# High-Bandwidth Frequency Stabilization of a Fibre-Laser Frequency Comb

C.R. Locke, T.M. Fortier, J.J. McFerran,
E.N.Ivanov, A.N. Luiten
School of Physics
University of Western Australia
Australia
clocke@physics.uwa.edu.au

P.S. Light, F. Benabid
Centre for Photonics and Photonic Materials
University of Bath, Claverton Down, BA27AY, Bath
UK

***Abstract*— The linewidth of single modes in fibre-laser mode-locked laser is typically substantially higher than those derived from bulk solid-state mode-locked lasers. Active frequency stabilization of fibre combs has been hampered by the long lifetime of the population inversion in the fibre that prevents high bandwidth control of dispersion fluctuations. We present the means for external stabilization of the comb using an acousto-optic modulator.**

## I. INTRODUCTION

The output of a mode-locked laser consists of a train of optical pulses with a repetition frequency of $f_r$ . Examined in the frequency domain this pulse train appears as a comb of spectral lines with the frequency of the nth line given by $f_n = n f_r + f_{ceo}$ where $f_{ceo}$ is the carrier-envelope offset frequency. The development of stabilization techniques for these two parameters and the subsequent application of the stabilized combs to high precision spectroscopy and optical clockwork has been one of the recent highlights of experimental physics.

There has been much effort in recent times to developing frequency metrology technology based around fiber mode-locked lasers rather than previously employed solid-state laser materials e.g. Titanium:sapphire. This effort is motivated by the lower cost, smaller size and the long-term turnkey operation of the fibre laser systems when compared with the solid-state alternative. However, until very recently fibre laser systems have exhibited higher frequency noise and broader linewidths for the comb members than, for example, Ti:sapphire lasers [1,2]. This recent work modified the pump laser diodes output fluctuations to passively reduce the linewidth of a comb element from the typical level of 1-5 MHz down to a few hundred kilohertz. These researchers then employed an active second order phase-locked loop with 100 kHz bandwidth to collapse the phase fluctuations so that the integrated phase noise is of the order of 1 rad [2]. This comb is then suitable for accurate frequency measurement applications such as shown in [1].

In this letter we have taken a different approach that does not require modification of the fiber laser or the pump diodes. It can be readily applied to commercially available fibre laser devices without modification to the laser or amplifier stages. Our approach is to make use of a fibre-based acousto-optic modulator (AOM) to directly shift the frequency of all the comb elements in order to suppress dispersion-related fluctuations in $f_{ceo}$. Since the bandwidth of the AOM is potentially substantially higher than the free-running linewidth of a comb member it is possible to directly collapse all of the energy of a comb member into a well-defined "delta-function".

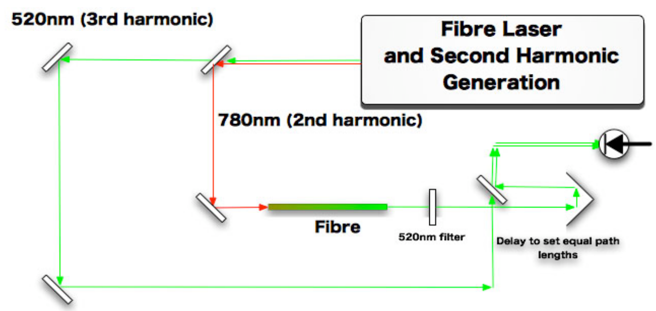


Figure 1: Experimental setup

A standard commercial mode-locked laser fiber laser system (Toptica Er:fibre in this case) drives a periodically-poled KTP crystal. The laser delivers a 100 fs duration pulse at 1560nm with 94MHz repetition rate, which will be passed through an AOM crystal. The signal then passes through an Er:fibre amplifier before being focused into a PP-KTP crystal, generating 80 mW of radiation near 780 nm while simultaneously giving 4μW of 520 nm (the third harmonic of 1560nm). The 780nm radiation then passes through special intersection points in the cladding of a microstructured fibre with an underlying Kagome structure [3,4,5]. The high degree of confinement at these intersection points leads to strong spectral broadening of the light that can be exactly tailored to meet our requirements. Figure 2 illustrates launching the laser into different intersection points to create different output colour.

1-4244-0647-1/07/$20.00 

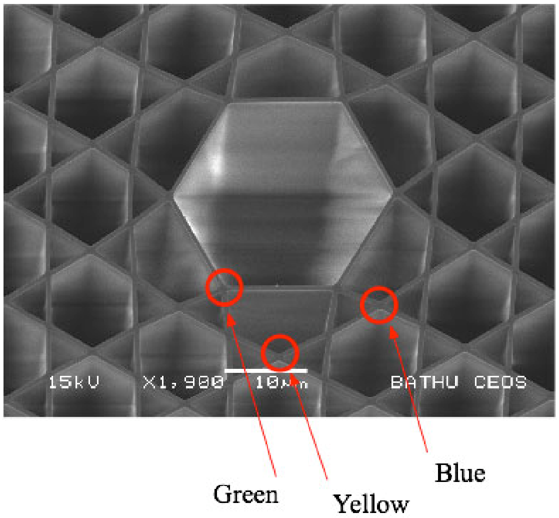


*Figure 2: Cross section of Kagome fibre*

We select a particular intersection point in which the majority of the power of the broadened spectrum spectrally overlaps the third harmonic radiation from the nonlinear crystal (illustrated as 'Green' above), the resulting spectrum is shown in figure 3.

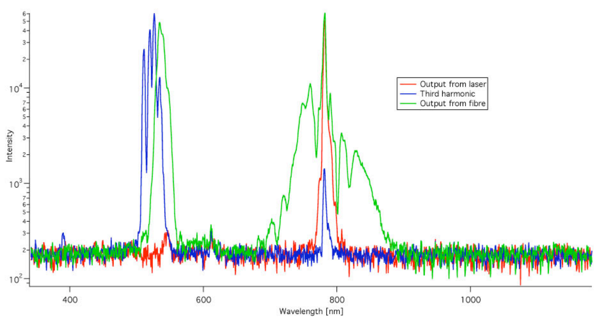


*Figure 3: Spectrum comparing output from Kagome fibre and third harmonic. The Kagome fibre delivers the majority of the power of the broadened spectrum to overlap the third harmonic.*

We have inserted a variable temporal delay at the output of the fibre so that the third harmonic 520nm pulse arrives at the same time as the fibre-broadened 780nm pulse on the photodiode. If the frequency of the nth mode of the 1560 nm comb is written as

$$f_{n|1560} = nf_r + f_{ceo} + f_{AOM} \quad (1)$$

then the 520nm comb modes will be

$$f_{m|520} = mf_r + 3f_{ceo} + 3f_{AOM} \quad (2)$$

while the 780 nm comb can be written as

$$f_{j|780} = jf_r + 2f_{ceo} + 2f_{AOM} \quad (3)$$

where $f_{AOM}$ is the driving frequency of the AOM. The difference frequency generated by interference of the broadened 780 nm comb and the 520nm comb on the photodiode will contain the following frequencies;

$$f_{m|520} - f_{j|780} = (m - j)f_r + f_{ceo} + f_{AOM} \quad (4)$$

After stabilizing the repetition rate, the beat note on the photodiode will be stabilized by holding

$$f_{ceo} + f_{AOM} \quad (5)$$

constant. This holds all the frequency of the modes of all three spectra at a stable value irrespective of the fluctuations of the pump power.

## II. Results

### A. Repetition Rate

Figure 4 shows the scheme we use to measure fluctuations of the repetition rate. We reduce the repetition rate from 95MHz to below 300Hz by heterodyning it against a high quality synthesizer in order to reduce counter noise.

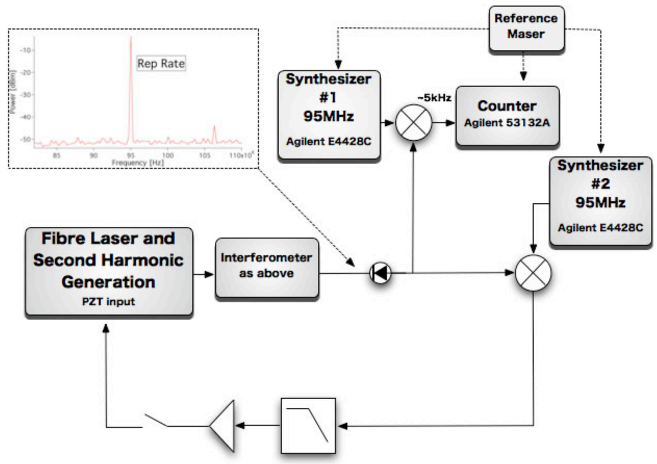


*Figure 4: Measurement and control of repetition rate*

We employ the PZT internal to the laser to control the repetition rate. We employ a SRS 560 with gain of 10x and low pass filter bandwidth of 10kHz, followed by a gain of 15x in the PZT driver. The locked repetition rate SRAV is shown in figure 5 and is measurement system limited.

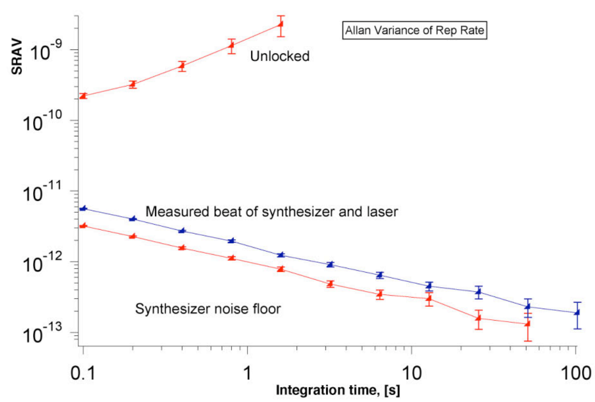


*Figure 5: SRAV of repetition rate*

We have measured the transfer function of the PZT by phase-locking a high quality synthesizer to the repetition rate and applying a periodic chirp to the PZT and measuring the transfer function on an FFT, as shown in figure 6.

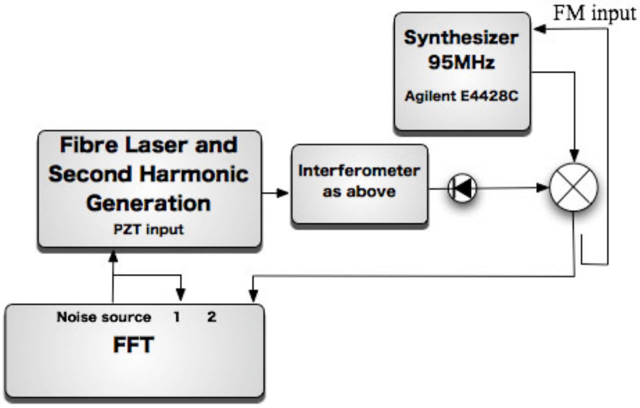


*Figure 6: Setup to measure transfer function of PZT*

The performance of the PZT in Hz/V is shown in figure 7.

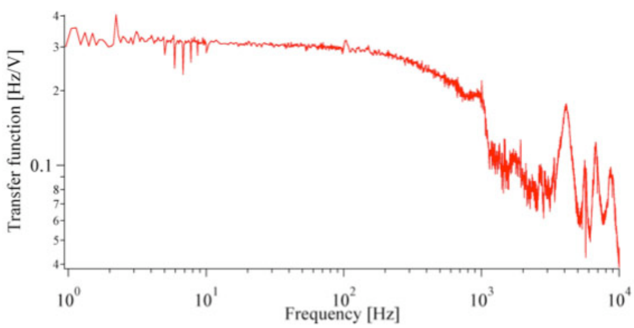


*Figure 7: Transfer function of PZT*

## B. *Offset Frequency*

We have extracted $f_{ceo}$ and obtain a signal to noise ratio of 30dB in a bandwidth of 9 MHz. The 3dB linewidth of this signal is around 400kHz in our case. This is limited by the amount of power present in the third harmonic arm of the interferometer.

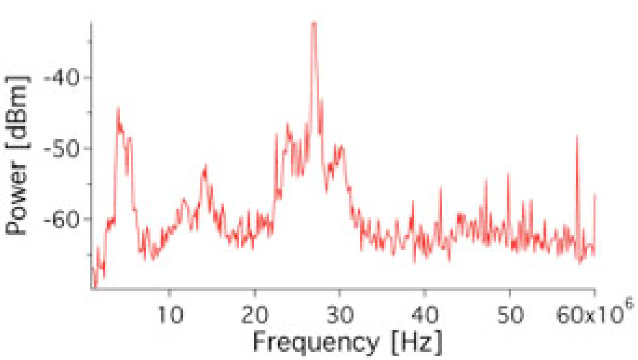


*Figure 8: Offset frequency*

Free running offset frequency fluctuations are shown in figure 9, measured by suitable filtering to select the offset frequency and logging $f_{ceo}$ on a counter.

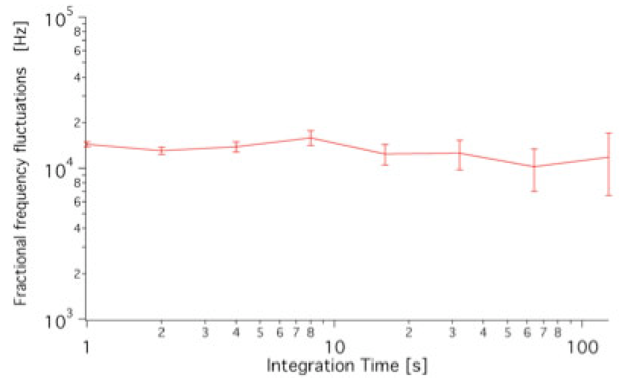


*Figure 9: Fluctuations of the offset frequency*

The conventional method to control the offset frequency is via pump laser current modulation. We have measured the transfer function of this control system (figure 10). We note that the bandwidth of the pump diode control is only around 30kHz whereas the free running line width of $f_{ceo}$ is around 400kHz. In order to collapse all the power into a well-defined carrier signal it will be necessary to have a control bandwidth around 10 times greater than the linewidth of $f_{ceo}$.

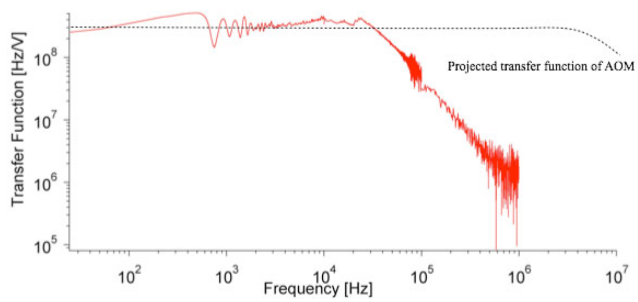


*Figure 10: Transfer function of pump power control*

Also shown on figure 10 is the manufacturer-provided transfer function of the AOM we plan to use, which has a modulation bandwidth of 4MHz.

Initial measurements with a free space AOM to control the offset frequency are shown in figure 11. This figure shows that tuning of $f_{ceo}$ is possible with an AOM but variations in the pointing of the output signal of the AOM led to variations in the efficiency of the $f_{ceo}$ signal.

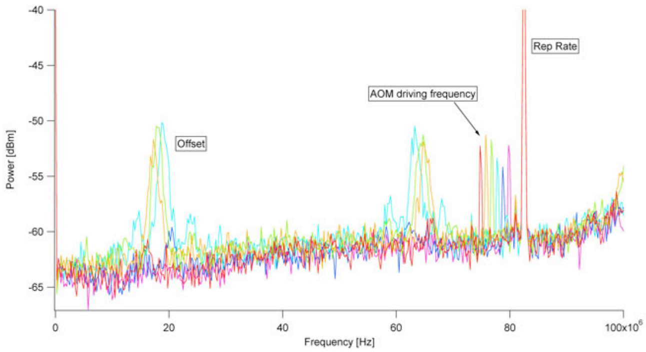


*Figure 11: Double pass free space AOM, illustrating how a change in AOM driving frequency shifts $f_{ceo}$*

We configured the free-space AOM in a double pass configuration to reduce the beam pointing variations but the output power was then inadequate for our requirements. The solution is to make use of a fibre-coupled AOM inserted into the laser before the amplification stages (rather than after the amplification as was done with the free space device). In this case the fibre amplifier will compensate the insertion loss of the AOM.

## III. Future Work

We plan on installing an IntraAction AOM FCM-401E5C and anticipate that this will meet our requirements. The bandwidth of the AOM (4MHz) is substantially higher than the free-running linewidth of a comb member as well as that of pump laser current modulation (30kHz). It should be possible to directly collapse all of the energy of a comb member into a well-defined delta-function.

## Acknowledgment

We thank all members of the Frequency Standards and Metrology Group at UWA for their help and support. We thank Francois Couny for drawing and providing the Kagome fibre. This work is funded by the Australian Research Council.

## References

[1] W. Swann, J. J. McFerran, et al. Opt Let 31(20), 3046–3048 (2006).

[2] J. J. McFerran, W. Swann, B. Washburn, and N. Newbury, Optics Letters 31(13), 1997–1999 (2006).

[3] F. Benabid, J.C. Knight, G. Antonopoulos, P.S.J. Russell, Science 298 (2002) 399-402.

[4] P. Glas, D. Fischer, G. Steinmeyer, A. V. Husakou, J. Herrmann, R. Iliew, N. Skibina, V. Beloglasov, and Y. Skibina, Applied Physics B-Lasers and Optics 81, 209–217 (2005).

[5] F. Couny, F. Benabid & P. S. Light, Opt. Lett. **31** (2006) 3574-3576.