Journal of Physics: Conference Series

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To cite this article: A Kalaydzhyan *et al* 2016 *J. Phys.: Conf. Ser.* **741** 012084

Journal of Physics: Conference Series **741** (2016) 012084 doi:10.1088/1742-6596/741/1/012084

Ultrahigh precision synchronization of optical and microwave frequency sources

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Abstract. In this paper we demonstrate that balanced optical-microwave phase detectors (BOMPD) are able to provide a robust long-term optical-RF synchronization with sub-femtosecond residual timing drift over 24 hours in laboratory conditions without active temperature control of optical and electronic paths. Moreover, 10.833 GHz Sapphire-loaded cavity oscillator (SLCO) was successfully disciplined by 216.66 MHz laser oscillator using the BOMPD which resulted in a sub-femtosecond RMS jitter integrated from 1 Hz to 1 MHz.

1. Introduction

Optical frequency combs have become a part of everyday high-accuracy frequency and phase measurements by the outstanding spectral resolution and possibility to reference to both optical and radio-frequency (RF) standards [1]. In particular, they find a place in ultra-low phase noise microwave generation based on direct detection of the pulse train emitted by a mode-locked laser (MLL). Such systems can achieve sub-femtosecond short-term stability of the generated multi-GHz signals [2]. However, nonlinear effects by the photodetection degrade long-term phase stability of the extracted microwave signals by making it sensitive to optical power fluctuations and environmental drifts [3]. This fact forces to study the electro-optical features of each particular photodetector used in an experiment to find its optimal operation conditions and minimize the influence of non-linear effects.

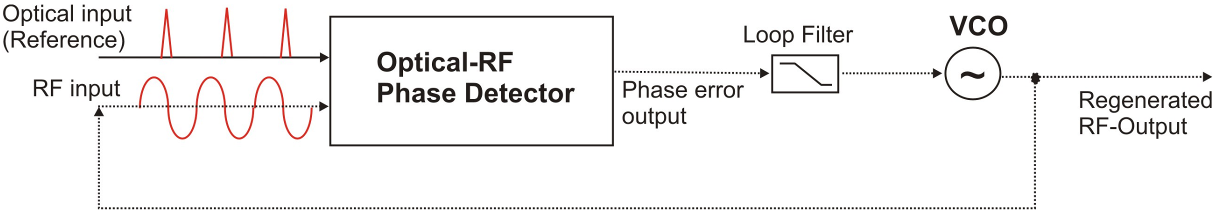

Figure 1. Schematic diagram of an opto-electronic phase-locked loop.

There is a workaround for these issues - one should utilize the detected signal as a frequency reference in a RF phase-locked loop (PLL) that would be insensitive to the input optical power fluctuations. Narrowband voltage-controlled oscillators (VCOs) can be disciplined by an optical pulse train generated by a femtosecond MLL to significantly improve its long-term stability. Such a perfect marriage requires a matchmaker who translates frequency and phase stability from optical domain to electronic domain, a hybrid optical-microwave phase detector (see Figure 1). Various schemes of such phase detectors were successfully implemented to the hybrid PLLs [4, 5], however their high sensitivity to temperature and humidity drifts put obstacles in the way to achieve sub-1-fs RMS stability over several hours of operation.

2. Experiment

Here, we are using a hybrid balanced optical-microwave phase detector (BOMPD) to connect a 216 MHz MLL (OneFive) and a 10.8 GHz Sapphire-loaded cavity oscillator (PSI) together in the optoelectronic PLL. The BOMPD operation principle is based on balanced optical heterodyne detection with use of the fiber Sagnac interferometer [6]. In addition to the last modifications of the BOMPD scheme [4] with multi-GHz and, therefore, unidirectional phase modulation of the optical pulses in the Sagnac loop, we have implemented an independent RF demodulation arm for the error signal (see Figure 2). The signal demodulation is performed at the lowest possible frequency (half of the MLL repetition rate) to maximize SNR at photodetection and to minimize thermally- and humidity-induced phase drifts in the electronic and optical paths for long-term stability.

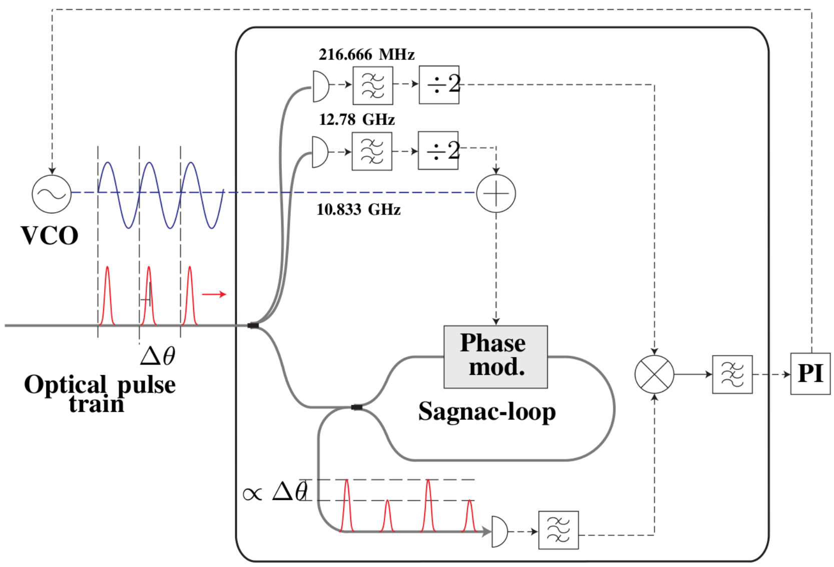

Figure 2. Scheme of the BOMPD with an additional independent reference path down-mixing of the modulated pulse train at the output of Sagnac-loop interferometer. Much lower operating frequency of this reference path makes possible further suppression of the photodetection noise floor without limiting of the PLL's operating bandwidth.

Microwave phase trimmers in the RF paths were replaced by free-space optical delay lines to eliminate the spurious losses and improve precision of phase tuning. Low power consumption low noise RF amplifiers (Micran) have eliminated the need of active cooling of electronics and, as consequence, improved the thermal stability of the setup.

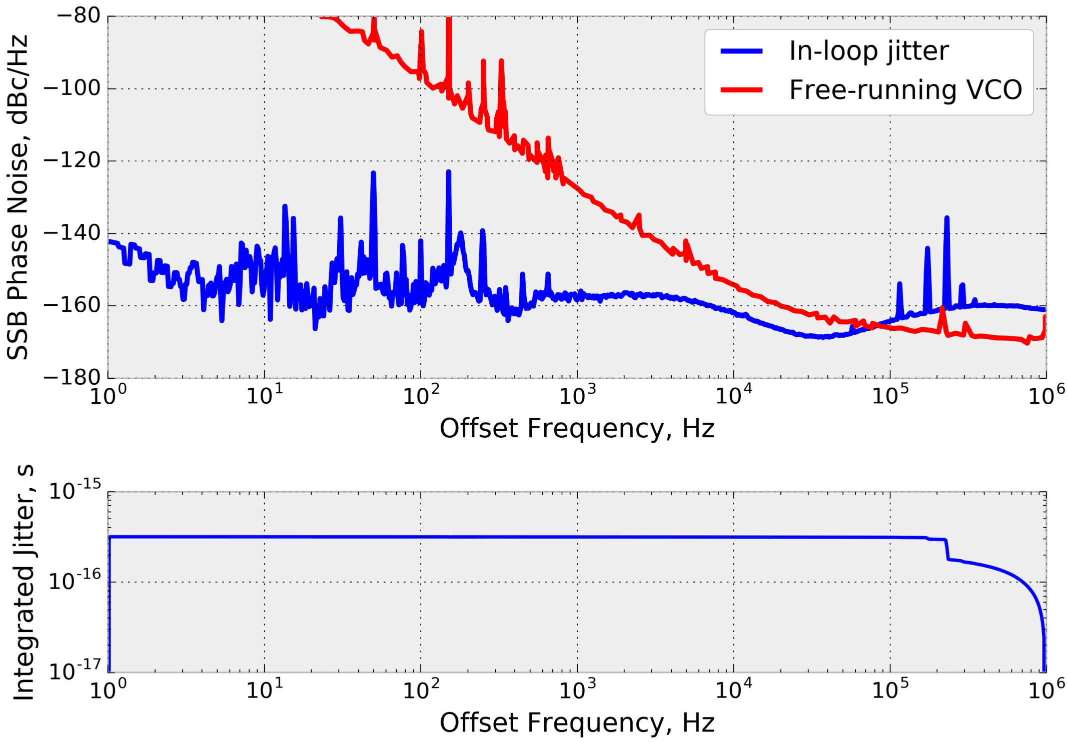

Figure 3. *Top:* Variation of the single-sideband (SSB) phase noise of the free-running SLCO (red) and residual in-loop phase noise of the locked PLL (blue) at 10.833 GHz carrier frequency with offset frequency. *Bottom:* Integrated RMS in-loop jitter of the locked PLL.

As one would expect, phase noise performance of the VCO improves dramatically after switching on of the PLL (see Figure 3). The SSB phase noise curve of the 10.833 GHz carrier stays mainly below -140 dBc/Hz level except several sharp spikes at 50 Hz, 150 Hz and others which are induced by external noise sources, such as 50 Hz power lines, air conditioning system, EMI and others. However, they don't influence much on the value of RMS jitter integrated from 1 Hz to 1 MHz which remains on the level of about 500 as.

Thanks to the optimized power consumption of the RF paths of the BOMPD and, therefore, reduced heat production, it became possible to place the whole setup into thermo-insulating housing without a danger of running out of operating temperature ranges of power RF amplifiers. After a warming-up process the temperature of the most of system components is passively stabilized within a range of 0.1 K, while the value of relative humidity could drift by about 2% per day. The result of the long-term out-of-loop measurement captured by the second identical BOMPD one can observe on Fig. 4. One can see a day-night cycle oscillation, because some components of the PLL are still placed outside of thermo-insulating housing. However, the RMS drift of the regenerated 10.833 GHz signal stays below 1 fs for one day of operation.

The measurement result (Figure 4) shows long-term stable drift with sub-femtosecond RMS deviation for 24 hours of optical to microwave synchronization.

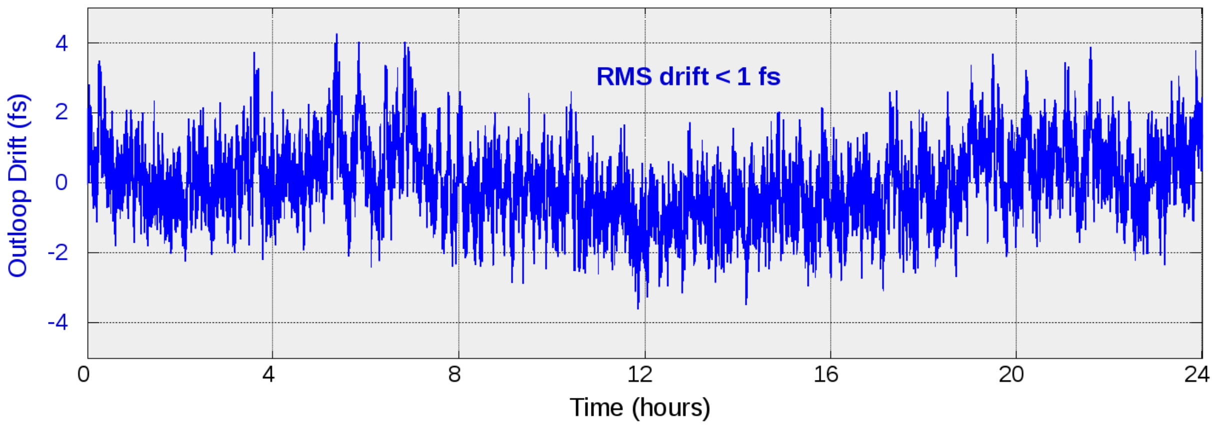

Figure 4. Long-term drift of the system. The RMS value stays slightly below 1 fs during the 24 hour experiment (ADEV $< 1.15 * 10^{-20}$ for 1 day).

3. Conclusion

We have achieved optical-to-RF synchronization of a 10.833 GHz SLCO with a 216.66 MHz laser frequency comb with residual RMS jitter of about 0.5 fs integrated from 1 Hz to 1 MHz and sub-femtosecond daily drift. The new scheme of the hybrid phase detector will be used in one of the future FEL timing distribution systems. In order to make the design of the BOMPD more compact and, therefore, even more stable all RF paths will be placed on a single ceramic PCB (see Figure 5).

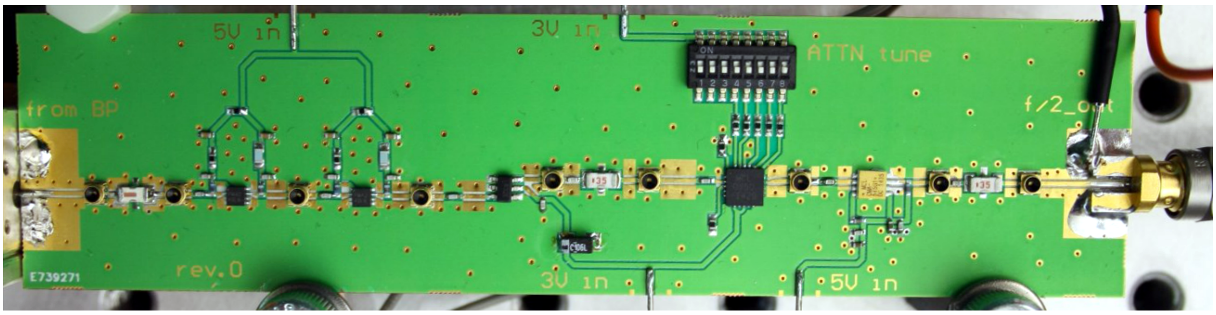

Figure 5. Microwave components of one of the BOMPD path's placed on a customized ceramic PCB.

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Corrigendum: Ultrahigh precision synchronization of optical and microwave frequency sources

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We would like to acknowledge the contribution of M Xin, K Shafak and W Wang to this work by adding their names as co-authors of the published article. The correct list of authors for the paper 'Ultrahigh precision synchronization of optical and microwave frequency sources' is

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