BALANCED OPTICAL-MICROWAVE PHASE DETECTOR FOR 800-nm PULSED LASERS WITH SUB-FEMTOSECOND RESOLUTION

K. Şafak†, H. P. H. Cheng, A. Dai, P. Schiepel, E. Cano, J. Derksen, A. Berlin, M. Neuhaus
Cycle GmbH, Hamburg, Germany
F. X. Kärtner, Deutsches Elektronen Synchrotron and Center for Free Electron Science,
Hamburg, Germany

Abstract

We report a novel optical-to-microwave phase detector designed for 800-nm pulsed laser operation. The detector is based on electro-optic sampling between the microwave and the optical pulse train which is incorporated into a fiber-based Sagnac interferometer containing a phase modulator. The detector has a timing resolution of 0.01 fs RMS for offset frequencies above 100 Hz and a total noise floor of less than 10 fs RMS integrated from 1 Hz to 1 MHz.

INTRODUCTION

Modern light-matter interaction experiments conducted in free-electron lasers, ultrafast electron diffraction instruments and extreme light infrastructures require synchronous operation of microwave sources with femtosecond pulsed lasers [1,2]. In particular, Titanium-sapphire (Ti:Sa) lasers have become the most common near-infrared light source used in these facilities due to their wide gain spectrum, translating into wavelength tunability and ultrashort pulses at around 800-nm optical wavelength [3]. Therefore, a highly sensitive optical-to-microwave phase detector operating at 800 nm is an indispensable tool to synchronize these ubiquitous lasers to the microwave clocks of photon science facilities. Electro-optic sampling is one approach that has proven to be the most precise in extracting the relative phase noise between microwaves and optical pulse trains [4-7]. However, their implementation at 800-nm wavelength has been so far limited to a few specialized laser laboratories [3,8].

Here, we show a novel optical-microwave phase detector designed for 800-nm operation promising 10-fs level synchronization precision from 1 Hz up to 1 MHz offset frequency.

OPERATION PRINCIPLE

Operation principle of the detector is based on a differentially-biased, fiber-based Sagnac interferometer (SGI) and synchronous detection at half the repetition rate of the optical pulse source. This scheme adopted from the balanced optical–microwave phase detectors (BOMPD) previously demonstrated for 1550-nm operation by our former group members [6,9]. Figure 1 shows the schematic of our 800-nm BOMPD. As inputs, the detector takes an 800-nm pulsed laser (e.g., a Ti:Sa laser) and a microwave signal whose frequency is a higher harmonic of the laser's pulse repetition rate. The optical signal is split into two arms. The first arm (i.e., bias arm) is tapped off by a photodiode to generate a high-frequency (multi GHz) microwave signal which is adjusted in amplitude and phase to achieve quadrature bias. The second arm is sent into a fiber-based SGI containing an optical phase modulator. When both the bias and the microwave signals are applied to the modulator, any phase error between the laser and the microwave source induces an amplitude modulation in the pulse train.

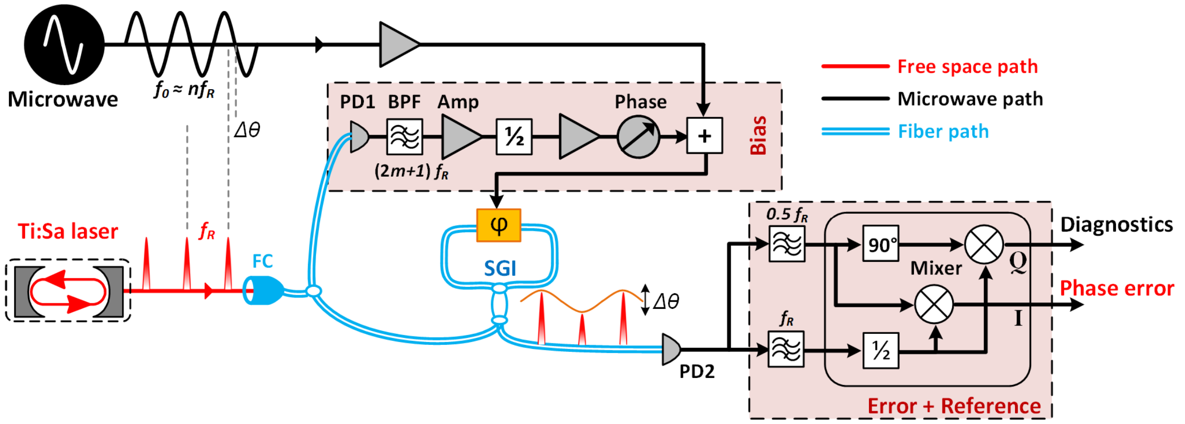

Figure 1: Schematic of the 800-nm BOMPD. Δθ: Phase error between the microwave and optical pulse train; PD: photodetector; BPF: bandpass filter; Amp: electronic amplifier; ½: frequency divider; Phase: RF phase shifter; +: microwave diplexer; φ: electro-optic phase modulator; SGI: Sagnac-interferometer; FC: fiber collimator, I: in-phase output, Q: inquadrature output.

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† kemal.shafak@cyclelasers.com

Upon photodetection, the SGI output contains the phase error information (Δθ) at half frequencies of its odd harmonics (i.e., $(m+0.5)f_R$) besides the regular harmonics of the repetition rate (i.e., nf_R) which can serve as a reference signal for down-mixing to baseband. The phase error at $f_R/2$ and the reference signal at f_R are bandpass filtered and sent into an I/Q demodulator. The in-phase output of the demodulator gives the phase error signal of the 800-nm BOMPD at baseband; whereas, the quadrature output can be used as a diagnostic tool, for example, to check and observe the bias signal mismatch.

All detector electronics of the BOMPD (highlighted with red boxes in Figure 1) are designed and integrated into two printed circuit boards (PCB). This allows a compact detector footprint and enhanced environmental insulation which is suitable for accelerator and facility environments. Figure 2 shows the photo of the 800-nm BOMPD containing all the elements in an environmentally insulated enclosure.

Figure 2: Photo of the 800-nm BOMPD.

PERFORMANCE CHARACTERIZATION

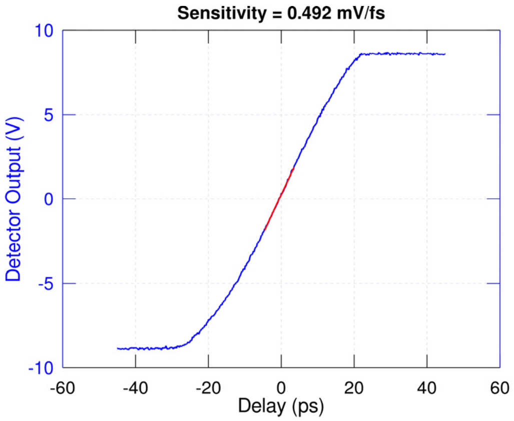

Figure 3: Timing sensitivity of the 800-nm BOMPD.

The performance of the 800-nm BOMPD is characterized using a 79.333 MHz Ti:Sa laser and a 5.712 GHz microwave signal. Figure 3 shows the characteristic BOMPD curve when the optical and microwave inputs are freely running. The zero-crossing slope shows the timing sensitivity of the detector which is found to be 0.492 mV/fs (±0.037 mV/fs) after 11 consecutive measurements. As can be inferred from the zero-crossing of the timing sensitivity curve, the detector has a linear detection range of more than 20 ps.

The detector noise floor is measured at the phase error output with a baseband analyzer when the microwave input is turned off and the BOMPD is properly biased with the optical signal. As shown in Figure 4, the integrated noise floor is less than 4 fs RMS for 1 Hz - 100 kHz and less than 10 fs RMS for 1 Hz – 1 MHz.

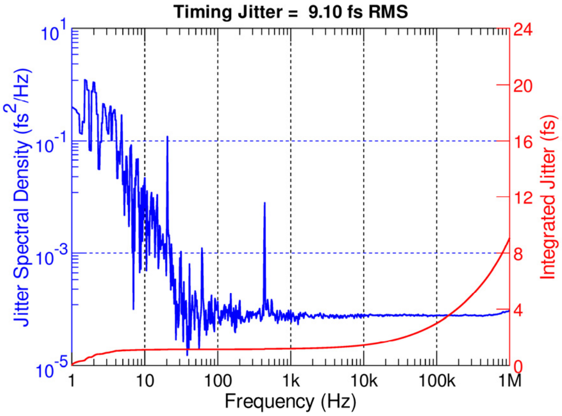

Figure 4: Noise floor of the 800-nm BOMPD.

We define the “timing resolution” of the BOMPD as the minimum timing jitter that can be detected by the detector at a certain offset frequency. This can be calculated from the measured noise floor in Figure 4. Table 1 shows the noise floor (i.e., jitter spectral density in units of (fs^2/Hz)) and the corresponding timing resolution of the detector at different offset frequencies. The detector has an outstanding timing resolution of ~10 attoseconds for offset frequencies above 100 Hz.

We can further define a so-called “dynamic range” for the BOMPD as the ratio of the linear detection range to the timing resolution at a certain offset frequency. As can be seen in Table 1, the 800-nm BOMPD has a dynamic range larger than 45 dB for all offset frequencies above 1 Hz.

Table 1: Timing Resolution and Dynamic Range

Frequency (Hz)	**Jitter Spectral Density (fs^2/Hz)**	**Resolution (fs)**	**Dynamic range (dB)**
1	0.40	0.631	45.009
10	0.02	0.148	51.318
100	1.36×10^{-4}	0.012	62.349
1k	9.41×10^{-5}	0.010	63.142
10k	7.88×10^{-5}	0.009	63.527
100k	7.80×10^{-5}	0.009	63.549
1M	9.59×10^{-5}	0.010	63.100

SUMMARY

In this paper, we have shown a novel optical-to-microwave phase detector designed for 800-nm pulsed laser operation. The detection scheme is adopted from our previous works on 1550-nm BOMPDs [2,6,9] and further developed to be suitable for 800-nm optical input with customized electronics and mechanics. The detector has a noise floor of only 9.1 fs RMS integrated from 1 Hz up to 1 MHz and outstanding timing resolution in the order of few attoseconds for offset frequencies above 100 Hz.

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