

Intensity and Phase Noise of Optical Sources

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Noise is the limiting factor for many photonics applications such as optical communications or measurements. Therefore, it can be crucial to properly measure and specify the noise properties of optical sources.

The phenomenon of noise in optics appears in a great variety of forms and has a profound impact on many applications in photonics. The difficulty of dealing with noise (as well as the intellectual pleasure for the more experienced) has several reasons: the fundamentally different physical origins of noise issues, the often non-obvious interplay of noise phenomena, the subtleties of noise measurement techniques, and sometimes also the mathematical machinery required for noise specifications and calculations. In any case, noise can and should be quantified in situations where it matters, and proper noise specifications help the system designer to avoid trouble as well as the component manufacturer to convince customers of the suitability and quality of his products. Competence on noise issues allows one to resolve many issues before one goes into costly and time-consuming experiments.

In the following we deal with intensity and phase noise in optics, focusing on issues of measurement and specification.

Intensity Noise

Fig. 1: Intensity noise spectrum of a diode-pumped miniature Nd:YAG laser. A detector with a bandwidth high enough to record the relaxation oscillations (corresponding to the peak) will display much higher noise than a slow detector.

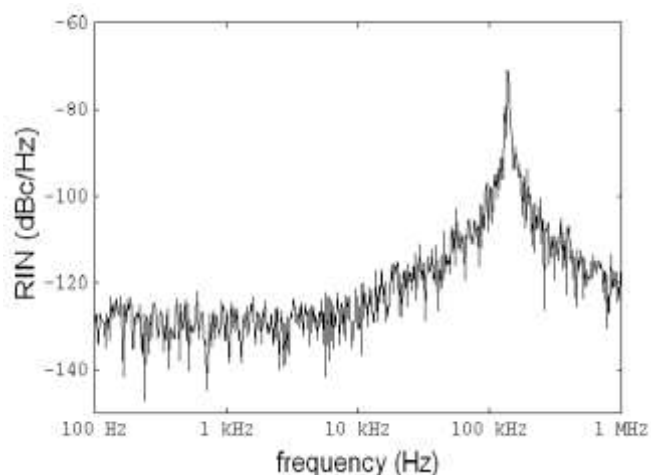


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The simplest kind of noise of lasers and other light sources is intensity noise, with which one actually means noise of the optical power. Frequently encountered specifications like “ $\pm 1\%$ ” are not convincing. They suggest that the power always stays within 1% of its average value, while in reality there is usually a smooth probability distribution without sharp edges. Moreover, the registered fluctuations can strongly depend on the measurement bandwidth (see Fig. 1), so that a number without specification of a bandwidth is actually meaningless. Actually one would often like to know the spectral distribution of noise in the form of a power spectral density $S(f)$ of the optical power, usually normalized to the average value to result in relative intensity noise (RIN) in units of 1/Hz, or in dBc/Hz when quoting $10 \cdot \lg(S(f) \cdot 1 \text{ Hz})$. The variance (mean squared fluctuation, i.e., square of rms value) of relative intensity is then the power spectral density integrated over the measurement bandwidth.

Intensity noise measurements are usually done with a photodiode, the output of which is analyzed either with an electronic spectrum analyzer or with a digital sampling card. A

spectrum analyzer directly delivers a power spectral density, but correct noise measurements require the use of suitable device settings (e.g. “sample”, not “peak” mode for the electronic detector) as well as a correction of adding typically ≈ 2 dB to take care of the effective noise bandwidth and some averaging issues. (Unfortunately, lots of incorrect data are spread due to a lack of knowledge on these issues.) An interesting alternative technique relies on a sampling card for direct recording of the optical power fluctuations, followed by numerical Fourier analysis on a PC. This technique delivers valuable time-domain information and allows to measure correlations between fluctuating quantities, but also has its subtleties, e.g. the need for so-called window functions to avoid artifacts in the obtained noise spectra.

Photodetection also introduces noise, which may mask the laser noise. Thermal and other noise from the detector electronics may be minimized with suitable design (although less easily for high detection bandwidths) to reach the level of shot noise, for which the light source rather than the detector is to be blamed – except if the detector requires optical attenuation, which raises the shot noise level.

Phase Noise and Linewidth

Here we consider only single-frequency lasers, as used e.g. for optical sensors. Quantum noise, cavity vibrations and other effects cause the optical phase to undergo a so-called random walk. Phase fluctuations are best quantified with a power spectral density $S_\phi(f)$, or alternatively as frequency noise with $S_\nu(f) = f^2 S_\phi(f)$. For a free-running oscillator, $S_\phi(f)$ diverges for $f \rightarrow 0$. This divergence is related to the unbounded drift of the phase (which lacks a “restoring force”) and needs proper handling e.g. when phase noise is calculated from a recorded beat note. It also causes a finite value of the linewidth, which is the width of the main peak in the power spectral density of the optical field. The linewidth depends on the measurement time as long as that is not long enough to fully resolve the low-frequency part of the noise spectrum.

Phase noise is most often obtained from beat measurements – either from a beat note between two different lasers, or between the laser output and a delayed portion of it, often with an additional frequency shift provided by an acousto-optic modulator (\rightarrow delayed self-heterodyne measurements, see Fig. 2). The delay is often achieved with a long optical fiber. If this can be longer than the coherence length, one can use simple processing techniques as the fluctuations of both signals are statistically independent. If this is impractical, more sophisticated techniques of data analysis can be employed. The most flexible measurement scheme is again based on recording the beat signal with a sampling card, even though the initial efforts for data processing are more extensive than with a spectrum analyzer.

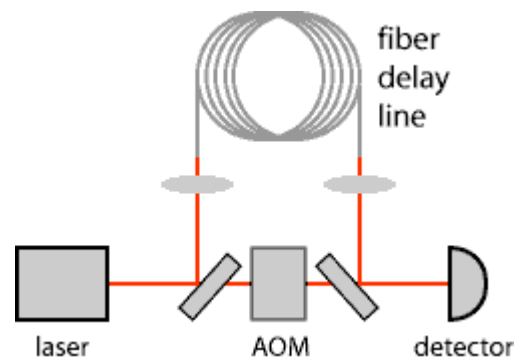


Fig. 2: Delayed self-heterodyne setup for phase noise and linewidth measurements. The mirrors next to the acousto-optic modulator (AOM) have a reflectivity of e.g. 50%. The detector records the beat note between the frequency-shifted part and the delayed part of the laser light.

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