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All-fiber-based photonic microwave generation with 10^{-15} frequency instability

Yifei Duan (段怡菲)[1,2], Yafeng Huang (黄亚峰)[1,2], Yanli Li (李彦黎)[1,2], Yating Wang (王亚婷)[1,2], Meifeng Ye (叶美凤)[1], Ming Li (李 明)[3], Yinnan Chen (陈胤男)[1,2], Jiaqi Zhou (周佳琦)[4], Lingke Wang (汪凌珂)[1**], Liang Liu (刘 亮)[1], and Tang Li (李 唐)[1*]

[1] Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] University of Shanghai for Science and Technology, Shanghai 200093, China
[4] Shanghai Key Laboratory of Solid-State Laser and Application, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

*Corresponding author: litang@siom.ac.cn
**Corresponding author: lkwang@siom.ac.cn
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We demonstrate an all-fiber-based photonic microwave generation with 10^{-15} frequency instability. The system consists of an ultra-stable laser by optical fiber delay line, an all-fiber-based “figure-of-nine” optical frequency comb, a high signal-to-noise ratio photonic detection unit, and a microwave frequency synthesizer. The whole optical links are made from optical fiber and optical fiber components, which renders the whole system compactness, reliability, and robustness with respect to environmental influences. Frequency instabilities of 3.5×10^{-15} at 100 s for 6.834 GHz signal and 4.3×10^{-15} at 100 s for 9.192 GHz signal were achieved.

Keywords: ultra-stable laser; optical frequency comb; photonic microwave generation.
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1. Introduction

Ultra-stable microwave generation is of importance in diverse fields including atomic frequency standards, high precision radars, communications and navigations, high-speed electronics, long baseline interferometry, and high precision timing synchronizations[1–6]. Especially, in the fountain clock systems, the short frequency instability is mainly limited to the quantum projection noise (QPN)[7]. However, the inherent phase noises of the microwave oscillator depress the performance of the fountain clock via the Dick effect, which makes it impossible to approach the QPN limits[8,9]. Thus, improving the performance of the local microwave oscillator can greatly reduce the Dick effect and thus the frequency instability of the fountain clock[7].

Benefitting from the technology progress of ultra-stable lasers and optical frequency combs (OFCs), photonic microwave generation has gained remarkable research attention since the early 2000s[10–13]. In 2011, the National Institute of Standards and Technology (NIST) reported an ultra-stable photonic microwave source based on an ultra-stable cavity stabilized laser and Ti:sapphire OFC. A 10 GHz ultra-stable microwave source with a frequency instability of 8×10^{-16} at 1 s was demonstrated[14]. To achieve tunable microwave frequency, Physikalisch-Technische Bunde-sanstalt (PTB) introduced a low-noise frequency synthesizer to develop a 9.192 GHz microwave source with frequency instability of 1×10^{-14} at 1 s[15]. In the same year, System of Time and Frequency Reference (SYRTE) obtained a 9.192 GHz microwave source with frequency instability better than 4×10^{-15} at 1 s, using a similar method[16]. In 2017, the National Time Service Center, Chinese Academy of Sciences (NTSC) reported a photonic frequency source based on a Fabry–Pérot cavity ultra-stable laser, which produced a frequency-tunable 9.192 GHz signal with frequency instability of 7×10^{-15} at 1 s[17].

Yet, the impact of these photonic microwave sources based on ultra-stable lasers with bulk optics stems is from several practical obstacles including complex optical structure, expensive cost, environmental sensitivity, and un-tunable optical frequency. To overcome these shortcomings, fiber stabilized lasers should be a promising candidate to generate a reliable, cost-efficient, and transportable ultra-stable microwave. Recently, Kwon *et al.* reported an all-fiber-based photonic generation that stabilizes multiple OFCs directly to a single fiber delay line (FDL) with frequency instability of 5.7×10^{-15} at 0.4 s[18]. But, the long-term frequency instability gets worse due to the environmental interference on the fiber links.

In this paper, we demonstrate an all-fiber-based photonic microwave generation system. The system consists of a fiber interferometer stabilized laser, an all-fiber-based "figure-of-nine" OFC, a high signal-to-noise ratio photonic detection unit, and a microwave frequency synthesizer. Frequency instabilities of 3.5×10^{-15} at 100 s at 6.834 GHz and 4.3×10^{-15} at 100 s at 9.192 GHz are achieved. This integrated and transportable microwave system with high performance has the potential to be applied in field detection, geodesy, and transportable fountain clocks as well as local oscillators.

2. Experiment Setup

The experiment setup is shown in Fig. 1. The all-fiber-based photonic microwave generation system consists of four units: an ultra-low-noise fiber-interferometer-based laser, an OFC locked on the ultra-stable laser, an OFC's repetition frequency detection system with high signal-to-noise ratio (SNR), and a low-phase-noise frequency synthesizer.

The first unit is a narrow linewidth continuous-wave (CW) laser reference, which is based on a fiber Michelson interferometer. Compared to previous works[19], we take several methods to improve the instability of the laser: using a 5 km FDL to reduce the noise limits caused by the $1/f$ spectral intrinsic thermal noise; placing the fiber interferometer into a vacuum tank with a multi-layer thermal shield and two-stage active temperature controller[20]; designing a vibrating insensitive fiber spool to reduce low-frequency vibration noise[21]; stabilizing the optical power and RF power injected into the fiber interferometer to reduce the effects on long-term frequency stability by power fluctuations. The frequency instability of the laser is better than 5×10^{-15} over a time scale of 1–100 s.

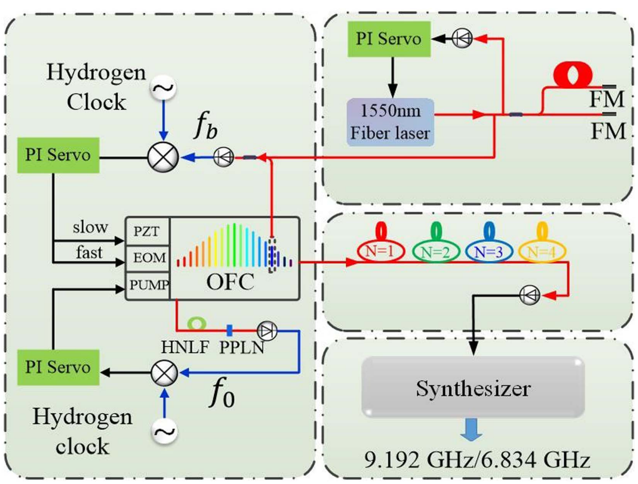

Fig. 1. Scheme of the all-fiber-based photonic microwave generation system, including narrow linewidth CW laser, fiber-based OFC, high signal-to-noise ratio photo detection unit, low-phase-noise frequency synthesizer. PZT, piezo actuator; EOM, electro-optic modulator; HNLF, highly nonlinear fiber; PPLN, periodically poled lithium niobate.

The second unit is a home-made fiber-based OFC, which is used as a frequency divider to deliver the frequency stability from the optical to microwave domain. The source of the OFC is an Er-doped mode-locked laser based on a polarization maintaining fiber, which is shown in Fig. 2. The proposed laser design has a typical figure-of-nine structure, with a center wavelength of 1550 nm[22,23]. The source laser can produce self-started pulses with 100 nm optical bandwidth and 106 fs pulse width. After two stages of the Er-doped fiber amplifier (EDFA), the average output power could be scaled up to more than 200 mW under 166.7 MHz repetition rate. In the liner arms of the figure-of-nine laser, we set a piezo actuator (PZT) and a bulk electro-optic modulator (EOM) to obtain the repetition rate tuning of a large dynamic range and fast response via modulation on the cavity length. We obtained the cattier-envelope-offset frequency (f_{ceo}) of the OFC with more than 30 dB SNR after a highly nonlinear fiber (HNLF) and periodically poled lithium niobate (PPLN). The OFC was locked in two dimensions. On the one hand, the f_{ceo} was locked on a hydrogen clock (T4 Science, iMaser 3000). To depress the electronic noise that arose by the servo circuit, we used a tracking oscillator to improve the SNR of the f_{ceo} up to 50 dB. On the other hand, one comb line of the OFC around 1550 nm was locked on the ultra-stable laser, by which the performance of ultra-stable laser could be delivered to the comb line of the OFC and thus down converted to the microwave domain by the adjacent comb line beat.

The third unit consists of a repetition rate multiplier based on a cascaded optical fiber ring interferometer and a high-speed photodiode (PD) with a bandwidth of 22 GHz (Discovery Semiconductors HLPD DSC30S). The major noise for detecting repetition rate is thermal noise, shot noise, and amplitude-to-phase conversion (APC) noise caused by the saturation effect of the PD[24]. We adjusted the bias voltage of the PD to set the working point at which the APC coefficient is near zero, by which the APC noise could be depressed over 20 dB. To reduce the influence of thermal noise and shot noise in photo detection, we used a four-stage optical fiber ring interferometer to multiply the pulse repetition frequency of the OFC[25].

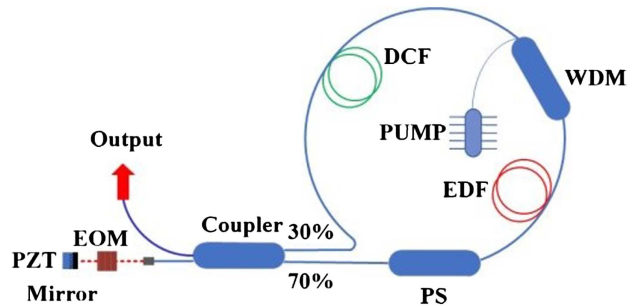

Fig. 2. Setup of the Er-doped mode-locked laser. WDM, wavelength division multiplexer; EDF, Er-doped fiber; DCF, dispersion compensating fiber; PS, phase shifter.

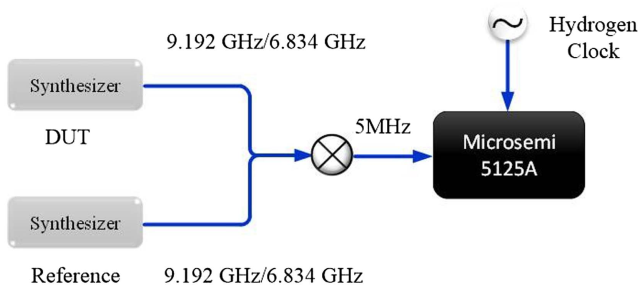

Fig. 3. Measurement setup of the frequency instability and phase noise.

The time delay of the fiber loop was precisely controlled to depress the useless harmonics. After the interferometer, we obtained the 48th harmonic of the repetition rate at 8 GHz, which has a signal to useless harmonics ratio over 25 dB. The interferometer was packaged into a thermally isolated foam to avoid the external temperature interference, and the ratio of the signal to useless harmonics can remain unchanged over a few hours.

The last unit is a low-phase-noise microwave frequency synthesizer, converting the signal from 8 GHz to 6.834 GHz and 9.192 GHz, which can be finely adjusted for rubidium and cesium fountain clocks.

3. Results and Discussion

To evaluate the performance of the microwave generation system, we constructed another separate and identical reference system. In this reference system, we locked a commercial OFC (Menlo FC 1550-250-WG) with a repetition rate 250 MHz on another identical ultra-stable laser and detected the 32nd harmonic of the repetition rate at 8 GHz through a five-stage fiber ring interferometer. The beat frequency of the device under test (DUT) and reference system is adjusted to 5 MHz through minor adjustment by the frequency synthesizer. As shown in Fig. 3, we compared the beat signal with the reference of a commercial hydrogen clock, which has a frequency instability of 10^{-13} at 1 s, to get the frequency stability and phase noise through the phase noise and Allan deviation test set (Microsemi 5125A).

The relative frequency instabilities characterized by the Allan standard deviation and phase noise of the microwave generation are shown in Fig. 4. After the frequency synthesizer, the 6.834 GHz microwave frequency instability [Fig. 4(a), black line] is 4.2×10^{-15} at 1 s, 3.5×10^{-15} at 100 s, and 4.4×10^{-15} at 400 s, and the phase noise [Fig. 4(c), black line] is under −91.4 dBc at 1 Hz and −131.5 dBc at 1 kHz; the 9.192 GHz microwave frequency instability [Fig. 4(b), black line] is 4.2×10^{-15} at 1 s, 4.3×10^{-15} at 100 s, and 6.8×10^{-15} at 400 s, and the phase noise [Fig. 4(d), black line] is under −90.4 dBc at 1 Hz and −130.7 dBc at 1 kHz. The green line shows the frequency instability and phase noise of the ultra-stable reference laser, the blue line shows the residual noise of the synthesizer, and the red line shows the residual noise of the OFC and the synthesizer.

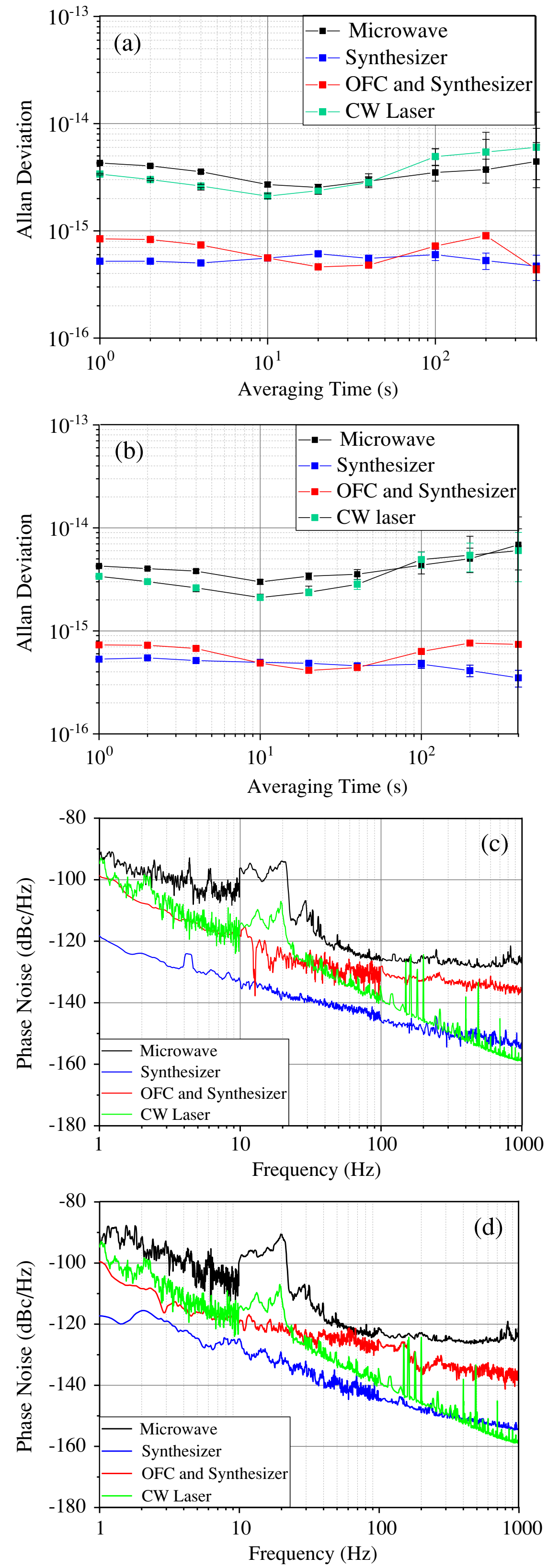

Fig. 4. Frequency instability characterized by the Allan standard deviation at (a) 6.834 GHz, (b) 9.192 GHz and phase noise at (c) 6.834 GHz, (d) 9.192 GHz. Black line: ultra-stable photonic microwave. Green line: ultra-stable CW laser. Red line: the OFC and the frequency synthesizer. Blue line: the frequency synthesizer.

According to Figs. 4(a) and 4(b), the frequency instabilities of two microwave signals have similar tendencies. The performance is limited by the ultra-stable reference laser, especially at the long-term time scale. The residual frequency instability of the OFC and frequency synthesizer is better than that of the CW laser by near an order of magnitude, while the latter accounted for a greater proportion. Thus, the influence from the OFC and the synthesizer is negligible. As shown in Fig. 4, the instability of the CW laser is higher than that of the microwave at some points after 40 s. It is because the results were not measured at the same time, due to the influences by the environmental fluctuations.

As for Figs. 4(c) and 4(d), the phase noise of the microwave signal is accumulatively contributed from all components. It is mainly limited by the ultra-stable laser in the low-frequency range under 20 Hz and the OFC in the high-frequency range above 20 Hz. The influence from the synthesizer is negligible. The bulge in the microwave signal between 10 Hz and 20 Hz arises from the unidentified seismic noise in the laboratory, while it is also shown in the ultra-stable laser comparison.

4. Conclusion

In conclusion, we have demonstrated an all-fiber-based photonic microwave generation system based on an all-fiber stabilized ultra-stable laser and a fiber-based OFC. From the laser source to the photodetector for photonic microwave generation, the optical link is made from an optical fiber and pig-tailed fiber components. Besides, frequency instabilities better than 4.3×10^{-15} at 100 s at 6.834 GHz and 3.5×10^{-15} at 100 s at 9.192 GHz of the generated microwave signals were achieved. Benefitting from the all-fiber optical layout, the system is compact, stable, and easy to integrate. This integrated microwave source could be used as a local oscillator of the transportable fountain clock to improve the short-term frequency instability caused by the Dick effect. Moreover, it will be applied in more outfields and portable scenarios in virtue of the reliable performance.

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