The Role of Electric-Preamplifier Noise on Determining the Frequency Instability of the Optical-Comb Based Frequency Transfer System

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Abstract—As an essential active device, electrical preamplifier has significant effect on frequency stability, which is extremely demanded by a frequency transfer system. In this work, we build an optical-comb based frequency transfer system and investigate the influences of the preamplifier noise in determining the ultimate frequency instability of the system. The experimental results show that increasing the amplifier gain has no contribution to the frequency instability improvement when the amplifier noise is higher than that of the measuring device, and a frequency instability of 2E-14@1 s is achieved with the amplifier gain varying from 1 to 100. Moreover, if a frequency instability below 1E-15@1 s is to be transferred, the noise of the amplifier should be carefully calibrated and controlled, e.g., below 1E-7 V at 0 dB gain.

Index Terms—Frequency transfer, preamplifier, noise

I. Introduction

The fiber frequency transfer technique aims to transmit an ultra-stable frequency standard using standard commercial fiber from the local to the remote end, so that the frequency stability can be recovered at the remote end [1]. The frequency transfer technology has been widely used in the fields of high-precision comparison of atomic clocks, time awarding system and exotic physics detection [2], [3]. Basically, the frequency signal is delivered with a certain carrier, e.g. repetition frequency of optical frequency combs [4], [5], amplitude and frequency of continuous laser [6], [7]. The frequency transfer based on the frequency combs is discussed in this work.

To achieve high precision evaluation and compensation of the noise in the frequency transfer system, heterodyne method is generally used [1]. In the heterodyne method, the signals from the local and remote ends are compared to obtain an output voltage that reflects the phase difference between them. However, the voltage fluctuation could be extremely small when the phase difference $\Delta\varphi \simeq \pi/2$, thus the result would be limited by the measurement equipment, e.g. the precision of the digital multimeter (DMM) and noise of electronic instruments. In order to precisely measure the instability of the signal, the most intuitive way is to amplify the signal using ideal preamplifier before it enters the DMM, so that the signal fluctuation is much greater than the precision of DMM. Since there is no ideal device in real experiments, the preamplifier gain and noise level would both affect the stability evaluation of the noise measuring system.

In this work, we built a comb-based frequency transfer system, and analyzed the influence of the preamplifier used in the system.

II. Experimental Setup and Measuring Model

The schematic diagram of the frequency transfer system we built is shown in Fig. 1. The comb is splitted into two parts by a 50:50 beam splitter, and each part is adjusted to 1 mW using Erbium-doped fiber amplifier (EDFA). One of the outputs is detected using a photodetector (PD), and the other one passes through a 100 km fiber link, detected by a PD, and phase modulated by an electronic phase shifter (PS). Here the fiber link includes 100 km fiber, dense wavelength division multiplexer (DWDM), EDFA and dispersion compensation fiber (DCF) to compensate the power loss and the dispersion of the signal. The outputs of the two PDs are filtered via two 100 MHz low-pass filters (LPFs), and the 100 MHz sinusoidal signals are obtained and afterwards compared with a mixer. The output voltage is low-pass filtered, amplified and measured with a $6_{1/2}$ DMM. The measurement results can therefore reflect the phase noise in the fiber link.

Assuming the input signal of the mixer's Local end is

$$V_{\mathrm{L}}(t) = V_1 \cos(\omega_{\mathrm{r}} t), \tag{1}$$

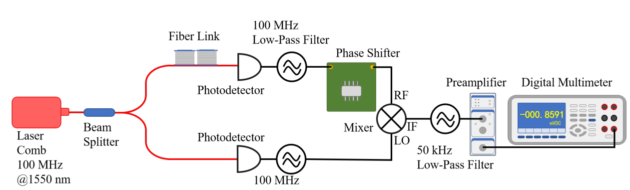

Fig. 1. Schematic diagram of the frequency transfer system.

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and that of the Radio end is

$$V_{\mathrm{R}}(t) = V_2 \cos(\omega_{\mathrm{r}} t + \Delta\varphi(t)), \tag{2}$$

where ω_r indicates the repetition frequency, and $\Delta\varphi(t)$ is the phase noise introduced by the fiber link. If the mixer is identical, and by adjusting the PS, the output signal can be written as $V_{\mathrm{out}} = V_0[\sin(\varphi(t)) + \sin(2\omega_{\mathrm{r}} t + \varphi(t))]$. After being filtered by the LPF, the signal becomes

$$V_\varphi(t) = V_0 \sin(\varphi(t)), \tag{3}$$

where $\varphi(t) = \Delta\varphi(t) - \pi/2$ is a relative phase shift.

Mainly limited by the mixer's input voltage, V_0 cannot be infinitely large (the best working point in our system gives $V_0 = 156$ mV). Since the short-term phase fluctuation introduced by the fiber is very small, the relative fluctuation in V_{out} is easily drown in the DMM background noise, and beyond the compensation ability of PID controller, especially when $\varphi(t) \simeq \pi/2$ (i.e., $V_\varphi(t) \simeq V_0$).

The signal detected by DMM can be divided into two parts and written as

$$V_{\mathrm{det}} = V_\varphi(t) + N_{\mathrm{D}}(t), \tag{4}$$

where $N_{\mathrm{D}}(t)$ is the background noise of DMM. From the ideal voltage-phase conversion relation, the calculated phase noise would be

$$\phi(t) = \arcsin\left(\frac{V_{\mathrm{det}}(t)}{V_0}\right). \tag{5}$$

Thus, the calculated frequency fluctuation is

$$\delta f(t) = \frac{1}{2\pi} \frac{\dot{V}_\varphi(t) + \dot{N}_{\mathrm{D}}(t)}{\sqrt{V_0^2 - V_\varphi^2(t) - N_{\mathrm{D}}^2(t) - 2N_{\mathrm{D}}(t)V_\varphi(t)}}. \tag{6}$$

Considering when $\varphi(t) \simeq 0$, we have $V_{\varphi 1}(t) \simeq 0$ and $\dot{V}_{\varphi 1}(t) \gg \dot{N}_{\mathrm{D}}(t)$, so the result can be simplified as

$$\delta f_1(t) \simeq \frac{1}{2\pi V_0}\left(\dot{V}_\varphi(t) + \dot{N}_{\mathrm{D}}(t)\right). \tag{7}$$

And for $\varphi(t) \simeq \pi/2$ case, one has $V_{\varphi 2}(t) \simeq V_0$ and $\dot{V}_{\varphi 2}(t) \ll \dot{N}_{\mathrm{D}}(t)$. Thus

$$\delta f_2(t) \simeq \frac{1}{2\pi} \frac{1}{\sqrt{2V_0 N_{\mathrm{D}}(t)}} \dot{N}_{\mathrm{D}}(t). \tag{8}$$

Comparing Eq. (7) and Eq. (8), one can obtain

$$\frac{\delta f_1(t)}{\delta f_2(t)} = \sqrt{\frac{V_0}{N_{\mathrm{D}}(t)}} \cdot \frac{\dot{N}_{\mathrm{D}}(t)}{\dot{V}_{\varphi 1}(t)}. \tag{9}$$

According to our experimental results, $\frac{\delta f_2}{\delta f_1} \sim 10$, indicating that when the phase drifts to $\pi/2$, the detected noise floor would be at least an order of magnitude higher than that when $\varphi(t) \simeq 0$.

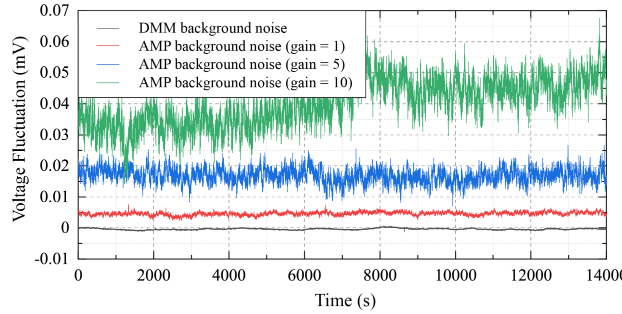

Fig. 2. Noise output of the preamplifier.

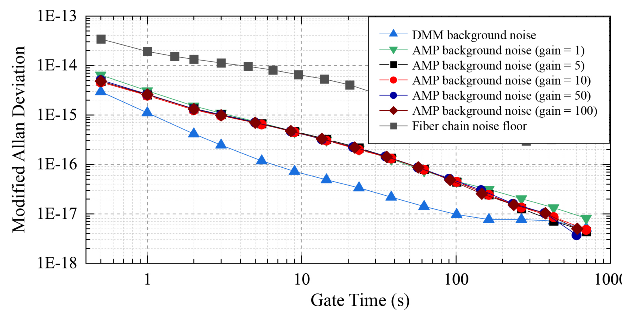

Fig. 3. Background noise of preamplifier and DMM when $\varphi \simeq 0$ and the fiber link noise floor.

III. Results

When amplifying the signal using a preamplifier (SRS, SIM910 JFET Preamp), the noise of it with different gains would be directly added on the output voltage, as shown in Fig. 2. $V_{\mathrm{max}} \simeq \alpha V_0$.

Acting the amplifier on a heterodyne voltage signal with $V_0 = 156$ mV (the best working point), we obtain the modified Allan deviation, shown in Fig. 3. The result shows that no matter how large the gain is, the amplifier has the same influence on the measurement limit. For $\varphi(t) \simeq 0$ case, this limit is already lower than the detected phase fluctuation ($\sim 10^{-14}$@1 s), which means that the amplifier has no improvement on the measuring system performance at all.

While when the phase drifts to $\varphi(t) \simeq \pi/2$, the result is shown in Fig. 4. As we see, the background noise of the DMM and the amplifier are all raised to a level higher than that of the actual frequency transfer system noise ($\sim 10^{-14}$@1 s). In this case, the measured fiber link noise level is limited not only by the DMM limit, but also by the amplifier background. In other words, a preamplifier that has higher background noise than DMM will have no improvement on measuring the true fiber link noise. On the contrary, it may even worsen the performance of the measuring system.

IV. Conclusion and Discussion

In this work, we analyzed the influence of preamplifiers on noise evaluation of a comb-based frequency transfer system. It shows that it's impractical to measure a

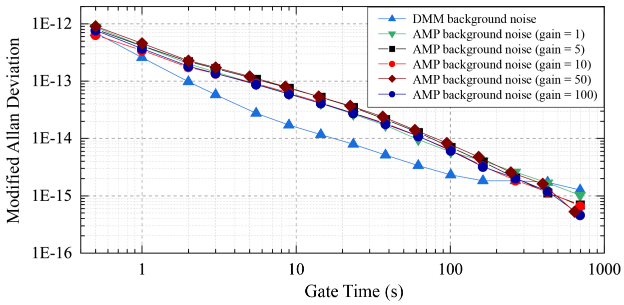

Fig. 4. Background noise of preamplifier and DMM when $\varphi(t) \simeq \pi/2$.

fiber link noise (converted to voltage) lower than the DMM background simply by amplifying the heterodyne signal (no matter how large the gain is), unless the amplifier has lower noise than the fiber link itself. In that case, if the fiber link noise is already higher than the DMM background, amplifiers will be redundant. Thus, for practical situation, only when the fiber link is long enough, can $\varphi(t)$ drift to $\pi/2$, under which situation, the fiber noise converted to voltage is already higher than the DMM background. In addition, we haven't found a preamplifier that has lower noise than the $6_{1/2}$ DMM background. In conclusion, to evaluate the noise of a comb-based frequency transfer system, if there is a DMM that has precision of $6_{1/2}$ digits, it will be neither necessary nor practical to improve the instability by amplifying the heterodyne signal. Moreover, if a frequency instability of 1E-15@1 s is to be transferred, the amplifier noise should be well calibrated and controlled below 1E-7 V at 0 dB gain.

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