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Optimization of material and grating geometry for narrow linewidth DFB lasers

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Demanding for narrow linewidth and stable lasers for several applications:

- Metrology
- Quantum (e.g. laser cooling)
- Sensing (e.g. LIDAR)
- Telecommunications
- Positioning (e.g. GPS)
In semiconductor lasers the linewidth is described by the Schawlow-Townes formula

\[
\Delta \nu = \frac{\Gamma_{active} R_{spont} \hbar \nu (\alpha_i + \alpha_m) \alpha_m (1 + \alpha_H^2) v_g^2}{8\pi P_{out}}
\]

- \( \alpha_i \) internal losses of the material.
- \( \Gamma_{active} \) mode confinement in the active region.
- \( R_{spont} \) spontaneous emission rate.
- \( \alpha_m \) mirror losses.
- \( P_{out} \) power output from the laser.
- \( \alpha_H \) linewidth enhancement factor
- \( V_g \) group velocity.

J. Buus, et al., Tunable Laser Diode and Related Optical Sources, 2014
For a typical doping profile, p- and n-doped average absorption are $\alpha_p = 22 \text{ cm}^{-1}$ and $\alpha_n = 1 \text{ cm}^{-1}$ in InP-based.

Reduction of material losses in “pulling” the mode out of the highly lossy p-doped material.

FRL in the n-doped region has higher refractive index than claddings hence:

- pulls the guided mode out of the p-doped hence decreases $\alpha_i$
- decreases $\Gamma_{\text{active}}$
From an existing 3QW wafer emitting at 1550 nm, the FRL geometry was optimised:

- 500 nm thick FRL with no spacing from active area
- Reduction of QW number $n_{QW}$ from 3 to 2

Fit of the material parameters from differential efficiency $\eta$ in Broad Area Lasers (BALs).

Measured internal losses $\alpha_i = 4.13 \text{ cm}^{-1}$ lower in comparison with the non-optimised wafer with $\alpha_i \approx 10 \text{ cm}^{-1}$
From Schawlow-Townes formula, inverse relationship between linewidth and power output.

However, in real lasers verified just for a limited power range before linewidth broadening.

\[ \Delta \nu = \frac{\Gamma_{\text{active}} R_{\text{spont}} \nu (\alpha_i + \alpha_m) \alpha_m (1 + \alpha_H)^2}{8 \pi P_{\text{out}}} \]

\( \alpha_H \) depends on the injection current and, as a consequence, on the power output.
• Longitudinal single-mode operation with a side mode suppression ratio (SMSR) exceeding 60dB.

• Very accurate selection of the emission wavelength

• Suitable for complex grating engineering on both transverse and longitudinal directions

• No material regrowth required

• Simple fabrication technology
Longitudinal Spatial Hole Burning (LSHB)

Phase shift layer is necessary for single mode operation but affects the electric field uniformity. For high-power operation the electric field distribution, and gain in turn, is peaked at the phase shift layer.

LSHB due to the correlation between the carrier concentration and the refractive index in semiconductors.

- Enhanced by non-uniformity in cavity field.
- Increases of the linewidth enhancement factor $\alpha_H$ and causes mode hopping.

Engineering of the grating geometry to uniform the electric field across laser cavity.

$\Delta \nu = \frac{\Gamma_{\text{active}} R_{\text{spont}} h \nu (\alpha_i + \alpha_m) \sigma_m (1 + \alpha_H^2 \gamma_s^2)}{8 \pi P_{\text{out}}}$
Chirped Grating

Standard solutions to uniform the cavity field include:


However both method are longitudinally engineered and have strict fabrication tolerances (i.e. \(\approx 1 \text{ nm}\)).

**Grating coupling chirp**

• Better fabrication tolerances for transverse direction (i.e. \(\approx 10 - 100 \text{ nm}\)).
• Critical parameters: chirp length \(L_{\text{chirp}}\) and chirp depth \(\kappa_{\text{min}}\)
• Constant average in the chirp region \(n_{\text{avg}} = \sqrt{\frac{n_{\text{eff1}}^2 + n_{\text{eff2}}^2}{2}}\)

\[\Delta \nu = \frac{\Gamma_{\text{active}} R_{\text{spont}} h \nu (\alpha_i + \alpha_m) \alpha_m (1 + \alpha_m^2)}{8 \pi P_{\text{out}}}\]
The aim of the central chirp is “to screen” the effect of the phase shift layer on the field distribution.

From simulations the optimal chirp length is $L_{\text{chirp}} = 3 \, \mu m$

Sweep on the chirp depth $\kappa_{\text{min}}$ allows to finely tune the field distribution inside the cavity.

The best cavity field uniformity, closest to the uniform grating, is obtained for $\kappa_{\text{min}} \approx \frac{\kappa_{\text{max}}}{2}$
Results

Single mode operation over a wide current range

Power output as high as $96\, mW$

High side-mode suppression ratio

$70\, dB$
Under the same fabrication conditions, chirped grating lasers have narrower linewidth than standard phase shifted lasers at high injection currents and high-power operation.
Conclusions

• Improvement of the mode profile for low losses (i.e. $\alpha_i = 4.13 \text{ cm}^{-1}$) at 1550 nm wavelength

• Improvement of the single-mode and narrow linewidth range (i.e. no linewidth broadening until $I = 500 \text{ mA}$) through chirped grating

• Narrow linewidth (i.e. $\Delta \nu \approx 100 \text{ kHz}$) and high power (i.e. $P_{out} \approx 100 \text{ mW}$) lasers emitting at 1550 nm wavelength
Thank you for your attention

Any question?
Fabrication Process

1. **EBL mask definition**
   - **Upper cladding**
   - **Active region**
   - **Lower cladding**
   - **Substrate**

2. **Cladding dry etch**

3. **SiO$_2$ passivation**

4. **PMMA mask definition**

5. **SiO$_2$ etch**

6. **P-contact metal evaporation**

7. **Substrate thinning**

8. **N-contact metal evaporation**
Mode 1 \[ \Gamma_{active} = 0.4\% \]

Mode 2 \[ \Gamma_{active} = 1.1\% \]
Multiple Quantum Well (MQW) active region to finely tune the optical transition through QW geometry.

For narrow QWs, the QW number does not affect mode profile but just mode confinement \( \Gamma_{active} = n_{QW} \Gamma_{1QW} \).

For high-power operation the best condition is to maintain low carrier density to avoid detrimental effects, such as junction heating or higher/non-radiative transitions.

Low \( \Gamma_{active} \), hence low \( n_{QW} \), and long laser cavity \( L \) allows to have low carrier density also in power regimes.

Typical values for \( n_{QW} \) are 3-5 for InP-based and 1-2 for GaAs-based materials.
• Strong and clear RF signal with a large number of points (i.e. 10000 points)

• Voigt fit (convolution of Gaussian and Lorentzian lineshape)

• Linewidth measurement at -3dB from the peak are analytically calculated from the FWHM at -40dB and -50dB from the peak. This measurement is not depending on the fit quality so it can be considered a reliable value but represent an upper limit.
Linewidth in chirped gratings

The measured linewidth for DFB lasers with and without chirp clearly shows that the chirped grating allows to reach larger injection current before to have linewidth broadening.
• The asymmetry in the cavity reflectivity does not dramatically affect the electrical field distribution, others cavity modes with a different field distribution do not lase as they do not overlay the active region.

• The chirped grating ensures a uniform field distribution also for single-facet cavity
Pound-Drever-Hall Technique to lock the absolute wavelength to a stable reference through electronic feedback

Ultimate aim is the integration of the laser and stabilization setup in an enclosed package