Fraunhofer

UK

FRAUNHOFER CENTRE FOR APPLIED PHOTONICS CAP

Comparative study of techniques for measurement of linewidth and frequency-noise of single-frequency lasers

Gerald M. Bonner[1]*, Craig Hunter[1,2], Brynmor E. Jones[1], Matthew S. Warden[1], Jack W. Thomas[1], Loyd J. McKnight[1], Alexander A. Lagatsky[1], David J. M. Stothard[1], Jonathan M. Jones[3], Yeshpal Singh[3], Kai Bongs[3], and Fedor V. Karpushko[4]

*Corresponding author: gerald.bonner@fraunhofer.co.uk

[1]Fraunhofer Centre for Applied Photonics, Fraunhofer UK Research Ltd, 99 George St, Glasgow, G1 1RD, UK
[2]Institute of Photonics, Department of Physics, University of Strathclyde, 99 George St, Glasgow, G1 1RD, UK
[3]School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK
[4]UniKLasers Ltd, Bavelaw Business Centre, 46a Bavelaw Road, Edinburgh, EH14 7AE, UK

INTRODUCTION

Narrow-linewidth, single-frequency lasers find applications in many fields, especially quantum technologies, which require sources at various wavelengths, often with very specific frequency and linewidth specifications.

Laser linewidth is a more subtle concept than it may appear at first glance. The measurement timescale is essential, but is not always quoted. Which fluctuations in frequency contribute to the linewidth, and which are considered long-term drift depends on the context in which the laser is to be used. Also, while the linewidth is a useful single-number description of a laser's stability, full information about the laser's behaviour in the frequency domain requires the frequency noise power spectral density (PSD).

To better understand their capabilities, multiple measurement techniques have been applied to an in-house, breadboard Nd:YAG ring laser operating at 1064 nm, locked to a Fabry-Perot reference cavity (Thorlabs SA200-8B).

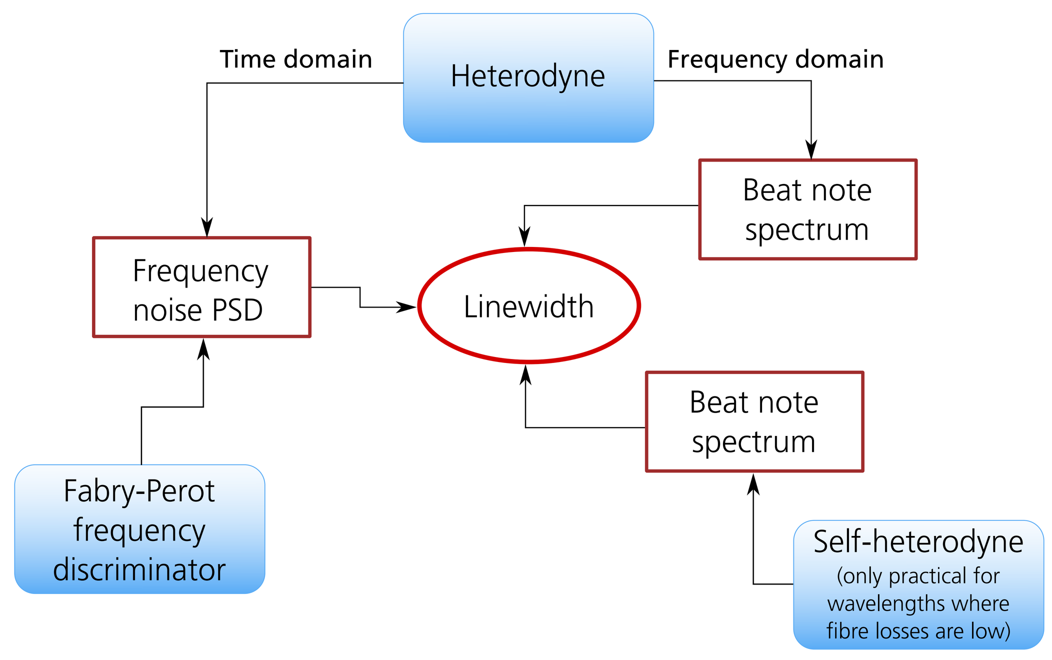
TECHNIQUES

Frequency discriminator - slope of peak of Fabry-Perot cavity used to measure frequency fluctuations over time, from which frequency noise PSD was calculated.

Heterodyne measurement - beat note between ring laser and commercial NPRO (Coherent Inc, Mephisto, specified linewidth of 1 kHz over 100 ms), recorded in frequency domain (RF spectrum analyser) and in time domain (high-speed digitiser). Time-domain data used to calculate frequency noise PSD [1] (independent measurement from frequency discriminator approach).

Linewidth calculated from PSD via the β-separation line [2, 3], which indicates which regions should be integrated to calculate FWHM linewidth.

Self-heterodyne measurement [4] - beating of laser field with delayed copy of itself. A 25-km fibre delay was used, giving linewidth over 125 µs.

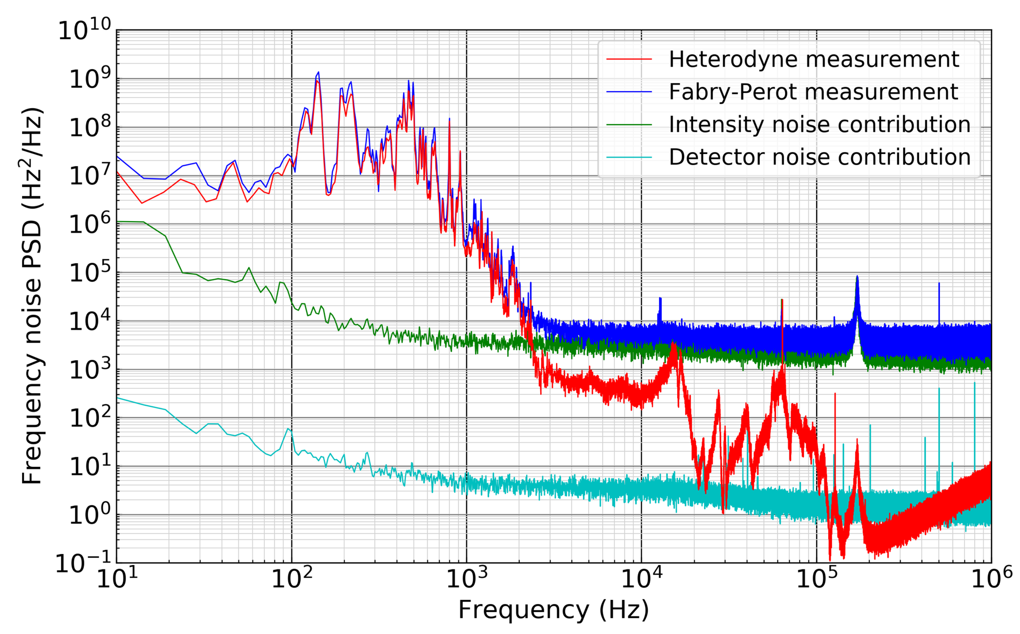


RING LASER - SIDE-OF-FRINGE LOCKED

On the **right** is shown the frequency noise PSD of the ring laser measured with a Fabry-Perot frequency discriminator, and the intensity and detector noise contributions to that measurement, along with the PSD calculated from the beat note of the ring laser and the Mephisto. (Since the Mephisto is much more stable than the ring laser, the latter is dominated by the frequency noise of the ring laser.)

It can be seen that the heterodyne technique is sensitive to noise features obscured by the laser intensity noise in the Fabry-Perot measurement. Otherwise, the two techniques agree very well on the features of the spectrum.

Applying the β-separation line technique (see below for an illustration with a different data set), yields linewidths of 706 kHz and 582 kHz from the Fabry-Perot and heterodyne measurements respectively.



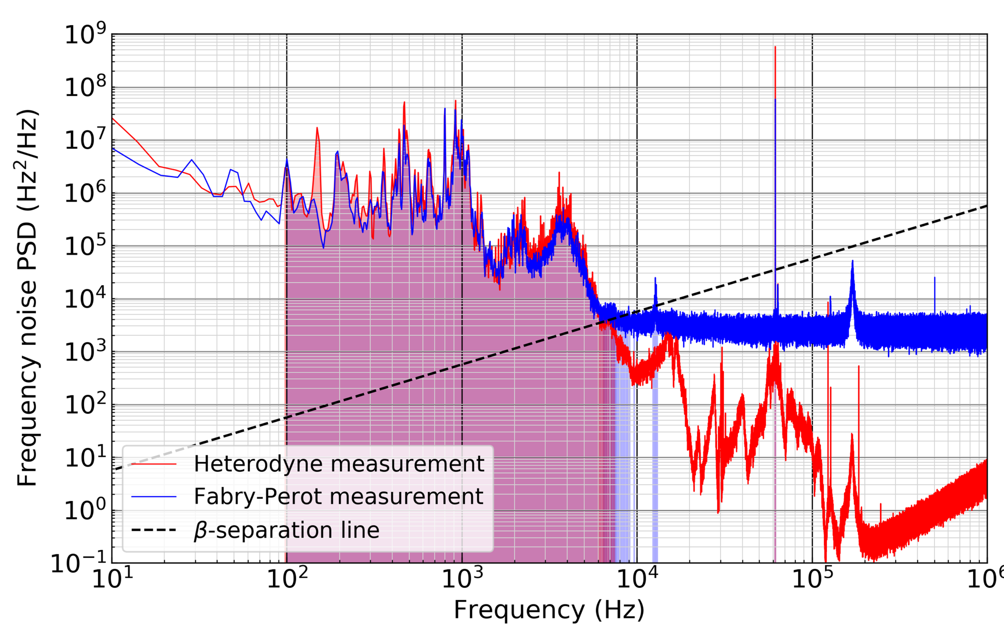
RING LASER - DITHER LOCKED

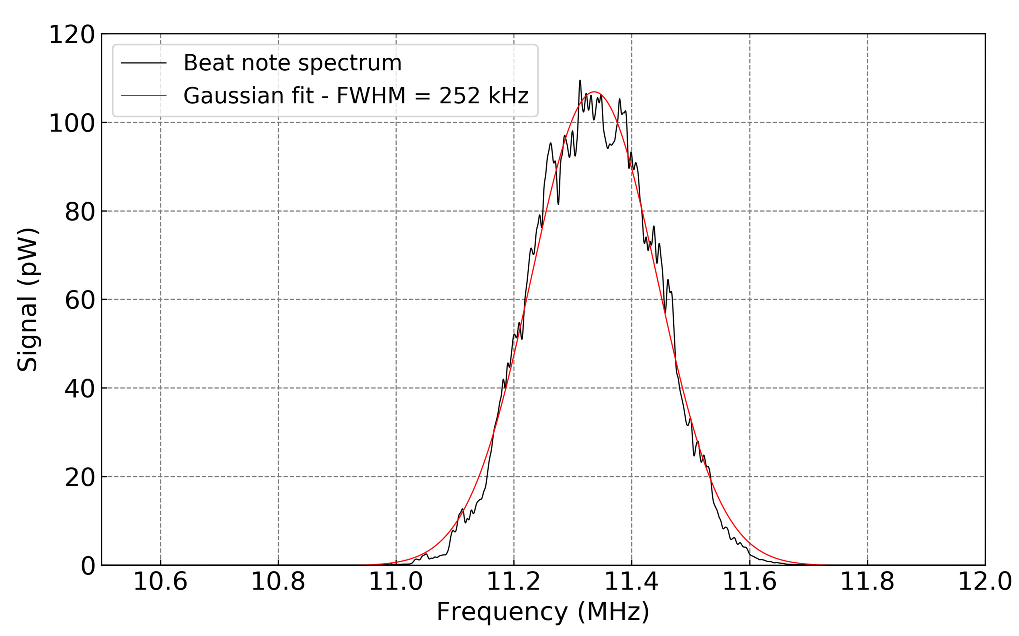
Below left - frequency noise PSD (linewidths from β-separation line)
Heterodyne measurement - 246 kHz over 10 ms
Fabry-Perot measurement - 152 kHz over 10 ms

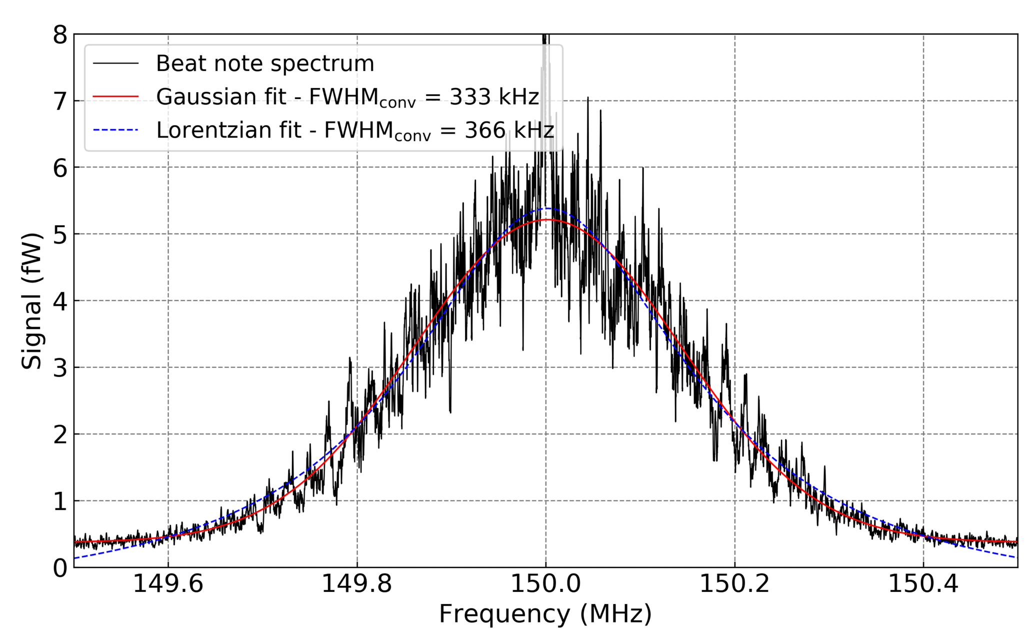
Below middle - beat note spectrum measured on RF spectrum analyser
Linewidth - 252 kHz over 10 ms

Below right - self-heterodyne signal (self-convolution of laser spectrum)
Gaussian fit - linewidth 235 kHz over 125 µs
Lorentzian fit - linewidth 183 kHz over 125 µs
For comparison, heterodyne-measured PSD yields 181 kHz over 125 µs.

Fabry-Perot-based measurement of PSD yields accurate locations of noise peaks (above limit of intensity noise) but accurate calibration of magnitude is very difficult. Heterodyne of two lasers yields more accurate results.





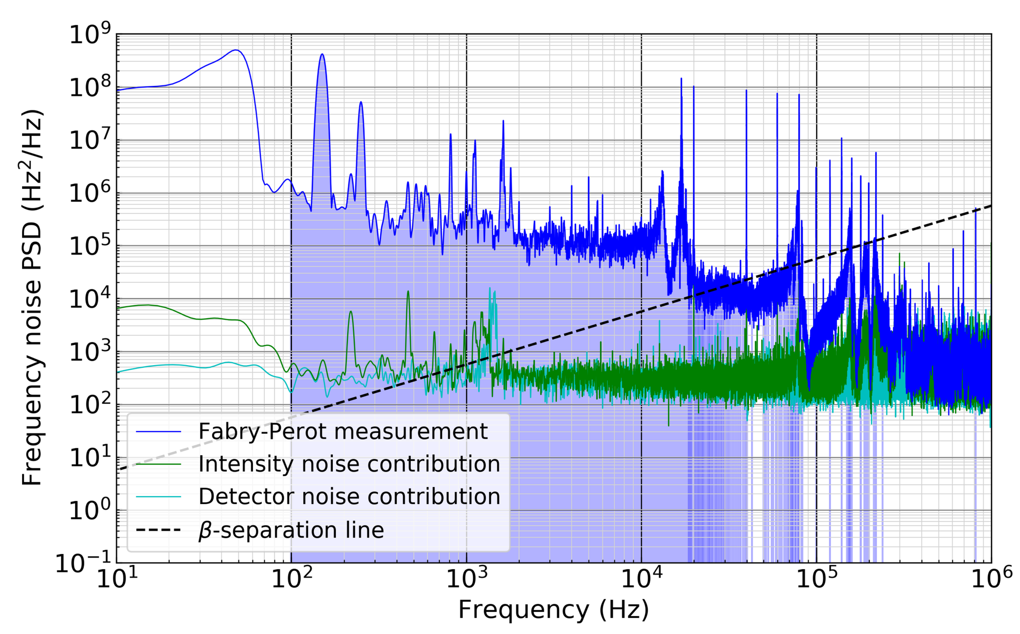


APPLICATION TO LASER PRODUCT DEVELOPMENT

Work is ongoing to apply these techniques to commercial laser products under development for quantum technologies and other applications. On the **right** is shown the frequency noise PSD of a prototype 698 nm laser (UniKLasers Ltd), as measured with a Fabry-Perot frequency discriminator. The laser was free-running. This measurement yields a linewidth of 437 kHz over 10 ms, but as noted above, the magnitude of the PSD and linewidth determined by this technique are subject to significant uncertainties.

This measurement showed large noise peaks at 20 kHz and its harmonics. These have been attributed to the digital communications line between the laser head and driver. This has now been replaced with an analogue line and it is expected that this will significantly improve the linewidth.

Measurements will soon be performed with two improved prototypes, via the heterodyne technique.



CONCLUSIONS AND FUTURE WORK

Fabry-Perot-based measurement of frequency noise PSD is a quick and relatively simple way to identify frequencies of key noise features. However, it is difficult to accurately calibrate the magnitude of the PSD, and hence obtain accurate linewidths.

If two identical lasers are available, or a much narrower laser at the same wavelength, then heterodyne measurements yield better results. Measuring the beat note in the time domain as well as the frequency domain provides much more information on significant noise frequencies as well as the linewidth.

Ongoing work will extend these experiments to study the time-dependence of the linewidth [1], and apply these techniques to lasers at various wavelengths of interest for quantum technologies (including 698, 780 and 813 nm).

REFERENCES

[1] N. Von Bandel, M. Myara, M. Sellahi, T. Souici, R. Dardaillon, and P. Signoret, "Time-dependent laser linewidth: beat-note digital acquisition and numerical analysis," Opt. Exp. 24, 27961-27978 (2016)
[2] G. Di Domenico, S. Schilt, and P. Thomann, "Simple approach to the relationship between laser frequency noise and laser line shape," Appl. Opt. 49, 4801-4807 (2010)
[3] N. Bucalovic, V. Dolgovskiy, C. Schori, P. Thomann, G. Di Domenico, and S. Schilt, "Experimental validation of a simple approximation to determine the linewidth of a laser from its frequency noise spectrum," Appl. Opt. 51, 4582-4588 (2012)
[4] T. Okoshi, K. Kikuchi, and A. Nakayama, "Novel method for high resolution measurement of laser output spectrum," Electron. Lett. 16, 630-631, (1980)

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding from Innovate UK and the Engineering and Physical Sciences Research Council.

IN PARTNERSHIP WITH

UNIKLASERS

UK National Quantum Technology Hub Sensors and Metrology

UNIVERSITY OF BIRMINGHAM