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Laser Linewidth, Frequency Noise and Measurement

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LASER LINEWIDTH AND FREQUENCY NOISE SPECTRUM DENSITY

Single Frequency Laser and Frequency (phase) Noise

Ideally, a single frequency laser operates at single frequency with zero linewidth. In a real world, however, a laser has a finite linewidth because of phase fluctuation, which causes instantaneous frequency shifted away from the central frequency: $\delta\nu(t) = (1/2\pi)\, d\varphi/dt$.

Linewidth

Laser linewidth is an important parameter for characterizing the purity of wavelength (frequency) and coherence of a light source. Typically, laser linewidth is defined as Full Width at Half-Maximum (FWHM), or 3 dB bandwidth **(SEE FIGURE 1)**

Direct optical spectrum measurements using a grating based optical spectrum analyzer can only measure the laser line shape with resolution down to ~pm range, which corresponds to GHz level. Indirect linewidth measurement can be done through self-heterodyne/homodyne technique or measuring frequency noise using frequency discriminator.

Frequency Noise Power Spectrum Density

Frequency noise power spectrum density reveals detailed information about phase noise of a laser, which is the root cause of laser spectral broadening. In principle, laser line shape can be constructed from frequency noise power spectrum density although in most cases it can only be done numerically. Laser linewidth can be extracted.

Correlation between laser line shape and frequency noise power spectrum density (ref [1])

$$S_E(\nu) = E_0^2 \int_0^\infty \cos[2\pi(\nu-\nu_0)\tau]\exp\left[-4\int_0^\infty S_\nu(f)\frac{\sin^2(\pi f\tau)}{f^2}df\right]d\tau, \quad (1)$$

$S_E(\nu)$: *laser optical power spectrum density (PSD) – laser line shape*

$S_\nu(f)$: *frequency noise power spectrum density*

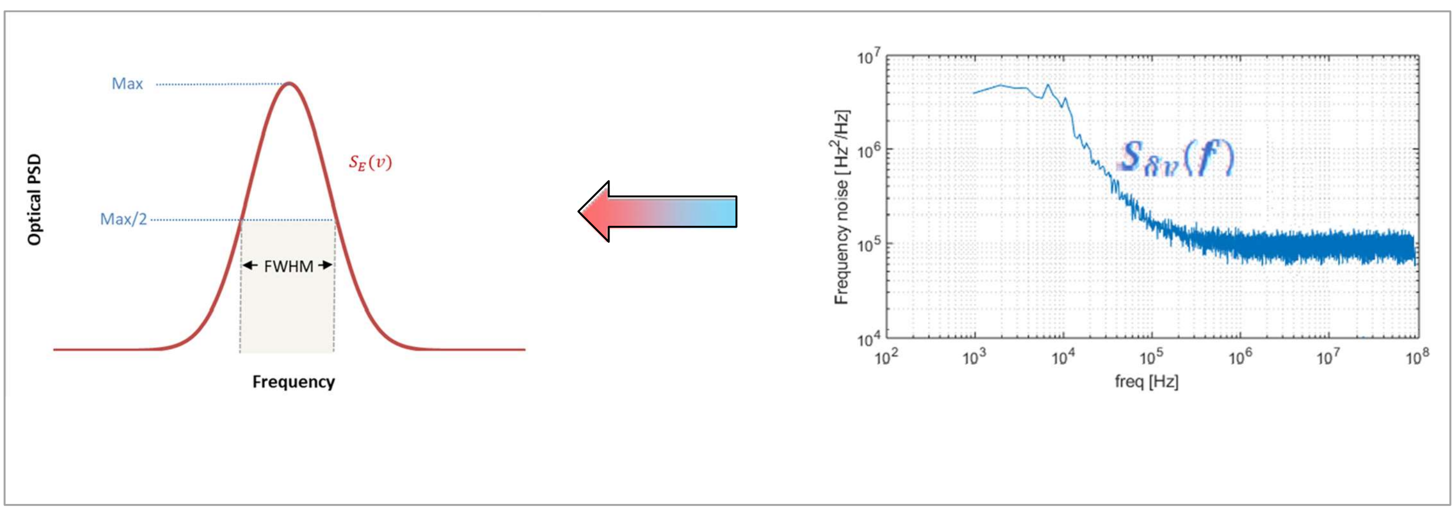
Laser light field: $E(t) = E_0 \exp[i(2\pi\nu_0 t + \varphi(t))]$

Equation (1) is difficult to calculate, but a simpler expression gives a good approximation (ref [2])

An effective integrated linewidth $\Delta\nu\_int$ can be found by solving the equation:

- $$\int_{\Delta\nu_{int}}^{\infty} S_\varphi(f)df = \int_{\Delta\nu_{int}}^{\infty}\frac{S_\nu(f)}{f^2}df = \frac{1}{\pi}rad^2$$

FIGURE 1



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FREQUENCY NOISE SOURCES

Frequency noise spectrum typically comprises two noise components: White Noise and Flicker (1/f) Noise (Random-walk noise ignored). White noise is from intrinsic spontaneous emission. Flicker (1/f) noises are caused by the fluctuations from different sources such as laser cavity, driver circuit etc. Low noise laser current source (< 500 pA/Hz^1/2) is essential to accurately measure laser linewidth.

White noise generates Lorentzian line shape. 1/f noise generates Gaussian line shape. Overall line shape has Voigt profile, which is the convolution of Lorentzian and Gaussian functions.

In the simplified case of only white noise, laser linewidth can be analytically expressed as FWHM = π * frequency noise (Hz^2/Hz). For convenience, ORTEL's laser linewidth spec is defined as: π * frequency noise (Hz^2/Hz) @100 kHz. **(SEE FIGURE 2 & 3)**

FIGURE 2

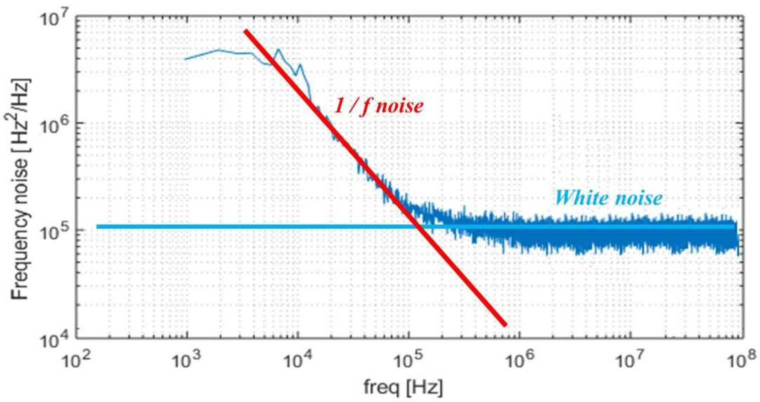
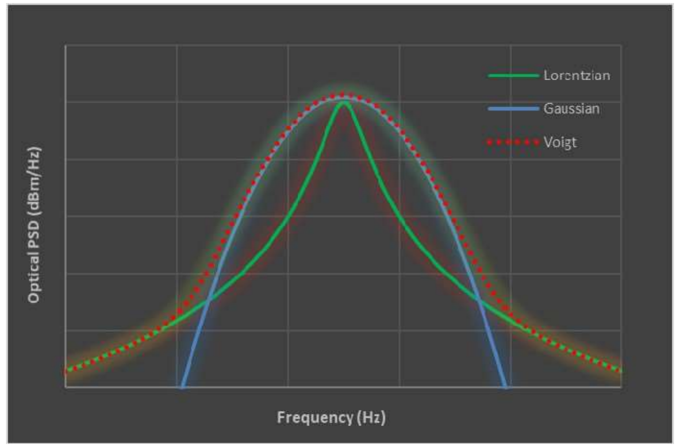


FIGURE 3



LINEWIDTH AND FREQUENCY NOISE MEASUREMENT

Measurement Methods

Self-heterodyne and self-homodyne techniques: These techniques detect the beat signal between the laser and the delayed / frequency shifted version of itself. The difference between the self-heterodyne and self-homodyne techniques is that an AO modulator is used for frequency shift in self-heterodyne technique.

Frequency discriminator technique: This technique converts the optical phase noise into variations of intensity. It also uses an interferometer, and the detection is at or near quadrature point.

Selection of Optical Path Delay

To measure the laser linewidth using self-heterodyne/homodyne technique, a delay length larger than the coherence length of the laser source should be used. If the laser linewidth is very small, the delay length required may become impractical.

For frequency noise measurement using frequency discriminator, a delay that is much shorter than laser coherence length (in the range of meters) is usually used. The measured RF range corresponds to free spectral range (FSR) of the interferometer, which is related to delay length.

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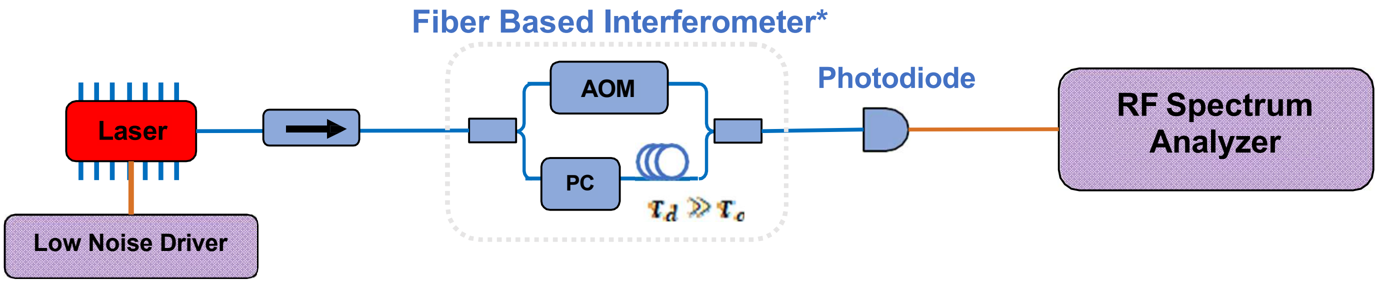
MEASUREMENT SETUP

FIGURE 4

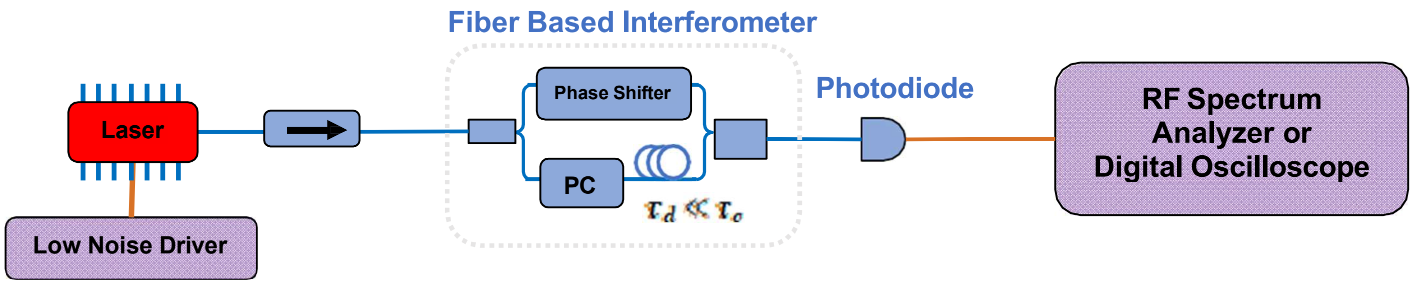
Delayed Self-Heterodyne/Homodyne Setup



***** No AOM for self-homodyne setup***

FIGURE 5

Frequency Discriminator Setup



REFERENCES

[1] Gianni Di Domenico, Stéphane Schilt, and Pierre Thomann, Simple approach to the relation between laser frequency noise and laser line shape, Applied Optics, Vol. 49, 25, 4801 (2010)

[2] Minh A. Tran, Duanni Huang, and John E. Bowers, Tutorial on narrow linewidth tunable semiconductor lasers using Si/III-V heterogeneous integration, APL Photonics 4, 111101(2019)