LABORATORY EXPERIMENT OF 9.2 GHz FREQUENCY TRANSFER WITH A FIBER

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Abstract

We report the preliminary laboratory experiments on a 9.2 GHz frequency signal transfer through a 10 km commercial 1550 nm fiber spool in NIM. Theory analysis shows that increasing modulation frequency can significantly enhance the detecting sensitivity of fiber noise, as well as the sensitivity of compensating the noise. Because of the phase shift induced by fiber dispersion between the two first sidebands of EO (electro-optical) modulated optical carrier, beat signal between them, which can not be detected without phase shift, can be used as transferred signal with double modulation frequency. With actively canceling the noise induced by fiber, we have obtained a stability of about 8E-16/1000s up to now only with slow loop servo actuating by MDL (Motor Drove Delay Line).
Key words: Frequency standard transfer, fiber; sidebands beating; EOM.

1. Introduction

With the developments of laser cooling fountain clock and optical clock, the stability of time and frequency primary standard is significant enhancing [1, 2, 3]. Problems are rising at the same time: how to compare those clocks, and how to use them without stability degrades? The existing time and frequency transfer systems, such as TWSTFT, GPS Common View, TV carrier wave, and so on, are not very suit for the comparison and transfer of those standards because of the high cost or great stability loss [4]. More and more laboratories are considering how to transfer those standards with least stability loss. Optical fiber, which isolated from the electromagnetism environment, and well isolated from temperature or stress disturbance when embedded under ground, is very stable for signal transfer. With the optical communication development, the fiber nets are well constructed, as well as the relatively technology and apparatus. Especially with EDFA, the distance of optical signal transferring in fiber is great increased without any conversion between optics and electrics. All of these made optical fiber the best medium for the high stability time and frequency transfer. From the late eighties to recently, JPL, NIST, JILA, LNE-SYRTE, and other international metrology laboratories have developed high stable frequency transfer system with fiber link to transfer and compare frequency signal synthesized from such as H maser, fountain clock or optical clock [5, 6, 7, 8, 9].

National Institute of Metrology (NIM) of China had constructed the NIM4 laser cooling cesium fountain clock with uncertainty of 5E-15 by 2003, and now is under constructing the transportable fountain clock named NIM5 with predicted uncertainty of 2E-15[10]. The second fountain NIM5 and the time keeping lab will be moved to Changping campus of NIM, which is about 45 km away from our current Hepingli campus. Following those labs mentioned above, we are going to construct a fiber link to transfer RF frequency between the two campuses.

In this paper we report the preliminary experiment of transferring 9.2GHz frequency signal through a 10 km commercial G.652 fiber spool in laboratory. In the second part the transfer theory of single mode fiber is introduced to explain why phase modulation with 4.6GHz modulation frequency is used for optical carrier modulation. In the third part, by characterizing the phase relationship of modulated optical carrier and the dispersion of fiber, we innovatively propose the side bands beating technique with significantly enhancing of the detecting and compensating sensitivity of fiber induced noise. In the forth part, we present the realization system and corresponding important equipments. In last part we give the preliminary results of experiment on our laboratory simulated 10km fiber frequency transfer system, the transfer stability with actively fiber noise cancelling is approach to 8E-16 at 1000s averaging time.

2. Theory Analysis

In order to make use of the existing fiber resource, we choose commercial G.652 single mode fiber ring to simulate 10km transfer link in laboratory. 1550nm laser output from a DFB is modulated by an EOM and transferred through the 10km fiber. Here we introduce single mode fiber transferring character and analyze the relationship between fiber and signal transferring through it.

As well-known, there is only the base mode can be transferred in a single mode fiber and the transfer constant β is only determined by the fiber's configuration and the frequency of transferred laser in it. So β can be written as

$$\beta(w) = F\{\varepsilon(x,y), w\} \qquad (1)$$

where w the frequency of transferred laser, and $\varepsilon(x,y)$ the transverse construct of fiber, a function of w. If the carrier laser frequency is w_0, modulating signal frequency is Ω, then $w = w_0 + \Omega$. Since $\Omega << w_0$, β can be extended as

$$\beta(w) = \beta(w_0) + \frac{d\beta}{dw}\Big|_{w=w_0}(w-w_0) + \frac{1}{2}\frac{d^2\beta}{dw^2}\Big|_{w=w_0}(w-w_0)^2 + \frac{1}{6}\frac{d^3\beta}{dw^3}\Big|_{w=w_0}(w-w_0)^3 + ...$$

$$= \beta_0 + \beta_0^{'}(w-w_0) + \frac{1}{2}\beta_0^{''}(w-w_0)^2 + \frac{1}{6}\beta_0^{'''}(w-w_0)^3 + ...$$

$$= \beta_0 + \beta_0^{'}\Omega + \frac{1}{2}\beta_0^{''}\Omega^2 + \frac{1}{6}\beta_0^{'''}\Omega^3 + ... \qquad (2)$$

Here $\beta_0^{'}$, $\beta_0^{''}$ and $\beta_0^{'''}$ are the first, second and third order differential of β at the frequency point $w = w_0$ respectively. And compare to $\beta_0^{'}$, $\beta_0^{''}$ and $\beta_0^{'''}$ are too small and be ignored. Define by $f(t)$ the modulating signal, and L fiber length, $\phi(t)$ the demodulating signal at the end of the fiber, we have:

$$\phi(t) = f(t - \beta_0^{'}L) \qquad (3)$$

This means single mode fiber is a time delay system for the modulating signal, and the magnitude of delay is $\beta_0^{'}L$. Expressing by the phase relationship between modulating and demodulating signal, the phase shift of transferred signal can be written as:

$$\varphi(t) = \Omega\beta_0^{'}L \qquad (4)$$

When fiber suffers from the temperature fluctuation or stress, transfer constant and fiber length will consequently change $\Delta\beta_0^{'}$ and ΔL .Then the phase change of transferred signal can be written as:

$$\Delta\varphi = \Omega(\beta_0^{'}\Delta L + L\Delta\beta_0^{'}) \qquad (5)$$

There have two interesting points revealed:

The first, fiber noise induced by environment perturbation will cause the phase shift of transferred signal. So we can actively adjust fiber length to control the phase shift. In our experiment, two kinds of fiber length delay line, motorized delay line (MDL) and fiber stretcher (FST) are introduced to compensate the fiber noise or the phase shift on transferred signal. The relative information and experiment results will show in follow.

The second, higher modulating frequency makes greater phase shift change on the demodulating signal with the same noise induced by fiber. So we can increase the detecting sensitivity of fiber noise by enhancing the modulating frequency, as well as realizing higher efficient of compensation. According to existing technology level on the fiber communication, phase modulation by EOM has the highest modulation frequency with considerable modulating depth. On the other hand, Outside phase modulation has no chirp effect on the laser source. So we use this modulation method to realize higher frequency modulating.

A phase modulated optical carrier can be written as:

$$v_{PM} = V_{cm}\cos(\omega_c t + M_p \cos\Omega t) \qquad (6)$$

Extended by Fourier series,

$$v_{PM} = V_{cm}\sum_{n=-\infty}^{\infty} J_n(M_p)\cos[\omega_c t + n\Omega t] \qquad (7)$$

Where,

$$J_n(M_p) = \frac{1}{2\pi}\int_0^{2\pi}\exp(jM_p\cos\Omega t)\exp(-jn\Omega t)d\Omega t \quad ,$$

$J_n(M_p)$ the n order Bessel function of the first kind with parameter M_P. For phase modulation, M_P means modulation depth. The property of first kind Bessel function is as below:

$J_n(M_p) = J_{-n}(M_p)$, while n is even number;

$J_n(M_p) = -J_{-n}(M_p)$, while n is odd number.

This means the first two sidebands of phase modulated optical carrier, which are the main power frequency components besides the base frequency of carrier, have same amplitude with anti polarity, as shown in fig1. In other word, the first two sidebands have a fixed phase difference π. It means that the

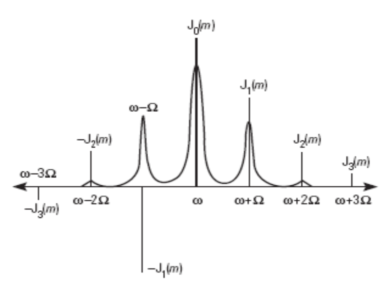

Fig1, frequency spectral of phase modulated carrier

beat of the two side bands of an EO modulation, which we expect to use as the transferred signal, can not be detected because of interferometric cancellation. But on other side, the beat signal between them can be well detected by photodiode with the hypothesis that there has an additional phase shift φ upon the π difference. The current signal of detecting photodiode can be written as:

$$I_{+1,-1} = -V_{cm}^2 J_1^2(M_p)\sin(2\Omega t - \varphi)\sin\varphi\,, \qquad (8)$$

with $\sin\varphi$ the amplitude fluctuation of current, $\sin 2\Omega t$ the current frequency.

In fact, while transferring along the fiber link, the modulated carrier is dispersed. Especially the G.652 fiber which not only we used and but also commonly used in national fiber net, has a relative big dispersion on 1550nm wave band. This means the two first sidebands of modulated carrier will have considerable phase delay between each other after fiber transferring, and the phase delay is directly proportion to frequency difference. Considering a phase modulated signal, which frequency difference between two first sidebands is 2Ω , transferring in G.652 fiber with the dispersion coefficient $D(\lambda)$, the phase shift can be written as:

$$\varphi = 2\Omega(\lambda^2 / c)D(\lambda)L \qquad (9)$$

with λ carrier wavelength, c optical velocity in vacuum. By that phase delay, these two sidebands can beat well at the end of transfer link.

Fig.2 and fig.3 show beat signals between the two first sidebands of EOM modulated 1550nm carrier after fiber transferring 10km and 20km in each. The

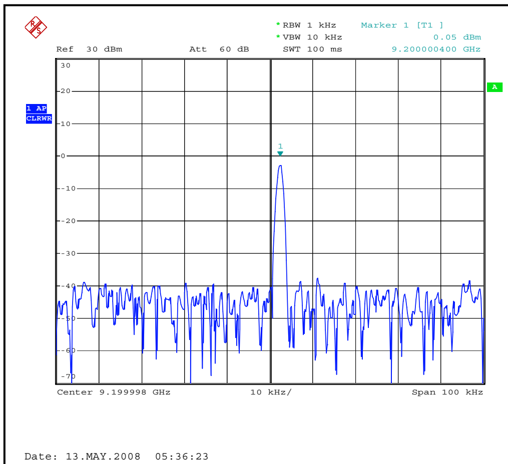

fig2. Beat signal between the first sidebands of modulated carrier after 10km fiber transferring

dispersion coefficient of fiber is about 15ps/nm·km and the modulating frequency is 4.6GHz. So by theory calculation, the phase shift between first sidebands is:

$$\varphi = 2\pi \times 0.01 \times L\,. \qquad (10)$$

L, the length of carrier transferring in fiber, is 10km and 20km corresponding to fig.2 and fig3. And the current amplitude coefficients are 0.58 and 0.95 in each. Conversion to power relationship, the power of 20km transferred signal is about 5dB bigger than that of 10km signal. Seeing from Fig.2 and Fig.3, which are the printed screen figures of beat signal from spectrum analyzer, the power of 10km fiber transferred beat signal is 0dBm and 5.6dBm of 20km

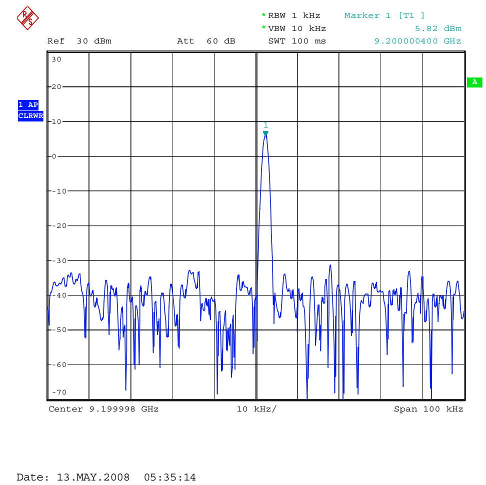

fig3. Beat signal between the first sidebands of modulated carrier after 20km fiber transferring

respectively. It is well accord to theory value.

It is very lucky that the dispersion of fiber can be well scaled. The fiber dispersion can be well measured, and control by many method. A commonly used effective method is inserting dispersion compensating fiber (DCF), which has reverse great dispersion to G.652 fiber. So it is very ease to adjust the dispersion of whole fiber link, as well as receive good beat signal from the transferred phase modulation carrier.

3, Scheme of Experiment

According to the theory analysis, we know that (1) phase modulation by EOM can be used to enhance significantly the sensitivity of fiber noise detecting and compensating; (2) dispersion of fiber can be used to make considerable beat signal between the two first sidebands of phase modulated carrier. To utilize the existing 10Gb/s fiber communication technology, we choose 4.6GHz as the EOM phase modulating frequency. In this frequency point we can find ready-made EOM with considerable modulation depth, and its double frequency of beating signal from the two first sidebands of phase modulated carrier, is at 9.2GHz, where relevant detecting PD is well commercial and relative cheap. On the other hand, because 9.2GHz is near the frequency of cesium clock, it is easy to compare the transferred frequency with that of cesium frequency synthesizer.

Fig.4 shows the scheme of frequency standard transferring with fiber. 1550 nm laser output from a commercial DFB laser with power stabilizing is injected in and phase modulated by a fiber-free space-fiber system, which consists of two fiber couplers, two lenses, some pieces of mirror and an

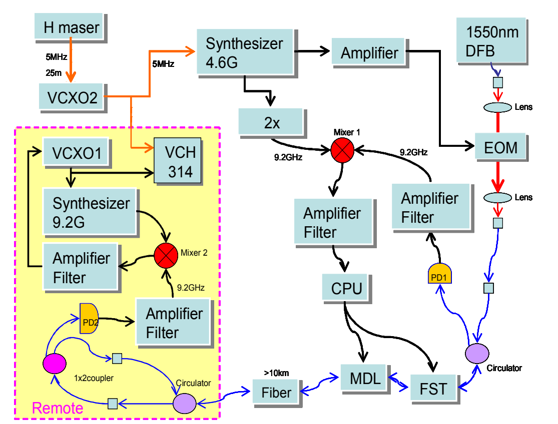

Figure4, Scheme of experiment

EOM at 4.6GHz modulation frequency. The modulating signal is synthesized from 5MHz output of H maser, which locates at the timekeeping laboratory, about 25m distance to our laboratory with different ground connection. In order to filter the short time noise introduced by the 25m coaxial cable line, a voltage controlled oscillator (VCXO2) is phase cohered to H maser output 5MHz signal. Then synthesizer output splits into two parts, one part with -6dBm is amplified up to 1.5w, and fed into EOM as the modulating signal; the other part with 15dBm is doubled to 9.2GHz by a multiplicator as the local reference signal, which then mixes with transferred 9.2GHz signal by a mixer.

In series, modulated carrier feeds into fiber link. At local end, a fiber circulator is used to assort the forward and backward laser. The forward laser transfers through MDL, FST and a 10km fiber pool in turn, arriving at the simulated remote end. Here MDL and FST are the fiber noise compensating actuator. MDL, with an motor droved pyramid mirror, which can be moved forward and backward to change the optical length between the fiber input and output link, has 18cm compensating range, but the respondence frequency is lower at 5Hz, mainly limited by RS232 serial communication and motor action. FST, drove by PZT, has a faster resonance frequency up to 2.5 kHz. But limited by PZT drive capacity, the maximal compensating range is only 3mm. Those two actuators can be used to compensate the fiber noise of different frequency bands.

At the remote end, modulated carrier laser splits and couples by a system consists of a circulator and a 1x2 coupler. The forward single trip signal output from circulator is fed into the coupler, one part of coupler output injects to PD2 for detecting the transferred 9.2GHz beat signal, the other part couples back into the circulator and then transfers backward to the local end as the circulator output for detecting the transferred 9.2GHz beat signal with a round trip by PD1.

At local end, detected 9.2GHz beat signal of round trip mixes with the reference 9.2GHz signal doubled from 4.6GHz synthesizer output. The beat signal on PD1 is phase modulated by the optical path noise of the fiber in its forward and backward journey so the mixed signal between it and the doubled local oscillation frequency can be used as error signal to actively compensate the noise of the fiber by MDL and FST.

At remote end, an evaluation system for transferred 9.2GHz signal is also constructed. Output of a 9.2GHz synthesizer, referencing to a voltage controlled oscillator (VCXO1), mixes with the transferred 9.2GHz signal by Mixer2, and then the IF output of it feeds back as the control voltage to phase stabilize VCXO1. In a short word, VCXO1 is phase locked to the transferred signal, and its RF output 5MHz signal is phase cohered to the local reference frequency and can be used as the transferred reference frequency at remote end. In lab, comparing the 5MHz output signal of VCXO1 with that of H maser by a phase comparator (VCH314), the stability of transferred signal is measured.

4. Results of experiment

MDL and FST are used to compensate the noise induced by fiber. Fig5 and fig6 show the phase

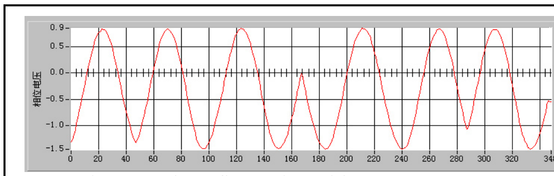

Figure 5, Phase fluctuation with MDL sweep

transferred signal change with the sweeping of MDL and FST.

In fig5, MDL is set to sweep triangularly between -60ps and 60ps optical delay length. By the MDL operation system, the delay length value shows in unit of ps, and 1ps is about 0.3mm correspondingly. It is difficult to verify the physical start poison of MDL on the start time. But at 48 point in figure, we can see that the phase of transferred signal is reflected, and we can sure that MDL runs at -60ps, one of the inflexion of triangle sweep. From this point, MDL keeps running to another inflexion at 60ps, and arrive at 168 point in figure. Then MDL turns back, the phase reflects again, and at the point of 288, phase of transferred signal recover, and MDL sweeps back to -60ps. It is very clear that the phase of transferred signal change 2π while MDL sweeps over about 55ps. Because the phase signal sample from the photodiode PD1, where transferred signal goes a round trip, the optical length change suffered by transferred signal is double of MDL swept. So phase change 2π, corresponding to optical length change of 110ps, which is about 33mm, as well as on wavelength of transferred 9.2GHz signal from the beat between first sidebands of modulated carrier.

In Fig6, FST scans as sine wave between the 0v and

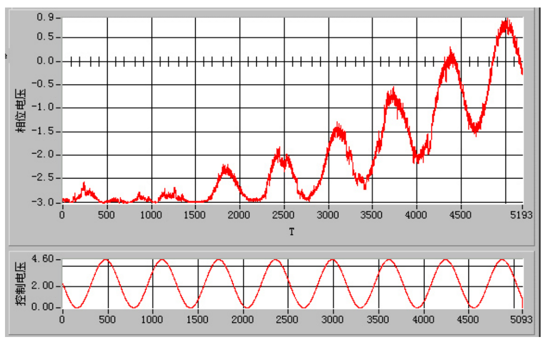

Figure 6, Phase fluctuation with FST sweep

4.6v peak-peak voltage on the PZT driver, showing as down part of figure, and the phase of transferred changed, showing on up part of figure corresponding. We can see the phase change like some kind of fluctuation modulated with a sine wave. Because the delay range of FST is about 3mm by the highest PZT voltage of 5v, the phase change introduced by FST is relatively small than that by temperature fluctuation, which disturbed phase of transferred signal through 10km fiber link.

By those experiments, we are sure that MDL and FST can be used to control the optical length of transferred signal, as well as compensate the phase change of transferred signal.

At present experiment, we use MDL to compensate the fiber noise. With actively canceling the disturbances induced by fiber, we have phase locked the 9.2 GHz transferred frequency and Figure7 shows the curve of phase signal from the mixer in local end

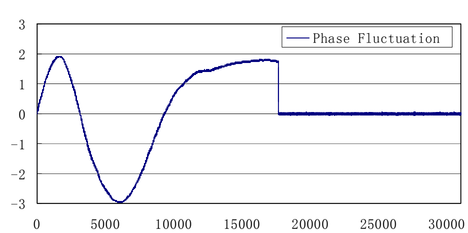

Figure 7, Phase fluctuation with locking off and on

with actively locking off (left part) and on (right part) in two days. At 1000 s time scale, the phase stability is 100 times better compared to free running. At longer time scale the phase stability is improved up to 500 times.

To identify the stability of the transferred frequency in the lab, the 5 MHz output of VCXO1 is synchronized to the 9.2 GHz frequency transferred through the fiber and detected by PD2 in the remote end and compared with the local 5 MHz reference frequency from H-maser by a phase comparator VCH-314. Figure8 shows the Allan deviations of this comparison. The curve with squares denotes the stability of VCXO1 locked to the transferred frequency, and the curve with diamonds indicates stability of VCXO1 locked directly to H-maser. In

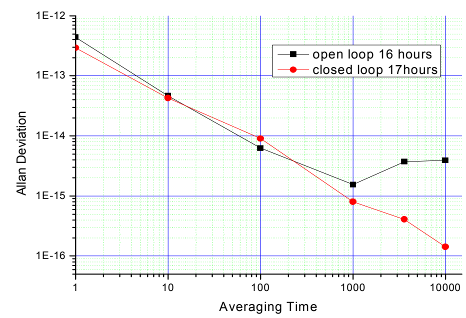

Figure8, Allan deviation of transferred frequency stability

short time scale the stability showed in figure 7 is limited mainly by stability of the VCXO itself, which is in the order of E-13. But at 1000 s and 10000 s averaging time, the fiber noise is significantly cancelled with actively compensating, and the stability of transferred signal reaches 8E-16 and 2E-16 respectively.

To increase transferring length and improve the short term stability, we will use a 50 km fiber to replace the 10 km one and introduce a fast control loop of a PZT drove fiber stretcher (FST) soon.

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