Progress on Development of Photonic Microwave Generation at NTSC

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***Abstract*—We demonstrate the ultra-stable microwave frequency sources aiming to improve the short time instability of primary frequency standards. These sources are realized by using photonic generation approach, and composed of ultra-stable lasers, optical frequency combs, and optical signal detecting parts. This paper reported a 48th harmonic (9.6 GHz) of optical frequency comb is photodetected by a balanced optical-microwave phase detector with frequency instability of 2.8×10^{-15} @ 1s. Further improvement is undergoing.**

***Keywords*—photonic microwave generation; ultra-stable laser; optical frequency comb; optical-microwave phase detector**

I. Introduction

Microwave signals with ultrahigh frequency stability play key roles in many fields such as deep space navigation [1], ultrahigh resolution radar [2], atomic frequency standard [3], and ultrahigh resolution very-long-baseline-interferometer [4]. State-of-the-art primary frequency standards based on cold atoms fountain clocks exhibit quantum projection noise of $10^{-14}/\tau^{1/2}$ for short term stabilities. However, most of the fountain clocks use the local oscillator based on quartz-oscillators limit the frequency stability to a level of $10^{-13}/\tau^{1/2}$ due to the Dick effect [3]. The Dick effect can be eliminated by using the ultrahigh frequency stability microwave signal as the local oscillator of fountain clock. Therefore, ultra-stable photonic microwave source is one solution for eliminating Dick effect.

II. Experimental Setup

The setup of the photonic microwave source is shown in Fig1. The photonic frequency source is composed of three parts: an ultra-stable laser [4], an optical frequency comb [5] and an optical-microwave phase detector (OM-PD) [6].

The photonic microwave generation stabilizes the repetition rate (f_r) of optical frequency comb to a continuous wavelength (CW) laser at 1550 nm wavelength, and the carrier-envelope-offset frequency (f_{ceo}) is frequency stabilized at the same time. Then a balanced optical-microwave phase detector is used to regenerate the wanted microwave signal. In this case we choose the 48th harmonic of optical frequency comb, which is 9.6 GHz. We built two identical but independent systems to evaluate the frequency instability.

In this experiment, a 1555 nm CW laser is frequency stabilized onto the resonant frequency of the Fabry-Perot (FP) cavity by PDH technique. The CW laser copies the frequency stability of the cavity length, resulting in a stable frequency reference of 193 THz with a relative instability of ~ 7×10^{-16}@1s. The details of the ultra-stable laser will be found in ref 4. Then an erbium-doped-fiber-based optical frequency comb is used as a frequency divider. While the carrier-envelope-offset frequency (f_{ceo}) is stabilized onto a stable RF reference frequency, and one tooth of the comb is stabilized onto the ultra-stable CW laser. Therefore, we can obtain the ultra-stable repetition frequency(f_r).

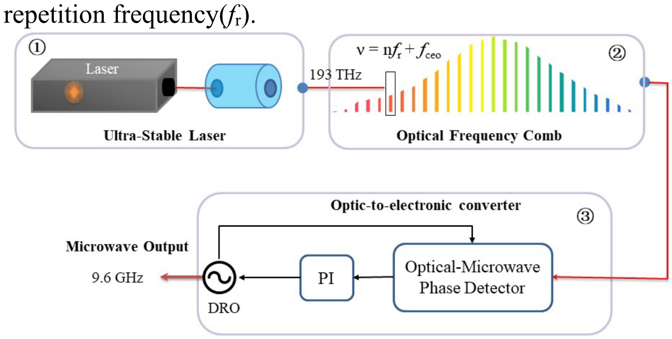

Fig. 1 Setup of the photonic microwave source, including ultra-stable CW laser, erbium-doped fiber-based optical frequency comb and optical-microwave phase detector. DRO: dielectric-resonator oscillator; PI, proportional-integral controller.

For long-term stable, high-precision synchronization between microwave DROs and mode-locked Er-fiber optical frequency combs, we detect and compensate for the phase error between them in the optical domain using an optical-microwave phase detector [7]. Fig. 2 shows the schematic of the optical-microwave phase detector. The OM-PD has an optical fiber Sagnac-Loop Interferometer including a unidirectional highspeed LiNbO3 phase modulator and a non-reciprocal phase shift of $\pi/2$. The optical pulse is introduced into the optical fiber loop by the circulator, the microwave signal whose frequency is integral multiple of laser repetition rate modulate the optical pulse by the phase modulator. The power difference between the two Sagnac-loop outputs is proportional to the phase error between the optical pulse train and the microwave signal (θ_e). When detected by a balanced photodetector, the output voltage signal can be used for precise optical-microwave phase detection. Therefore, we can phase lock the DRO frequency based on the output voltage by using a PI controller. Finally, we

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can regenerate the ultra-stable frequency with the value of Nf_r from the phase stabilized DRO.

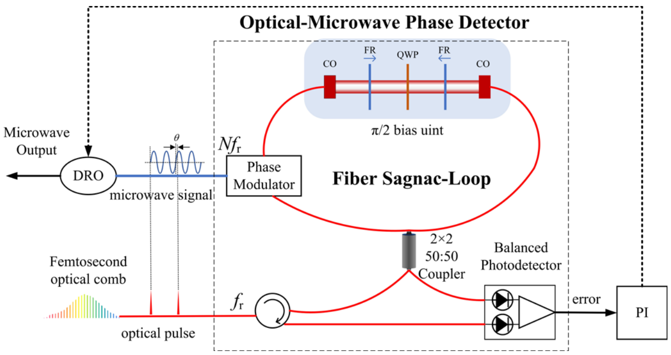

Fig. 2 optical-microwave phase detector. DRO, dielectric resonator oscillator; PD, photodiode; FR: Faraday rotator; QWP: quarter waveplate; CO: coupler; f_r, pulse repetition rate. PI, proportional-integral controller.

We use a 9.6 GHz (48th harmonic of the optical frequency comb) DRO to sample the optical pulse in this case. And we built 2 identical but independent systems to evaluate the frequency instability of microwave signals. Fig. 3 shows the relative frequency instabilities of the photonic microwave source. The black squares show the frequency instability of ultra-stable CW laser is 8×10^{-16} @ 1s. The out-loop frequency instability of the comb indicated by red circles is $\sim1\times10^{-16}$ @ 1s. The blue triangles demonstrate the frequency instability of optical-microwave phase detector is 2.8×10^{-15} @ 1s. The dark cyan inverted triangles show the fractional frequency instability of 9.6 GHz microwave signal.

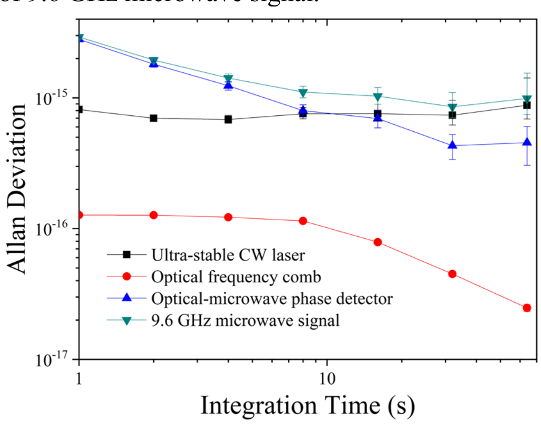

Fig. 3. The black squares: fractional frequency instability of the ultra-stable CW laser. The red circles: fractional frequency instability of optical frequency comb. The blue triangles: fractional frequency instability of optical-microwave phase detector. The dark cyan inverted triangles: fractional frequency instability of 9.6 GHz.

These results show the frequency instability of the obtained microwave signal is mainly limited by the optical-microwave phase detector at 1-3 s. And the frequency instability line is upturned after 30 s. We guess the reason might be the exposed optical fiber is affected by the laboratory temperature.

III. Conclusions

We have reported a 9.6 GHz photonic microwave signal, which are referenced to an ultra-stable CW laser at 1555 nm wavelength. Then an Er: fiber-based optical frequency comb and an optical-microwave phase detector divided and converted the ultra-stable laser to 9.6 GHz microwave signal. In this experiment, we get a 9.6 GHz photonic microwave signal with frequency instability of $\sim3\times10^{-15}$ @ 1s. The further experiment is ongoing, we will demonstrate the details later.

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