Laser Phase Noise

Application note on phase noise in single frequency lasers V1.0 October 2013

Laser phase noise is a frequency-domain view of the noise spectrum around the laser signal. It is related to fluctuations of the optical phase of the laser's output.

Phase noise may occur in the form of a continuous frequency drift, or as sudden phase jumps, or as a combination of both. Due to various influences, even a single-frequency laser will not exhibit a perfect sinusoidal oscillation of the electric field at its output. There are fluctuations of the power and the optical phase ϕ. The latter can be quantified by the power spectral density (PSD) of the phase fluctuations with a phase noise PSD $S_\phi(\omega)$, having units of rad^2/Hz (or simply Hz^{-1}, as radians are dimensionless). This leads to a finite linewidth of the laser output. The linewidth of a laser, typically a single-frequency laser, is the width (typically the full width at half-maximum, FWHM) of its optical spectrum. Particularly in cases with 1/f frequency noise, a linewidth value alone may not be regarded as completely characterizing the phase noise. It is prudent to measure the whole Fourier spectrum of the phase or instantaneous frequency fluctuations and characterize it with a power spectral density.

Phase noise is directly related to frequency noise, as the instantaneous frequency is essentially the temporal derivative of the phase. For example, white (frequency-independent) frequency noise corresponds to phase noise with $S_\phi(\omega) \approx 1/\omega^2$.

The fundamental origin of phase noise is quantum noise, in particular spontaneous emission of the gain medium into the resonator modes, but also quantum noise associated with optical losses. In addition, there can be other noise influences such as those due to vibrations of the cavity mirrors or to temperature fluctuations.

Application Implications

In any optical fiber interferometric system (such as acoustic, magnetic and acceleration sensors, spectroscopy/LIDAR and coherent optical fiber communications), there are many noise contributions which limit the sensitivity of such devices. The presence of laser phase noise limits the resolution of these interferometric sensors. Phase noise in an interferometric system is strongly dependent on the optical path difference between the arms of the interferometer. Low phase noise lasers are often utilized for interferometric sensor applications demanding 10s of kilometers of coherence length. The lasers are commonly designed into a Michelson, Fabry-Perot or Mach Zender interferometric configuration. Therefore, lasers with low phase noise/narrow linewidth are often required. This is especially significant as the optical path difference in the arms of the interferometer increase, the phase noise contribution increases accordingly, which can increase the system noise thus limiting the minimum detectable signal.

Lower the phase noise, the narrower the linewidth. Narrow linewidth is important in coherent optical systems where optical phase information is utilized. Though, a narrow linewidth from a laser source is not always desirable. A large coherence length implies that interference effects can easily spoil the beam profile. In laser projection displays, speckle effects can disturb the image quality. For transmission of light in passive or active optical fibers, a narrow linewidth can cause problems due to stimulated Brillouin scattering. It is then sometimes necessary to increase the optical linewidth, for example by fast dithering of the instantaneous frequency via current modulation of a laser diode or with an optical modulator.

Phase noise definitions

The measurement of the phase fluctuations of a sinusoidal voltage signal is defined as:

$S(t)=V_0\cos[\omega_0 t+\varphi(t)]$

Where V_0 is the amplitude of the signal, ω_0 is the nominal frequency and $\varphi(t)$ is the random varying phase, assumed $\ll 1$ radian. When this signal is mixed with another signal

$R(t)=V_0\cos[\omega_0 t+\gamma(t)]$

in phase quadrature, the mixer acts as a phase detector resulting in a voltage signal proportional to the phase difference of the two signals:

$V(t)=\varphi(t)-\gamma(t)$

where again it is assumed $\gamma(t)\ll 1$ rad. Phase fluctuations $\varphi(t)$ and $\gamma(t)$ relative to the ideal $V_0\cos(\omega_0 t)$ are termed the absolute phase noise of their respective signals. The power spectra of the absolute phase fluctuations $\varphi(t)$ and $\gamma(t)$ are defined as $S_\varphi(\omega)$ and $S_\gamma(\omega)$, respectively.

A single source measurement technique utilizes a Frequency discriminator (FD) method. This is a single source method, where the signal from the device under test is split and a relative delay is imposed before being applied to the mixer. The resulting voltage signal can be shown to be

$S_{FD}(\omega)=2\cdot S_\phi(\omega)\cdot(1-\cos(\omega\tau))$

where τ is the relative delay between the two signals from the device under test.

Laser phase noise testing

Phase noise measurements are often based on a recorded beat note between two lasers on a fast photodiode. Alternatively, it is possible to record a beat note of the laser output with a different portion of the same laser output, which is subject to a long delay, e.g. by propagation through a long span of optical fiber. Laser noise often depends on ambient conditions. Therefore, it is essential to know what the ambient conditions are for which certain specifications apply. In particular:

- Does it apply to constant room temperature, or for arbitrary temperature changes within the allowed range of operation temperatures?
- Is it valid immediately after switching on the device, or only after a long warm-up time?
- Is a vibration-free/acoustic-free environment assumed?

One method of measuring laser phase noise is shown in Figure 1. The laser is sent through an optical path mismatch. One leg of the mismatch contains a piezoelectric cylinder, wrapped with optical fiber, which is used to impose the phase generated carrier. The modulation frequency is generally in the 20-50KHz range. The mismatch is on the order of 100 meters in order to scale the phase noise contribution above other possible sources of noise during the measurement, (system noise etc.) The laser and optical path mismatch are isolated from acoustics in an acoustical isolation enclosure. This enclosure is then isolated from vibration using an air mount structure. The optical path mismatch is packaged to provide a level of acoustic and vibration isolation.

The output from the path imbalance is then photo-detected and demodulated using a receiver. This voltage signal is then measured using a suitable spectrum analyzer.

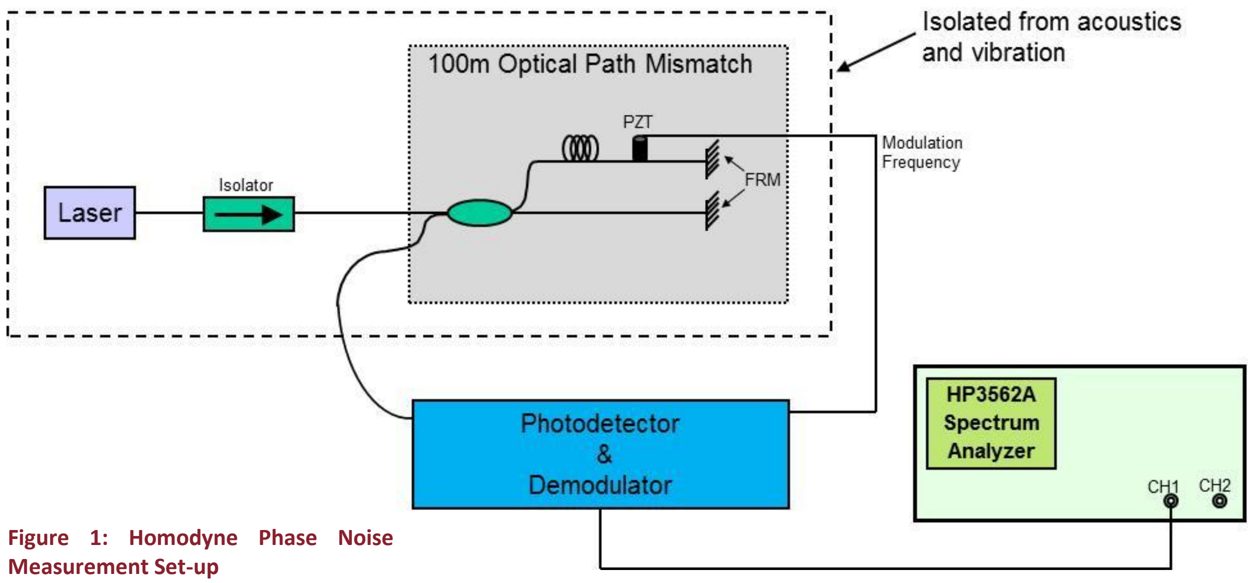

Figure 1: Homodyne Phase Noise Measurement Set-up

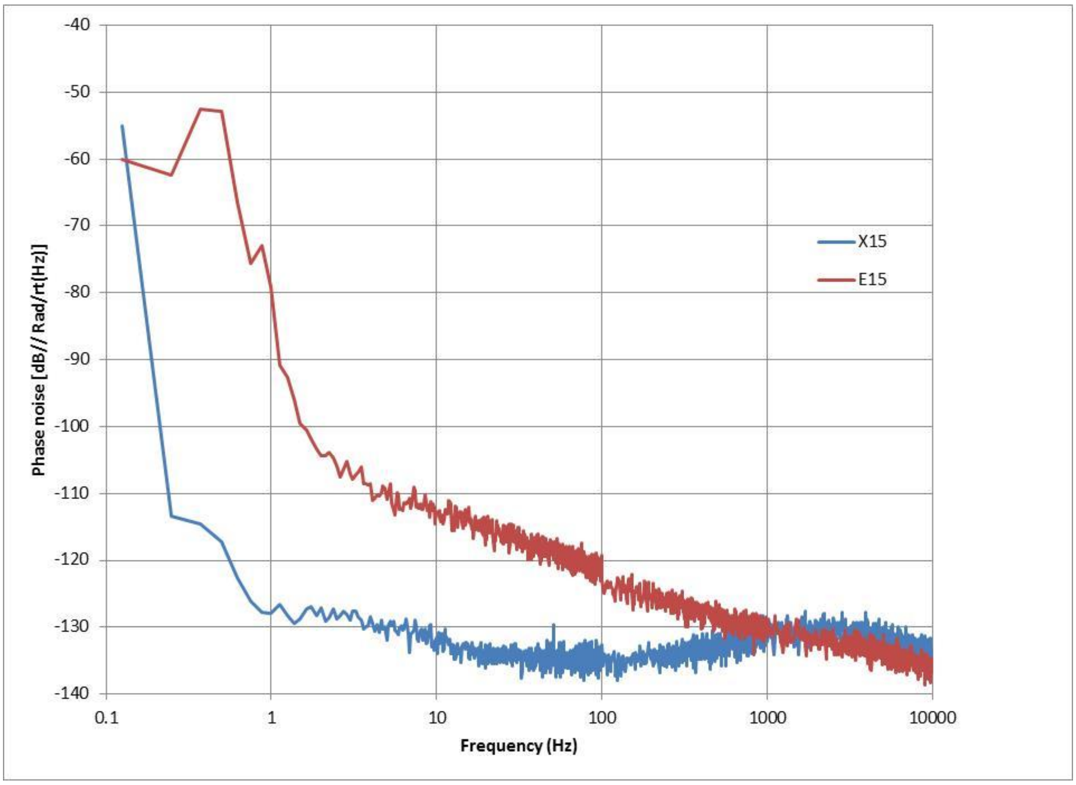

Figure 2: Phase noise of the Koheras E15 and X15 laser modules. Plots are normalized to an optical path imbalance of 1m.

Bibliography

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