Polarization Mode Noise in Ultra-low Drift Phase Reference Distribution System over a Fiber Network

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***Abstract* — The impact of polarization mode noise on the temporal drift of a delivered analogue phase reference signal through an optical fiber network is studied. The relationship between the dispersion of the state of polarization, change of the state of polarization and the maximum temporal drift of the LO signal is established. The resulting temporal drift can be larger than the PMD value of the receiver under certain conditions. It is a significant contributor to the temporal drift in the ultra-low drift phase reference distribution system, especially when motion of the fiber has to be present in the system.**

***Index Terms* — Optical fiber, phase reference, phase drift, polarization mode dispersion, analogue signal, state of polarization dispersion, state of polarization change**

I. INTRODUCTION

Optical fiber has advantages of flexibility, broadband and low loss transmission performance. When environmentally isolated, the stability of fiber cable is considerably greater than open-air paths. Hence, fiber networks can be widely used in transmitting frequency standards and timing signals [1-3]. In many applications, a high quality analogue continuous wave (CW) signal must be generated at a central site and then delivered to different remote sites through the optical fiber distribution network. Such distributed local oscillator (LO) signals require very high temporal stability, especially for millimeter/submillimeter wave applications. For instance, the photonic LO distribution network in ALMA [4] requires an LO signal at a frequency up to 142 GHz to be delivered over 16 km of fiber with a stability of better than 12 fs over any period of 300 seconds (measurement interval). Furthermore, this requirement applies when the antennas are being re-oriented.

The phase jitter of the delivered LO signal is usually dominated by jitter from the photonic LO generator [3,5], while lower frequency phase drift includes contributions from the LO generator and from the delivery system. In a typical photonic LO distribution system, the delivery fibers must be well insulated from environmental acoustic noise and large thermal changes. These delivery fibers are then followed by a moving joint, such as a fiber wrap, to allow the antennas to be rotated to the orientation of interest (Fig. 1). A photoreceiver at the antenna will convert the distributed photonic LO signal to the electrical LO signal. To achieve high temporal stability over long distances, the length of the fiber has to be actively controlled by Line Length Correction (LLC) schemes [3]. By using a highly stable narrow linewidth laser and fiber stretcher, the effective fiber length can be controlled to a fraction of the optical wavelength, thus providing excellent stability. However, the system stability can suffer signification degradation if any delivery fiber outside of the LLC loop suffers temperature change or varying tension. It is desired that the LLC is extended as close as possible to the receiver, and must include the antenna wrap where the fiber will be under variable tension.

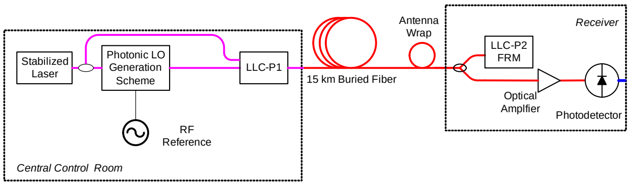

Fig. 1 Simplified System Setup of the Photonic LO Distribution System with a Fiber Wrap to Allow the Antenna Rotation. LLC-P1 and LLC-P2 stands for different parts of the Line Length Correction scheme. For details see reference 3.

As the length of the delivery fiber, including the part of the fiber wrap, is locked, one may assume that its effective length does not change, and therefore does not contribute to the phase drift. However, the true propagation time for the light in the fiber is determined not only by the physical length and the effective refractive index of the fiber, but also by the input polarization of the light and the Polarization Mode Dispersion (PMD) vector of the fiber. Although it is known that PMD in the delivery fiber and also in the photoreceiver play a role in the propagation delay in the system, the true effect has not been well analyzed for analogue LO signals. This paper will focus on these effects to study the limits on temporal drift placed by polarization mode noise.

II. STATE OF POLARIZATION DISPERSION

Polarization Mode Dispersion (PMD) has been long recognized as one of the major limiting factors in modern optical communication systems. Its influence on the digital signal transmission system has been extensively studied, often in the field of pulse spreading. Unlike chromatic dispersion, the influence of PMD on a

CW system is not just the introduction of a fixed phase bias.

Due to the random mode coupling between different sections of the single mode fiber, the State of Polarization (SOP) at the output of the delivery fiber can take an arbitrary state on the Poincare Sphere. For a well insulated buried fiber and stable input, the output SOP does not change over short time scales. When the LO frequency is much less than the bandwidth of the Principle States of the Polarization (PSP) of the fiber, the precession rate of the SOP around the PSP is given by

$$\frac{d\underline{S}}{d\omega} = \underline{\Omega} \times \underline{S} \tag{1}$$

where $\underline{S}$ is the output SOP vector, $\underline{\Omega}$ is the PMD vector, and ω is the angular optical frequency.

State of Polarization Dispersion (SOPD) is defined by the SOP angle difference between the wavelengths on the Poincare Sphere. The origin of SOPD could be the SOP misalignment in the photonic LO source, or purely due to the PMD in the fiber distribution network. In our analysis we assume that the SOPD from the source is zero, i.e. there is perfect polarization alignment between the wavelength components in the photonic LO source. The maximum SOPD can then be estimated by

$$SOPD = DGD_{\lambda} \cdot \Delta\omega \tag{2}$$

where DGD_{λ} is the differential group delay (DGD) at the local wavelength λ, and $\Delta\omega$ is the angular frequency difference between the wavelength components in the photonic LO source.

It can be shown that if detected by an ideal photodetector, the SOPD induces power degradation in the LO power by

$$\zeta_{SOPD} = \left(\cos\left(\frac{SOPD}{2}\right)\right)^2 \tag{3}$$

For a 16 km long fiber link with PMD coefficient 0.05ps/km$^{1/2}$, we can estimate that the SOPD for a 142 GHz dual laser signal [3] is between 0 to 0.535 rads, for all but half-an-hour in one year (statistically). This leads to a maximum power degradation of 0.31 dB. Increase in the PMD in the link will directly increase the maximum SOPD and reduce the efficiency. This effect will well certainly limit the maximum distance that the LO signal can be distributed directly.

Although the PMD value of the fiber varies randomly with time and external perturbations, and the DGD at a particular wavelength can change even more rapidly, these are still relatively stable for a buried fiber link.

III. STATE OF POLARIZATION CHANGE

When the fiber is under external perturbation the SOP of the output will change. A good way to describe this change is to use a State of Polarization Change (SOPC). The SOPC is defined as the angular change between the SOPs at the end and at the beginning of a measurement time.

$$SOPC = \arccos\left(\frac{\underline{S_{t1}} \bullet \underline{S_{t2}})}{\underline{S_{t1}} \cdot \underline{S_{t2}}}\right) \tag{4}$$

In the system, most of the SOPC will come from the movement of the fiber wrap during the 300 s measurement interval. The motion of the single mode fiber inside the wrap will result in only small local DGD change, yet still enough to change the output SOP completely (thus the SOPC is random between 0 to 2π). On the other hand, as the fiber wrap is located at the end of the transmission system, the polarization change will not result in variation of the input PMD vector or of the magnitude of the DGD for the whole fiber link.

Optimal design of the fiber wrap to reduce the SOPC is possible. By experiment we have found that bend-only wraps seem to provide the best performance in terms of reduced SOPC while the antennas rotate. It is estimated that SOPC of better than 0.14 rads can be achieved.

IV THE PMD OF THE PHOTORECEIVER

The photoreceiver may consist of an optical amplifier, optical isolators and a high speed photodetector. None of these components, including the optical fiber can be assumed birefringence free. Since the SOP from the delivery system is not necessary linear, and also suffers SOPC, the photoreceiver can not be made using PM components. Generally speaking, the optical isolators, which are essential to stop the reflections from the photodetector, are responsible for most of the PMD of the photoreceiver. PMD values for the receiver will typically be of the order of a few hundreds fs. The PSP of the receiver is random, but remains fixed in time. The magnitude of the DGD of the receiver is flat over a wide wavelength range, due to the limited number of birefringent sections, and the dominance of the optical isolator.

V ANALYSIS FOR THE POLARIZATION MODE NOISE IN THE RECEIVER

Since it is assumed that the system has a perfect LLC and also perfect insulation of the buried fiber, the light entering the fiber wrap can be assumed to be constant during each period of the measurement interval. Therefore, the SOPD caused by the buried fiber can be emulated by a polarization misalignment between the two lasers, as shown in Fig. 2. This SOPD in the photonic LO generator will create a fixed phase bias, but does not change in time as long as the SOPs of the lasers remain unchanged. The fiber wrap basically is a short piece of single mode fiber without sharp bending. It can be represented by a polarization transformer which responds similarly to all wavelengths because of its low PMD. The fact that the wrap is situated within the LLC loop makes the polarization rotator a good way of representing the fiber wrap function. The PMD receiver can be represented by a waveguide with PMD followed by an ideal photodetector.

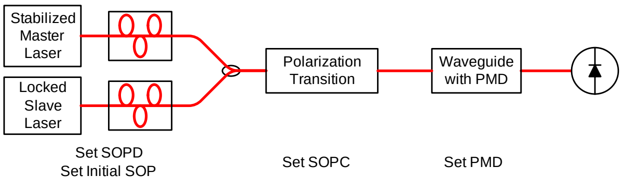

Fig. 2 Representation of optical components in the system used for the analysis

The Jones Vector of the two wavelengths at the input to the receiver is known as a function of the rotation angle of the polarization rotator. The lightwaves are then decomposed into two modes along the two PSPs of the receiver. Because no mode coupling occurs between the orthogonal PSPs, the components along the two PSPs are assumed to propagate independently of each other, and to emerge from the waveguide still orthogonal to each other. There is no beating between the components which are along the two PSPs. When detected at the photodetector, the components in the two PSPs beat separately, resulting in two beat signals with the same frequency. The overall beat signal is the vector sum of the two.

Due to the DGD of the waveguide, the two PSP modes suffer differential group delay as set by the PMD value of the waveguide. As we know the properties of the beat signals of the components before the waveguide (corresponding to the case of detection in an ideal receiver), and know the influence of the waveguide on these components, we are able to determine the phase of the detected signal. The phase drift is obtained by the changes in the phase difference between the detected signal and the reference signal (detected by a PMD free receiver) when the angle of the polarization rotator is varied.

The worst case is found when the SOPs of the two wavelengths are moving on the same great circle as the PSPs of the receiver on the surface of the Poincare Sphere. An analytical result is shown in Fig. 3, where the LO signal is set at 100 GHz and the PMD of the receiver is 200 fs. The SOPC changes from $-\pi$ to π, corresponding to a full SOP rotation on the Poincare Sphere. The different curves correspond to cases of the SOPD varying from 0 to 2 radians, at a gradient of 0.2. Apparently when the SOPD increases to a value greater than the 0.8 rads, the maximum temporal drift and the maximum temporal drift rate begin to increase significantly. For a small SOPC, the worst case corresponds to the case in which the frequency average SOP is at quadrature with the PSPs. A good approximation to describe the maximum temporal drift due to a small SOPC when the SOPD is kept to less than 0.8 rads (45 degree) is given by

$$0.55 \cdot DGD_R \cdot \sin(SOPC) \qquad (5)$$

where DGD_R is the DGD of the receiver.

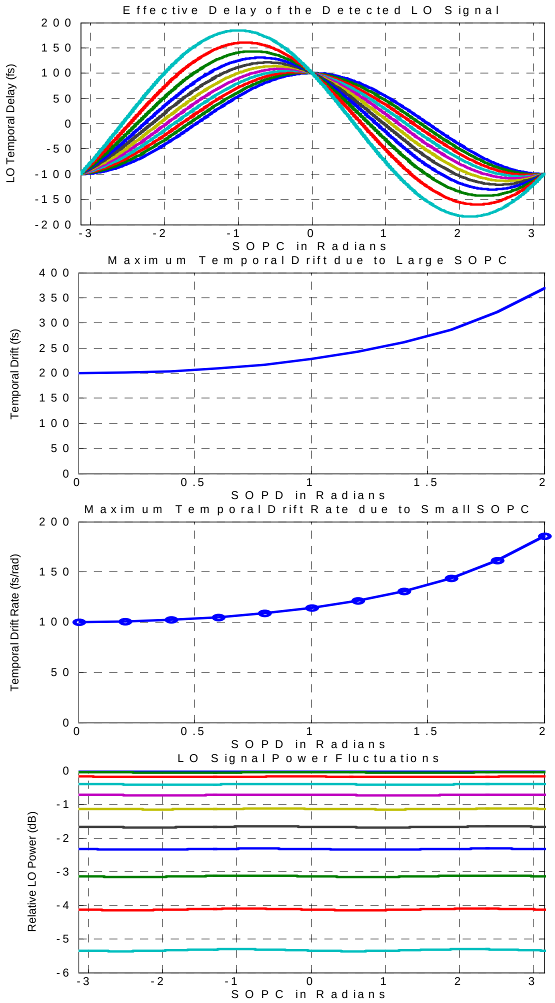

Figure 3. Analytical results of the polarization mode noise of a 100 GHz Photonic LO distribution system. The system has a receiver with a DGD value of 200 fs. All the results shown are corresponding to the worst case.

VI. NUMERICAL SIMULATION RESULTS

Numerical models have also been developed. The simulated system configuration is presents in Fig. 4. The SOPs of the two lasers are set to be in perfect alignment in the 3 dB coupler. Fiber models describing the chromatic dispersion and polarization mode dispersion are developed and used in the simulation. At the output from the fiber, the polarization is randomly distributed on the surface of the Poincare Sphere. The SOPD is also a random quantity governed by the PMD of the fiber. The fiber wrap is simulated by a section of fiber with constant effective length. Part of the fiber forms a loop (1.5 cycle). The radius of the fiber loop varies from 0.1 m to 0.03 m in the simulation, which introduces the SOPC.

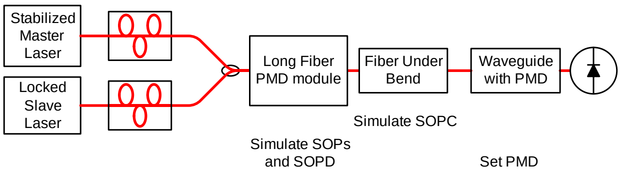

Fig. 4 Block diagram of the numerical model

Fig. 5 shows the simulated LO phase variations. Altogether there are 525 iterations. Within each iteration, the distribution fiber remains the same but the fiber wrap changes its radius from 0.1 m to 0.03 m. This corresponds to the case that within measurement time, the buried fiber is stable, resulting a fixed SOPD and polarization. In between the iterations, the distribution fiber is different, corresponding to the long-term evolution of the PMD in the fiber. The simulation shows that the LO signal drift is almost always within the range of -100 to + 100 fs, with only a few exceptions, and even the exceptions are very close to ±100fs.

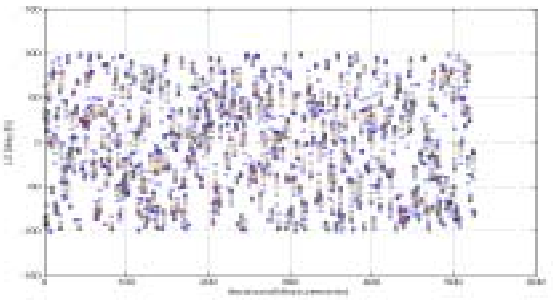

Fig. 5. The recorded LO delays from the numerical simulation

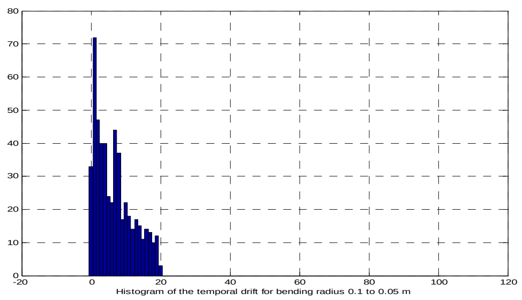

Fig. 6. Histogram of the temporal drift in the simulation

The temporal drift within each of the iterations is limited. This represents the temporal drift of the LO signal due to the SOPC which is originated from the movement of the fiber wrap. For the full wrap range, a maximum drift of 48 fs is observed. Fig. 6 shows the histogram of the drift where the fiber wrap is only bent from 0.1 m to 0.05m. In this case, a maximum SOPC of 0.4 rads is expected in the wrap. Therefore, according to equation (5), we could expect a maximum temporal drift of 21.4 fs should the SOPD from the fiber reach its extremes. For the 525 iterations, the histogram shows that a maximum temporal drift of 20 fs is reached, which is in good agreement with the prediction. Meanwhile the histogram also shows that it is possible to have very small temporal drift in the same system. Therefore, due to the PMD evolution in the buried fiber, the temporal drift may change from time to time from zero to the maximum value predicted.

The simulation also shows that the wrap itself will introduce a very small temporal drift of less than 0.2 fs. This is believed due to the PMD changes in the fiber wrap.

VII. Conclusion

We have shown the significance of the polarization mode noise in a phase reference system with femto second order stability. The maximum temporal drift of the reference signal is affected by the SOPD and SOPC of the input photonic LO signal, as well as the PMD of the photoreceiver. Furthermore, the temporal drift is not very sensitive to the delivery frequency providing the SOPD is less than 0.8 rads, but is proportional to the PMD of the photoreceiver. The SOPD as a result of the PMD of the long fiber can potentially increase the maximum temporal drift due to polarization mode noise to a level that is greater than the PMD of the receiver. Good insulation of the fiber cable and an optimized fiber wrap design are required to reduce the SOPC in such a system.

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