An overview of large spot size laser structures

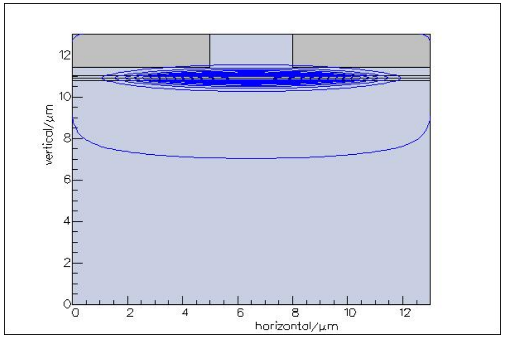
Brian Corbett

WWW • BRIGHTER • EU

Tutorial

High output power demands a wide aperture with a resultant large asymmetry in dimension of emission area in the transverse and lateral directions.

Brighter.EU is about controlling the optical energy primarily in the lateral direction



…but the transverse mode is single mode with $M^2 = 1$ so where is the problem?

Advantages of a large transverse mode size

1. Reduction in power density on the laser facet
   - Reduce the probability of COD (catastrophic optical damage)

$$P_{\max} = \frac{d}{\Gamma} W \frac{1-R}{1+R} P_{COMD}^{\text{int}}$$

2. Reduction in transverse far-field
   - Simplify the optics to control the laser emission
     - Lower numerical aperture optics
     - Less requirement on aspherical surfaces

3. Symmetrisation of beam
   - Simplify the optics and improved coupling to applications
     - eg coupling to fibres which have symmetric acceptance

4. Reduction in generation of nonlinearities
   - Filamentation, self focusing etc in the active layer
   - Results in improved beam quality

Main challenges in the design and realisation

- Reduction of the mode confinement inside the active layer
  - Need to have sufficient gain
    - Requires low additional losses and long devices

- Perhaps complicated and thick epitaxial structure
  - More parameters to optimise
    - Compositional and thickness control can be important
    - More material compositions may be required
    - More complex doping profile

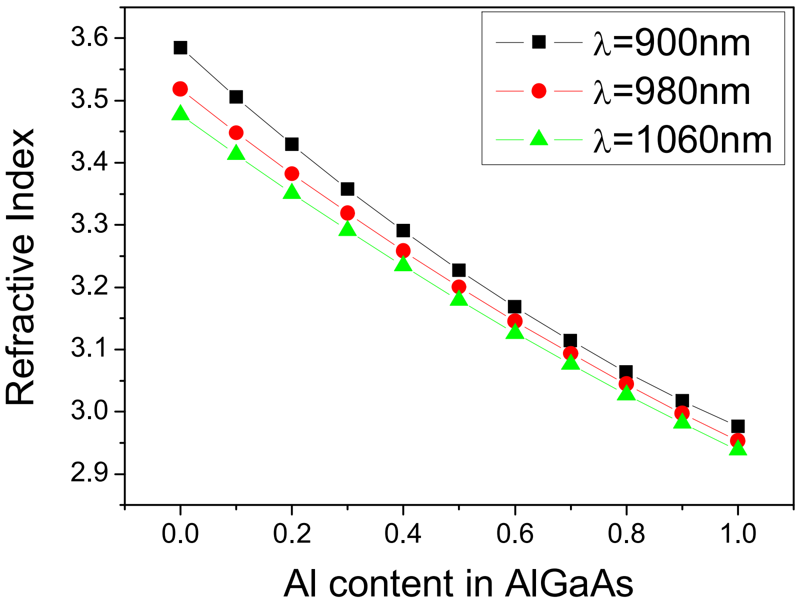
- Perhaps many additional interfaces and layers
  - Additional resistance

- Lateral mode control may be more difficult

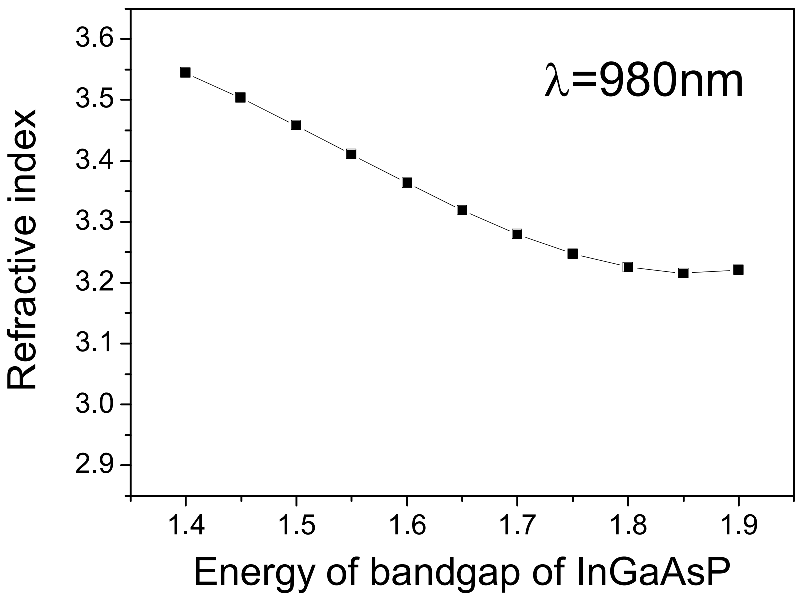
- Danger of coupling of the mode to the high index substrate

Refractive index palette around 980nm

$Al_xGa_{1-x}As$



$In_xGa_{1-x}As_yP_{1-y}$

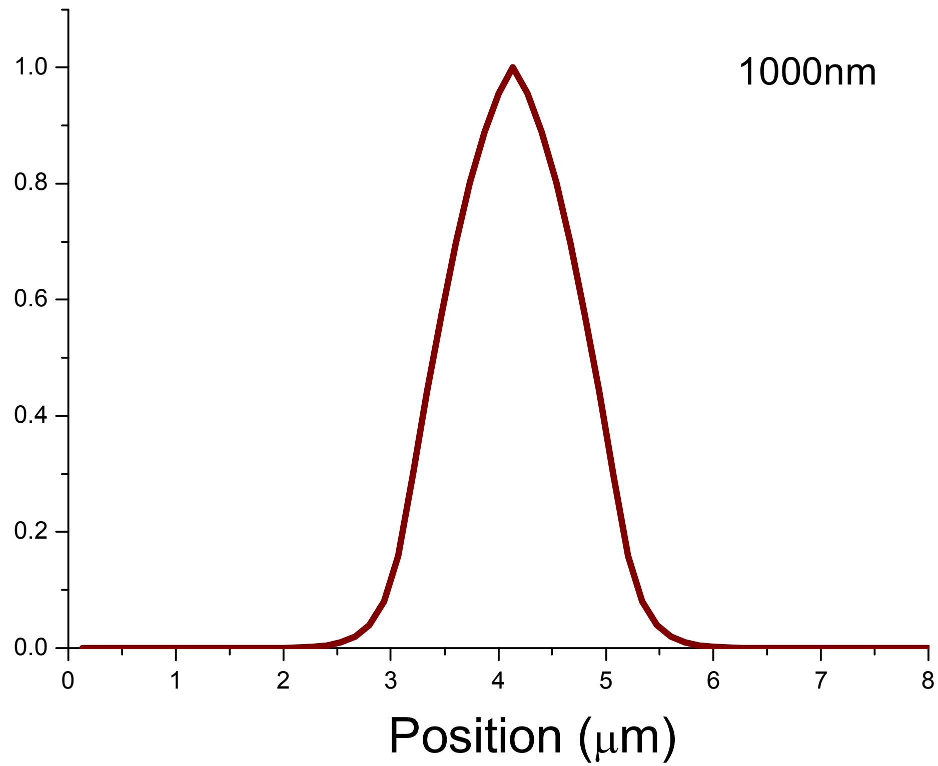


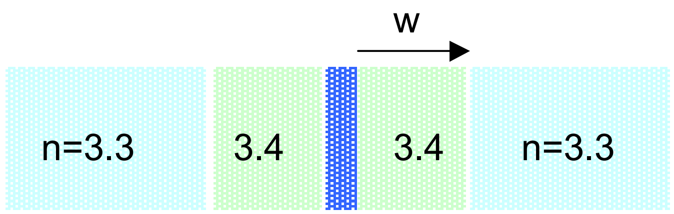
- Refractive index depends on temperature, carrier density, ordering, phase separation
- Index changes up to 0.6 are possible

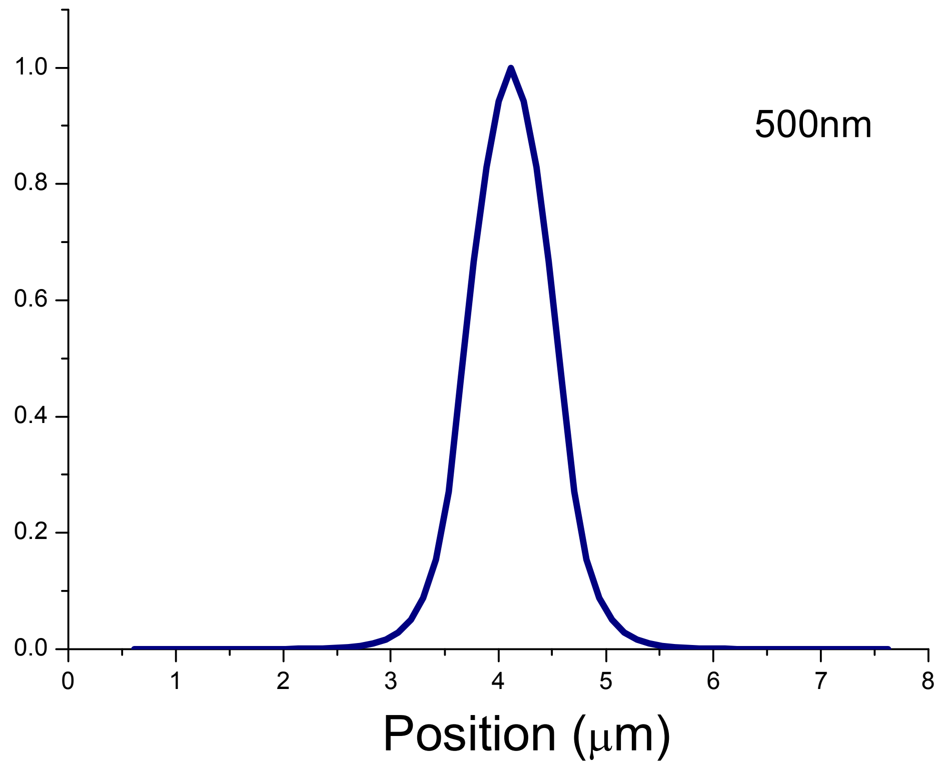
Gehrsitz et al., "The refractive index of AlGaAs below the band gap: Accurate determination and empirical modelling," J. Appl. Phys., 87, 7825 (2000); S. G. Wallace et al, "Refractive indices of InGaAsP lattice matched to GaAs at wavelengths relevant to device design," APL, 76, 2791 (2000)

Evolution of mode shape with width of guide

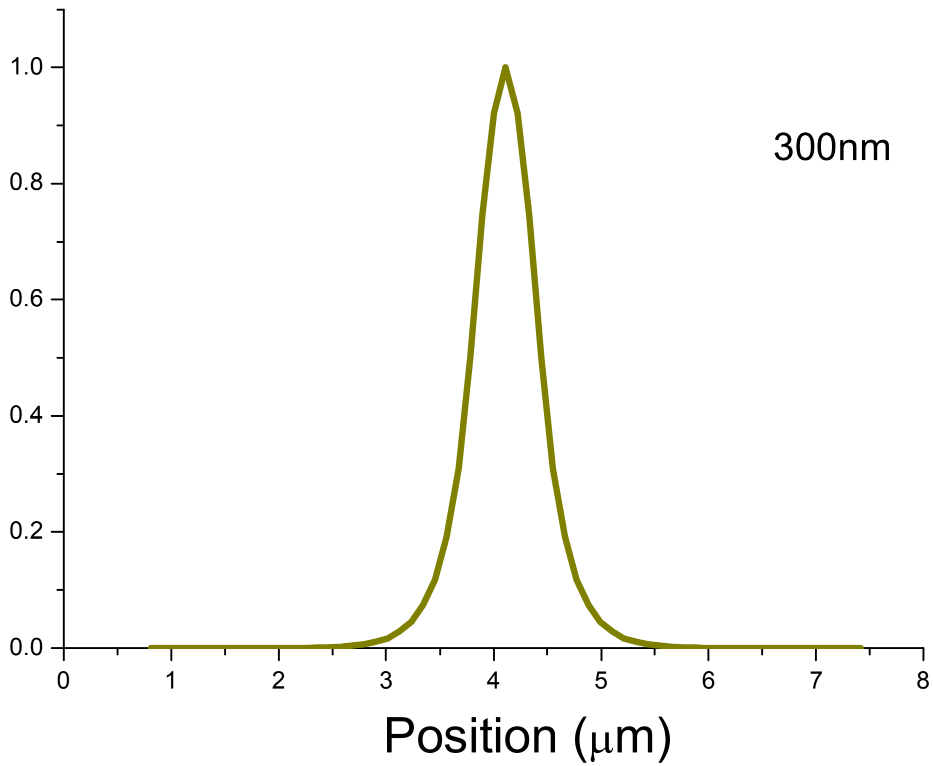
Refractive index of quantum well taken as 3.65 but this is not clear!

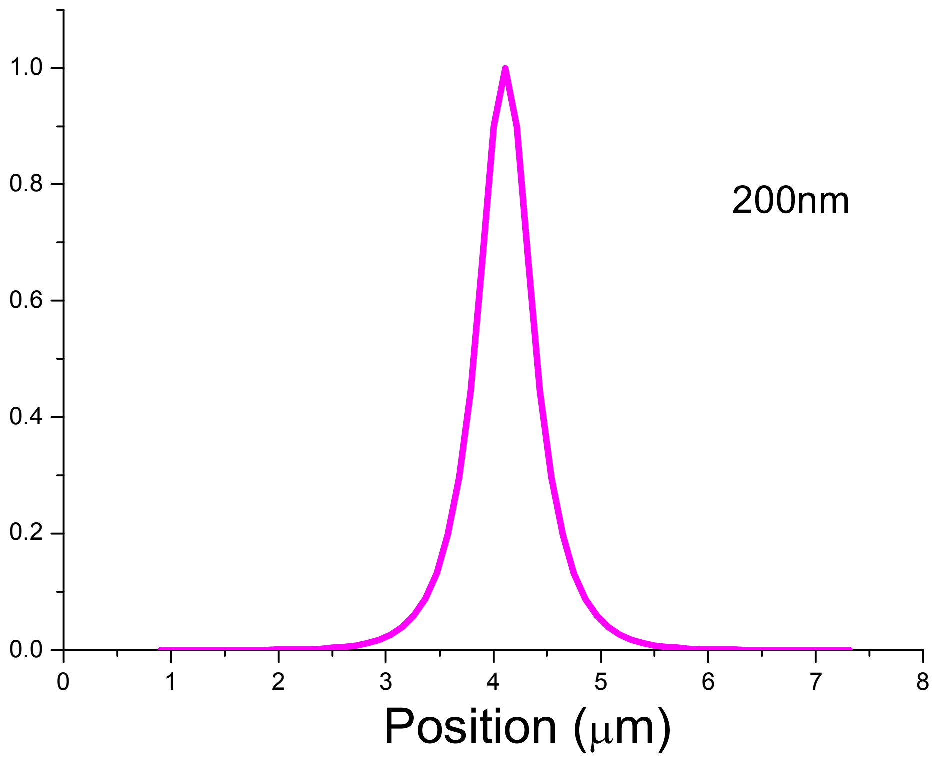




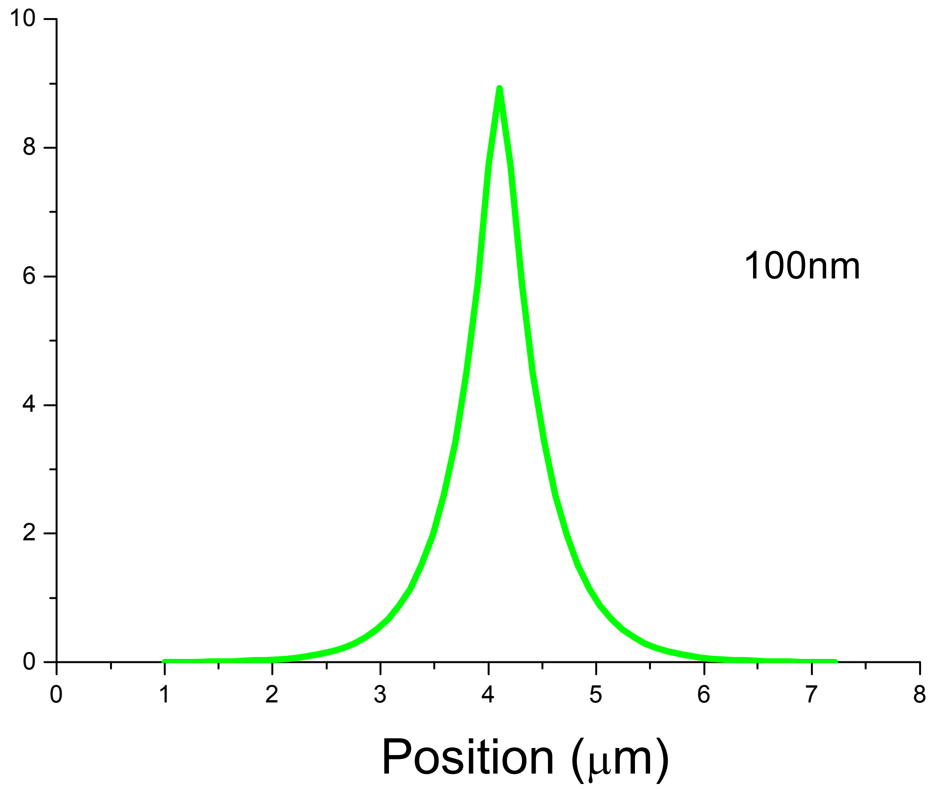


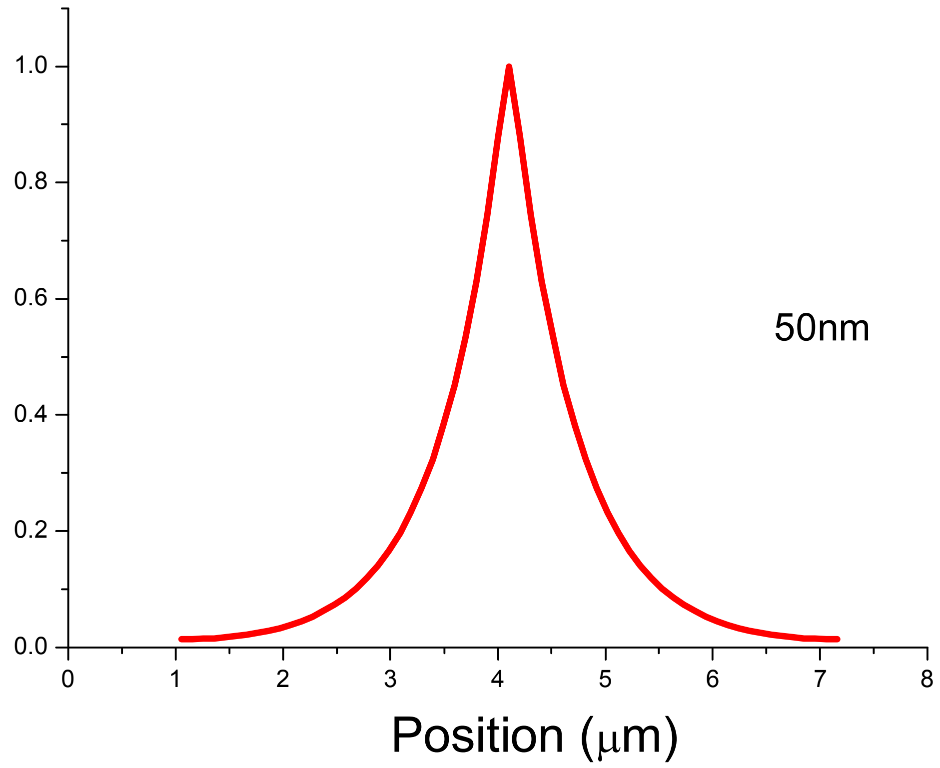
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
500nm
Position (μm)

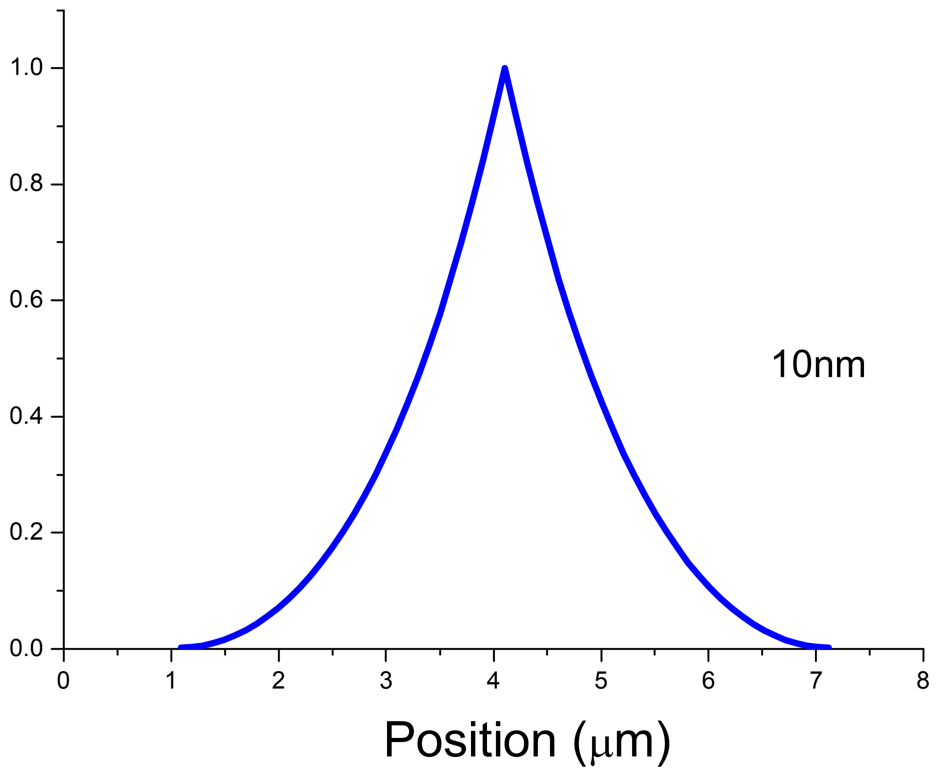

1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
300nm
Position (μm)



1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Position (μm)
200nm

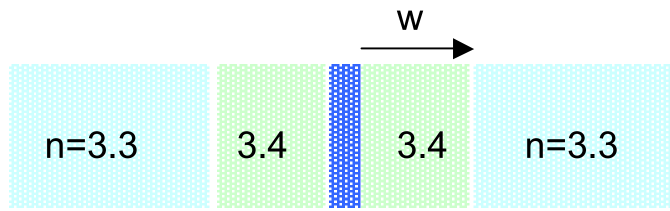

10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
100nm
Position (μm)

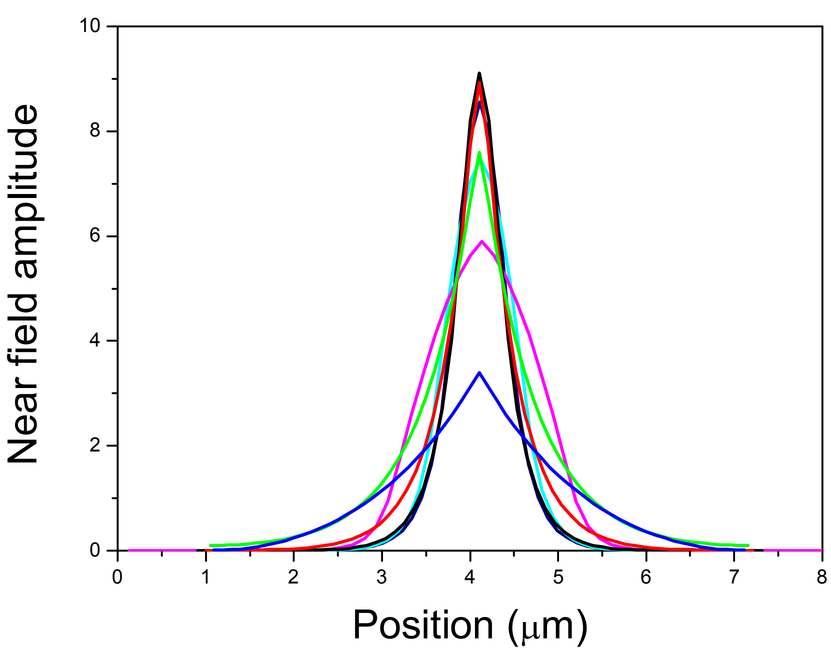

1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Position (μm)
50nm

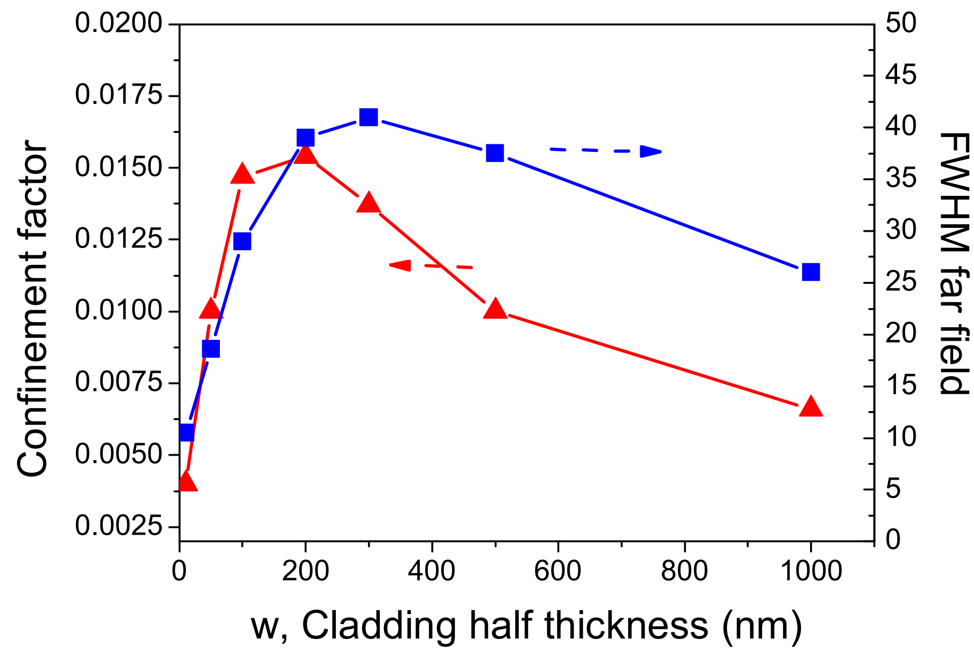


1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
10nm
Position (μm)

Symmetric waveguide with 7nm quantum well







Fundamental mode is:

Bell shaped for thick waveguides

Exponential for very thin waveguide

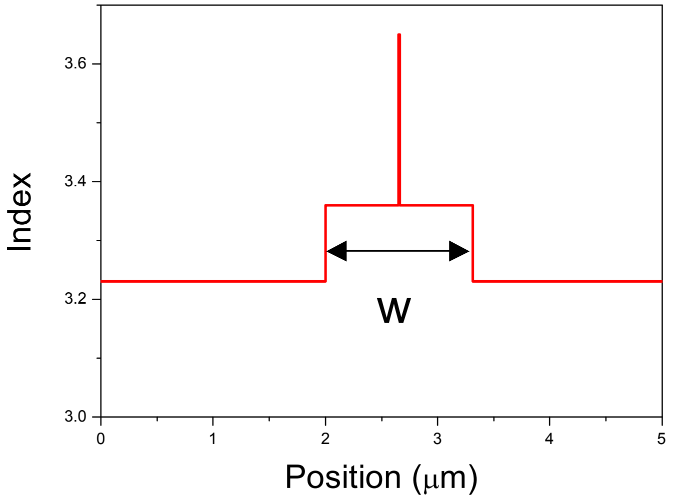
Strategies to obtaining large mode size

- Large optical cavity
- SPIN
- Trap layer
- LoGUIDE
- Photonic Bandgap Crystal
- SCOWL
- SMILE (exponential mode)
- Antiguide

Large optical cavity

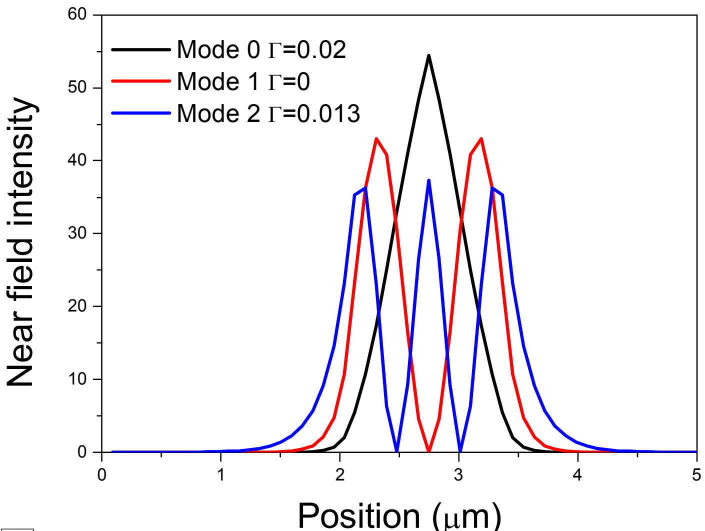
Broad waveguide design (Botez)

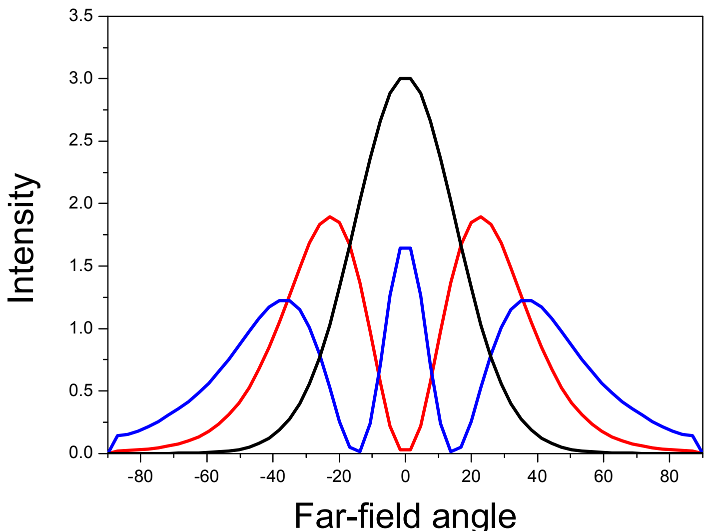
$$P_{max} = \frac{d}{\Gamma} W \frac{1-R}{1+R} P_{COMD}^{int}$$



Introduce higher order transverse modes:

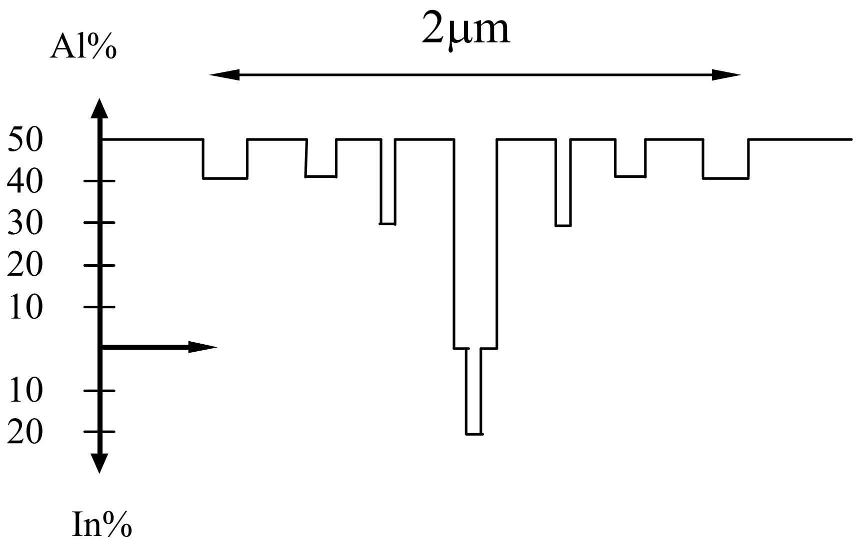
Discriminate by mode confinement, selective absorption loss, radiation loss

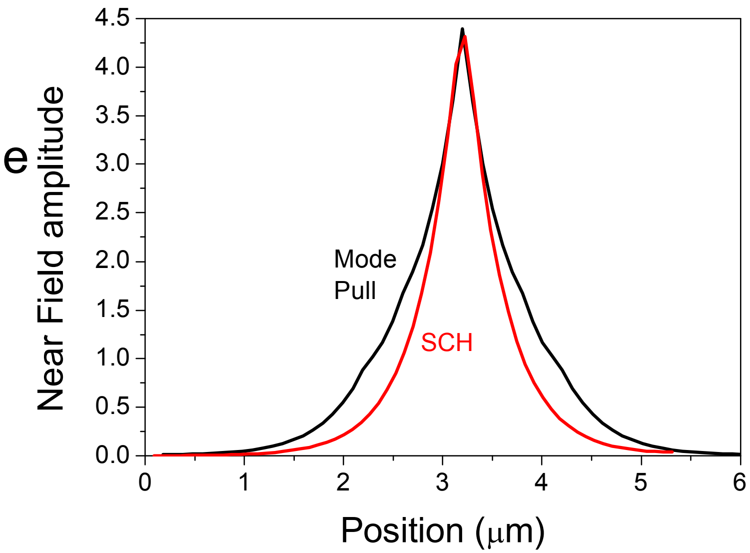


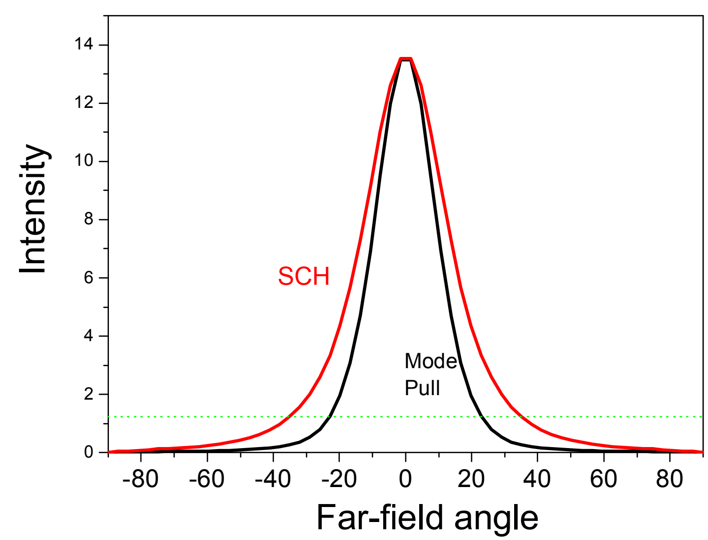


Mode shaping using 'mode pulling' layers

Narrow core to provide exponential mode
Subsidiary index guiding layers to spread the mode

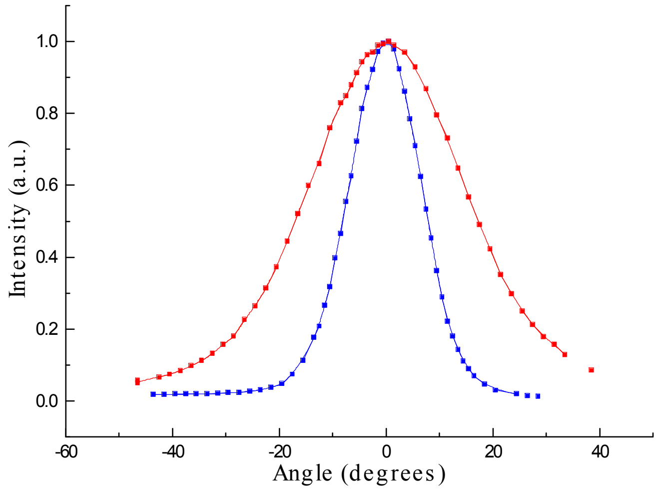






		Γ	FWHM	$1/e^2$
SCH	1x7nm well:	0.014	30	70
Shaped:	2x7nm wells:	0.023	21	45

Mode shaping characteristics



Transverse divergence reduced from 30 to 21 degrees

75% butt coupling efficiency to 50μm core fibre

O.P.Gough, et al, Proc. SPIE Vol. 3289, 143-150 (1998)
O.P.Gough, et at J. Sel. Topics in Quantum Electron., Vol 6, 571-576, (2000)

Free carrier absorption

- Originates from:
  - Absorption in cladding layer due to acceptors and donors
  - Absorption in active layer due to non-equilibrium carriers
  - Absorption in nominally undoped waveguide due to injected carriers

$$\alpha_p = \frac{e^3 \lambda^2 p}{4\pi^2 \mu_p m_p^2 n_r \varepsilon_0 c^3}$$

- Higher for p carrier due to low effective mass of light holes
- Depends on composition due to dependence on mobility
- Higher for longer wavelengths due to λ^2 dependence

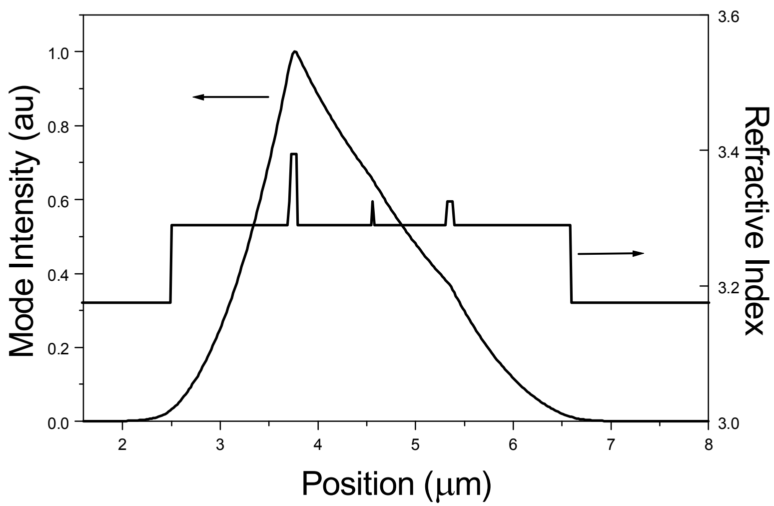
$$\alpha_{\text{int}} = \sum \Gamma_i \alpha_i$$

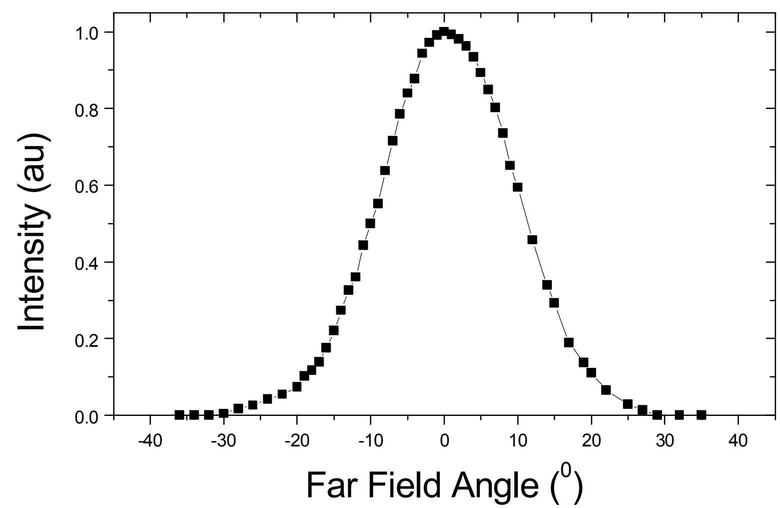
Asymmetric mode shaping at 1550nm

Typical ridge waveguide telecom lasers have far-field divergences in the 40 degree range and intrinsic losses in the 20-30cm^{-1} range.

Asymmetric mode pulling design to obtain transverse mode size of 3.1μm
FWHM transverse divergence to 22°
Losses measured at 10.4 cm^{-1} due to reduced overlap

Obtained 32 % butt coupling efficiency to single mode fibre.

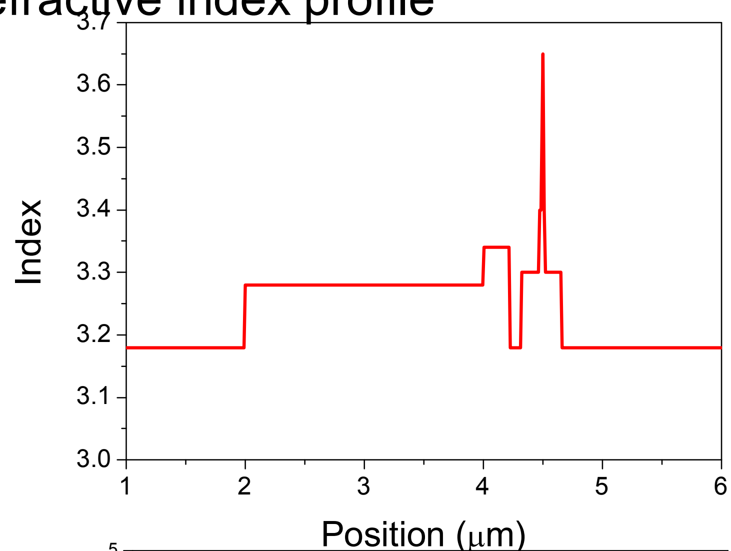


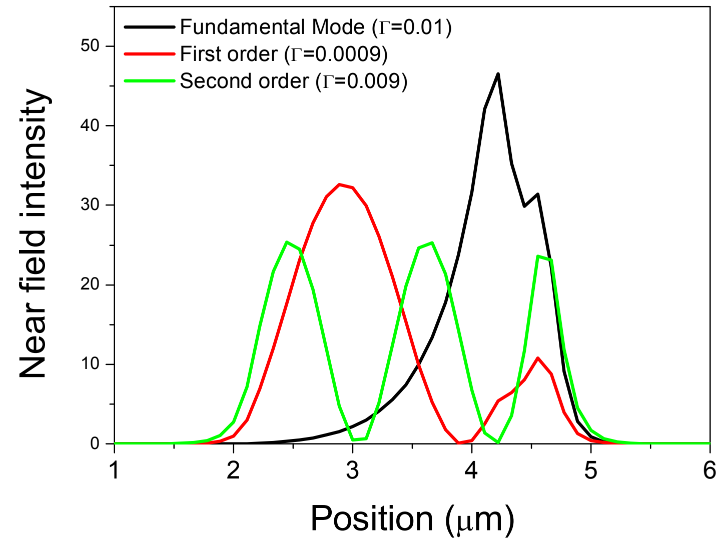


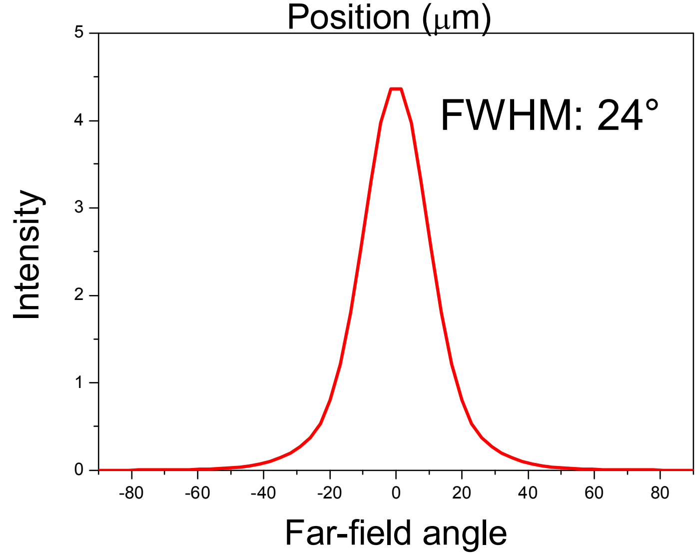
B. Corbett, et al, Electron. Lett., 38 515-516, (2002).

Optical trap layer

Refractive index profile







Fundamental Mode: Γ=0.01
First order: Γ=0.0009
Second order Γ=0.009

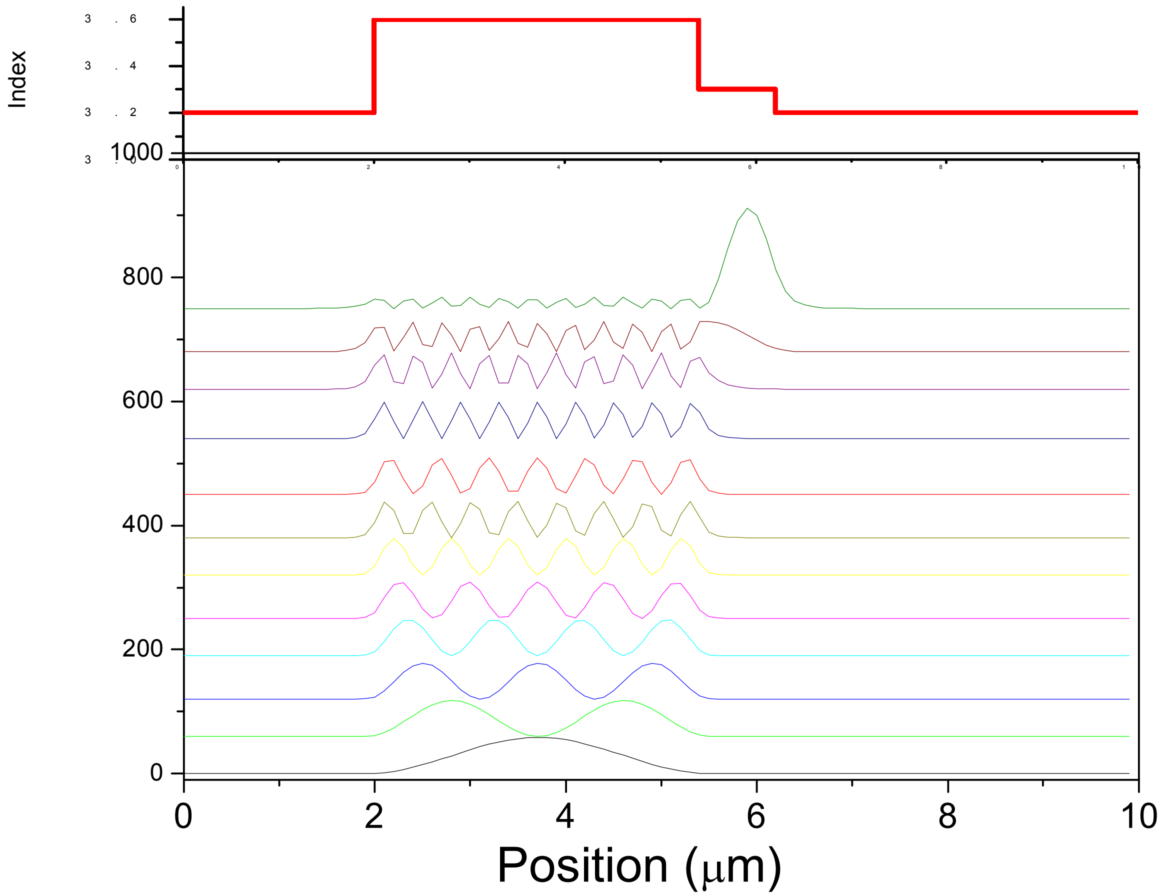
Need mode discrimination against 2^{nd} order mode

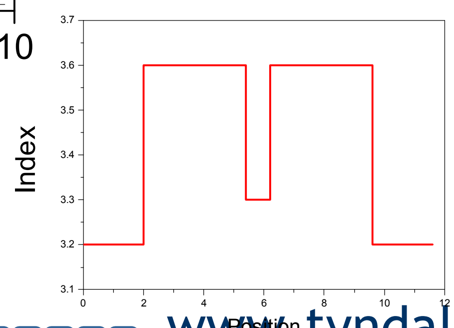
G.Iordache et al Electron Lett 35, 148 (1999)

Guiding in low index layer

Evolution of mode profile with mode number

Calculate the mode profiles for a multimode waveguide

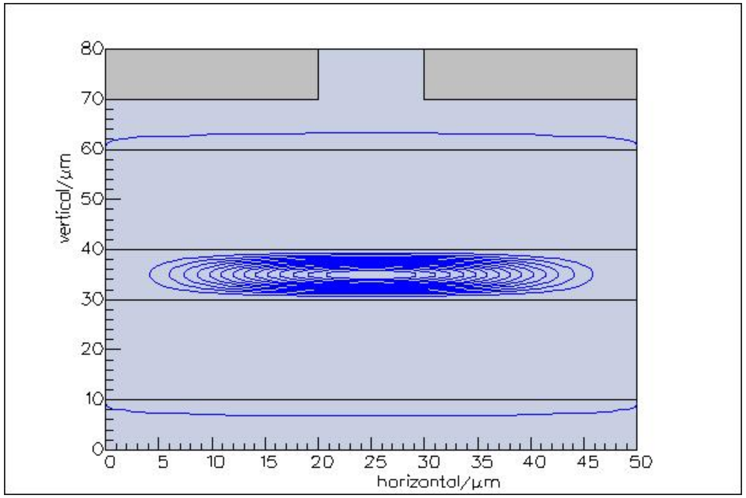




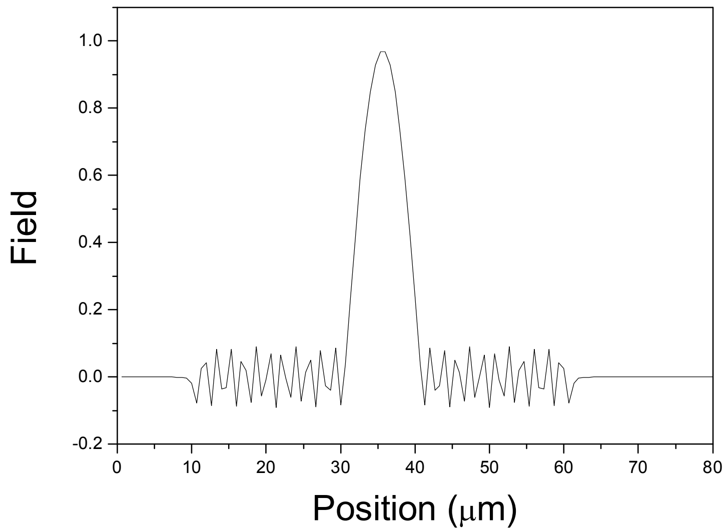
High intensity at the edge of the waveguide

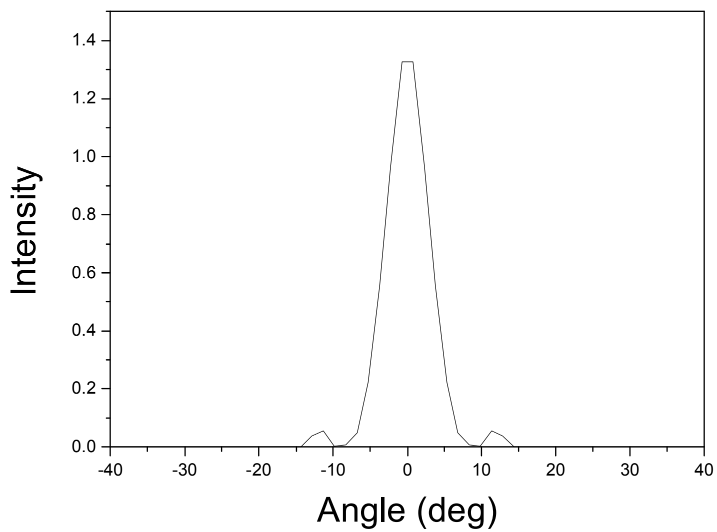
Use this concept in a back to back fashion

Implementation in a silica waveguides



20µm	n=1.46
20µm	n=1.6
10µm	n=1.5
20µm	n=1.6
20µm	n=1.46

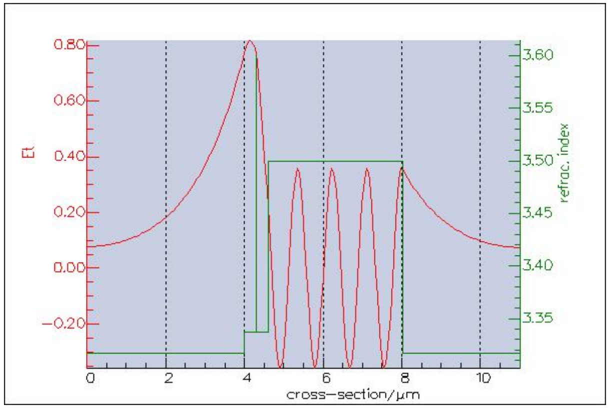


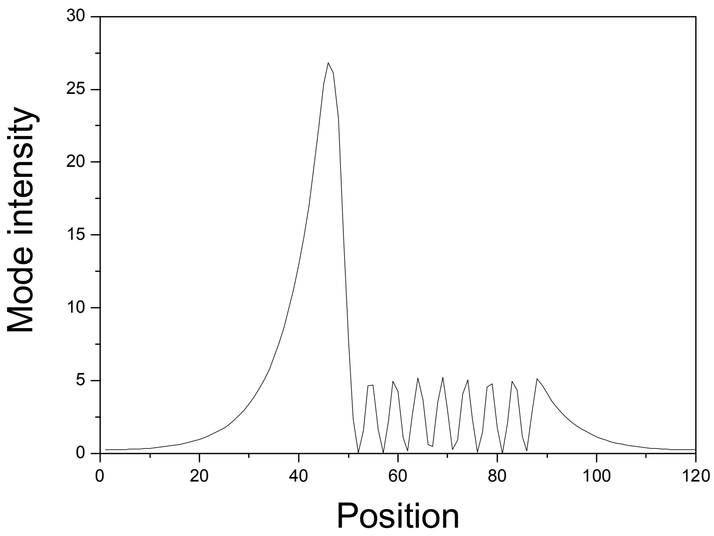


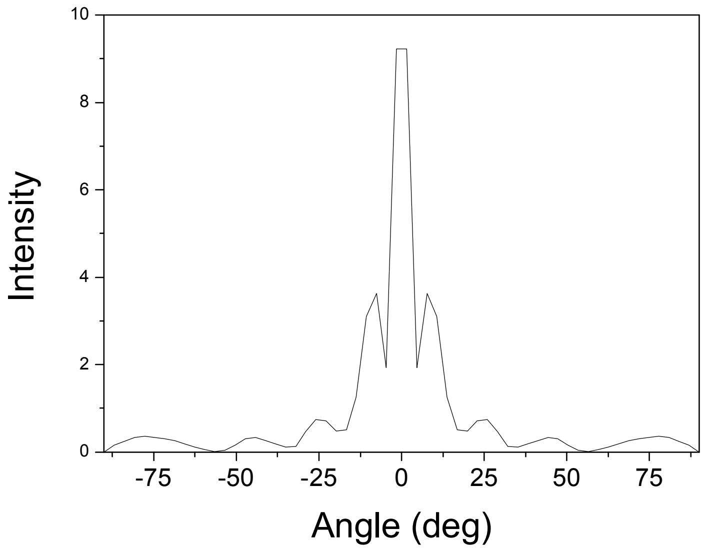
Mode size 10µm; Overlap 96%; θ_{FWHM}=6.8° Radiation loss =0.65cm^{-1}

Implementation in a GaAs waveguide

2μm	$Al_{.30}GaAs$	n=3.317
3.4μm	GaAs	n=3.5
0.6um	$Al_{0.27}GaAs$ (2QW)	n=3.337
4um	$Al_{.30}GaAs$	n=3.317



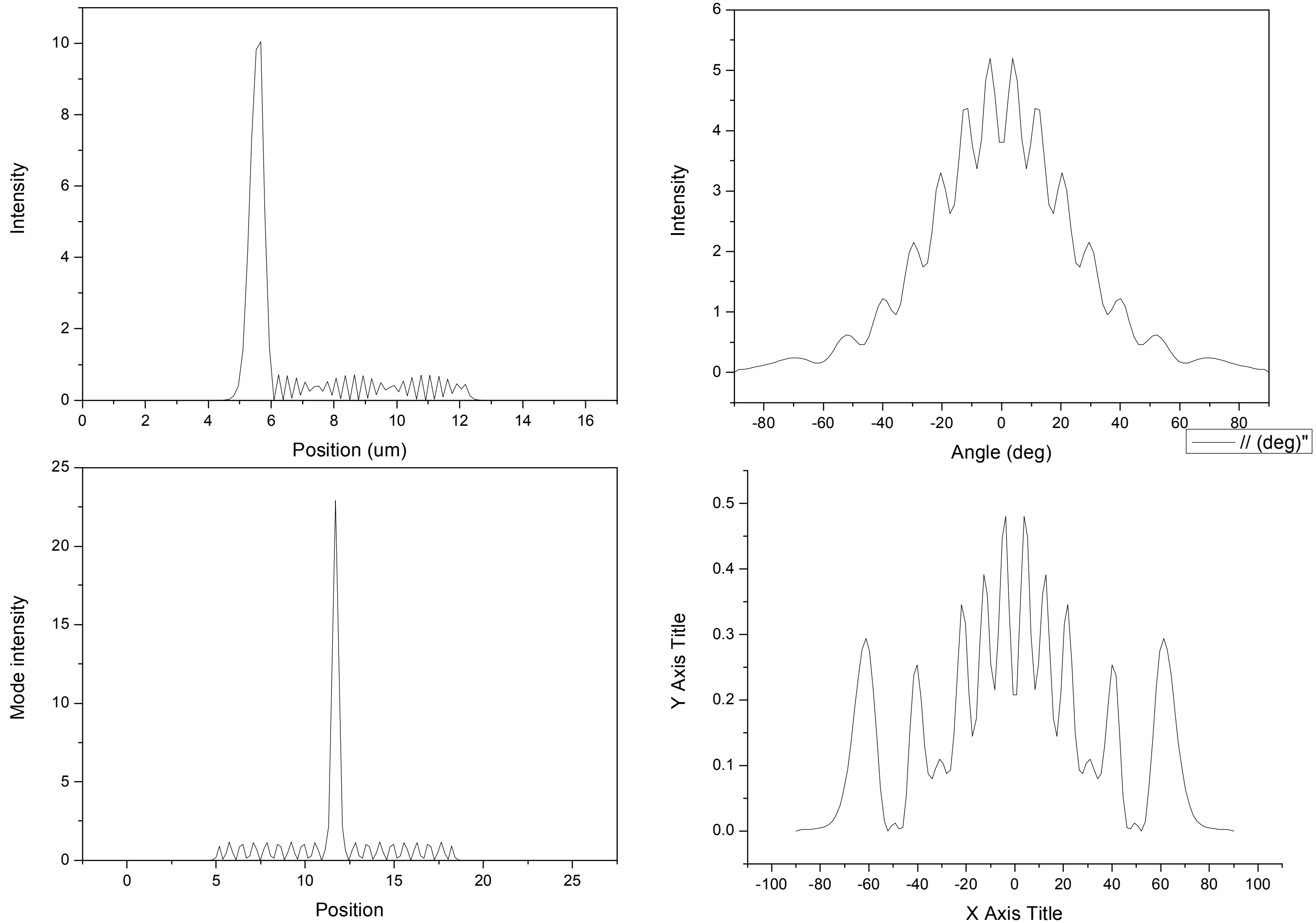




Γ=0.008, radiation loss 4cm^{-1} n_{eff}=3.3144

‘Imaginary’ waveguides

2um n=2.9
6um n= 3.5
1um n=3 (2QW)
4um n=2.9



Limited applicability in GaAs waveguides in a transverse direction
Possible to use in the lateral direction

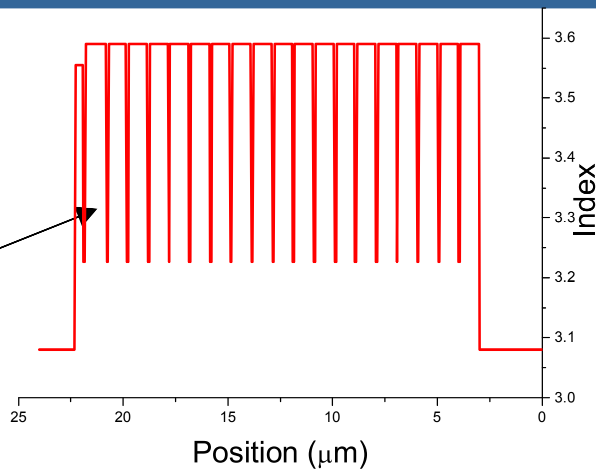
Photonic Bandgap Crystal

Being commercialised
by PBC (Israel)

In an infinite, periodic PBC have waves which propagate and a bandgap for others

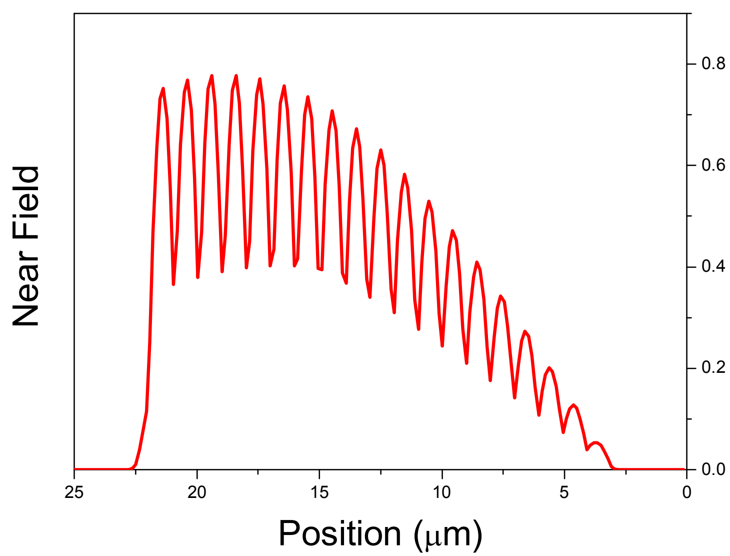
Basic concept

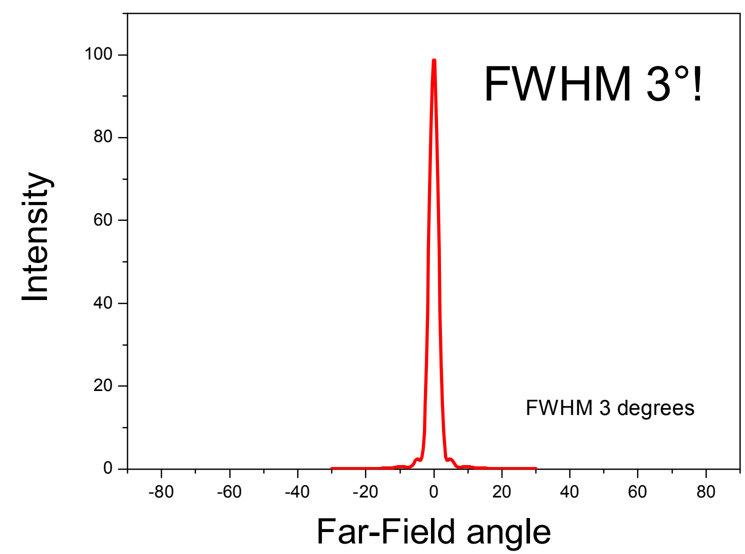
Refractive index profile



19 periods

Defect layer slightly thicker

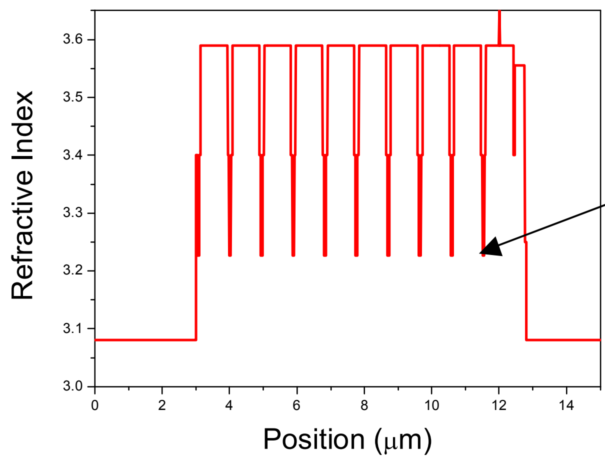




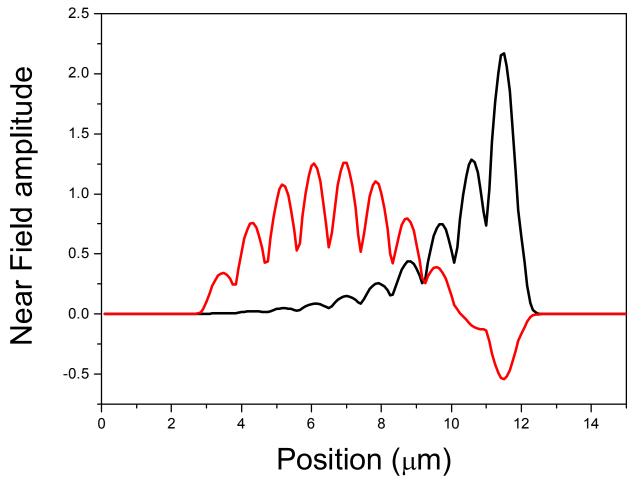
View as a very thick GaAs guiding layer with periodicity causing the mode to tunnel; or that the antiguidng layers spread the mode

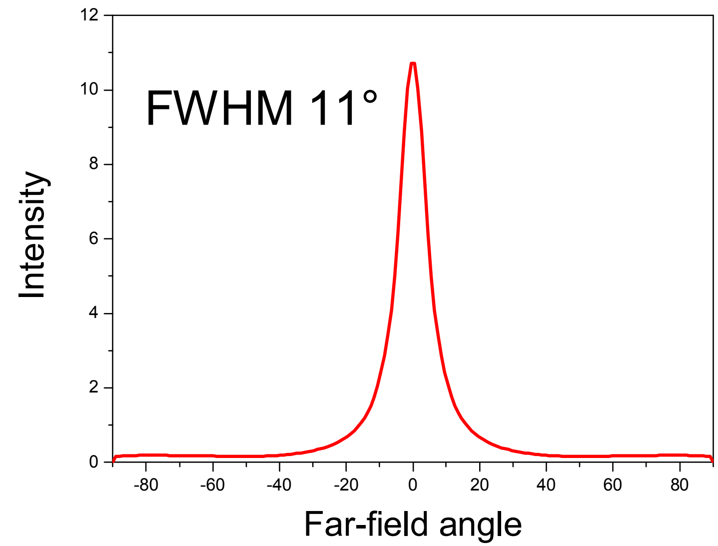
Practical design

Calculations based on structure in the patent using 10 periods



$Al_{0.55}Ga_{0.45}As$ with graded interface





2x7nm wells

Γ=0.015 for the fundamental mode

Can include an absorbing quantum well on the substrate side in order to suppress the higher order modes

Characteristics from PBC

State of the art for 980nm

Epilayer	14μm thick
FWHM:	4.8 – 6 degrees FWHM
L	4 mm
P_{max}	2 W at 3A
Loss	α~5cm^{-1}

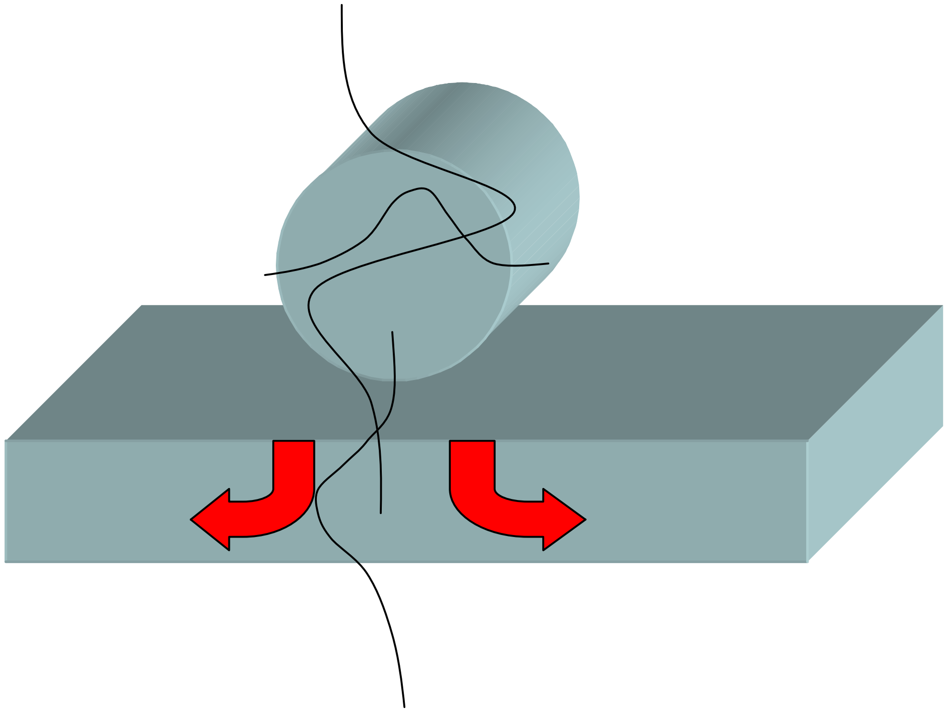
10 W at 650nm obtained under pulsed operation with 11 degree FWHM

+ Extremely large transverse spot size demonstrated and possible
+ Remarkable low divergence angle
+ Applicable to many material systems

- Limited by growth
- Difficult to control lateral profile

M. V. Maximov et al "Low divergence edge-emitting laser with asymmetric waveguide based on one-dimensional photonic crystal", physica status solidi (c), 2, 919, 2005

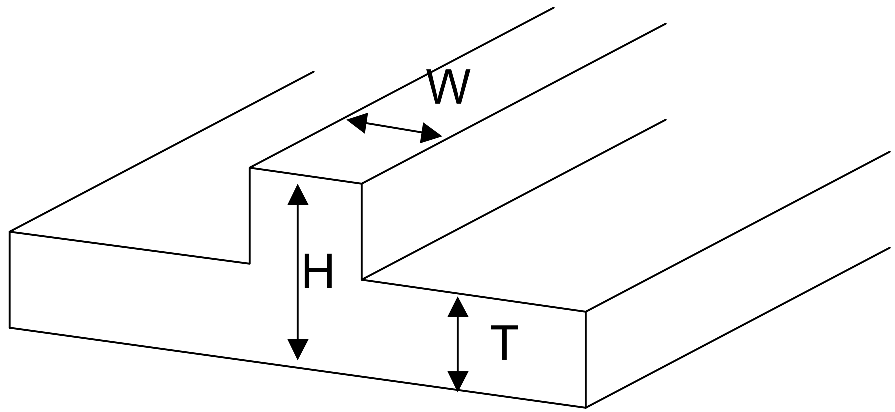
Slab coupled optical waveguides (SCOWL)



Method to obtain a single mode fibre waveguide in the absence of a cladding technology

Arnaud and Marcatelli (1974)

Modes are intrinsically 2D – scale with T/H and T/W

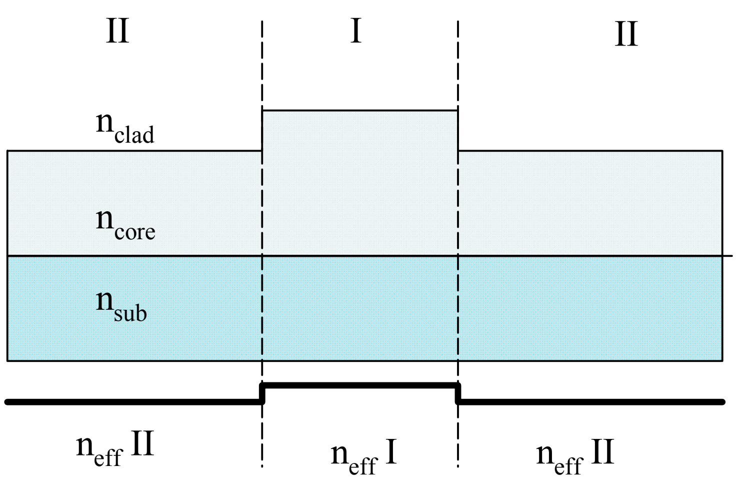


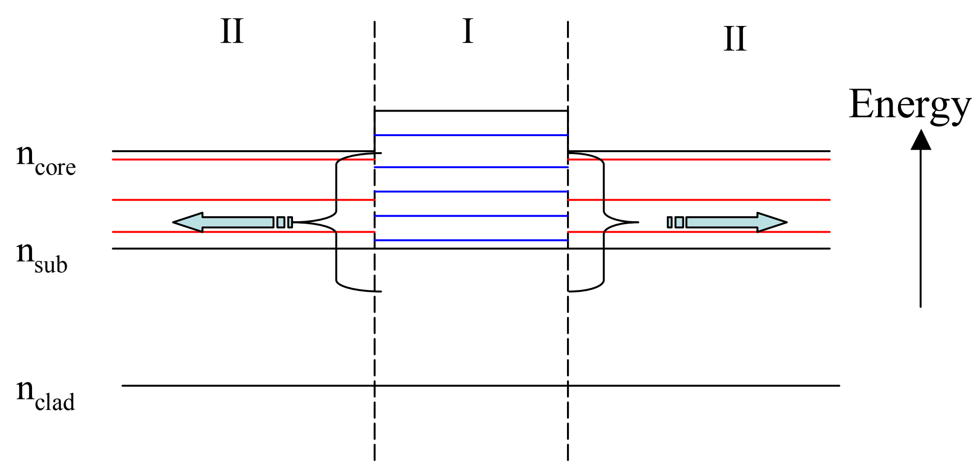
$$k_{Iz}^2 = \left(\frac{2\pi n_1}{\lambda}\right)^2 - \left(\frac{\pi M}{H}\right)^2 - \left(\frac{\pi N}{W}\right)^2$$

$$k_{IIz}^2 = \left(\frac{2\pi n_1}{\lambda}\right)^2 - \left(\frac{\pi M}{T}\right)^2 - k_y^2$$

Continuum of slab modes

Effective index approach





Discrimination against the high order modes by a high radiation loss

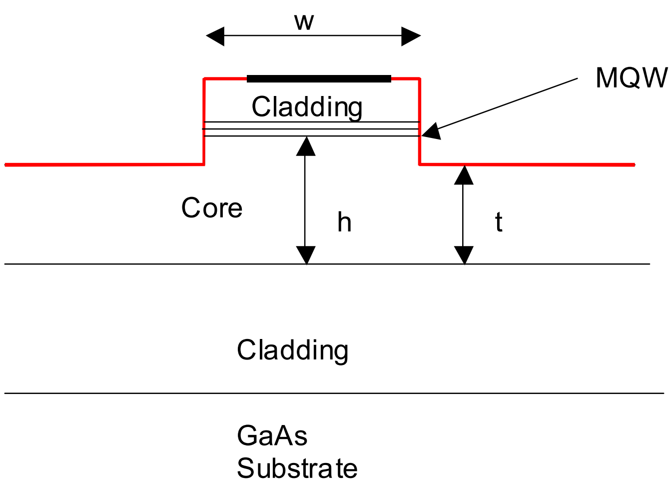
Single mode condition

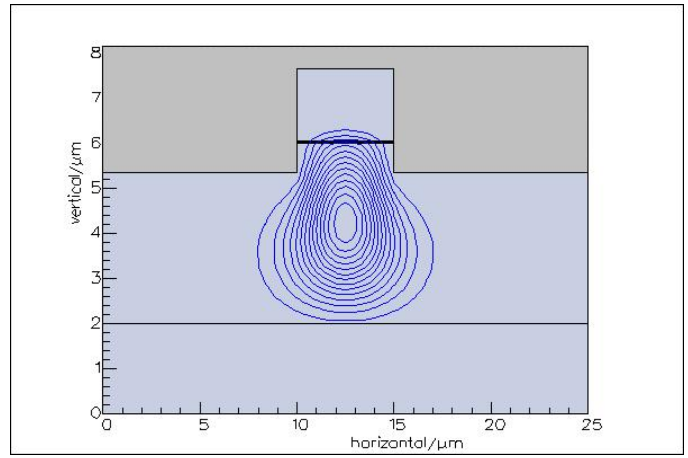
$$\frac{W}{H} < \frac{T/H}{\sqrt{1-(T/H)^2}}$$

W, H, T scaled to account for penetration of field into surrounding areas

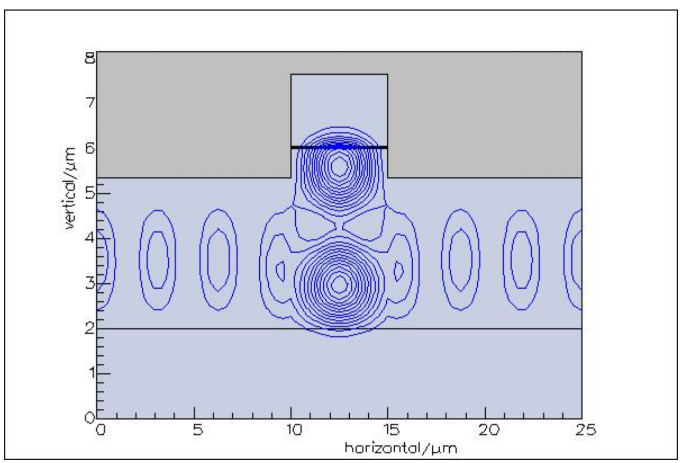
S. Pogossian, et al “The single mode condition for semiconductor rib waveguides with large cross section”, J. Lightwave Tech. 16, 1851 (1998)

Example SCOWL structure





Fundamental 2D mode



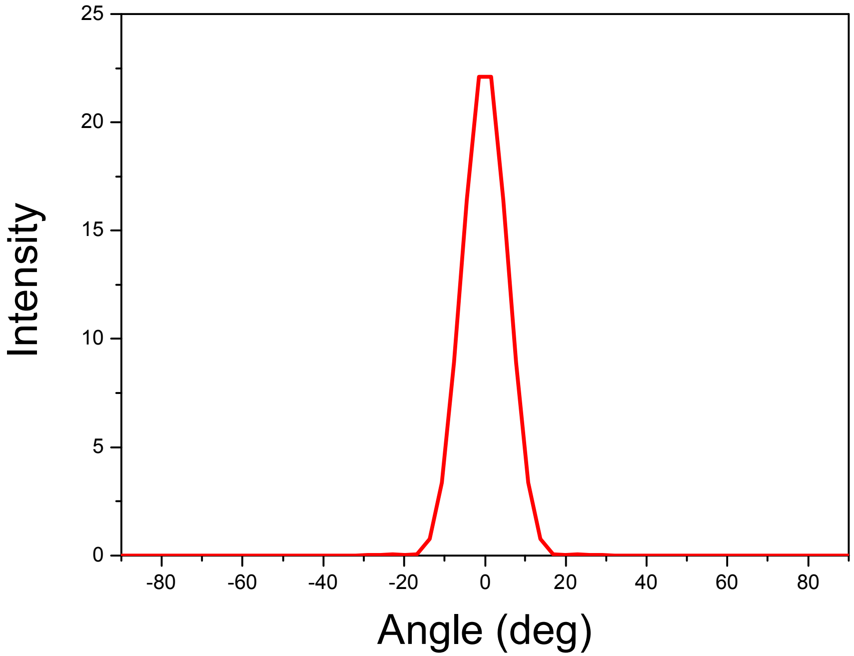
1D slab modes have similar Γ BUT the complete structure is a single mode guide

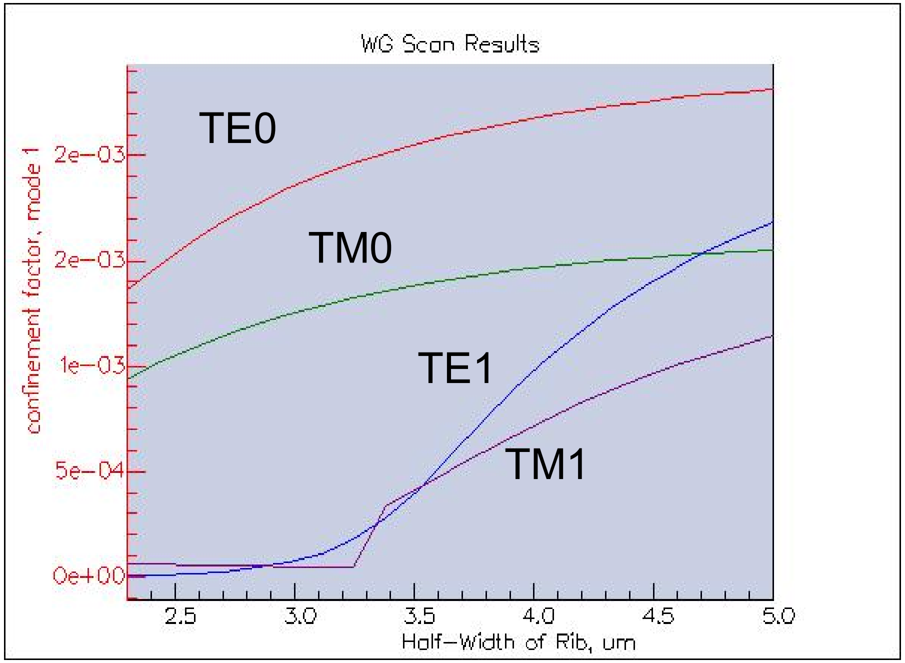
The SCOWL is a fully 2D structure and not just a perturbed 1D structure

Higher order mode with radiation loss of $35cm^{-1}$

Sensitivity to ridge width

Far-field





Ridge half-width

At ~6μm width ridge high order mode confinement becomes significant

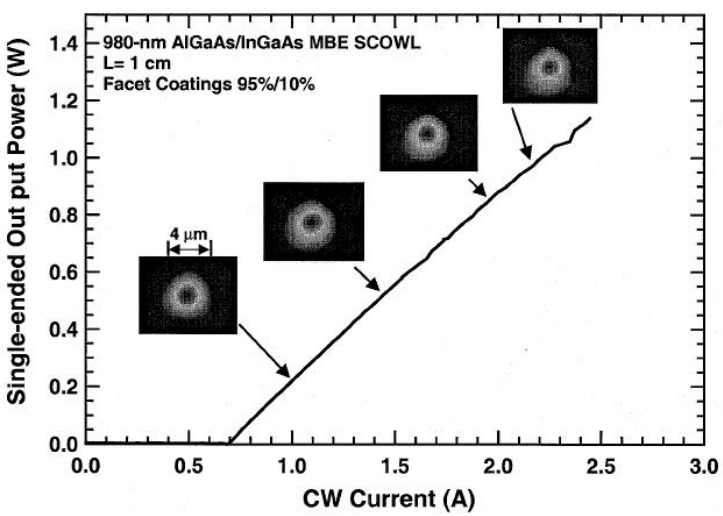
State-of-the-art QW-SCOWL performance

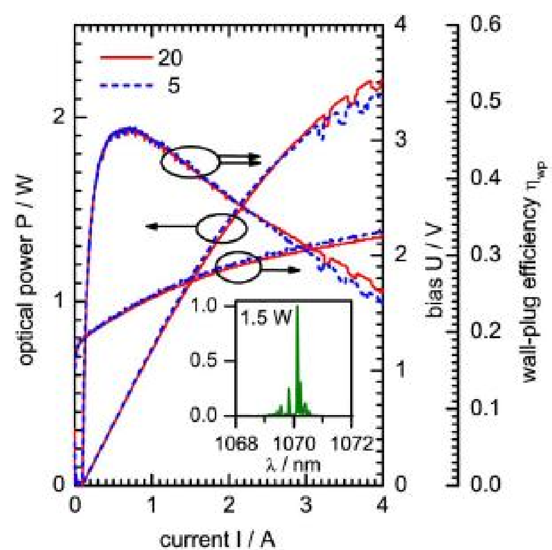
MIT

Device length	1cm
Threshold	0.7A
Power	1.2W at 2.3A
Far-field	10° x 11°

FBH

Device length	3.9mm
Threshold	0.1A
Power	2W at 4A
Far-field	9.2° x 15°
Max WPE	47% at 0.5W

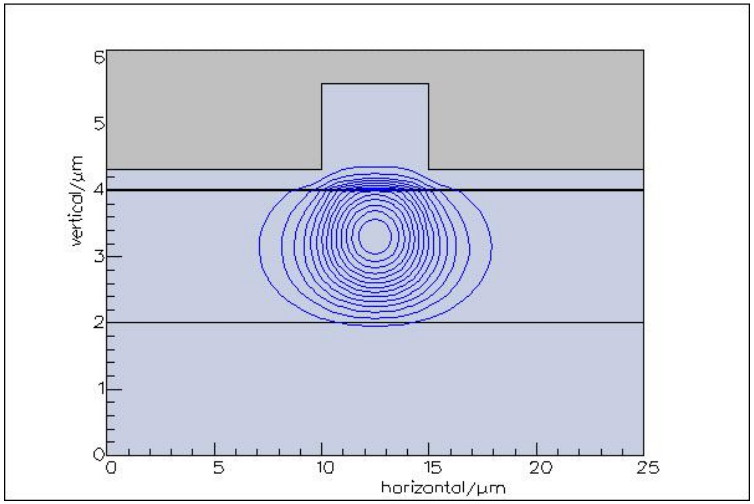


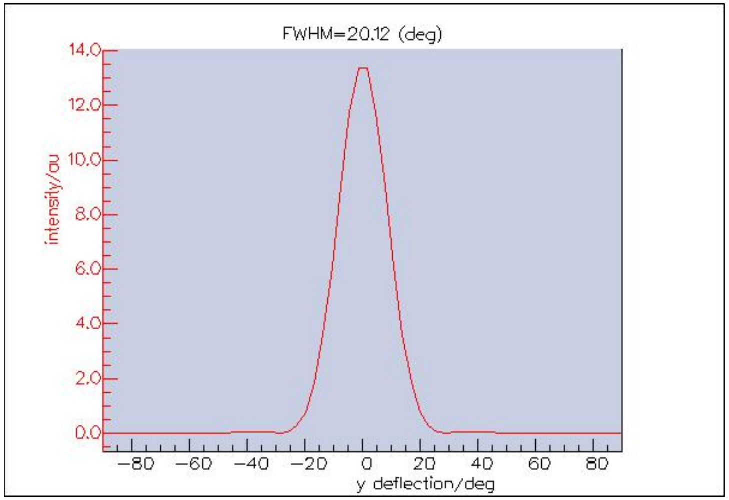


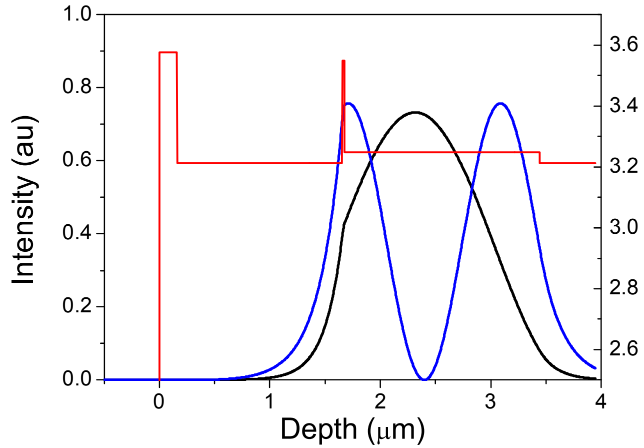
J. P. Donnelly, et al "AlGaAs–InGaAs Slab-Coupled Optical Waveguide Lasers", J. Quantum. Electron, 39, 289 (2003)
H. Wenzel et al "Fundamental lateral mode stabilised high power ridge waveguide lasers", Photon. Tech. Lett, 20, 214 (2008)

SCOWL with quantum dot active medium

Limited gain in quantum dot
Avoid etching through active layer

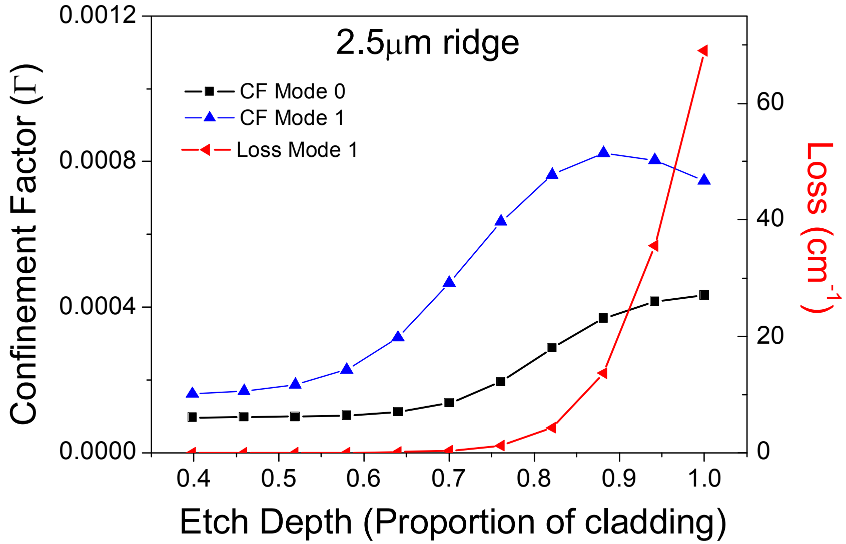


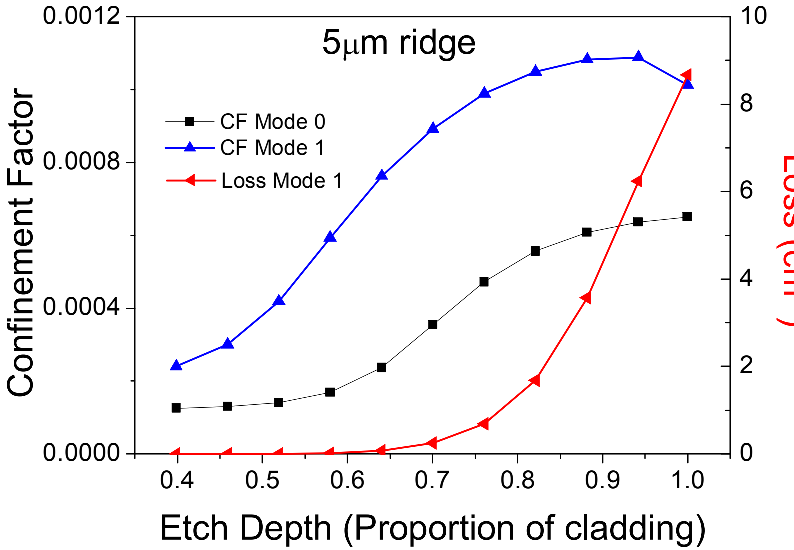




Design with a single layer of quantum dots grown by Wurtzburg

Selection of ridge width and device length



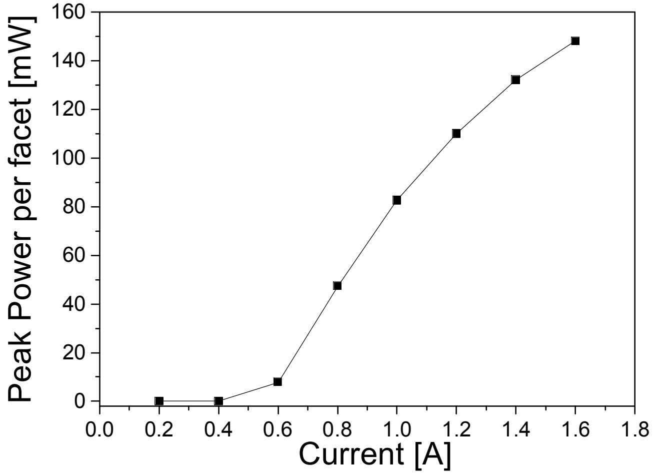


For fundamental mode operation $\alpha_m = \ln(1/R)/L << \alpha_1 / \ f - 1$

α_1 is the mode 1 loss

f is the ratio of confinement factors between the first and fundamental mode.

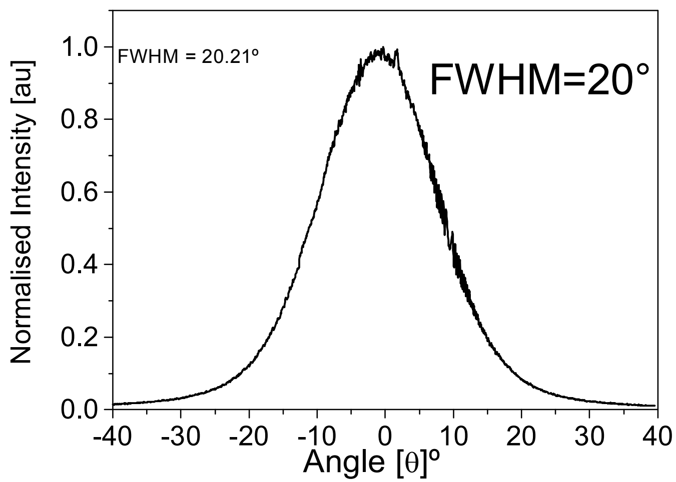
Quantum dot SCOWL characteristics

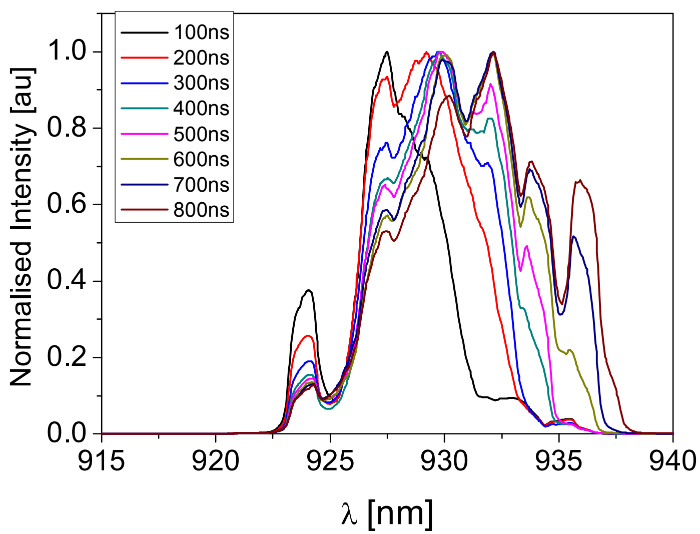


L=3.2mm η_{Total} = 0.38 W/A J_{th}=5.6 kA/cm^2

L=8.3mm η_{Total} = 0.2 W/A J_{th}=2.3 kA/cm^2

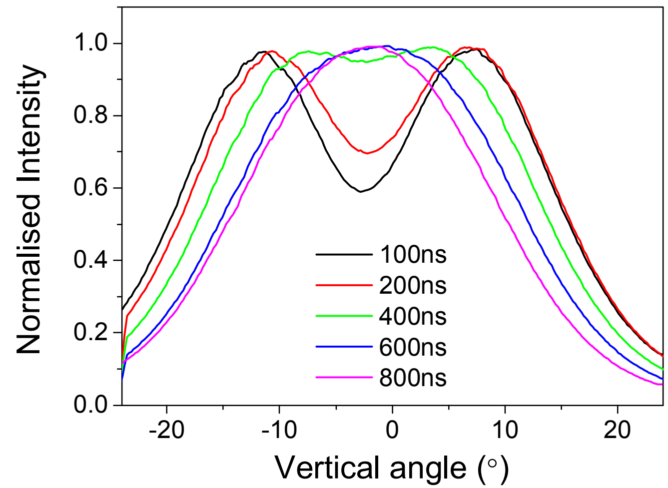
α_i = 4.8cm^{-1}; η_i = 0.88



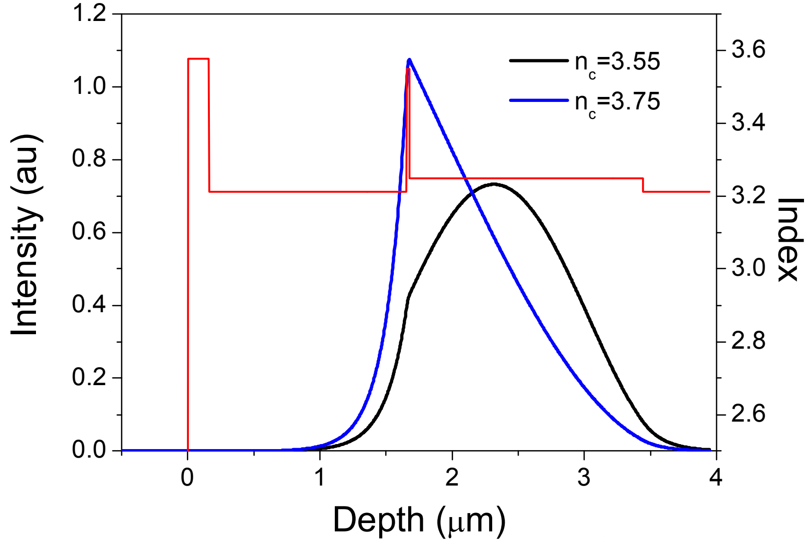


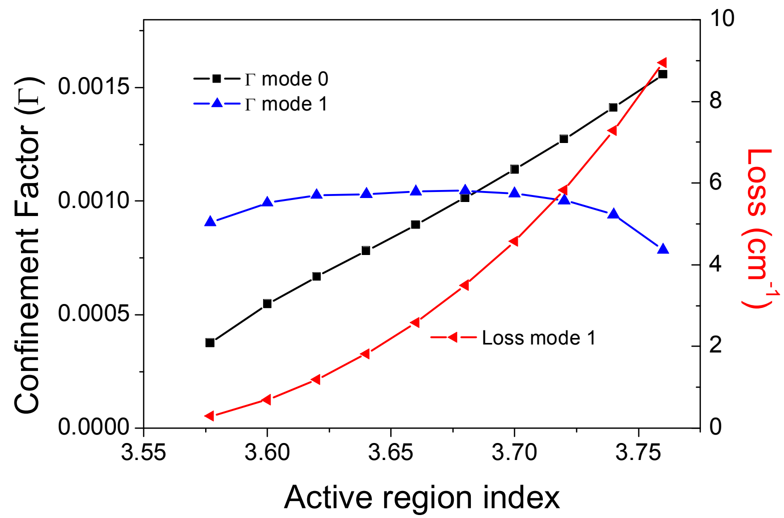
Record low divergence for quantum dot structure

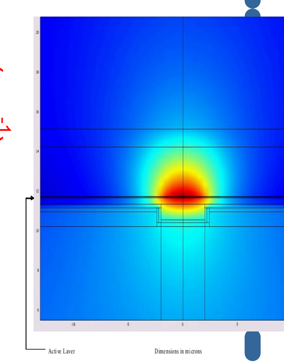
Far-field dependence on pulse-width



Explained by the an increase in a *transverse* lensing effect







B. Corbett, et al, “Modal Analysis of Large Spot Size, Low Output Beam Divergence Quantum-Dot Lasers”, Photon. Tech. Lett., Vol 19, pp. 916 – 918, (2007)

SCOWL summary

+ Very large, circular single mode spot size possible

+ True 2 dimensional mode guiding

- Low modal gain (0.1 of conventional)

- requires low parasitic losses and long devices

- Exposed quantum well region in original design

- Can be sensitive to precise structural and index parameters

+ quantum dot structure with record low divergence realised

Improved design of large spot size QD lasers

- Individual quantum dot layers have low gain due to limited density
- A minimum separation is required between dot layers to ensure equal dot size
- Avoid indirect AlGaAs (Al%>40%) as this increases the resistivity
- Design taking the variations of layer thicknesses and the Al content

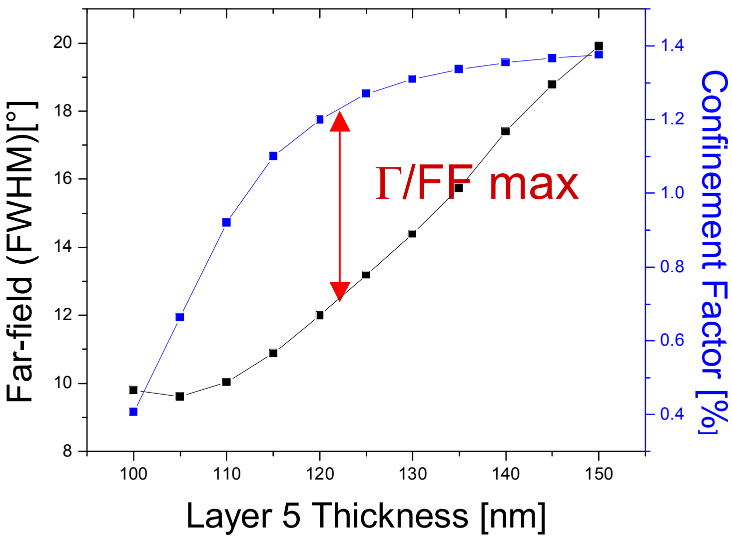
Solution:
A reasonable confinement factor requires the field maximum must overlap with the dots.

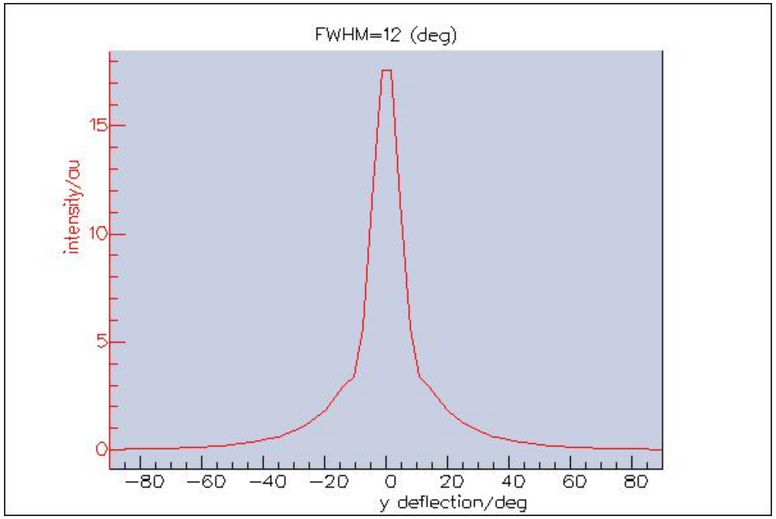
Use a thin core with exponential decay of mode

A slowly decaying exponential ensures the near field mode is large and giving a narrow far field.

Implementation in a QW laser structure

- Approach: maximise the ratio Γ/Farfield





<u>Characteristics:</u>

Γ = 0.0120

Far-field = 12° at FWHM and <40° @ $1/e^2$

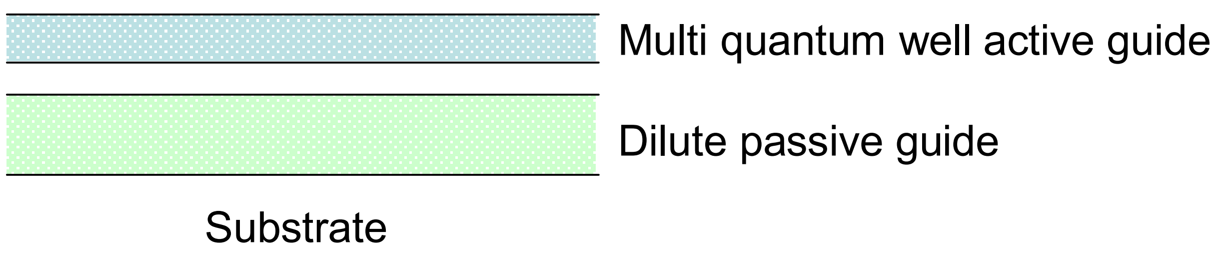
Approaches in InP technology

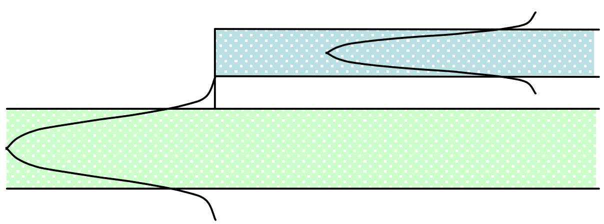
- Telecommunication devices must couple to single mode optical fibre
  - Mode adaptation a necessity
- Many approaches often based on regrowth techniques
  - Buried heterostructure has low index step
  - Active - passive separation
  - Selective area growth for lateral and vertical tapered structures

- Fundamental difference in properties compared with GaAs 980nm
  - Multiple quantum wells required for sufficient gain
  - High intrinsic (Free carrier) losses (α_i >10cm^{-1})
  - Low threshold required
  - InP is the lowest refractive index in the system

Example: Asymmetric Twin Guide

Technique requires one epitaxy step:





V. M. Menon, et al “Photonic Integration Using AsymmetricTwin-Waveguide (ATG) Technology: Part II—Devices, J. Sel. Topics in Quantum. Electron,. 11, 30, (2005)

Comparison of waveguide approaches

	Epi	Γ	θ_{FWHM}
Separate confinement heterostructure	3μm	0.024	30°
Broadened waveguide	4.5μm	0.02	36°
Mode spreading	5μm	0.023	21°
Trap layer	6μm	0.01	24°
SCOWL	9μm	0.003	11°
PBC	14μm	0.015	6°
Antiguiding structure	6μm	0.012	12°

Comparison of quantum dot approaches

Design	Dot layers	Confinement	Divergence (°)	Jth (A/cm^2)
Standard Q-Dot design	1	0.004	40	
SCOWL	1	0.0005	20	5600
SMILE	3	0.0048	20	600
DIABLO	**3**	**0.006**	**10**	

Conclusions

- Large spot size designs possible with different approaches
- Design dependent on refractive index palette
- Asymmetric structures reduce loss but reduce mode control
- SCOWL designs overcome this limitation with a true 2D mode
- Optimise Γ/θ
- Passive structures – need to incorporate carrier and thermal properties