Tackling non-linear laser tuning in Frequency Scanning Interferometry (FSI)

James Blanchard, Ben Hughes

National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

james.blanchard@npl.co.uk, ben.hughes@npl.co.uk

Introduction

To perform FSI measurements, a chirped optical pulse from a frequency tuneable laser is transmitted to and reflected by a target to the sensor where it beats with a local oscillator signal. The beat frequency is proportional to distance between the sensor and target. Signal analysis of the beat signal in the frequency domain allows signals from multiple targets to be isolated and processed individually. The distance of a target for an FSI measurement is described by:

$$D_i = c\frac{v_i}{2\,{}^{df}/_{dt}}\,(1)$$

where v_i is the signal frequency from the i^{th} target, D_i is the measured distance to the i^{th} target, c is the speed of light and df/dt is the tuning rate of the laser in Hz/s.
The basic range measurement resolution, $\varDelta D$, of FSI is governed by the Fast Fourier Transform (FFT) resolution and the laser chirp bandwidth, approximated by:

$$\Delta D\ =\frac{c}{2\,\Delta f}\,(2)$$

where c is the speed of light and Δf is the chirp bandwidth. To achieve high range resolution, a wider bandwidth chirp is required. For large volume FSI at NPL, C-band frequencies are used for their high eye-safe limits, wide availability of components and compatibility with Hydrogen Cyanide (HCN) gas cell references, bringing traceability to measurements.

The only commercially available tuneable laser that operates in the C-band with long coherence length for large volume applications, and a wide mode-hop free tuning range, is the New Focus TLB-8800.
Although this laser is favourable for FSI, it exhibits a non-linear tuning rate and has a long turnaround time due to mechanical tuning. Due to (1), df/dt presenting as non-linear will produce wide FFT measurement peaks from data captured over the full duration of a laser chirp, greatly increasing measurement uncertainty.

FSI can overcome the linearity problem using a technique called k-clocking. This involves sampling FSI signals with an analogue to digital convertor (ADC) that is clocked using a non-constant clock signal derived from the non-linear laser tuning using a Mach-Zehnder Interferometer (MZI). ADCs are designed to operate with a fixed clock and often varying this results in bad data acquisition, limiting the list of suitably fast ADCs (>150 MHz), available off-the-shelf, to a few very expensive options!
Presented is work carried out developing a new laser for FSI; capable of tuning linearly, enabling the use of cheaper, readily available constant clocked ADCs.

DFB Laser Array

DiLazaro, Nehmetallah [1] present the use of an array of distributed feedback (DFB) lasers (Fitel FRL15TCWB-D86-19610A) within a single device designed for telecoms applications.
Each laser element is tuneable over a 3.5 nm range in the C-band, such that their combined bandwidth covers the entire C-band. Each element can be chirped in turn with active linearisation (OPLL), where the resulting FSI measurement data stitched together, with the help of data from a HCN gas absorption cell, form an equivalent chirp of > 30 nm bandwidth. Work has been carried out by NPL to replicate and develop this research further to replace the current TLB-8800 laser.

Experimental Setup

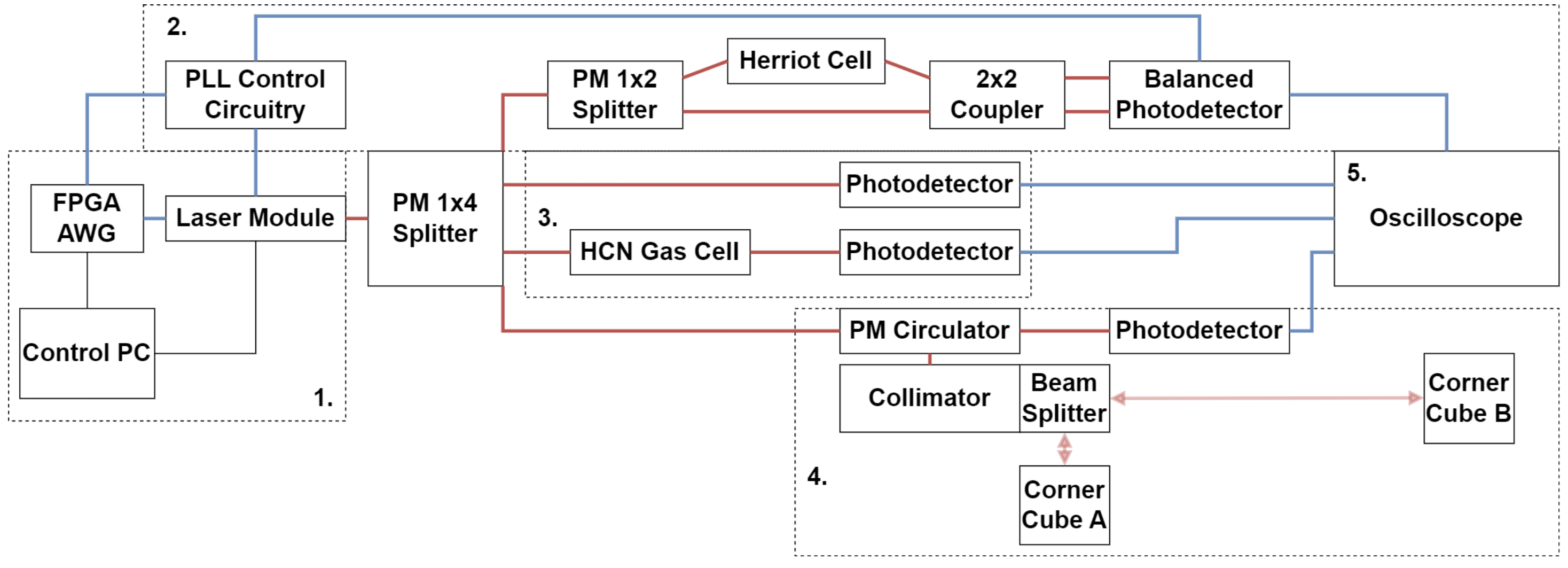

Figure 1: Block diagram of DFB laser linearisation and FSI measurement setup

1. Custom circuitry to control the laser array module consists of temperature and laser power controller; driving signal input; and 1x8 mux allowing selection of individual laser diodes. The laser is swept by applying a current ramp signal to the input via FPGA controlled waveform generator (AWG). The temperature controller is also capable of controlling the wavelength, but takes > 1 second to stabilise, thus is too slow to obtain fast FSI measurements.

2. To linearise the laser tuning, a portion of the laser output is fed to an MZI with a 3.2 m length Herriot cell for the long arm to produce a dispersion free clock derived from the tuning rate of the laser. This clocking signal is passed to a phase locked loop circuit that compares this with a static reference clock generated by the FPGA. The phase error between the two clocks generates an error signal that is filtered, scaled, and applied onto the input ramp signal. This creates a feedback loop that locks the clock generated by the MZI to the static reference clock, resulting in a linear tuning rate.

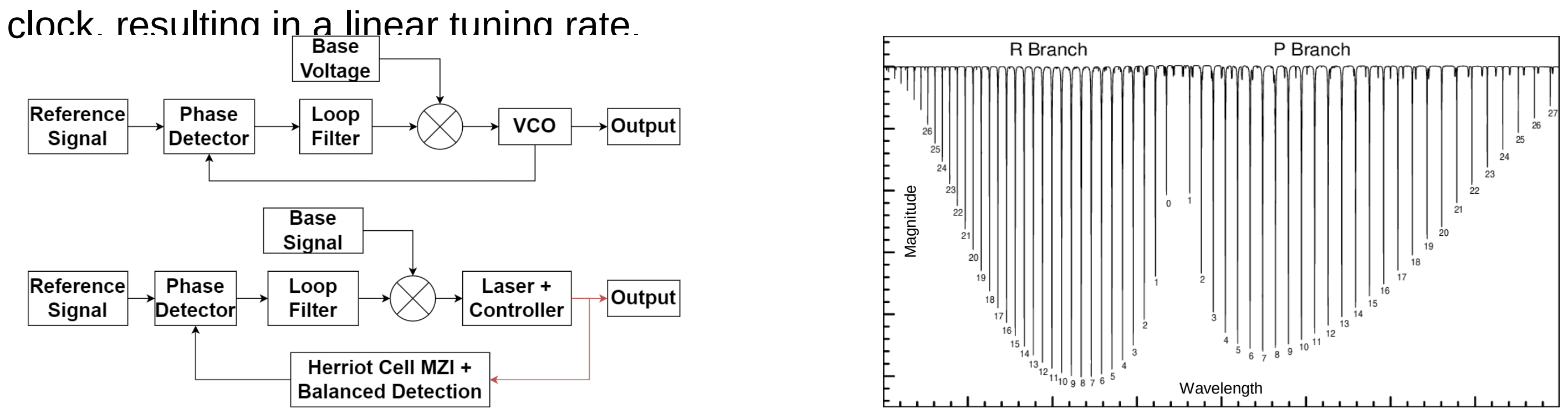

Figure 2: (Left) Phase locked loop vs Optical phase locked loop diagram. (Right) HCN gas cell absorption spectrum [2].

3. A portion of the laser signal is diverted through a HCN gas cell acting as a wavelength reference with a well-defined absorption peak spectrum over the C-band (figure 2). This allows for sub-chirp data to be stitched together by aligning each of the absorption peaks to their correct relative location. To account for varying signal amplitude across laser sub-chirps, a laser reference is measured with another portion of the laser output.

4. FSI measurements are taken with another portion of the laser output fed to a fibre circulator with a reflective coating on the input/output port. The back reflection from the coating acts as the local oscillator to create a beat frequency with the returning signal from a target. As FSI can distinguish multiple targets simultaneously, a beam splitter is used to divert a collimated beam to two targets, providing two coinciding target distance measurements to resolve when stitching the data.

5. An oscilloscope set at a fixed sample rate of 250 MHz is used as an ADC to demonstrate FSI measurements taken with a linear tuning laser.

Tuning Linearly

To determine tuning rate linearity of the laser, the clock signal generated by the laser through the MZI is captured, where phase is calculated and unwrapped. A linear best-fit is applied to the unwrapped phase and subtracted from each other to display the deviation the tuning rate of the laser has from linear.

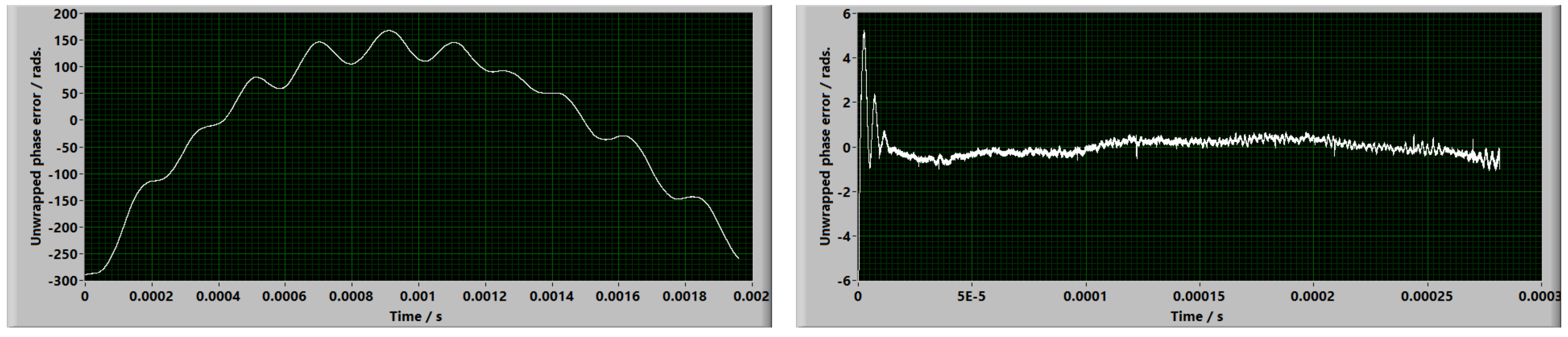

Figure 3: (Left) Unwrapped phase linear deviation of TLB-8800 mechanical laser. (Right) Unwrapped phase linear deviation of Fitel DFB Laser diode under active linearisation.

Figure 3 shows the tuning linearity of the TLB-8800 laser and a single diode of the DFB laser array under active linearisation. The tuning linearity shows an error range from +175 radians to -250 radians for the TLB-8800 compared to a linear fit, whereas the DFB laser under OPLL control produces phase error below ±1 radian. While the bandwidth of the TLB-8800 chirp is 11 nm, the DFB laser is just 1.2 nm. The intention is that an equivalent 11 nm bandwidth, linear tuned, chirp can be created with the DFB laser by stitching together sequential chirp data with assistance from the HCN gas cell.

Gas Cell and FSI data Stitching

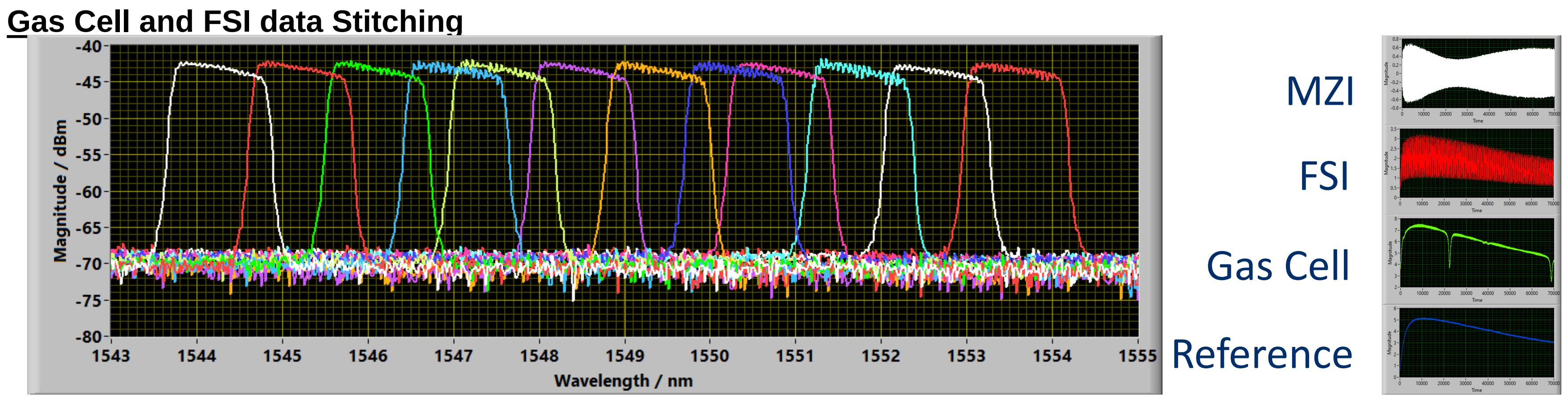

Figure 4: Spectra of 12 sequential DFB laser chirps and corresponding data captured for each one

Figure 4 shows spectra of 12 sequential, 1.2 nm DFB laser chirps spanning from 1544 nm to 1554 nm. For each chirp, an MZI, FSI, Gas Cell and reference measurement is captured. Each chirp must contain at least one HCN absorption peak for determining the relative position of the data, whilst overlapping in wavelength with the neighbouring chirp for a seamless data stitch. The following steps are taken to stitch the gas cell data together:

1. Find the position of each data set relative to each other with a non-linear least squares fit using: known frequency of each absorption peak, Y_i; Sample position of each absorption peak in data, X_i; and initial estimation of frequency per data sample, α.

   $$\begin{gathered} Y_i =\ \alpha\left(X_i - S_j\right) \\ 0\ \leq i < M - 1 (3) \\ 0\ \leq j < N - 1 \end{gathered}$$

   Solve for S_j, the number of indexes to shift each data set to the correct location, where M = number of gas cell peaks and N = number of sub chirps.

2. Plot corrected positions of each gas cell data set and concatenate to build up a complete gas cell absorption spectrum.

3. Apply relative positions of the stitched gas cell data to concatenate and stitch FSI data into a single data set, achieving higher resolution target measurement through higher bandwidth data.

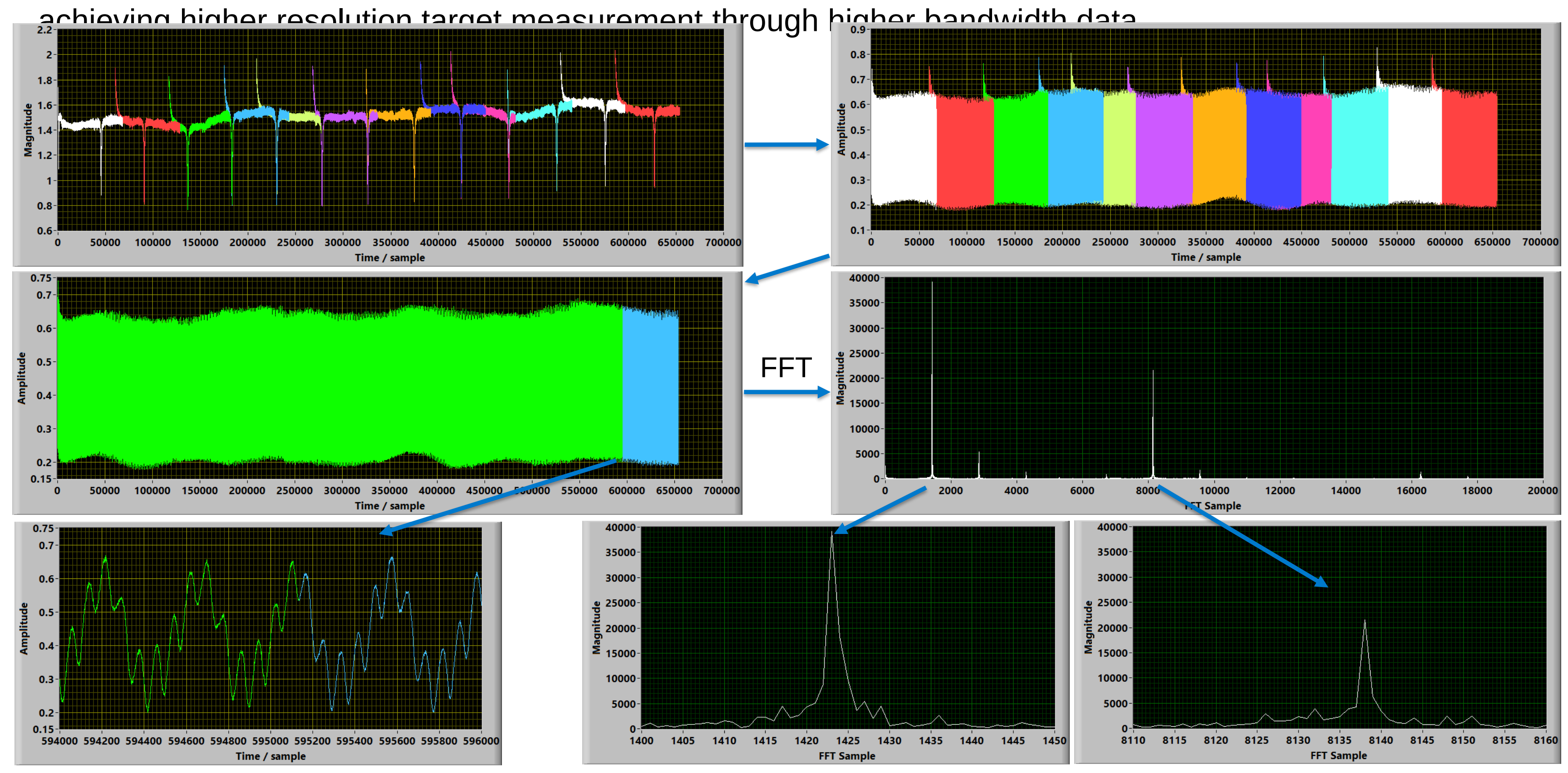

Figure 5: Steps taken to stitch sub-chirp FSI measurement data with HCN gas cell data.

Figure 5 shows the steps taken to stitch sub-chirp FSI data together using the HCN gas cell absorption peaks for relative positioning. The result is two sharp, symmetric, peaks for both return signal frequencies generated by corner cube A and B showing that the stitch location is correct.
This demonstrates that higher bandwidth FSI measurements can be produced by stitching together lower bandwidth laser sub-chirps with the aid of an HCN reference, and that active linearisation of the laser is producing a good FSI measurement with a static clocked ADC, removing the need for k-clocking.

Future Work

The next development step is to increase the laser chirp range by driving the laser diodes harder. This work was performed with 3 laser diodes chirped 1.2 nm at 10°C, 20°C, 30°C, 40°C to cover the spectrum, however temperature changes are slow to stabilise. Each diode can produce a wider bandwidth by increasing the current supplied to it and allowing consequent thermal effects to increase it further. This, however, comes at the risk of breaking the module as the current is increased beyond the manufacturer's specification. This has been successfully demonstrated by DiLazaro and Nehmetallah.

References

[1] T. DiLazaro, “Coherent Frequency-Modulated Continuous Wave Ladar Using a Distributed Feedback Laser Array”, Ph. D. dissertation, Dept. Elect. Eng, Catholic Univ. of America, 2018
[2] S. L. Gilbert, W. C. Swann, C-M. Wang, “Hydrogen Cyanide H13C14N Absorption Reference for 1530 nm to 1560 nm Wavelength Calibration — SRM 2519”, NIST Special Publication 260-137, (Nov. 1998)

www.npl.co.uk