Semiconductor Optical Communication Components and Devices

Lecture 24: Diode Laser Chirp

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http://www.iitk.ac.in/ee/faculty/det_resume/utpal.html
Assume a diode laser oscillating in a single mode (transverse and longitudinal). The linewidth of the is the $\Delta \nu_{\text{FWHM}}$ decided by the Fabry-Perrot cavity given by:

$$\Delta \nu_{\text{FWHM}} = \left( \frac{1 - R}{\pi \sqrt{R}} \right) \left( \frac{c}{2nL\cos\theta} \right)$$

However, single mode emission is affected by phase fluctuations due to spontaneous emissions of noncoherent photons. As the photon population and the carrier density in the cavity are coupled, fluctuations in the cavity gain due to photon fluctuation leads to a fluctuation in the effective index inside the cavity, leading to a fluctuation in the cavity resonant frequency. The change in the cavity frequency (intrinsic linewidth) is given by:

$$\Delta \nu = \frac{\hbar \nu}{4\pi \tau_{\text{ph}}^2} \frac{1 + \Delta n_r/\Delta n_i}{P_{\text{out}}},$$

Where the complex refractive index is $n = n_r + jn_i$

The reflectance ‘R’ of a FP spectrum analyzers are typically 0.99 and as seen from the above equation the spectral bandwidth is very narrow. On the other hand for a typical FP semiconductor cavity $R \approx 0.35$. Therefore the cavity linewidth is much larger than the cavity linewidth and can be $\sim 1 \text{nm}$. On the other hand for very stringent requirements of WDM, where DFB lasers are used, the laser linewidth could be less by an order of magnitude.
Laser Chirping:
Whenever a diode laser is modulated the number of carriers in the active region changes. The rate of stimulated emission changes and the photon output also changes. Unfortunately, the refractive index is also dependent on the number of carriers, as given in the plot below [Mendoza et al, J. Appl. Phys., 51, 4365(1980)].

Consider the laser with a narrow linewidth (red curve). As the modulation current is increased the change in the cavity refractive index is also increased. The cavity modes sweep over larger and larger frequency range and an average measurement of the spectrum shows a much larger linewidth (as given by the other curves).

\[ \Delta n_r = -AN+B \]

Where \( A \) is a constant and \( B \) is a function of the detuning factor from the band edge.

\[ \Delta n_r = -\frac{Ne^2\lambda^2}{(8\pi^2\varepsilon_0nc^2m^*)} \]
Laser Chirping:

Chirping therefore limits the bit rate that the laser can be operated at, where:

\[
\text{Bit Rate } R \leq \frac{1}{4\sigma} = \frac{\lambda}{4} \sqrt{\frac{1}{2\pi c_0 D L}}
\]

For lasers with narrow linewidths

Assuming a Gaussian pulse of width \( \sigma \)
Where \( D \) is the dispersion of the communication channel at \( \lambda \) and \( L \) is the length of the channel.

When a laser is switched from below threshold to full power the effect of Chirping is maximum and it can be somewhat reduced for Fabry Perrot cavity lasers by reducing the overshoot of the photons from the steady state value and by applying a pre pulse of \( \sim 20\% \) of the main current pulse before the application of the actual signal pulse.

Therefore for all practical high speed communication systems modulation is done by biasing the laser well above threshold (see lecture on modulation of Laser Diodes) where Bandwidth is proportional to the square root of the bias current. Even then the limit for a 100Km long channel is \( \sim \) few GBits only.
Chirping in Diode Lasers

\[ P_{\text{out}}(z) = P_{\text{out}}(0) \cdot \exp \left( -j \frac{2\pi}{\lambda_0} n_r z - \frac{2\pi}{\lambda_o} n_i z \right)^2 \]

\[ \Gamma G = -\frac{4\pi}{\lambda_o} n_i \]

for \( \tilde{n} = n_r + jn_i \)

\[ \alpha_H = \frac{dn_r}{dn_i} = -\frac{4\pi}{\lambda_o} \frac{1}{\Gamma dG} \frac{dn_r}{dn} \]

\[ v = m \frac{c_o}{2n_r L} \]

\[ \frac{dv}{dN} = -m \frac{c_o}{2n_r L} \frac{1}{n_r} \frac{dn_r}{dN} = -\frac{c_o}{\lambda_o n_r} \frac{dn_r}{dN} \]

\[ \Delta v \approx -\frac{c_o}{\lambda_o n_r} \frac{dn_r}{dN} \Delta N \]

\[ \Delta v(t) = \frac{\alpha_H}{4\pi} \frac{dG}{dN} \frac{c_o}{n_r} \Delta N = \frac{\alpha_H}{4\pi} \frac{1}{P_{\text{out}}} \frac{dp_{\text{out}}(t)}{dt} \]

Small signal
Laser Chirping:

Chirp parameter in DFB laser

\[
\frac{\Delta v}{\Delta I} = \frac{\alpha}{8\pi} \left( \frac{hv}{q} \right) v_g \alpha_m \kappa \quad \text{Where} \quad \alpha_m = \frac{1}{2L} \ln\left( \frac{1}{R_1 R_2} \right)
\]

\( v_g \) is the group velocity of the photons in the cavity.
\( \kappa \) is the coupling between the photons and the grating of a DFB laser.
And \( \alpha \) is the chirp parameter.

Therefore in Fabry-Perrot lasers the control of \( \alpha \) is difficult, however in DFB lasers the frequency is essentially controlled by the Grating period and therefore if the period is tuned to the lower wavelength side of the gain peak, the chirp factor is lower. Again for QW lasers in DFB the density of states being constant for low powers the change is frequency is lower and \( \alpha < 3 \) can be obtained.

Even then this is not adequate for high frequency modulation and then one could use external cavities or more importantly use external modulators. However, this increases cost unless one can have them in integrated format. Isolation between the laser and the modulator is of extreme importance and this is where the challenge of the integration of Laser and Modulator lies.
1. At what frequencies should a diode laser be directly modulated to encounter chirping? What is the origin of chirping and how does it affect the bit rate of optical communication?

2. Does a negative chirp affect the maximum bit rate of transmission through a dispersive optical fiber in the same way as a positive chirp? Explain your answer.

3. An InGaAsP/InP DH single mode laser is operating at a power $P_0$ in the steady state with a FWHM linewidth of 0.5nm. Estimate the average linewidth of the laser due to chirp when it is modulated at a frequency $1.5\omega_0$ modulated to a power level of $2P_0$. $\omega_0 = 5$GHz and the Henry factor is $\alpha_H = 3.5$.

4. Does one expect the same $\alpha_H$ for all modes of a multimode semiconductor laser? Explain your answer.

5. Guess how the linewidth would be affected for a large signal modulated diode laser.
Review Questions - II

5. A direct detection optical fiber PCM communication system, operating at a wavelength of $\lambda_o = 1610\text{nm}$, is to operate over a distance of 50Km without any repeaters. The link is formed with a dispersion shifted (zero dispersion at 1550nm) silica fiber of 0.2dB/Km loss at the operational wavelength of $\lambda_o = 1610\text{nm}$ and a residual dispersion of 50 ps.Km$^{-1}$.nm$^{-1}$. The laser output is 200mW at a line-width of $(\Delta\lambda_{\text{FWHM}})_{\text{initial}} = 0.2\text{nm}$, as shown in the adjacent figure. The chirp in the laser, on modulation, is given as:

$$(\Delta\lambda_{\text{FWHM}})_{\text{final}} = \left[8.633 \times 10^{-24}\right] \cdot \text{Exp}(0.4 \cdot f_m) \text{ nm},$$

where $f_m$ is the modulation frequency in GHz. The modulation delay (exponential) for the laser, $t_d = 12.0\text{ps}$. The detector Noise equivalent power (NEP) is $12.6 \text{ pW}/\sqrt{\text{Hz}}$ and has a transit time limited 3dB bandwidth of 45GHz. (assume the pulses to be Gaussian in nature). What is the MAXIMUM POSSIBLE BIT RATE of the communication link? Show calculations to justify your conclusion. (May need iterative solution)