ratio. This can be achieved in a number of ways, such as increasing the optical power incident on the detector or decreasing the heterodyne detection frequency for higher detector responsivity.

Using the same experimental set-up, we also demonstrate long-term stability with 0.99 fs RMS and <7 fs pk-pk drift for over 10 hours (Fig. 3). This is a factor of 6 to 7 improvement over our previous work in [7] and is similar to that recently reported in [5]. In contrast to [5], however, our BOMPD with the simplified Sagnac loop and heterodyne detection is insensitive to long-term drifts caused by coupling ratio drifts, beam drifts, and imbalanced attenuation in the optical domain. Our long-term drift is caused instead by environmental perturbations to the mechanical stability of the electronics; vibrations from heat sink fans, mechanical stress, and thermal expansion all induce length changes in the RF cables, which translate into non-negligible phase drifts.

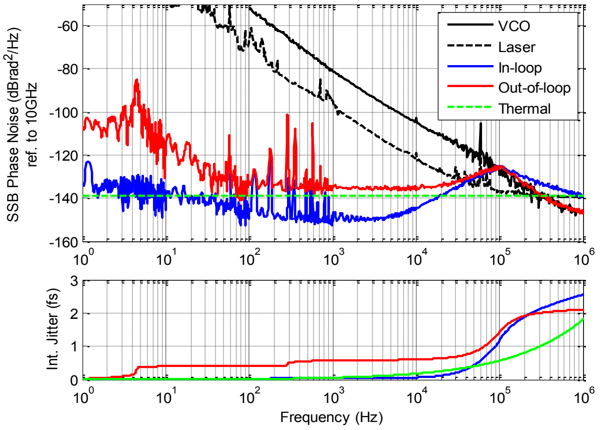

Fig. 2: Short-term timing jitter measurements; (top) single sideband residual phase error spectra; (bottom) integrated RMS timing jitter from 1Hz; 1 fs conservative estimate for BOMPD residual noise floor up to 100-kHz.

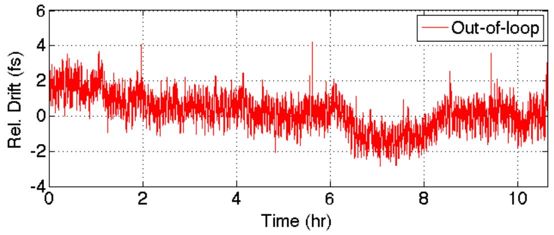

Fig. 3: Long-term timing drift measurements, referenced to 10 GHz. 0.99 fs RMS jitter and < 7 fs peak-peak over 10 hours

These results indicate that BOMPDs based on the SGI and heterodyne detection still offer great potential for improved long-term stable optical-RF extraction at the sub-femtosecond level. Future work that remains is to further increase the BOMPD phase sensitivity and to demonstrate true absolute optical-RF extraction via ultralow-noise oscillators.

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