ALMA Memo No.511

Cycle-slip-free fiber length stabilization system using a digital phase and frequency discriminator

Yohei Sato, Mitsuru Musha, Ken'ichi Nakagawa, Ken-ichi Ueda
Institute for Laser Science, Univ. of Electro-Communications (UEC), Chofu-shi, Tokyo, Japan
Akitoshi Ueda, Masato Ishiguro
National Astronomical Observatory of Japan (NAOJ), Mitaka-shi, Tokyo, Japan
2004-Dec-15

Abstract. We have developed a fiber length stabilization system (FLSS) for the photonic distribution of LO signals by using a digital phase and frequency discriminator (DPFD). Compared with a conventional analog double-balanced mixer (DBM) or a phase sensitive detector with an XOR gate (PSD), the DPFD has wider linear discrimination range by more than 1000 times, which enables cycle-slip-free FLSS. Moreover, it makes possible to stabilize the length of the fiber that is longer than the coherent length of the light source used in FLSS.

Introduction

For distributing a millimeter wave reference signal to each antenna in ALMA, it is planned to use a heterodyne beat note of two lasers and an optical fiber. To maintain a required phase stability of first LO at each antenna, the fiber length should be stabilized using a round-trip phase correction method [1]. A photonic reference signal around 100 GHz is generated by feeding the laser beat note into a photomixer located at each antenna. In order to detect the phase deference between the signals to and from antenna, a conventional analog double balanced mixer (DBM) or a digital phase sensitive detector using an XOR gate (PSD, fig.1(a)) has been used.

In spite of their high phase sensitivity, the conventional methods have following disadvantages. The slope sign of the phase signal from DBM or PSD is periodically changes in every π radian, which causes the cyclic slip of the phase locking scheme (solid trace in fig.2). Another disadvantage is that if the round-trip length exceeds the coherent length of the light source, the error signal arising from the length fluctuation is completely masked with the phase jitter caused by the light source (the phase jitter easily exceeds π radian). The cyclic slip and the low signal-to-noise ratio (S/N) are serious problems for the fiber length stabilization system (FLSS).

We have developed an FLSS with a servo system using a digital phase and frequency discriminator (DPFD) [2,3]. The DPFD is based on digital up and down

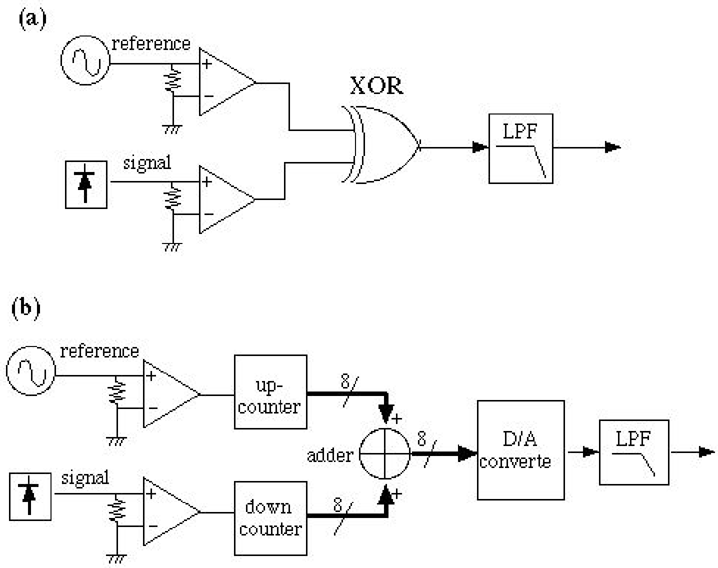

Figure.1: Schematic diagram of (a) conventional digital PSD and (b) digital phase and frequency discriminator (DPFD)

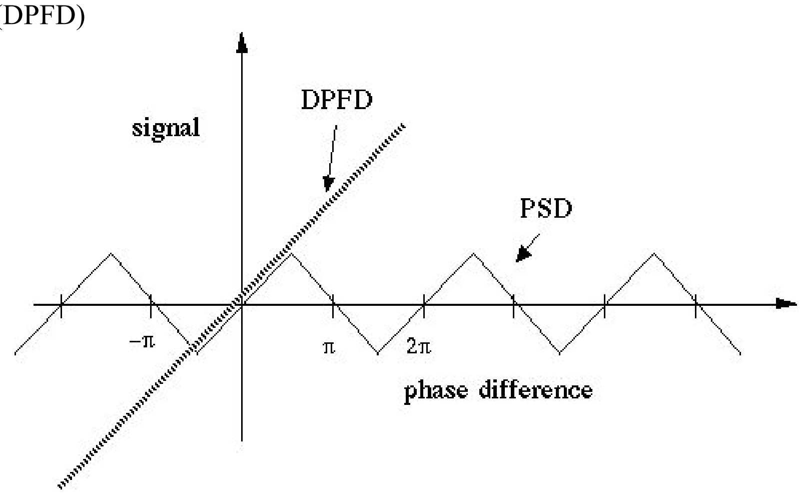

Figure.2: The phase error signals from PSD (solid trace) and DPFD (dotted trace)

counters (shown in fig.1.(b)), and the error signal from the DPFD is linearly proportional to the phase difference between the signals to and from the antenna whose linear range is limited by the bit number of the counters (dotted trace in fig.2). The wide linear phase discrimination range exceeding $\pm\pi/2$ radian permits the large rapid phase fluctuation while lock is maintained.

Experiments and results

Our FLSS consisted of a Michelson interferometer, and is shown in fig.3. The light source was an external-cavity laser diode (ECLD) with the wavelength of 1.542μm.

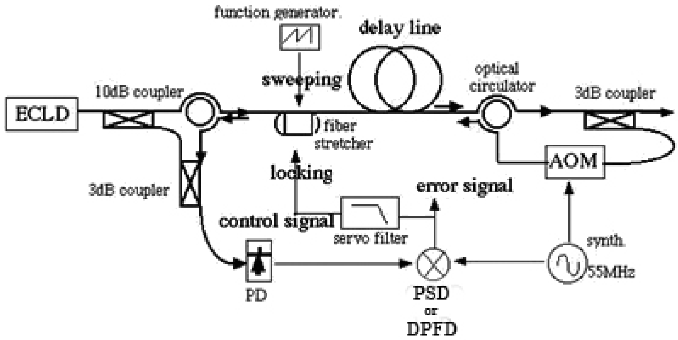

Figure.3: Schematic diagram of the fiber length stabilization system (FLSS). The fiber length can be swept by applying saw-tooth signal to the fiber stretcher, and the stabilization loop is closed when the control signal is applied to the fiber stretcher.

The linewidth of the ECLD was around 100 kHz, which corresponds to the coherent length of 3 km. The fiber-coupled laser light was divided into two by a 10-dB fiber coupler, and one light was used as a reference. After passing through a fiber stretcher and a long optical delay-line fiber, the received light at the end of fiber was frequency-shifted at 55 MHz by an acousto-optic modulator (AOM) in order to improve selectivity between the signals to and from antennas, and re-entered into the optical fiber by an optical circulator. The returned light through the optical delay-line fiber was recombined with the reference light with a 3-dB fiber coupler, and heterodyne beat note at 55 MHz was fed into PSD or DPFD.

Fig.4 shows a comparison of error signals from the PSD (a) and from DPFD (b), where the fiber length was swept by the fiber stretcher. The length of the optical delay line used in our measurements was 10m and 25km, which is shown in upper and lower figures. In the case of PSD, the S/N of the error signal became worse as the fiber length increased, and when the fiber length was 25km, the error signal was hardly distinguished from the noise. In the case of DPFD, on the other hand, the S/N of the error signal was not degraded as the fiber length became longer (the phase fluctuation at gray line was dominated by the fiber length fluctuation). It was proven that in the case of DPFD, the linewidth of the laser was not so critical as in the case of PSD for measuring the length fluctuation of the long fiber. This indicates that there is a possibility of relaxing a specification of the coherent length of the light source.

The optical fiber length was stabilized by applying the control signal from DPFD (fig.3) to the fiber stretcher. In the first experiment, shorter fiber delay-line (10m) was used. When the length correction servo loop was closed, the error signal was suppressed within 0.1 radian, and the temporal behavior of the fiber length fluctuation calculated from the control signal, and the fiber temperature are shown in fig.5(a) as black and gray traces, respectively. The fiber length correction servo was kept working without cyclic slip for more than 3 hours, and the fiber length fluctuation larger than 2.5 mm was suppressed.

The optical fiber used in this experiment was low thermal expansion fiber made by Furukawa Electric Co. Ltd., and the thermal expansion coefficient was measured to be

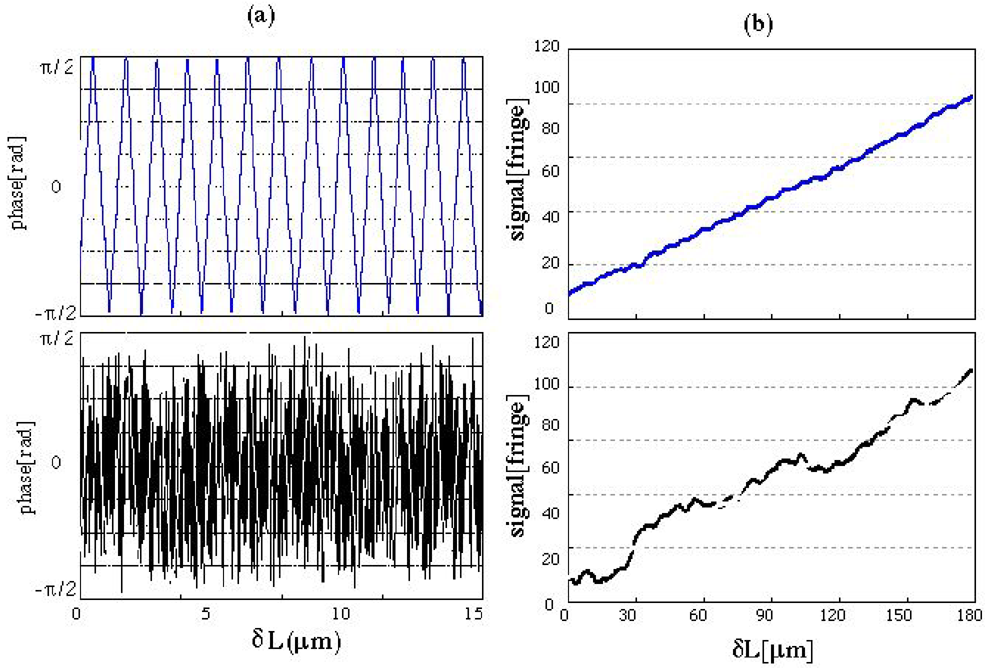

Figure 4: The error signals from (a) PSD and (b) DPFD. In both figures, the length of the fiber is 10m (upper case) and 25km(lower case).

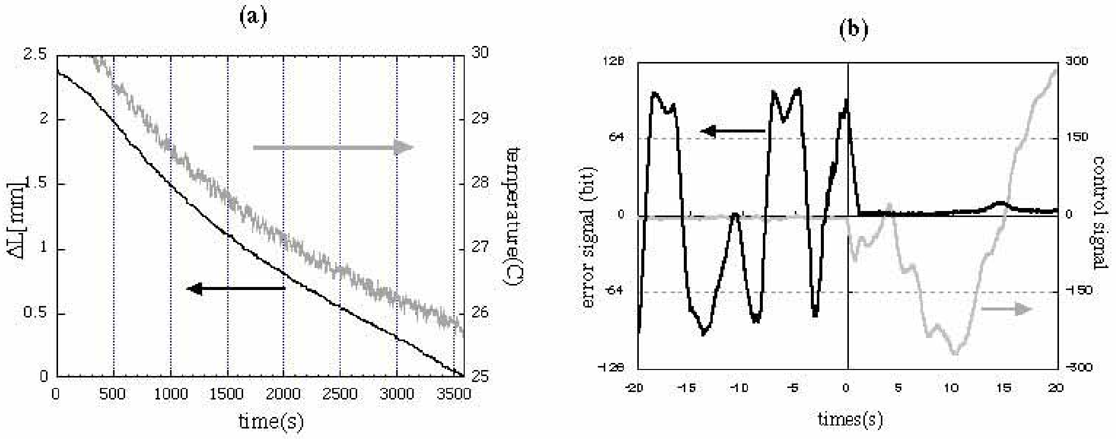

Figure 5: (a) The temporal behaviors of the fiber length fluctuation, which is calculated from the control signal (black trace), and the temperature of the fiber (gray trace). (b) The error (black) and control (gray) signal of the length correction servo at the fiber length of 25 km.

$\delta L/L=4.7\times10^{-6}$ /deg. Fig.5 (b) shows the error signal and control signal of the length correction servo at the fiber length of 25 km, (the length correction servo started on at the time of 0). The appropriate servo filter will improve the S/N of the error signal.

Conclusions

We have developed FLSS with the digital phase and frequency discriminator (DPFD). Compared with the conventional analog DBM or PSD, DPFD has much wider linear dynamic range in line length stabilization, which resulted in the stable operation of the fiber length stabilization system without cycle slips for more than 3 hours. This system can be operated with a light source whose coherent length is shorter than the fiber length, which relaxes the requirements for the laser linewidth. The bit number of the counters limits the linear dynamic range of the DPFD error signal, and the length fluctuation larger than 6mm can be measured by DPFD with 12-bit counters.

An alternative way of phase correction could be done offline (without mechanical servo system) if the linear discrimination range of DPFD is wide enough for measuring the fiber length fluctuation. The phase error could be corrected in the offline data calibration. This method avoids mechanical movements and is advantageous for long term stable operation.

References

[1] L.D'Addario, S.A.Banna, B.Shillue, M.Ishiguro, A.Ueda, K.Nalagawa, M.Musha, ALMA-memo No.445

[2] J.L.Hall, M.Long-Sheng, G.Kramer; IEEE J.of Quantum Electron. 23 (1987) pp.427

[3] M.Prevedelli, T.Freegarde, T.W.Haensch; Appl. Phys. B60 (1995) pp.241