Optical Delivery of Millimetre-Wave Reference Signal to Remote Sites

J. Estève, P. Shen and N. J. Gomes

Photonics Group, Department of Electronics, University of Kent, Canterbury CT2 7NT, UK.
Email: je25@kent.ac.uk, p.shen@kent.ac.uk, n.j.gomes@kent.ac.uk

Abstract: A millimetre-wave phase reference signal can be generated by heterodyning two laser frequency lines previously locked in phase. However, transmission through an optical fibre link may cause the power level and the phase stability of the reference signal to be degraded due to dispersion problems. These effects are examined using the VPIphotonics™ simulation tool. Preliminary results show a non negligible power penalty due to dispersion phenomena (0.75 dB) as well as a consequent phase drift.

1. Introduction

The Atacama Large Millimeter Array (ALMA) will be a large radio-telescope array located in Chile. Its main purpose will be to observe signals from space over a wide band of frequencies (30 – 950 GHz) with unequalled accuracy. In order to achieve this, ALMA will be made up of sixty four 12m diameter antennas each working in phase: the interferometric mode. The phase reference signal has to remain synchronised when it reaches each of the antennas to allow correct recovery of the "picture" observed by all the antennas.

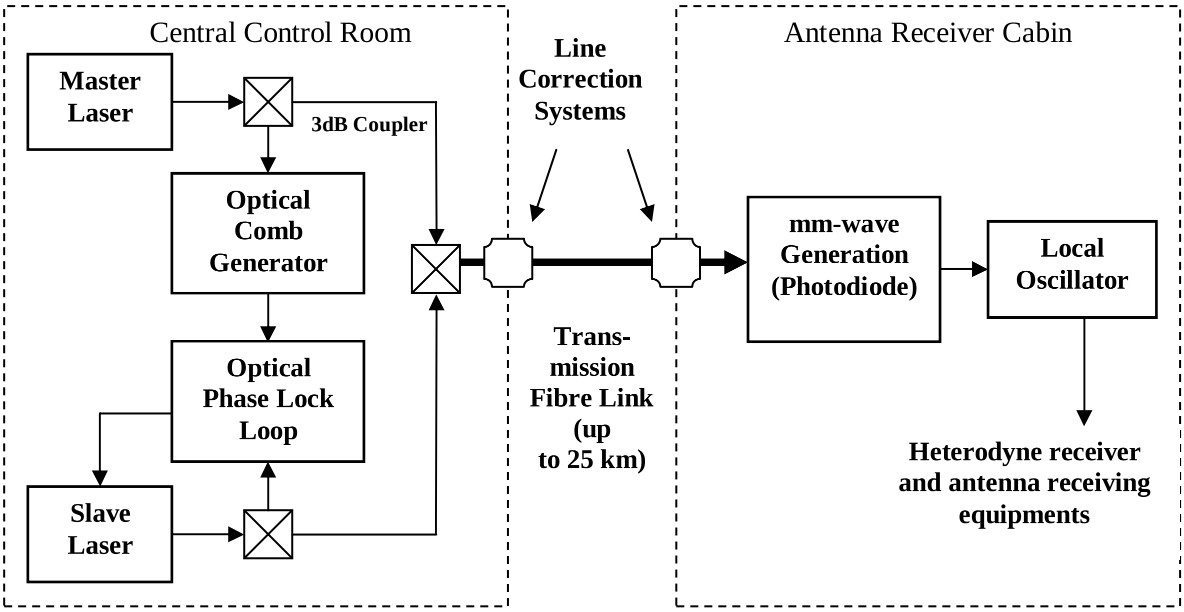

Figure 1: General ALMA phase reference signal generation and implementation.

The two laser frequency lines are separated by a tunable interval in frequency, proportional to the range of frequencies that will be observed by the radio telescope. The master laser is set at 1550 nm and the slave laser varies in a range of ±30-150 GHz compared to the master laser frequency [1]. Their location in the central control room is shown in Figure 1. The level of power detected at each of the antenna receiver cabins by the photodiode and from the transmission fibre link needs to be quantified in order to know if it will be sufficient to drive the receiving equipment (photodiode, SIS mixer). As attenuation and power splitting losses can be largely compensated by optical amplifiers, the detected power characterization in the transmission link will concentrate on the fibre birefringence, which causes non-optimum heterodyne detection of the two laser signals, and any related induced effects due to chromatic dispersion. If the birefringence leading to PMD and chromatic dispersion (CD) in the transmission link cause differential dispersion (delay) between the two laser signals, then the phase of the reference signal will be altered; this has to be evaluated and compared to the ALMA strict specifications.

The reference signal generation scheme and transmission path have been modeled and then simulated using the VPIphotonics™ package. This is a simulation analysis as an experimental method is under development in order to quantify the effects on the reference signal [2].

2. Theoretical Background

The background presented in this section is related to the VPI fibre simulation models [3]. The generalized nonlinear Schrödinger equation, used to describe the effects occurring during propagation in fibres, is:

$$\frac{\partial \underline{E}(z,t)}{\partial z} = [\underline{D} + \underline{N}] * \underline{E}(z,t) \quad (1)$$

where $\underline{E}(z,t)$ denotes the slowly varying complex envelope of the electric field of the light wave, $\left|\underline{E}(z,t)\right|^2$ characterised its power, $\underline{N}$ is the nonlinearity operator and $\underline{D}$ is the dispersion operator. The dispersion operator can also be written as:

$$\underline{D} = j\frac{\beta_2}{2} * \frac{\partial^2}{\partial t^2} + \frac{\beta_3}{6} * \frac{\partial^3}{\partial t^3} - \frac{\alpha}{2} \quad (2)$$

where:

$$\beta_2 = -\frac{\lambda_{ref}^2}{2\pi c} D_\lambda \text{ [s}^2\text{/m] (3) ,}$$

describes the first order group velocity dispersion (GVD) or chromatic dispersion, D_λ is the dispersion coefficient at the reference frequency.

$$\beta_3 = \frac{\lambda_{ref}^2}{2\pi c}(\lambda_{ref}^2 S_\lambda + 2\lambda_{ref} D_\lambda) \quad \text{[s}^3\text{/m]} \quad (4)$$

is the second order GVD or third order dispersion. It is related to the slope of the dispersion coefficient $S_\lambda = {dD_\lambda}/{d\lambda}$.

In order to model the variations of birefringence (due to changes in the refractive index of the core), the fibre is theoretically cut into many sections with constant birefringence. These are called scattering sections. The mathematical model for propagation within each section of birefringence is based on the modified nonlinear Schrödinger equations written for two orthogonal polarization components of the electric field. These polarization components correspond to the principal axes of polarization in the fibre section [3]:

$$\left[\frac{\partial}{\partial z} + \frac{\alpha_{fast,slow}}{2} + \beta_{1x,y}\frac{\partial}{\partial t} - j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial}{\partial t^3}\right] E_{x,y}(z,t) = -j\gamma\left[\left|E_{x,y}(z,t)\right|^2 + \frac{2}{3}\left|E_{x,y}(z,t)\right|^2\right] E_{x,y}(z,t) \quad (5)$$

where α_{fast} and α_{slow} are the slow and fast attenuation aligned with the x and y axes respectively. β_{1x} and β_{1y} [s/m] describe the GVD for the x and y polarization components respectively. Their values in each polarization scattering section depend on how the birefringence varies. If the birefringence varies randomly, then the values of β_{1x} and β_{1y} depend on the length of the scattering section z_{scatt}(which is randomly selected from a Gaussian distribution):

$$\beta_{1,x} = -\beta_{1,y} = \frac{D_{pmd}}{2\sqrt{z_{scatt}}} \quad (6)$$ where D_{pmd} is the PMD coefficient.

If the birefringence does not vary randomly, then the values of β_{1x} and β_{1y} do not depend on the length of the scattering section but on the value of the correlation length L_{corr} (distance over which the average power in the orthogonal polarization mode is within $1/e^2$ of the power in the starting mode):

$$\beta_{1,x} = -\beta_{1,y} = \frac{D_{pmd}}{2\sqrt{2L_{corr}}} \quad (7)$$

3. Experimental Setup

The simulation parameters have been set to match the SMF-28 fibre's characteristics [4]. These are: Reference frequency = $1.9354838*10^{14}$ Hz; Attenuation (α_{fast} or α_{slow}) = 0.3 dB/km; Dispersion = $1.735*10^{14}$ s/m^2; Dispersion slope = 92 s/m^3, D_{pmd} = 0.2 ps/km . From (7), $\beta_1 = 1*10^{-14}$ s/m, from (3), β_2 = $-2.21*10^{-35}$ s^2/m and from (4), β_3 = $6.855*10^{-41}$ s^3/m and thus can be considered as negligible. The scattering section is set to 200 m. The fibre length is varied from 1 to 25 km in the simulations. The "experimental" setup is shown in Figure 2; the initial optical comb generation has been replaced by a frequency shifter, which models the locked slave laser signal.

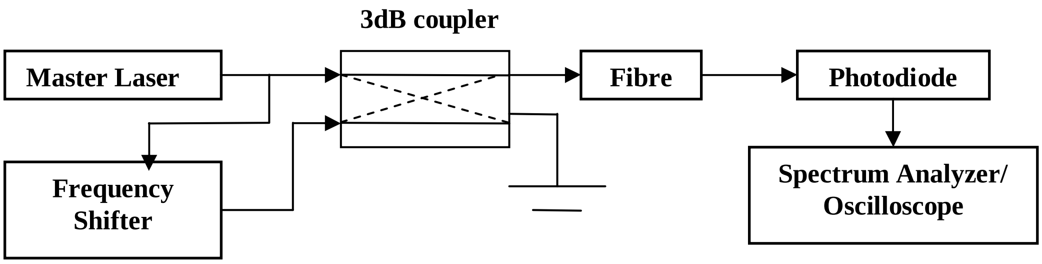

Figure 2: Test arrangement for VPI simulations.

4. Power Penalties Results

RF power has been measured for slave laser frequencies in a range of 1 to 150 GHz compared to the master laser frequency. Figure 3 shows that PMD's influence is characterized by a power penalty of 0.75 dB in the worst case. Moreover, its effect is more apparent at high slave laser frequencies and for certain distances of fibre: 10 to 21 km; it is almost insignificant for slave laser frequencies around 30 GHz and lower. From Fig.4, CD seems responsible for a power penalty of 0.11 dB in the worst case, much lower than the PMD effect, as expected since differential phase variations of the laser signal due to dispersion should not affect the RF power, only the phase of the detected RF signal. The PMD power penalty is due to birefringence causing a relative change in the state of polarization of the laser signals (the birefringence being the underlying cause of PMD). Further work is required to explain the observed variation of power penalty with the dispersion causing phenomena.

Figure 3: PMD RF power penalty.

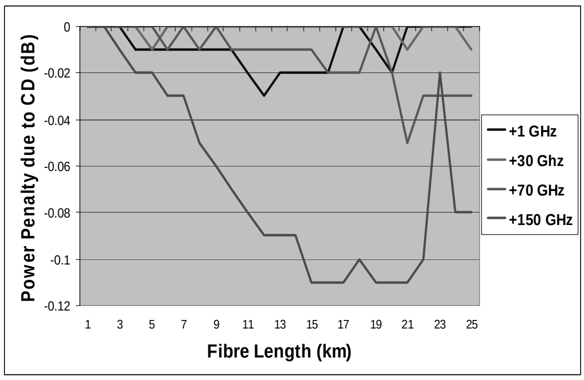

Figure 4: CD RF power penalty

Note: The birefringence varies depending on the refractive index in the fibre. Technical data provided for the SMF-28 fibre shows that the dependence of refractive index on temperature is 0.000012/ºC [4]. The Differential Group Delay (DGD) could be then modified and thus the PMD average value accordingly; this effect will be further investigated in future work.

5. Phase Stability

If differential phase drift occurs, due to different dispersion for the slave laser frequency line and the master laser frequency line, the heterodyned signal will also drift in phase providing an inaccurate phase reference. Here we make preliminary investigations of the effects of CD and PMD.

A realistic description of the polarization statistics is only possible if the number of scattering events is large. Figure 5 shows preliminary results obtained in the analysis of phase changes. This shows the phase shift in the received heterodyned signal due to CD and PMD by comparing with results of transmission in the same length of fibre with no dispersion. Typical values of CD and PMD for the SMF-28 fibre were again used. The phase shift is of more consequence for long distances of fibre; it reaches a maximum of 433 fs for 22.4 km of fibre and it is above 150 fs in most cases.

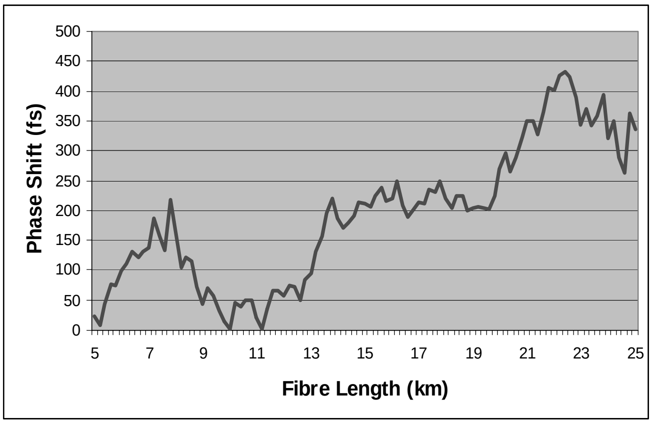

Figure 5: Phase drift due to dispersion phenomena

6. Conclusions and Further Work

It has been shown that birefringence/PMD can have a perceptible effect on millimeter-wave signal transmission for even short lengths of fibre, the maximum effect on the power penalty found to be 0.75 dB. This birefringence effect on power decreases when the slave laser frequency decreases, and is almost nonexistent for the lower frequencies. As for CD, its effect was found to be much less important than the PMD effect as expected.

The phase variation effect is an important consideration as the ALMA specification is for a minimum phase drift of 17 fs in order to realize very long baseline interferometry (VLBI) with other arrays. Our preliminary results indicate phase drift much greater than the ALMA requirement. Further work will need to verify these results with a more precise method and/or will need to remedy these problems in the ALMA photonic local oscillator system itself.

References

[1] P. Shen, P. A. Davies, W. P. Shillue, L. R. D'Addario and J. M. Payne, "Millimetre-Wave Generation Using an Optical Comb generator with Optical Phase-Locked-Loops", 2002 International Topical Meeting on Microwave Photonics, MWP 2002, Awaji, Japan, Technical Digest pp. 101-104, Nov. 2002

[2] P. Shen, N. J. Gomes, P. A. Davies, W. P. Shillue, P.G. Huggard and B. N. Ellison, "High Purity Millimetre-Wave Photonic Local Oscillator Generation and Delivery", 2003 International Topical Meeting on Microwave Photonics, MWP2003, Budapest, Hungary, Sept. 2003, accepted for presentation/publication

[3] Non Linear Dispersive Fiber Model and Non Linear Dispersive PMD Fiber Model, VPI™ User Guide.

[4] SMF-28 Technical Specifications, Corning. www.corning.com.