Modelling of External Cavity Laser Diodes

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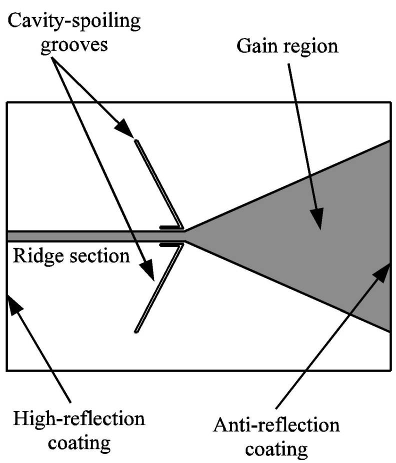
Presentation Outline

1. Laser Diode Modelling
2. External Cavity Laser Diodes
3. External Cavity Laser Diodes Models
4. Examples
   A. Talbot filter ECL
   B. Self-organising ECL
   C. Asymmetric feedback ECL
5. Experimental validation
6. Summary

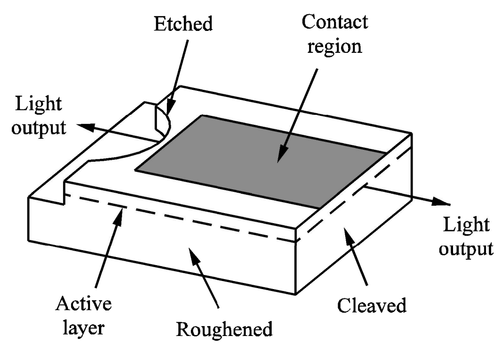
Laser Diode Modelling

Why do we need to develop laser models?

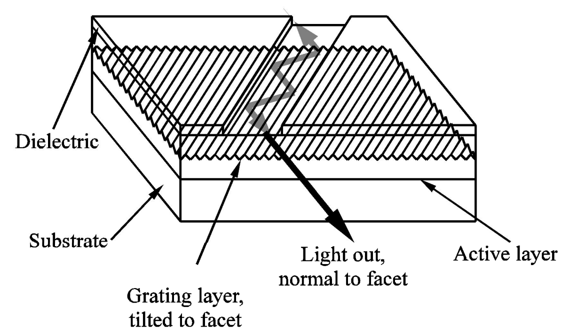
- Reduce time and cost of designing devices
- Understand the physics/operation of the device for optimisation
- To enable the exploration of novel device designs



Tapered Laser



Unstable Resonator Laser



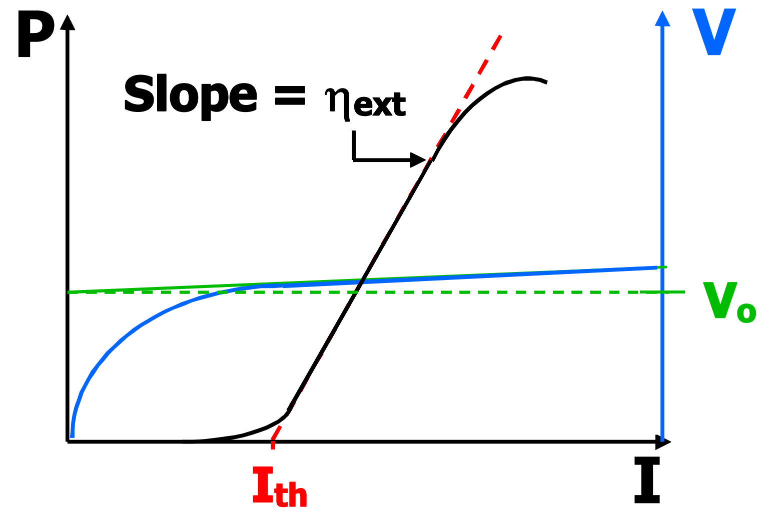
α-DFB Laser

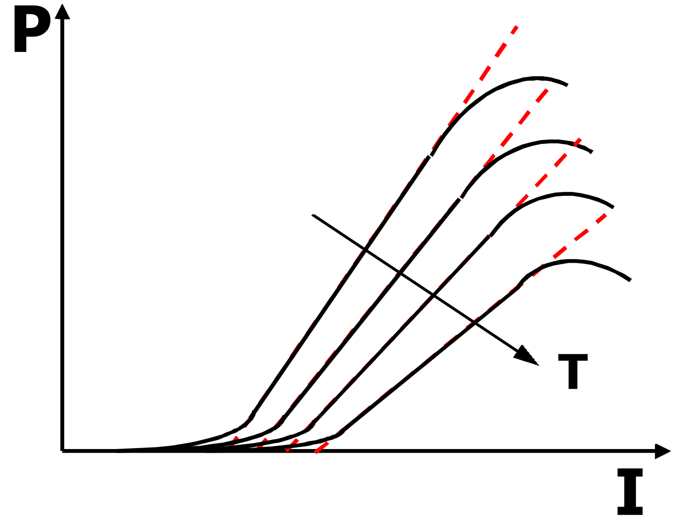
Basic electrical and optical performance

- V, P -vs- I
- I_{th}
- η_{ext}
- Wall plug efficiency

Thermal performance

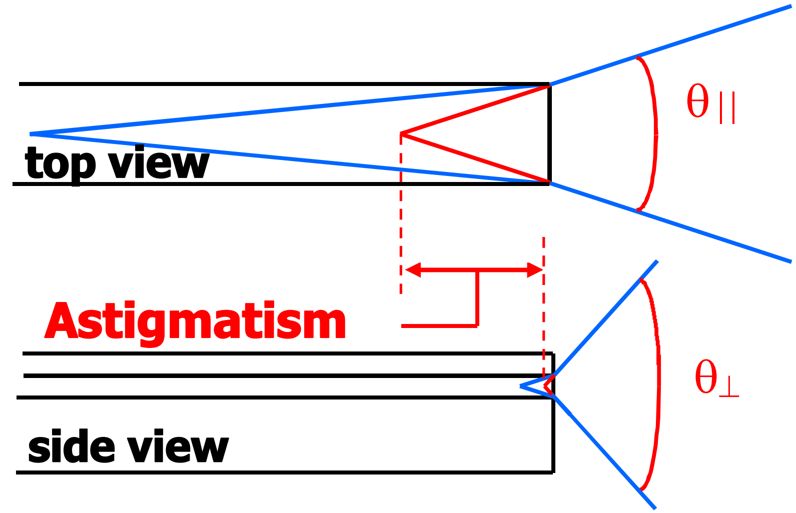
- T_0 $$I_{th} \,\alpha\, \exp\left(\frac{T}{T_0}\right)$$
- T_1 $$\eta_{ext} \,\alpha\, \exp\left(-\frac{T}{T_1}\right)$$
- Thermal rollover
- $d\lambda/dT$

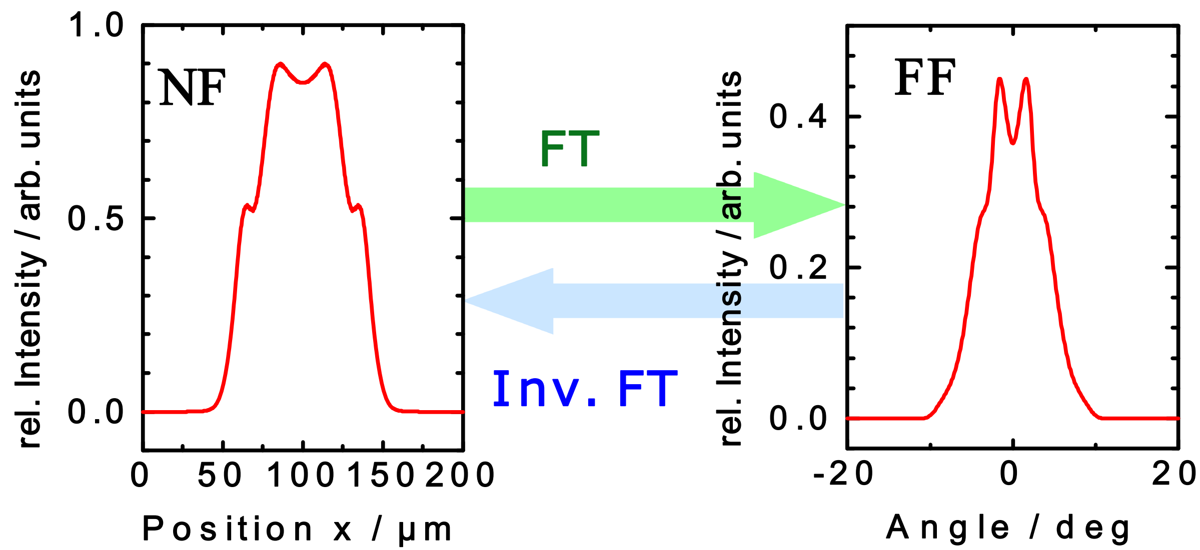




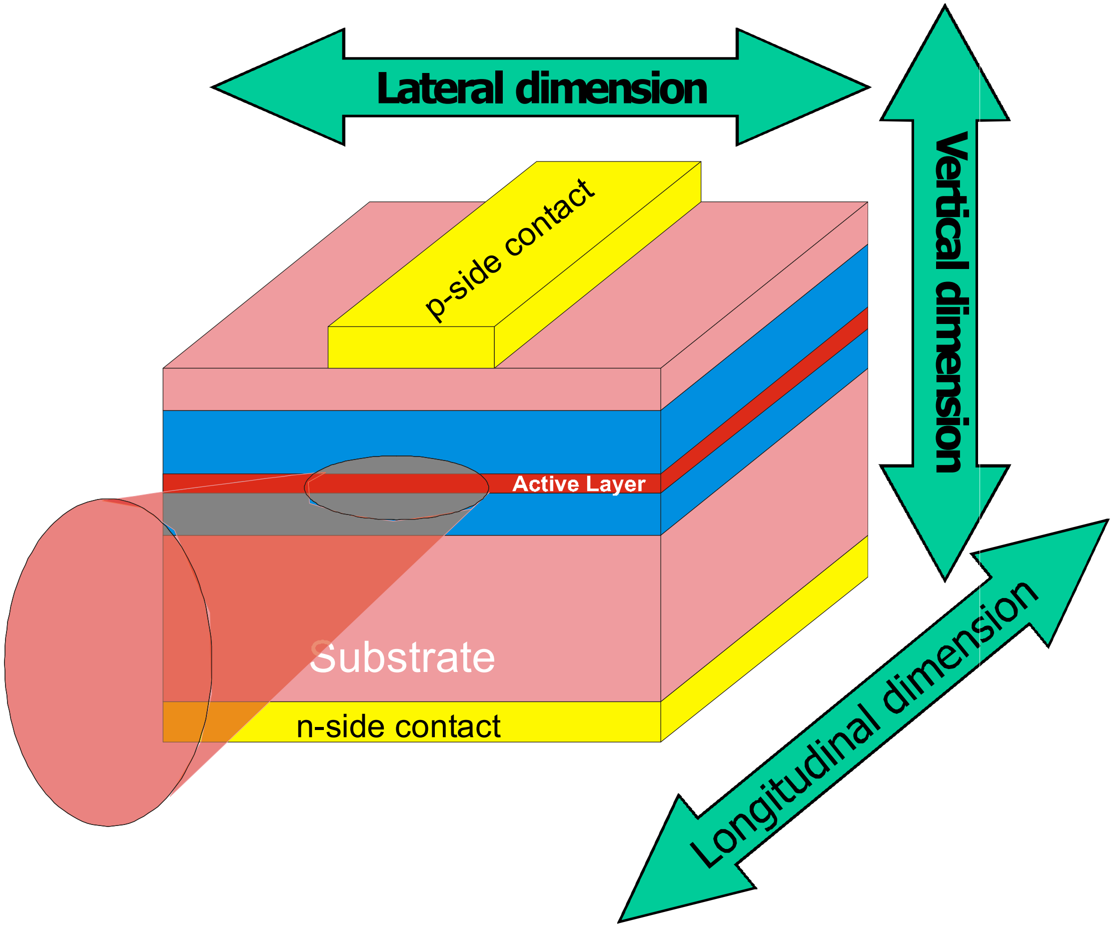
Beam quality

- Near-field patterns
- Far-field patterns
- Beam waist
- Astigmatism
- M^2





Dimensionality – 0D, 1D, 2D or 3D?



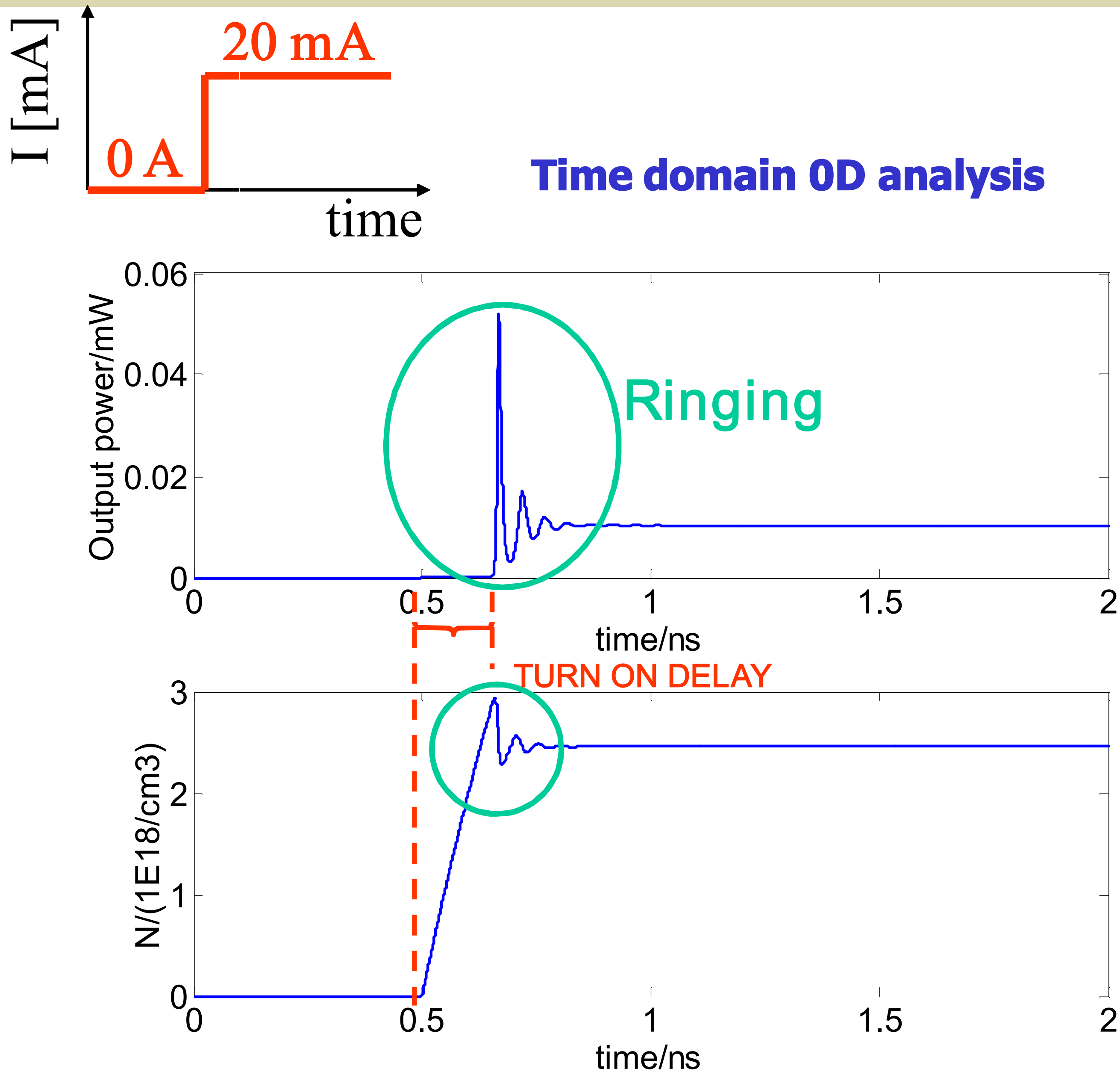
0D: Photon-carrier rate equations

1D: Vertical or lateral or longitudinal

2D: Any combination of two dimensions

3D: Vertical & lateral and longitudinal

- 0D rate equation model:
  - Photon rate equation
  - Carrier rate equation (equations)
- Advantages:
  - Efficient (seconds)
  - Fast calculation of key tradeoffs
- Disadvantages:
  - Useful only for initial analysis
  - Ignores the spatial details of analysed laser diode structure

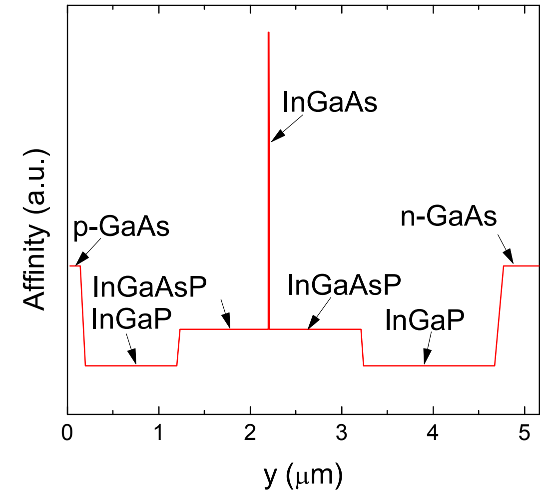


1D bipolar laser diode model

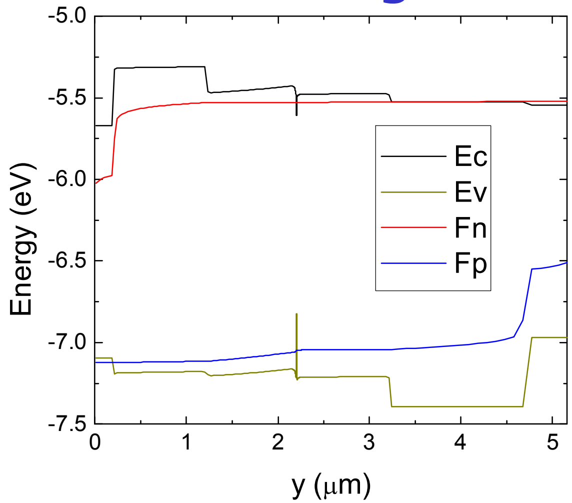
- 1D vertical bipolar model:
  - Poisson's equation
  - Drift-diffusion equations
  - Capture-escape equations
  - Photon rate equations

  } Newton's Method
- Advantages:
  - Efficient (seconds – minutes)
  - Useful for BA lasers, simulator calibration
- Disadvantages:
  - Ignores current spreading, diffusion in lateral direction

Layer structure



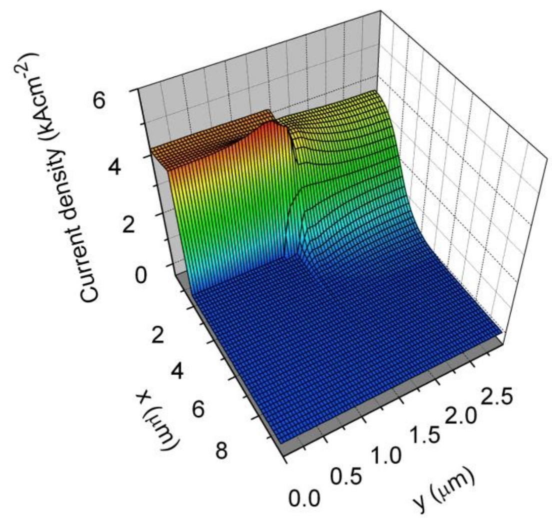
Band diagram



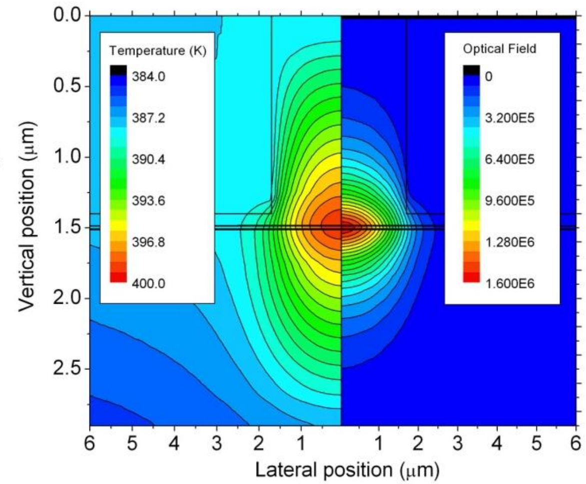
2D bipolar laser diode model

- 2D transverse (x-y) bipolar electro-thermal model:
  - Current spreading, Lateral diffusion
  - Heat spreading
- 2D (x-y) optical mode solver
- Advantages:
  - Efficient (10’s minutes)
  - Dynamic effects (small- and large-signal analysis)
- Disadvantages:
  - Only for longitudinally uniform structures

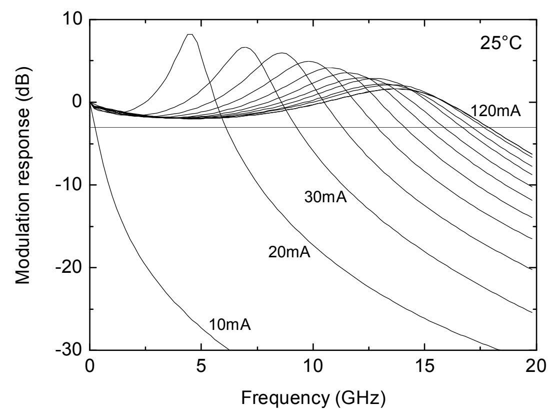
Current Density



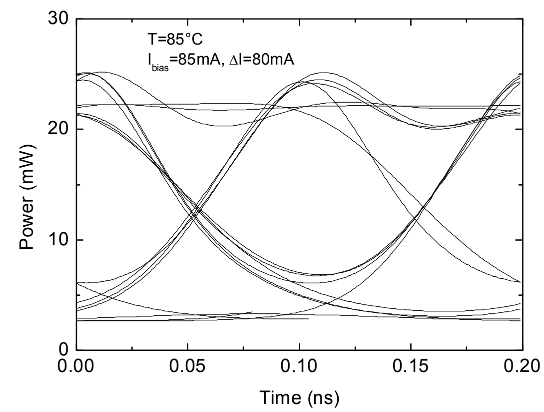
Optical & Thermal Profile



Small-signal Analysis

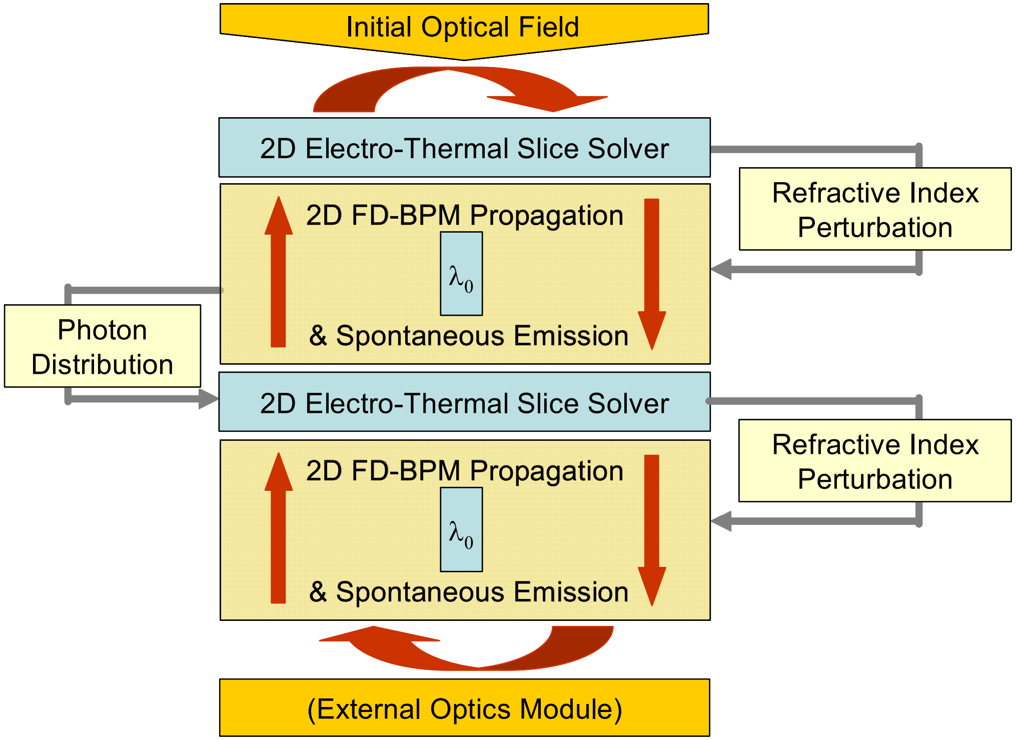


Large-signal Analysis

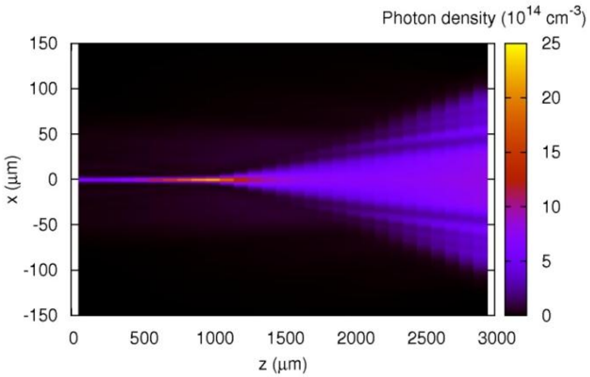


2.5D Bipolar monochromatic laser diode model

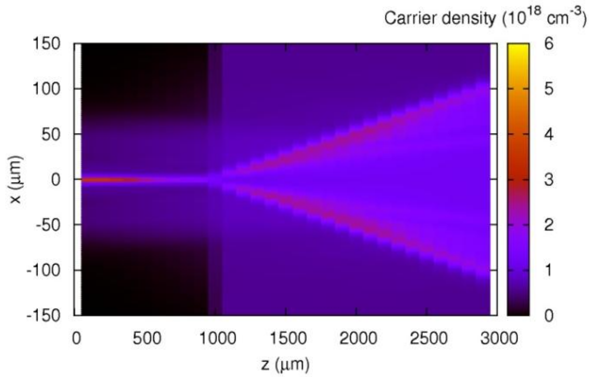
- 2D transverse (x-y) bipolar electro-thermal model
- 2D (x-z) WA-FDBPM
- Fox-Li iterative method
- Advantages:
  - Longitudinally non-uniform structures (arbitrary geometry, multi-section lasers)
  - Reasonably efficient (hours - 10’s hours)
- Disadvantages:
  - Does not consider spectral effects



Photon Density

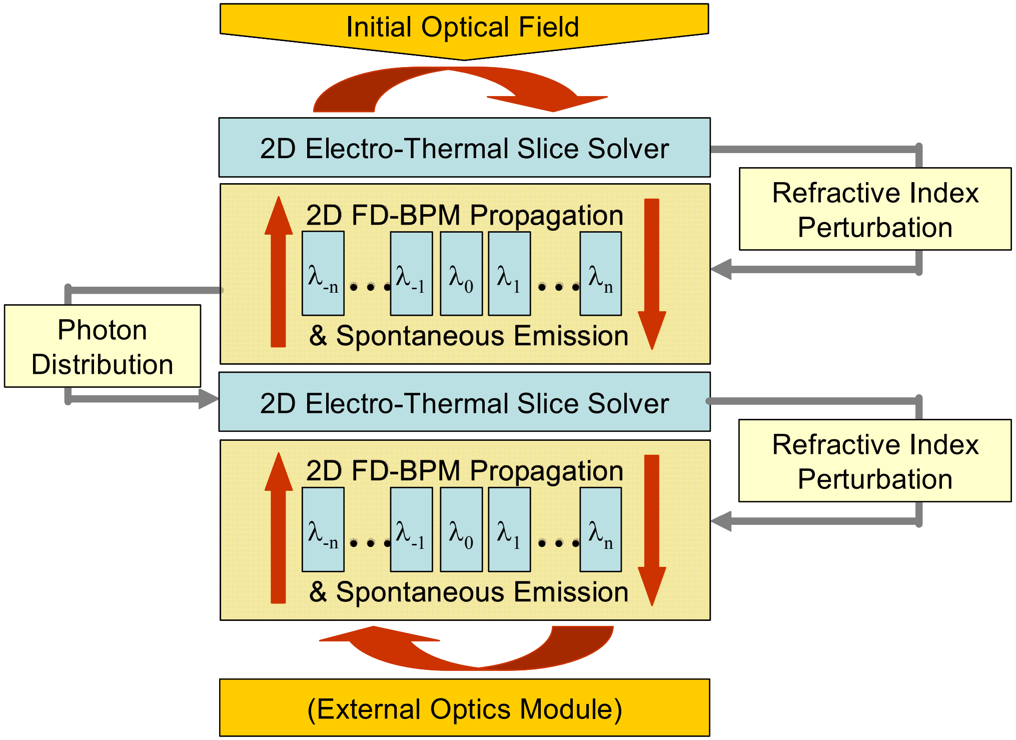


Carrier Density

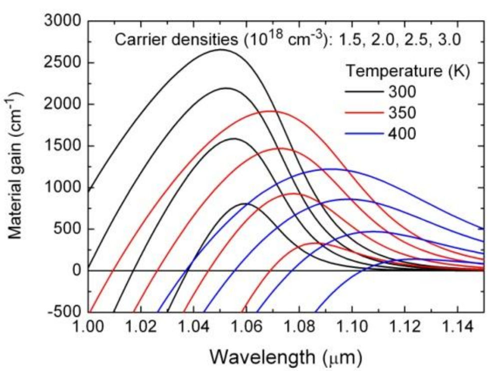


2.5D Bipolar spectral laser diode model

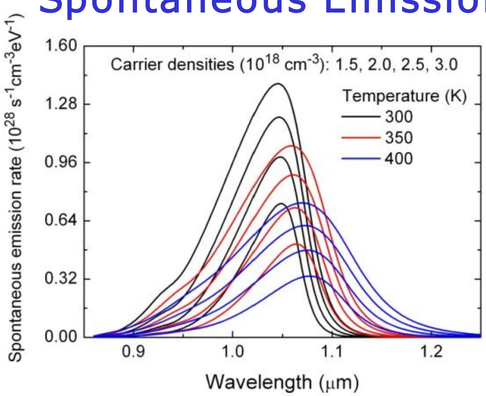
- 2D transverse (x-y) bipolar electro-thermal model
- 2D (x-z) WA-FDBPM
- Advantages:
  - Accurate (Spectral dependence of gain, spontaneous emission, index change)
- Disadvantages:
  - Computationally intensive (days)



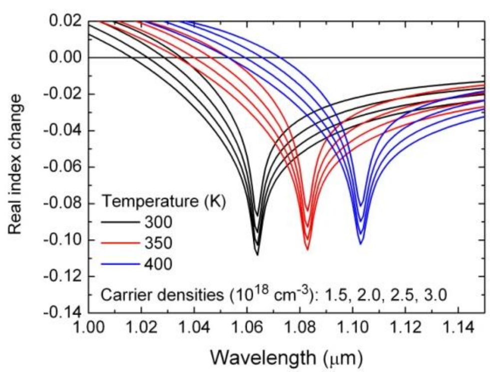
Gain



Spontaneous Emission

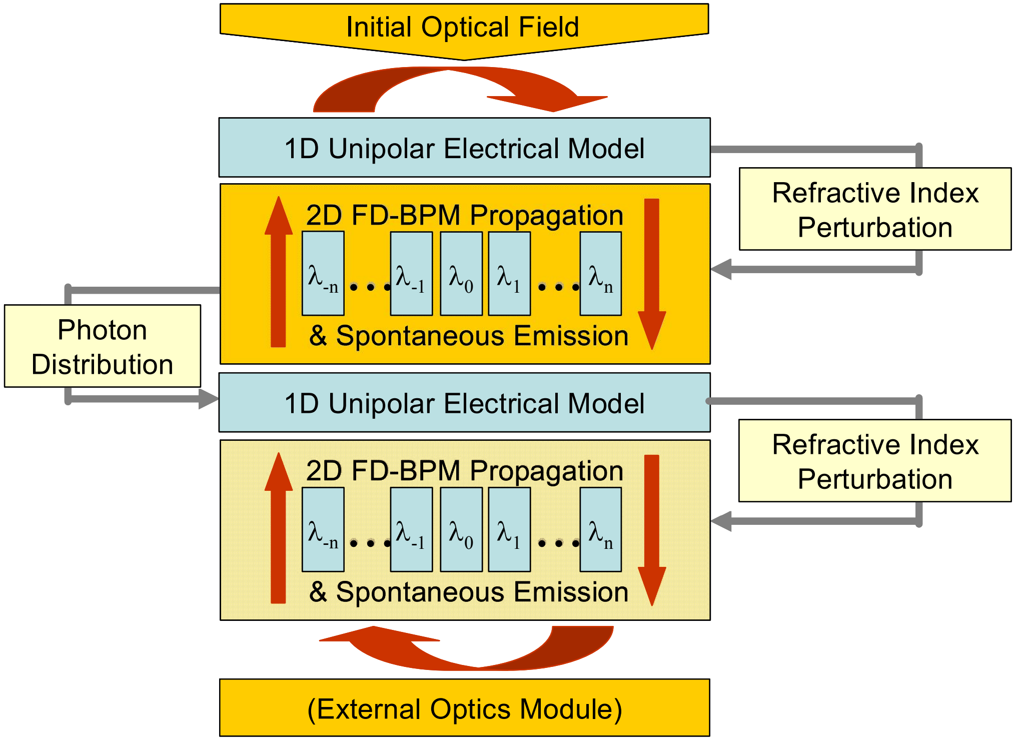


Index change

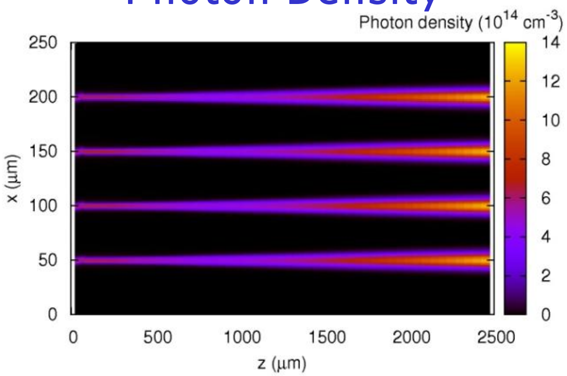


1.5D Unipolar laser diode model

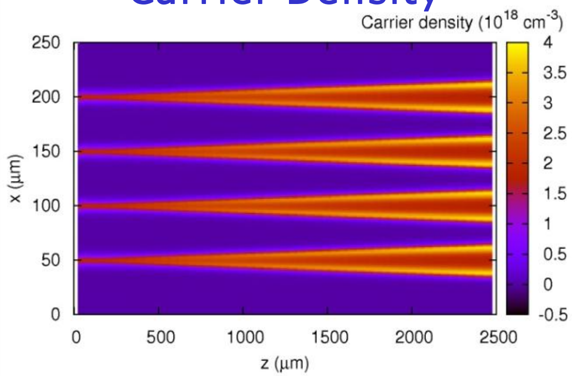
- 1D lateral (x) unipolar electrical model
- 2D (x-z) WA-FDBPM
- Advantages:
  - Efficient (10's minutes - hours)
  - Suitable for large structures (Array of emitters)
- Disadvantages:
  - Does not include thermal and current spreading effects



Photon Density



Carrier Density



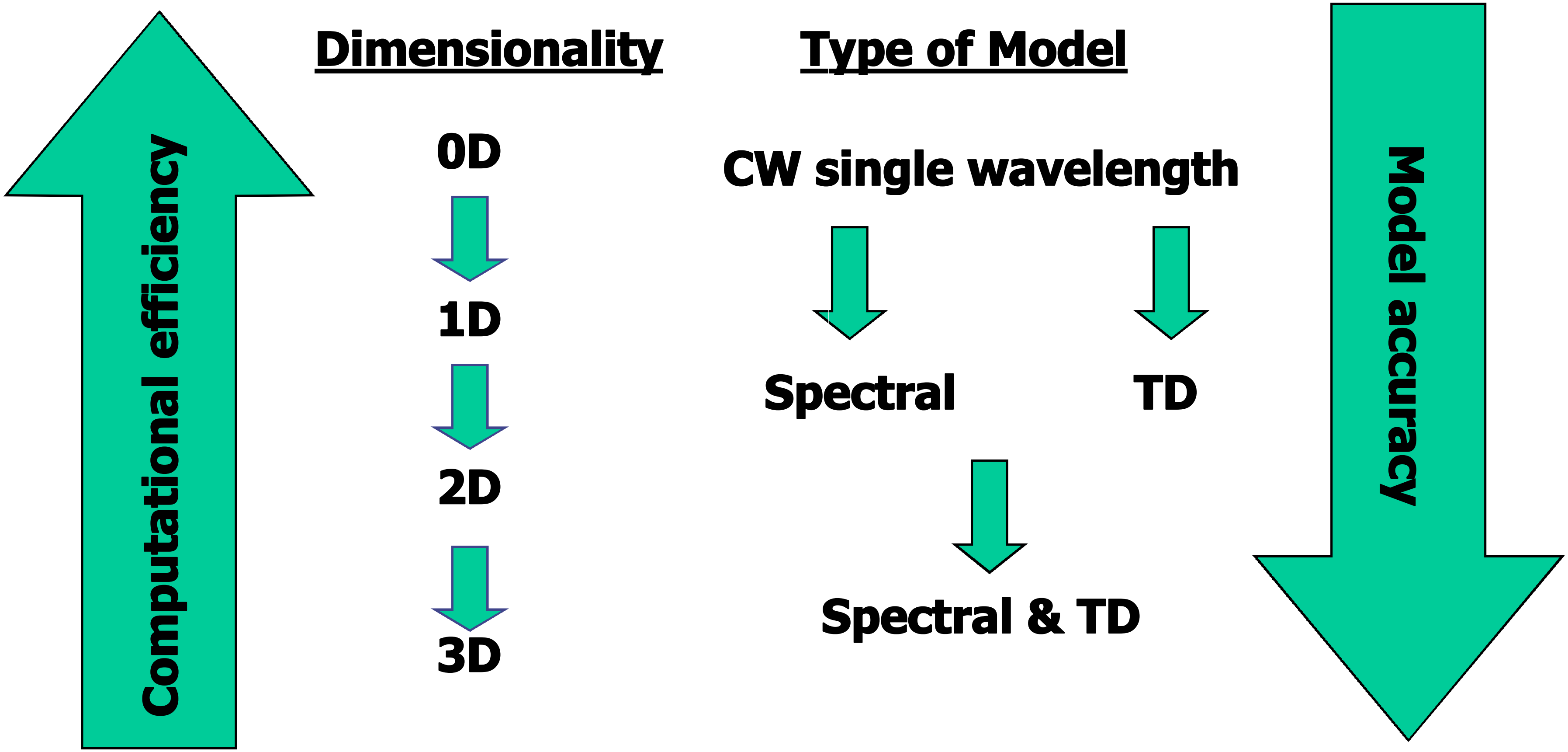
2D Unipolar time domain laser diode model

Time t_0 **Time $t_0 + \Delta t$**

- 1D lateral (x) unipolar electrical model
- 2D (x-z) TD FD model (envelope approximation)
- Advantages:
  - TD analysis of nonlinear interactions
  - Suitable for large structures (Array of emitters)
- Disadvantages:
  - Long calculation times and does not include thermal and current spreading effects

Forward wave

Backward wave


Computational efficiency
Dimensionality
0D
1D
2D
3D
Type of Model
CW single wavelength
Spectral
TD
Spectral & TD
Model accuracy

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External Cavity Laser Diodes

Example Applications

1. Wavelength beam combing

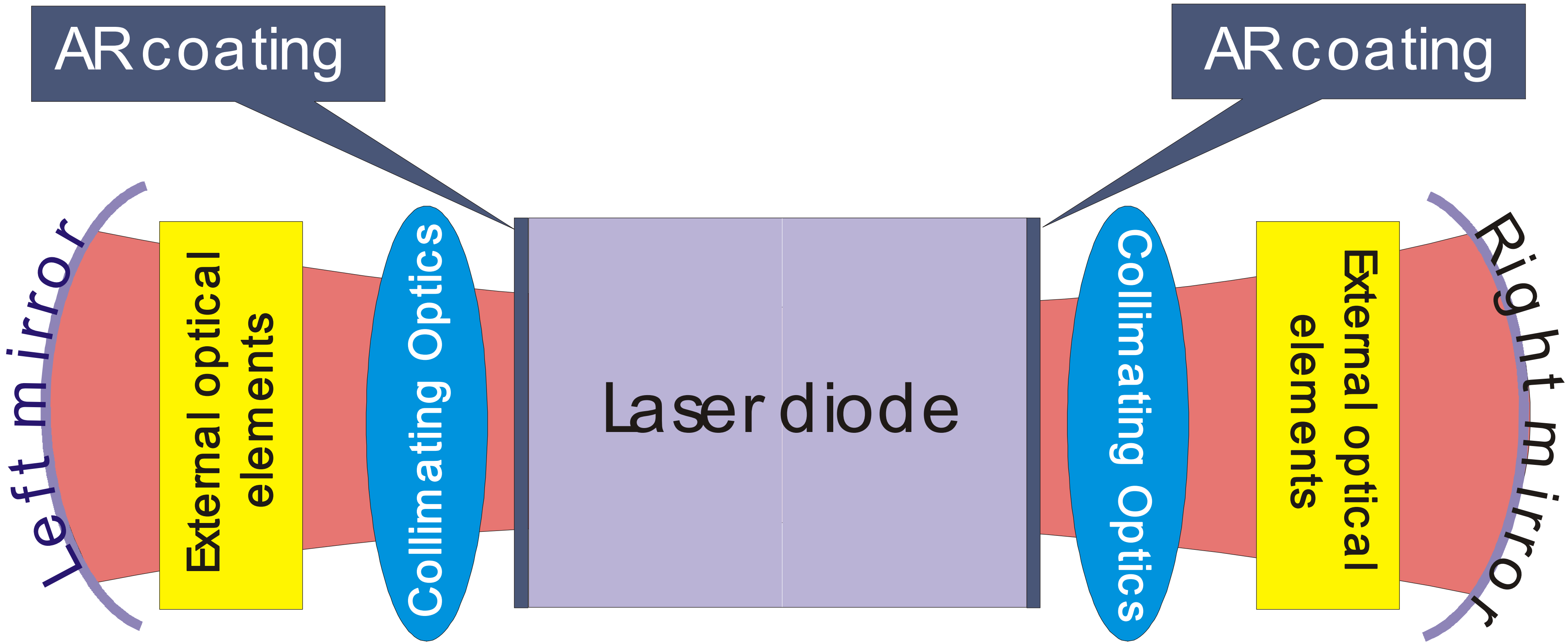
2. Brightness improvement in high power lasers

3. Output spectrum improvement

4. Frequency doubling

5. Mode-locking

Schematic Diagram of External Cavity Laser Diode



Characteristic features

1. Cavity length: several mm to cm

2. Cavity width: several mm (LD bars, arrays)

3. Wavelength spacing ~ 10 pm

4. Free running modes

External Cavity Laser Diodes Models

Requirements for Laser Diode Models

1. Ability to handle cavities with large length and width (arrays, bars)

2. Ability to handle small wavelength spacing

3. Easy coupling with external optics models

↓

Multidimensional, spectral laser diode models based on travelling wave approach (Fox-Li iteration)

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External optics models

1. Geometric optics based models

2. Wave optics based models

3. Models based on solution of Maxwell's equations

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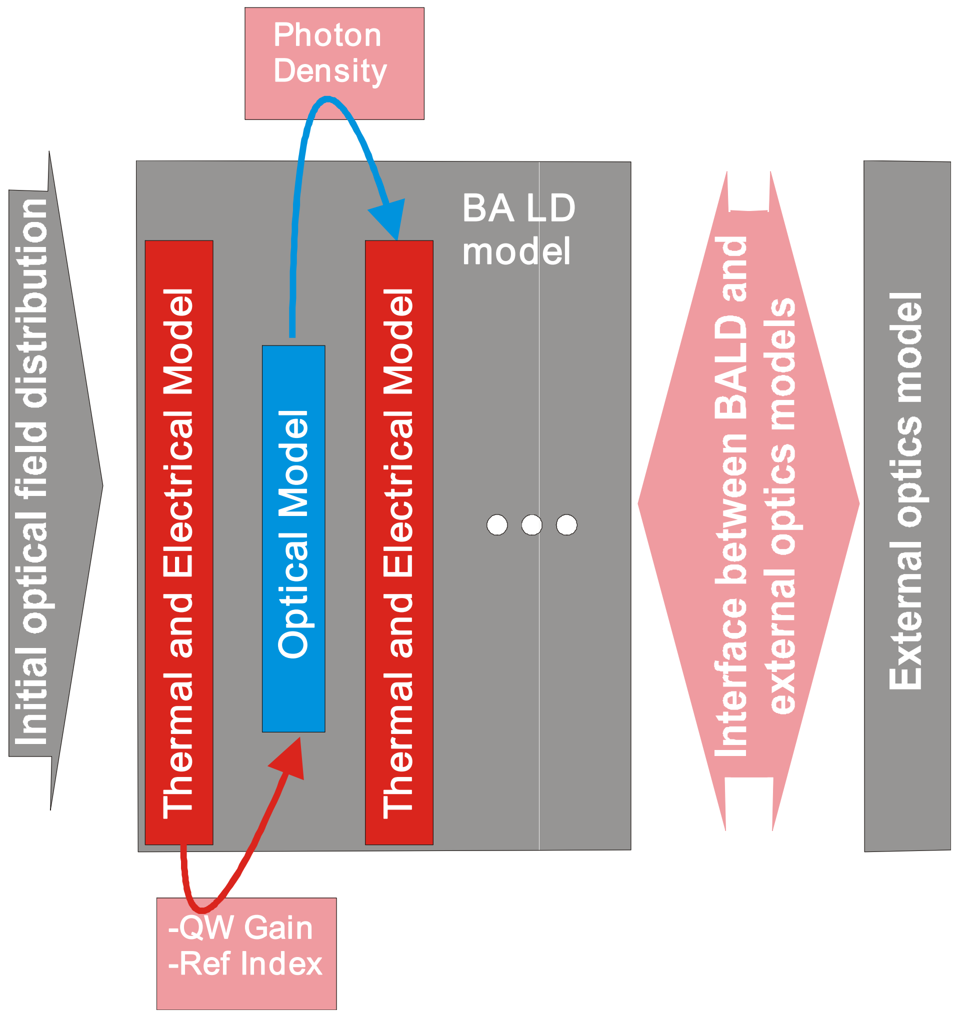
Generic Example of External Cavity Laser Diode Model

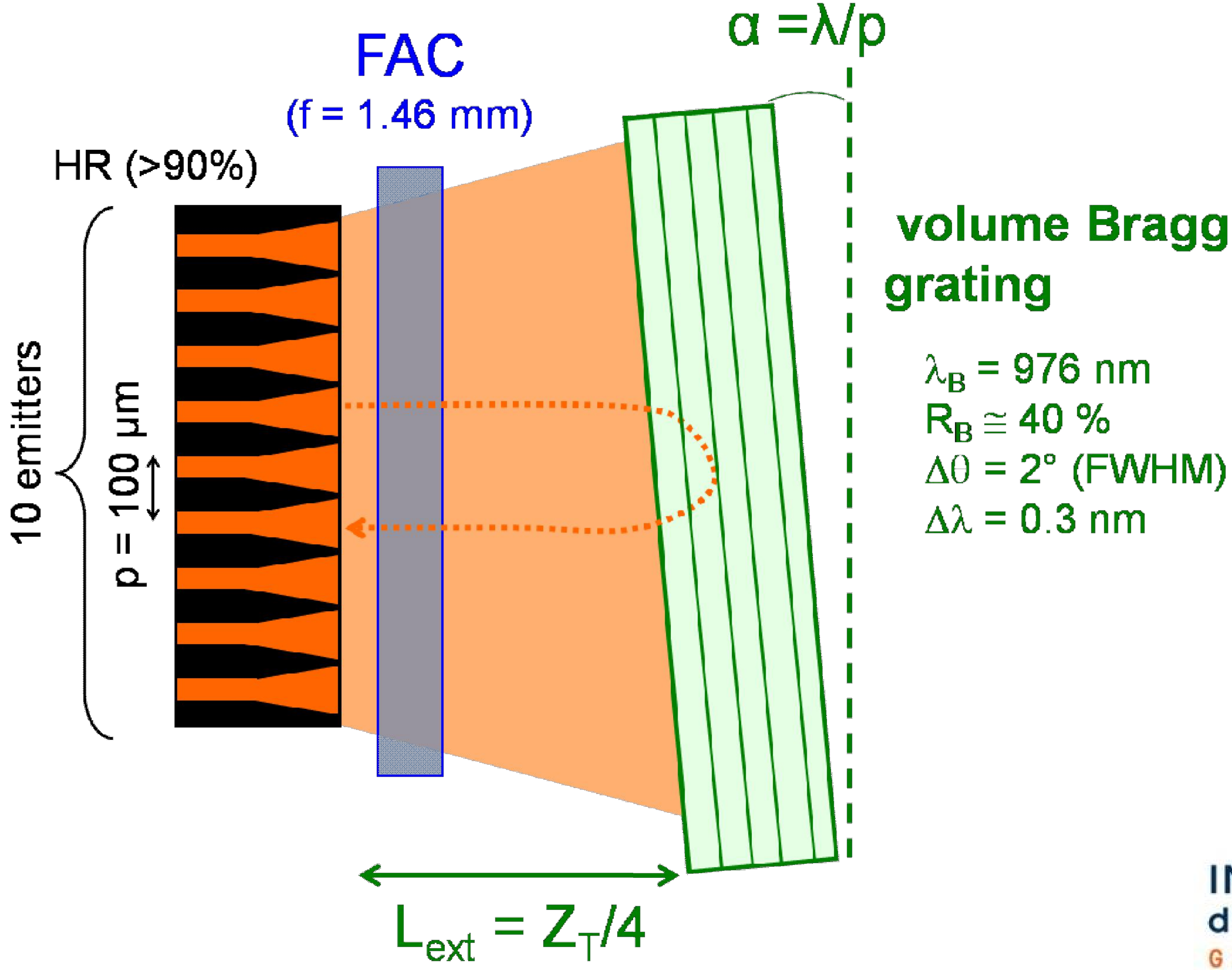


Examples

Case Study A:
Talbot Filter External Cavity Laser Diode

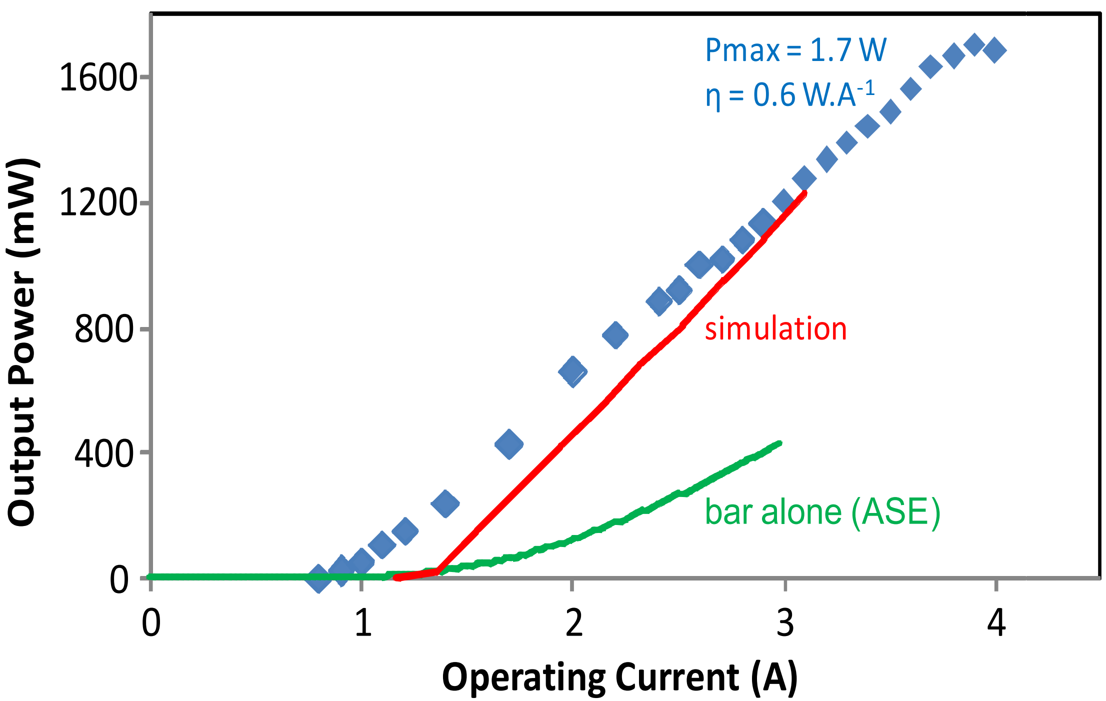
Model used: 1.5D Unipolar Laser Model

Talbot filter ECL geometry

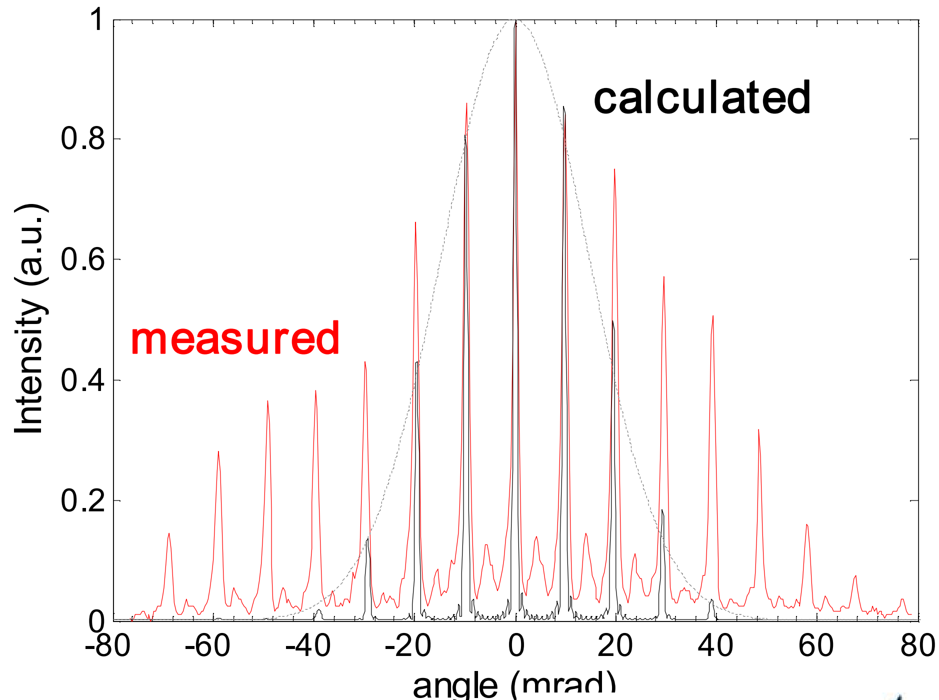


Talbot filter ECL modelling results

Light-current characteristic



Output spectrum



Conclusion

- Can accurately reproduce phase locking
- Reproduces the light-current characteristics and far field

Case Study B:

Self Organising External Cavity Laser

Model used: 0D,1D,1.5D Spectral Laser Model

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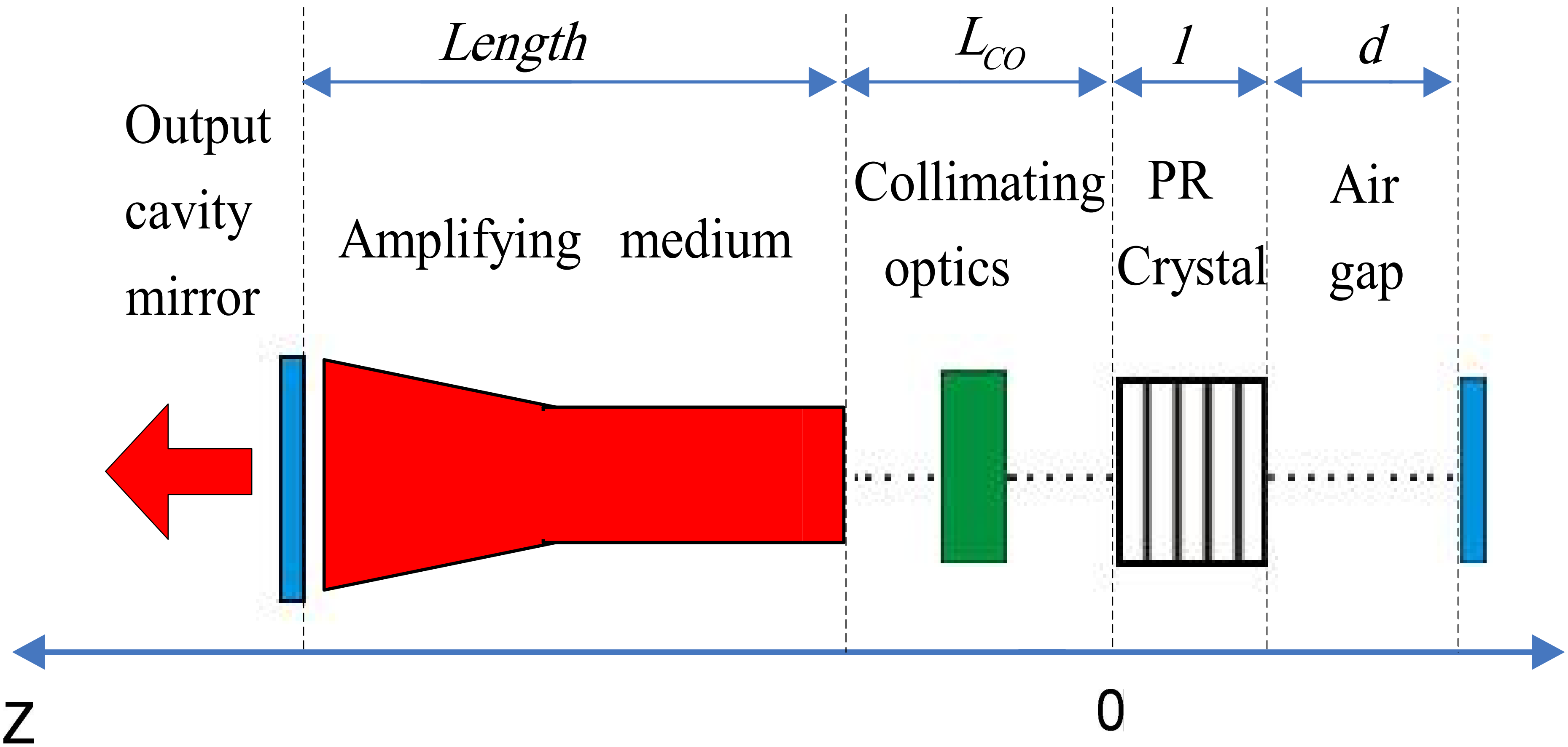
Self-organising ECL geometry



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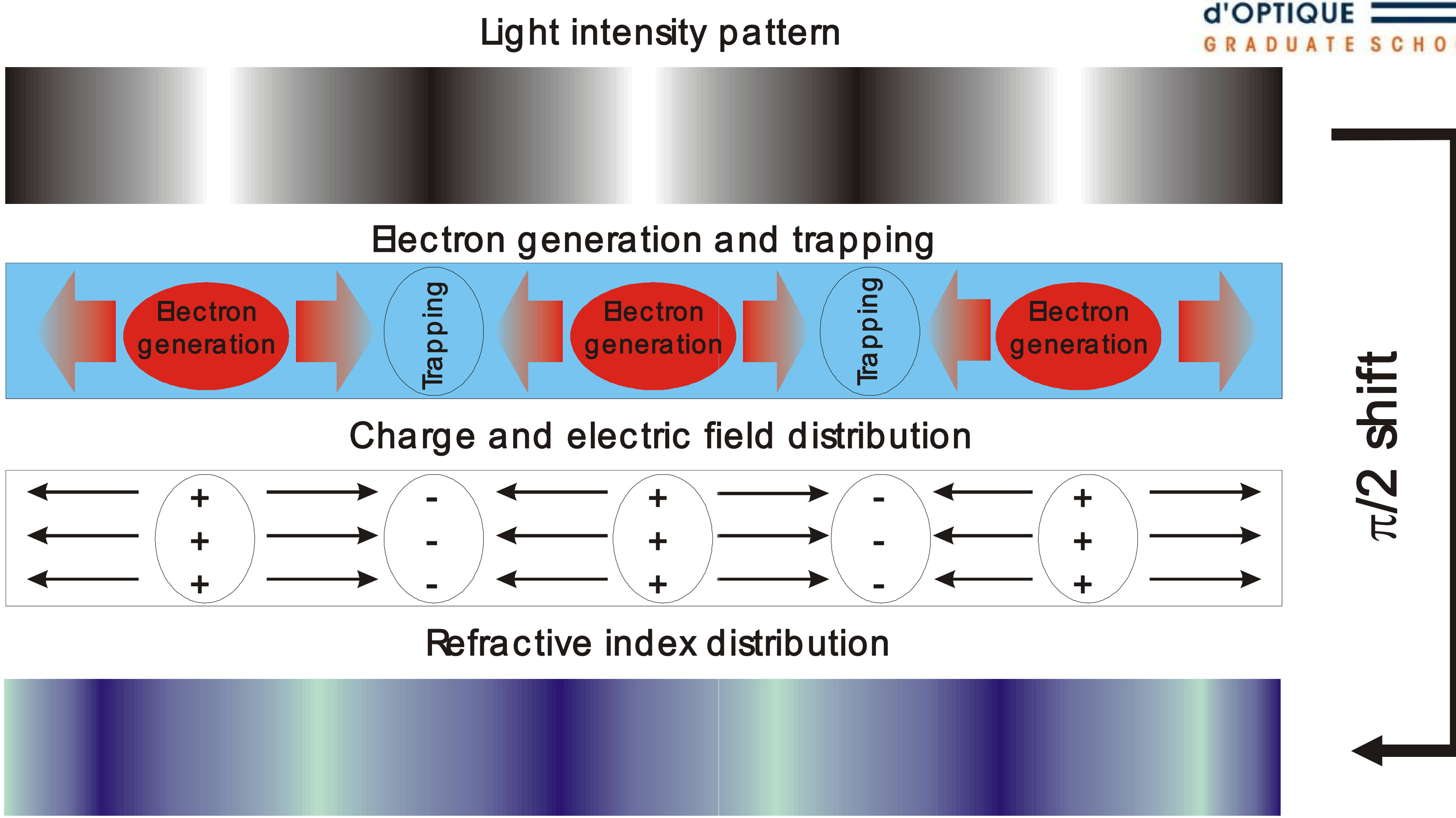
PR crystal



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Kukhtarev equations

$$\begin{cases} \dfrac{\partial \left(N_D^+ - N\right)}{\partial t} = -\dfrac{1}{e}\dfrac{\partial J}{\partial z} \\ \dfrac{\partial N_D^+}{\partial t} = \left(N_D - N_D^+\right)\left(sI + \beta\right) - \gamma_R \cdot N_D^+ N \\ J = eD_S \dfrac{\partial N}{\partial z} + e\mu N E_{SC} \\ \varepsilon_S \dfrac{\partial E_{SC}}{\partial z} = e\left(N_D^+ - N_A - N\right) \end{cases}$$

$$\frac{\partial^2 \psi(x,t)}{\partial z^2} + k^2 \psi(x,t) = 0$$

symbol	quantity
N_D	Ionised donor density
N	Electron density
J	Electron current density
Esc	Electric field intensity
I	Light intensity
Ψ	Scalar potential

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PR crystal mirror reflectivity

If only main longitudinal mode writes the grating and only first order terms are included the reflectivity is calculated from:

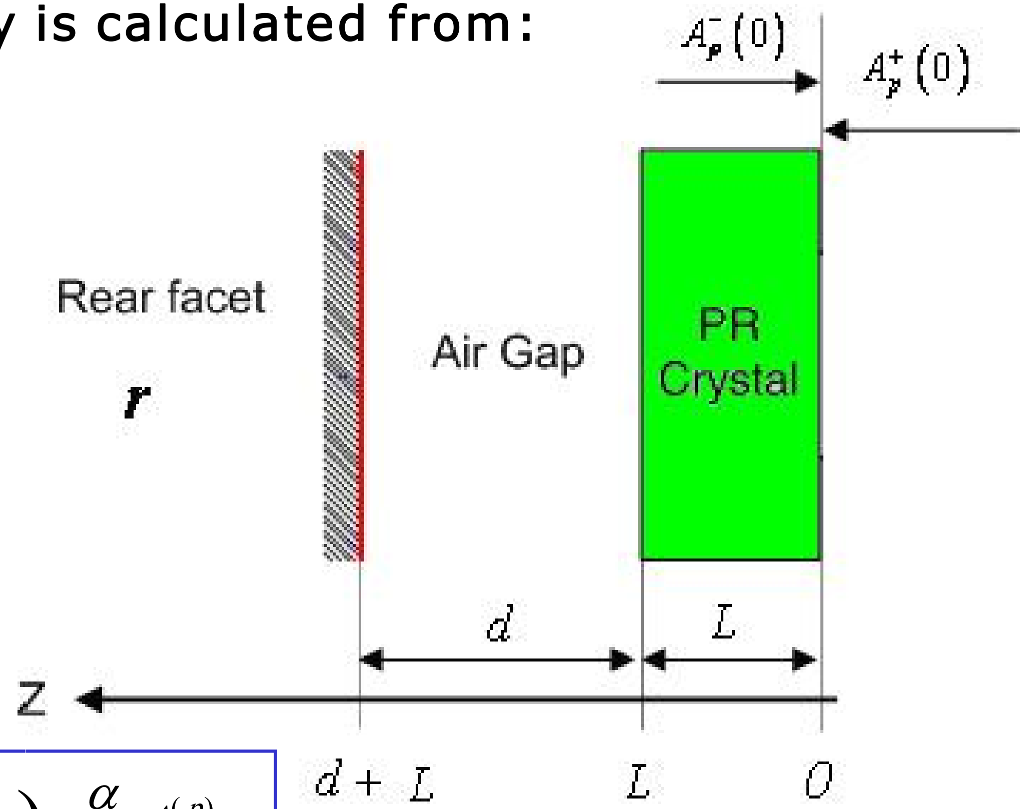
$$R = \frac{c_{21}\ \exp\left(-2ik^{(p)}(nl+d)\right) - rc_{11}}{rc_{12}\ \exp\left(-2ik^{(p)}(nl+d)\right) - c_{22}}$$

$$A_-^{(p)}(0) = RA_+^{(p)}(0)$$

$$A_-^{(p)}(l) = rA_+^{(p)}(l)\exp\left(2ik^{(p)}(nl+d)\right)$$

$$\begin{pmatrix} A_+^{p}(l) \\ A_-^{p}(l) \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix} \begin{pmatrix} A_+^{p}(0) \\ A_-^{p}(0) \end{pmatrix}$$

$$\begin{cases} \dfrac{\partial A_+^{(p)}}{\partial z} = -\dfrac{\Gamma}{4} M \ \ A_-^{(p)} \exp\left(-2in\left(k^{(p)} - k^{(0)}\right)z\right) - \dfrac{\alpha}{2} A_+^{(p)}, \\ \dfrac{\partial A_-^{(p)}}{\partial z} = -\dfrac{\Gamma}{4} M^* A_+^{(p)} \exp\left(2in\left(k^{(p)} - k^{(0)}\right)z\right) + \dfrac{\alpha}{2} A_-^{(p)}, \end{cases}$$



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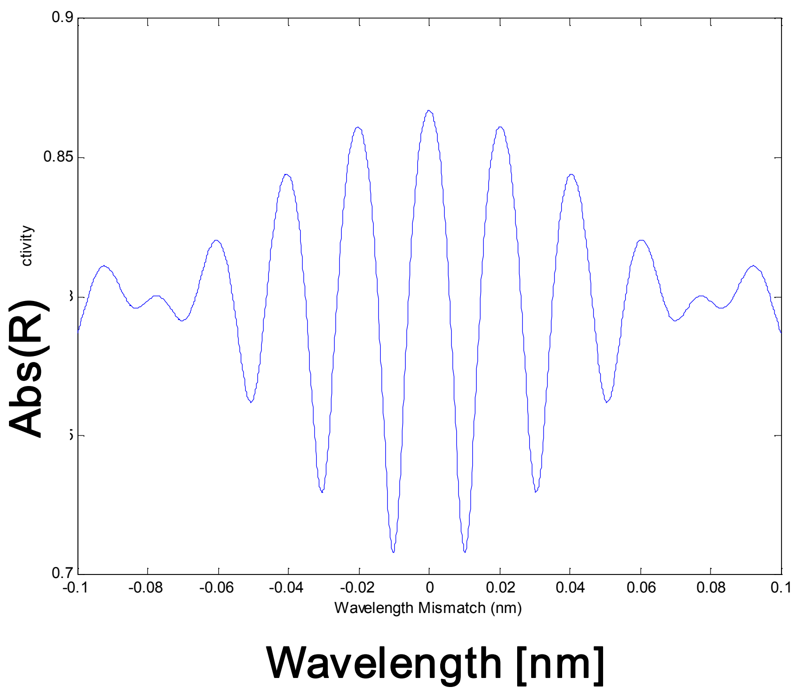
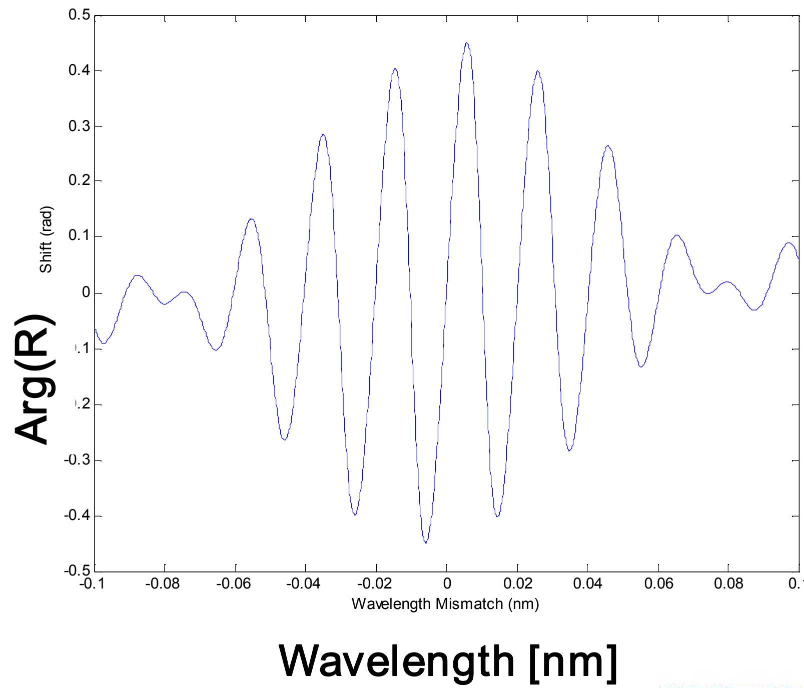
PR crystal mirror reflectivity

Simulation Parameters:
l = 0.3 cm; d = 3.0 cm, PR Gain coefficient = 3/cm;
Reflectivity of output mirror = $0.9^{1/2}$





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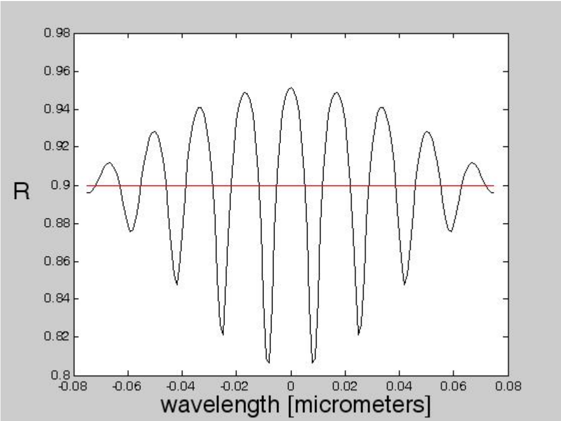
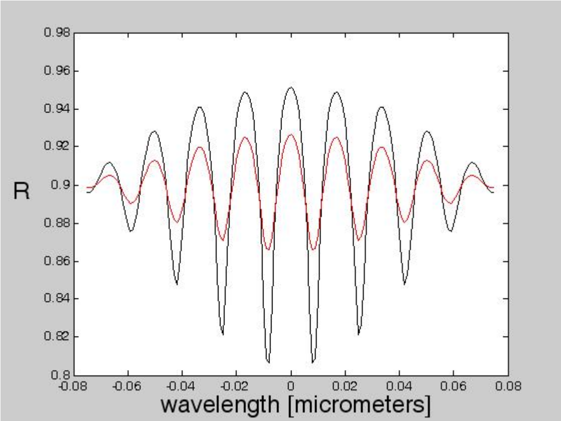
Time evolution of PR crystal reflectivity

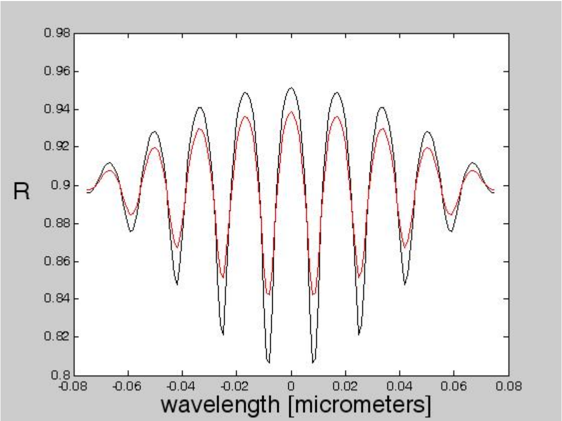
t = 0.0 s



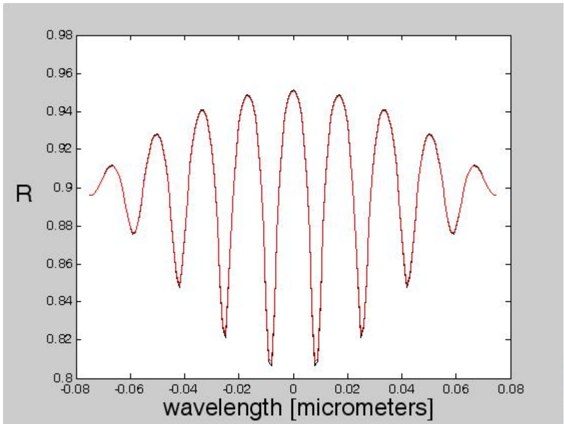
t = 0.3 s



t = 0.6 s



t = 2.7 s



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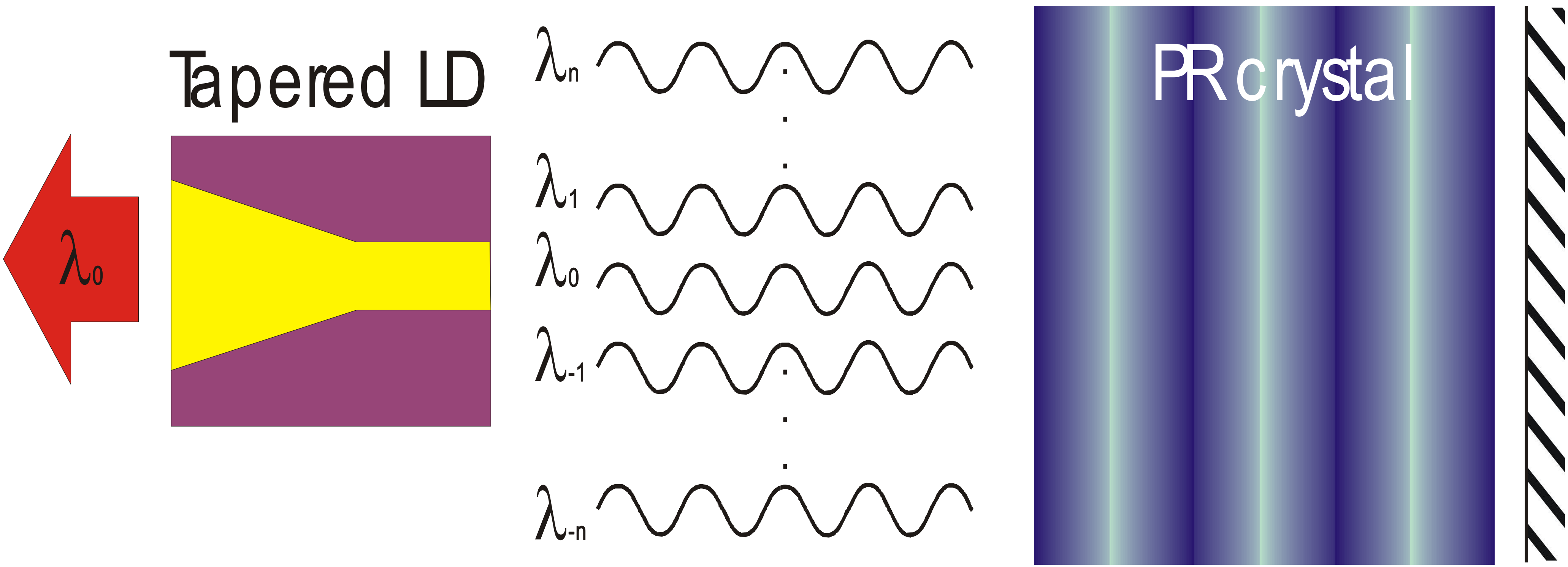
Principle of operation for self-organising tapered LD external laser cavity



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Steady State ECL Analysis

Assumptions and limitations

Only the main cavity mode writes the PR grating

1. The longitudinal mode beating freqency is too large to form a dynamic grating in the PR crystal. Hence, no direct coupling between longitudinal cavity modes by the PR crystal non-linearity.

2. Only the first harmonic of the longitudinal grating written by the light intensity is included. All higher harmonics are neglected, as they couple light to evanescent waves.

3. The PR crystal model is based on 1D plane wave approximation, discussed earlier.

4. The model calculates the field distributions of the possible cavity modes but does not allow determing neither their temporal evolution or stability, nor initial conditions under which they can be reached.

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Steady State ECL Analysis

Simulation and Results

Step 1: Calculate the resonant wavelength of the main mode of the cavity.

This is done by running repeateadly single wavelength LD model and taking the advantage of the fact that no phase shift is introduced by PR grating for the main mode.

Step 2: Calculate the resonant wavelengths for the side modes.

This is done by calculating the phase shift introduced by PR grating and performing an approximate plane wave analysis in order to calculate resonant wavelengths of the other longitudinal modes.

Step 3: Calculate the characteristics of the self organising tapered laser cavity.

This step is performed using the LD spectral model and the values of the PR crystal reflectivity obtained for the calculated resonant wavelengths.

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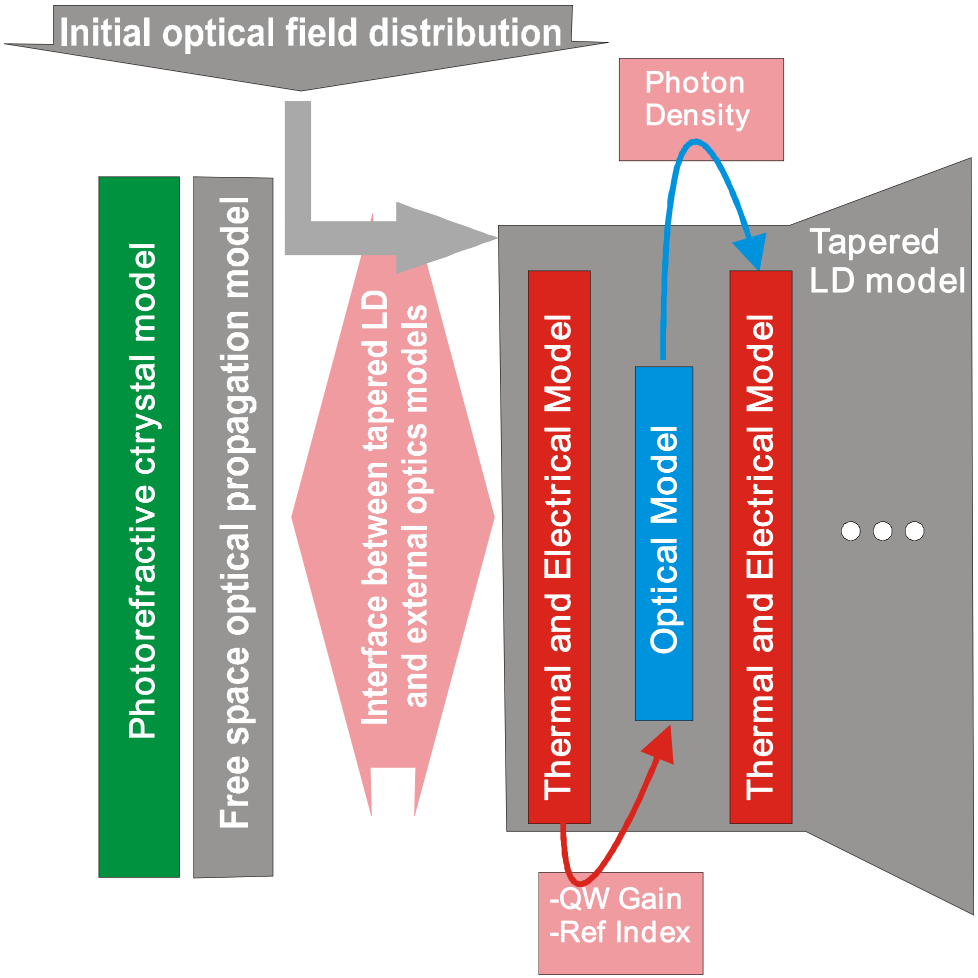
Steady State ECL Analysis

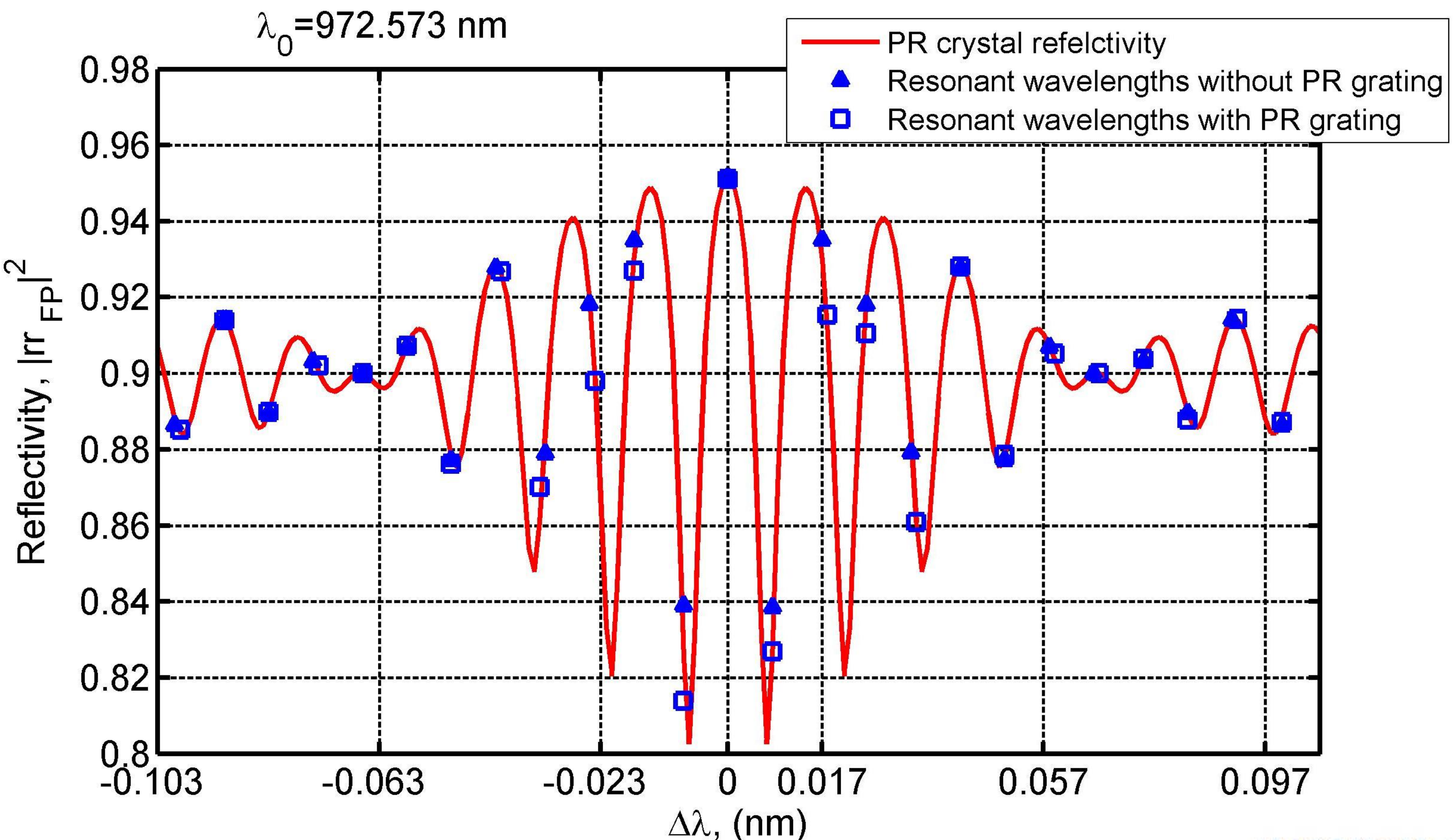
Simulation Flow Diagram



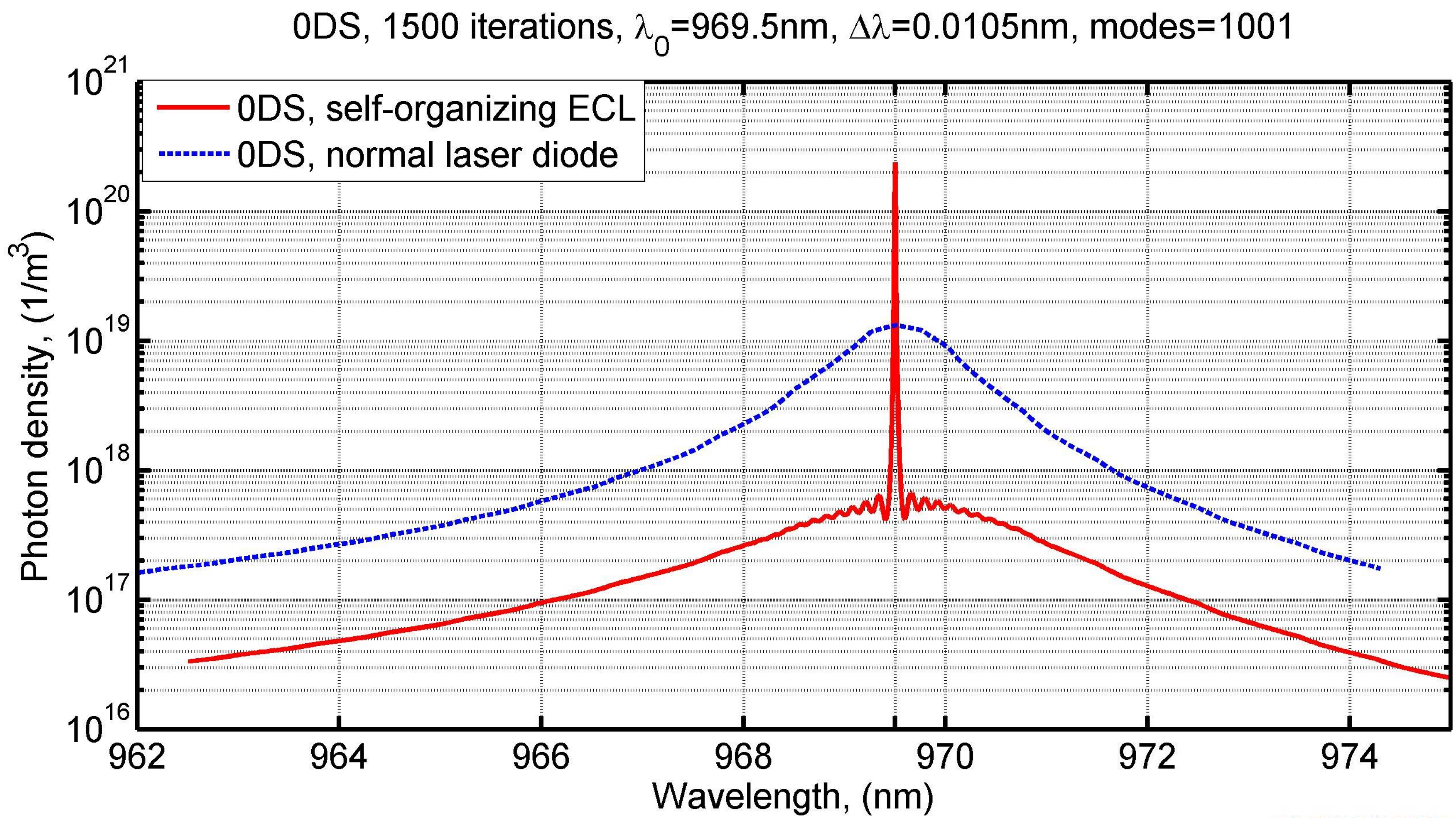
Simulation Parameters

Symbol	Definition	Value	Unit
l	PR Crystal Length	0.3	cm
d	Air Gap Length	3.0	cm
D	Length of laser diode	0.22	cm
Γ	PR Gain Coefficient	5.0	cm^{-1}
n	Refractive Index	2.4	
r	Reflectivity of Output Mirror	$0.9^{1/2}$	

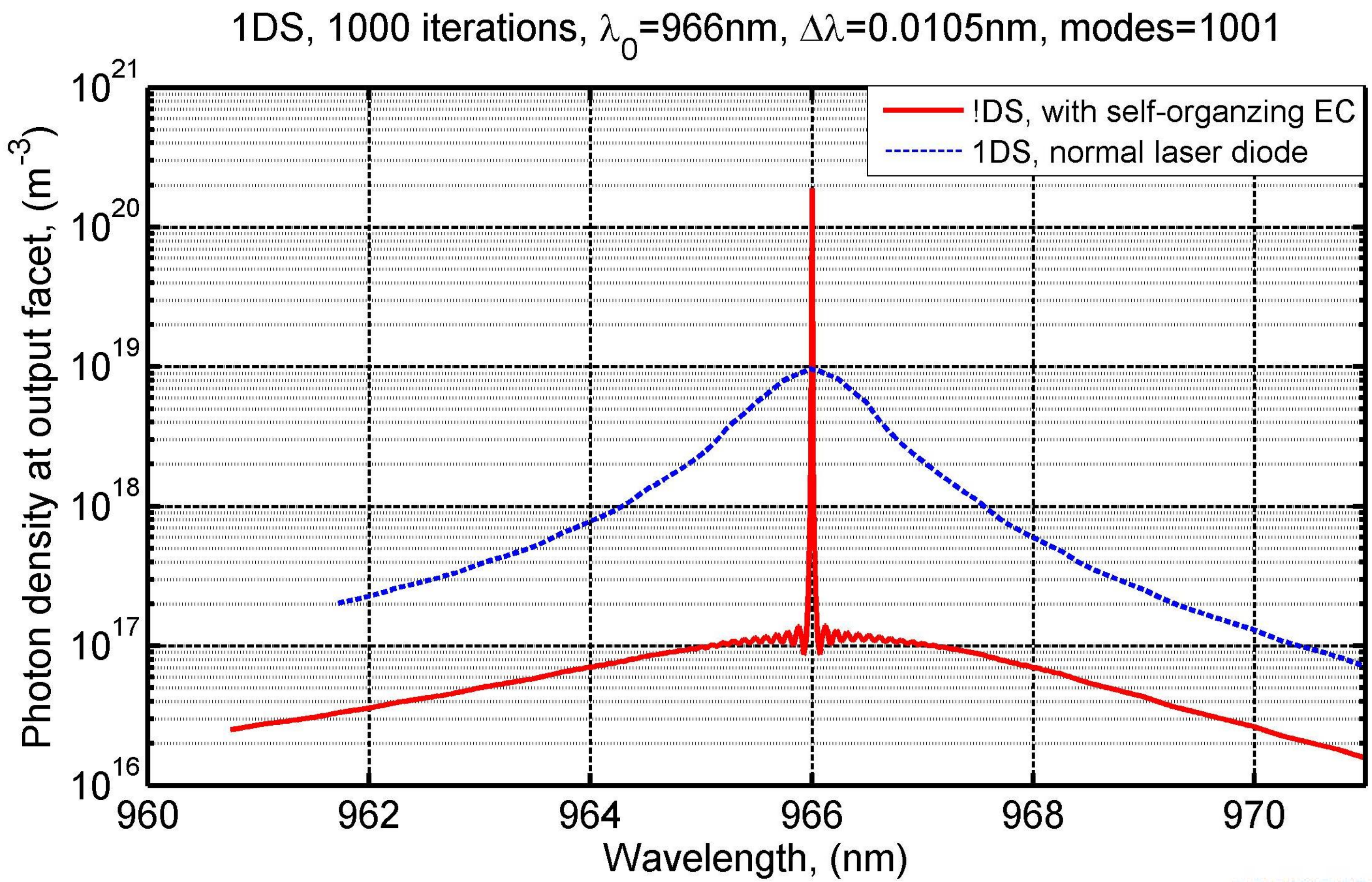
PR crystal grating reflectivity



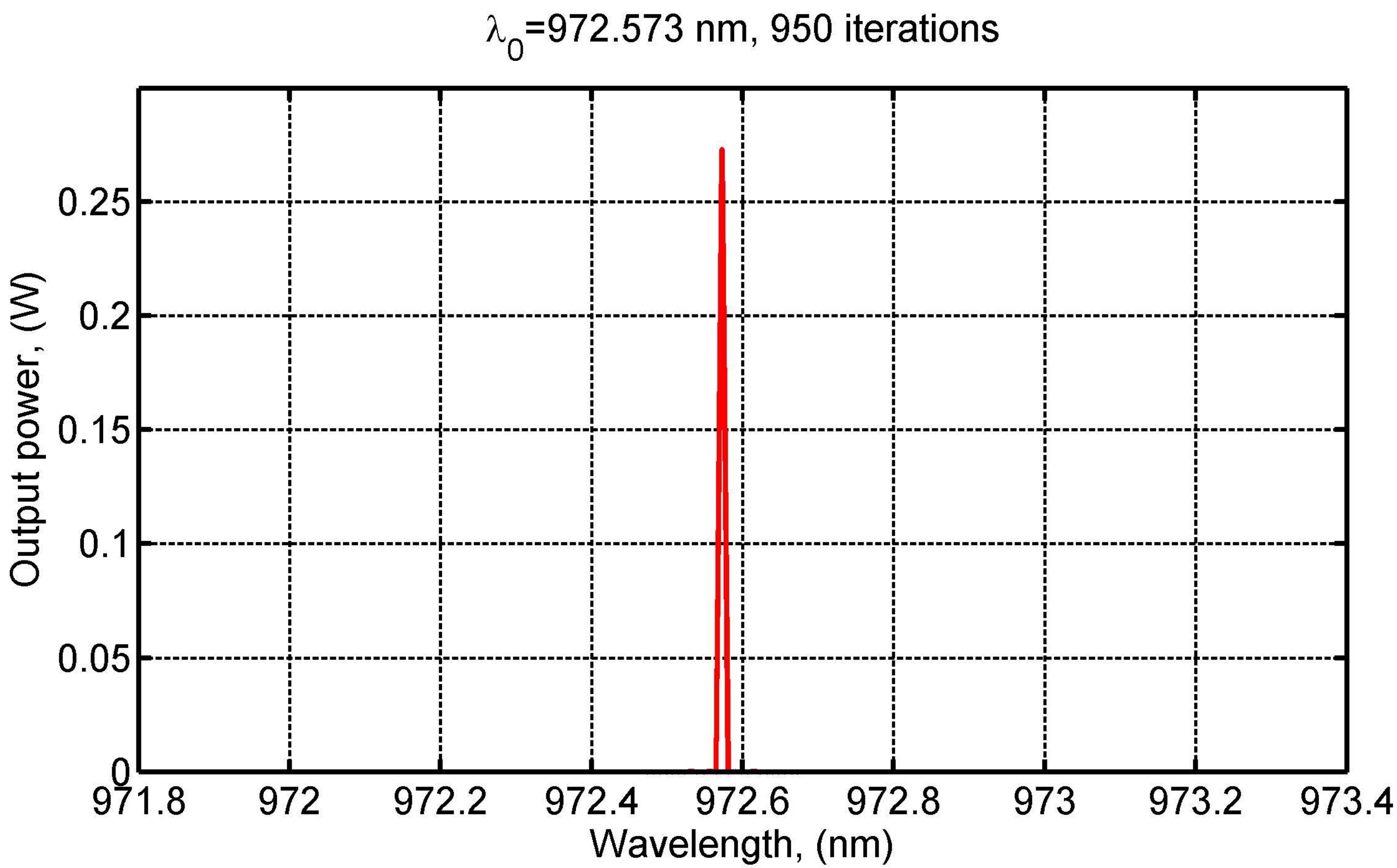
0D analysis of self organising ECL

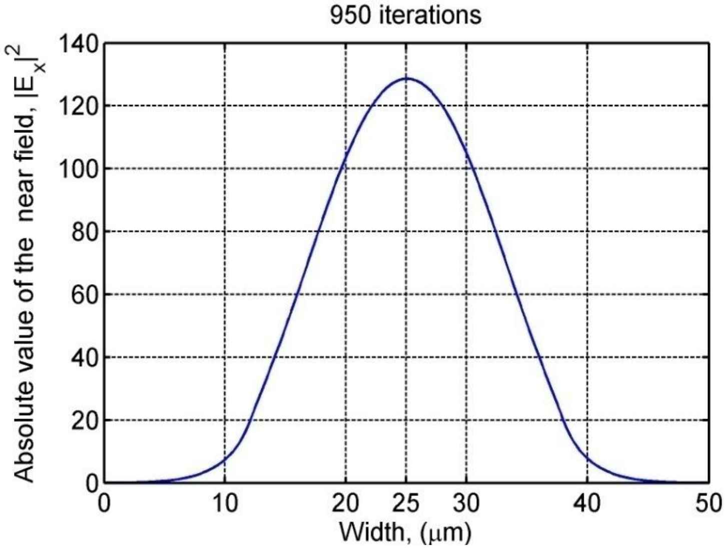


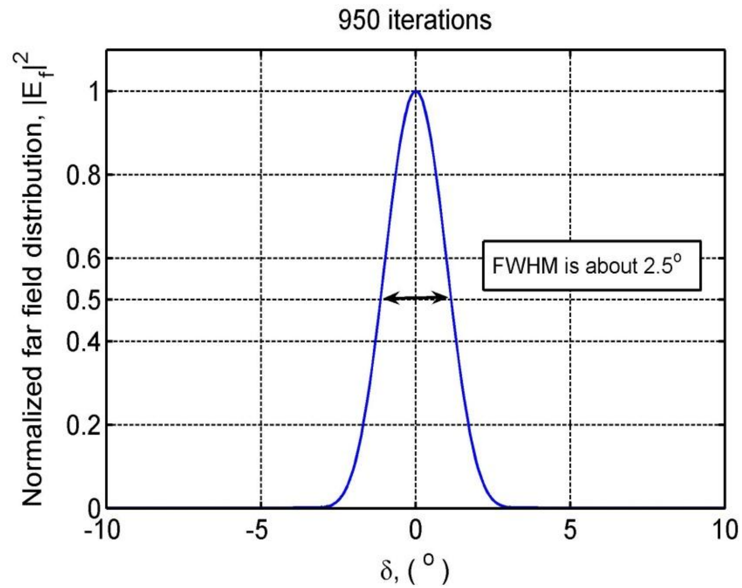
1D analysis of self organising ECL

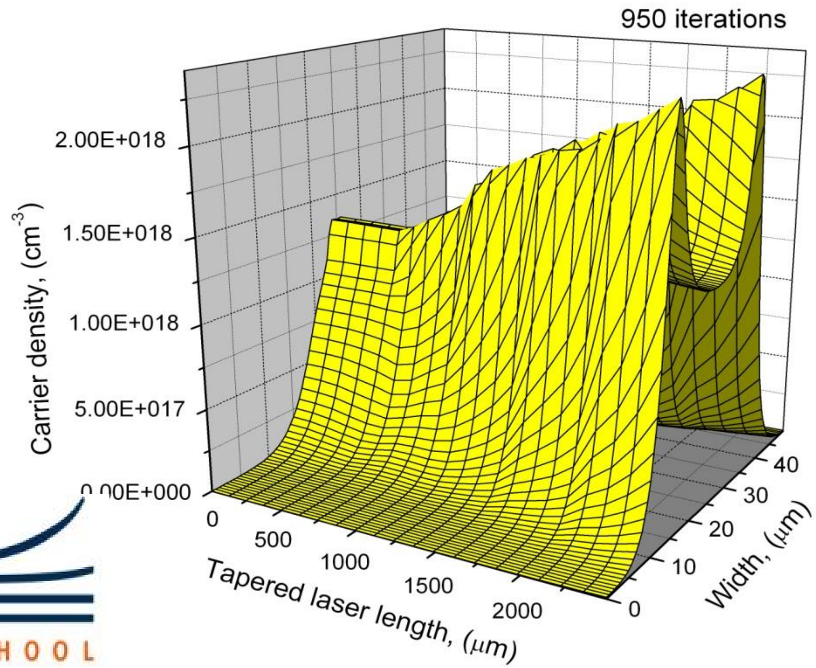


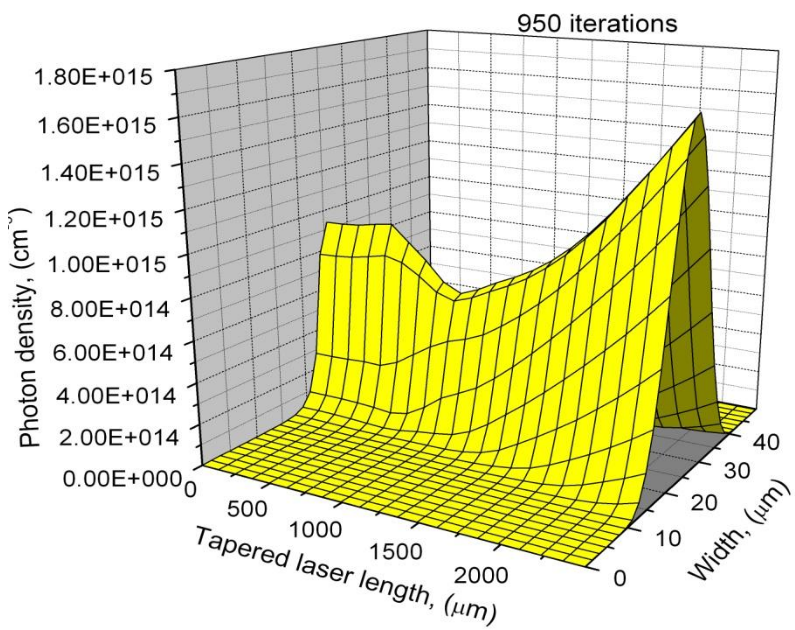
2D analysis of self organising ECL



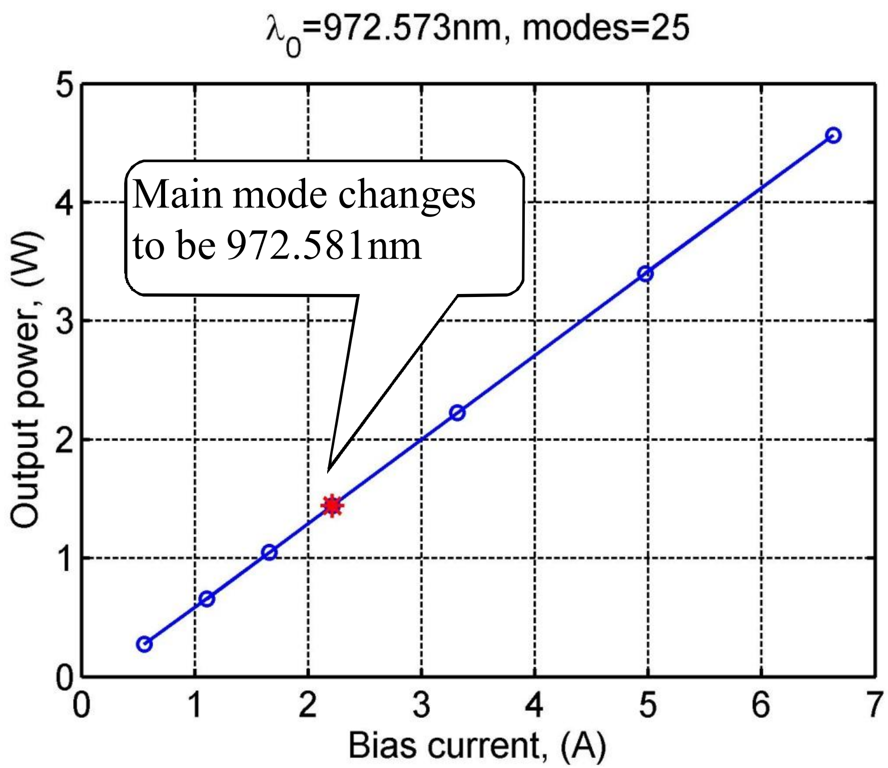


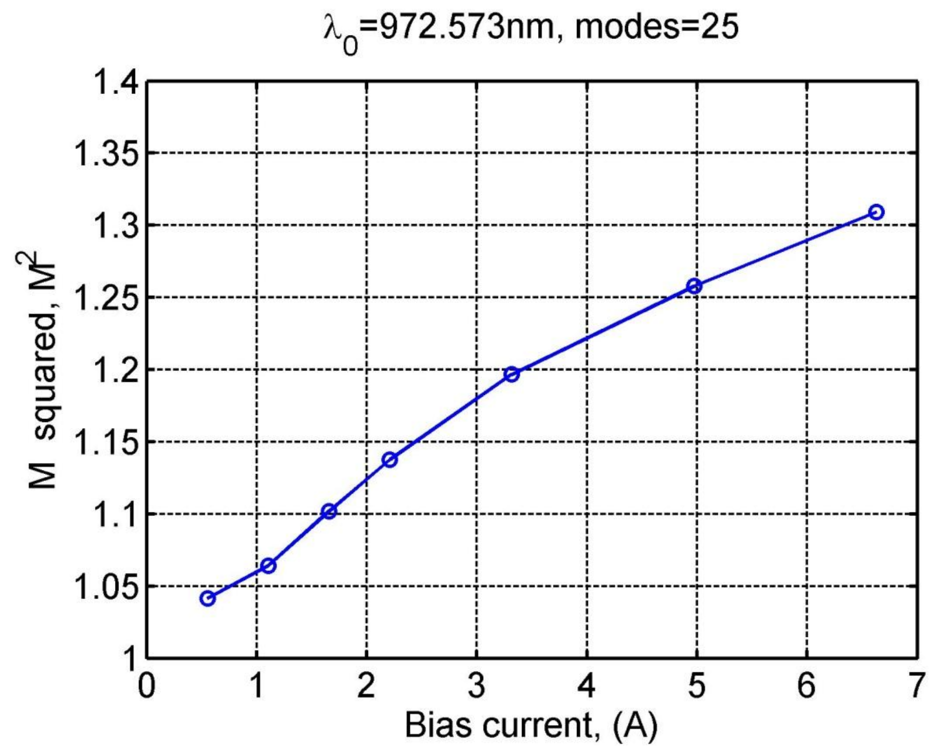






INSTITUT d'OPTIQUE GRADUATE SCHOOL


λ0=972.573nm, modes=25
Main mode changes to be 972.581nm
Output power, (W)
Bias current, (A)
0
1
2
3
4
5
6
7


λ0=972.573nm, modes=25
M squared, M2
Bias current, (A)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4

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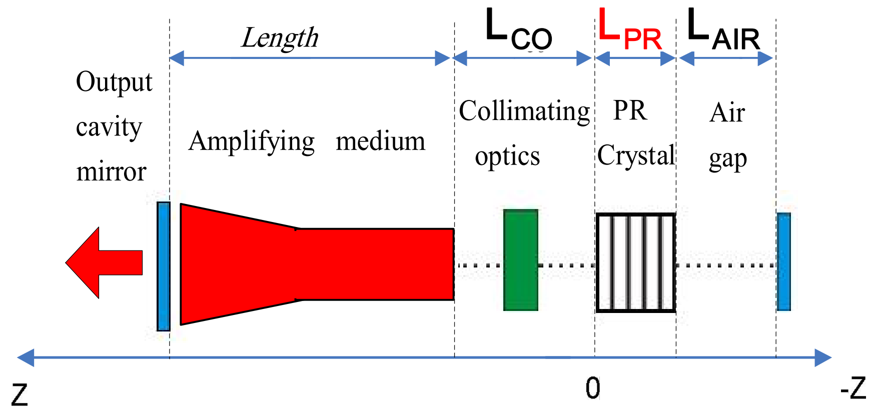
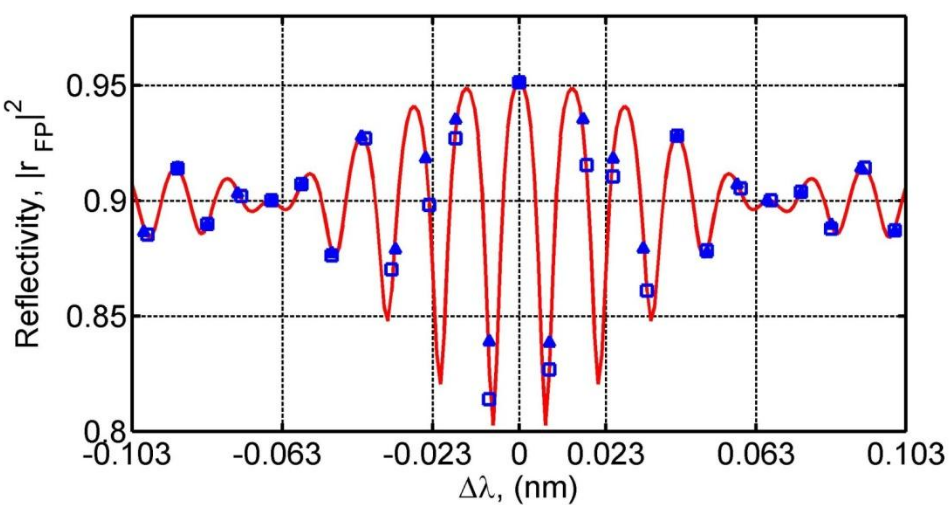
Influence of cavity section lengths

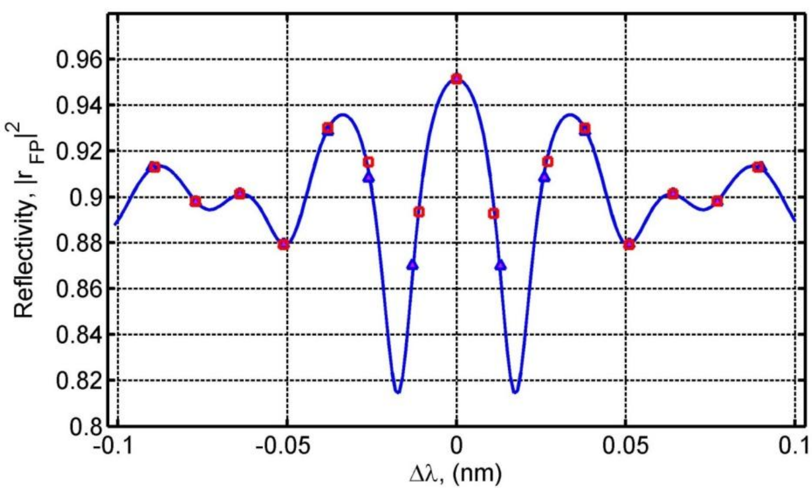
- Length of air gap changes reflectivity spectra and resonant wavelengths
- Stable single mode operation obtained



L_{AIR}=3.0cm, L_{PR}=0.3cm, L_{CO}=1.0cm



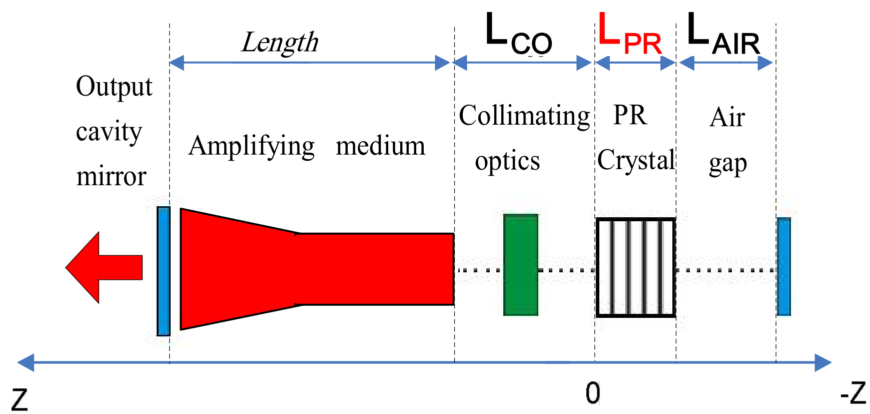
L_{AIR}=1.0cm, L_{PR}=0.3cm, L_{CO}=1.0cm



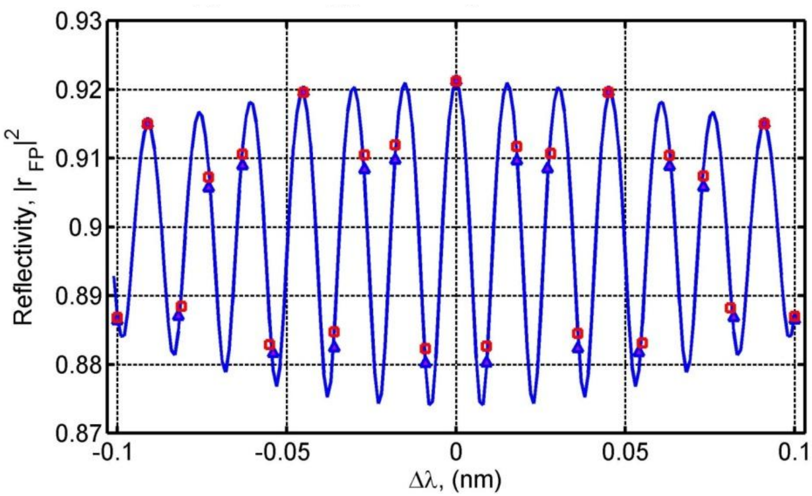
The University of Nottingham

Influence of cavity section lengths

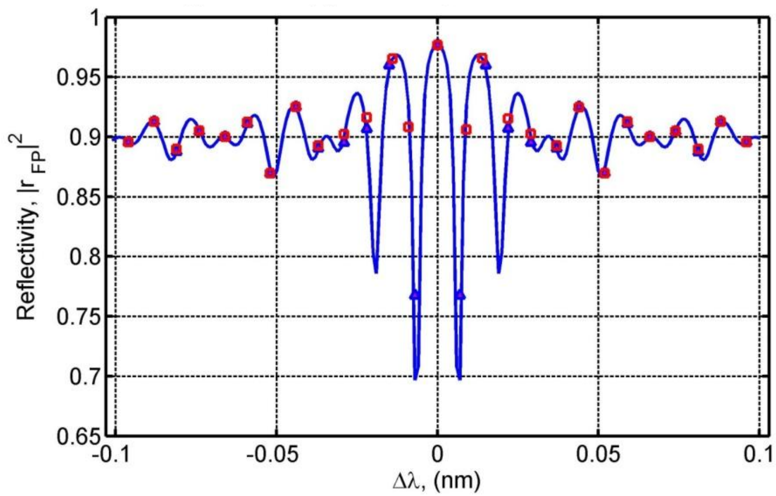
- Length of PR crystal changes reflectivity spectra and resonant wavelengths
- Stable single mode operation obtained



L_{AIR}=3.0cm, L_{PR}=0.1cm, L_{CO}=1.0cm

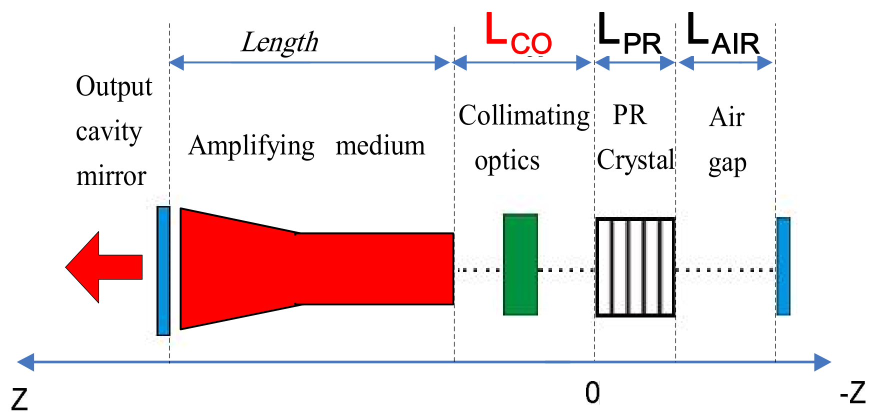


L_{AIR}=3.0cm, L_{PR}=0.6cm, L_{CO}=1.0cm

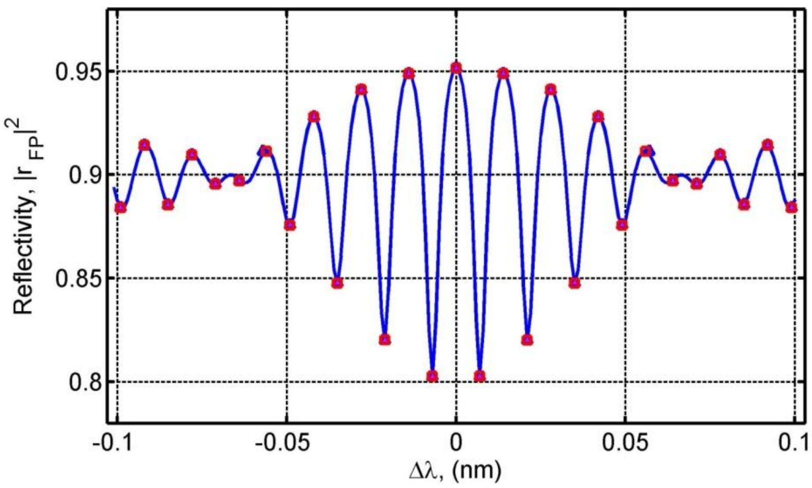


Influence of cavity section lengths

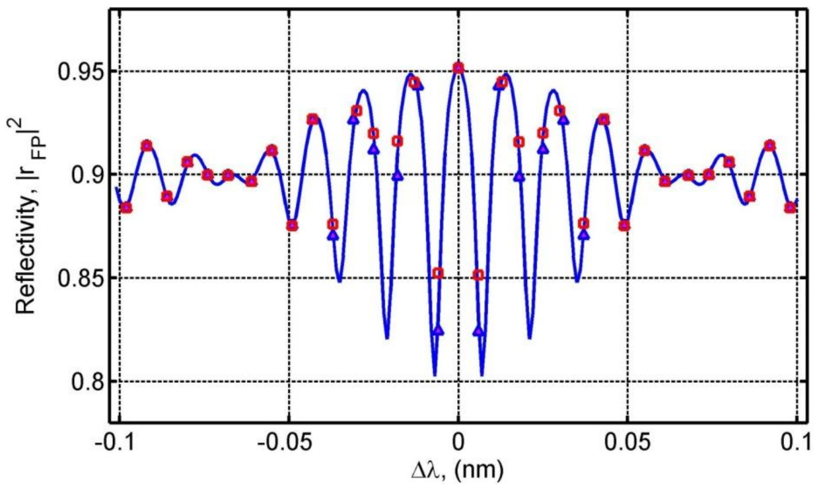
- Length of collimating optics section does **not** change reflectivity spectra but changes resonant wavelengths
- Stable single mode operation obtained



L_{AIR}=3.0cm, L_{PR}=0.1cm, L_{CO}=2.0cm



L_{AIR}=3.0cm, L_{PR}=0.1cm, L_{CO}=3.0cm



Conclusion

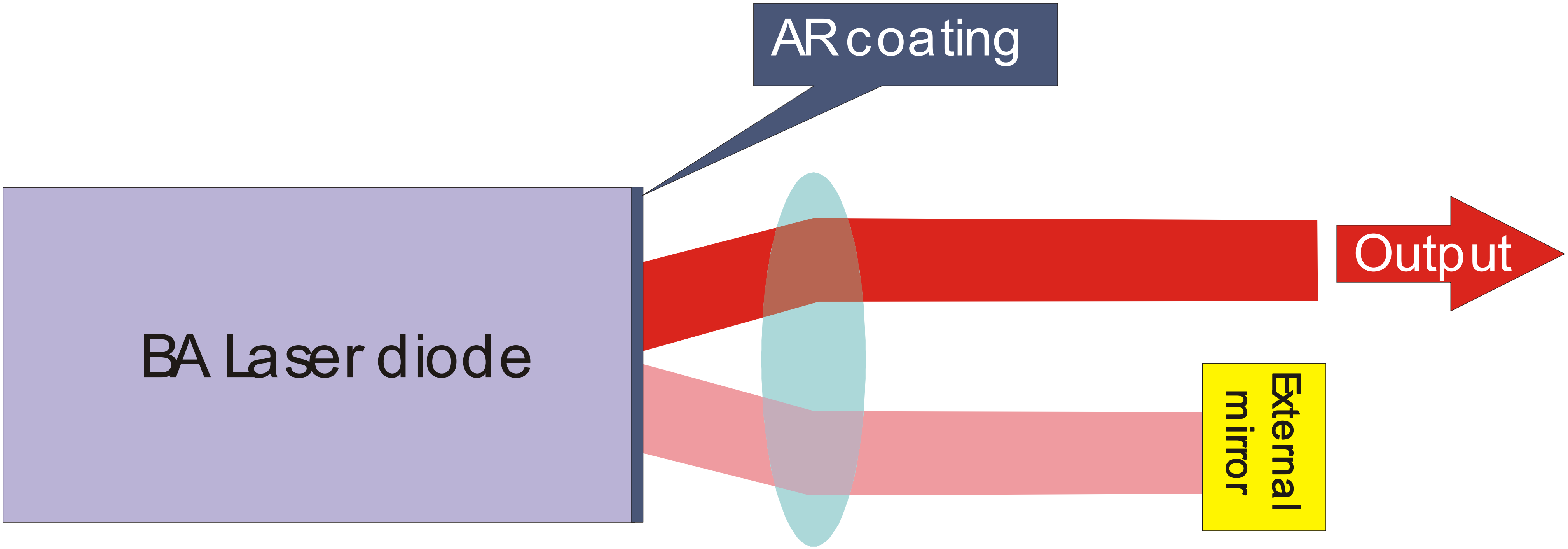
- Predicts that cavity modes with single wavelength exist
- Further development of the model needed to calculate self-consistently the output spectrum and its evolution

Case Study C:
Asymmetric Feedback
External Cavity Laser

Model used: 1.5D Unipolar Laser Model

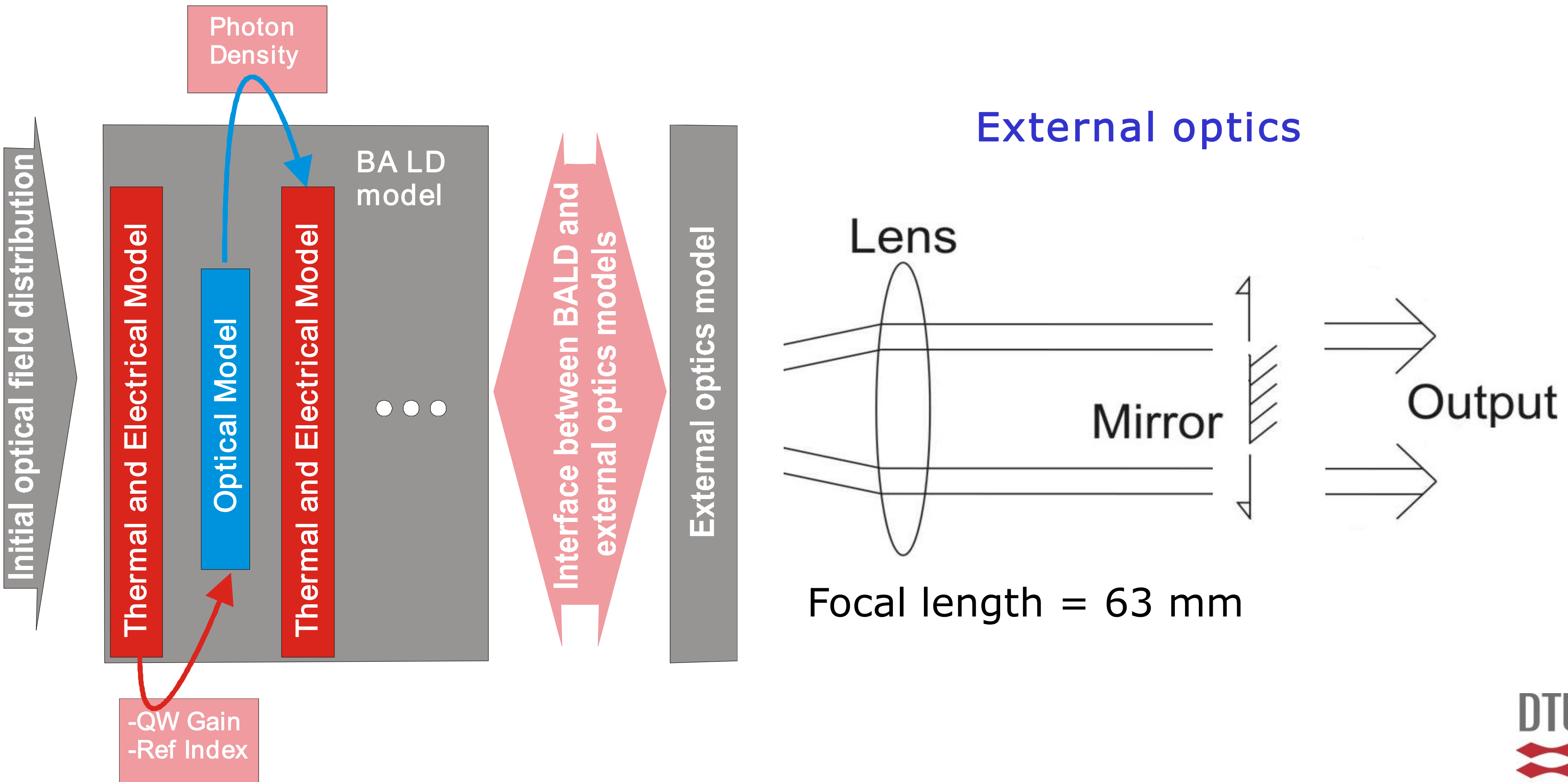
Asymmetric Feedback ECL geometry

A mirror stripe is placed in the external cavity to select lateral mode and provide asymmetric feedback.



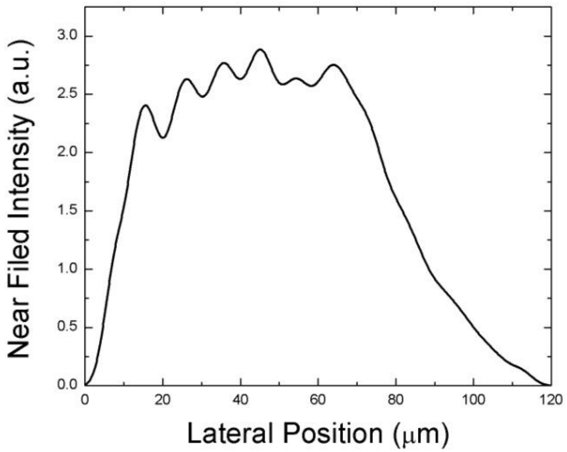
C. Asymmetric Feedback ECL

- Asymmetric feedback technique is investigated for improving the beam quality of broad-area diode laser.
- A free space propagation model is coupled to a 1.5D unipolar laser simulator

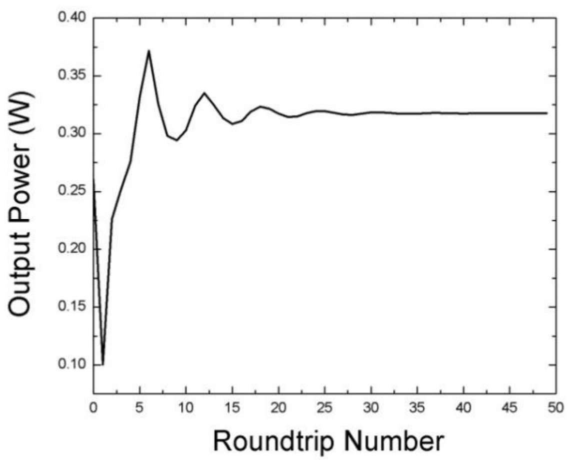


- BA laser: W = 100 μm, L = 1 mm, λ = 975 nm
- Initial field – "top hat profile"
- Simulation converges for a specific reflector width and position
    - Reflector width = 0.74 mm
    - Position of reflector = 2.97 mm from centre

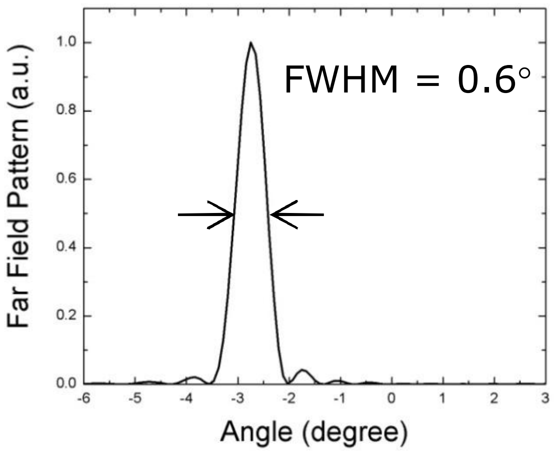
Near-Field Pattern



Power Convergence

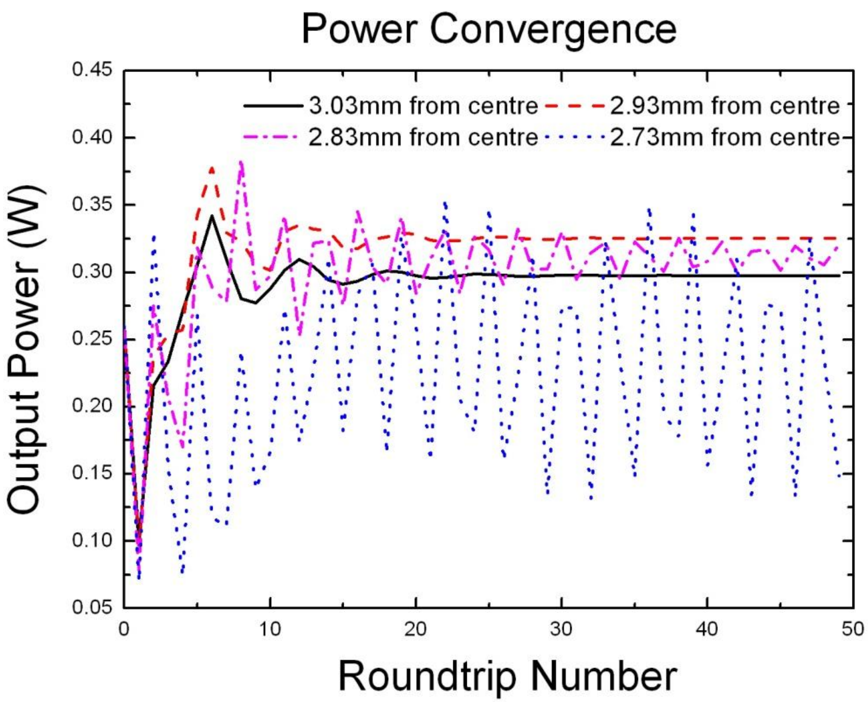


Far-Field Pattern

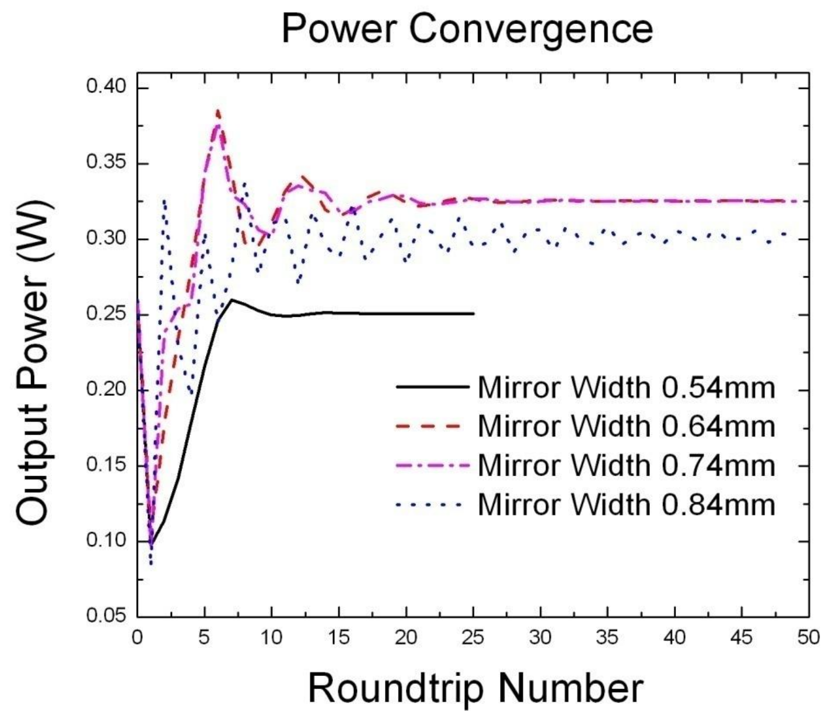


- Stable working condition related to both mirror width and position

Mirror Position

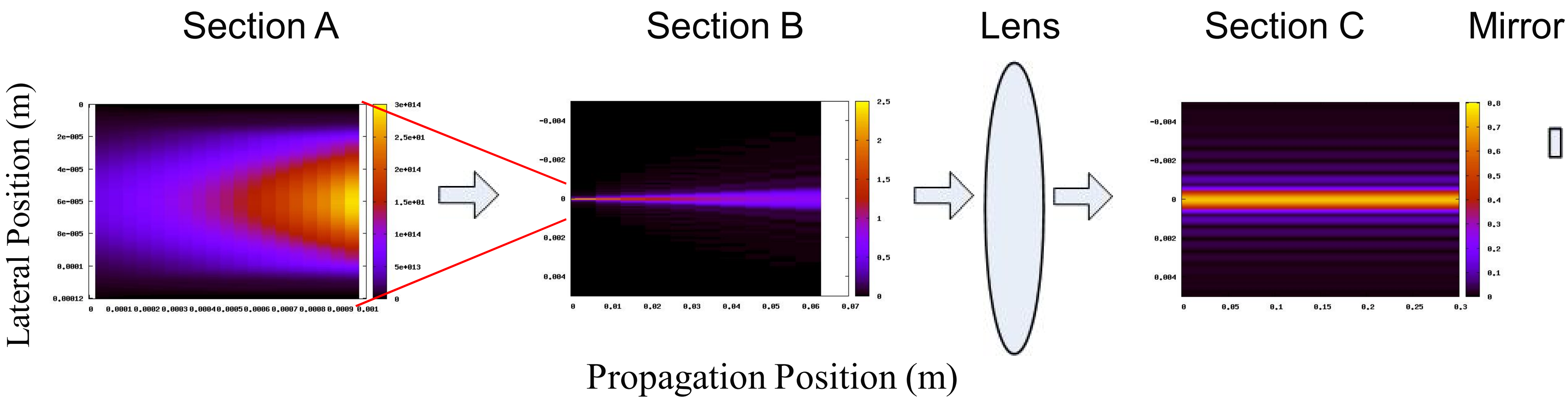


Mirror Width

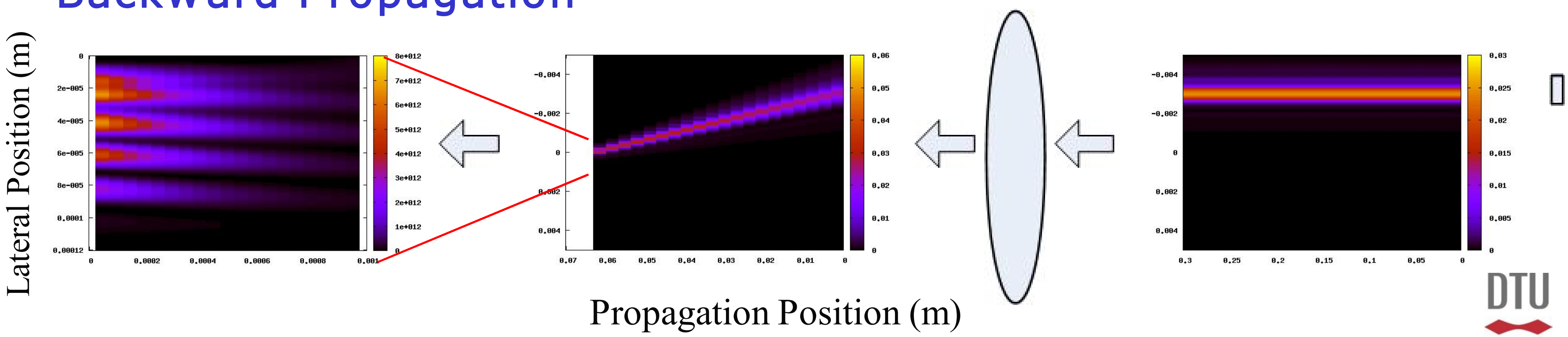


Field Evolution - 1st Round Trip

Forward Propagation

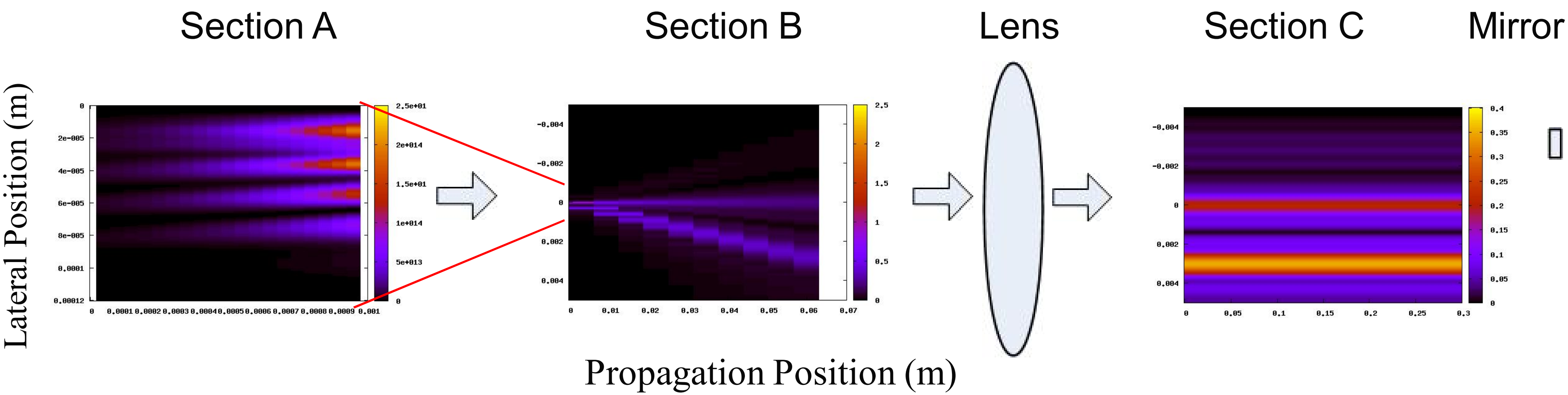


Backward Propagation

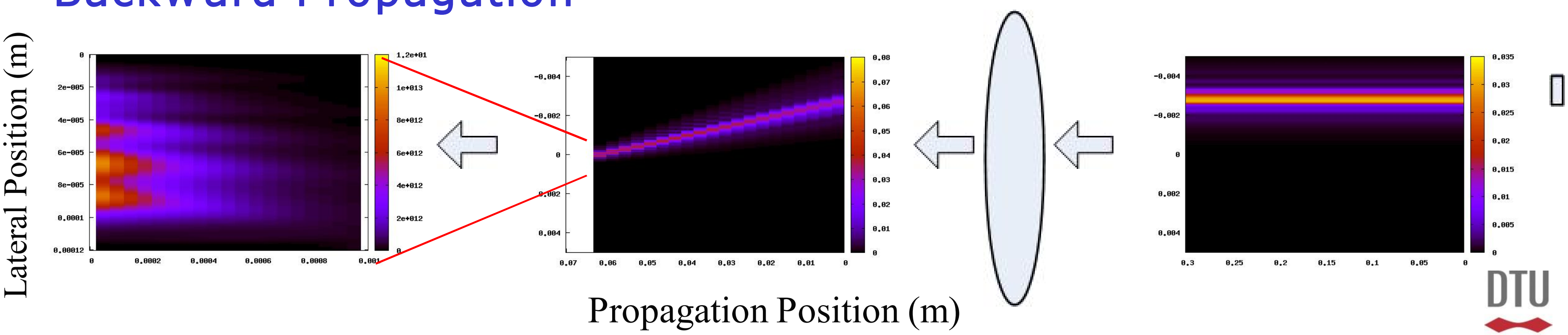


Field Evolution – 2nd Round Trip

Forward Propagation

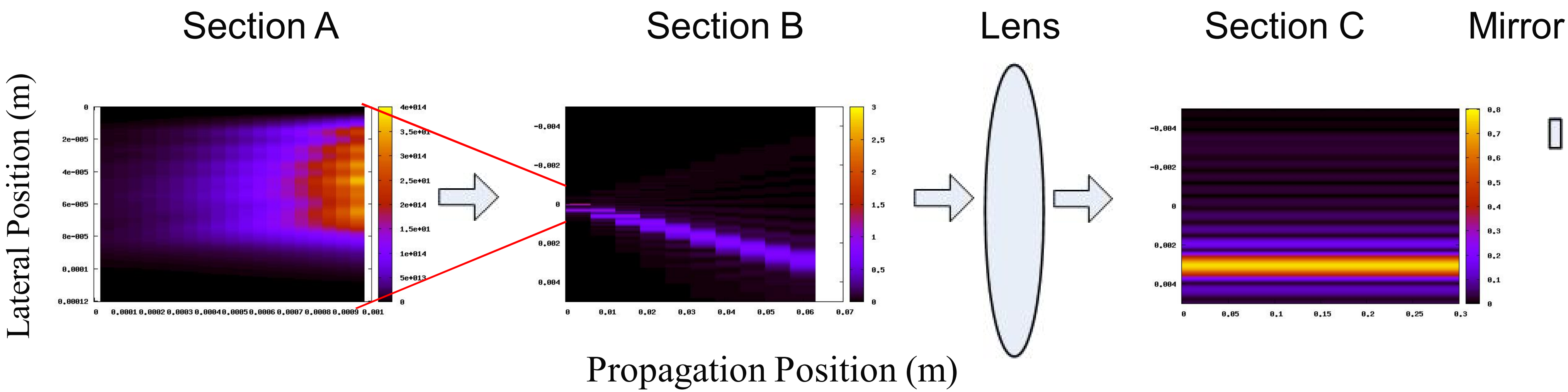


Backward Propagation

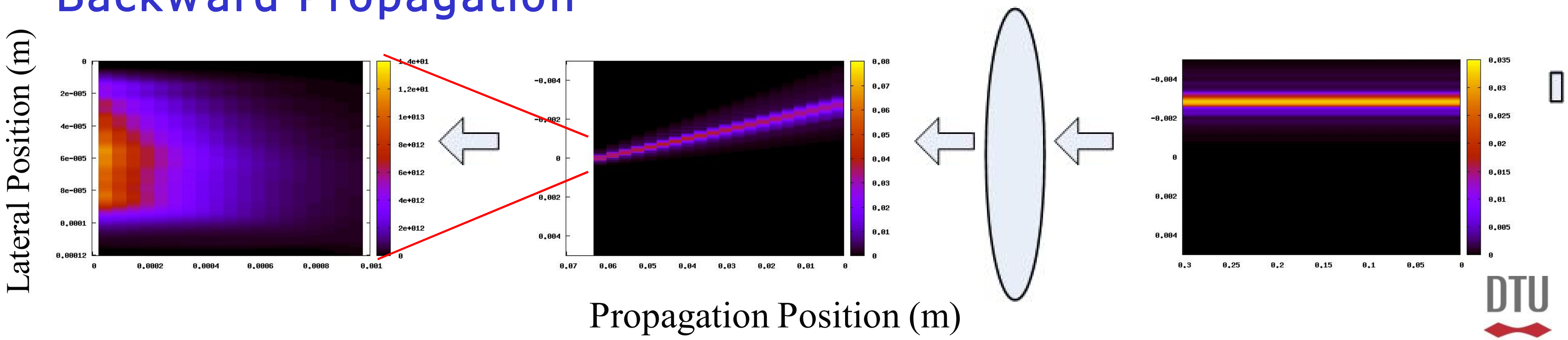


Field Evolution – Converged Solution

Forward Propagation

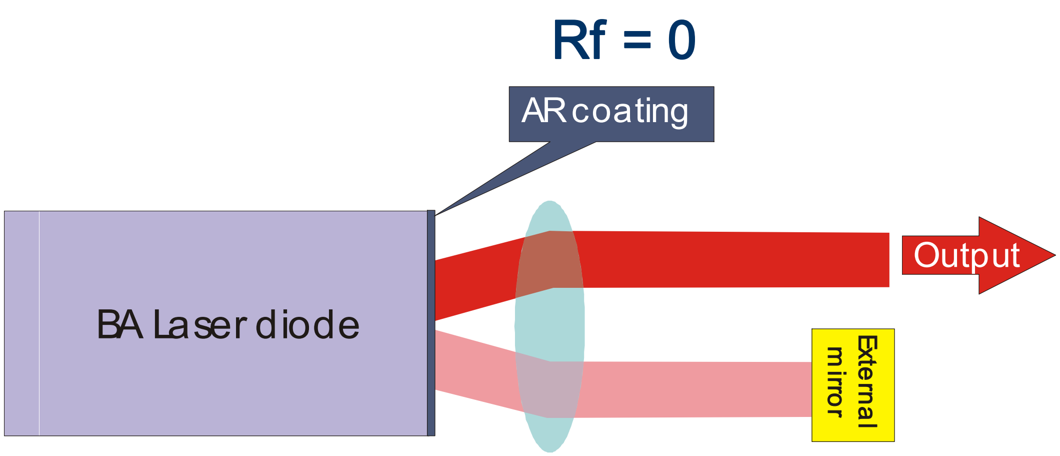


Backward Propagation

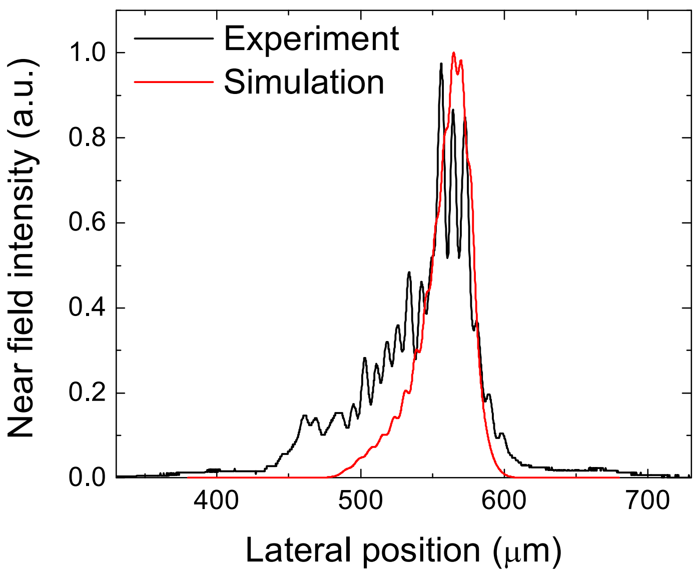


Effect of front facet reflectivity

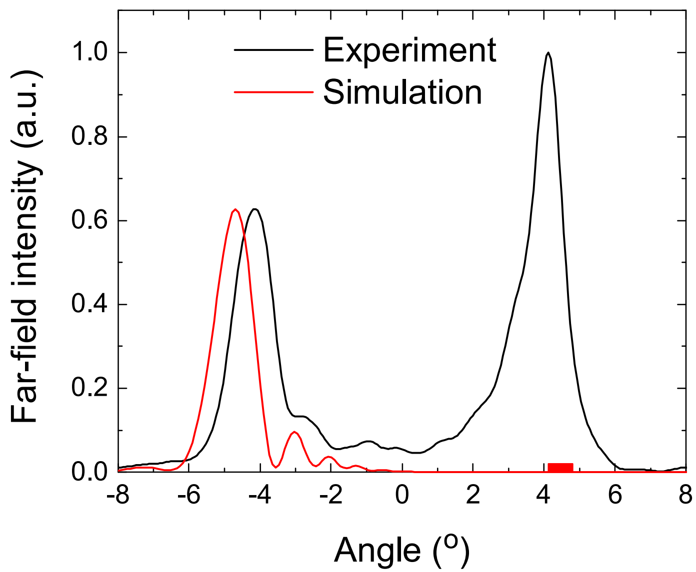
- Experimentally, lobe observed on feedback side
- No lobe on feedback side observed in simulation
- In previous simulation, front facet reflectivity was assumed to be zero.



Near-field

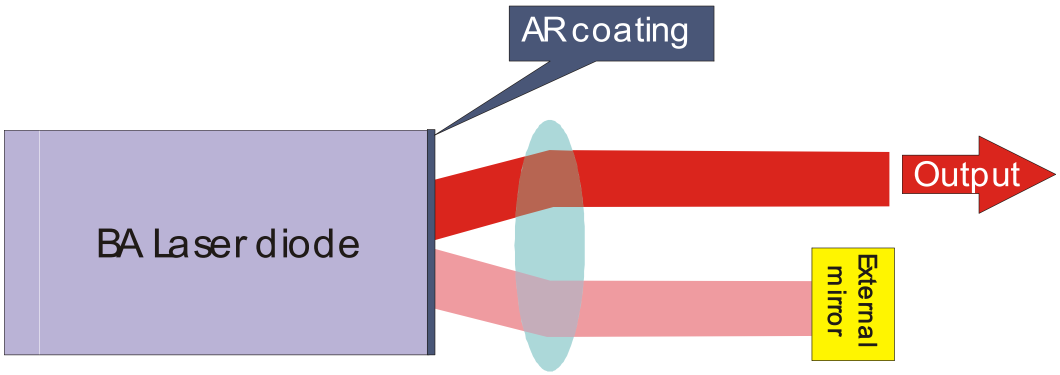


Far-field

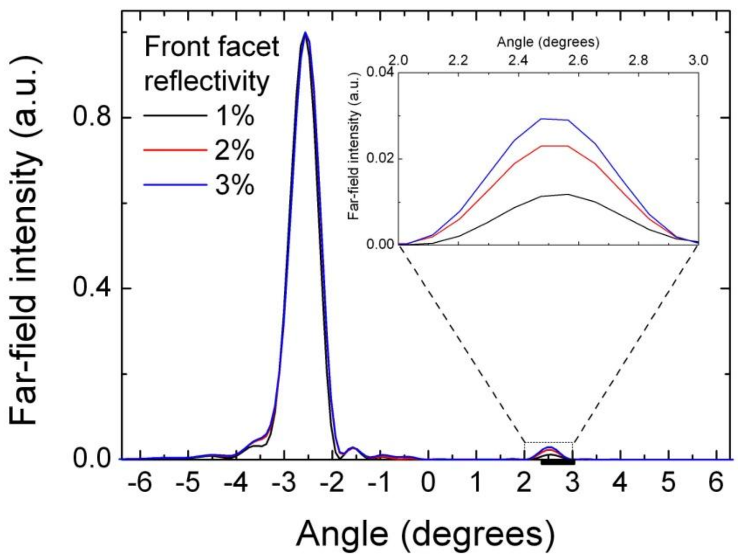


Effect of front facet reflectivity

- Lobe on feedback side increases with increase of front facet reflectivity
- Larger spatial hole with lower front facet reflectivity



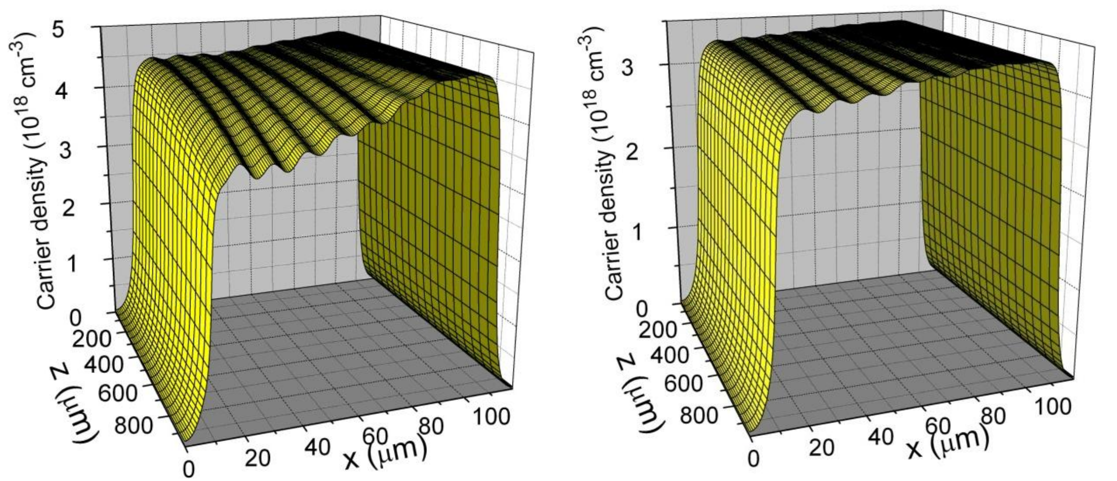
Far-field



Carrier density profile

1% Front Facet Reflectivity

3% Front Facet Reflectivity



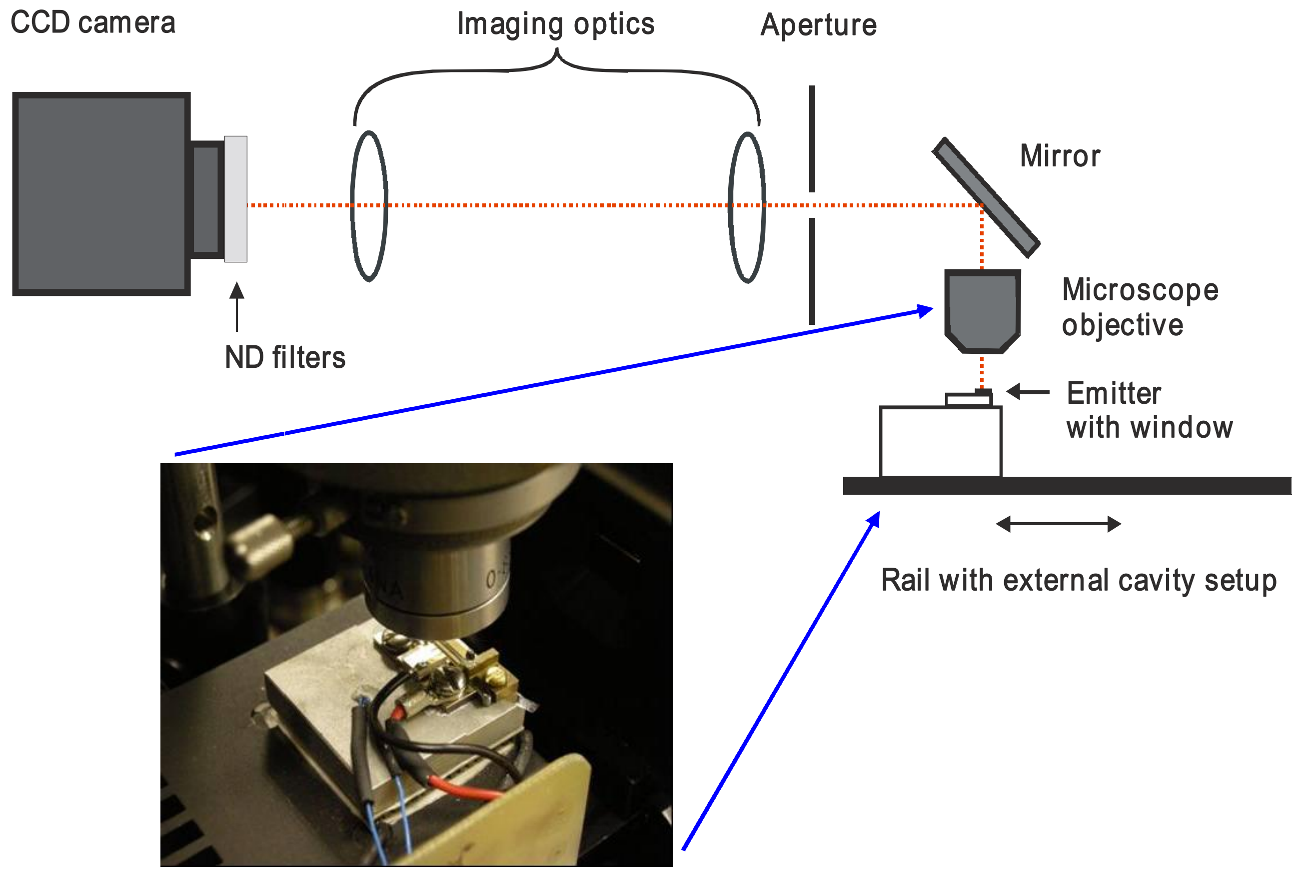
Conclusion

- Stable operation obtained for specific mirror position and width
- Works by providing selective feedback to a specific lateral mode
- Narrow far-field divergence and improved beam quality obtained using asymmetric feedback technique

Experimental validation

Experimental validation

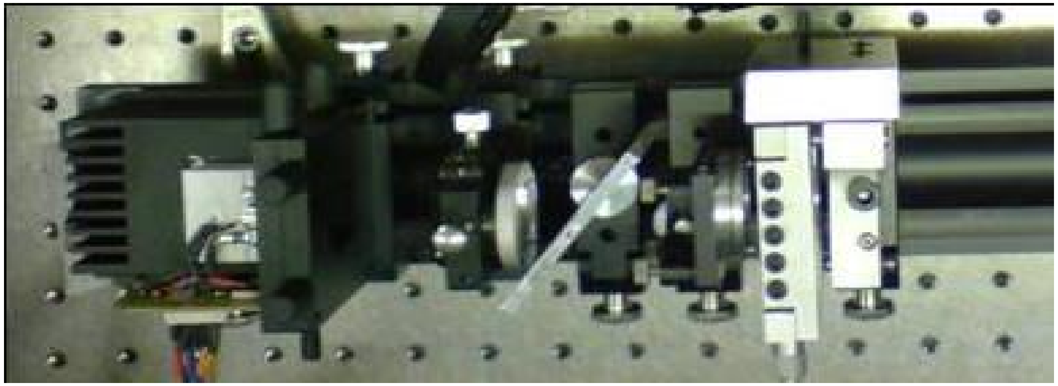
Imaging of spontaneous emission from a 980 nm broad area laser with a windowed n-contact in an asymmetric external feedback cavity

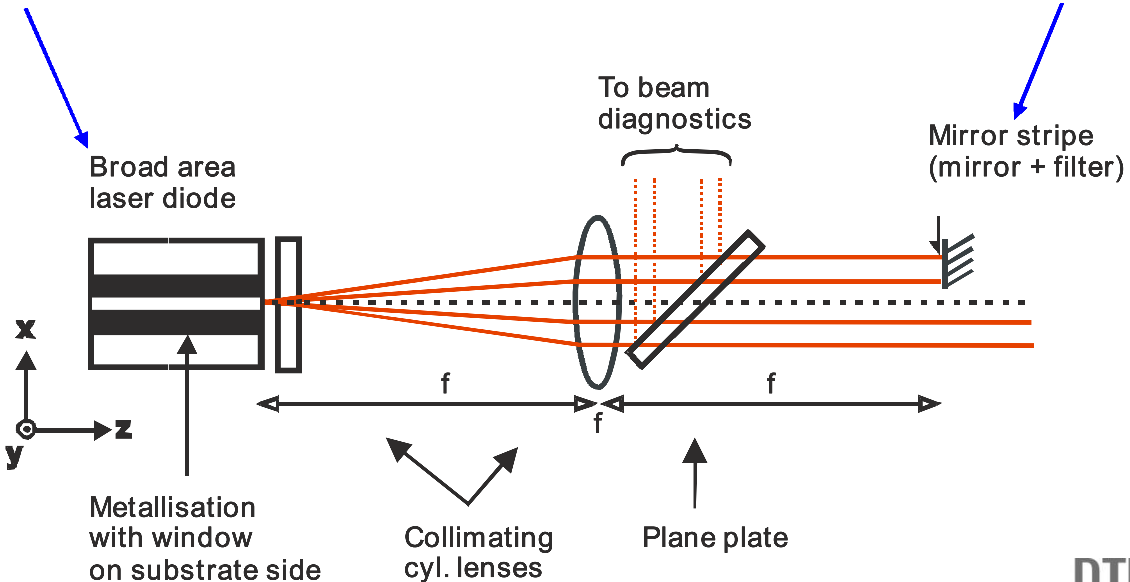


The Imaging System
&
Laser Mount

DTU

Imaging of spontaneous emission from a 980 nm broad area laser with a windowed n-contact in an asymmetric external feedback cavity

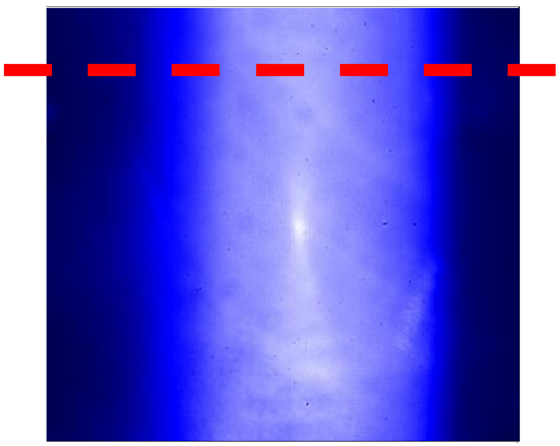




The External Cavity Laser Setup

Imaging of spontaneous emission from a 980 nm broad area laser with a windowed n-contact in an asymmetric external feedback cavity

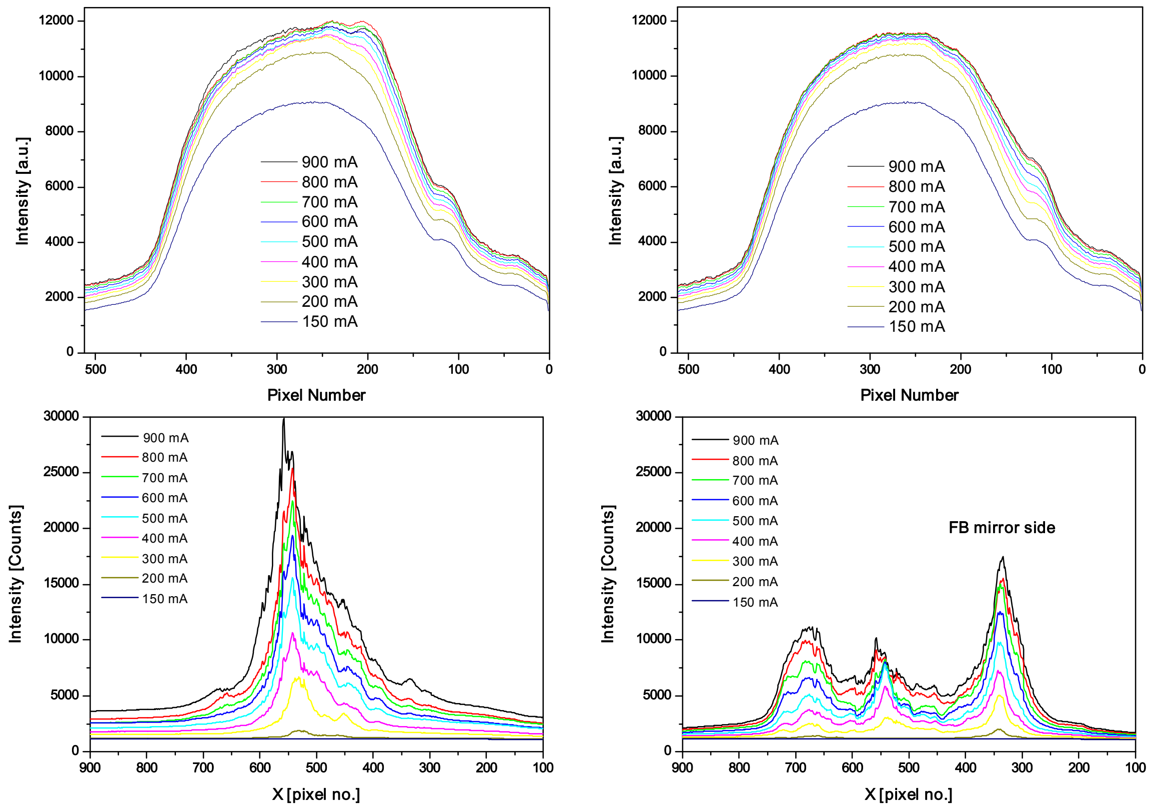
Spontaneous emission viewed through contact window (200µm x 200µm)



Freely running laser | With feedback (right side)

Spontaneous Emission

Far-Field



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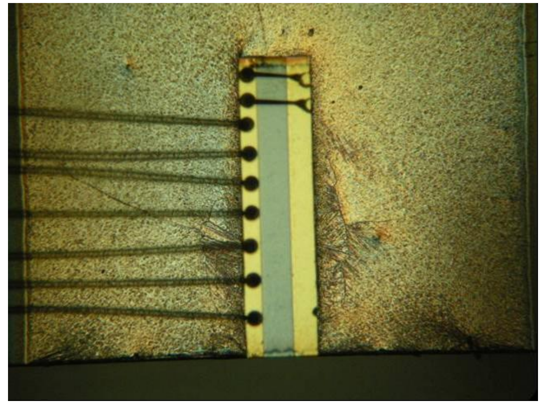
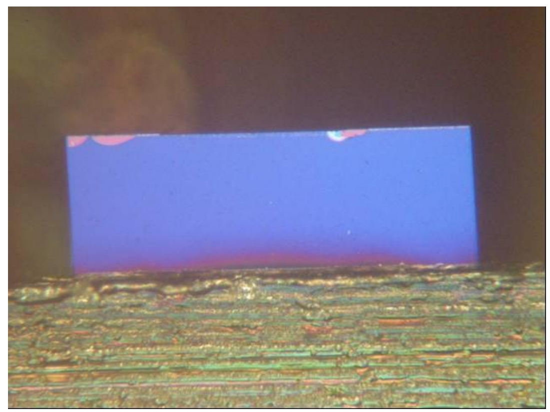
Imaging of spontaneous emission from a 980 nm broad area laser with a windowed n-contact in an asymmetric external feedback cavity



Top view of device with windowed n-contact

Broad Area Laser (III-V Lab), 975nm, 100 µm x 1.5 mm, HR (95%) / AR (0.1% - 1%)



Front view of device

Note that the facet coating appears non-uniform (red region around the emitter)

DTU

Experimental validation

- Modelling activities should be complemented by novel experimental validation methods
- Weak observed feedback level is probably due to front facet damage

Summary

Summary

- External cavity models combine laser diode models with external optical elements models
- Due to large cavity dimensions travelling wave approach is recommended
- Results obtained using developed models reproduce experimentally observed trends
- Modelling activities should be complemented by novel experimental validation methods