Semiconductor Optical Communication Components and Devices

Lecture 25: Diode Laser Noise

Prof. Utpal Das

Professor, Department of Electrical Engineering,
Laser Technology Program,
Indian Institute of Technology, Kanpur

http://www.iitk.ac.in/ee/faculty/det_resume/utpal.html
Laser Noise 1:

Spontaneous emission coupled to a lasing mode is a direct origin of quantum noise.

A spontaneously emitted photon becomes a small component of the stimulated emission field with a random phase. Random variation of the output intensity is described by “relative intensity noise” (RIN), and the noise leads to “signal to noise ratio” SNR.

The actual quantum noise properties of diode lasers are strongly affected by the competition between carrier & photon fluctuation, carrier induced refractive-index change, and current noise related temperature change.

For the two random processes fluctuations the characterization is most suitable when the analysis is done in the power spectrum along with its correlation.

Quantum mechanical Langevin equation method and the density matrix method are used for the analysis of AM and FM noise in semiconductor lasers.

The Marcovian fluctuation operator “F” gives rise to a Langevin distribution, where:

$$F_{\rho_{\nu}}(t) \approx 2\sqrt{\langle \rho_{\nu} \rangle} \cdot \text{Re}\{\exp[-j\phi(t)].E_{\text{sp}}\}$$

There would be a similar term for the carrier noise.

Where $\rho_{\nu}$ is the Photon number in the cavity and $E_{\text{sp}}$ is the complex spontaneous noise term, and $\phi$ is the phase.
Laser Noise 2:
Quantum Noise in Semiconductor Lasers

AM Noise

Spontaneous Emission

FM Noise

Carrier Noise

Anomolus Dispersion, Free Carrier Dispersion

Refractive Index Fluctuation

Current Noise

Temperature Impedance

Temperature Function

Laser Noise 3:

Let the fluctuations in the Carriers and Photons be:

\[ N(t) = \bar{N} + \delta N(t), \quad \bar{N} \text{ is the average} \quad & \quad \delta N \text{ is a delta function} \]

\[ \rho_\nu(t)d\nu = \bar{\rho}_\nu d\nu + \delta \rho_\nu(t)d\nu, \]

\[ \bar{\rho}_\nu d\nu \text{ is the average} \quad & \quad \delta \rho_\nu d\nu \text{ is delta function} \]

Using the Langevin distribution ‘F’ similar to random distributions of magnetic or electric dipoles where the average generation rate is G

\[ \frac{d\bar{N}}{dt} = G \]

For \( \alpha_i = \pm 1 \), \( F_N(t) = \frac{d[\delta N(t)]}{dt} = \sum_i \alpha_i \delta(t-t_i) \)

\[ \frac{dN(t)}{dt} = G + F_N(t) \]

Similarly \[ \frac{d\rho_\nu(t)}{dt} = G \rho_\nu + F_{\rho_\nu}(t) \]

\[ (F_N(t).F_N(t-\tau)) = \left\langle \sum_i \delta(t-t_i)\delta(t-\tau-t_i) \right\rangle = \delta(\tau) \left\langle \sum_i \delta(t-t_i) \right\rangle = \delta(\tau)G \]

By Fourier Transform the white power spectrum of \( F_N \) is:

\[ S_{NN}(\omega) = G \]
Laser Noise

The generation of photons is related to the recombination of electrons and absorption of photons generates electrons. Hence the correlation between the electrons and photons, ‘NN’, $\rho_vN$, $N\rho_v$, and $\rho_v\rho_v$ needs to be found using the Langevin function in each of the rate equations for the carriers and the photons, giving the power spectrum as:

$$S_P(\omega) = \hbar\omega P_{\text{out}} \left[ \left( a_1 \omega^2 + a_2 \right) |H(\omega)|^2 + 1 \right] + a_3 |H(\omega)|^2$$

Where $|H(\omega)|$ is the normalized frequency response of the laser, $a_1$, $a_2$, and $a_3$ are constants are given by:

$$a_1 = \frac{2V_a N}{\tau_{\text{ph}} \tau_{\text{sp}} \omega_r}, \quad a_2 = \frac{2V_a N}{\tau_{\text{ph}} \tau_{\text{sp}} \tau_c^2 \omega_r}, \quad a_3 = \frac{2V_a N^2 (\hbar \omega)^2}{\tau_{\text{nr}}}$$

Assuming that most of the photons are lost only through the end mirror/s.

Where $N$ is the carrier concentration, $V_a$ is the active region volume, $\omega_r$ is the laser resonant frequency, $\tau_{\text{sp}}$, $\tau_c$, and $\tau_{\text{nr}}$ are the spontaneous emission, total carrier, and nonradiative time constants, respectively.

$$\text{SNR} = \frac{\langle i_S^2 \rangle}{\langle i_N^2 \rangle} = \frac{P_{\text{out}}^2}{\langle \delta P(t)^2 \rangle} = \frac{P_{\text{out}}^2}{S_P(\omega)\Delta\omega}$$

The Relative Intensity Noise is:

$$\text{RIN} = \frac{1}{\text{SNR}} = \frac{S_P(f)}{P_{\text{out}}^2} \Delta f$$

Laser Noise 5 (Phase Noise)

Let the Schawlow-Townes linewidth $\Delta \nu_{ST} = \Delta \nu (\alpha_H = 0)$

$$\frac{d\delta \phi(t)}{dt} = 2\pi \delta v(t) = \frac{\alpha_H}{2} \Gamma \frac{dg}{dN} \frac{c_0}{n_r} \delta N(t) + F_\phi(t)$$

$$\delta v(\omega) = \frac{\alpha_H}{4\pi} \Gamma \frac{dg}{dN} \frac{c_0}{n_r} \delta N(\omega) + \frac{F_\phi(\omega)}{2\pi}$$

$$S_{\delta v \delta v}(\omega) = \frac{\Delta \nu_{ST}}{2\pi} (1 + \alpha_H^2 |H(\omega)|^2)$$

$$\sigma_{\delta \phi}(\tau) = 2 \Delta \nu_{ST} A$$

$$A = \int_{-\infty}^{+\infty} 1 + \frac{\alpha_H^2 |H(\omega)|^2}{\omega^2} (1 - \cos \omega \tau) d\omega$$

$$\Delta \nu = \Delta \nu_{ST} (1 + \alpha_H^2)$$

Let the Schawlow-Townes linewidth $\Delta \nu_{ST} = \Delta \nu (\alpha = 0)$

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$$\delta \nu(\omega) = \frac{\alpha_H}{4\pi} \Gamma \frac{d \gamma}{dN} c_o \delta N(\omega) + \frac{F_\phi(\omega)}{2\pi}$$

$$S_{\delta \nu \delta \nu}(\omega) = \frac{\Delta \nu_{ST}}{2\pi} (1 + \alpha_H^2 |H(\omega)|^2)$$

$$\sigma_{\delta \phi}(\tau) = 2 \Delta \nu_{ST} A$$

$$A = \int_{-\infty}^{+\infty} \frac{1 + \alpha_H^2 |H(\omega)|^2}{\omega^2} (1 - \cos \omega \tau) d\omega$$

$$\Delta \nu = \Delta \nu_{ST} (1 + \alpha_H^2)$$

Laser Noise 7 (enhanced noise due to scaling)

If the size of a laser diode cavity is reduced the active volume decreases and the number of photons and electrons also decrease. Therefore fluctuation of one photon even becomes a large fraction of the total number of photons present. This increases Relative Intensity Noise (RIN). Reducing laser diode dimensions therefore increases the negative feedback between chemical potential and injected current in a voltage biased device. Thus RIN in a scaled laser diode depends critically on whether the device is biased with a current or a voltage. In addition, RIN at low frequencies is enhanced while RIN at or near the resonant frequency $\omega_0$ is suppressed.

Photon statistics obtained for a photon number of $4 \times 10^6$ for consecutive time intervals of $10^{-13}$ s.

Review Questions:

1. What is the main source of Diode-Laser noise? Enumerate other sources of this noise.

2. Find the relative intensity noise at $\lambda=1.5\mu m$ for a laser operating at 100mW, with a small signal bandwidth of 30GHz. Given that the active volume is $250x4x0.01\mu m^3$, $\tau_{ph}=2.5ps$, $\tau_c=0.5ns$, $\tau_{nr}=1.0ns$, $N=10^{19}cm^{-3}$, $|H(\omega)|=\omega r^4/[(\omega r^2+\omega^2)+(\omega\gamma)^2]$, $\gamma=(2+0.3\omega r^2)x10^{-9}$, and $f_r=25GHz$.

3. If the resonance frequency of a diode laser is 15GHz and the small signal $f_{3dB}=30GHz$, what should be the range of the upper limit of the relative intensity noise given that at low frequency modulation the relative intensity noise at unit bandwidth is $-100dB/Hz$ and $\tau_c=1.0ns$.

4. How is the noise affected by the size of the cavity? Explain your conclusions.