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Influence of Asymmetry in the Compensation System of Stable Radio Frequency Dissemination Via Optical Fiber

Jinting Cong

Beijing University of Posts and Telecommunications, Beijing 100876, China

Abstract

In this paper, we study the limit of short-term and long-term performance which is caused by the system noise including fluctuations of the transfer links, dispersion and intensity noise in dissemination. We also discuss the Influence of temperature asymmetry and wavelength asymmetry in the compensation system , in the proof-of-concept simulations, 3000 km fiber links are established to disseminate a 10 GHz frequency signal, which the influence of temperature asymmetry can be ignored and the influence of wavelength asymmetry with a 100 MHz center frequency spacing exhibits a performance at the order of 10^{-16}/s.

Keywords

Asymmetry; System Noise; RF Signal Dissemination.

1. Introduction

The problem of transferring precision time and frequency (T/F) signals to a remote location is important in many areas, involving commercial applications and scientific experiments (e.g. telecommunications, metrology, navigation, and geodesy). Comparing with the satellite link, the optical fiber has recently attracted much attentions to build link for synchronization[1-3]. A number of projects have confirmed that T/F synchronization based on optical fiber link can achieve higher transmission accuracy[4-7]. This is because optical fiber has the characteristics of low loss, high stability, strong antielectromagnetic interference ability and wide distribution of existing optical fiber communication networks.

The noise of optical fiber link and the noise of active components are two factors that have great influence on the stability of RF phase stabilized transmission in optical fiber stabilized transmission system.The link noise of optical fiber, including the influence of temperature on fiber length and the influence of temperature on core refractive index, and the dispersion caused by laser wavelength jitter, the link noise causes phase jitter through the accumulation of delay jitter on optical fiber link, which leads to the deterioration of the system's Aron variance.The noise of active devices will lead to the decline of signal-to-noise ratio in the signal detection process, which will lead to the deterioration of the stability of the system.In order to reduce the influence of noise in optical fiber stable frequency transmission, it is necessary to design a reasonable stable phase transmission system for noise research. However, in the past, researchers at home and abroad mostly studied the noise of a single system, and few systematically classified and analyzed the noise and carried out simulation research based on actual experimental data. In addition, theoretical noise research and simulation of compensation system are also very rare.

2. Principle and Simulation

2.1. Noise Analysis

Several phase noise exists during the RF signal transmission, and the phase noise accumulates over the transmission paths, besides several noise sources of optical or electronic origin can introduce additional phase noise too. The phase noise over the optical fiber results from the transfer delay time which can be expressed as:

$$\tau = \frac{n_g * L}{c} \tag{1}$$

Where n_g is the group refractive index, L is the fiber length and c is the velocity of light in vacuum. As we know, the fiber length and refractive index will change with the temperature variation, resulting in the fluctuation of transfer delay time. Then the delay difference $\Delta\tau$ derivative with respect to the temperature T is

$$\frac{\Delta\tau}{\Delta T} = \frac{L}{c}\frac{\partial n_g}{\partial T} + L\alpha\frac{n_g}{c} \tag{2}$$

In addition to the two factors related to temperature, the dispersion of light on the optical fiber link also causes time jitter, and it can be expressed as

$$\Delta\tau = DL\Delta\lambda \tag{3}$$

where $D = \frac{\partial n_g}{\partial\lambda}/c$, which is the group dispersion parameter, its representative value is 17ps/nm*km, $\Delta\lambda$ is the optical wavelength shift when in single wavelength transmission scheme.

The transformation from time jitter to phase change on the fiber link can be expressed as

$$\Delta\varphi = 2\pi f\Delta\tau \tag{4}$$

And the instantaneous fractional frequency of the RF signal is

$$y(t) = \frac{d\Delta\varphi}{2\pi f_0 dt} \tag{5}$$

where f_0 is the average frequency of the oscillator over the entire measurement period. And the Allan variance can be expressed as

$$\sigma_y(\tau) = \sqrt{\langle\frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2}\rangle} \tag{6}$$

in which $\bar{y}_{k+1}$ and $\bar{y}_k$ are the instantaneous fractional frequency.

Sinusoidal curve can be used to model the change of ambient temperature with time as $\Delta T(t) = A\sin(2\pi t/T_1)$, where A denotes the amplitude and for buried fiber cables whose daily temperature variation is usually less than 1 °C, and T_1 (usually can be set as 1day) is the period.Thus the Allan variance of instability caused by temperature change in the length of optical fiber link can be calculated as follows

$$\sigma_{y,1}(\tau) = \frac{nLA}{c}\frac{\partial\Delta L}{\partial T}\frac{2}{\tau}\left\{\sin\left(\frac{\pi\tau}{T_1}\right)\right\}^2 \tag{7}$$

Similarly, the Allan variance of instability induced by the temperature change in the refractive index can also be expressed as

$$\sigma_{y,2}(\tau) = \frac{nLA}{c}\frac{\partial\Delta n}{\partial T}\frac{2}{\tau}\left\{\sin\left(\frac{\pi\tau}{T_1}\right)\right\}^2 \qquad (8)$$

And for the fluction caused by dispersion which is due to the optical wavelength instability, its instantaneous fractional frequency can be expressed as

$$y(t) = \frac{DL\partial\Delta\varphi(t)}{\partial t} \qquad (9)$$

Where $\partial\Delta\varphi(t)/\partial t$ is the fluctuation of optical frequency, its value depands on the laser performance.

We simulate the relative phase drifts of a 3000 km fiber link under a sinusoidal temperature variation which the temprature variation is 1 °C using Eq. (7) and (8), and plot the ADEV in Figure. 1. It shows that the 3000 km fiber link with a variation of temprature just exhibits a performance floor at the order of 10^{-17}/s and 10^{-13}/10000s.

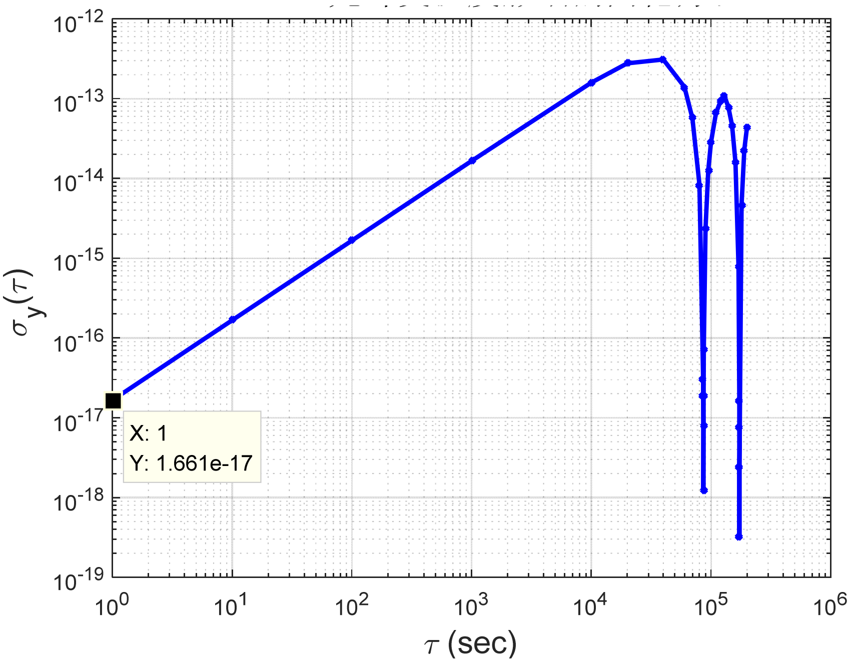

Figure 1. Instability which is impacted by temperature fluctuation including fiber length variation following with temperature and the fiber refractive index variation following with temperature

To achieve the laser frequency fluctuation, the experiment setup is shown in Figure.2. The laser to be tested (commercial DFB laser) and NKT fiber laser are coupled with an optocoupler. The coupled signal is attenuated by an optical attenuator to 0 dBm, and sent to the photodetector. The output signal is measured by a frequency counter to obtain the test laser frequency which is 7MHz/s.

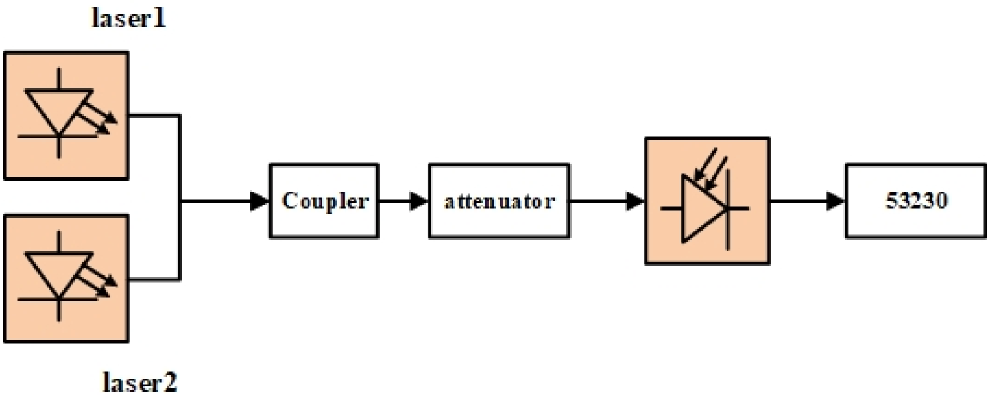

Figure 2. Laser frequency fluctuation experiment setup

We simulate the time delay drift in 3000 km fiber length with the laser frequency fluctuation using Eq.9 and plot the ADEV in Figure 3. Assuming that the dispersion compensation effect is 99.5%, its instability is 10^{-14}/s.

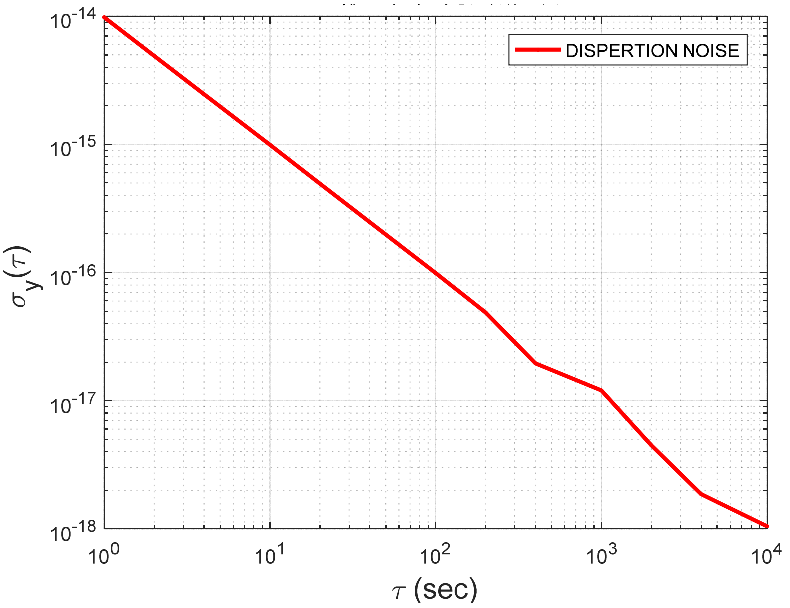

Figure 3. The simulations of Allan deviation of a 3000 km fiber link inflected by DFB laser frequency drift

Thus, we can see that the limit of short-term performance is affected by dispersion and the long-term performance floor results from temperature drift. In addition, the intensity noise of active devices will reduce SNR of the system, which will also lead to the deterioration of short-term stability.

2.2. Asymmetry Analysis of Compensation Link

Figure 4 shows the principle of the common phase stabilization scheme[8]. The RF signal can be transmitted to the remote end phase stably after three link transmissions.A phase change φp1 is induced due to the time delay of the fiber links, which can be expressed as cos(ωt + φp1). Then part of the signal is split out and fed into the fiber .The phase changes induced in the second and third trip are φp2 and φp3. So the accumulated phase change after the third trip is φp1 + φp2 + φp3. At remote end, the single-trip signal is converted to its triple-frequency version. The output, cos(3ωt + 3φp1), then is mixed with the returned signal, written as cos(ωt + φp1 + φp2 + φp3), to produce an intermediate frequency signal cos(2ωt + 2φp1-φp2-φp3). If the variation of the time delay and TIVGVD are ignored, an approximation can be made as φp1≈φp2≈φp3. Therefore the intermediate frequency signal is theoretically phase-stabilized and a stable RF signal cos(ωt) can be obtained at the remote end by frequency division.

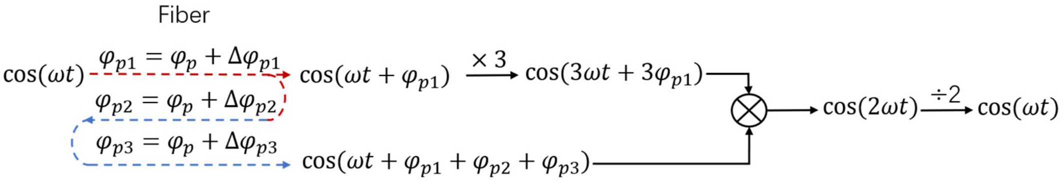

Figure 4. The principle of the phase stabilization scheme

Since the three phase of the transmission φp1≈φp2≈φp3, the compensation can be thought of as a perfect compensation, but in the actual conditions, due to the asymmetry of temperature, laser wavelength , and the optical fiber length asymmetry of EDFA, the accumulation of link transmission phase is often not same, so will lead to an inaccurate compensation the residual phase fluctuation $\Delta\varphi_r$ which can be expressed as[9]

$$\Delta\varphi_r = \Delta\varphi_3 - \frac{\Delta\varphi_1+\Delta\varphi_2}{2} \tag{10}$$

In order to obtain the actual temperature asymmetry, the laboratory temperature was collected and fitted. We simulate the compensated system with a asymmetric temperature change via 3000 km fiber length. And the Figure.5 shows that symmetrical temperature compensation is better than the other one in long distance transmission.

Since the influence of asymmetry is a rapidly changing process, only the short-term stability is considered, and it is possible to exist only in the case of ultra-long-distance transmission. The transmission delay of short distance transmission which is within the compensation bandwidth can be ignored.

In the case of buried fiber, the temperature drift is slow, so the time delay fluctuation caused by the change of optical path difference which results from the temperature change can be effectively compensated.

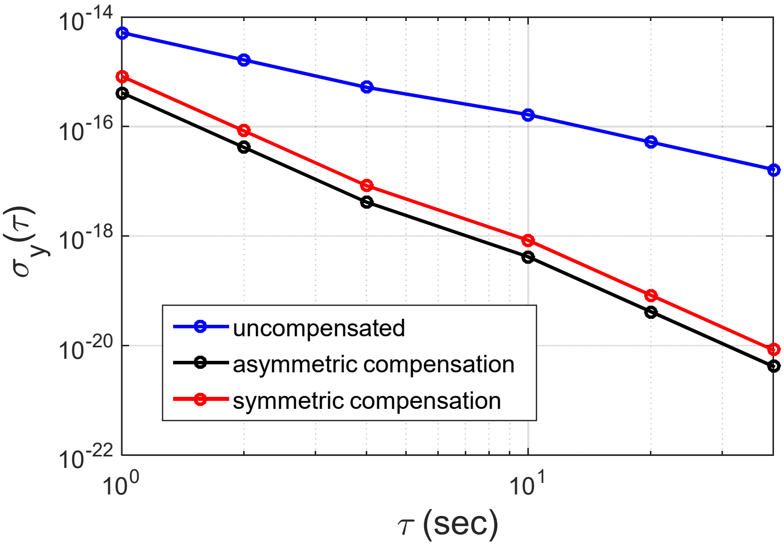

Figure 5. The simulations of temperature asymmetry via 3000 km fiber link

As far as we know, the restriction caused by the optical wavelength asymmetry cannot be compensated, when the wavelength of optical carrier signal is not same via the back and forward transmission, it will lead to a time delay expressed as

$$\Delta\tau = \mathrm{LD}(\lambda_1 - \lambda_2) \tag{11}$$

in which $\lambda_1$and λ_2 is the back and forward optical wavelength respectively. At this point, the variation of a single wavelength can be ignored [10]. According to above analysis, since L and D are respectively related to temperature change, but the impact of compensated temperature change is very low, so it can be ignored. Figure 6 shows the influence of wavelength spacing on link stability.

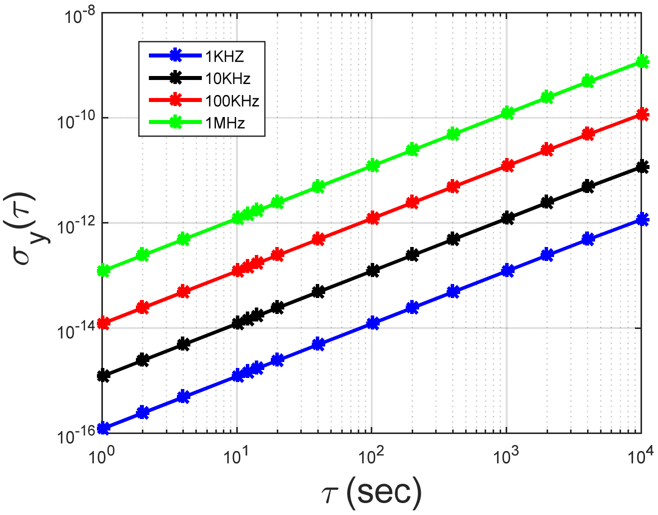

Figure 6. The simulations of wavelength asymmetry via 3000 km fiber link

When the center optical frequency gap between forward and back transmission is 1 MHZ, the instability of system is 10^{-16} /s.

3. Conclusion

In this paper, we firstly analyze the impact of temperature, dispersion in OE-EO transmission, and the main factors affecting the short-term and long-term stability of the system are obtained, in which the temperature affect the long-term performance and the dispersion as well as intensity noise affect the short-term performance.

Addition to it, we also discuss the impact of these two factors including temperature and dispersion in a compensated transmission. The compensated temperature noise via 3000km fiber link has an effect on the stability of the ADEV of 10E-18/s, and the asymmetrical effect of temperature variation over extremely long transmission cannot be ignored. According to that the wavelength spacing between back and forward wavelength will lead to group velocity dispersion and thus worsen the stability, the simulation of wavelength asymmetry is carried out. Via 3000 km optical fiber link, when the center frequency spacing is 100MHz, the ADEV is 10E-16/s.

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