kHz linewidth lasers using polarisation spectroscopy

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Abstract: Polarisation spectroscopy is a laser frequency stabilisation technique that probes the birefringence induced in an atomic medium by a circularly polarised pump laser beam. Due to polarisation spectroscopy being a refractive index based technique it is not limited by the lifetime of atomic states, unlike similar techniques such as saturated absorption spectroscopy. Polarisation spectroscopy has been shown to offer high bandwidth locking to an atomic reference, and linewidth narrowing, without requiring radio-frequency electronics. We investigate the noise-limited bandwidth of polarisation spectroscopy frequency discrimination and demonstrate sub-kHz laser linewidths with conventional external cavity diode laser (ECDL) using two similar setups and a heterodyne measurement.

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1. Results

1.1. Frequency Noise Measurements

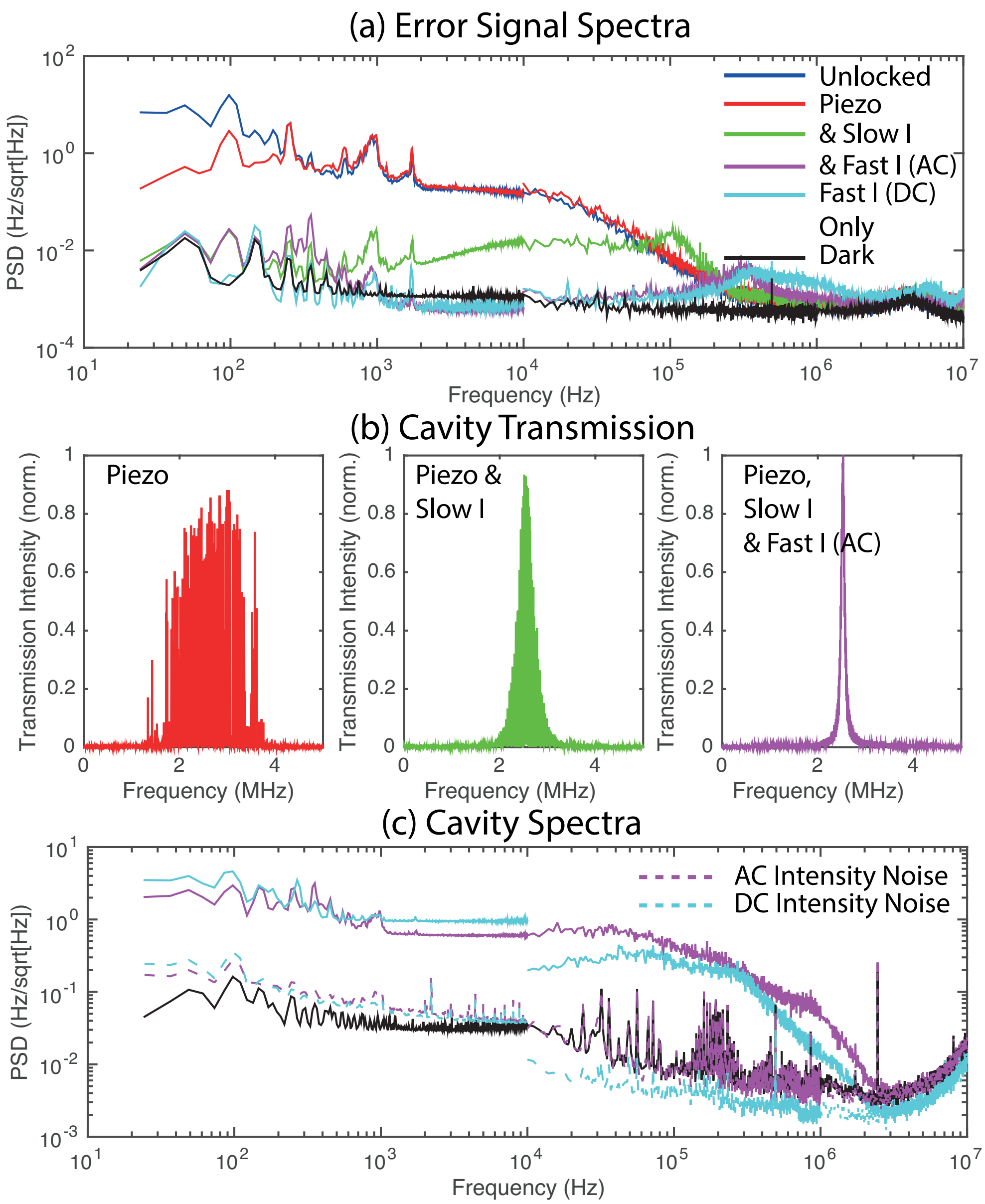

Fig. 1: Frequency Noise Measurements. (a) Linear spectral density (LSD) measurements of polarisation spectroscopy error signal frequency noise for a range of laser locking regimes: Piezo = piezo-only locking; Slow I = slow current feedback (40 kHz bandwidth); Fast I = fast current feedback (maximum 14 MHz bandwidth) fed straight to the diode either AC-coupled in combination with piezo and slow I feedback, or DC-coupled feedback only. (b) Cavity transmission intensity as a function of AOM frequency scanning around resonance for different locks. Cavity HWHM linewidth is 70 kHz, scan time was 10 ms. (c) LSD measurements of transmitted cavity signal at half peak height for high-bandwidth locks. Also shown are the intensity noise of the laser, measured by removing the cavity and measuring frequency fluctuations with an intensity equal to half the peak transmission intensity. For (a) and (c) noise below 10^4 Hz was measured using a computer sound card with a resolution bandwidth (RBW) of 12.2 Hz, noise between 10^4-10^6 Hz was measured with an spectrum analyser with a RBW of 30 Hz, and measurements above 10^6 Hz were measured with a spectrum analyser with a RBW of 300 Hz.

We investigated the efficacy of the polarisation spectroscopy locking set-up by analysing the error signal created. The frequency noise linear spectrum density (square-root of power spectral density) was determined with a computer sound card (low frequency) and RF spectrum analyser (medium and high frequency). The spectrum analyser was calibrated using the slope of the error signal and the known input impedance, while the sound card data was *matched* to the spectrum analyser data. Figure 1(a) shows the noise spectra for a number of different cases, with "AC" and "DC" referring to whether the laser head board was AC- or DC-coupled respectively *(AC cut-off=?)*. For the AC case, the piezo and low-bandwidth current feedback were also implemented, this was not the case for the DC locking, where all feedback was supplied through the fast current modulation input. Unsurprisingly, as the bandwidth of the locking increased, so did the reduction in noise, with the bandwidth of the piezo-only feedback being of order 200 Hz, slow current feedback being 70 kHz, and fast locking being 200 kHz. *Something about Bode bumps?*

The measurement of noise on the error signal for the fast current feedback is limited by the dark noise, measured by blocking the detectors, below approximately 30 kHz. This is due, in part, *to the suppression of noise within the feedback loop*. A more sensitive and precise measure of the frequency spectra requires a frequency discriminator. In this case we chose to use an ultra-stable cavity with a half-width-at-half-maximum (HWHM) linewidth of 70 kHz. The narrow linewidth of the cavity allowed us to measure noise up to 10 MHz, limited by the bandwidth of the detector. Figure 1(b) shows cavity transmission signals as the laser frequency is scanned with an AOM, with a sweep time of 10 ms. The resulting traces provide a clear illustration of the effect of increased locking bandwidth: with piezo locking only the peak appears broad as the laser jitters around the resonant frequency on the 10 ms timescale, as slow current feedback is applied the peak becomes narrower and taller, and finally we see the effect of high-bandwidth modulation with a peak that has a HWHM limited by the cavity finesse, indicating a laser linewidth much smaller than 70 kHz.

By choosing a static AOM frequency such that the transmitted laser intensity is half the peak intensity, and therefore the transmission-frequency response is approximately linear, we can analyse the frequency noise of the laser through the cavity transmission signal. This is shown in Fig. 1(c) for both the fast AC and DC locking, both now well above the dark noise. The other locks shown in Fig. 1(a) cannot be evaluated using this method, as they were too noisy to stay within the linear frequency response range of the cavity. The AC and DC locks are both flat at low frequencies, reducing above 50 kHz. The peaks in the dark noise between 10^4 and 10^6 Hz are due to electronic pick-up by the detector. The drawback of this method is that laser intensity noise is mapped into frequency noise. The laser intensity noise spectrum, measured at the same power as the locked transmission signal, is also shown in Fig. 1(c). The intensity noise is well below the cavity transmission noise and we can therefore assume that the measured spectrum is dominated by the frequency fluctuations of the laser.

We can extract a linewidth for the laser from the cavity data using two methods: first we can use the known bandwidth of the cavity to map the locked transmission signal to a *Gaussian/Lorentzian peak* and measure its linewidth *(Josh, is this correct?)*. For our system this gives a linewidth of ?? *approximately 5 kHz*. This method is sensitive to the laser intensity noise. To illustrate this, calculating a laser linewidth from the intensity noise gives a linewidth of ??, indicating that the real laser linewidth *is well below this value*. To extract an exact linewidth with this method, a cavity with a higher finesse would be required. The second method involves integrating the power spectral density to determine the rms linewidth *[cite* *negnevitsky2013]*. Performing this for the AC lock gives an rms linewidth of 350 Hz. Assuming the linewidth has a Gaussian shape gives a FWHM linewidth of approximately 850 Hz, much lower than that calculated using the above method. The results from these methods are summarised in Table 1.

Method	Linewidth (kHz)
(i) Map Gaussian (intensity)	5 ??
(ii) Map Gaussian (frequency)	5 ??
(iii) PSD Integral	0.85
(iv) Heterodyne	1 ??

Table 1: Linewidth calculation methods and results obtained. The mapping the transmission signal through a cavity with a HWHM of 70 kHz to a Gaussian signal [(i) and (ii)] is limited by the laser intensity noise. The results from integrating the power-spectral density signal (Fig. 1) and the Heterodyne beat-note (Fig. **??**) both give a value for the linewidth of less than 1 kHz.