Low Noise Photonic Microwave Oscillator Based on a Novel Repetition Rate Stabilization

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***Summary*— We present a compact and robust 10 GHz photonic microwave oscillator using an integrated nonlinear optical repetition rate stabilization mechanism for achieving a phase-noise level of -100, -125, -145, and < -160 dBc/Hz at 100 Hz, 1 kHz, 10 kHz and > 100 kHz, respectively, with an integrated timing-jitter < 3 fs (30 fs) over a 0.01s (1s) measurement time.**

Keywords—photonic microwave oscillators; femtosecond lasers; timing jitter; phase noise; repetition rate stabilization

I. Introduction

Ultralow noise microwave oscillators are essential to advanced applications such as radar, telecommunications, radio astronomy, and particle accelerators, among others. Photonic microwave oscillators utilize the ultra-high quality factors possible at optical frequencies and convert them to the microwave range by frequency division or optoelectronic conversion [1-2]. Among the reported techniques, optical frequency division (OFD) using an optical frequency comb referenced to a stable vacuum cavity has achieved the lowest phase noise in the generated microwave signal [3,4]. However, these systems could be more bulky and complex. Moreover, other explored efforts use optical fiber delay lines to stabilize the repetition rate of femtosecond lasers [5,6], achieving microwave generation at femtosecond level over extended measurement times up to 1 s.

Here, we report a photonic microwave oscillator adopting a novel repetition rate stabilization scheme using a fiber delay as a reference. Unlike the previous methods [5,6], the ultra-short optical pulse is delayed by a dispersion-compensated fiber spool without spectral filtering, taking advantage of the full optical power delivered by the femtosecond laser. Then, the timing jitter between the laser pulse train and the fiber-delayed pulse train is measured using a waveguide-based balanced optical cross-correlator (WBOC) [7-8]. Recently, it was shown that the WBOC shows a 100-fold improved timing sensitivity when compared to a standard BOC [9]. Two feedback control loops are implemented to achieve improved stabilization.

II. Experimental Setup/Methods

The optical source of the implemented photonic microwave oscillator setup is a MENHIR-1550 femtosecond laser with 1564nm center wavelength, 1 GHz repetition rate, supporting ~200-fs pulses. As depicted in Figure 1, the laser output is split into two paths, one serving as the source for the stabilization mechanism and the second for the out-of-loop microwave generation.

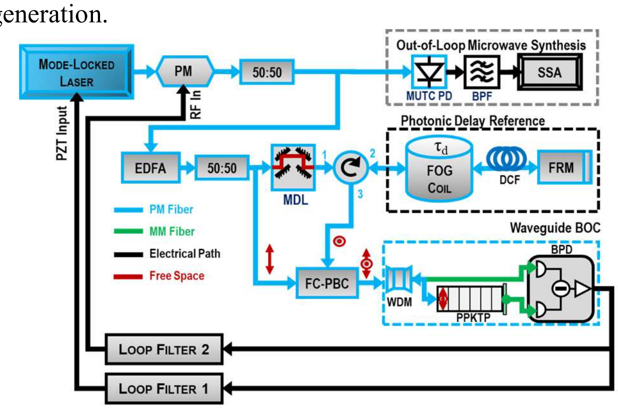

Fig. 1. Photonic microwave oscillator setup with repetition rate stabilization of a femtosecond laser (MENHIR-1550) locked to a fiber optical delay line using a waveguide-based balanced optical cross-correlator (WBOC) as timing detector. EDFA: Erbium-doped fiber amplifier, MDL: motorized delay stage, FC-PBC: fiber-coupled polarization beam combiner, DCF: dispersion compensating fiber, FRM: Faraday rotating mirror, WDM: wavelength division multiplexer, PPKTP: periodically poled potassium titanyl waveguide, BPD: balanced photodetector, PZT: piezoelectric transducer, MUTC PD: modified uni-traveling-carrier photodetector, BPF: bandpass filter.

For the repetition rate stabilization, the optical pulse train is split in two, where one is delayed via the photonic delay reference path. The reference path is a 1-km dispersion compensated fiber link acting as a photonic delay (τ_d), winded up in a fiber optic gyroscope spool (FOG coil) and followed by a Faraday rotating mirror (FRM) to reflect the pulse train with orthogonal polarization back and avoid interference. The pulse trains are then orthogonally recombined using a fiber-coupled polarization beam combiner (FC-PBS) and fed into the waveguide-based balanced optical cross-correlator (WBOC). The WBOC is used as a timing detector, with a sensitivity of ~25 mV/fs at a 4 MHz bandwidth, and provides a baseband signal containing the timing information of the pulse train relative to the delayed version at the photonic reference.

A home-built Erbium-doped fiber amplifier (1.5 m of gain fiber) is used to increase the available optical power, further boosting the timing sensitivity of the WBOC.

To stabilize the repetition rate of the laser, an initial feedback control loop is implemented to adjust a piezoelectrically (PZT) mounted intracavity laser mirror, which stabilizes the pulses cavity roundtrip time to be a sub-multiple of the photonic reference's delay ($\delta f_{rep}/f_{rep} \sim \delta\tau_d/\tau_d$). The noise reduction is proportional to the overall feedback loop gain. A motorized delay line (MDL) overlaps the two pulses in the linear range of the timing detector [9].

A second feedback loop on a fast-phase modulator at the output of the femtosecond laser is used to remove high-frequency noise even beyond the resonance of the PZT. This second control loop can only be activated once the laser is locked to the reference line with the first loop filter. Thus, the optical phase or rather delay change remains within the dynamic range of the phase modulator (about one optical cycle at 1564 nm ~ 5 fs).

For the out-of-loop microwave generation, the split output from the phase modulator is coupled into a modified uni-traveling carrier (MUTC) photodetector [10]. The photocurrent is then filtered to extract the 10^{th} harmonic of the laser repetition rate, obtaining a 10 GHz microwave signal with a power of -1 dBm. The phase noise of the microwave signal is then measured with a signal source analyzer (R&S®FSWP).

III. Results/Discussion

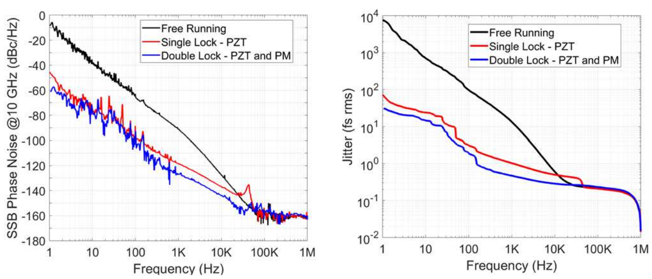

Fig. 2. Left: Out-of-loop single-sideband phase noise spectrum for the 10 GHz harmonic filtered from the photocurrent of the free-running femtosecond laser (black) when using a single feedback loop only (red) and a double feedback loop including the PM. Right: Integrated timing jitter for the different cases.

Fig. 2 shows the out-of-loop phase noise measurements of the photo-detected microwave signal at 10 GHz and their integrated timing jitter. Here, the black curve corresponds to the free-running laser. In contrast, the red curve shows the photonic delay-stabilized version using a single feedback loop via a PZT-controlled intracavity mirror, and the blue curve shows the double feedback loop version, which includes the phase modulator at the laser output.

One initial observation is the significant noise reduction for frequencies below 50 kHz. The limiting factor of the single feedback loop is seen at the peak around 45 kHz, where the feedback loop's bandwidth is in resonance with the PZT of the laser. Further increasing the feedback loop gain results in the further excitation of the resonant frequency of the PZT and its harmonics, deteriorating the phase noise performance. For this reason, a second feedback loop on an external optical phase shifter was introduced to suppress the high-frequency timing jitter directly. When activating the second feedback loop, one immediately observes the cancellation of the servo bump around 45 kHz. This then allows further increasing the feedback loop gain at the first control loop, leading to a 10 dB phase noise improvement over frequencies below 50 kHz compared to the single feedback loop. In the frequency range between 10 and 150 Hz, most of the phase noise spurs are attributed to the 50 Hz electrical line noise and its intermodulation distortion harmonics present in the electronic components of the setup. The noise floor of about -165 dBc/Hz for frequencies higher than 100 kHz is currently limited by the phase modulator and the available power at the 10 GHz harmonic from the photocurrent.

IV. Summary and Outlook

A microwave photonic oscillator based on a femtosecond laser stabilized via a fiber optical delay reference was introduced. By referencing the laser to the photonic delay, the synthesized microwave signal shows a phase noise reduction of up to 40dB in near-to-carrier offset frequencies.

Introducing a second feedback loop in the photonic microwave oscillator demonstrates a suppression on the high offset frequencies, improving phase noise performance of about 10 dB. For frequencies below 100 kHz, the phase noise spectrum approaches a 20 dB/dec slope (-60 dBc/Hz to -145 dBc/Hz from 1 Hz to 10 kHz.

An integrated timing jitter below 3 fs (30 fs) up to 100 Hz (1 Hz) is achieved. We expect further improvements in phase noise by optimizing feedback loop parameters. Adding a pulse interleaver would help increase the generated RF power at higher harmonics reducing the noise floor at higher offset frequencies. A careful design of the power supplies around the whole system would help to reduce the noise spurs present in the 10-150 Hz frequency range.

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