Optic Frequency Transfer via Fiber Based on Digital Phase Unwrap Technology

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Summary—This paper provides FPGA-based phase unwrapping technique for demonstrating long-distance optical frequency transfer link with large noise level. And it is used in a 550 km spooled fiber with an instability of 4.3×10^{-20} at 10,000s averaging time.

Keywords—optical frequency transfer,phase noise detector,FPGA-based phase unwrapping technique, frequency instability

I. INTRODUCTION

In the fiber-based optic frequency transmission, phase noise induced by fiber is an important factor affecting the transfer performance, and the noise adds up as the fiber distance increase[1][2]. Currently, analog or digital phase detector[3] is usually used for phase noise detection and cancellation in an optical frequency transfer system[4]. Hence, to increase the linear dynamic response range, the frequency division ratio is increased, which will lead to a lower resolution of the output signal, and is not flexible enough. The FPGA-based phase detecting and unwrapping technique[5] can make the phase considerably stretchable by algorithms, even up to ±65536π with limited FPGA resources.This paper compares the dynamic linearity range of the traditional analog and digital phase frequency detector with FPGA-based phase detecting and unwrapping techniques on the same noise. The FPGA-based phase detecting and unwrapping technique was found to have higher linearity and larger dynamic range. Then this technique is used in a 550 km optical frequency transfer via spooled fiber link with an instability of 4.3×10^{-20} at 10000 s, which effectively avoids circle-slips caused by insufficient frequency division multipliers. This paper provides a method for demonstrating long-distance optical frequency transfer link with large noise level.

II. PHASE UNWRAP TECHNIQUE

Phase unwrap technique is to accumulate the phase differences with the wrapped characteristic of the phase detector output by means of digital operation to achieve unwrapped phase difference. The traditional FPGA-based digital IQ phase detector uses two multipliers and filters to separate the I and Q components of the beat signal, and then obtains the phase differences which ranges from (-π, π) through the arctangent function in the CORDIC algorithm[6]. In order to make the wrapped phase difference linearly correlated with the original phase difference, on the basis of the traditional digital phase detector result, the digital operation is used to accumulate the phase detector result, and the calculation method is shown in (1) and (2):

$$\Delta\varphi\left(k+1\right)=\varphi\left(k+1\right)-\varphi\left(k\right),\quad k\in\left\{1,2,3,\cdots,n\right\} \tag{1}$$

Where φ(k) is the instantaneous phase difference demodulated by the digital phase detector, k is a positive integer that represents a clock cycle. According to (1), the phase error Δφ is obtained by subtracting the adjacent phase differences from the detector. At the bottom of the FPGA, signed numbers are stored as complements. Based on the subtraction algorithm of FPGA, the calculated phase error is still continuous at the time of π to -π or -π to π phase reversal.

$$\Phi\left(t\right)=\int\Delta\varphi\left(k\right)dt \tag{2}$$

Where Φ(t) represents the instantaneous phase difference between the beat-note signal and the reference signal.As shown in (2), the instantaneous true phase difference is obtained by adding up the phase error, so as to achieve a linear correlation between the demodulated phase difference and the original phase difference.

In our configuration, the phase unwrap technique is implemented in the platform based on a Xilinx Zynq7000 FPGA. The phase difference data length of the digital phase detector output is 10 bits, of which 7 bits hold the decimal places, so the resolution of the digital phase detector is 0.0025rad. The phase error data length is 10 bits, and the accumulated phase difference data length is 26 bits, so the linear range of phase difference obtained by the phase unwrap technology can reach the ±65536π, which greatly expands the linear dynamic response range of the phase-locked loop, thereby reducing the circle-slips caused by the phase-locked loop.

In this paper,the current phase demodulation methods used in the phase noise cancellation process of optical frequency transmission system via fiber link are tested. The tested signal is the in-loop beat–note signal of the optical frequency transmission system via 200km communication fiber , and the phase noise power spectral density(PSD) of the link is shown in Fig.1(a), according to (3) the phase difference at this moment is calculated,where Φ is the phase difference and S(Φ) is the phase noise of the each frequency at this moment, ν is the frequency. The calculated phase difference is 600rad at this moment,and the result is shown in Fig.1(b).

$$\Phi = \sqrt{\int S(\Phi)\, dv} \tag{3}$$

Since the phase noise of the communication fiber link fluctuates by nearly an order of magnitude in one day, the phase difference will also change.It can be calculated the phase difference is about three times as much as the original according to (3). Traditional analog phase detectors and digital phase detectors expand the phase comparison range by expanding multiples of the divider on the front end of the phase detector, so the difference between day and night of phase noise should be considered when selecting the multiples of divider. Therefore, it is necessary to choose the three times larger than the original divide multiples when optical frequency transmit on communication optical fibers. At the same time, as the frequency multiple increases, the bandwidth of the filter decreases, thereby increasing the difficulty of design. Fig.2 shows the phase demodulation result of the simultaneous in-loop beat-note through three different phase demodulation schemes, where the blue line is the output result of the analog frequency divider and phase detector with a ratio of 128,and the green line is the output result of digital frequency divider and phase detector with a ratio of 1280.Comparing the two results, the digital frequency divider and phase detector has less wrapped times of phase difference and better linearity than the analog times frequency divider and phase detector. Fig.2 (b) is the phase difference after the digital IQ phase detector and phase unwrapped of the in-loop beat-note signal in the same time, which shows that the phase difference is no phase wrapped and it is limited to the data storage spaces after the phase error is accumulated in the program.

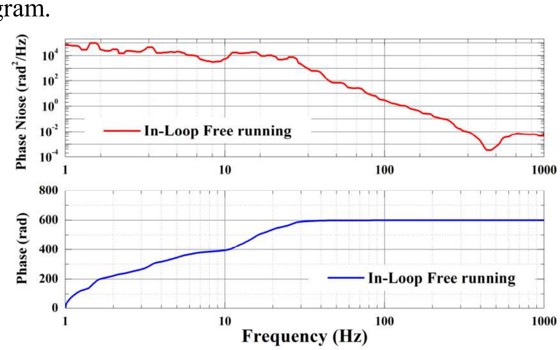

Fig. 1. Phase noise power spectral density(PSD) (a) and the calculated phase difference (b) of free running in-loop beat-note signal via the 200km link

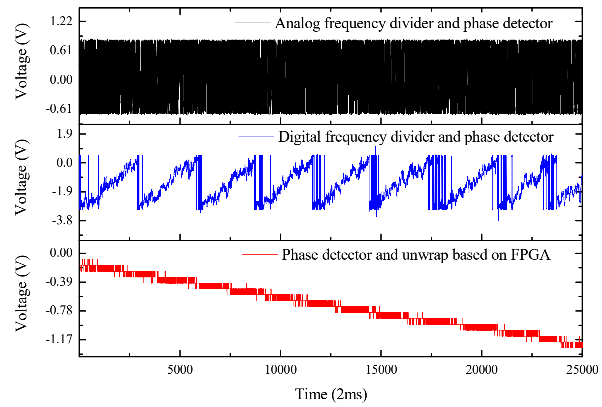

Fig. 2. the phase demodulation result of the simultaneous in-loop beat-note through three different phase demodulation schemes

III. Application of Phase Unwrap Technique in Optical Frequency Transfer

The structural schematic of active noise suppression of optical fiber optical frequency transmission system is shown in Fig. 3, the sender and receiver are located in the same laboratory[7]. The phase difference with wrapped characteristics of the phase detector output is accumulated using phase unwrap technology. The accumulation result is sent to the PID and fedback with a Direct Digital Synthesizer (DDS). Among them, the fiber link is composed of eleven 50km spooled fibers and 5 bidirectional erbium-doped fiber amplifiers(bi-EDFA). Fig. 4 shows the in-loop beat signal after the phase noise is compensated , where the yellow line is the in-loop beat-note frequency obtained by the frequency counter(K+K FXE) working on λ-type mode, and the blue line is the corresponding phase difference of the in-loop beat-note calculated by the yellow line. It can be seen from the blue line that there is no phase circle-slips in the phase-locked loop during the entire test process, of which there are some burrs in the first half and the second half, because the spooled fibers is exposed in the air, it is easy to be affected by various noise interferences during the day, and it is uninvolved at night, so the beat-note signal in the middle part is relatively smooth.

The out-loop beat-note between the reference signal and the output signal of link is measured by a frequency counter (K+K FXE) working on λ-type mode. And transfer instability versus time is evaluated by calculating Overlapping Allan deviation of the frequency data, which is shown in the Fig. 5. In the figure, the blue-purple line is the noise floor of the optical frequency transmission system of the optical fiber, the black line is the frequency instability of the unstabilized 550 km optical frequency transmission, and the red line is the frequency instability of the out-loop beat-note signal after the phase noise cancellation. At averaging time from 2,000 s to 10,000s, the instability of stabilized 550km link gradually deviates from the 1/τ slope,which may be caused by the fluctuates of laboratory temperature.Thus, the transfer instability of the 550 km link reaches 4.3×10^{-20} at 10,000 s averaging time.

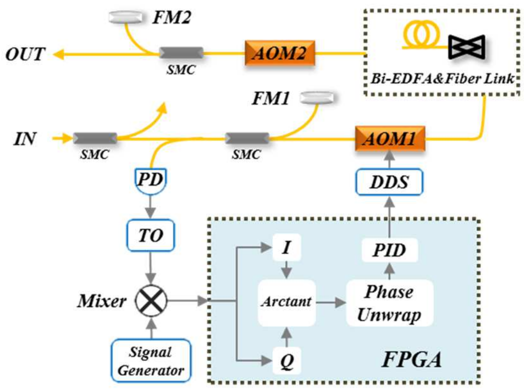

Fig. 3. The structural schematic of active noise suppression of optical fiber optical frequency transmission system. SMC, single mode coupler; PD, photo diode; AOM, acousto-optic modulator;FM, Faraday rotating mirror ;TO, tracking oscillator;I,in-phase;Q, quadrature ; DDS , Direct Digital Synthesizer.

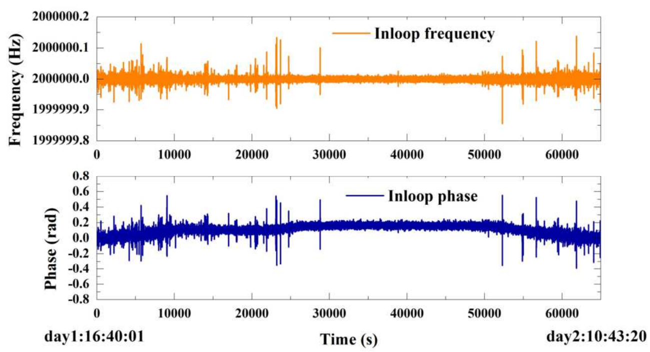

Fig. 4. In-loop participating noise after the phase noise is compensated

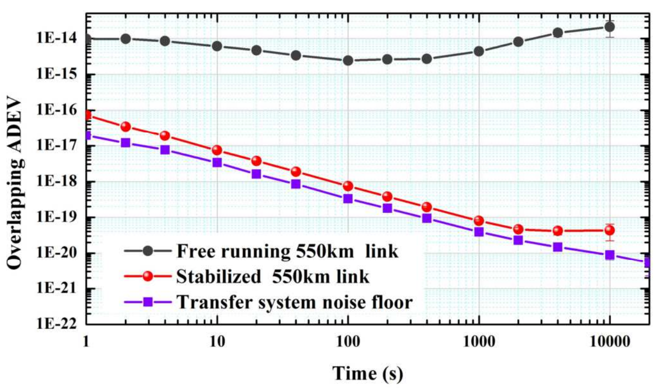

Fig. 5. Transfer instability of the 550km spooled fiber link

IV. Conclusions

In conclusion, phase unwrap technology can achieve infinite extension of phases within the storage limitation and it is suitable for fiber link with large phase noise level.The circle-slips of the phase-locked loop caused by the wrapped phase is reduced, and frequency transfer instability on 550km spooled fiber can achieve 4.3×10^{-20} at 10,000s averaging time. This result provides a validation of the principle for demonstrating long-distance optical frequency transfer link with large noise level. In order to improve the long-term instability of the transmission so that it can reach the 10^{-21} order of magnitude of the transfer system noise floor, it is also necessary to eliminate the influence of the temperature changes on the asymmetrical part of optical modules, and add a polarization automatic controller[8] to the system to optimize the signal-to-noise ratio(SNR) of the out-of-loop beat-note signal, thereby reducing the circle-slips caused by the measurement[9].

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