EFFECT OF ACTIVE FIBRE STABILIZATION ON GROUP AND PHASE DELAY

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Abstract

Many current optical timing schemes use detection of the pulse group or phase delay through an optical fibre to allow them to stabilize propagation through the fibre to the fs or sub-fs scale. However, it is recognised that stabilizing one leaves a residual drift in the other.

We have contructed a phase delay detector to investigate the phase-group delay walk-off (PGW) in fibre distribution systems. The phase monitor uses polarisation rotation associated with sub-wavelength delays in the fibre to detect changes in the carrier phase of ultrashort pulses. Used in conjunction with a group delay monitor, we can measure the PGW in actively stabilized fibre links and its implications on the feasibility of stabilizing both carrier and envelope phase in pulsed synchronisation systems. The ability to stabilize both the carrier and envelope phase in these systems could give the higher resolution of interferometric based stabilization systems while continuing to deliver ultrashort pulses for use at delivery sites.

INTRODUCTION

An optical clock distribution system is being developed on the ALICE accelerator at Daresbury Laboratory. The system is based on a mode-locked laser fibre stabilization scheme which delivers the clock signal with ultrashort optical pulses over an actively stabilized optical fibre. Such systems have been shown to deliver clock stability with rms jitter as low as 5 fs [1].

In contrast to short pulse synchronisation schemes, inteferometric timing schemes can offer link stabilities to the 800 as level by utilizing the finer scale carrier oscillations [2]. However, while RF modulation on the carrier can be used to deliver a clock signal to remote sites, these systems require a secondary laser at the remote site to synchronize with if short short pulses are required locally. Furthermore, the difference in phase and group velocity in the fibre means that any RF modulation imposed onto the optical signal is not fully stabilised by stabilisation of the phase transit time. This is due to the phase velocity being proportional to the refractive index of the medium and the group velocity being proportional to its derivative as given by

$$\upsilon_\phi = \frac{\omega_0}{\beta_0}\left(\frac{d\beta}{d\omega}\right)_{\omega=\omega_0}\upsilon_g . \qquad (1)$$

Interferometric schemes can instead employ a scaling factor to account for the differences in phase and group delay in their fibre [2]. While this is a good approximation for static fibre it is not evident that stresses and geometry changes to fibre when stretched at high frequencies can be accounted for with a fixed calibration factor. Thus, to effectively compensate for both the phase and group delay changes in a link it is necessary to simultaneously monitor both of these changes in real time.

In looking at the effect of fibre stretching on changes to the group and phase velocity of distributed signals, we aim to gain an understanding of the level and characteristic of residual phase jitter on a group delay stabilized link. This will enable us to assess the feasibility and methods for simultaneous stabilization of both group and phase delay in our system.

DETECTION SCHEMES

To monitor both the phase and group delay in the fibre link, we used a configuration as shown in Fig. 1. Short 65 fs pulses from a mode-locked Erbium fibre ring laser are

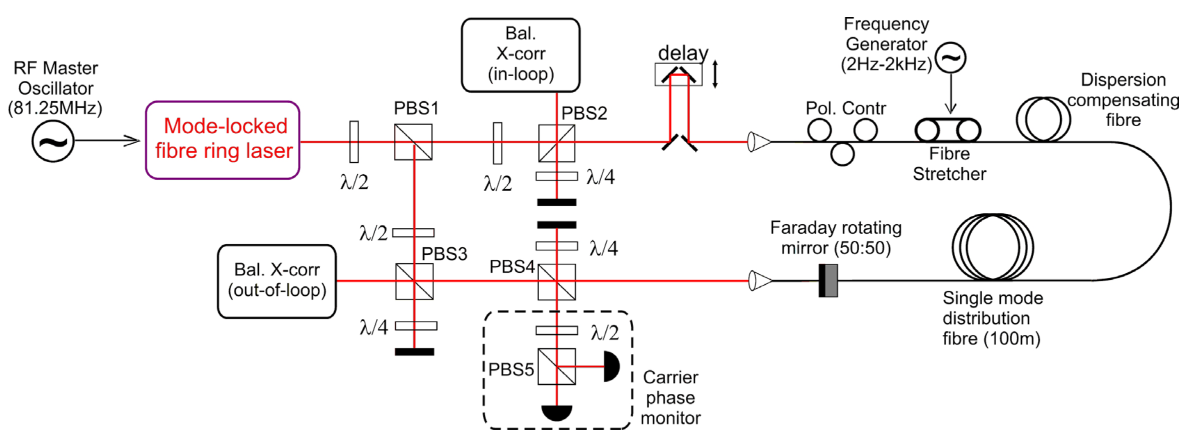

Figure 1: Layout of monitoring system to simultaneously measure the phase and group delay of pulses through the fibre link.

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propagated through a 100m dispersion compensated fibre link. They are then partially reflected back from the far end to provide a link stabilization signal. The relative delay between the reflected signal and the reference signal is monitored using a balanced optical cross-correlator incorporating a 4mm PPKTP crystal for SHG, and stabilized by feedback to a fibre stretcher and free space delay stage. A second optical cross-correlator at the far end of the fibre link enables out-of-loop monitoring of the group velocity against a reference tap off from the main laser.

To simultaneously monitor the phase delay between the pulses, a polarising beam splitter (PBS4) is inserted with a shorter time delay for the reference such that the reference and fibre output pulses overlap when the balanced cross-correlator passes through its zero crossing position. This allows for monitoring of carrier phase changes in the fibre at the nominal locking position of the fibre stabilization system, which is also where it is most sensitive to group delay changes.

Carrier Phase Monitoring

The relative carrier phase changes in the fibre are monitored interferometrically as shown in Fig. 2.

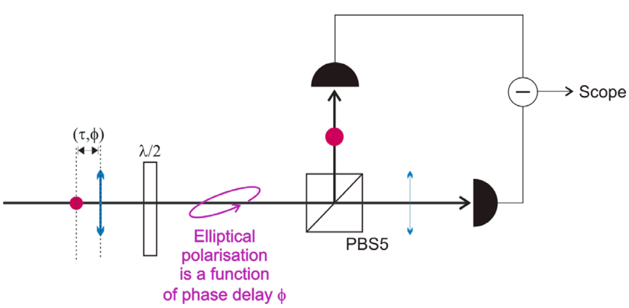

Figure 2: Phase delay monitor using polarisation interference. The pulses interfere to give a total elliptical polarisation which has ellipticity as a function of φ. The visibility of the fringes is a function of τ.

The fibre output signal is combined with the reference in a polarising beam splitter (PBS4). The orthogonal signals are then both rotated by 45 degrees and passed through a second polarising beam splitter (PBS5), such that the power in each pulse is equally split into orthogonal components. The corresponding components of the two pulses thus interfere and the signal at each photodiode is the sum the two pulses along a tilted axis. A change in phase delay between the two signals thus gives constructive interference in one axis while giving destructive interference in the other. The photodiode powers for each of the polarisations, assuming identical Gaussian pulses can thus be given as:

$$S(\tau) = A + 2(A - 1)\cos(\phi)\exp\left(-\frac{\tau^2}{4t_0^2}\right) \qquad (2)$$

$$P(\tau) = A - 2(A - 1)\cos(\phi)\exp\left(-\frac{\tau^2}{4t_0^2}\right) \qquad (3)$$

Where A is the pulse amplitude, t_0 is the pulse width and φ and τ are the phase and group delay between them respectively.

SCOPE OF PGW MONITOR

With the setup described we were able to simultaneously monitor the frequency response of the phase-group delay walk-off (PGW) in fibre. This is shown in Fig. 3 where we have scanned a free space delay line to characterise the whole range of interference between the pulses. In black is the phase delay monitor measurement showing the differential interference fringes (P-S). The observed side lobes arise from the cross correlation of the reference pulse which exhibits small wings with the side lobes of the fibre output pulse which suffers from incomplete compensation of third order dispersion in the fibre link. The operational setpoint of the two monitors are adjusted to give maximum fringe visibility at the zero crossing of the balanced cross-correlator shown in red. Measurements of delay are taken near this point where both the optical cross correlator and the phase delay monitor have their greatest sensitivities.

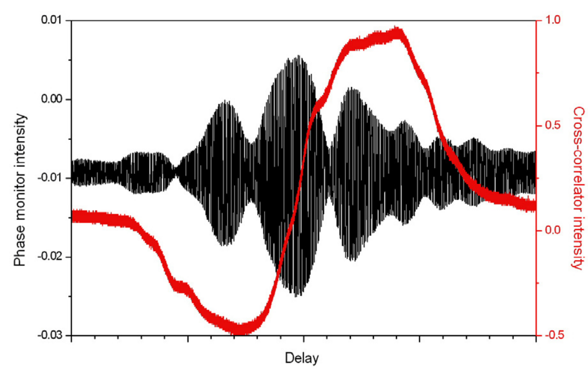

Figure 3: Relative positions of phase (black) and group (red) monitor signals over an approx. 2ps range.

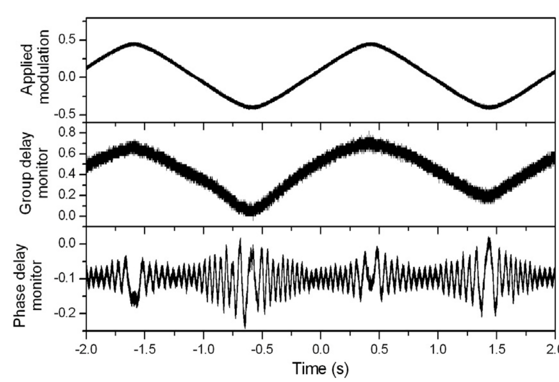

Figure 4: Phase and group monitoring of a 0.5 Hz modulation applied to the fibre stretcher.

To demonstrate and measure the correlation between the phase and group delays, we applied a 0.5 Hz sinusoidal modulation to the fibre stretcher we would normally use for link stabilization. The results are shown in Fig. 4. We observe that the phase monitor accurately

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captures the fringes as the delay sweeps through them in one direction before turning around. We can also see that because the optical link is required to be unlocked during this measurement that the overall drift in the fibre can also be observed with the group delay monitor. Similar measurements modulating the fibre stretcher at other frequencies and amplitudes could be used to determine the level at which PGW could vary with kHz level link stabilization.

Response to Locking

As an initial assessment of how much independent phase compensation would be required when the link is group delay stabilized, we monitored the PGW while the link was locked to a bandwidth of 5 kHz. The stretcher in this case was thus responding to the actual link fluctuations rather than an applied modulation. The frequency spectrum of the fringes when the link is locked and unlocked are shown in Fig. 5.

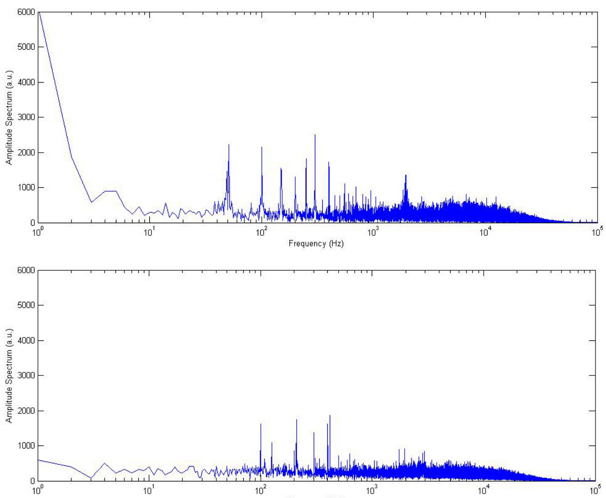

Figure 5: Spectrum of fringes when the link is unlocked (top) and locked (bottom).

We observe that in the unlocked case, there is a peak at 2 kHz which corresponds to the interferometric drift speed of the link and equates to approx. 1fs/ms. The sharper peaks at 50 Hz and harmonics are attributable to the current locking of our laser to RF. When the link is locked, we can see that some of the 50 Hz oscillations in the laser have been compensated for by the link feedback. However due to the rapid nature of the compensation, we can observe that the peak at 2 kHz has now been redistributed towards higher frequencies. This is because the link is locking to an rms timing jitter of 10.2 fs, as measured by the out-of-loop group delay monitor, which is greater than the period of the carrier.

CONCLUSIONS AND OUTLOOK

We have contructed phase and group delay monitors to measure the PGW of our timing link. The configuration allows for direct comparison of the phase and group delay response of optical fibres stretched at frequencies as well as when the system is actively locked. Improved calibration of the monitors' responses will enable unwrapping of the interference fringes into a measured delay giving the ability to independently monitor the phase and group delay in timing distribution links. This monitoring paves the way for future investigations of compensating for these two delays independently.

In the presented measurements, we have assumed that carrier-envelope changes in our laser occurs on longer timescales than the round trip time of the optical link (~1 µs). Comparison of the laser and fibre link stability using these monitors would assertain whether CEP stabilisation of the laser is neccessary for short pulse clock delivery at sub-fs stabilities.

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