Static and dynamic performance optimisation of a 1.3 µm GaInNAs ridge waveguide laser

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Presentation Outline

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1. Introduction
2. Device structure
3. Design of high-speed lasers
4. Description of laser simulator
5. Optimisation of design parameters
6. Results
7. Conclusion

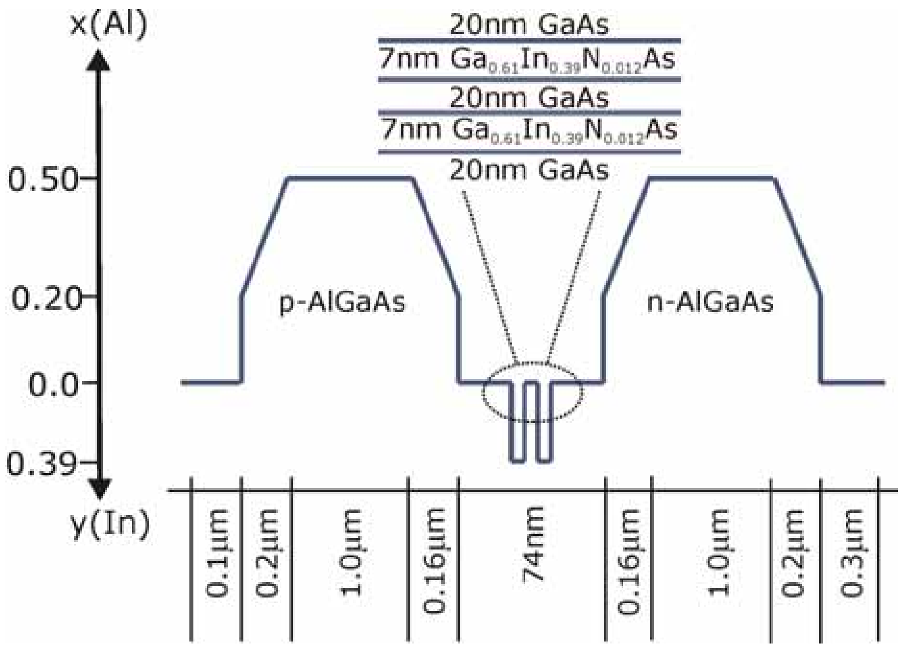
Dilute Nitride Lasers

- Market growth of 10 Gb Ethernet is increasing – growing demand for low cost transceivers which require uncooled directly modulated lasers
- Large bandgap bowing of dilute nitride material system allows long wavelength lasers to be grown on GaAs substrates
- Low cost alternative to InP lasers due to cheaper and larger GaAs wafers
- Dilute nitride lasers have a large conduction band offset – good high temperature performance
- State-of-the-art devices have a maximum modulation bandwidth ~17 GHz at RT - can this performance be improved further?

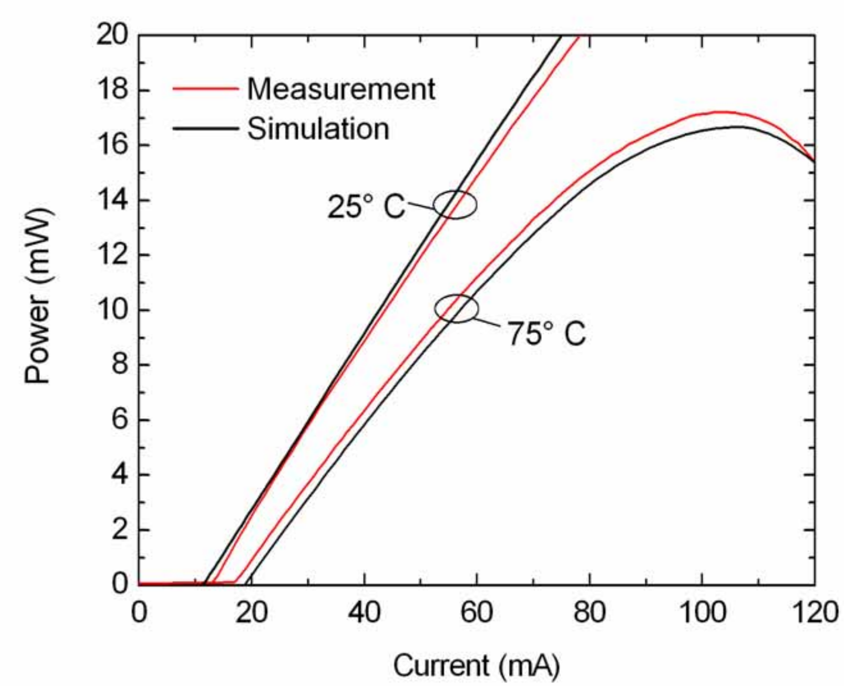
Reference: *Y.Q. Wei, et al., IEEE J. Quantum Electron. Vol. 42, p. 1274, 2006.*

Dilute Nitride Laser Structure

- 7nm $Ga_{0.61}In_{0.39}N_{0.012}As$/GaAs DQW, $Al_{0.50}Ga_{0.50}As$ cladding layers.
- Simulation parameters calibrated and good agreement with experiment obtained. τ_{SRH}=0.5 ns and $C_{CHSH}=1x10^{-28}$ cm^6s^{-1}.



Reference structure



Reference: *Y.Q. Wei et al., Appl. Phys. Lett., Vol. 88, 051103, 2006.*

Design of High-Speed Lasers

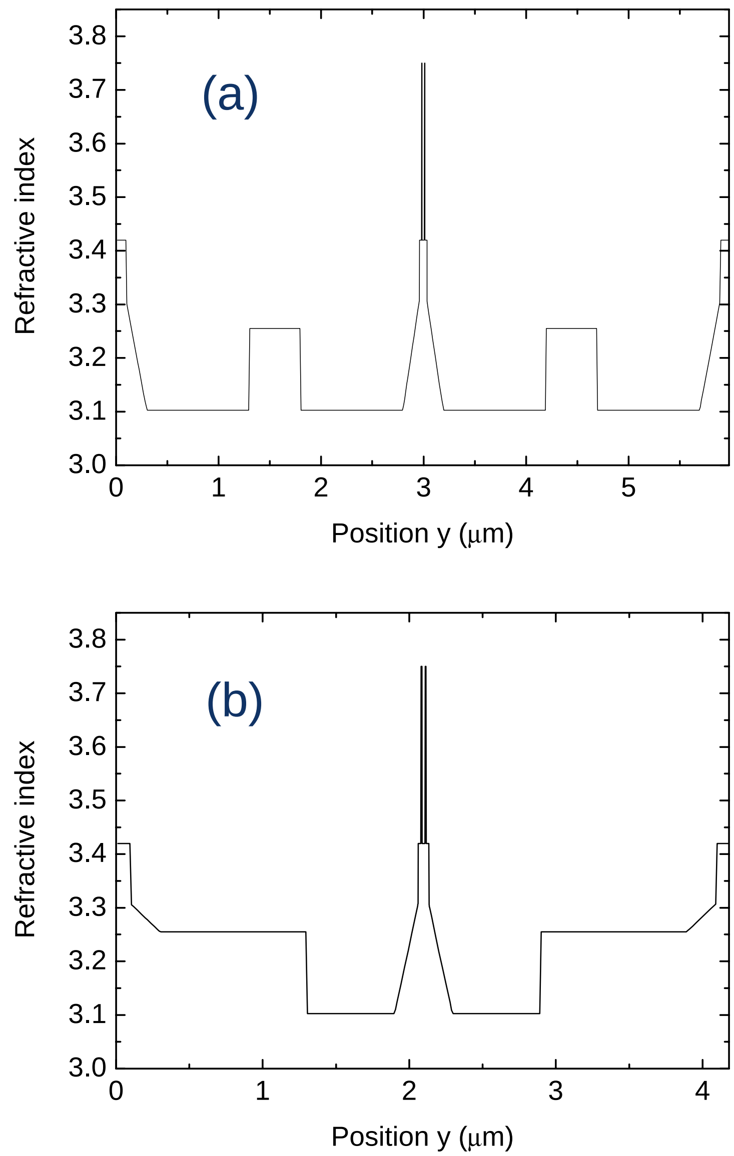
- Parameters affecting high speed performance
- Analytical expression derived from small-signal analysis of carrier and photon rate equations:

$$f_R = \frac{1}{2\pi}\sqrt{\frac{v_g \Gamma \frac{dg}{dn}}{eV_{act}}(I - I_{th})}$$

- Differential gain controlled by QW design
- Minimum length limited by self-heating effect
- Confinement factor is main design parameter controlling the modulation bandwidth

Low index layer structure

- Γ can be increased by reducing the index of the cladding layer – this results in unacceptable increase in far-field divergence (target FF-FWHM <35°)
- Two approaches to simultaneously achieve high confinement factor and low vertical divergence :
  - (a) Low index layer inserted in the cladding layers - more suited for high-power lasers
  - (b) Low index layer inserted between GRIN and cladding layers - preferred for high-speed lasers due to fewer interfaces, reduced series resistance



Reference:

1. *J. Temmyo and M. Sugo, Electron. Lett., Vol. 31, No. 8, p. 642, 1995.*
2. *G.W. Yang, et al., J. Appl. Phys., Vol. 83, No. 1, p. 8, 1998.*
3. *M. Dumitrescu, et al., Opt. Quantum Electron., Vol. 31, p. 1009, 1999.*

Description of 2D Laser Simulator

Poisson's Equation

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \nabla \phi) + q(p - n + N_D^+ - N_A^-) = 0$$

Continuity Equations

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J_n} - (R_{nr} + R_{spont} + R_{cap}^{n}) \qquad \frac{\partial n_w}{\partial t} = \frac{1}{q} \frac{dJ_{nw}}{dx} - (R_{nr}^{qw} + R_{spont}^{qw} + R_{stim}^{qw} - R_{cap}^{n})$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J_p} - (R_{nr} + R_{spont} + R_{cap}^{p}) \qquad \frac{\partial p_w}{\partial t} = \frac{1}{q} \frac{dJ_{pw}}{dx} - (R_{nr}^{qw} + R_{spont}^{qw} + R_{stim}^{qw} - R_{cap}^{p})$$

Photon Rate Equations

$$\frac{dS_m}{dt} = v_g (G_m - \alpha) S_m + \beta r_{spont}^{qw}$$

Optical model

$$\nabla^2 \Phi + \left(k(x,y)^2 - \beta(\omega)^2 \right) \Phi = 0$$

Thermal model

$$\rho_L C_L \frac{\partial T}{\partial t} = \nabla \cdot \left(\kappa \nabla T \right) + H$$

Description of 2D Laser Simulator

Small-signal Analysis

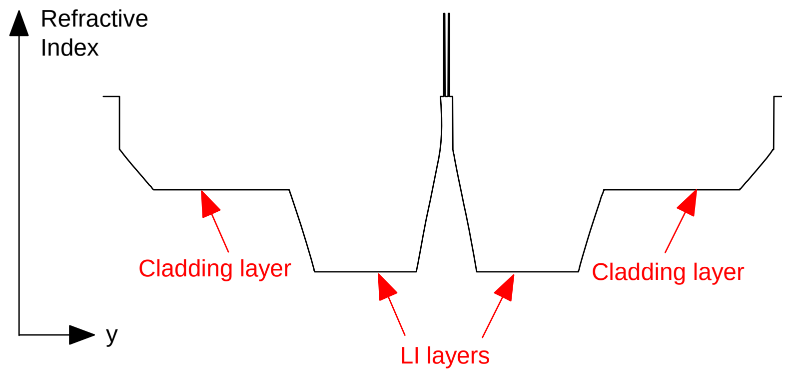
- Follow approach by S. Laux, IEEE Trans. Electron. Devices, Vol. 32, No. 10, p. 2028, 1985 – Sinusoidal Steady-State Analysis (S^3A)
- Perturbation to steady-state solution of the form $x = \bar{x} + \tilde{x}\exp(j\omega t)$
- Insert into device equations and perform Taylor series expansion keeping first order terms of $\exp(j\omega t)$

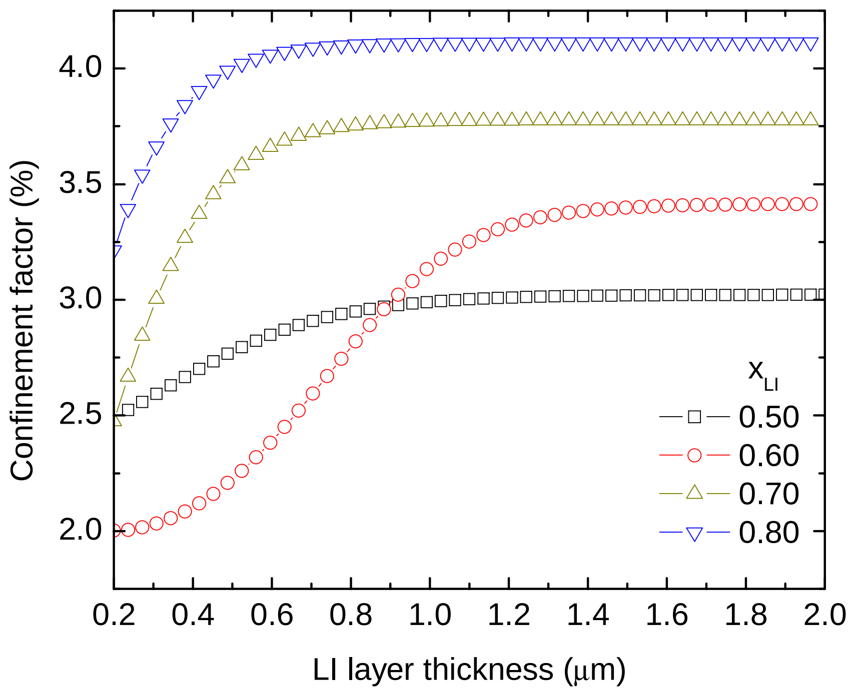
Large-signal Analysis

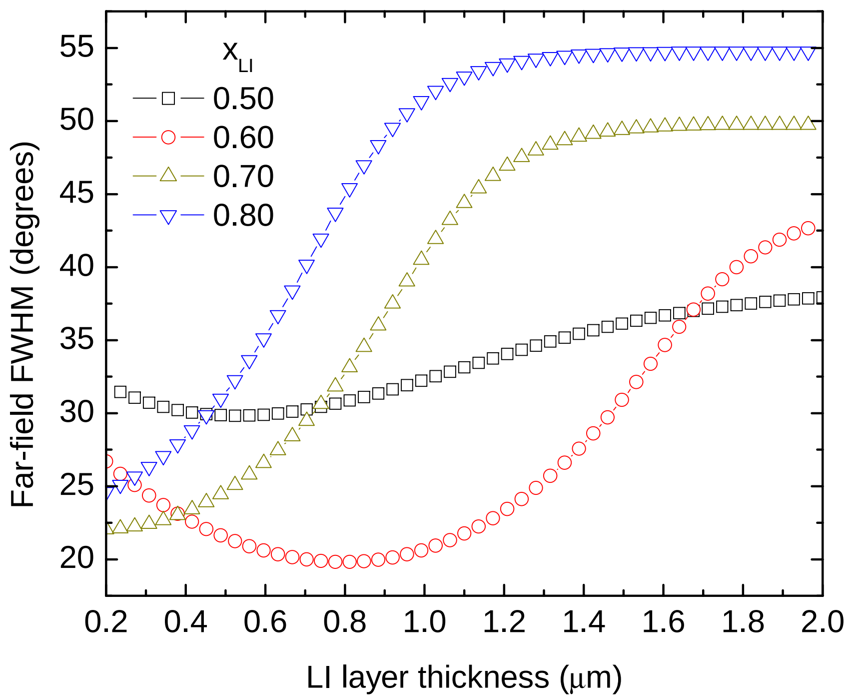
- Use backward Euler method (implicit scheme) – unconditionally stable

Low index layer structure

- Vary W_{LI} and x_{LI}
- Fixed x_{cl}=0.40, W_{cl}=800nm
- x_{LI}=0.80 gives highest Γ
- FF-FWHM <35° achievable with W_{LI}=600nm

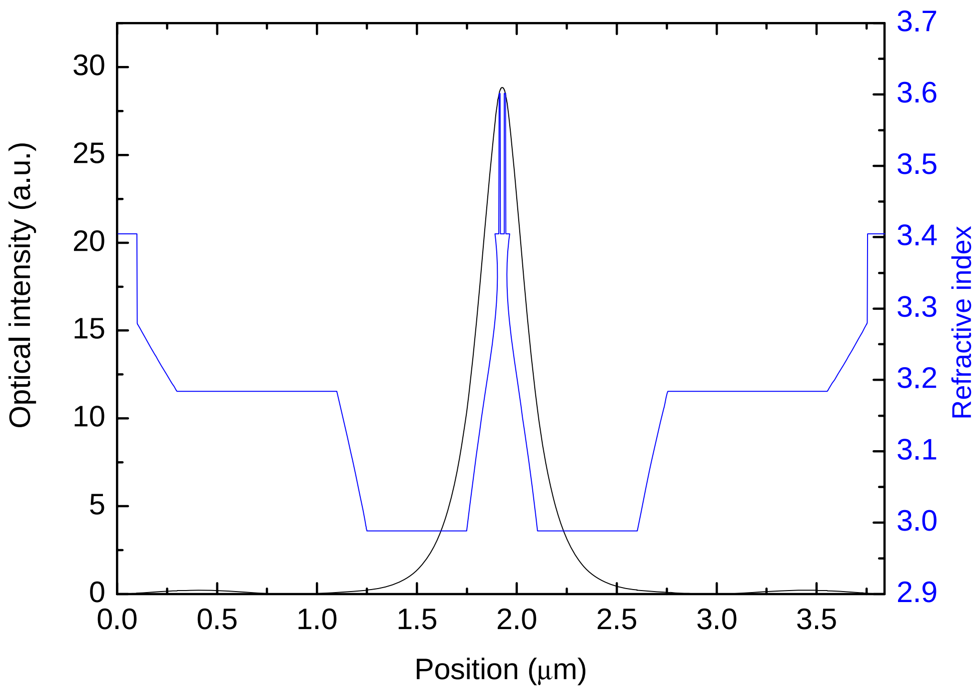


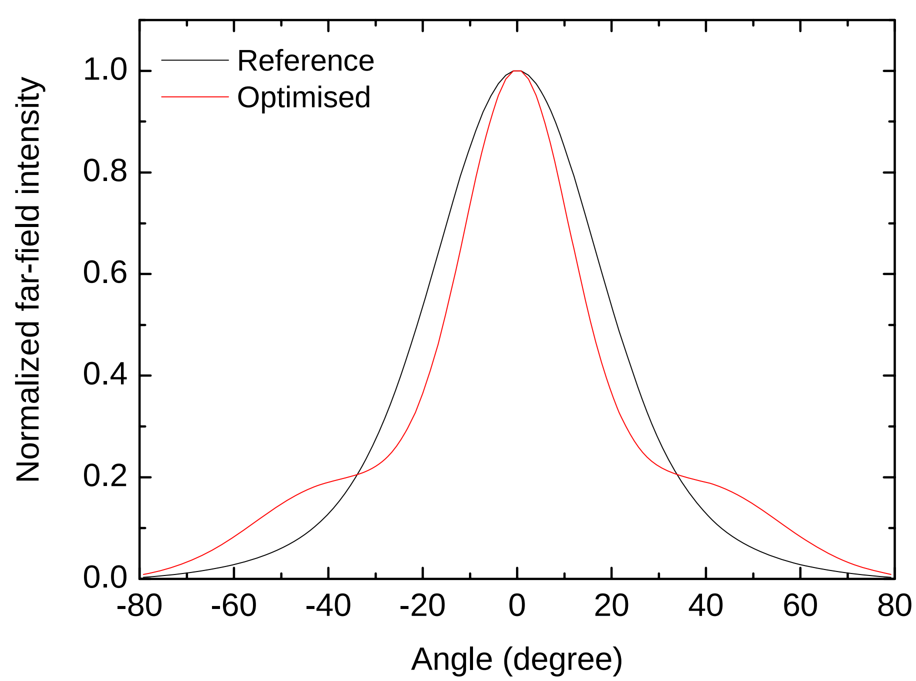




Low index layer structure

- Final structure has a confinement factor of 4.0% (compared to 3.5% for reference structure)
- Vertical FF-FWHM is ~12° smaller than the reference structure

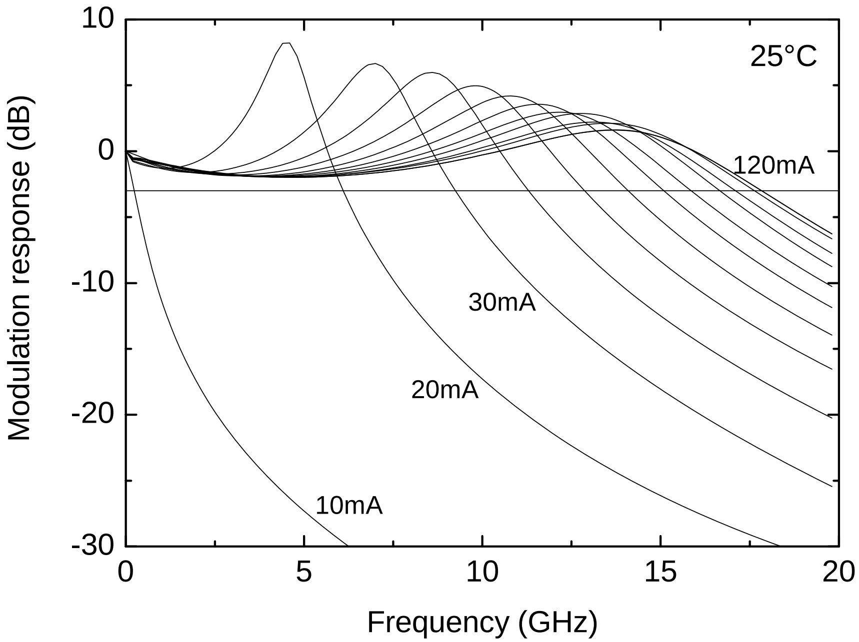




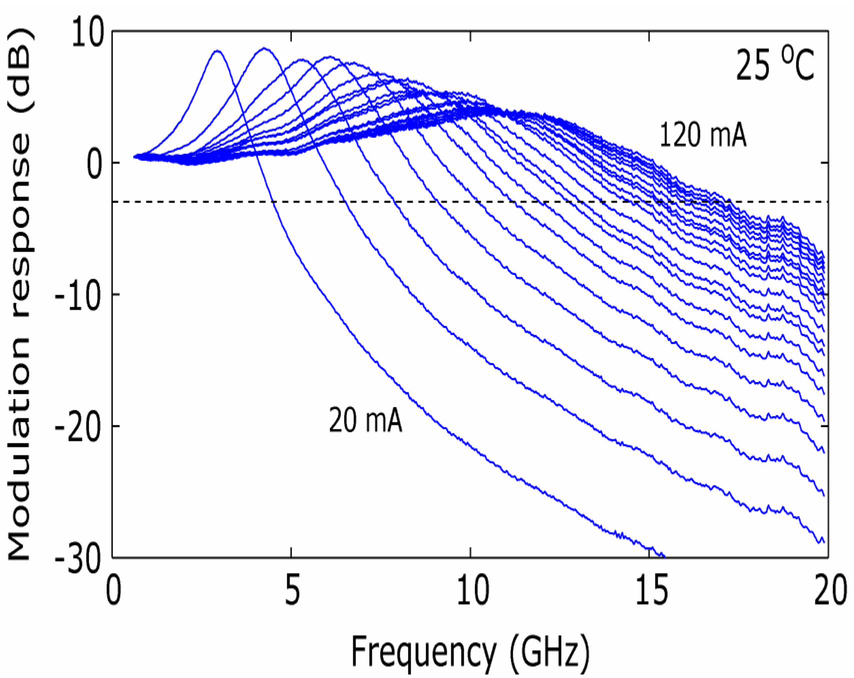
Small-signal analysis

- Reasonable agreement obtained between simulation and experiment - with maximum 3dB bandwidth of ~18 GHz at 25°C

Reference structure



Simulated



Experimental

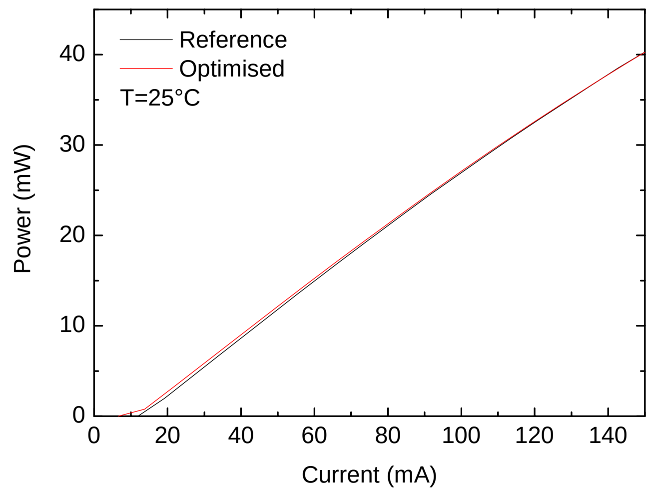
Reference: *Y.Q. Wei, et al., IEEE J. Quantum Electron. Vol. 42, p. 1274, 2006.*

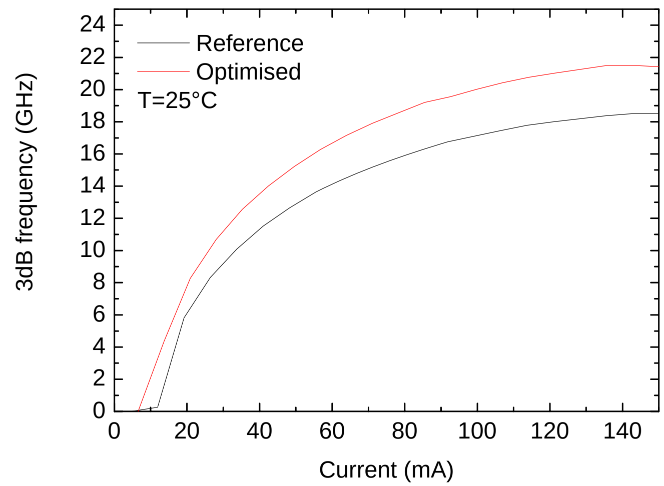
Low index layer structure

- Static and dynamic performance
- 3.4 x 350 μm^2 RW laser

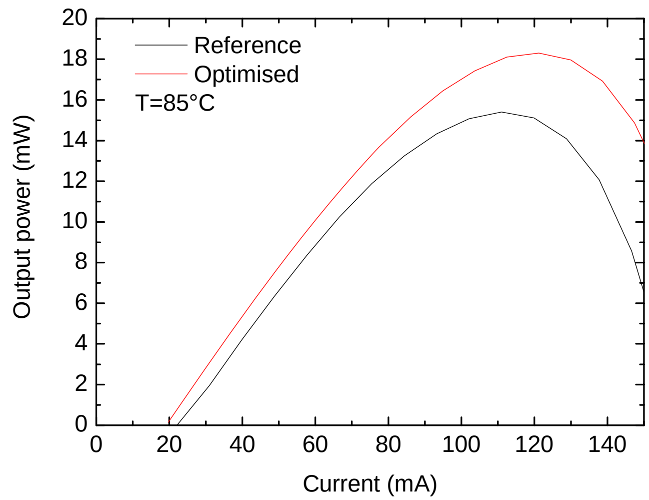
Power | *Bandwidth*

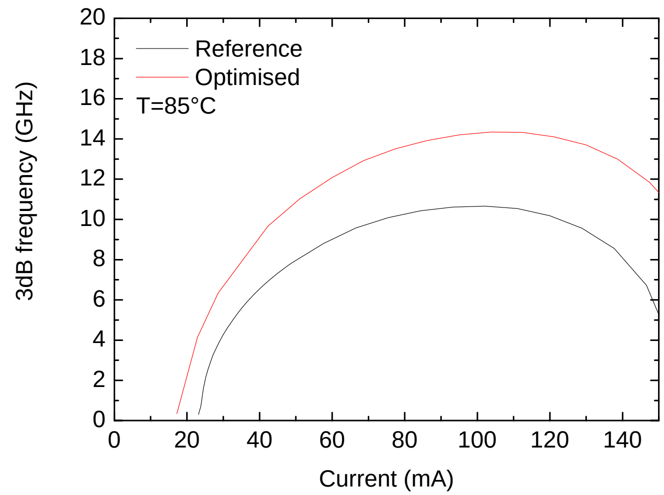
25° C





85° C





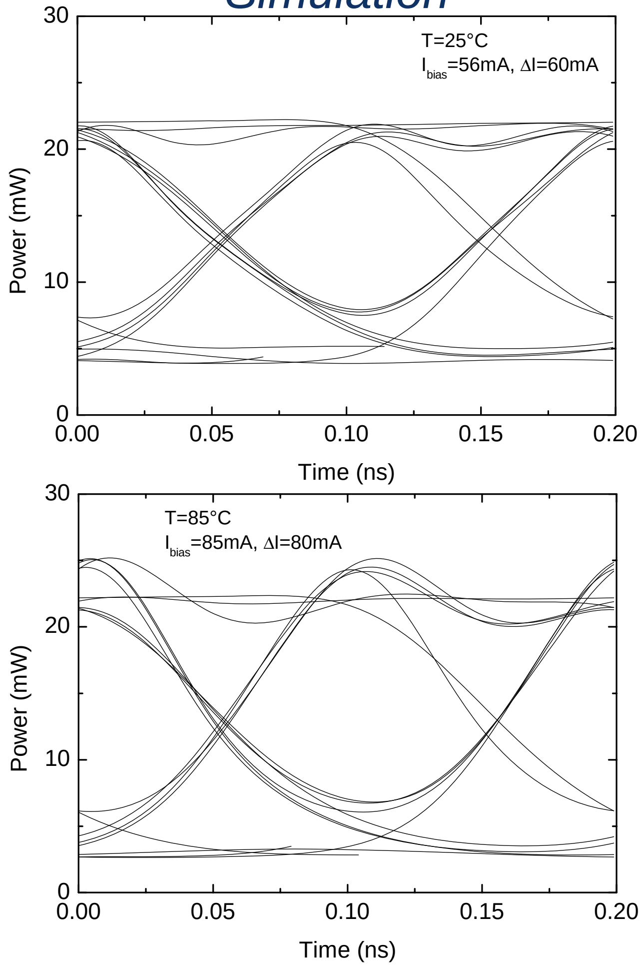
Large-signal analysis

- 3.4 x 350 μm^2 RW laser from reference structure
- Simulation against experiment at 10Gb/s (passed through a 7.5GHz Bessel filter)

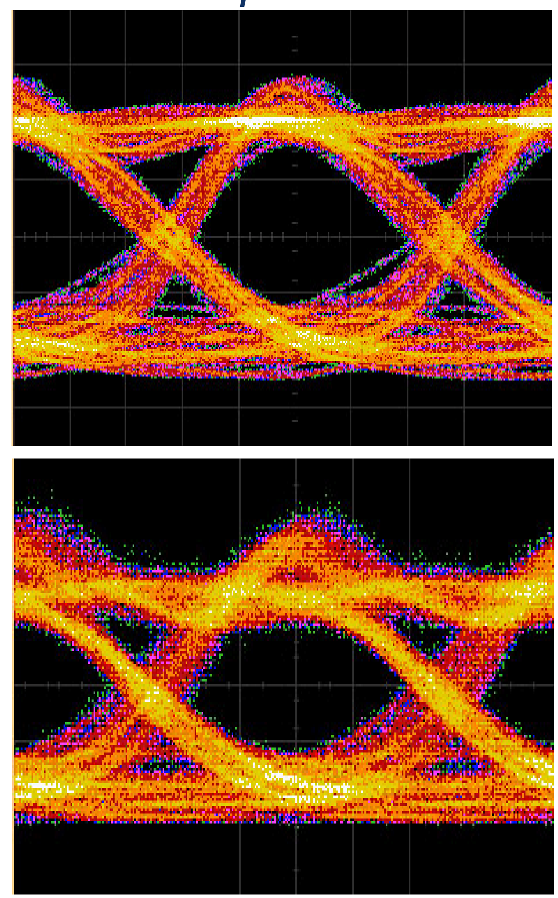
Simulation

25° C

85° C



Experiment



Reference: *J.S. Gustavsson, et al., Electron. Lett., 42, 20061517, 2006*

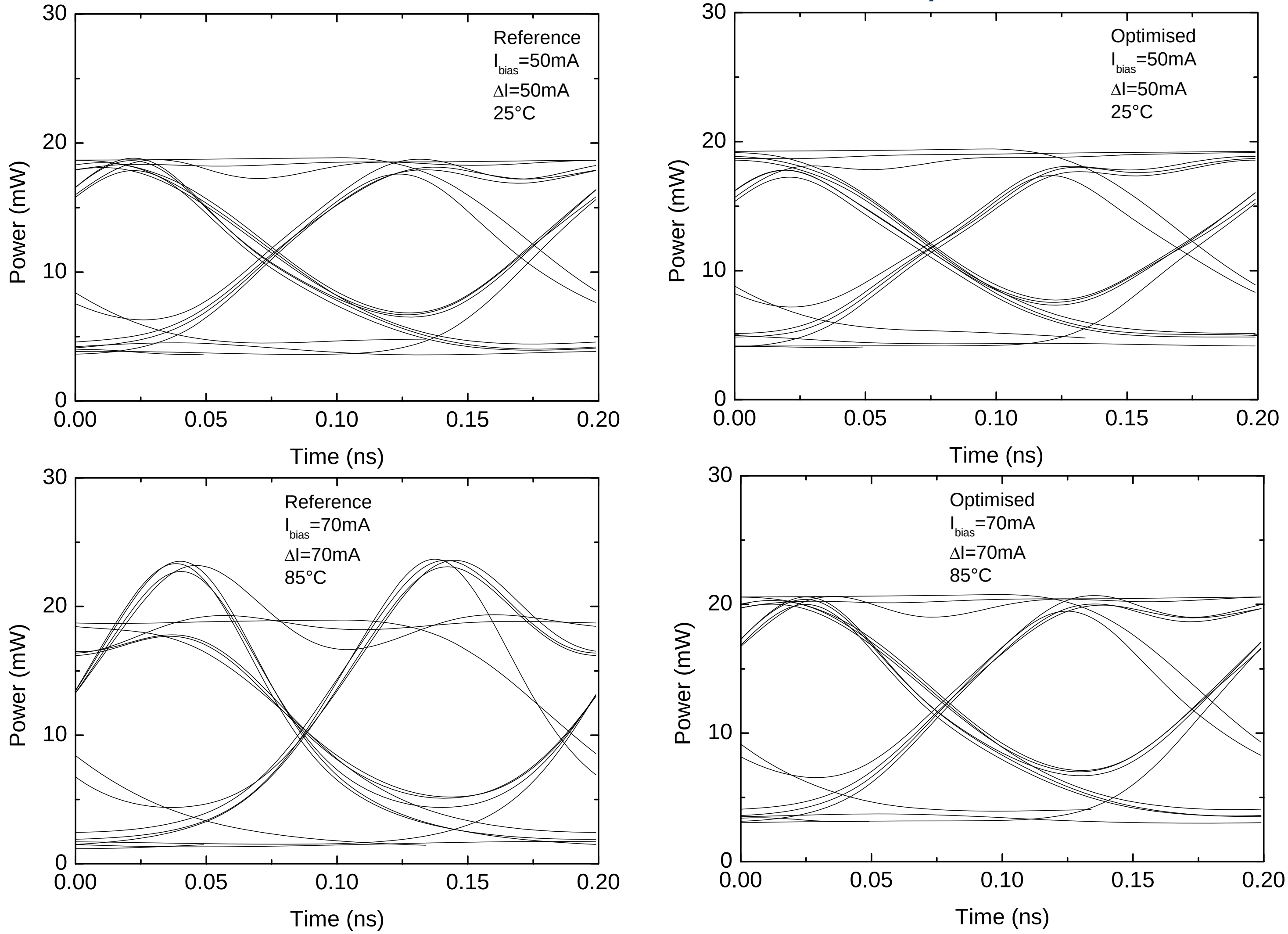
Low index layer structure

- 3.4 x 350 μm^2 RW laser
- Optimised structure has better high-temperature performance (less ringing)

Reference *Optimised*

25° C

85° C



Conclusion

- The layer structure of a GaInNAs EEL has been optimised by inserting a low-index layer between the GRIN waveguide and cladding layer to achieve high Γ and low vertical divergence.
- Optimised structure has improved performance in terms of threshold current, slope efficiency, modulation bandwidth and improved large-signal digital modulation response at high temperature.
- Small-signal and large-signal models developed and agree with experiment.
- Even better performance possible as material quality continues to improve.