# Laser spectral linewidth

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***Spectral linewidth is a measure of the spectral content of the laser light. This value varies over many orders of magnitude depending on the type of laser: carefully stabilized continuous wave lasers may have spectral linewidth values of less than a Hz, while e.g. pulsed femto-second lasers may cover a spectral range of several THz.***

***The fundamental value for the spectral linewidth is given by the Shawlow-Townes expression which is essentially the contribution to the linewidth due to phase changes from spontaneous emission processes. For rare earth doped solid state lasers such as erbium doped fiber lasers the value for the Shawlow-Townes linewidth is in the range of mHz.***

***In general the fundamental linewidth of a narrow linewidth laser is difficult to measure: all methods of measurement will be subject to a finite measurement time and during this time the narrow line of the laser light will be subject to frequency jitter from different sources such as pump laser noise, acoustic noise, vibrations a.o.***

***For the case of narrow linewidth lasers therefore, the measured linewidth can be viewed as the integrated frequency jitter due to technical noise sources over the integration time of the measurement setup.***

## Linewidth measurement methods

### Self-heterodyne method:

One frequently used method for measuring laser spectral linewidth is the self-heterodyne beat method. In this method, the signal is passed through a fiber Mach-Zender interferometer with a path length imbalance in one arm and an AOM frequency shifter in the other (fig.1). An often used path length imbalance for narrow linewidth lasers is 25 km which corresponds to a temporal delay of approximately 120 µsec. Light from the two arms interfere at the receiver to produce a spectrum with a shape and width that depends on the laser linewidth.

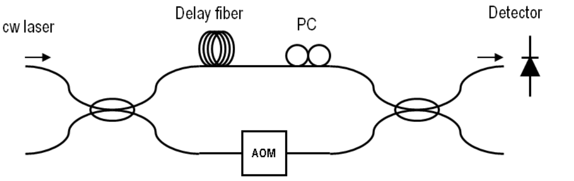


**Figure 1: Self-heterodyne linewidth measurement setup**

The analysis of the resulting spectrum falls in two regimes: one for lasers with a coherence length shorter than or comparable to the interferometer delay, and another for lasers with longer coherence length (the sub-coherent domain). Laser light with a coherence length shorter than the path length imbalance will ideally produce a Lorentzian spectrum with a half width at half max equal to the laser light spectral linewidth (fig.2).

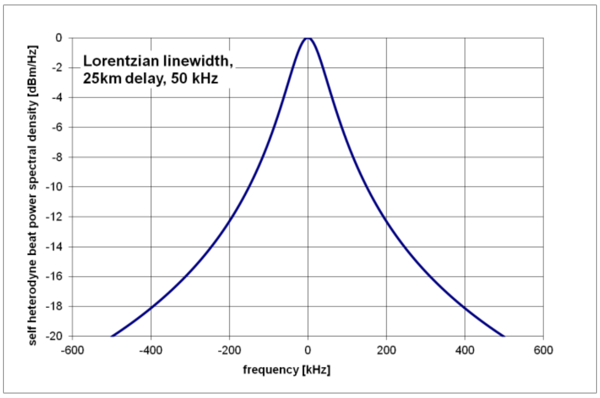


**Fig. 2: Theoretical Lorentzian lineshape function of light with a linewidth 50 kHz using self-heterodyne linewidth measurement with 25 km delay fiber.**

'Ideally' in this context refers to the fact that it is strictly true only for lasers with a white frequency noise spectrum (corresponding to an exponential decay of temporal coherence). Most lasers with a very narrow linewidth will have a spectrum that contains a substantial contribution from Gaussian type noise sources (examples of which include pump noise, vibrations, and acoustic noise). This results in a more complex Voigt profile, which is a convolution of a Gaussian and a Lorentzian profile. For rare earth doped fiber lasers the value of the Lorentzian linewidth is often small enough that the lineshape function is predominantly Gaussian. This corresponds to a frequency noise spectrum that follows a 1/f function to high frequencies (> MHz). In fact the white noise floor often does not show in the spectrum at all; instead the spectrum follows the 1/f behavior up to frequencies where contributions from shot noise and ASE start to dominate. Despite this laser manufacturers often extract a conservative measure for the Lorentzian linewidth by measuring the spectral width of the self-heterodyne lineshape 20 db below the peak where the contribution from the Gaussian is less pronounced. The corresponding Lorentzian half width is easily calculated as approximately 10% of the 20 dB width.

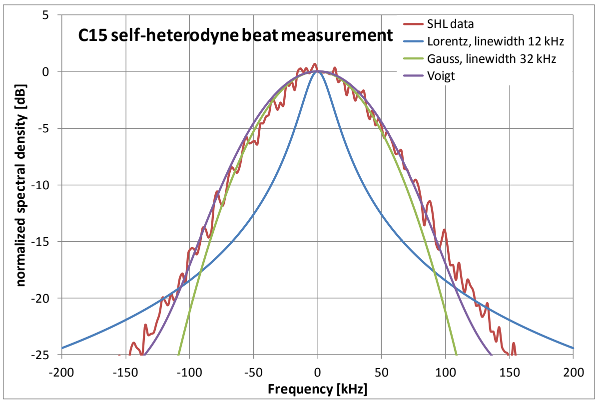


**Fig. 3: C15 laser self-heterodyne linewidth data (25 km delay fiber) plotted together with different lineshape functions: Lorentzian (12 kHz), Gaussian (32 kHz), and Voigt.**

Fig. 3 illustrates a self-heterodyne measurement for a C15 laser: the half width of the measured self-heterodyne linewidth data is approximately 32 kHz, while the 20 dB half width is approximately 120 kHz. The figure shows the corresponding Gaussian with a half width of 32 kHz and the Lorentzian lineshape function with a 20 dB half width of 120 kHz, corresponding to a Lorentzian linewidth of 12 kHz; neither the Gaussian nor the Lorentzian lineshape function provide a good fit. The Lorentzian that intersects the data at the -20 dB points obviously represents a very poor fit, and only tradition justifies using this number as a measure for the laser Lorentzian linewidth (which clearly is significantly narrower). A Voigt fit is shown for comparison.

For lasers with a coherence length significantly longer than the interferometer imbalance the self-heterodyne lineshape function deviates significantly from the Lorentzian lineshape function. This is due to coherent interference of light from the two interferometer paths. Fig. 4 illustrates the case for light with 700 Hz linewidth. The lineshape function consists of a Dirac delta function at the AOM frequency combined with the interferometer transfer function, where the depth of the ripples is determined by the laser linewidth. Measurement noise and finite system bandwidth will modify the theoretical lineshape function and obscure the real value of the depth of the ripples.

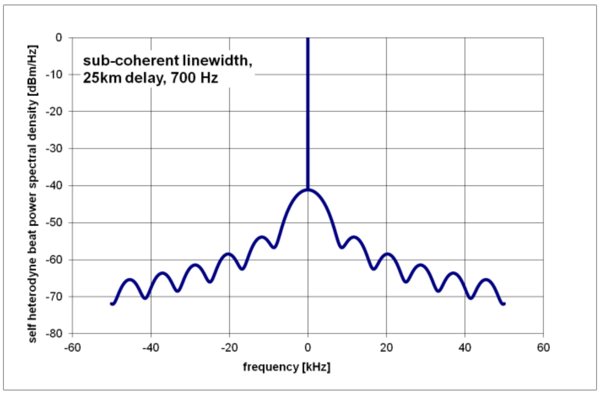


**Fig. 4: Theoretical lineshape function for sub-coherent light with a linewidth of 700 Hz using self-heterodyne linewidth measurement with 25 km delay fiber**

While this type of lineshape function is in itself an indication that the linewidth is less than roughly 1 kHz, the linewidth is best obtained by fitting the data to the measured lineshape function. Fig. 5 illustrates a sub-coherent linewidth measurement on an E15 laser along with the lineshape function corresponding to a linewidth value of of 200 Hz.

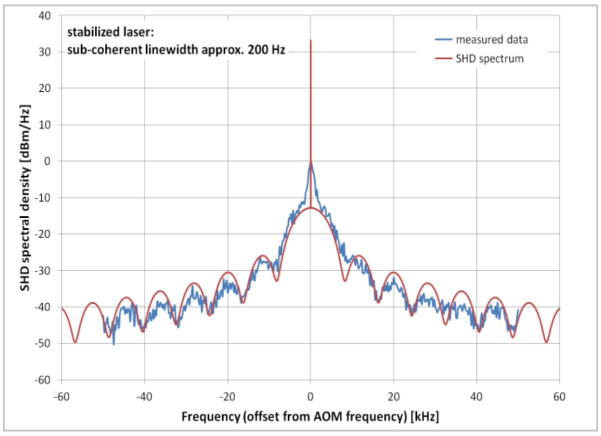


Fig. 5: Stabilized E15 laser with a sub-coherent linewidth of approximately 200 Hz obtained by fitting measured data to the sub-coherent lineshape function (25 km delay fiber)

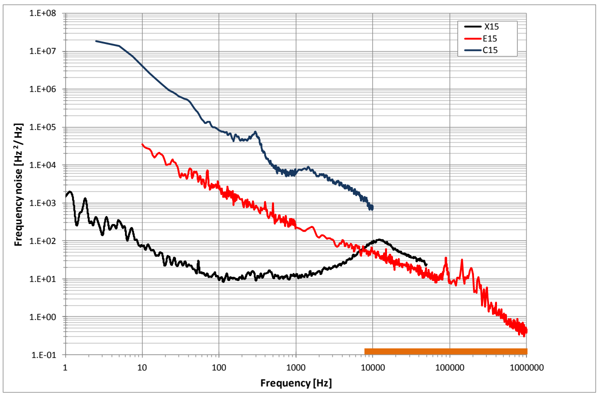


Fig. 6: Frequency noise for laser types X15, E15, C15. Orange line indicates roughly the integration range that corresponds to self-heterodyne linewidth measurement with a 25 km fiber delay.

## Integration of phase noise

An alternative way of measuring the linewidth is based on integrating the frequency noise:

$$\Delta\nu_{rms}^2 = \int_0^\infty S_{\Delta\nu}(f) \cdot df$$

Where $S_{\Delta\nu}(f)$ is the frequency noise spectral density function (measured in $Hz^2/Hz$). While this approach has theoretical validity, at least for lasers dominated by 1/f noise, it only makes sense if the frequency range of integration is known. For comparison with the self-heterodyne beat method with 25 km delay fiber, integration should be performed from approximately 10 kHz and up to the upper frequency limit of the setup. The frequency noise for E15, X15 (stabilized version of E15), and C15 fiber lasers are shown in fig. 6.

## Heterodyne beat note linewidth

The term 'heterodyne beat note linewidth' loosely covers the linewidth of the narrow laser line that is subjected to frequency jitter due to technical noise, leading e.g. to kHz linewidth values when measuring with the self-heterodyne beat method and 25 km delay as described above. The exact width of this line is very difficult to measure, but calculations based on fundamental laser parameters for rare-earth doped fiber lasers indicate values in the mHz range. The straight forward approach to obtain a measure for this value is (as alluded to by the name) to beat the laser under test either with a stable narrow line source or with a similar laser. If the beat note can be captured with sufficient resolution, the linewidth can be measured. The challenge in capturing a representative measure lies with the technical noise: to measure sub-Hz linewidth values requires that the beat frequency does not drift outside the span of the measurement window during measurement. For most lasers this is a serious limitation unless they are stabilized to a very high degree. An example of such a laser is Menlo's ORS1500, which is a fiber laser locked to an ultra-stable low thermal expansion interferometer (http://www.menlosystems.com/assets/datasheets/MENLO-ORS1500-datasheet-2013-07-3w.pdf). This makes it possible to produce a beat note with a linewidth < 0.3 Hz (fig. 7 & fig. 8). The drawback is the size and complexity of such a system which renders it practical only for specialized applications.

Fig. 7: MenloSystems ORS1500 stabilized fiber laser

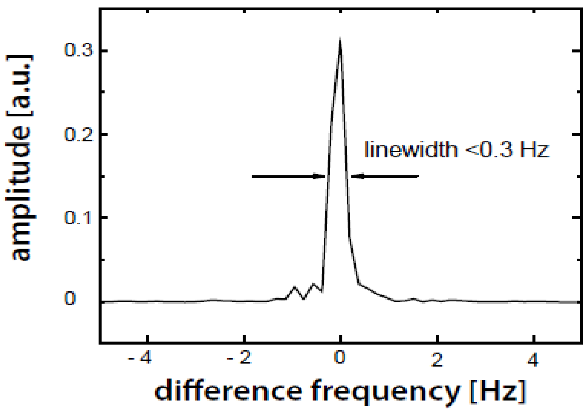


Fig. 8: Beat note between two MenloSystems ORS1500 stabilized fiber lasers: linewidth < 0.3 Hz

For the compact, stabilized X15 laser, the residual frequency drift inhibits a measurement of the heterodyne beat note linewidth to such low values, but it is still possible to capture a linewidth value of a few 10's of Hz.

## A note on coherence

The coherence time of the laser light is ideally inversely related to the linewidth by the relation $\Delta\nu = 1/(\pi \cdot \tau_{coh})$. This relation is only strictly true for the case of Lorentzian linewidth. As described above, for narrow linewidth lasers such as rare-earth doped fiber lasers the measured linewidth is best viewed as the integrated frequency jitter of a much narrower line. Therefore, if the measured linewidth is used, the coherence time (and coherence length) is always much larger than the value dictated by this inverse relation.

## Laser linewidth summary

| | SHD linewidth | | | Heterodyne beat note linewidth |
|---|---|---|---|---|
| | 3-dB Gaussian | 20-dB Lorentzian | sub-coherent | |
| **E15** | NA | NA | 100 Hz | NA |
| **X15** | NA | NA | 100 Hz | << 50 Hz |
| **C15** | < 50 kHz | < 15 kHz | NA | NA |
| **Y10** | < 70 kHz | < 20 kHz | NA | NA |

## References / suggested reading

[1]http://www.rp-photonics.com/self_heterodyne_linewidth_measurement.html

[2]http://www.rp-photonics.com/linewidth.html?s=ak

[3] Fritz Riehle, "Frequency Standards, Basics and Applications", Wiley 2004, section 3.4