External-cavity designs for phase-coupled laser diode arrays

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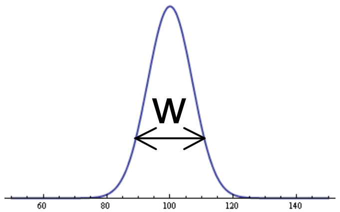
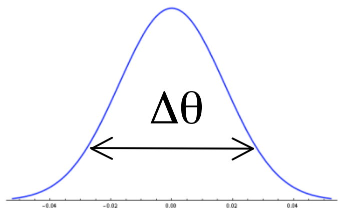
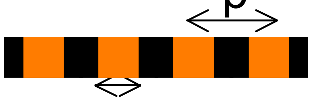
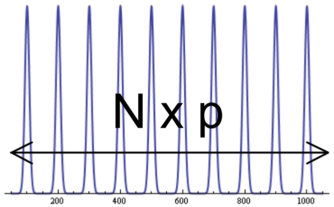
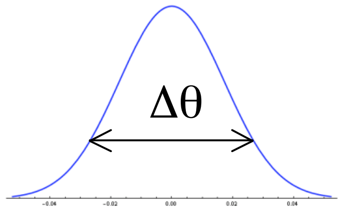
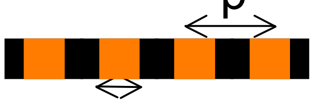
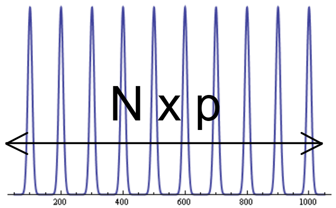
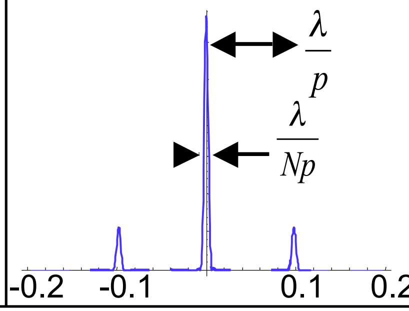
Outline

- Introduction
- Talbot external cavity
  - Principles
  - Numerical modelling
  - Experimental results
- Angular filtering external cavity
  - Numerical modelling
  - Experimental results
- Conclusion

Introduction

	Near Field (µm)	Far Field (radians)	Brightness (W/cm²/sr)
1 laser diode 			$B_1 = \frac{P}{S_{em}\Omega} \propto \frac{P}{w \cdot \Delta\theta}$
N *incoherent* laser diodes 			$B_N \propto \frac{w}{p} B_1 \le B_1$
N *coherent* laser diodes 			$B_N^{coh} = N \times B_1$

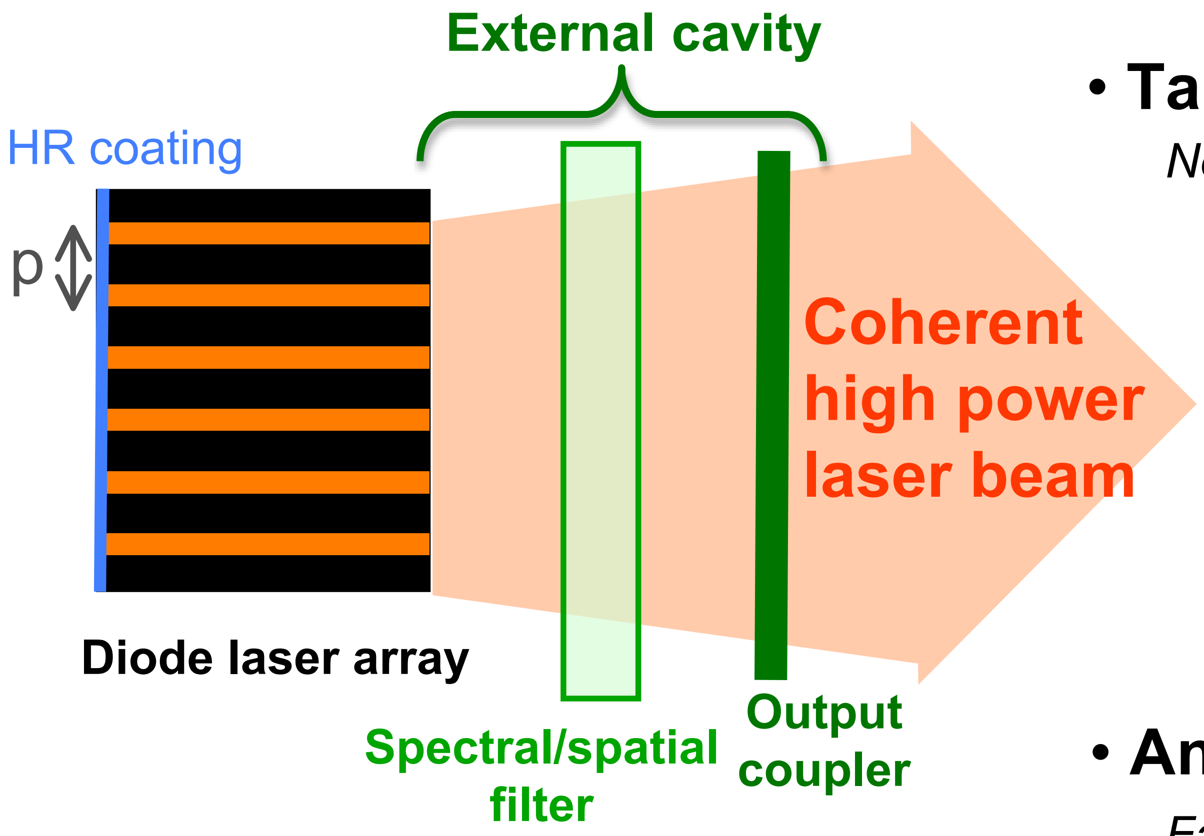
Coherent emisson of identical emitters in parallel

⇒ **scalability of the power & the brightness**

External cavity designs

Purpose : passive coherent combining of diode lasers

⇒ to induce an efficient coupling between emitters



- **Talbot self-imaging effect**

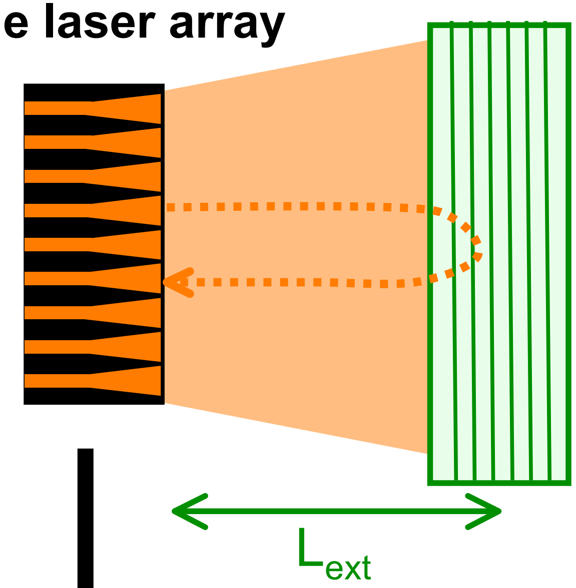
  Near-field diffraction phenomenon

- **Angular filtering**

  Far-field filtering

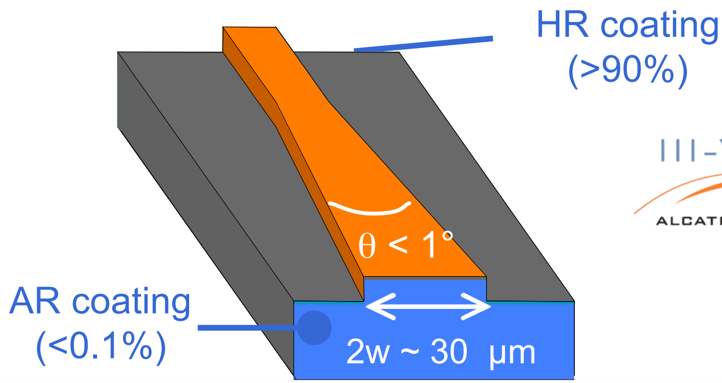
Experimentally …

Diode laser array



Index-guided tapered emitter

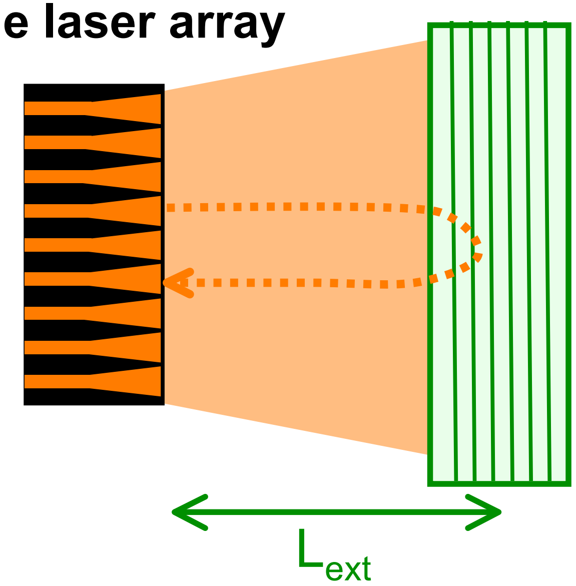
Single mode operation ($M^2 < 2$)
High power (single emitter ≤ 1 W)
(bar : 0.4 W/emitter)



Krakowski *et al.* Elec. Lett. **39** (15) 1122 (2003)

Experimentally …

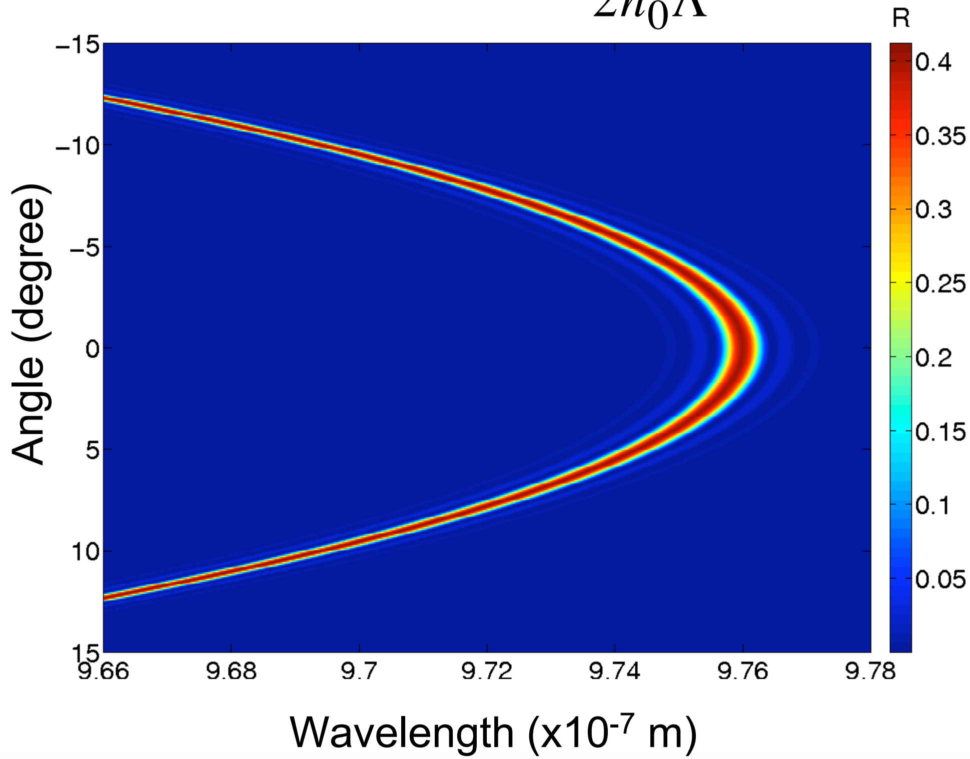
Diode laser array



Volume Bragg grating

Angular + spectral selectivity

$$\cos(\theta_{inc}) = \frac{\lambda}{2 n_0 \Lambda}$$



θ_{inc}-λ map for a reflective volume Bragg grating

(Λ = 325 nm, n_0 = 1.5000, d = 0.7 mm)

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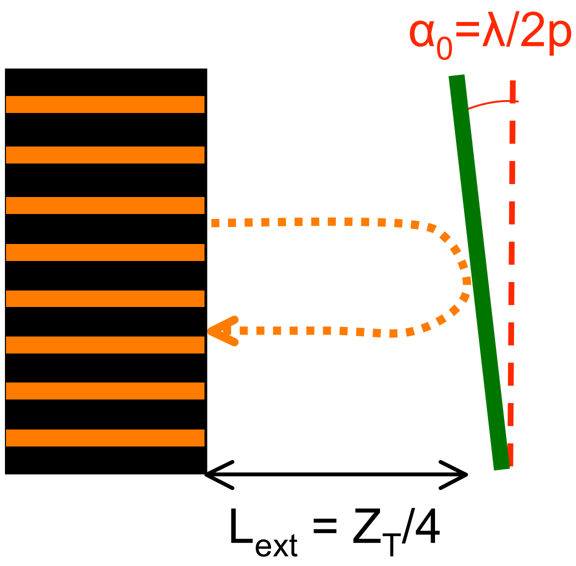
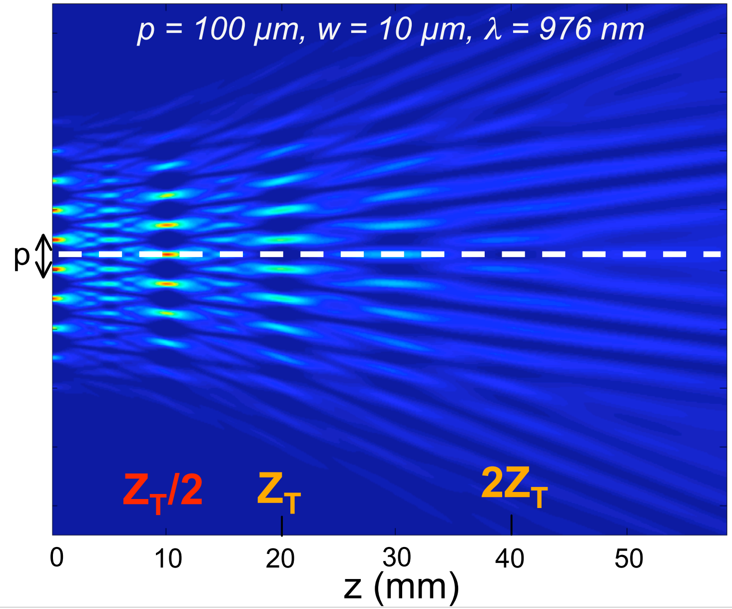
Talbot external cavity

Talbot effect = Near field diffraction self-imaging of periodical objects resulting from multiple beam interferences



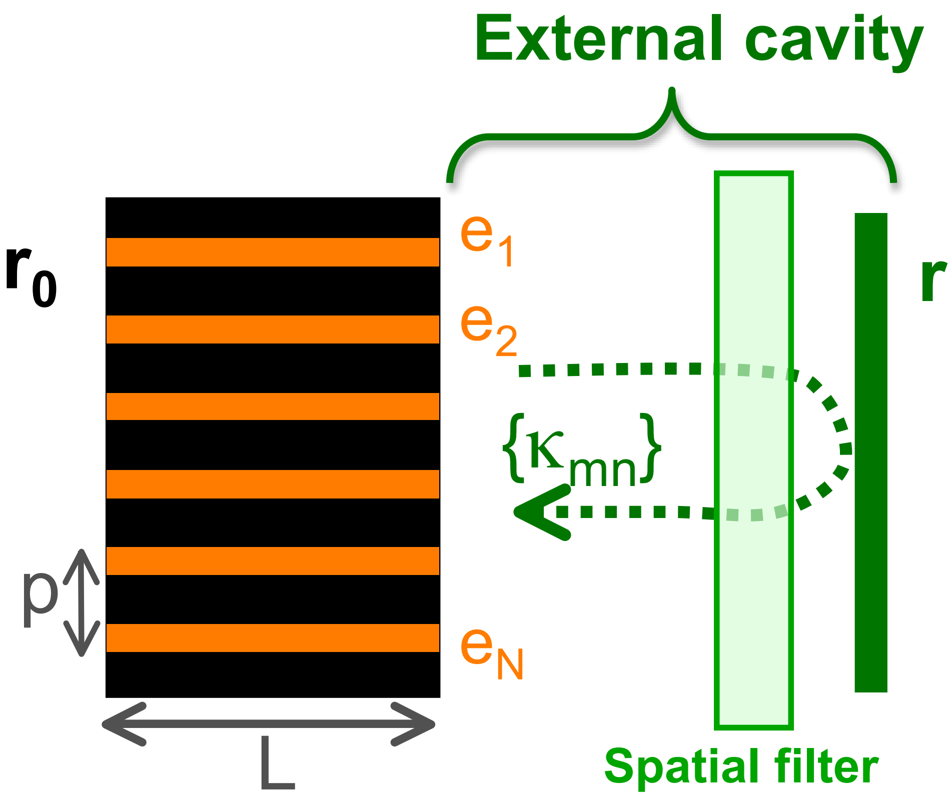


Talbot external cavity set-up

propagation of 10 in-phase Gaussian-shaped emitters

- **Self-images** (amplitude & phase) at :
  - multiple of the Talbot distance $Z_T = 2p^2/\lambda$
  - fraction of Z_T : p/2 lateral shift of the in-phase mode at $Z_T/2$
- Edge losses due to finite size of the array

Numerical modelling of external cavities



- N single-mode emiters
- Coupling matrix

$$\kappa_{mn} = \frac{\int_{-\infty}^{+\infty} e_m^*(x) \times C[e_n](x)\,dx}{\int_{-\infty}^{+\infty} e_m^*(x) \times e_m(x)\,dx}$$

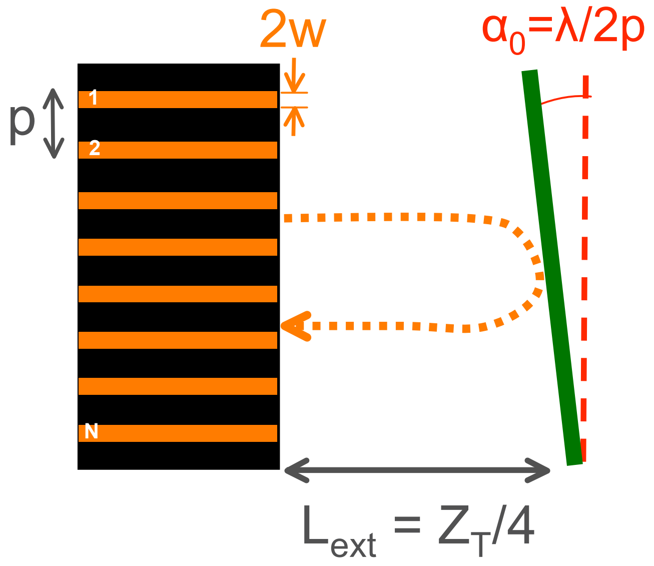
$C[e_n]$: operator describing beam propagation + filtering

$$r_0 r\, e^{2i\varphi} e^{2gL} \{\kappa_{mn}\} \times \vec{E} = \vec{E}$$

➔ N eigenmodes = N array supermodes

Near-field + far-field profiles

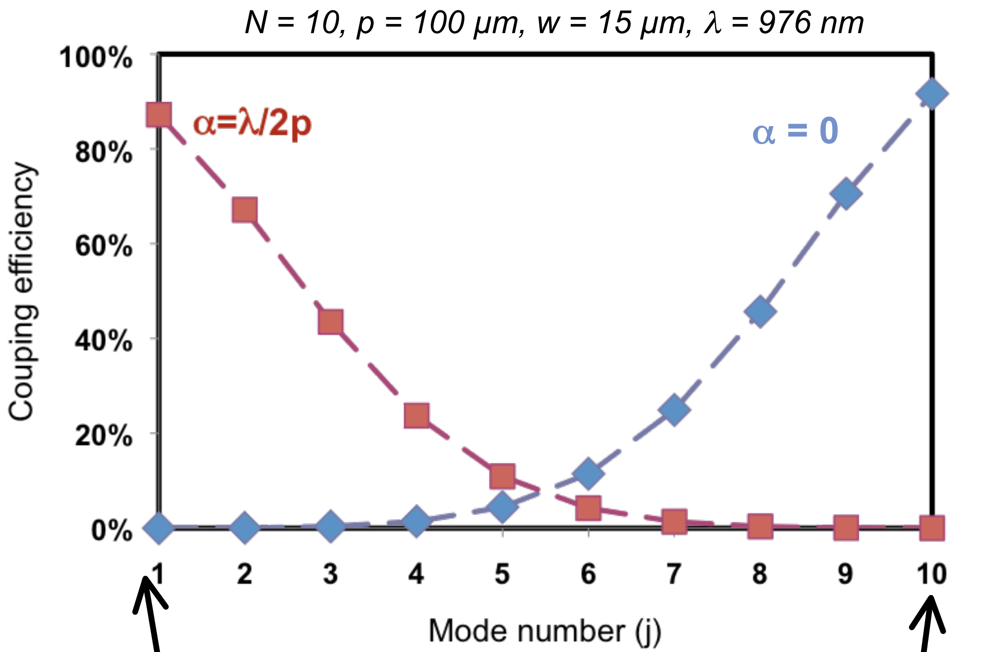
Talbot cavity : modal selectivity



C[e_n] : free-space propagation on $2L_{ext}$ distance, with angled reflection

$\Rightarrow$ **$\alpha = \lambda/2p$** :
in-phase mode selection

Computation of the coupling efficiency of each array transverse supermode



in-phase mode

(All emitters at the same phase)
0 –0 –0 – 0 - 0…

out-of-phase mode

(adjacent emitters with π dephasing)
0 – π – 0 – π – 0 – π – 0 …

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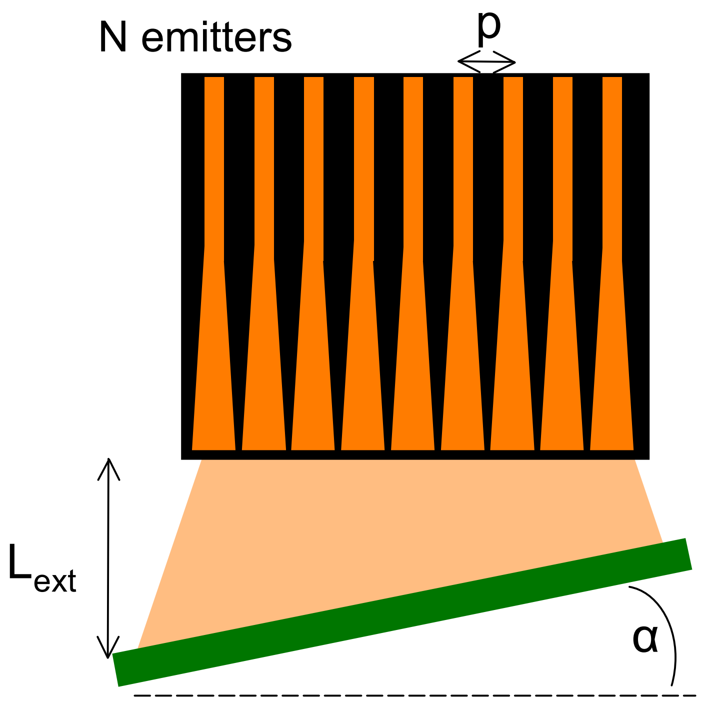
Model Description

- Fox & Li iterative approach :
  a seed is propagated back and forth until a steady state is reached



Semiconductor laser module

- *2D Wide Angle Finite Difference BPM*
- *1D electrical model*
- *isothermal*
- *monochromatic (λ = 975 nm) – TE polarized*

The University of Nottingham

J. J. Lim et al, IEEE JQE **41** (4), 506-516 (2005)

External cavity module

- *Fresnel diffraction*
- *tilt of the external mirror*

➔ Near Field and Far Field profiles, Output Power, Intensity Map

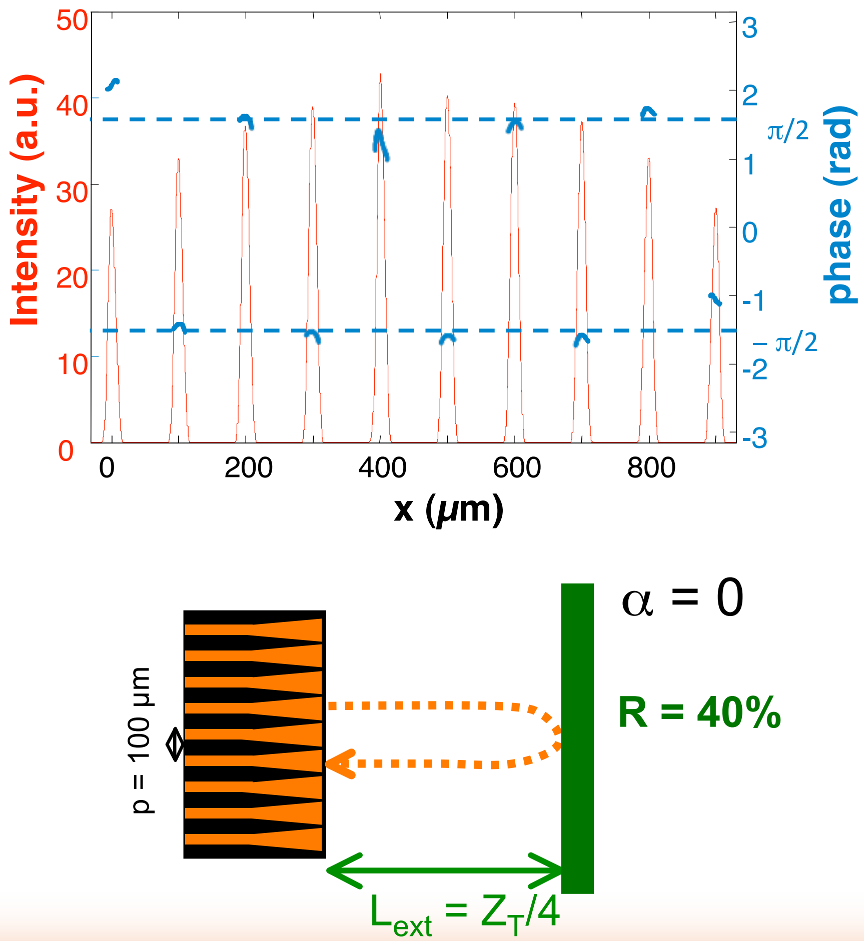
J.J. Lim *et al*, Journ.Selec.Top.Quant. Elec 15, 993-1008 , *invited*, (2009)

Modal Discrimination

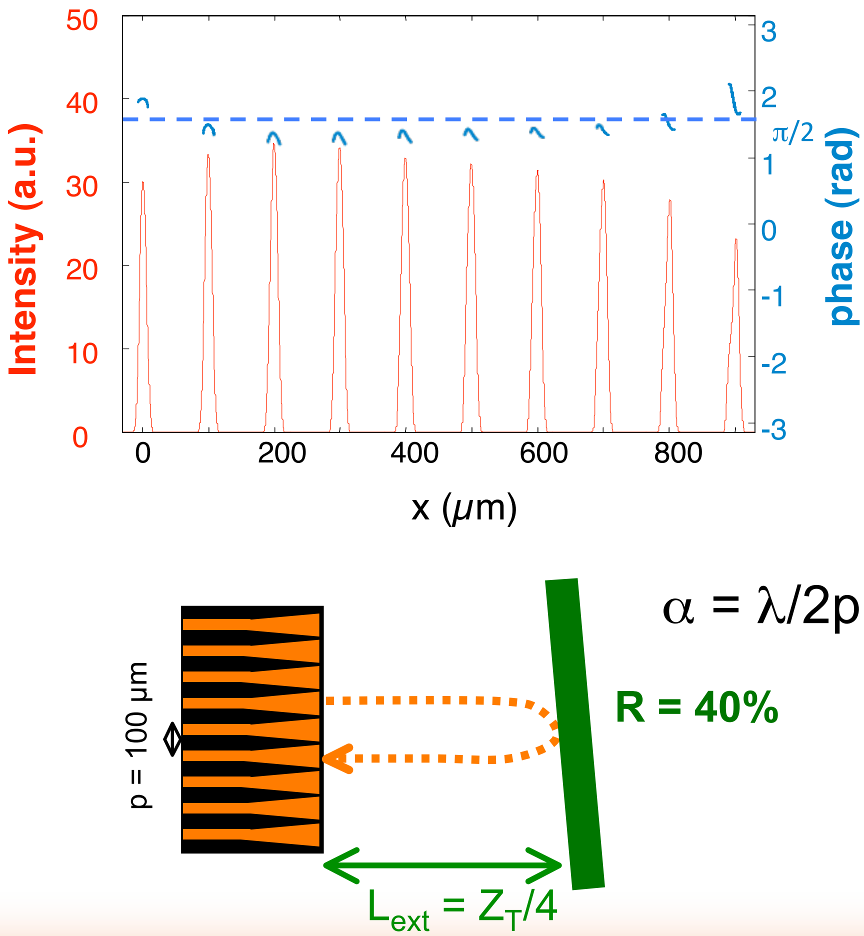
Index-guided tapered laser bar :
N = 10, p = 100 µm, w = 15 µm, λ = 975 nm

Near field profile :

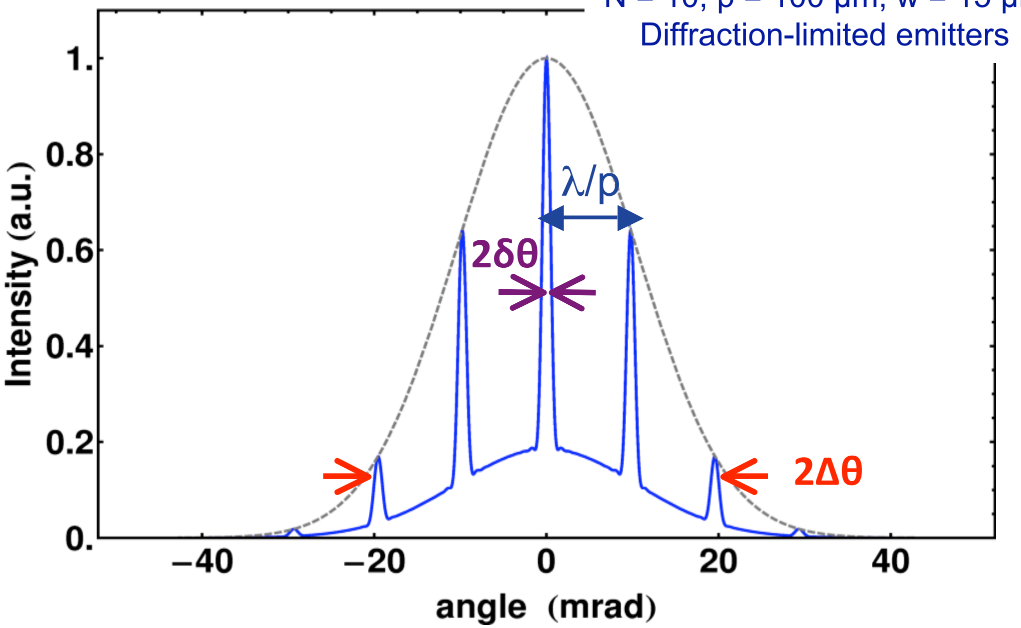
out-of-phase mode



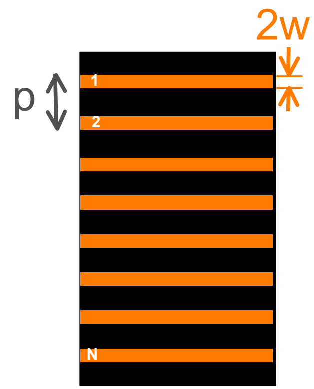
in-phase mode



Far-field characterization criteria



33% : In-phase operation
+ 67% incoherent operation



Phase-locked diode laser array

Effective beam quality factor of the emitters :

➔ Average beam quality of individual emitters

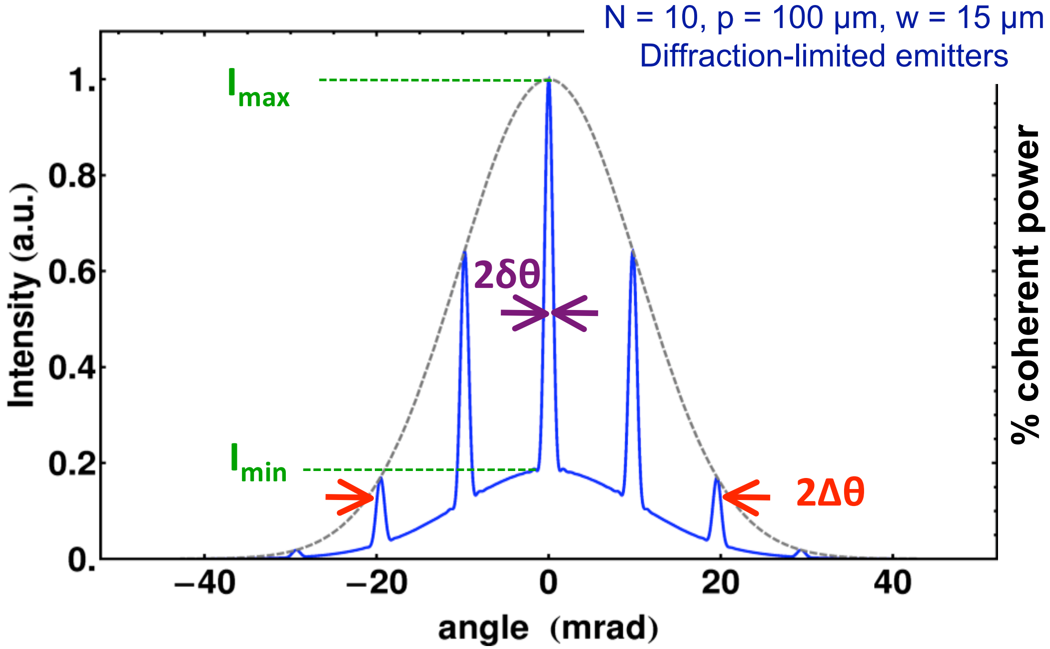
$$M_{em}^2 = \frac{\Delta\theta}{\lambda/\pi w}$$

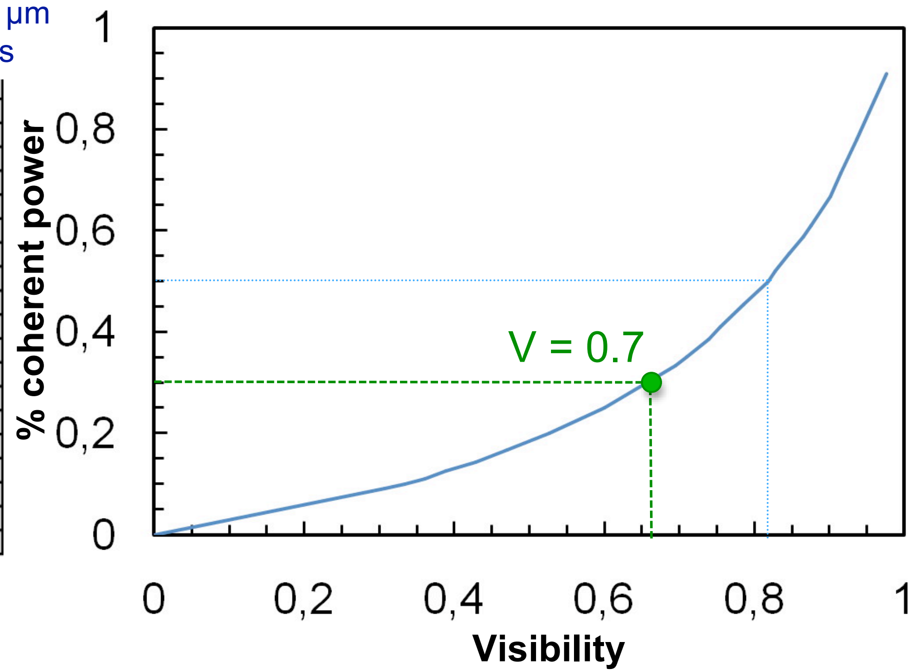
Effective beam quality factor of the whole bar :

➔ Number of phase-locked emitters

$$M_{bar}^2 = \frac{2\delta\theta}{\lambda/Np}$$

Far-field characterization criteria





Effective beam quality factor of the emitters :

$$M_{em}^2 = \frac{\Delta\theta}{\lambda/\pi w}$$

Effective beam quality factor of the whole bar :

$$M_{bar}^2 = \frac{2\delta\theta}{\lambda/Np}$$

Fringes visibility :

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

➔ Spatial coherence of the laser emission

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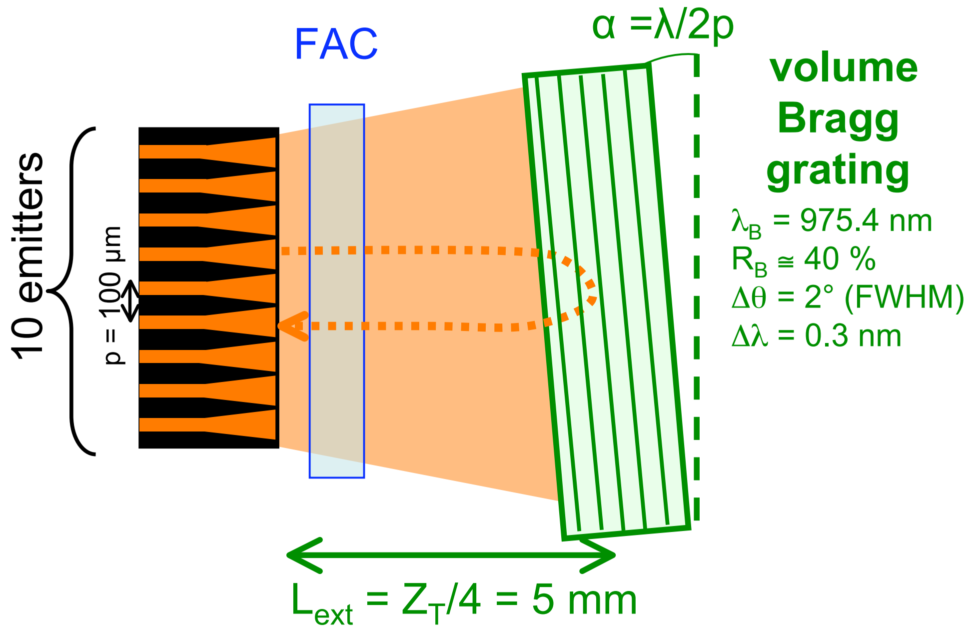
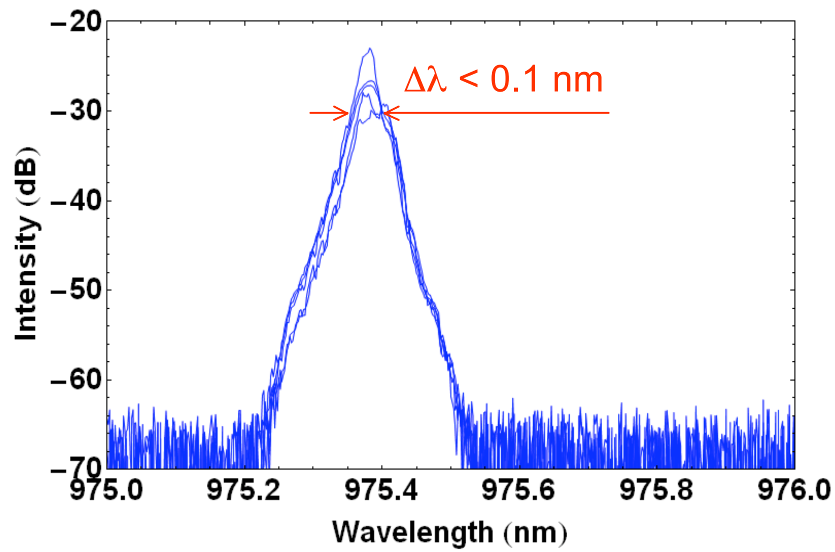
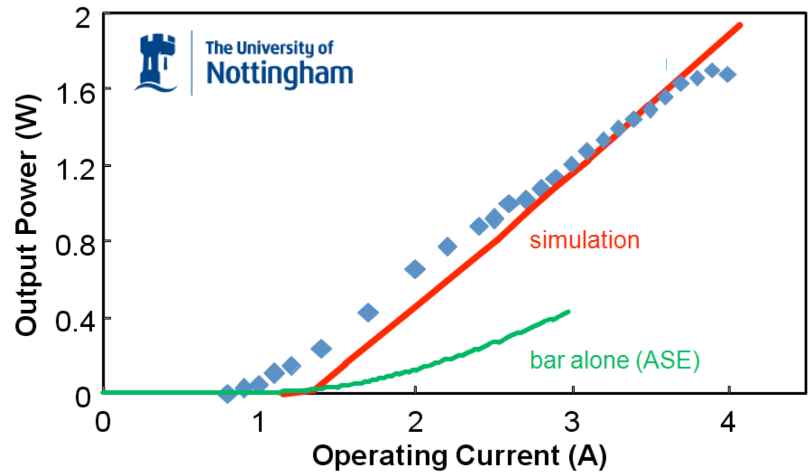
External Talbot cavity Set-Up



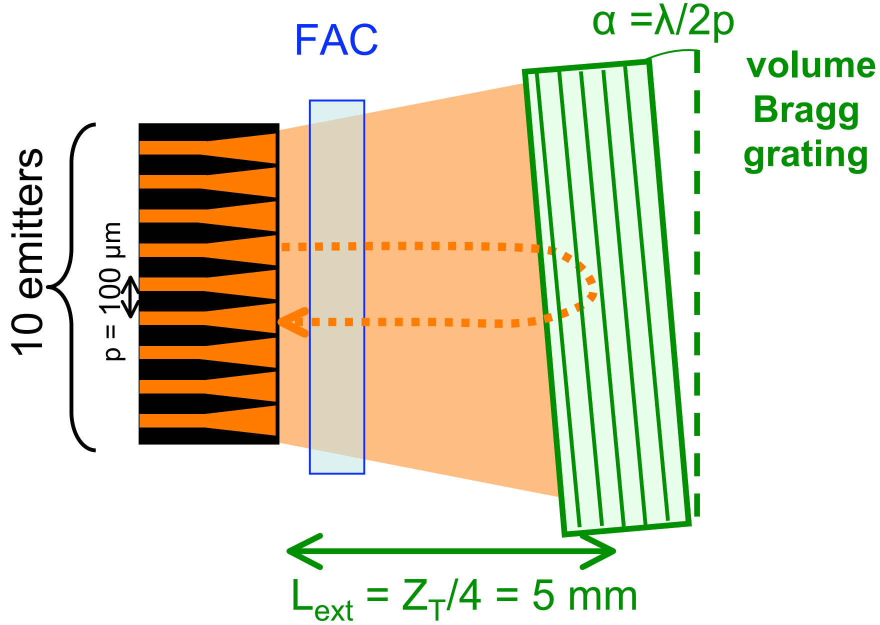


- Spectral locking of each laser diodes
- Narrow linewidth (Δλ < 0.1 nm)

- Laser threshold I_{th} = 0.9 A
- P_{max} = **1.7 W** @ 4 A (4 x I_{th})

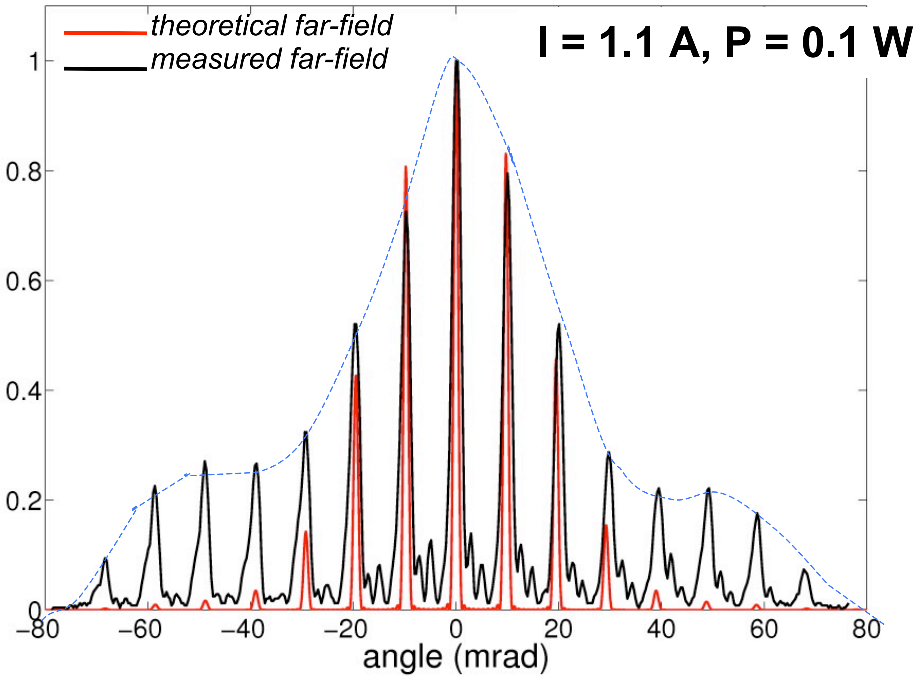


External Talbot cavity Set-Up



D. Pabœuf *et al*, Appl. Phys. Lett. **93**, 211102 (2008)

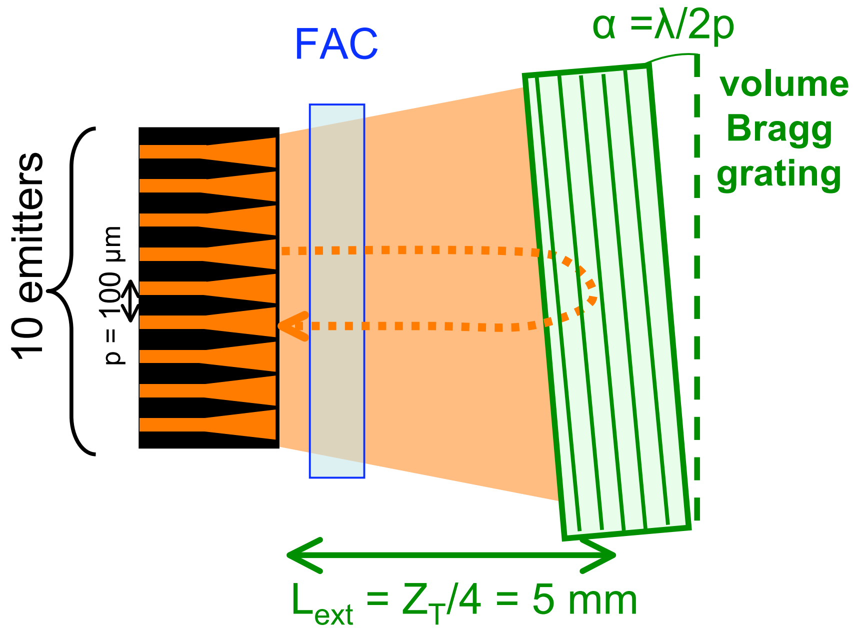
Far-field angular profile



	$I = 1.2\ I_{th}$	
M^2_{em}	2.8	*Effective beam quality factor of the emitters*
M^2_{bar}	2.1	*Effective beam quality factor of the whole bar*
V	0.90	*Fringes visibility*
% coherence	70%	

High coherence of the phase-locked operation deduced from the fringe visibility

External Talbot cavity Set-Up



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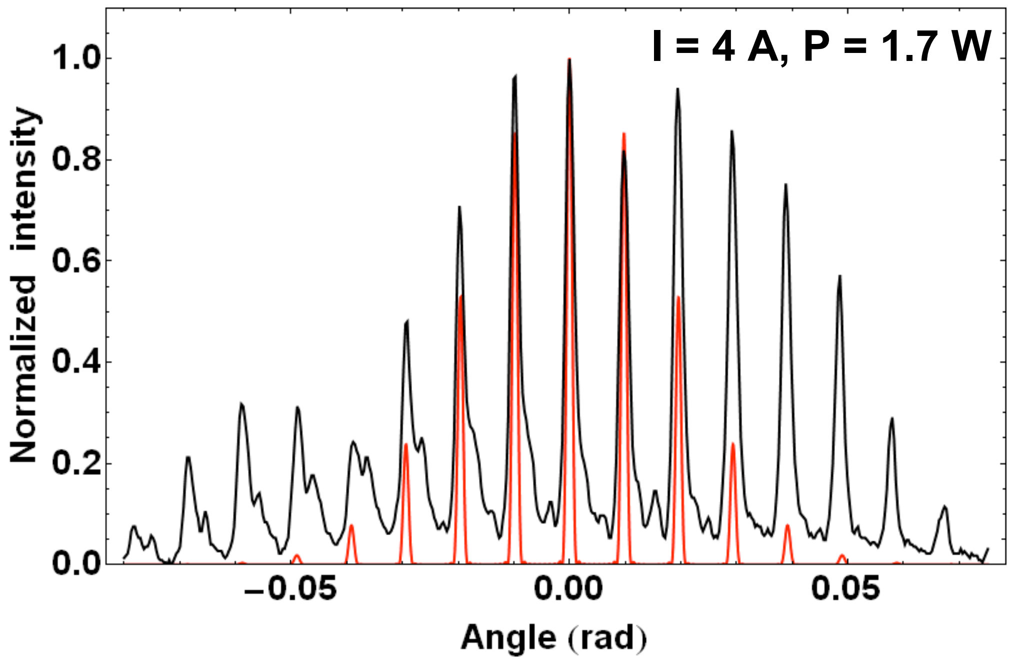

	$I = 1.2\ I_{th}$	$I = 3.3\ I_{th}$	$I = 4.4\ I_{th}$
M^2_{em}	2.8	3.1	3.1
M^2_{bar}	2.1	1.4	2.0
V	0.90	0.90	0.82
% coherence	70%	70%	50%

Degradation of the coherence at maximum output power

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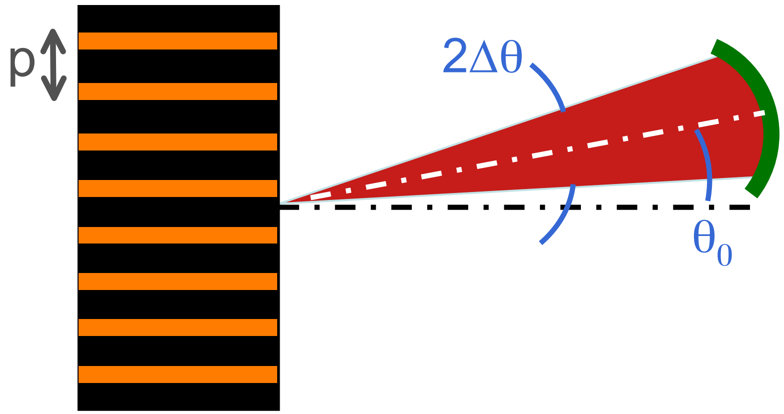
Angular filtering extended-cavity



Chang-Hasnain et al., Appl. Phys. Lett. **50** (21) 1465 (1987)

Angular selective feedback :

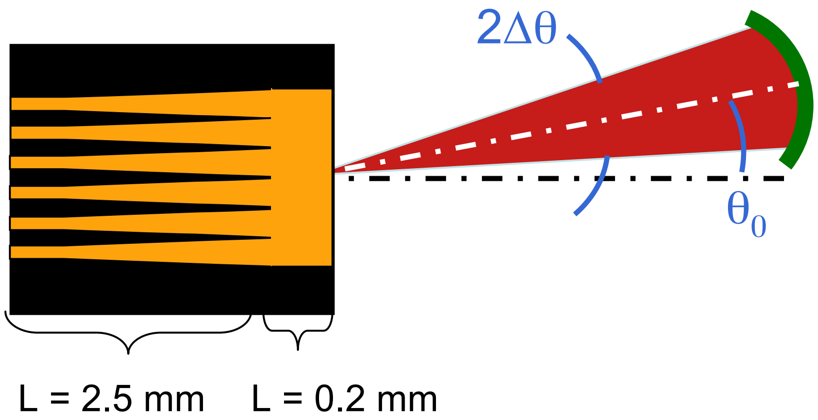
Selection of the array supermode of highest overlap with the angular filter in the far field

⇒ Numerical modelling :

C[e_n] : filtering of angular components in the far-field profile

Angular filtering extended-cavity

⇒ Application to high filling-ratio array:



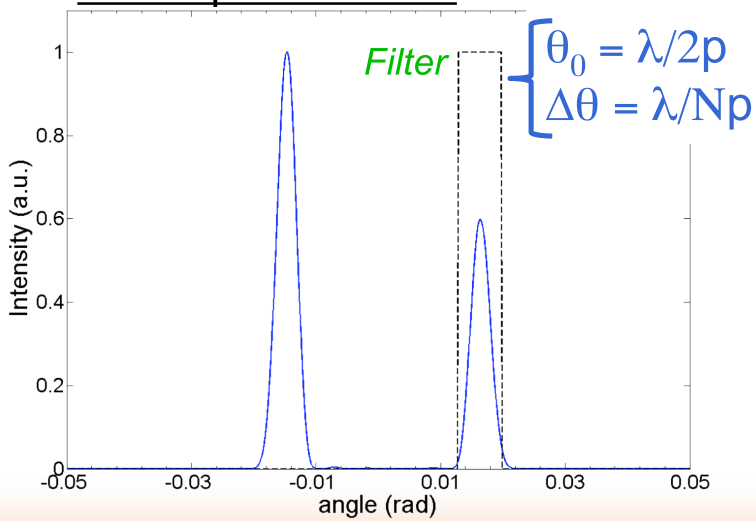
6 adjacent **index-guided tapered** lasers

Pitch p = 30 µm ⇒ Filling ratio ≅ 100%

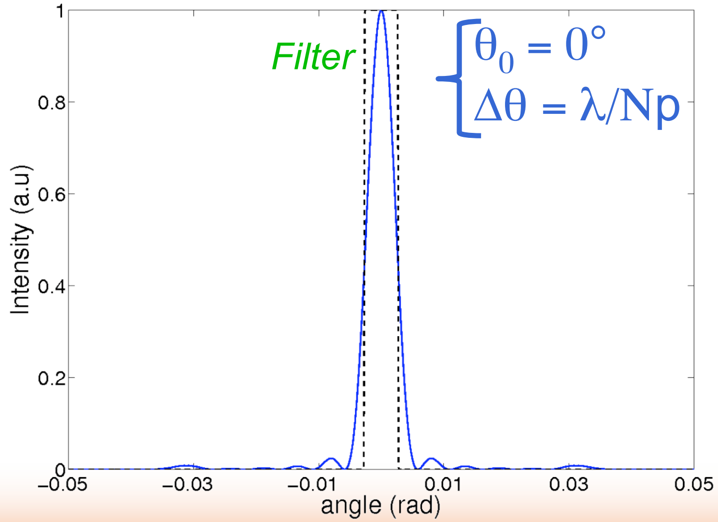
No coupling between adjacent emitters

⇒ Reduced number of peaks in the coherent far-field profiles

Out-of-phase mode



In-phase mode



Angular filtering extended-cavity

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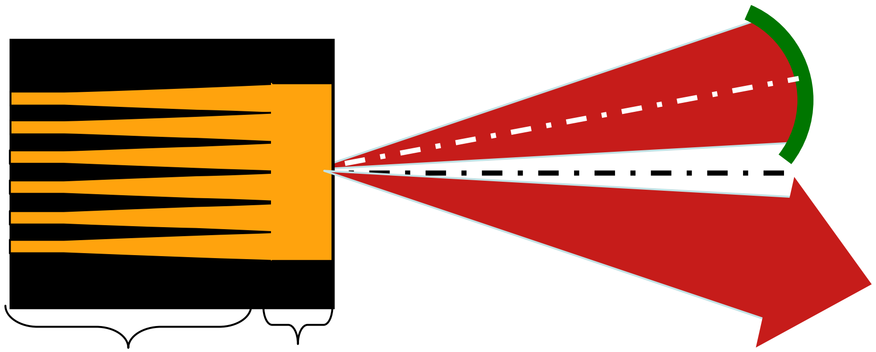

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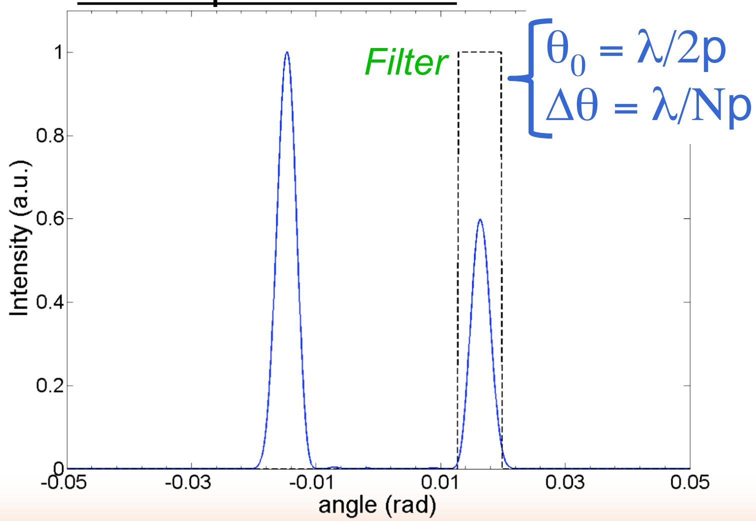
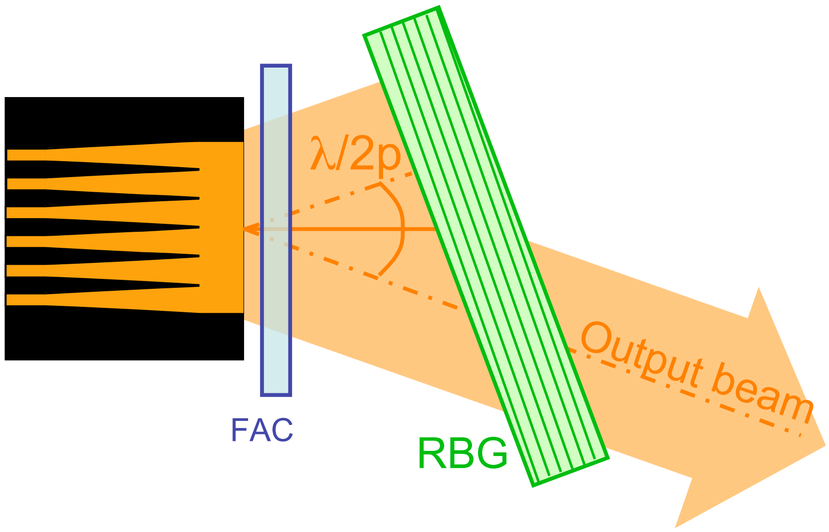


Feedback direction ≅ λ/2p (= 16 mrad)
corresponds to one of the lobe in the out-of-phase array supermode

Output beam on the symmetric lobe

Angular filtering with Transmission Bragg Grating

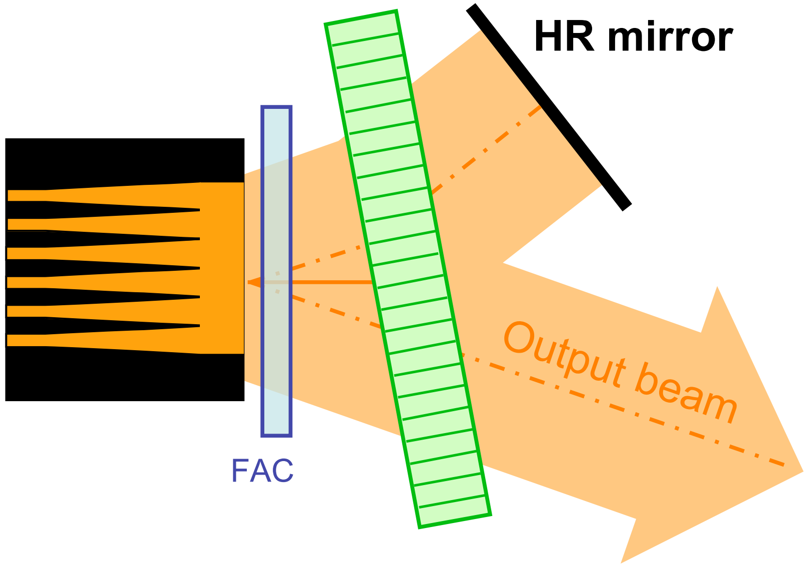


Reflection Bragg grating (RBG):

R ≥ 99% at 979 nm

$\delta\lambda \cong 0.3$ nm

$\Delta\theta_{1/2} = 35$ mrad = 2°

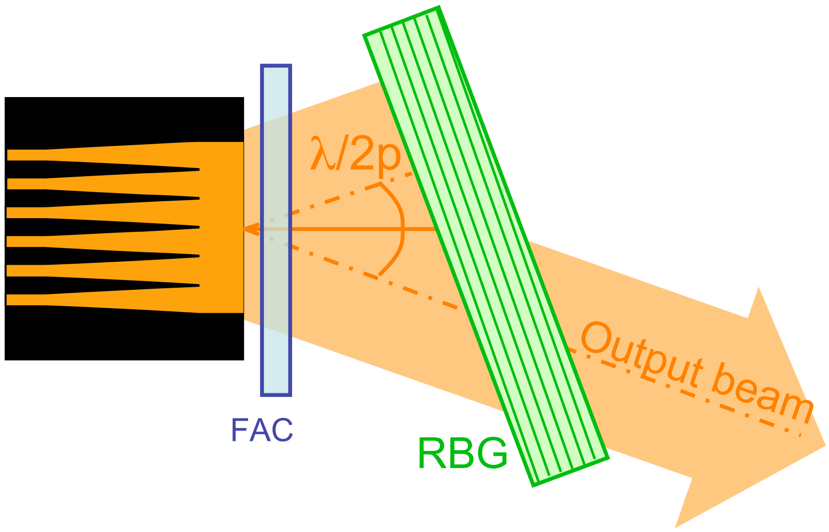


Transmission Bragg grating :

Diffraction efficiency = 90%

$\Delta\theta_{1/2} = 9$ mrad

Angular filtering with volume Bragg Grating



Reflection Bragg grating (RBG):

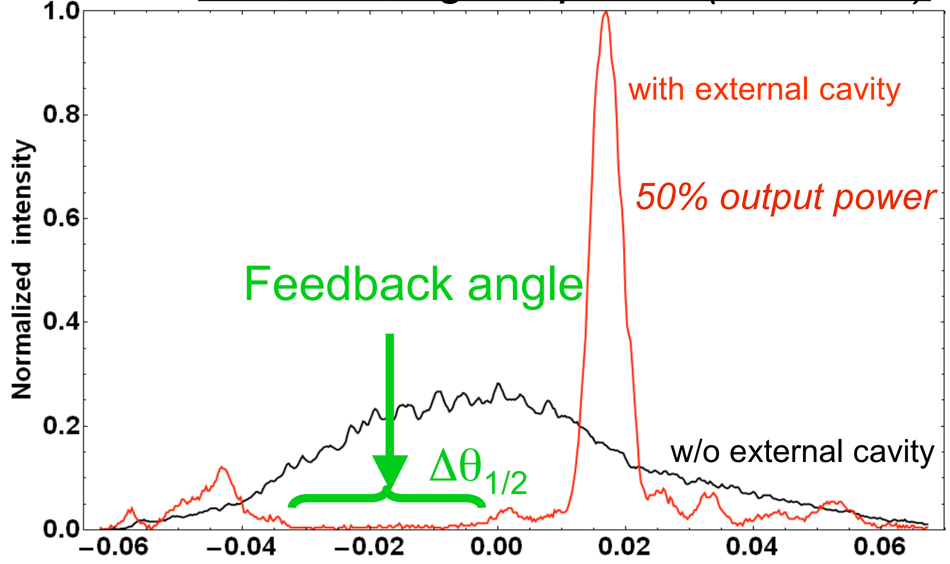
$R \geq 99\%$ at 979 nm

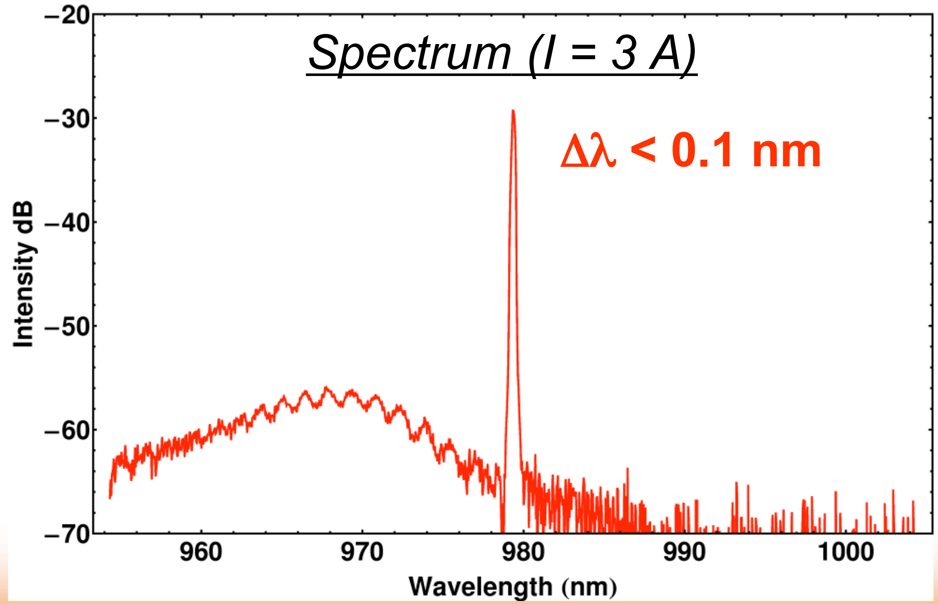
$\delta\lambda \cong 0.3$ nm

$\Delta\theta_{1/2} = 35$ mrad = 2°

Output power ≤ 0.7 W

Wavelength locked to 979 nm, $\Delta\lambda < 0.1$ nm





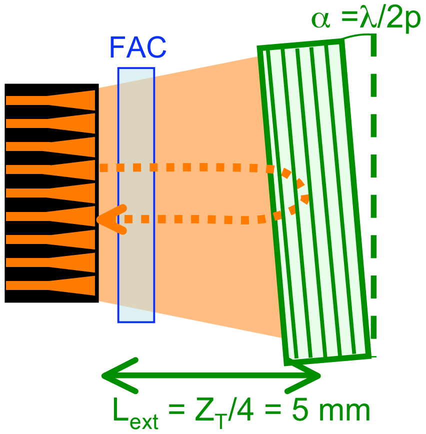
Paboeuf et al, CLEO Europe (2009)

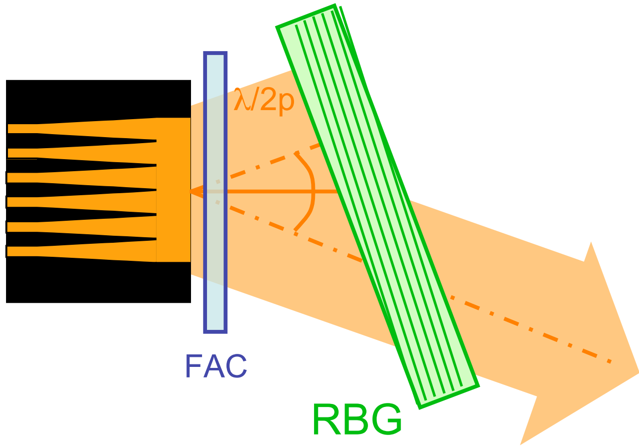
Summary

-Numerical model to predict the modal properties of the extended-cavity diode laser bars + propagation within the semiconductor lasers

-Passive, self-organized, phase-locking architectures :

Talbot cavity vs Intracavity angular filtering :





- In-phase mode selection with a high coherence
- P_{max} = 1.7 W @ 4 A (4x threshold)

- Out-of phase mode operation
- Quasi diffraction limited beam ($M^2 < 2$)
- Output power limited by AR coating

-Narrow spectrum → $\Delta\lambda < 0.1$ nm thanks to Bragg gratings

scalable to high output powers

well-adapted to high filling-factor arrays