Photonic Millimeter-wave generation and transmission system applicable to the high-frequency Radio Interferometers

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***Abstract*— In the field of high-frequency radio interferometer, Atacama Large Millimeter/sub-millimeter Array (ALMA), its highest receiving frequency reaches 950 GHz. To receive such high frequencies, a higher reference frequency is required (as much as over 100 GHz). To maintain signal coherency, this reference signal has to be highly stable. To address these issues, we have developed a new method to generate and transmit a reference signal in the form of frequency difference between two coherent light waves. The two transmitted optical signals require phase stability better than 10^{-13} (1sec) in white phase noise in the Allan standard deviation.**

I. Introduction

One method to generate two optical signals is producing them from a pair of laser sources using optical phase lock loop for feed back control, however, optical phase lock loop has a stability problem in its operation. A good alternative method to the optical phase lock scheme is the lithium niobate ($LiNbO_3$) Mach-Zehnder optical intensity modulator which is capable of generating two highly stable optical signals (upper sideband and lower sideband components) by applying a sinusoidal microwave signal to an input laser signal. Compared to the current optical phase lock scheme, the Mach-Zehnder modulator has significant advantages in terms of stability (free from the influence of the input laser line-width), robustness to mechanical vibration and acoustic noise, and capability of maintaining polarization state of the input laser. During the signal transmission through the fiber cable, the cable length delay fluctuation is caused together with polarization mode dispersion, which will impact the performance of coherent signal distribution. We have developed the phase stabilizer using the double difference round-trip phase measurement method with Michelson's interferometer. The roundtrip phase measurement is performed on each lightwave signal separately. The Round-trip phase measurement method is helpful for successful delay compensation of the microwave signal which is converted from the two coherent optical signals by a photo mixer.

II. Astronomical requirements

The modulation signal is transmitted via one optical fiber in the form of frequency difference between two coherent optical signals. These two optical signals are subsequently converted into millimeter-wave signal by the photo mixer. The region from 27 GHz to 122 GHz (Table I) is used for operational frequency for 10-band receivers. The two-tone generator requires polarization maintaining capability as well as mechanical vibration and acoustic noise robustness to avert the impact of the polarization effect on the photo-mixer and that of the polarization mode dispersion on the transmission fiber.

TABLE I
Required frequency range.

	Reference freq. range (GHz)	Local freq. range (GHz)
Band 1	27.3-33.0	27.3-33.0
Band 2	79.0-94.0	79.0-94.0
Band 3	92.0-108.0	92.0-108.0
Band 4	68.5-75.5	137.0-151.0
Band 5	87.5-99.5	175.0-199.0
Band 6	74.3-87.7	223.0-263.0
Band 7	94.3-121.7	283.0-365.0
Band 8	79.4-97.6	397.0-488.0
Band 9	102.3-118.0	614.0-708.0
Band 10	88.8-104.2	799.0-938.0

According to the system-level technical requirements of ALMA, the instrumental delay/phase error of the 1st Local system should be 53 fs in the short time period, and the difference between 10 sec averages at intervals of 300 sec should be 17.7 fs in RMS. When these values are converted to the Allan standard deviation using Equations (3), (4), and (5), it turns out that the noises are white phase modulation noise and flicker frequency modulation noise. The short time stability of white phase modulation noise is obtained Eq. (3): $\sigma_y(\tau = 1) = 9.2 \times 10^{-14}$. Calculating from Eq. (5) and 10 seconds averaging, the required stability is $\sigma_y(\tau = 1) = 1.56 \times 10^{-16}$ (flicker phase modulation noise) in the long-time period.

III. Photonic millimeter-wave generator

In the high-extinction ratio lithium niobate ($LiNbO_3$) Mach-Zehnder intensity modulator [1], [2], [3], the optical

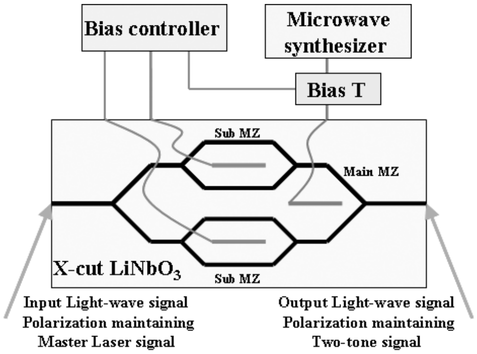

Fig. 1. Simplified structure of an optical modulator with two arms and electrodes. Optical phase of each arm is controlled by applying DC bias to the electrodes. Amplitude imbalance due to fabrication error is compensated with sub-Mach-Zehnder trimmers. When two lightwaves are in phase, the output optical signals are strengthened each other. On the other hand, when the phases of the input lightwaves are shifted, the phase-shifted lightwaves are radiated away as higher-order waves, and do not reach the optical waveguide. This is the main feature of the Mach-Zehnder modulator.

frequency difference between two optical signals is exactly twice (or four times) the modulation frequency, and the output signal is equivalent to FSK (frequency shift keying) spectrum. Compared to the optical phase lock scheme, the Mach-Zehnder modulator (shown in Fig. 1) has significant advantages in terms of robustness to mechanical vibration and acoustic noise, stability (free from the influence of the input laser line-width), and capability of maintaining polarization state of the input laser. The Mach-Zehnder modulator is so reliable that it has been used for optical submarine cables. The estimated lifetime of the Mach-Zehnder modulator extends to several decades.

The output spectrum depends on the DC bias voltage applied to the electrodes in the Mach-Zehnder structure. The Mach-Zehnder modulator has the following two operation modes.

A. Null-bias point operation mode

When the bias of the Mach-Zehnder modulator is set to a minimum transmission point (null-bias point), the first-order upper side band (USB) and lower side band (LSB) components are strengthened, and the carrier is suppressed (Fig. 2). The frequency difference between the two spectral components is twice the modulation sinusoidal signal frequency. As the spectral components generated by the optical modulation are phase-locked, it is possible to construct a robust system without using any complicated feedback control technique. However, as the modulation frequency is limited by the frequency response of the modulator, the frequency upper limit of the two optical signals can not be higher than 100 GHz in the null-bias point operation mode. For this reason, the null-bias point operation mode is suitable for the low-frequency application.

B. Full-bias point operation mode

When the bias is set to a maximum transmission point (full-bias point), the second-order USB and LSB are strengthened,

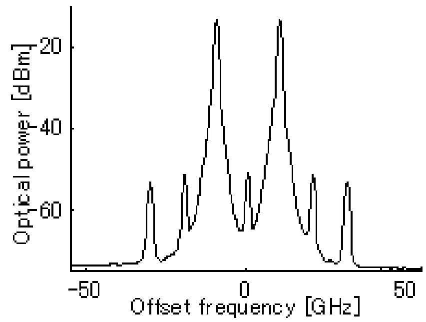

Fig. 2. When the bias of the Mach-Zehnder modulator is set to a minimum transmission point (null-bias point), the first-order USB and LSB components are strengthened, and the carrier is suppressed. The frequency difference between the two spectral components is exactly twice the modulation signal frequency. Each sideband signal spectrum shows a copy of the input laser spectrum. High carrier suppression ratio of 50 dB was demonstrated by the null-bias point operation mode using the integrated Mach-Zehnder modulator with an intensity trimmer in each arm (sub-Mach-Zehnder interferometer).

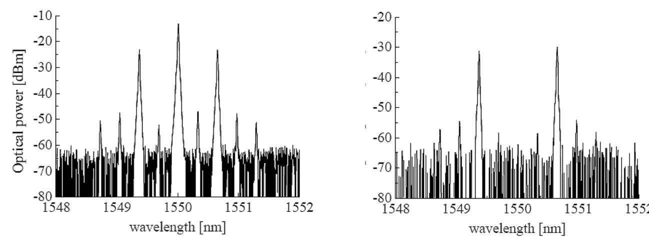

Fig. 3. When the bias of the Mach-Zehnder modulator is at full-bias point, the odd-order sideband components are suppressed. In this case, the optical frequency of even-order (zero- and second-order) components is remained (left chart). Eliminating the zero-order component (carrier: input lightwave), the remaining is a two-tone optical spectrum whose frequency is four times the modulation frequency (right chart).

and the carrier is not suppressed. If the extinction ratio of the Mach-Zehnder modulator is high, undesired odd-order USB and LSB components can be successfully suppressed with this technique. When the odd-order sideband components are suppressed in this mode, the optical frequency of even-order (zero- and second-order) components is remained (Fig. 3 left side). Eliminating the zero-order component (carrier), the remaining is a two-tone optical spectrum whose frequency is four times the modulation frequency or $4fm$ (fm is the modulation frequency of the RF signal applied to the modulator). The frequency difference between the zero-order and second-order components is $2fm$. When $4fm > 50$ GHz, the frequency difference is large enough that the zero-order component can be eliminated with a conventional optical filter (Fig. 3 right side). The optical signal filtered by the optical filter is amplified by an optical amplifier. At this point, the first-order components are suppressed by the Mach-Zehnder modulator with high extinction ratio to prevent undesired spurious signals.

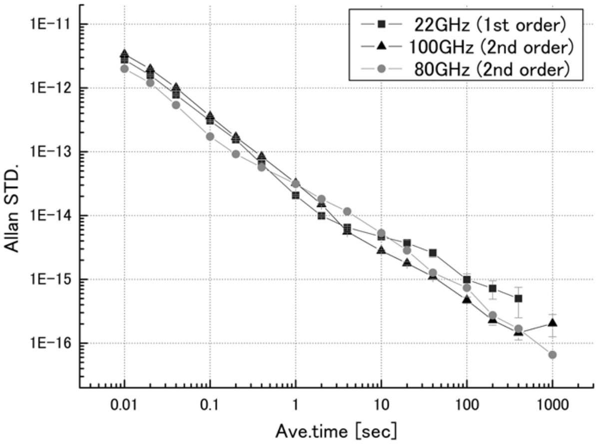

Fig. 4. Measured phase stabilities of the Mach-Zehnder modulator, the first-order 22 GHz signal and the second-order 100 GHz signal.

C. Measured phase stability

Phase stability of the Mach-Zehnder modulator measured using the Allan standard deviation is shown in Fig. 4. The stability is independent of the input laser line-width, the input lasers are a DFB-laser (10 MHz line-width) and a fiber-laser (1 kHz line-width).

D. Estimated coherence loss

Measured phase noise of the Mach-Zehnder Modulator is $\sigma_y(\tau = 1) = 2.4 \times 10^{-14}$. In the phase modulation noise case, the coherence loss due to the phase noise will be constant, because the loss due to white phase modulation noise is independent of integration time.

IV. Round-trip phase stabilizer

In the field of high-frequency radio interferometers, there is a growing need for the photonic highly-stable signal generation and distribution system,[5], [6], [7]. Figure 5 shows the basic concept of the round-trip phase stabilizer[8] for the two coherent-optical-signals. Under the effect of polarization mode dispersion (PMD) [9], [10], [11], the transmission line lengths (the length of the signal path in the optical fiber cable) are different between the two coherent-optical-signals which are transmitted as a set.

The phase of these signals (λ_1 and λ_2 in wavelength) at the starting point of the roundtrip transmission is assumed to be zero, and the phase of these signals which have returned to the starting point are obtained from the following equations: $[(2\pi m)+\phi_1]$ for λ_1, and $[(2\pi n)+\phi_1+2\Phi]$ for λ_2, respectively, where m and n are integers and Φ is the variable which is controlled by a phase shifter. The signal phase at the middle point of the roundtrip transmission (at the other end of the fiber) can be expressed as follows: For λ_1, $(\phi_1/2)$: m is even or $[(\phi_1/2)+\pi]$: m is odd, and: For λ_2, $[(\phi_2/2)+\Phi]$: n is even or $[(\phi_2/2)+\pi+\Phi]$: n is odd. Therefore, the transmitted signal phase is $(\phi_1/2) - [(\phi_2/2) + \Phi]$ or $(\phi_1/2) - [(\phi_2/2) + \Phi] + \pi$. If we adjust the phase Φ as follows;

$$\phi_1 = \phi_2 + 2\Phi. \quad (1)$$

the signal phase at the antenna is the same as or just π different from the signal phase at the starting point of the roundtrip transmission.

A. Round-trip optical double-differential phase measurement scheme

The basic configuration of the system is shown in Figure 6. Signals generated by the two coherent-optical-signals generator[3],[4] are sent to the antennas from the base-station (ground unit), together with PMD caused by the rotation and coupling of the fiber cross section signals. At each antenna, frequency-shift modulation (ϕ_{PLO}, angular frequency is ω_c) is performed by the Acoust-Optics frequency shifter for the received optical signals which are then reflected by the optical reflector and returned to the shifter. The signals pass through one path in transmission. The frequency shift modulation is used to distinguish the round-trip signal from back-scattered signals. The phase difference between the signal at the starting point of the roundtrip transmission and the returned signal is detected by Michelson's interferometry to perform correlation of the orthogonal signals which are generated by a 90-degree phase shift of $2\omega_c$ (50 MHz). These orthogonal signals are not required for the phase-lock to the modulation signal at the antenna. Since the modulation frequency ($2\omega_c$) is small, its PMD (the second order PMD) can be ignorable (the estimated deviation value is shown in the next subsection). The round-trip phase measurement method is helpful for successful delay compensation of the microwave signal which is converted from the two coherent-optical-signals by a photo mixer.

In this method, a Faraday-reflector or a mirror both can be used as the reflector at the antenna. In the case of the Faraday reflector, The route of the transmitted and return of light are not completely corresponding. This difference becomes a fixed phase offset. However, the change of the phase offset can be compensated by the phase locked loop. The fixation phase offset does not influence the transmitted phase stability. In the case of using the Faraday rotator and a polarization splitter, it becomes advantageous with respect to the carrier noise ratio. The influence such as back-scattering can be reduced by separating polarization.

B. Laboratory Tests

A block diagram of the performance measurement system is shown in Figure 7. A set of the two coherent-optical-signals generated is divided into two signals: one is transmitted to the phase stabilizer system and the other to the photo mixer (Nippon Telephone and Telegraph (NTT) unitraveling-carrier photo-diode[12],[13]) as a reference signal. The signal passes through a 10-km Single-Mode Fiber cable with/without the phase stabilizer.

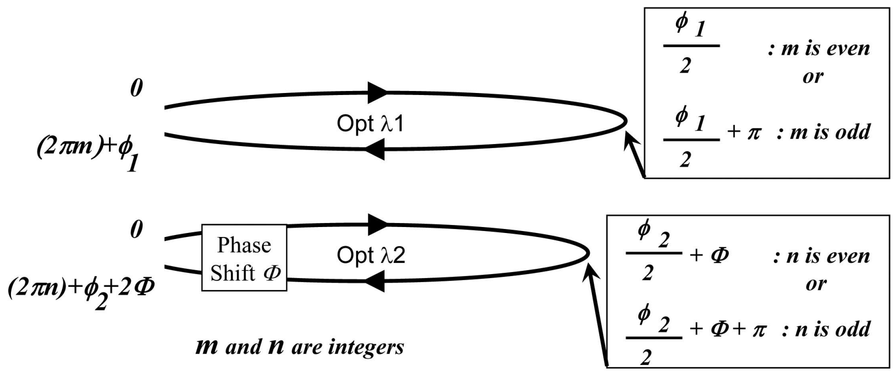

Fig. 5. Basic concept of the round-trip phase stabilizer. The two coherent-optical-signals (λ_1 and λ_2) are transmitted in one single-mode-fiber. Under the effect of PMD, the transmission line lengths (the length of the signal path in the optical fiber cable) are different between the two coherent-optical-signals. The effect of PMD will be expressed in this figure.

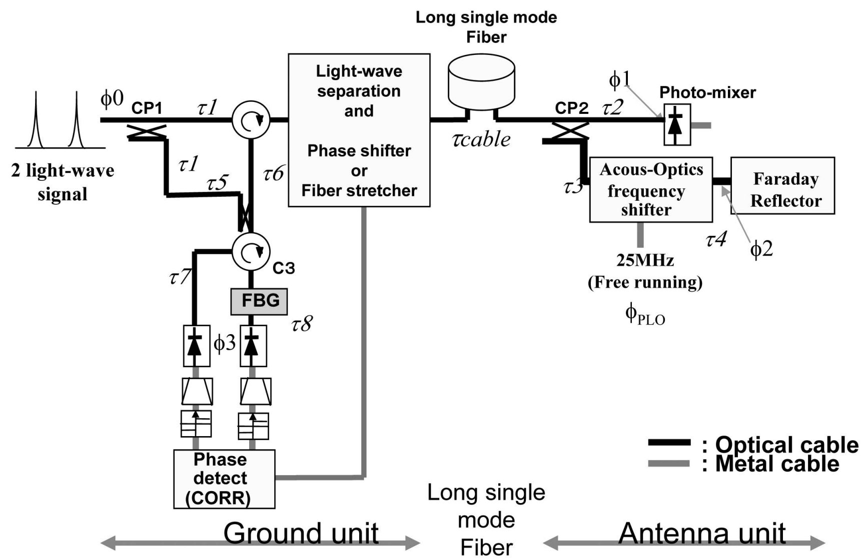

Fig. 6. The round-trip optical phase measurement scheme of the round-trip phase stabilizer.

We measured the phase stability (Fig. 8) of the transmitted signal (80 GHz) at the antenna through the single mode fiber cable (10 km) in the time-domain Allan STD method[14],[15] by a time interval analyzer: TSC-5110A. The measurements were conducted with/without the phase stabilizer to check the improvement of the phase stabilizer in the interferometric system.

When the optical signal (80 GHz) is transmitted through the single mode fiber cable (10 km), the phase stability begins to degrade around 10 seconds integration time. In the case of using the phase stabilizer, the degradation of the phase stability is staved off. The measured phase noise is the white phase noise.

1) Verification results: In the ALMA Specification, instrumental delay/phase error on the 1st Local oscillator should be 53 fs (rms) in the short term, and long term drift should be 17.7 fs between 10 sec averaging at intervals of 300 seconds. On the other hand, in the very long baseline interferometer [16], [17] (VLBI), the requirements of 320 GHz are as follows: $\sigma_y(1\ sec) < 2 \times 10^{-13}$, $\sigma_y(100\ sec) < 1.3 \times 10^{-14}$ and $\sigma_y(1000\ sec) < 3 \times 10^{-15}$.

The behavior of phase noise can be analyzed by the Allan standard deviation [14], [15]. The frequency instability is the frequency change induced by internal or external factors within a given time interval. In other words, the frequency instability is defined as the degree to which the output frequency remains

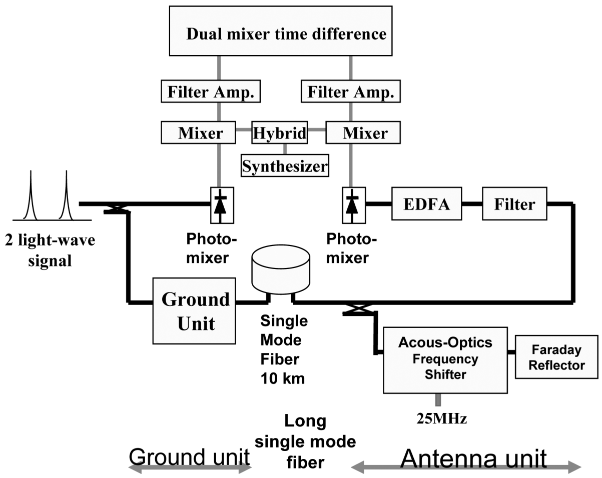

Fig. 7. A block diagram of phase stability measurement system. The signal is provided from the two coherent-optical-signals generator.

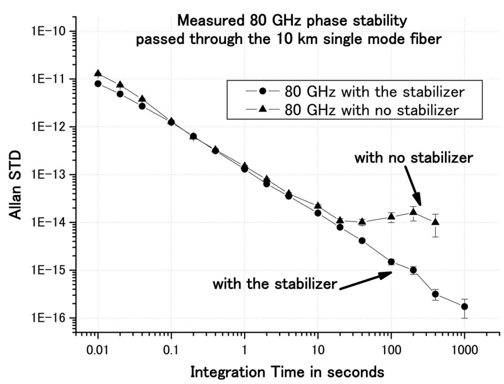

Fig. 8. The 80 GHz phase stability that passed through the 10 km fiber. The phase stability begins to degrade around 10 seconds integration time. In the case of using the phase stabilizer, the degradation of the phase stability is staved off.

constant over a specified period of time.

Noises are classified into the following five types according to the noise generation mechanism: white phase modulation noise (τ^{-1}), flicker phase modulation noise (τ^{-1}), white frequency modulation noise ($\tau^{-1/2}$), flicker frequency modulation noise (τ^{0}) and Random Walk frequency modulation noise ($\tau^{1/2}$) [18]. Some of these noises are generated by electronic equipment or by changes in the environment (such as temperature change).

The coherence loss due to the instability in the frequency standard for *T-sec* integration times is estimated Eq. (2) [16], [17], [19].

$$L_c = \omega_o^2 \big[\frac{\alpha_p}{6} + \frac{\alpha_f}{12} T + \frac{\sigma_y^2}{57} T^2 \big] \quad (2)$$

where

TABLE II
VERIFICATIONS MATRIX.

ALMA Specifications	Measured Values
53 fs (rms) in short-term 17.7 fs in long-term	42 fs (short) 13 fs (long)
Required Phase stability for VLBI $\sigma_y(1sec) < 2 \times 10^{-13}$ $\sigma_y(100sec) < 1.3 \times 10^{-14}$ $\sigma_y(1000sec) < 3 \times 10^{-15}$	Measured Phase stability $\sigma_y(1sec) < 7.3 \times 10^{-14}$ $\sigma_y(100sec) < 1.79 \times 10^{-15}$ $\sigma_y(1000sec) < 2.29 \times 10^{-16}$

L_c the loss of coherence,
ω_o the angular frequency of local oscillator,
α_p the Allan variance $[(standard\ deviation)^2]$ of white phase noise at 1 sec,
α_f the Allan variance $[(standard\ deviation)^2]$ of white frequency noise at 1 sec,
σ_y^2 the constant Allan variance $[(standard\ deviation)^2]$ of flicker frequency noise,
T the integration time [sec].

Coherence loss and time error are calculated by the Allan standard deviation. One of the stability measurement methods in time domain is the Dual-Mixer Time Difference (DMTD) method [15] which is adopted by NIST (National Institute of Standards and Technology, USA), NICT (National Institute of Communications and Technology, Japan) and other time/frequency standard institutes. Using this method, the phase stability of a device-under-test can be obtained without influence of unstable local frequencies of the measurement system. The Dual-Mixer Time Difference method allows time measurements and frequency and frequency stability measurements for sample times as short as a few milliseconds or longer without dead time. Moreover, the phase noise in the measurement system can be canceled out with this method.

The total system instability is calculated by RSS (root sum square) of the Allan standard deviation of each component. Time error of phase noise is calculated as follows:

$$Time\ error = \frac{T \times \sigma_y(T\ sec)}{\sqrt{3}}$$

$$= \frac{\sigma_y(1\ sec)}{\sqrt{3}} \quad (3)$$

$$in\ white\ Phase\ Modulation\ noise$$

$$= \frac{\sigma_y(1\ sec)}{\sqrt{T}} \quad (4)$$

$$in\ white\ Frequency\ Modulation\ noise$$

$$= \frac{T \times \sigma_y(1\ sec)}{\sqrt{\ln 2}} \quad (5)$$

$$in\ flicker\ Frequency\ Modulation\ noise$$

The verifications matrix is shown in Table II. The measured values meet the ALMA specifications.

V. Conclusion

Based on our experiment results, we propose a new high carrier suppression optical double-sideband intensity modulation technique using the integrated $LiNbO_3$ Mach-Zehnder modulator which is capable of compensating the imbalance of the Mach-Zehnder arms with a pair of active trimmers (null-bias operation mode). The full-bias point operation mode introduced in this paper is also a novel modulation technique for the second-order harmonic generation. The Mach-Zehnder modulator can generate two coherent light waves with frequency difference equivalent to four times the modulation frequency. Photonic local signals of 120GHz can also be generated using this technique.

The two spectral components of the two optical signals generated with this technique are phase-locked without using any complicated feedback control. All of the measurements were carried out on a table (without vibration isolation) in a normally air-conditioned room without acoustic noise isolation. In short, all of the measurements were performed under normal environment. Temperature change and mechanical vibrations may have affected the output lightwaves to some degree, however there was no chaotic phenomenon such as mode hopping or mode competition during the experiments. Based on these results, we concluded that the proposed techniques will be useful to construct a robust, low-cost and simple setup for the photonic local signals.

Compensation of the Local signal transmission delay is an indispensable technique for accurate interferometrical observation. PMD delay, which is caused during the signal transmission, needs to be reduced because it deteriorates the accuracy of the delay amount by affecting the signal polarization and wavelength. The two coherent-optical-signals generator [3], [4] is required to help stabilization of polarization, and to maintain the high extinction ratio, and to keep the signal state of polarizations in stable condition for preventing the delay generation.

We proposed the double difference phase measurement method. The method is also available to use the fiber stretcher instead of the phase shifter. The Double-difference method is more robust to external influences and more accurate than the current scheme which uses one of the two optical signals for measurement. This method can reduce deterioration in the signal phase stability caused by the long fiber signal transmission.

The performance advantages of the system are:

1) The modulation signal (ω_c) transmission and its phase compensation are not required (the modulation signal on the antenna is generated by a free-running oscillator);
2) External noise (acoustic noise, vibration noise) on the long single mode fiber cable is dealt with a common noise; and
3) The PMD problems are reduced, as the round trip delays on the two optical signals are measured and compensated independently.

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