Optimization of material and grating geometry for narrow linewidth DFB lasers

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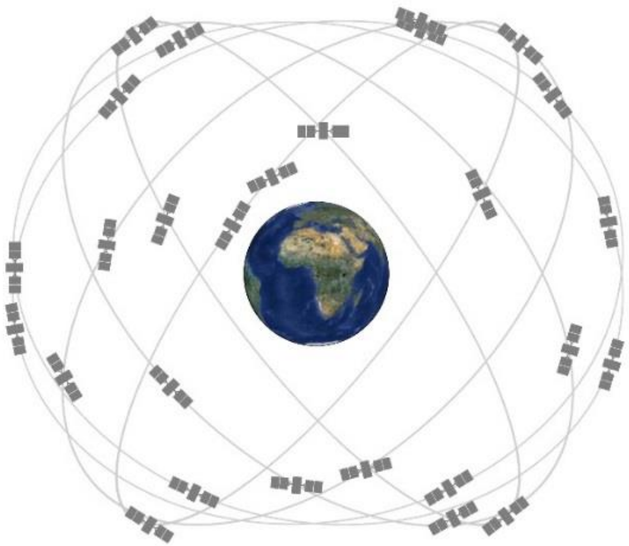
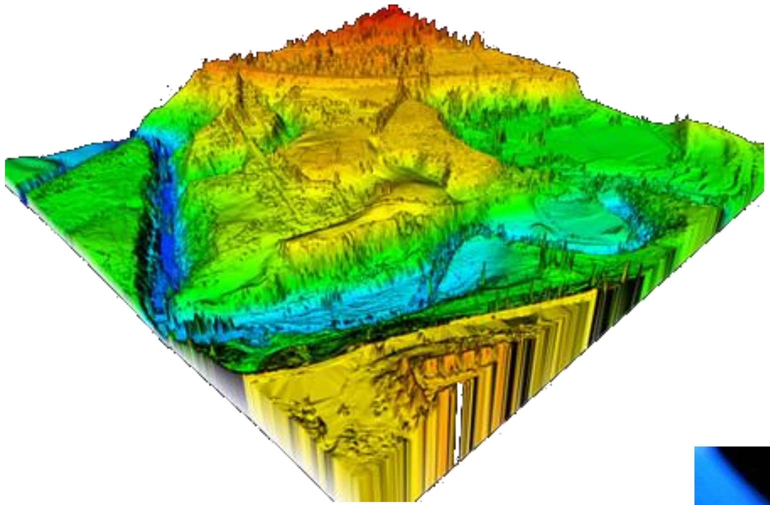
INSPIRING PEOPLE

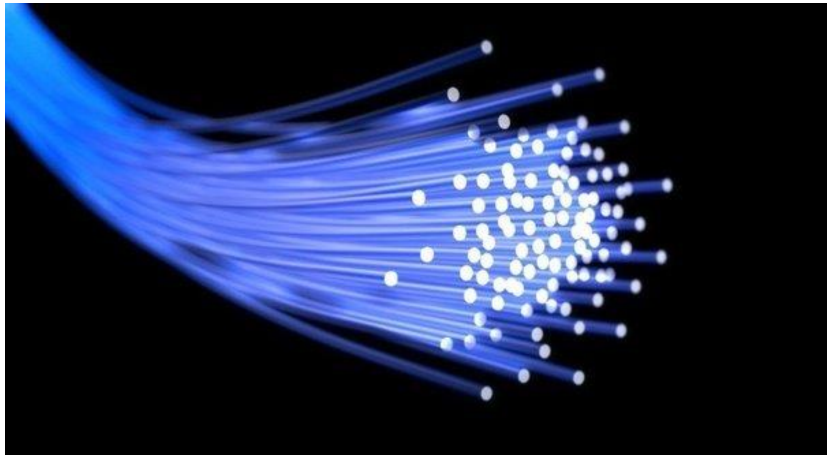
Applications

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)





Schawlow-Townes laser linewidth

In semiconductor lasers the linewidth is described by the Schawlow-Townes formula

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

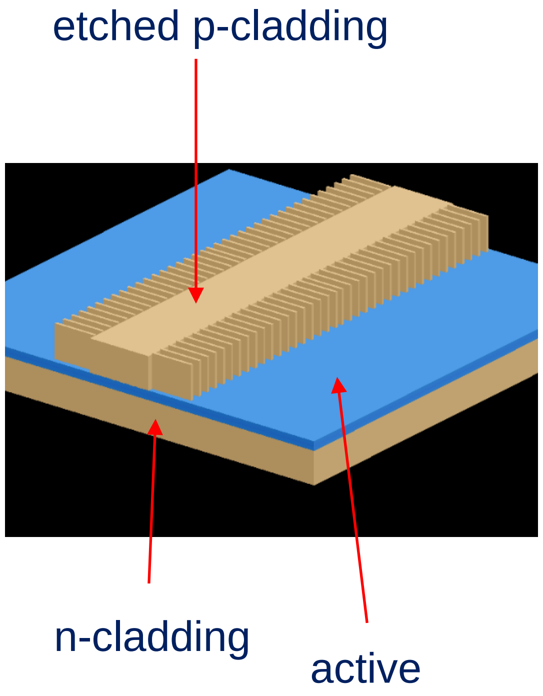
J. Buus, et al., Tunable Laser Diode and Related Optical Sources, 2014

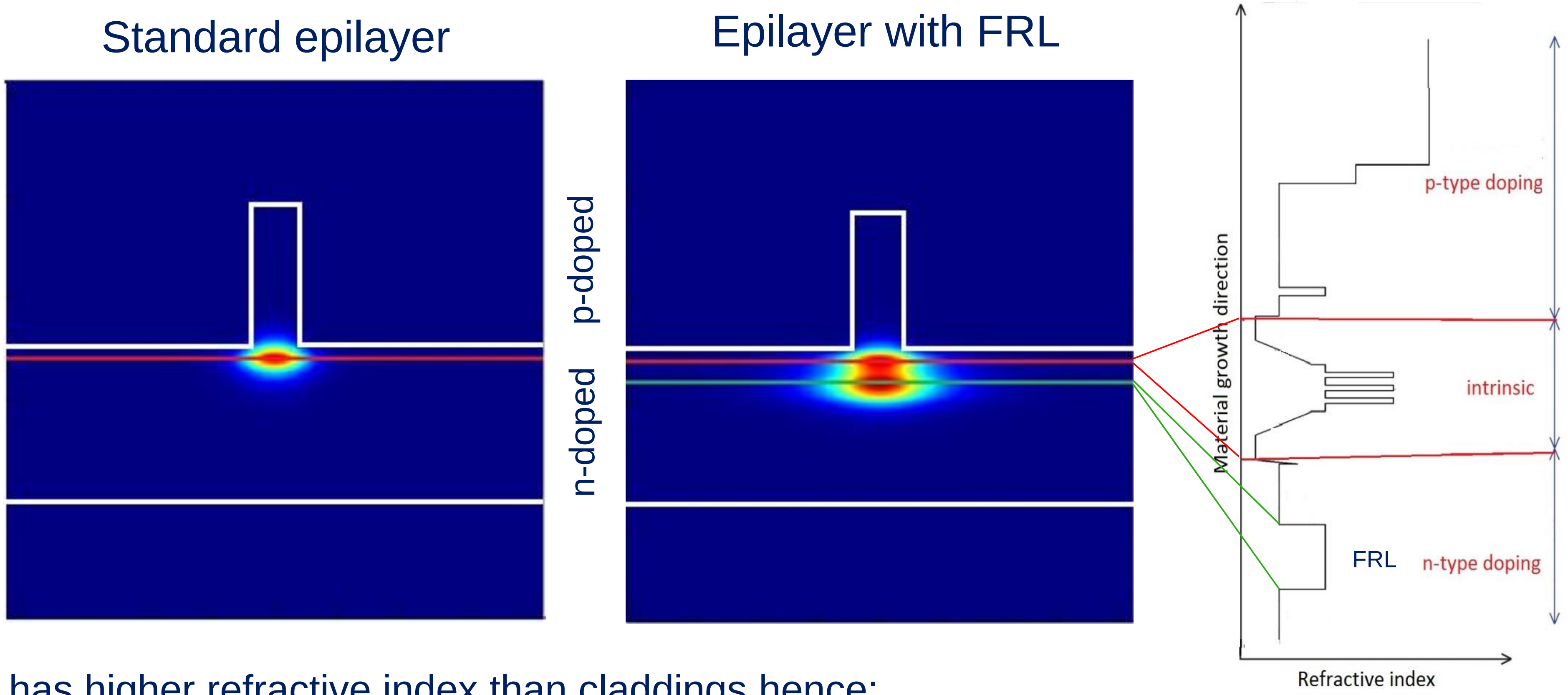
- $\boldsymbol{\alpha_i}$ internal losses of the material.
- $\boldsymbol{\Gamma_{active}}$ mode confinement in the active region.
- $\boldsymbol{R_{spont}}$ spontaneous emission rate.
- $\boldsymbol{\alpha_m}$ mirror losses.
- $\boldsymbol{P_{out}}$ power output from the laser.
- $\boldsymbol{\alpha_H}$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

Far-field Reduction Layer (FRL)

For a typical doping profile, p- and n-doped average absorption are $\alpha_p = 22\ \mathrm{cm}^{-1}$ and $\alpha_n = 1\ \mathrm{cm}^{-1}$ in InP-based.

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





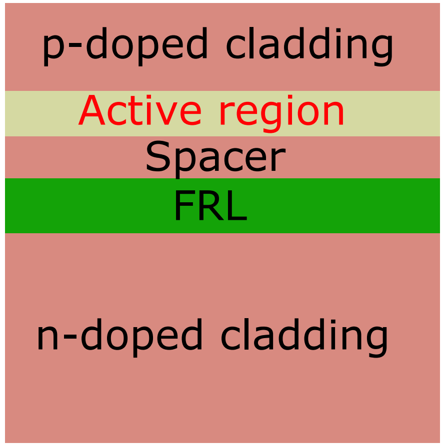
FRL in the n-doped region has higher refractive index than claddings hence:

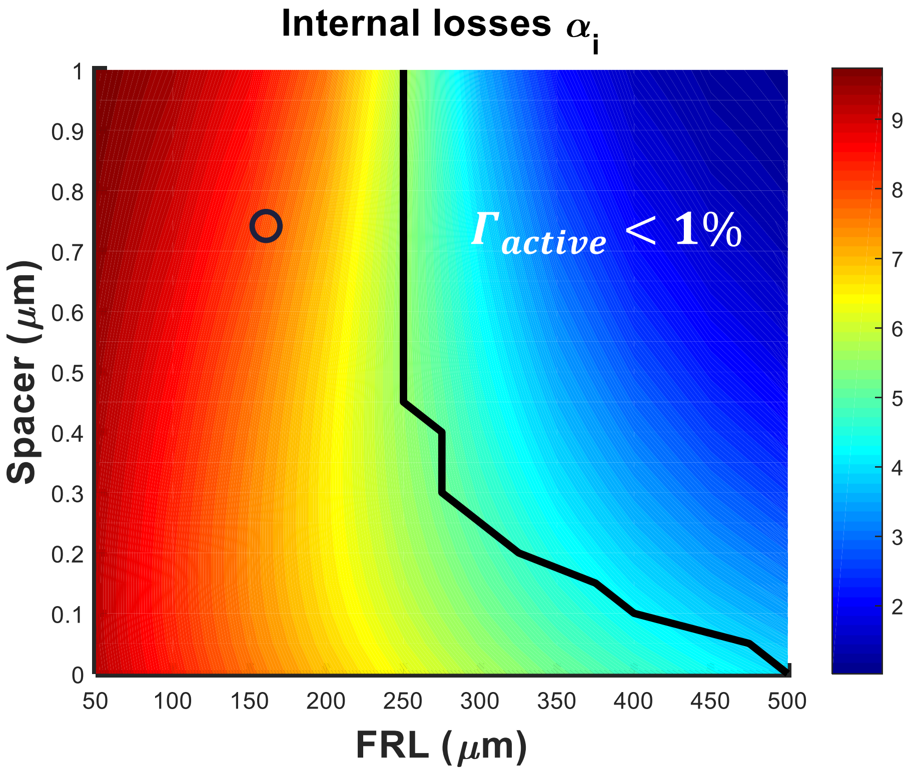
- pulls the guided mode out of the p-doped hence **decreases** $\boldsymbol{\alpha_i}$
- **decreases** $\boldsymbol{\Gamma_{active}}$

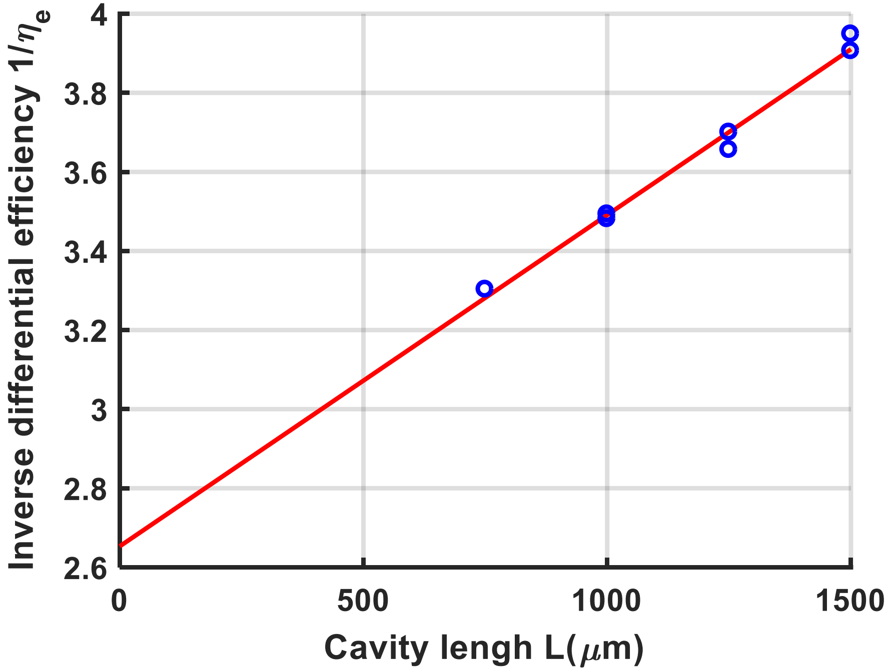
$$\Delta\nu = \frac{\Gamma_{active} R_{spont} h\nu (\alpha_i + \alpha_m)\alpha_m (1 + \alpha_H^2) v_g^2}{8\pi P_{out}}$$

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 $\boldsymbol{n_{QW}}$ from 3 to 2







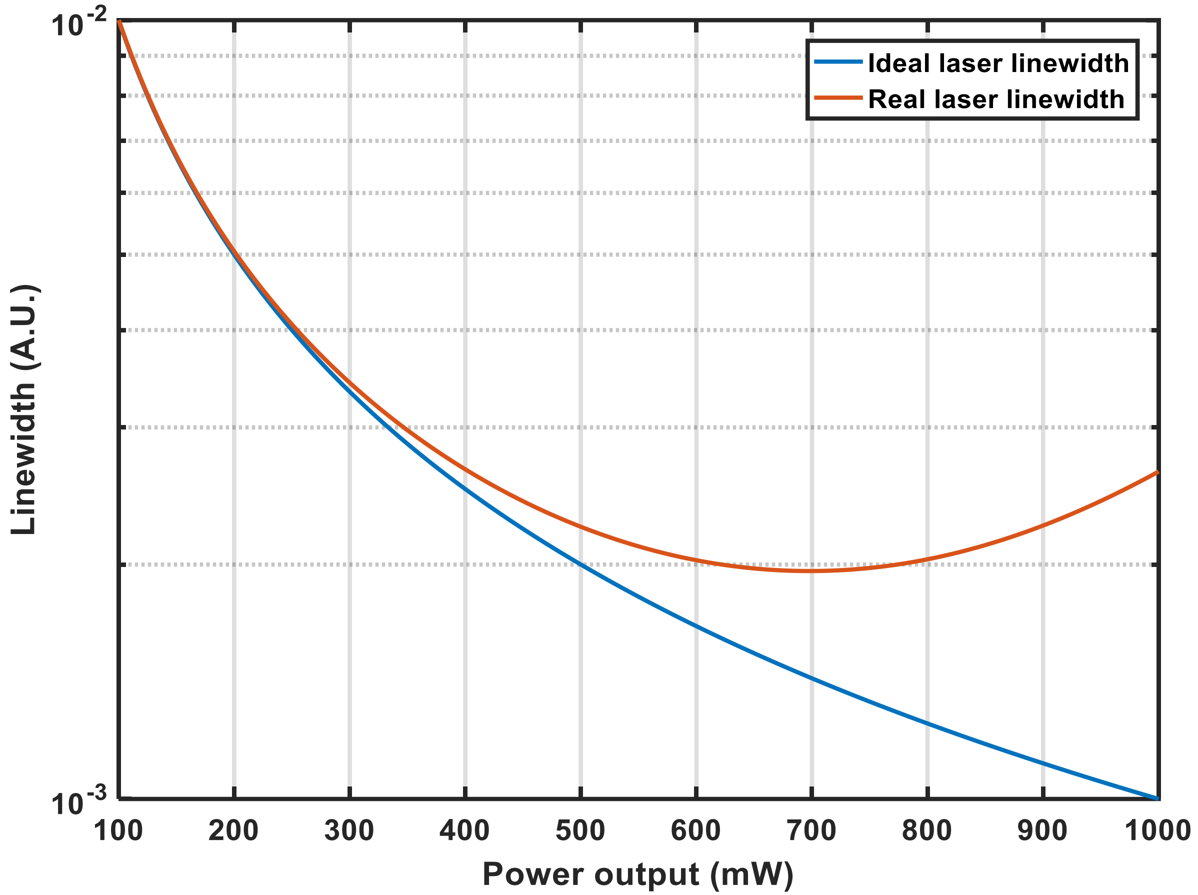
Fit of the material parameters from differential efficiency η_e in Broad Area Lasers (BALs).
Measured **internal losses** $\boldsymbol{\alpha_i = 4.13\ cm^{-1}}$ lower in comparison with the non-optimised wafer with $\boldsymbol{\alpha_i \approx 10\ cm^{-1}}$

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

Linewidth in high-power operation

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.

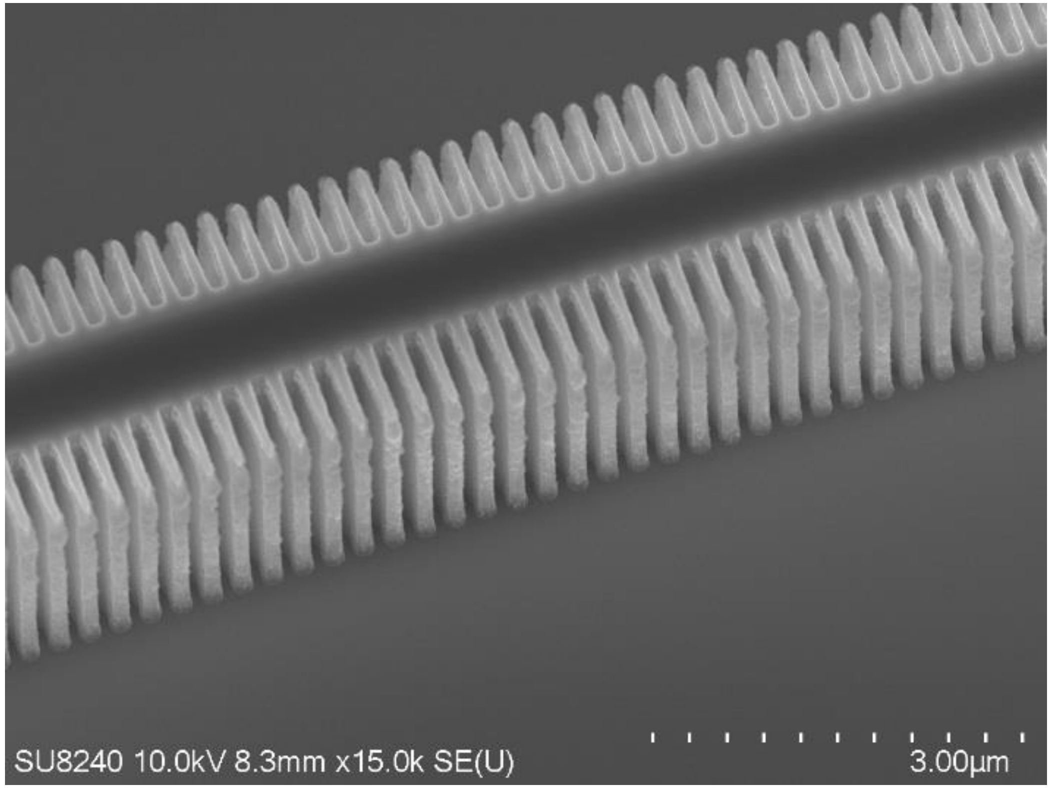


$\boldsymbol{\alpha}_{\mathrm{H}}$ depends on the injection current and, as a consequence, on the power output.

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

Sidewall DFB gratings

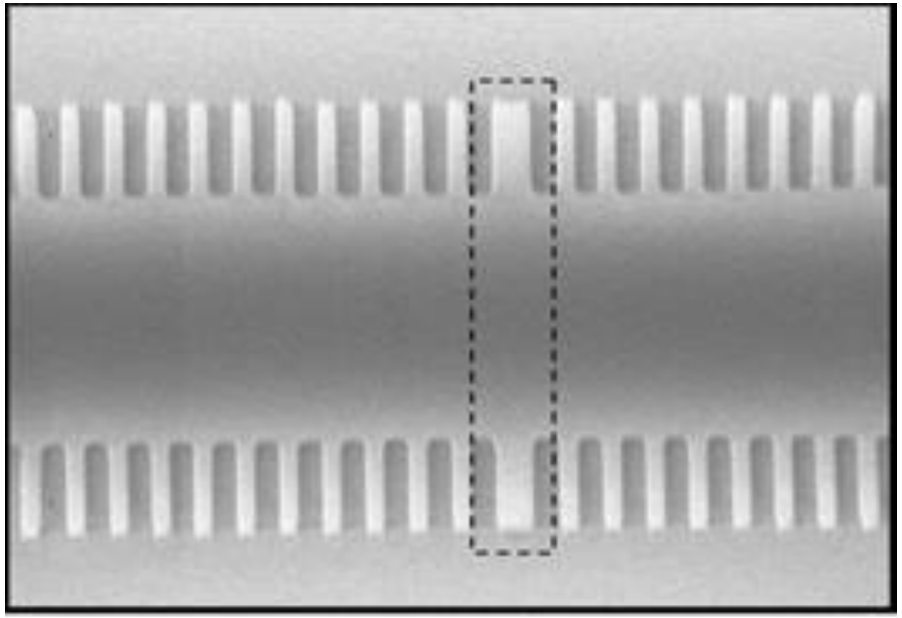
- Longitudinal single-mode operation with a side mode suppression ratio (SMSR) exceeding *60dB*.
- Very accurate selection of the emission wavelength
- Suitable for complex grating engineering on both transverse and longitudinal directions
- No material regrowth required
- Simple fabrication technology

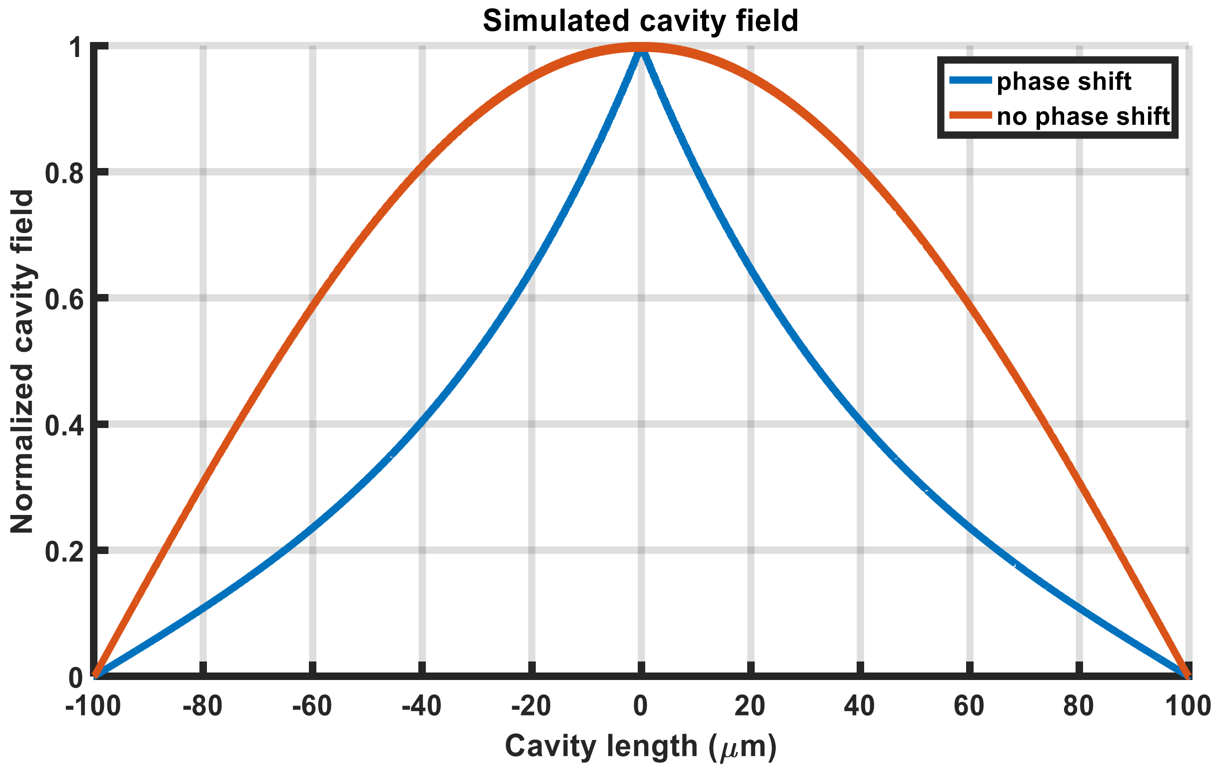


Longitudinal Spatial Hole Burning (LSHB)

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 α_H and causes mode hopping.

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

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

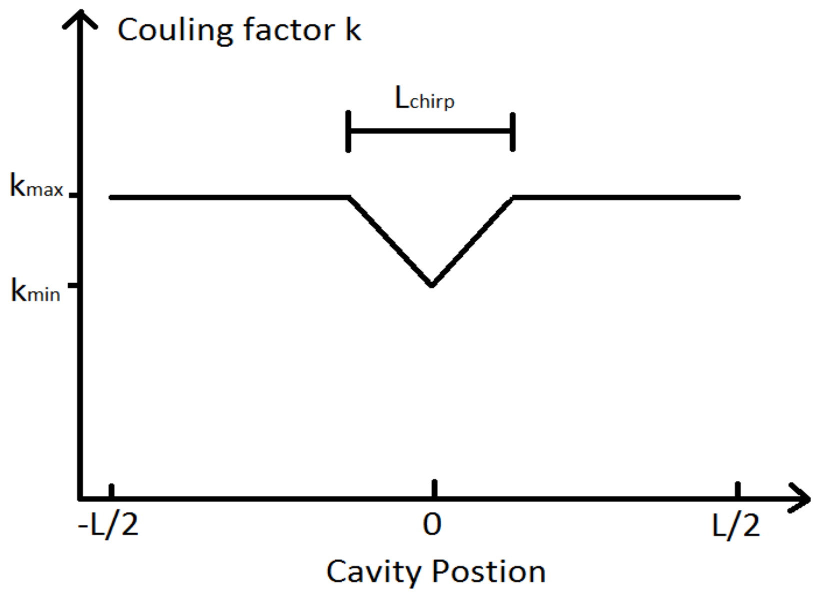
Standard solutions to uniform the cavity field include:

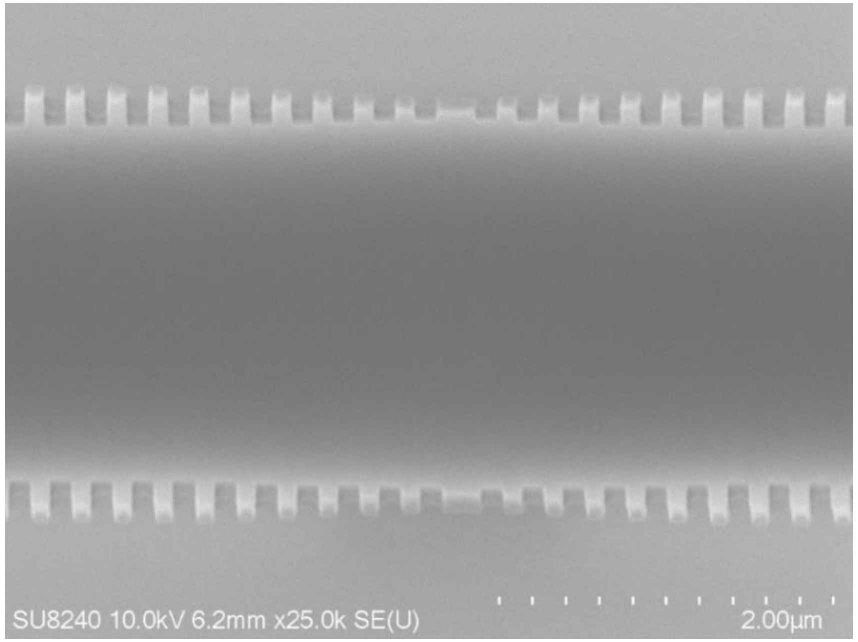
- Distributed phase shift layer [P. Zhou, et al. J. Appl. Phys., Vol. 70, No. 3 (1991)]
- Chirped grating period [M. Okai, et al. Electronics Letters, Vol. 29, pp. 1696-1697 (1993)]

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

Grating coupling chirp

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





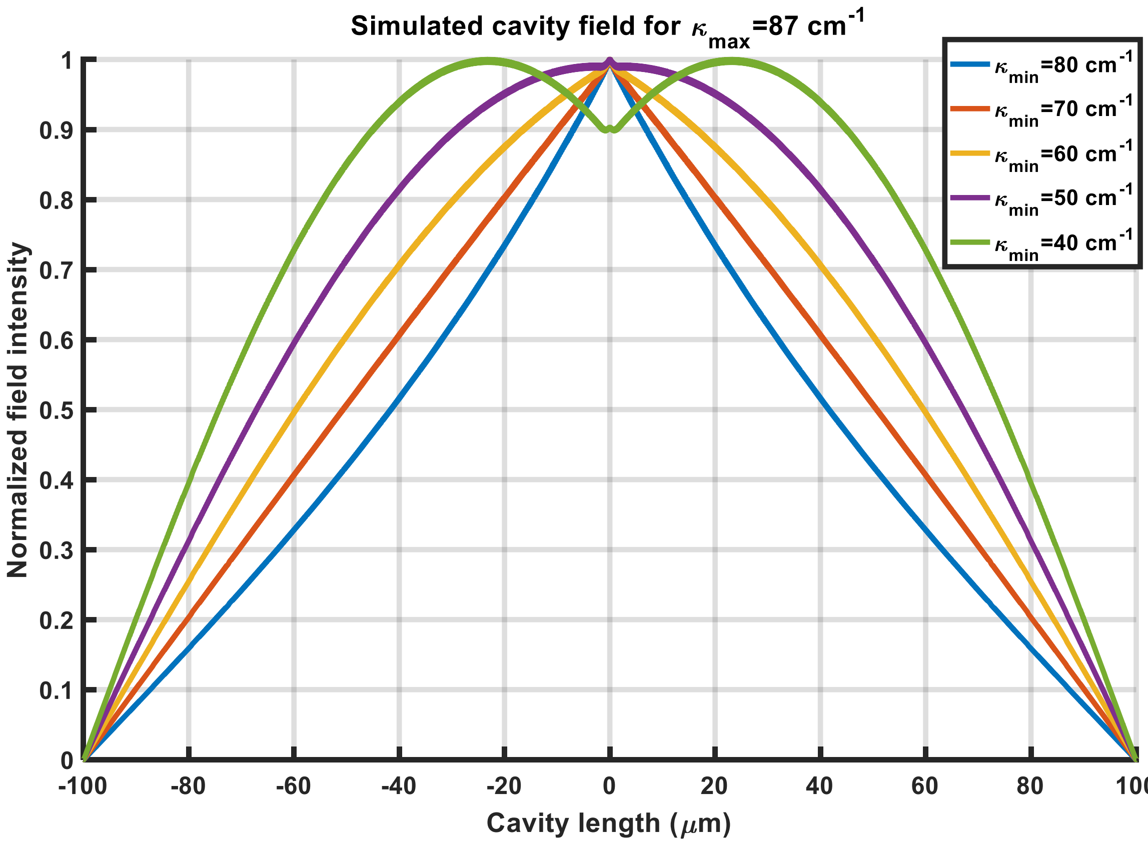
$$\Delta\nu = \frac{\Gamma_{active} R_{spont} h\nu(\alpha_i + \alpha_m)\alpha_m(1 + \alpha_H^2)v_g^2}{8\pi P_{out}}$$

Chirped Grating

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 $L_{chirp} = 3\ \mu\mathrm{m}$

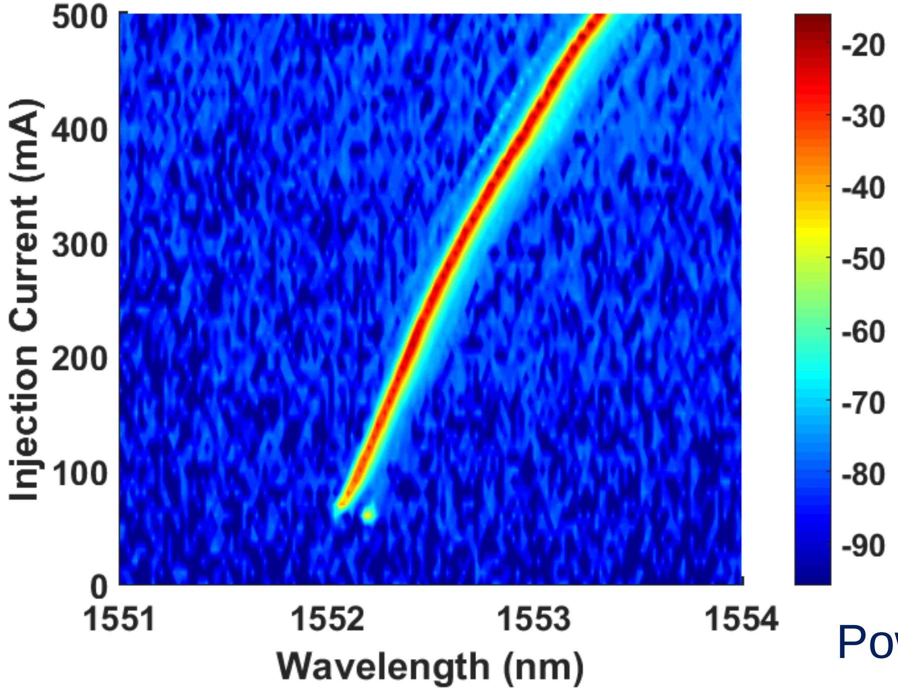
Sweep on the chirp depth κ_{min} allows to finely tune the field distribution inside the cavity.



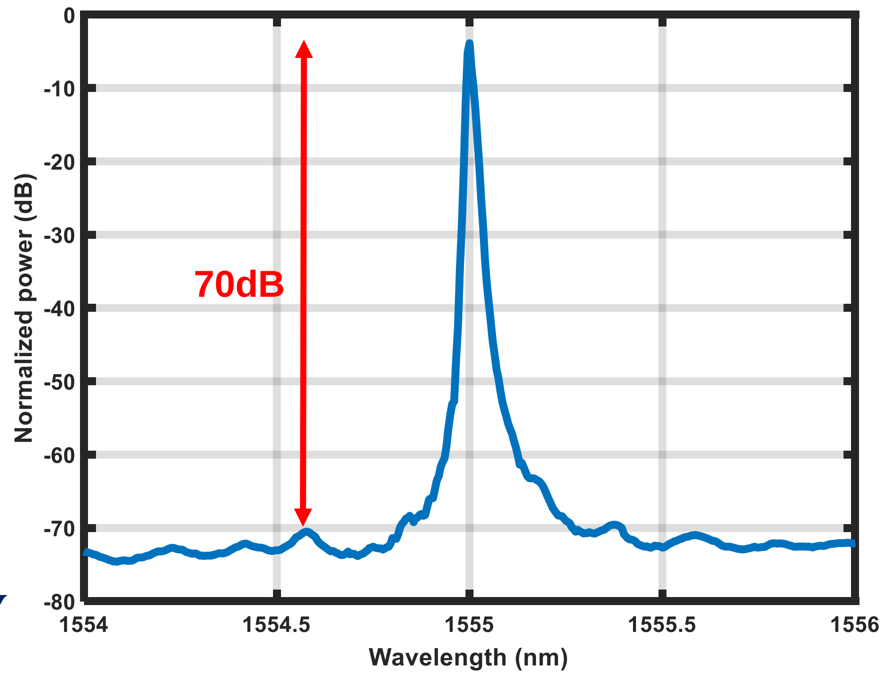
The best cavity field uniformity, closest to the uniform grating, is obtained for $\kappa_{min} \approx \frac{\kappa_{max}}{2}$

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

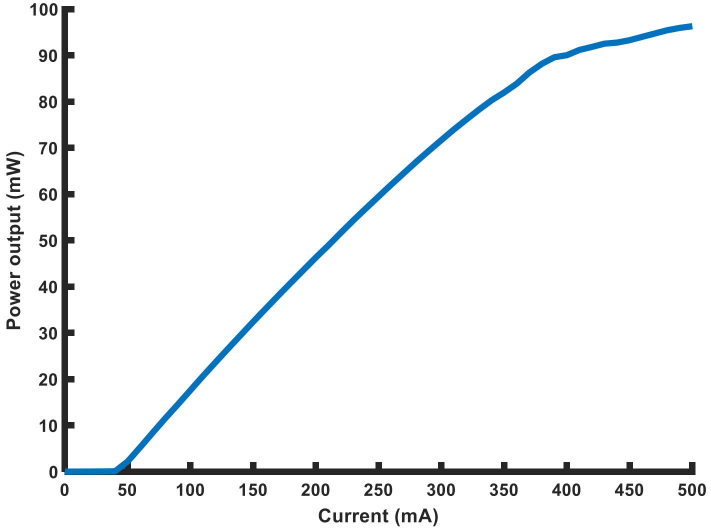
Single mode operation over a wide current range



High side-mode suppression ratio

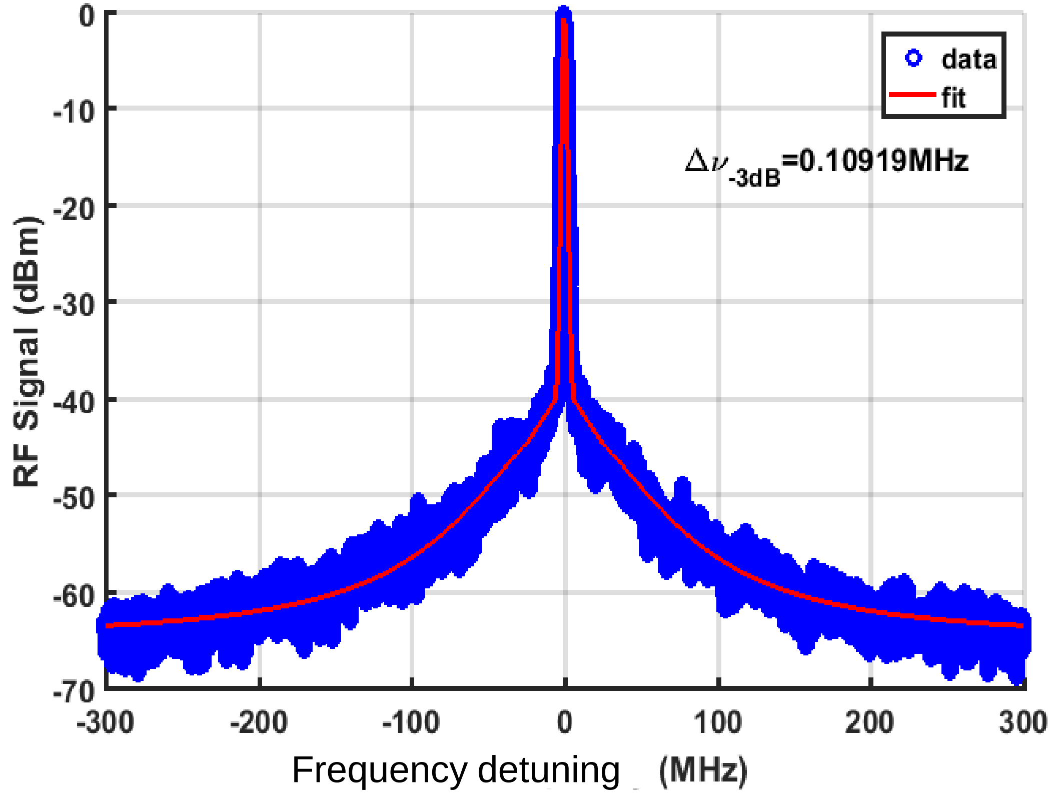


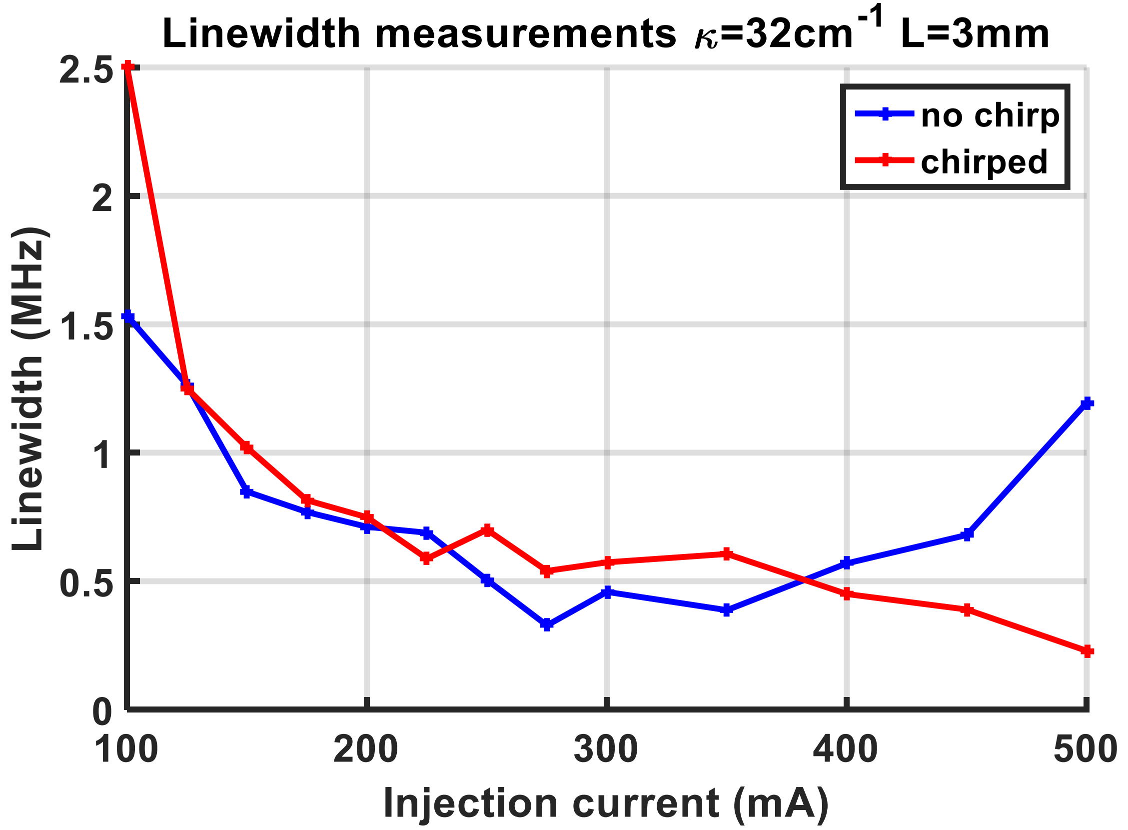
Power output as high as $96mW$



Linewidth in chirped gratings

Measurement of the DFB laser linewidth





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. $\alpha_i = 4.13\ \mathrm{cm}^{-1}$) at $1550\ \mathrm{nm}$ wavelength
- Improvement of the single-mode and narrow linewidth range (i.e. no linewidth broadening until $\mathrm{I} = 500\ \mathrm{mA}$) through chirped grating
- Narrow linewidth (i.e. $\Delta\nu \approx 100\ \mathrm{kHz}$) and high power (i.e. $\mathrm{P}_{out} \approx 100\ \mathrm{mW}$) lasers emitting at $1550\ \mathrm{nm}$ wavelength

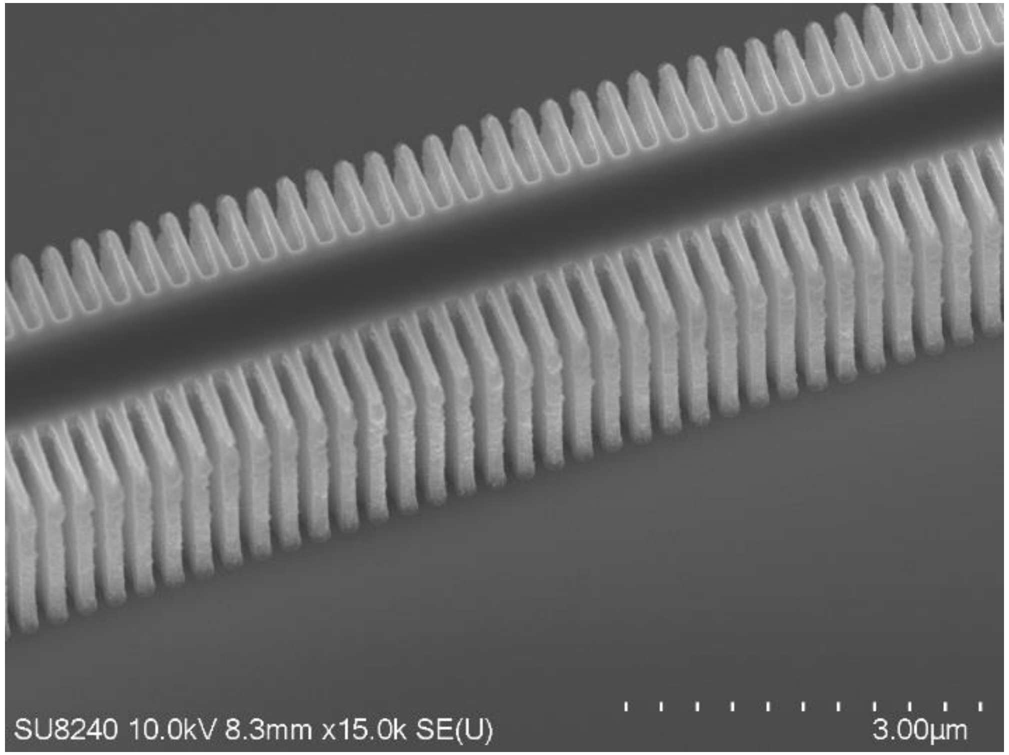
University of Glasgow

Acknowledgement

dstl

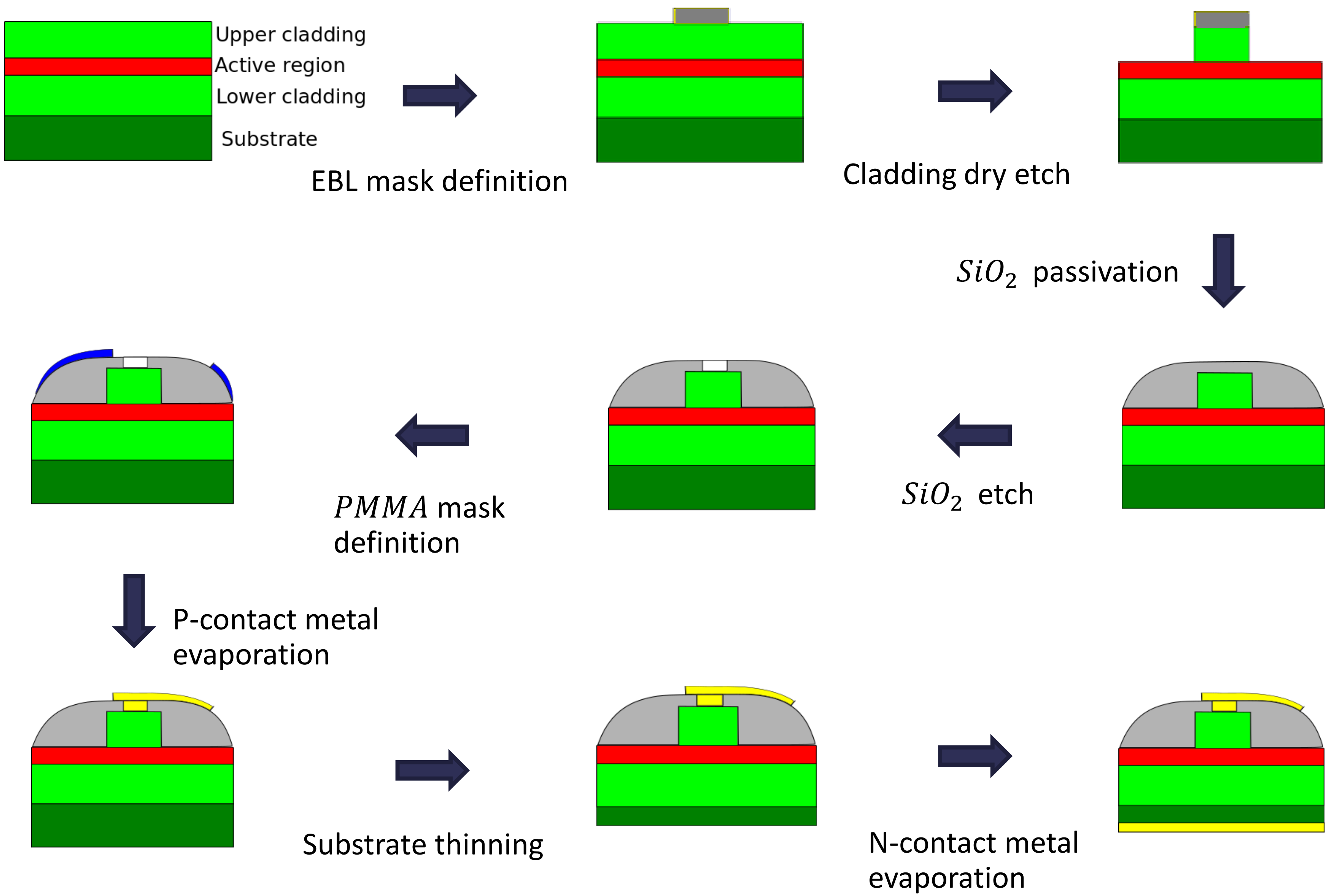
JWNC
The James Watt Nanofabrication Centre

Thank you for your attention

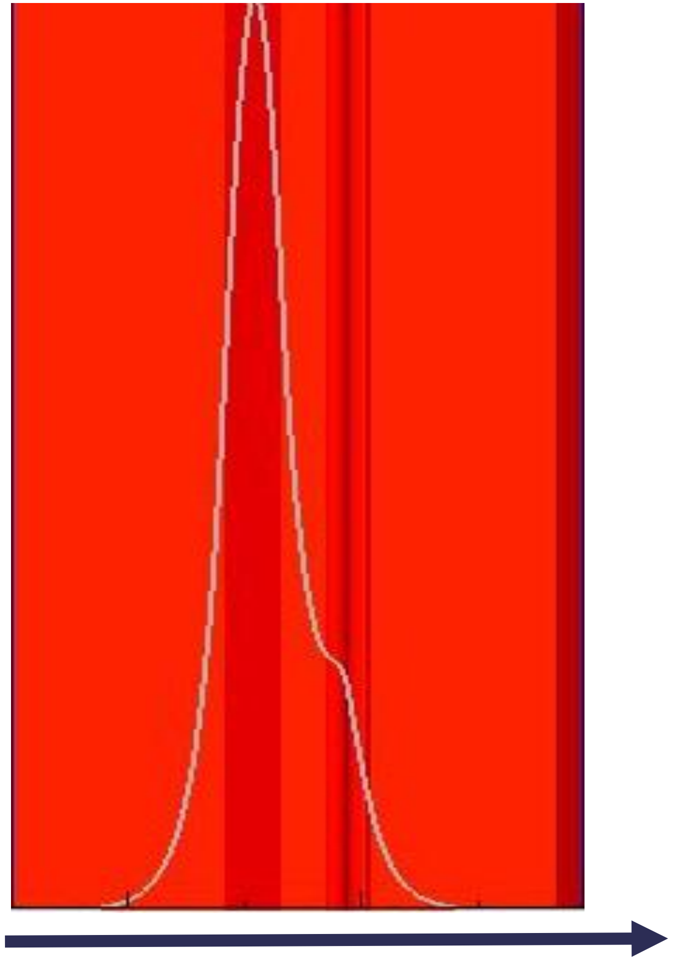


Any question?

Fabrication Process

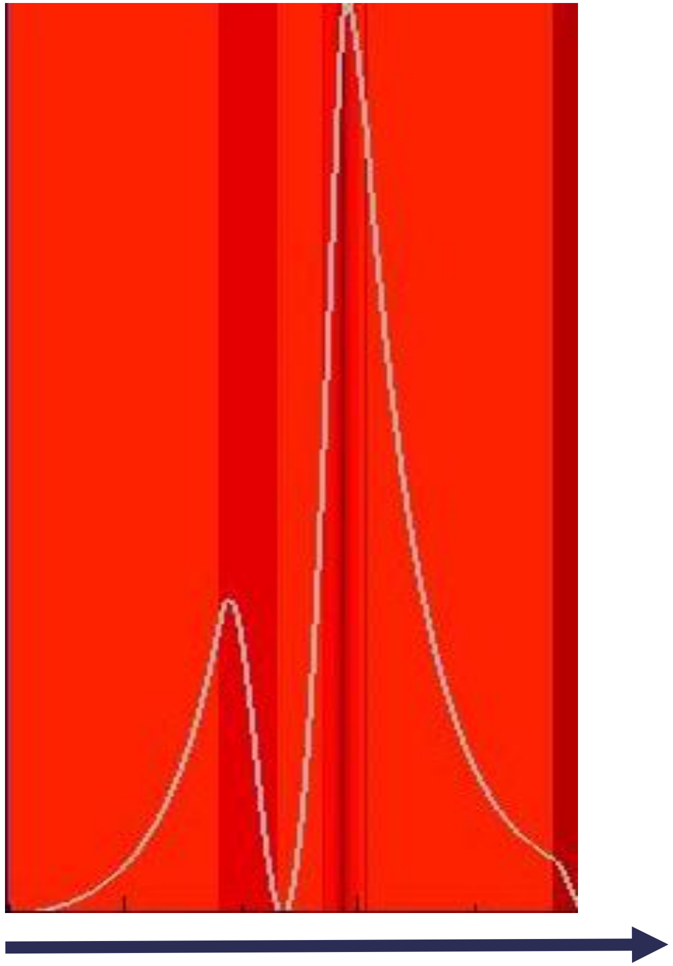


Mode 1 $\Gamma_{active} = 0.4\%$



Epilayer growth direction

Mode 2 $\Gamma_{active} = 1{,}1\%$



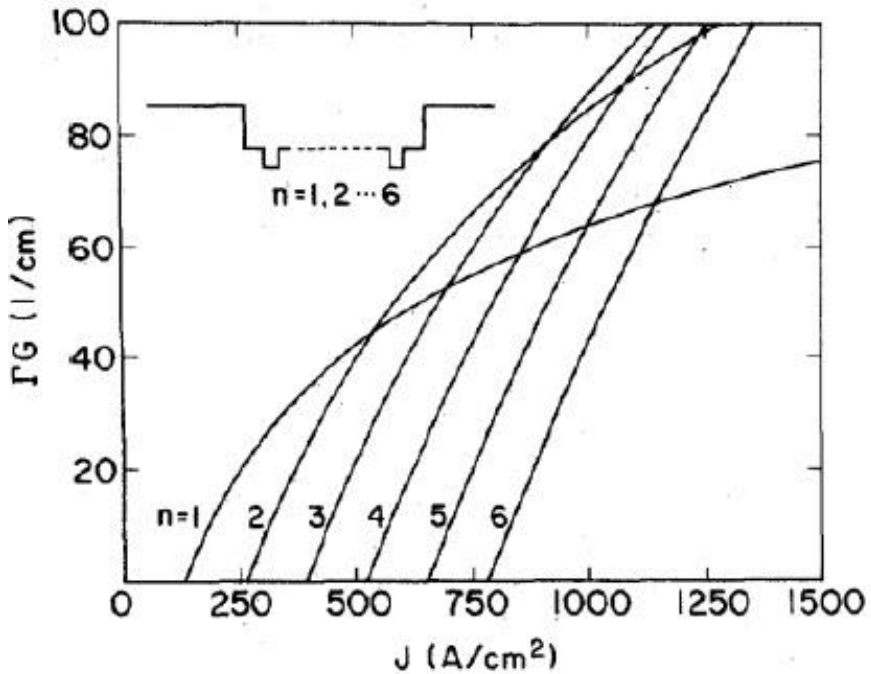
Epilayer growth direction

Quantum Well number

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 $\boldsymbol{\Gamma_{active}} = \boldsymbol{n_{QW}\Gamma_{1QW}}$.

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.



P.W.A. McIlroy, et al., IEEE Journal of quantum electronics, Vol QE-21, No. 12 (1985)

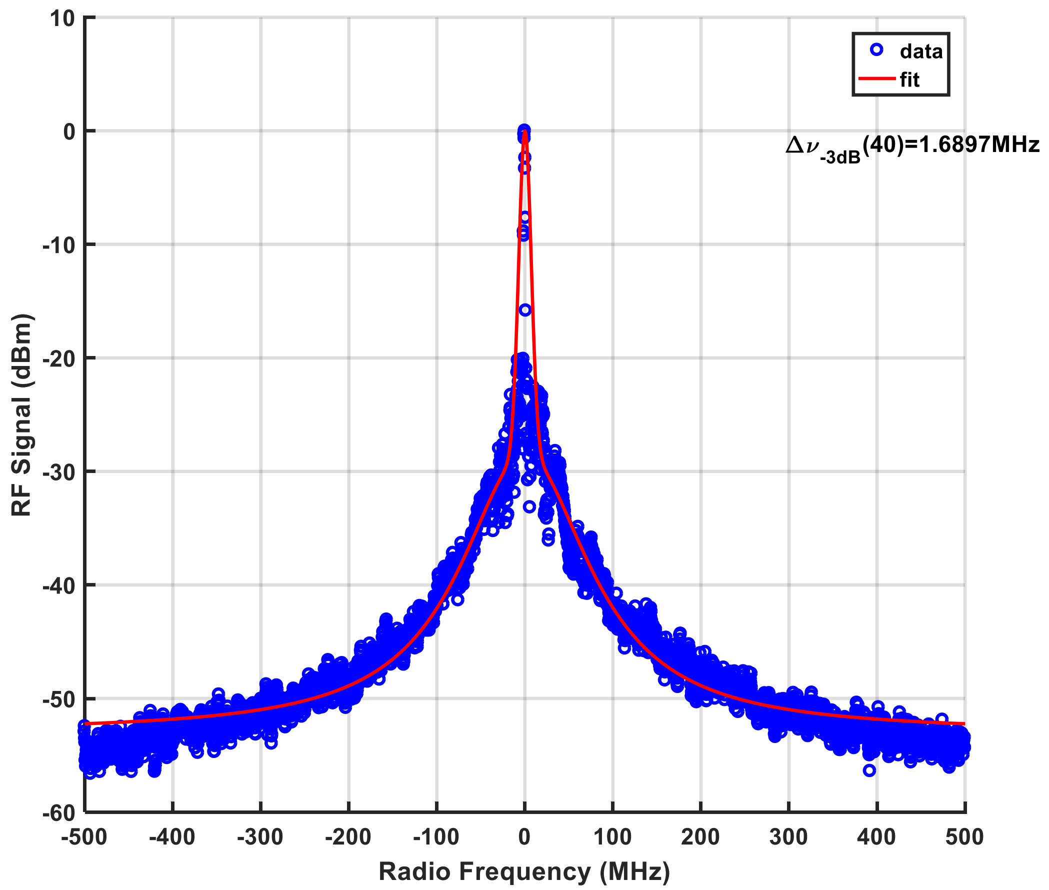
Low $\boldsymbol{\Gamma_{active}}$, hence low $\boldsymbol{n_{QW}}$, and long laser cavity $\boldsymbol{L}$ allows to have low carrier density also in power regimes.

Typical values for $\boldsymbol{n_{QW}}$ are 3-5 for InP-based and 1-2 for $GaAs$-based materials.

Linewidth measurement and fit

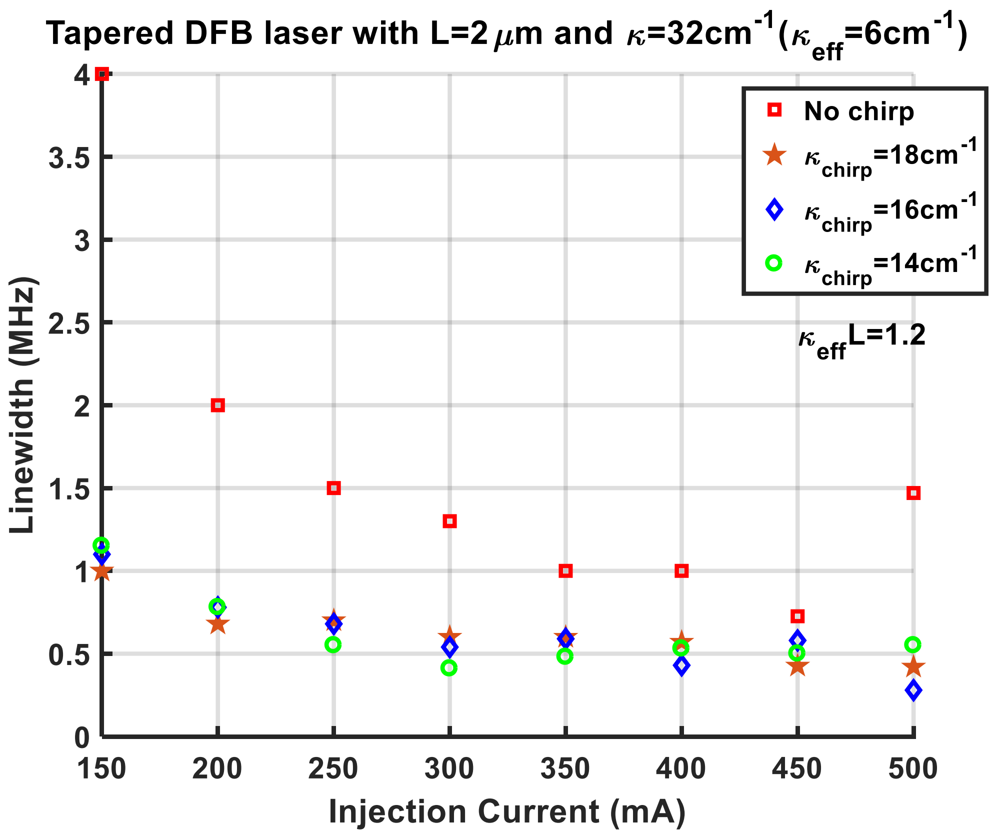
- Strong and clear RF signal with a large number of points (i.e. 10000 points)

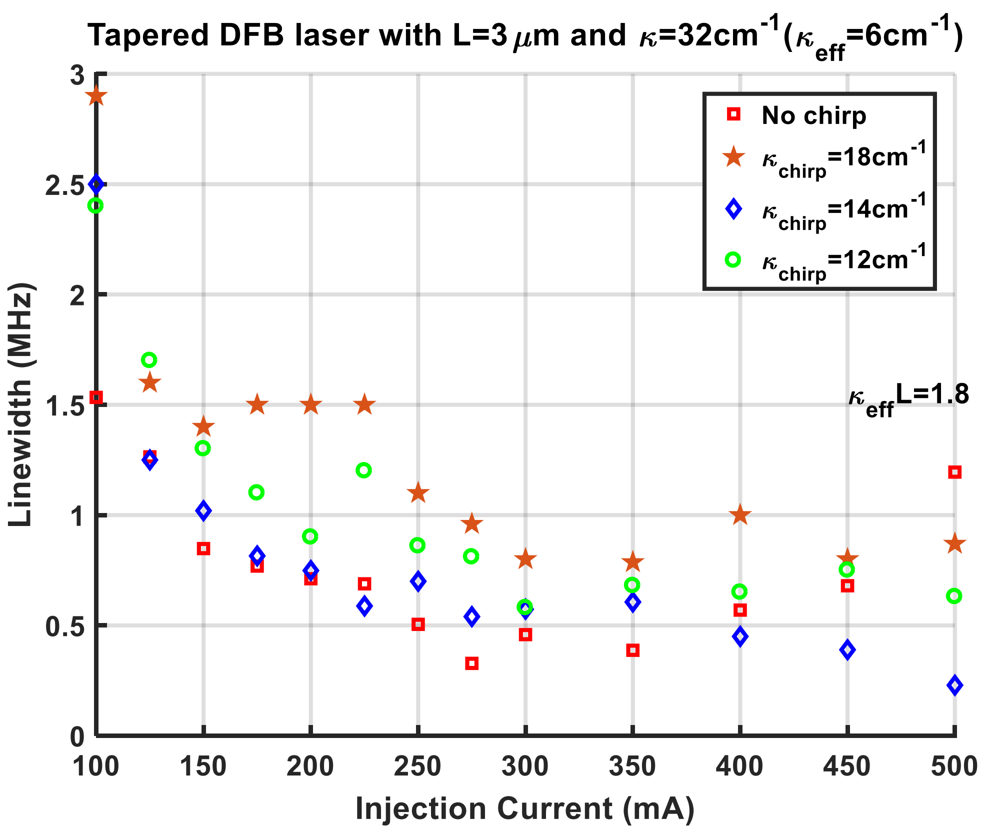
- Voigt fit (convolution of Gaussian and Lorentzian lineshape)



- Linewidth measurement at -3dB from the peak are analitically 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.

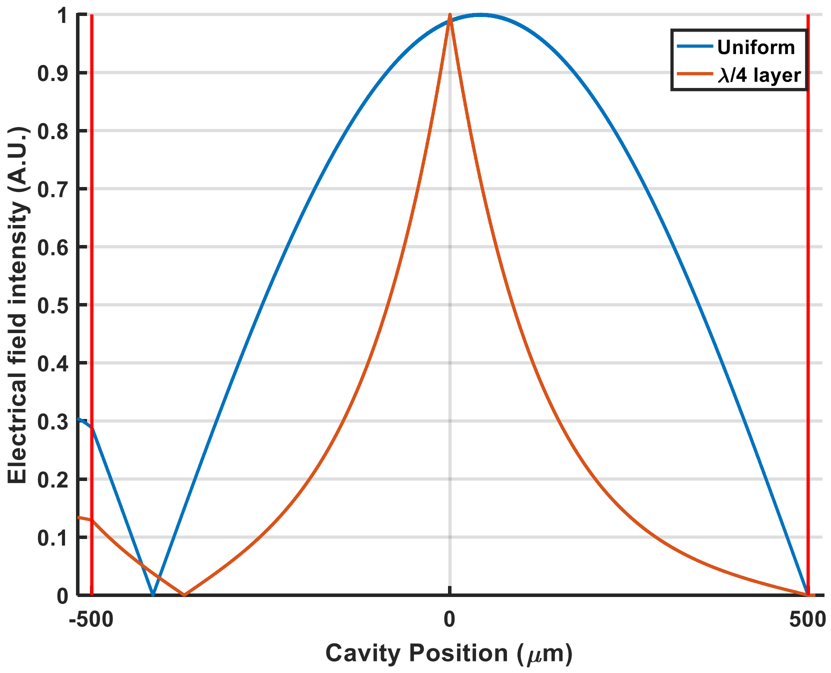
Linewidth in chirped gratings

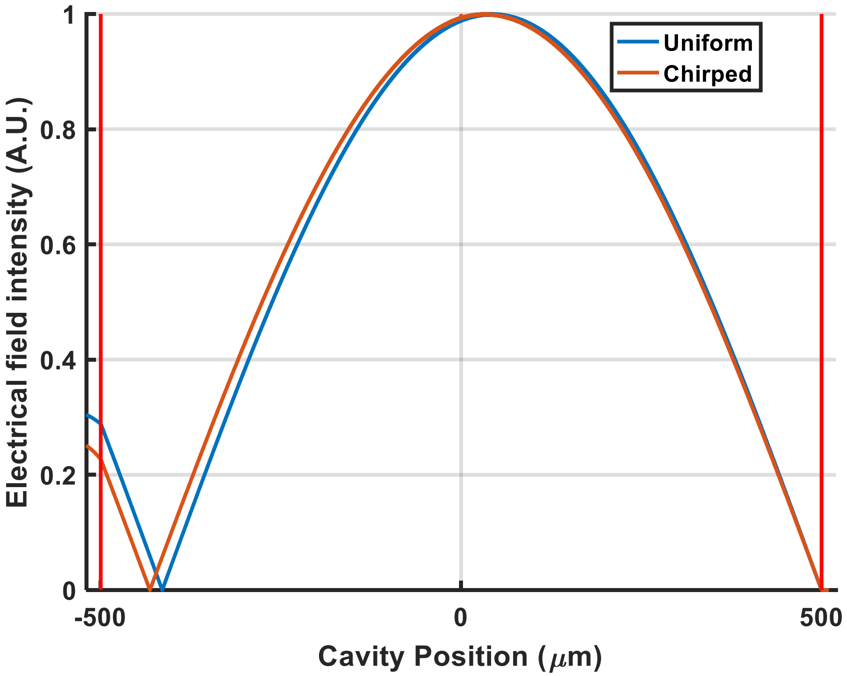




The measured linewidth for DFB lasers with and without chirp clearly shows that the chirped grating allows to reach larger injection current before to have linewidth broadening.

Electical field distribution in laser cavity

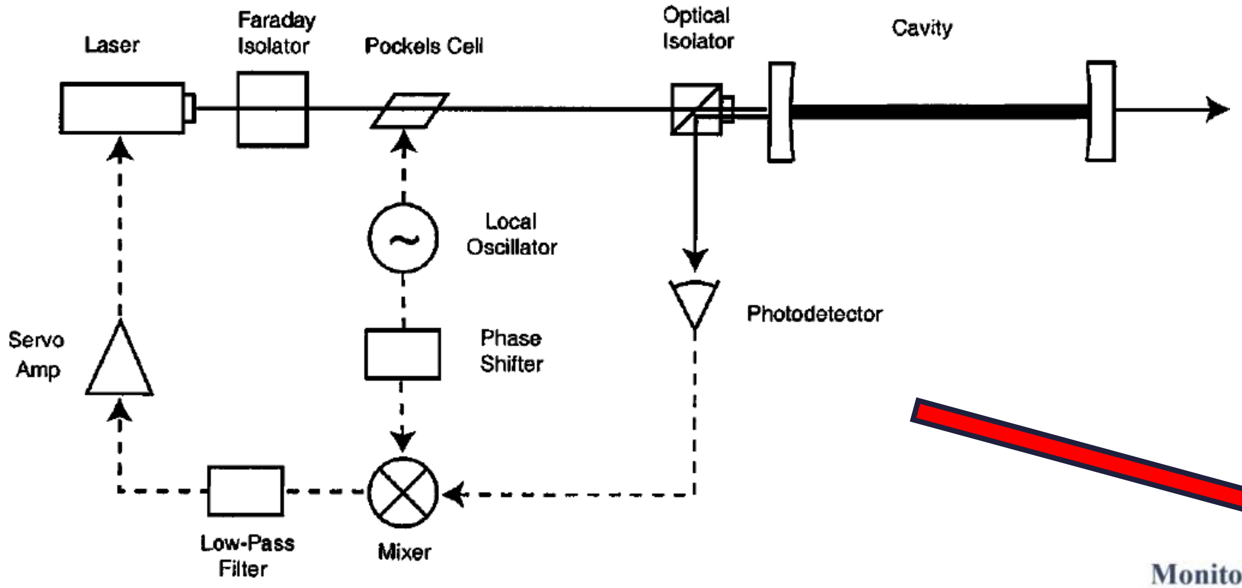


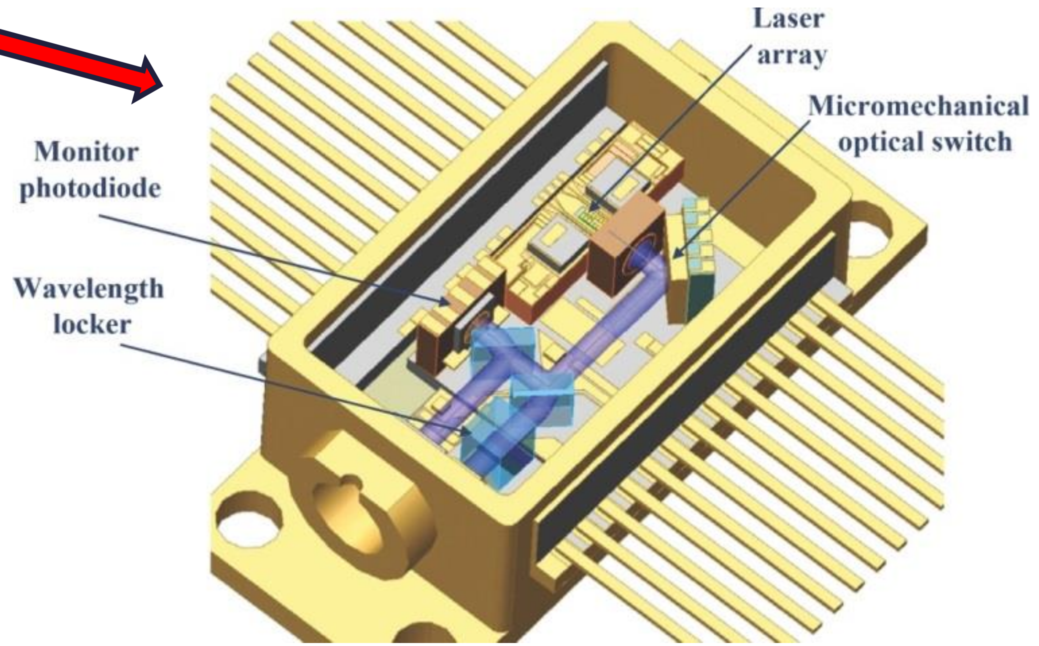


- The asymmetry in the cavity reflectivity does not dramatically affect the electrical field distribution, others cavity modes with a different field distribution do not lase as they do not overlay the active region.
- The chirped grating ensures a uniform field distribution also for single-facet cavity

Integration: PDH stabilization setup

Pound-Drever-Hall Technique to lock the absolute wavelength to a stabile reference through electronic feedback





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