Robust optical injection locking to a 250 MHz frequency comb without narrow-band optical pre-filtering

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Abstract: A semiconductor laser was injection locked to a single optical frequency comb mode with a dither-free phase locked loop. The standard deviation was 0.014Hz over 24 hours with an Allan deviation of 1×10^{-17} at 10s averaging.

1. Introduction

Optical frequency combs (OFC) have applications in optical-frequency metrology due to their high stability and regular frequency spacing of modes. Access to the large number of stable and narrow linewidth modes of an OFC also has applications in other fields such as terahertz generation [1], arbitrary waveform generation [2] and dense wavelength division multiplexing for telecommunications [3]. Even more applications would be possible if more power was available in each individual mode, which is typically in the nW regime, and if there was an easier way to manipulate individual modes. Injection locking is a potential method to overcome this limitation by allowing selective amplification of individual OFC modes [4].

Optical injection locking (OIL) [4], in which a much higher power slave laser can be forced to adopt the frequency characteristics of light from a much lower power master laser injected into its cavity, provides a potential way to overcome this limitation. Selected individual comb modes, as required for a given application, can be fed into (low cost) semiconductor lasers which then generate light with the same frequency and phase coherence properties but at much higher power levels [5].

The locking only remains active if the detuning between the master frequency and the slave's free running frequency remains within the locking range. This can be overcome by combining injection locking with a phase locked loop (PLL) [6], where the injection locking keeps the frequencies strongly synchronised and the phase locked loop keeps the detuning small. Kim et al. [7] have demonstrated stable optical injection locking using this combination but required extraction and injection of a single comb mode using an ultra-narrow-band Fabry-Perot filter. A dithering technique was also required for the phase locked loop which may be undesirable in many applications.

In this investigation, we significantly narrowed down the OIL locking range, allowing us to lock to a single comb mode even when over 200 comb modes were injected into the semiconductor laser. Subsequently, this new approach allowed us to obtain an error signal for the PLL without dithering of the semiconductor laser current.

2. Injection locking mechanism and feedback loop

Frequency variations in the slave laser due to the limited stability of its temperature/current controller can cause the slave laser to unlock as its free running frequency drifts outside the locking range. A slow feedback loop can be used to control the driving current of the slave laser in order to keep the free running frequency within the injection locking range. Despite the slave frequency being locked to the master over the locking range, the slave output is phase shifted with respect to the master by [8]:

$$\Delta\varphi = -\sin^{-1}\left(\frac{2\Delta\omega}{\Delta\omega_{LR}}\right) - \tan^{-1}\alpha \qquad (1)$$

where $\Delta\omega$ is the difference in angular frequency (detuning) between the free running slave laser and the master comb mode, $\Delta\omega_{LR}$ is the injection locking range and α is the linewidth enhancement factor (~4 for our laser).

Measuring $\Delta\varphi$ leads to an error signal for the slow feedback loop. In previous work [7], the injected signal consisted of one strong mode and several weaker modes (obtained via a narrow Fabry-Perot filter); all within the locking range. When the master-slave frequency detuning is varied, all these modes move together on the phase delay curve (Fig. 1a), since they are all within the locking range. A mixer was used to obtain the amplitude of the beat signal between the dominant locked mode and the adjacent weaker modes (Fig. 1b). As this signal is symmetric with a single minimum at $\Delta\omega = 0$, dithering was required to obtain a signal suitable for the feedback loop (Fig 1c).

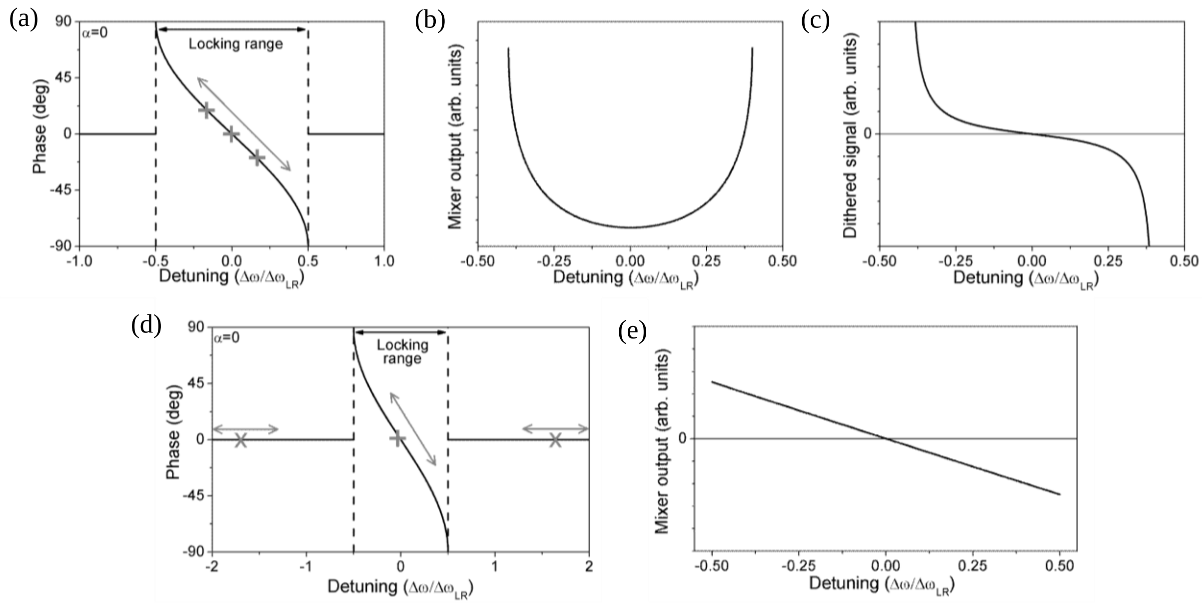

Fig. 1. When several modes are within the locking range, they move together along the phase shift curve (a). The mixer output is then an odd function (b). Dithering the slave laser current gives an even function suitable for feedback (c). However, when only a single mode lies within the locking range (d), the mixer output is directly an odd function (e).

In contrast, we obtained a smaller locking range by using lower injection powers [4] (< -50dBm per comb mode) and had a higher repetition rate by a factor of 2.5. As a result, only one mode lies within the locking range (Fig. 1d). Consequently, narrow band filtering of the comb is not required and many modes can be simultaneously injected into the slave laser. As an additional benefit, the beat signal is also changed as it is now composed of the laser output and the adjacent comb modes which are weakly reflected off the laser front facet. The mixer operated as a phase detector gives an output which is monotonic in form and with a zero crossing at $\Delta\omega = 0$ as shown in Fig 1e. This output is already suitable for use as an error signal for a feedback loop and hence a dither is not required.

3. Experimental set up

The experimental set up is shown schematically in Fig. 2. The fibre based frequency comb is a Menlo Systems FC1500-250-WG with a repetition rate (mode spacing) of 250 MHz.

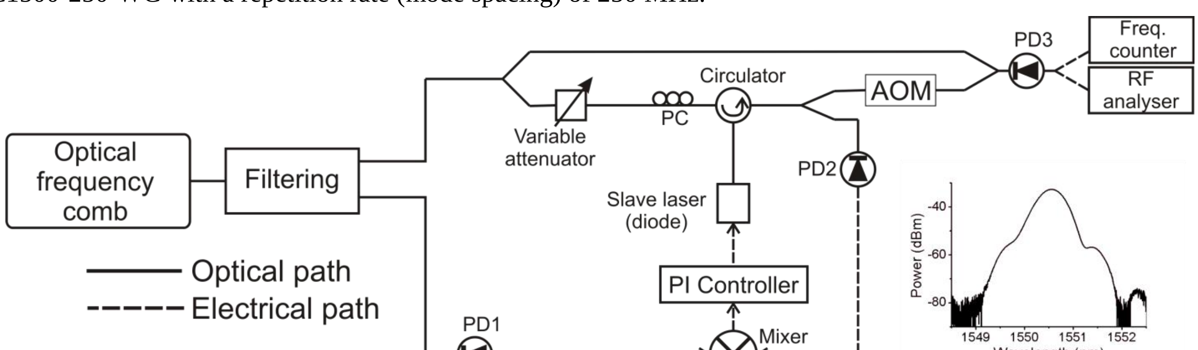

Fig. 2. The experimental set up. PI = proportional-integral controller; PD = photodetector; PC = polarisation controller; AOM = acousto-optic modulator. The inset shows the spectrum after filtering.

A 0.5-nm spectrally wide comb signal (spectrum shown in Fig. 2) is first obtained using standard low-cost fibre-coupled telecom filters. The photodetector PD1 is used to provide a 250 MHz RF reference signal. One of the filter outputs is split into two arms with one arm used for injection locking and the other used as a reference for characterisation. The slave laser is a discrete mode semiconductor laser from Eblana Photonics (Dublin, Ireland) with no built-in isolator. The laser output is split into characterisation and feedback arms. PD2 detects the beat signal produced by the output of the slave laser and the comb modes which are reflected off the laser front facet, as described in section 2. The signal in the characterisation arm is frequency shifted by a 35 MHz acousto-optic modulator (AOM). This is then recombined with the same comb modes as those used for injection and detected at PD3.

4. Results

The feedback loop was able to maintain injection locking for more than 24 hours. The stability of the injection locked laser frequency with respect to the injected comb line was measured by monitoring the 35 MHz beat signal at the output of PD2 with a gate time of 1 s. The frequency counter was referenced to the same 10 MHz oscillator used for the stabilisation of the repetition rate and OFC carrier offset frequency. The variation in frequency over 8 hours of the locking is shown in Fig. 3a. This has a maximum peak to peak value of 0.14 Hz and a standard deviation of 0.014 Hz. The overlapping Allan deviation is shown in Fig. 3b which has a value of 1×10^{-17} at a sampling time of 10 s, an improvement of almost two orders of magnitude relative to previous results [7].

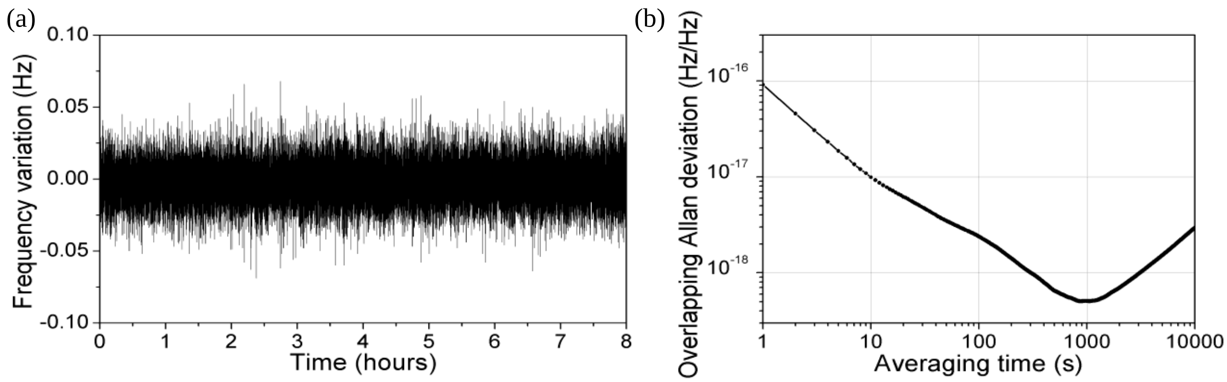

Fig 3.(a) The frequency variation of the beating signal between the 35 MHz shifted diode output and the original frequency comb line (only 8 hours are shown) and (b) the corresponding Allan deviation.

5. Conclusion and future work

We have injection locked a semiconductor laser to an individual mode of a frequency comb using a simplified method compared to previous demonstrations. The need for narrow filtering of the comb has been avoided by using low injection powers to reduce the locking bandwidth. This has also allowed us to use a dither-less electronic feedback to maintain the locking. The feedback was able to maintain the locking for at least 24 hours with a maximum peak to peak frequency error of 0.14 Hz, a standard deviation of 0.014 Hz and an overlapping Allan deviation of 1×10^{-17} at a sampling time of 10 s. In the future we plan to simultaneously lock additional lasers to different modes of the same OFC which can then be used for the efficient generation of arbitrary waveforms, or high repetition rate optical pulses.

We would like to thank to Eblana Photonics, Ireland for the discrete mode laser. This research has received funding from the European Communities Seventh Framework Program FP/2007-2013 under grant agreement 255368 (TOP CLASS).

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