Volume Bragg grating external-cavity designs for coherent emission of an array of tapered diode lasers

David Pabœuf, Gaëlle Lucas-Leclin, Nicolas Michel, Michel Calligaro, Michel Krakowski, Patrick Georges

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Outline

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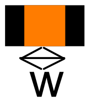
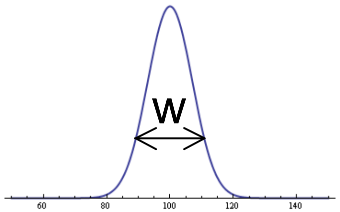
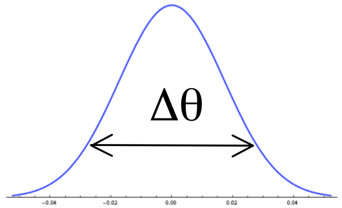
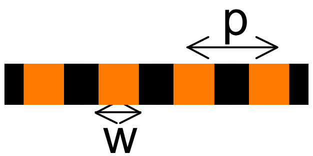
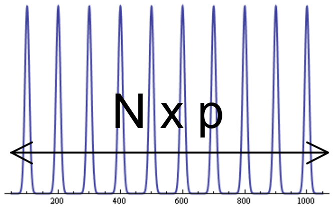
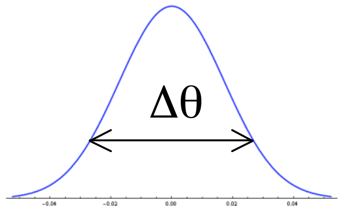
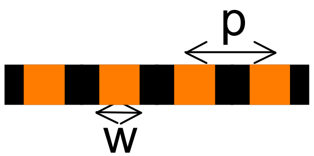
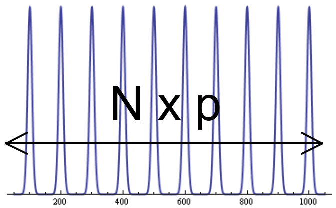
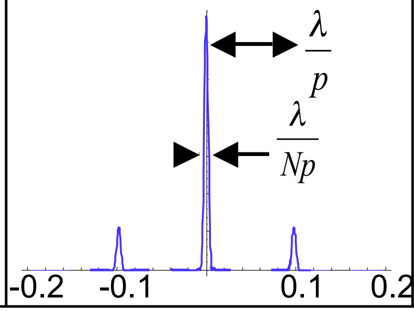
- Conclusion

Introduction

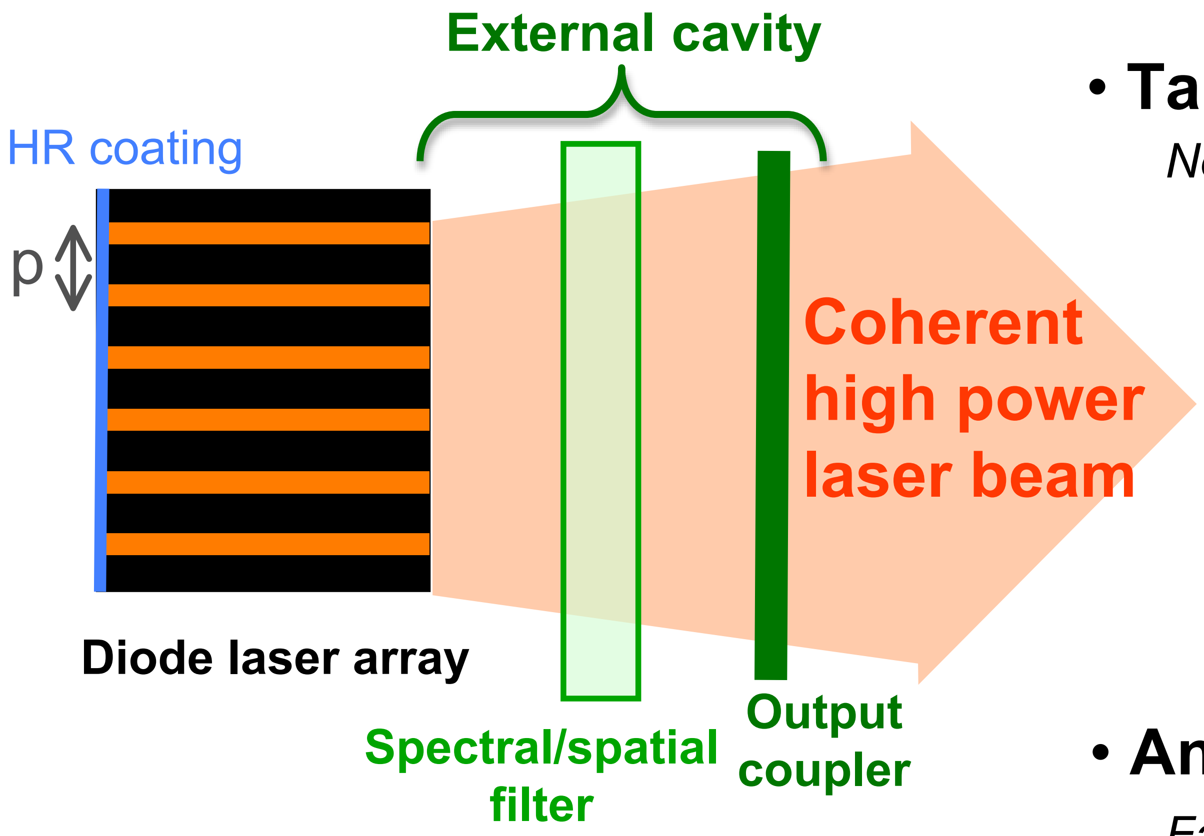
	Near Field (µm)	Far Field (radians)	Brightness (W/cm²/sr)
1 laser diode 			$B_1 = \frac{P}{S_{em}\Omega} \propto \frac{P}{w \cdot \Delta\theta}$
N *incoherent* laser diodes 			$B_N \propto \frac{w}{p} B_1 \leq B_1$
N *coherent* laser diodes 			$B_N^{coh} = N \times B_1$

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

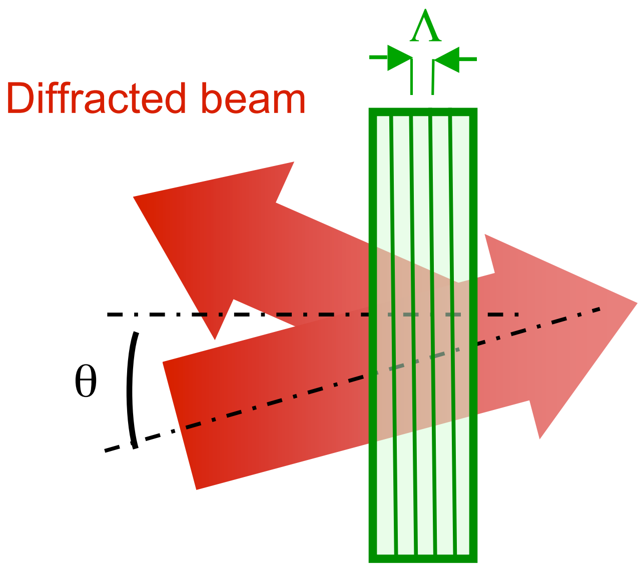
External cavity designs

Purpose : passive coherent combining of diode lasers

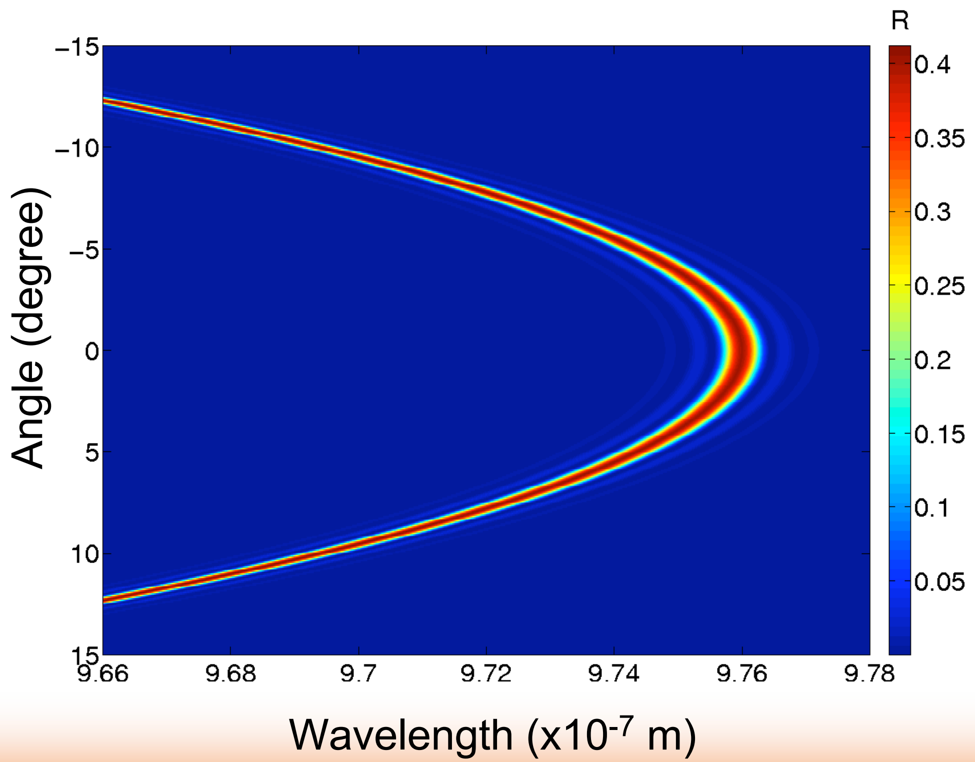
⇒ to induce an efficient coupling between emitters

\+ wavelength stabilization

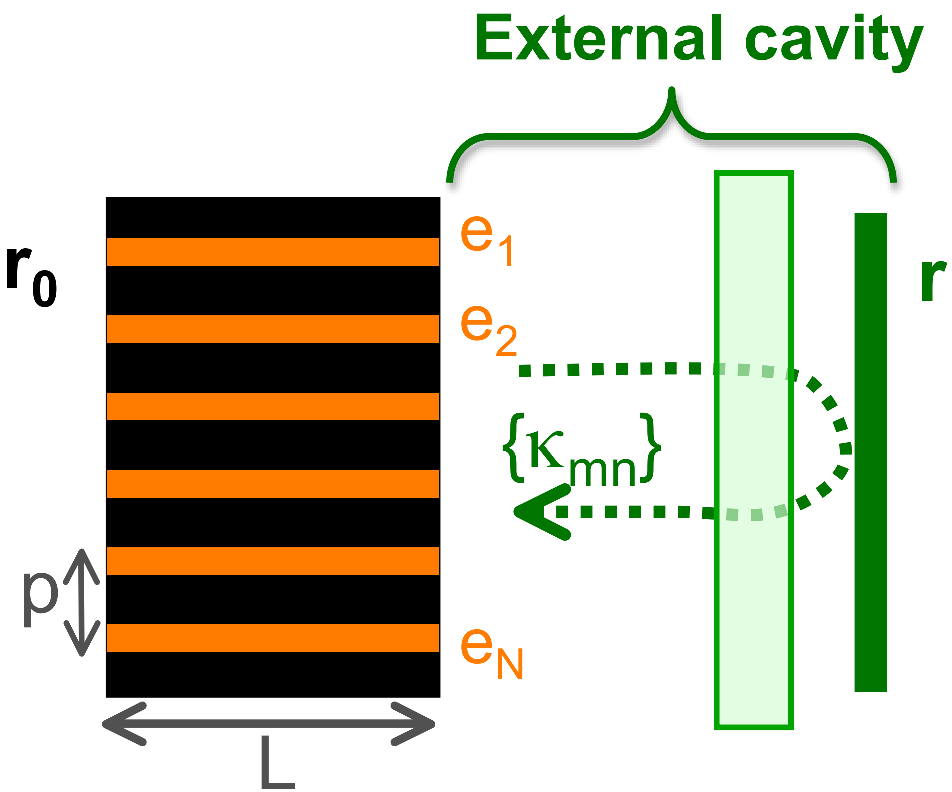
⇒ volume Bragg gratings : Angular + spectral selectivity



Reflection Bragg grating



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

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

➔ N eigenmodes = N array supermodes

Near-field + far-field profiles

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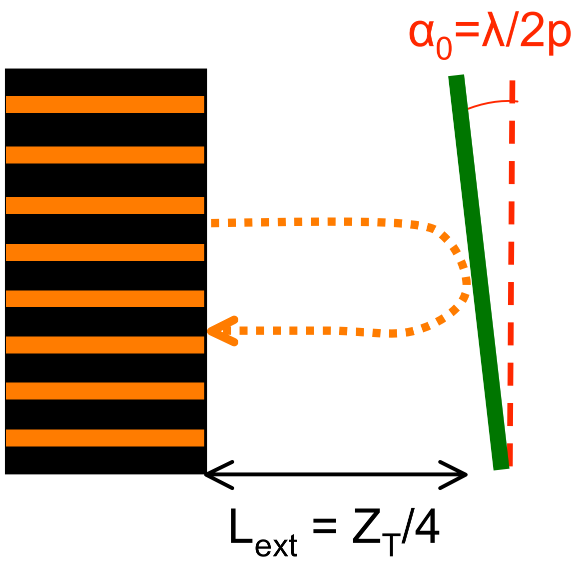
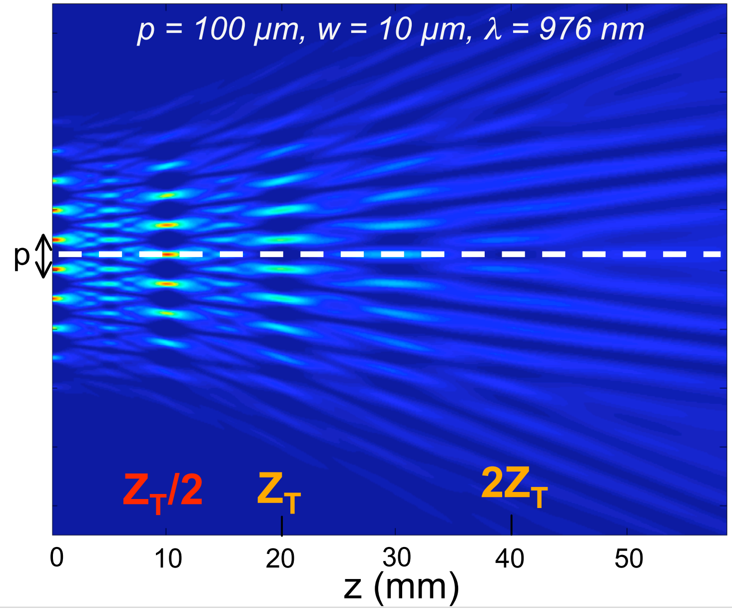
Talbot external cavity

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



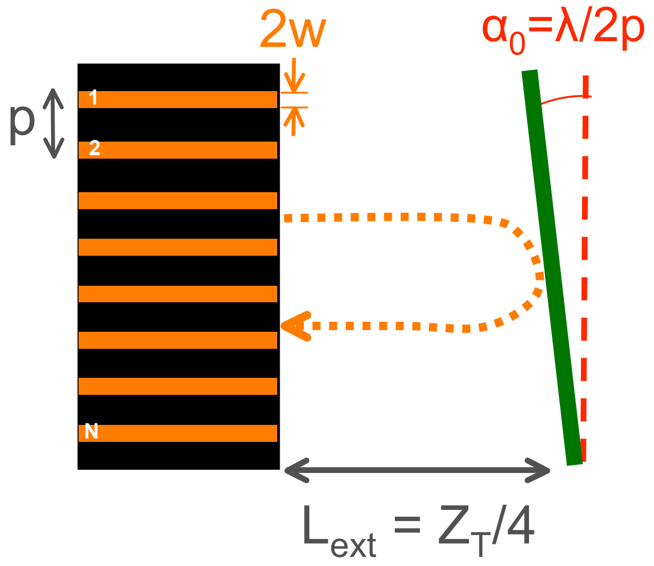
Talbot external cavity set-up



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

Talbot cavity : modal selectivity

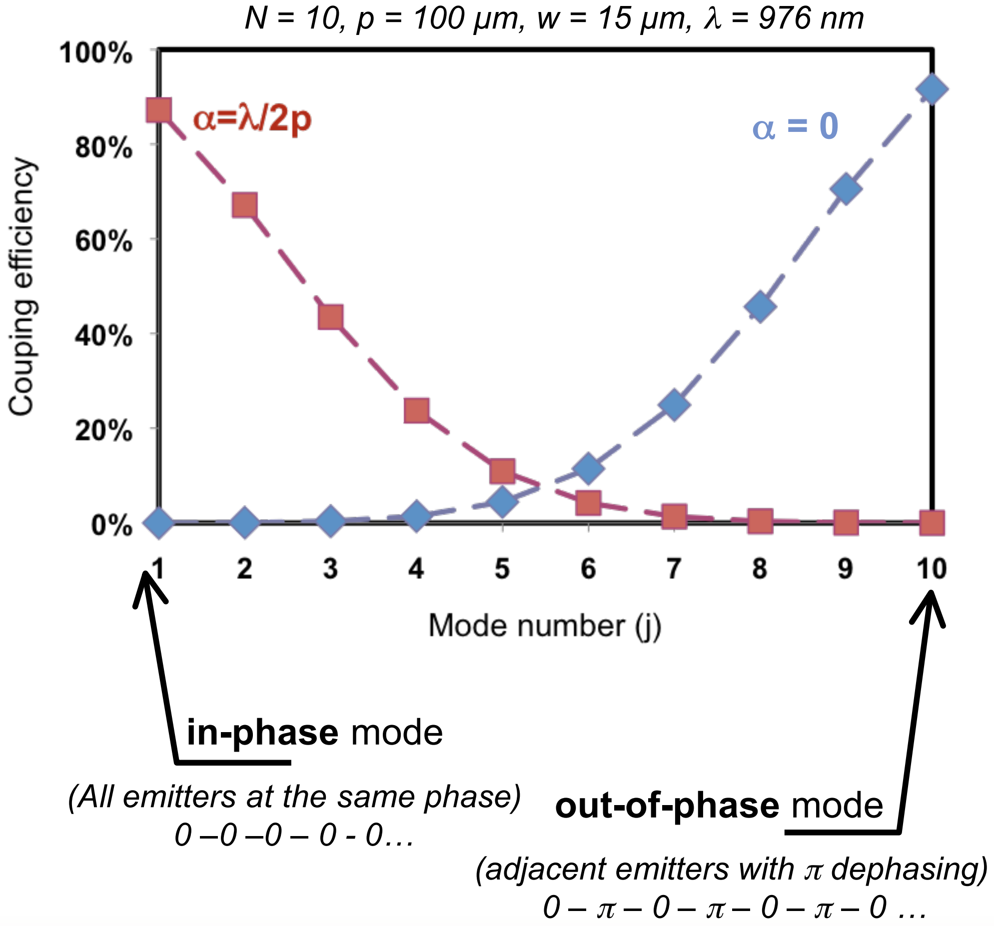


C[e_n] : free-space propagation on $2L_{ext}$ distance, with angled reflection

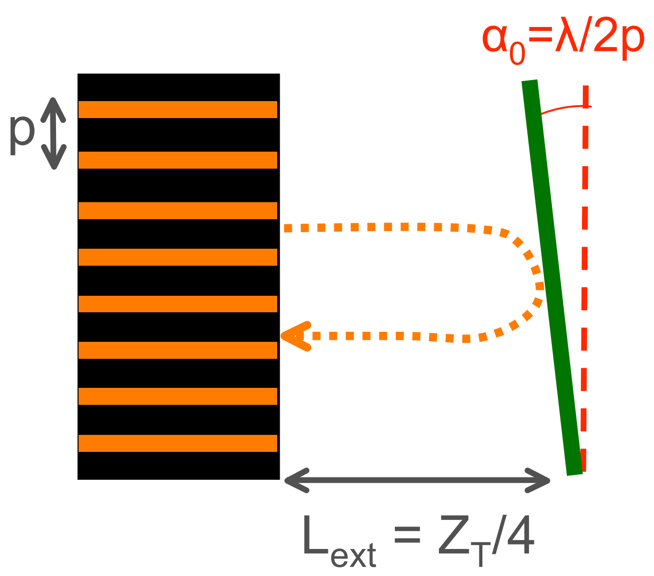
$\Rightarrow$ **$\alpha = \lambda/2p$** :

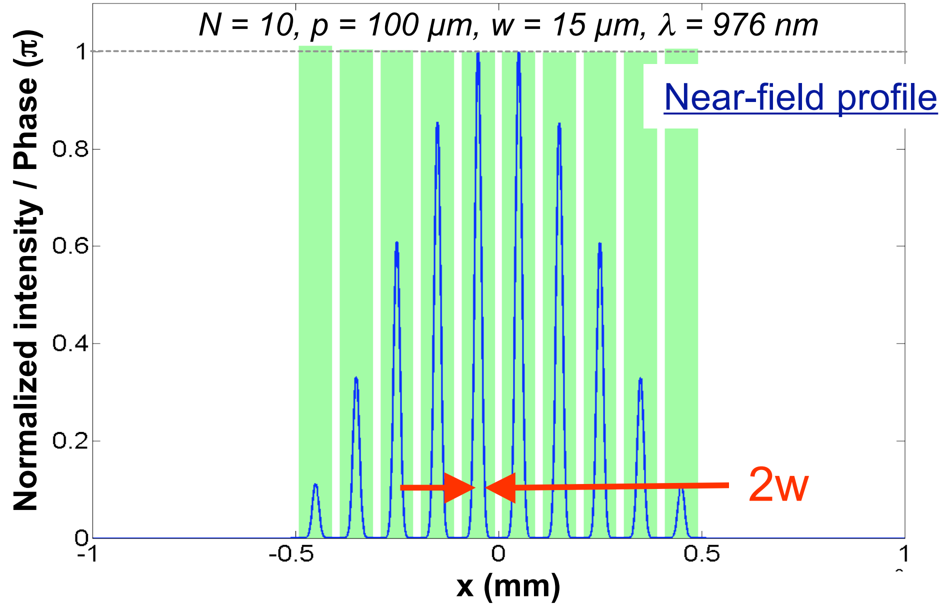
in-phase mode selection

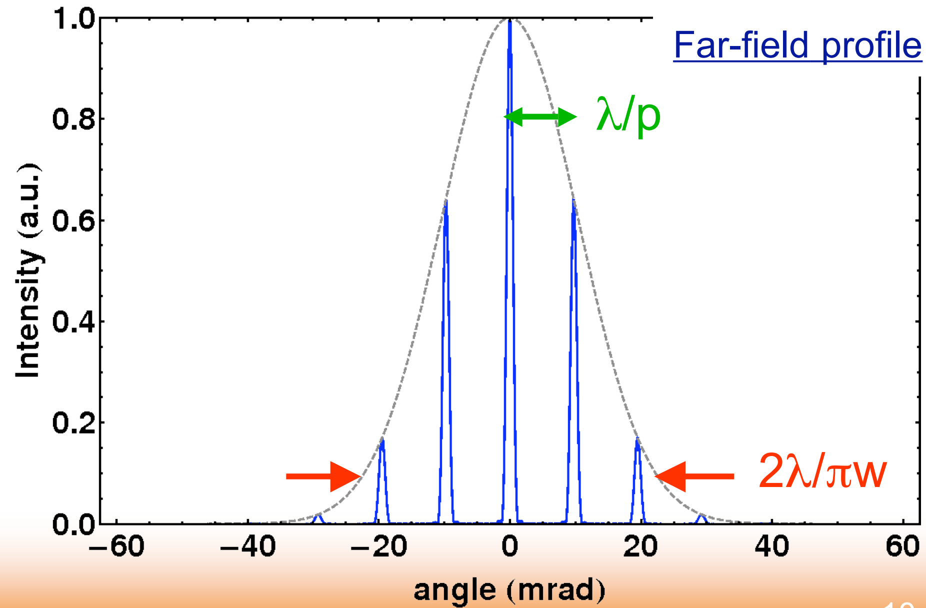
Computation of the coupling efficiency of each array transverse supermode



Talbot cavity : in-phase mode







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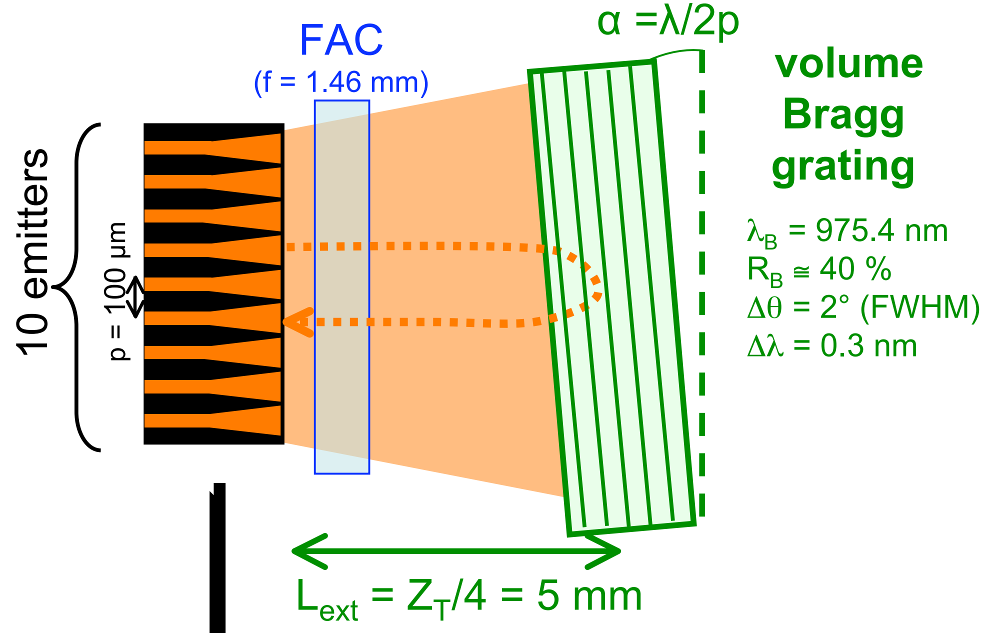
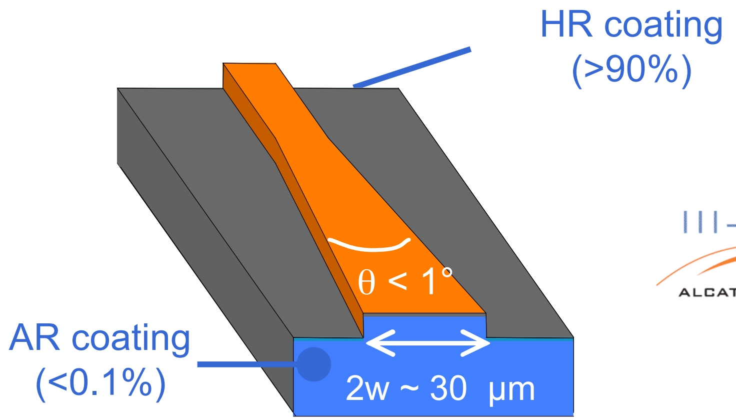
External Talbot cavity Set-Up



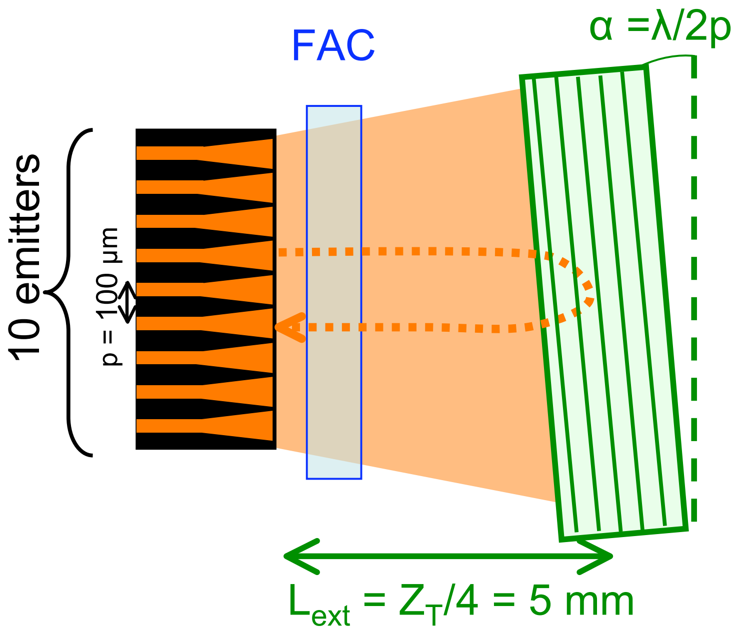
Index-guided tapered emitter

Single mode operation ($M^2 < 2$)
High power (1 W)

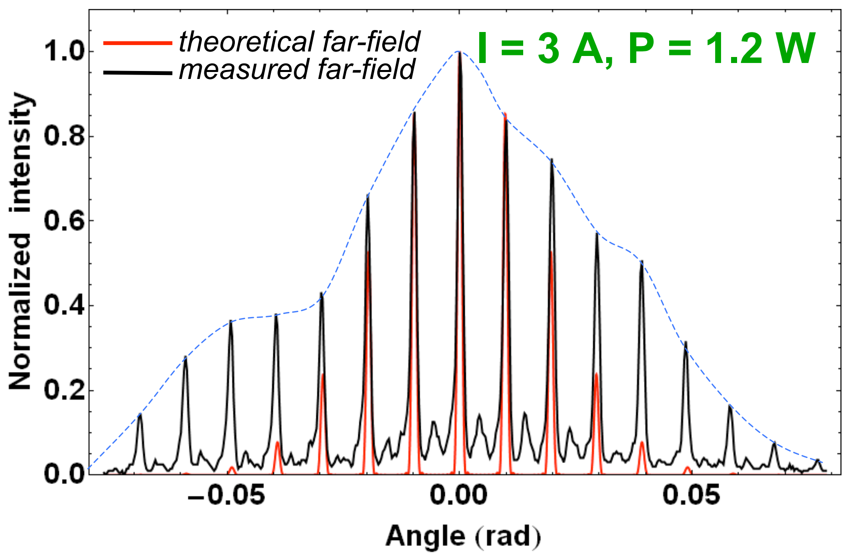


Krakowski *et al.* Elec. Lett. **39** (15) 1122 (2003)

External Talbot cavity Set-Up



Far-field angular profile



- Far-field profile :

central peak width = 1.2 mrad (FWHM) ≅ λ/Np

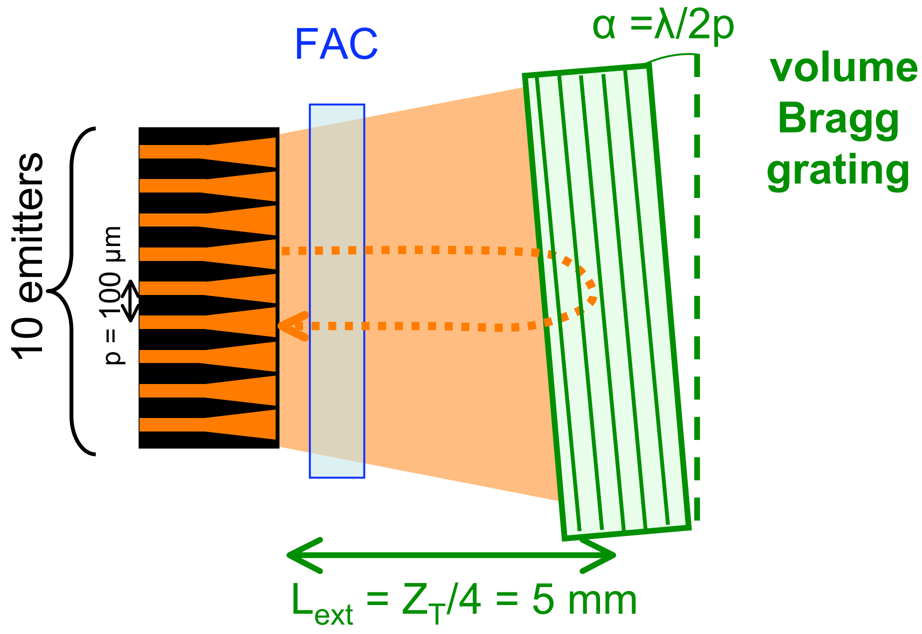
envelope width = 40 mrad (FWHM)

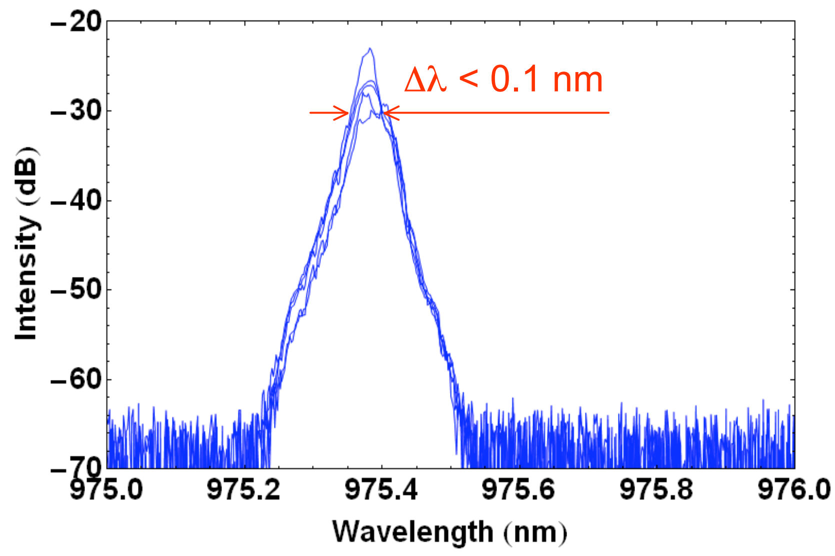
- High coherence evaluated from the fringe visibility: V=0.80

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

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

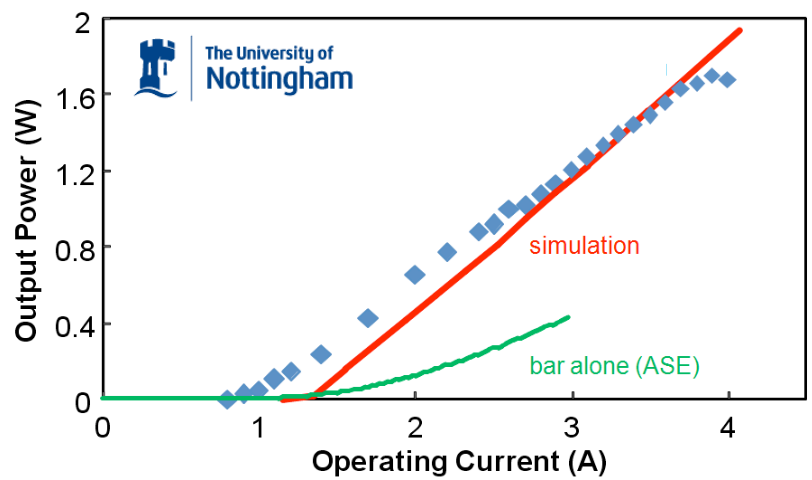
External Talbot cavity Set-Up





- Spectral locking of each laser diodes
- Narrow linewidth ($\Delta\lambda < 0.1$ nm)

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



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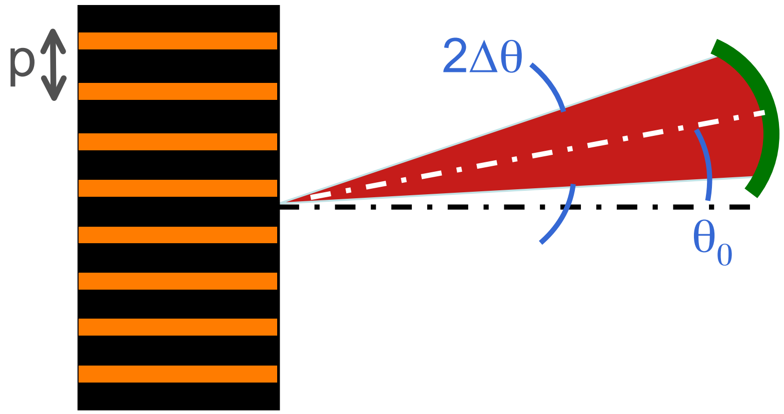
Angular filtering extended-cavity



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

Angular selective feedback :

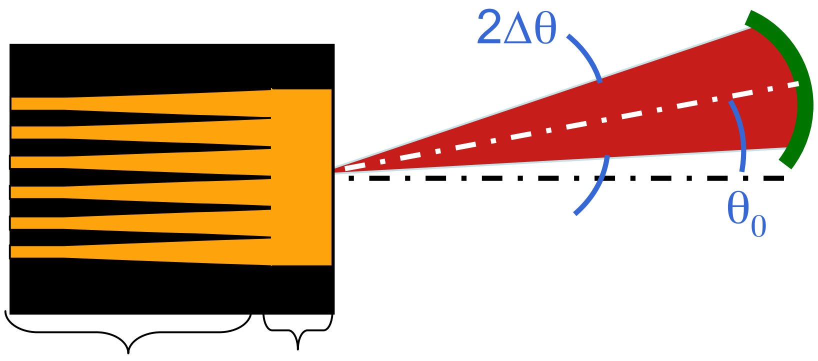
Selection of the array supermode of highest overlap with the angular filter in the far field

⇒ Numerical modelling :

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

Angular filtering extended-cavity

⇒ Application to high filling-ratio array:



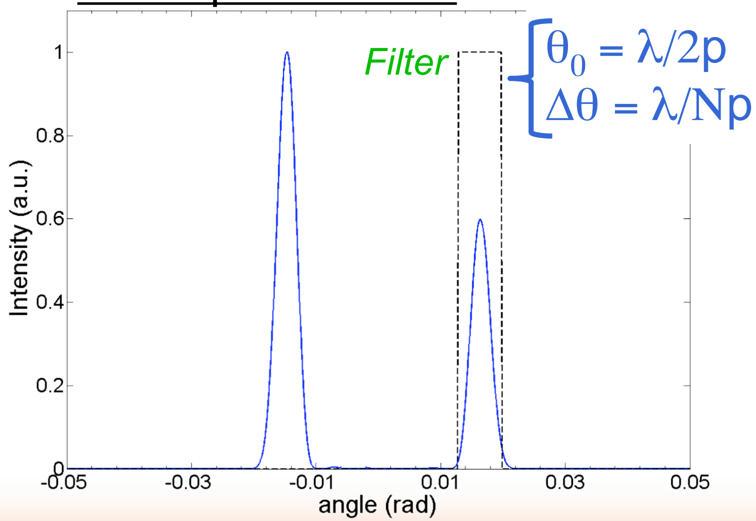
6 adjacent **index-guided tapered** lasers

Pitch p = 30 µm ⇒ Filling ratio ≅ 100%

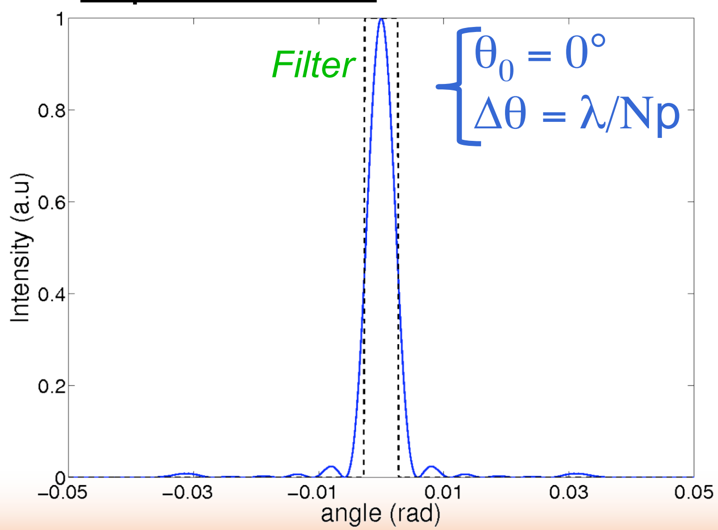
No coupling between adjacent emitters

⇒ 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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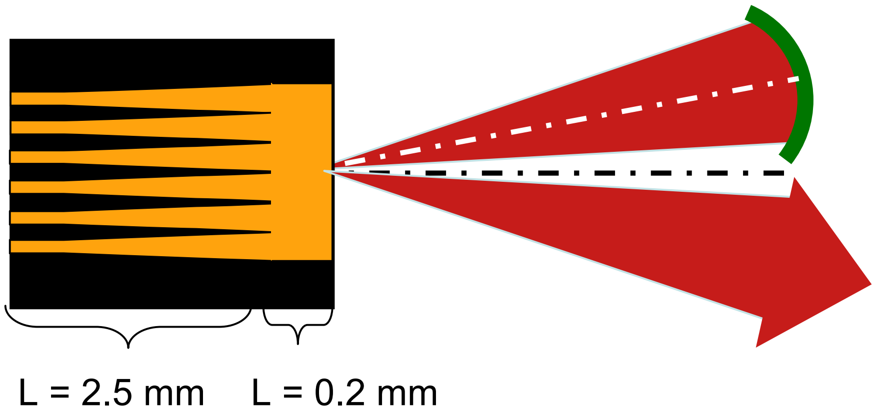

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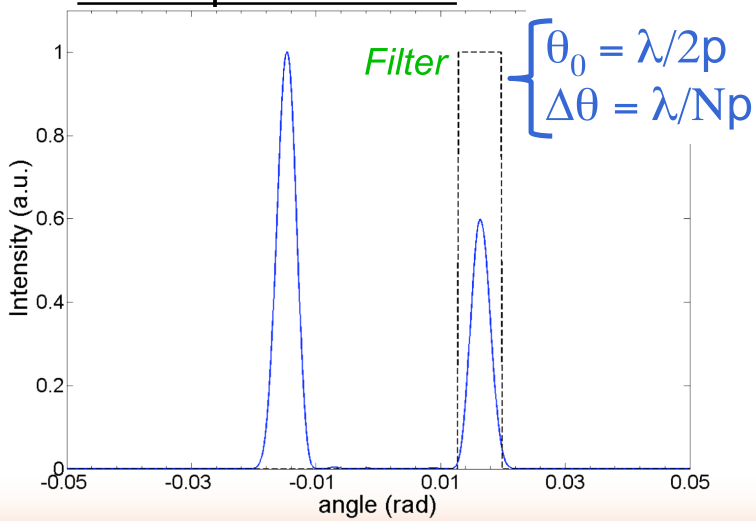
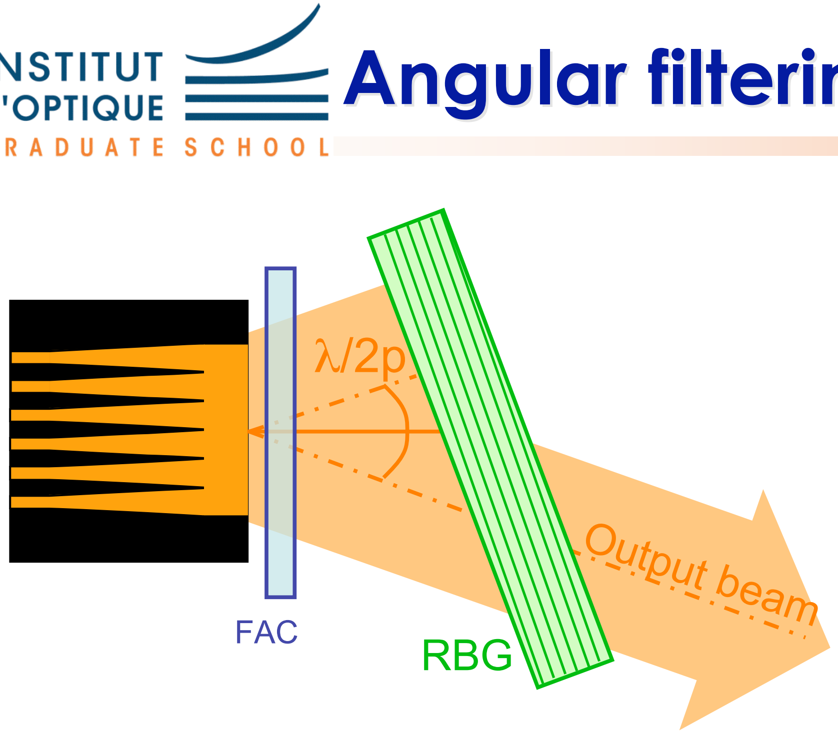


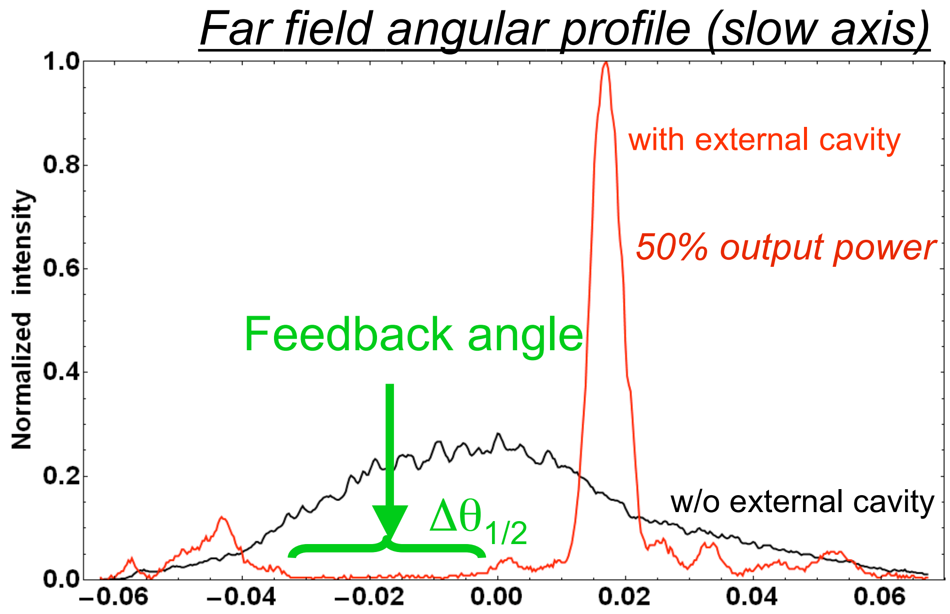
Feedback direction ≅ λ/2p (= 16 mrad)

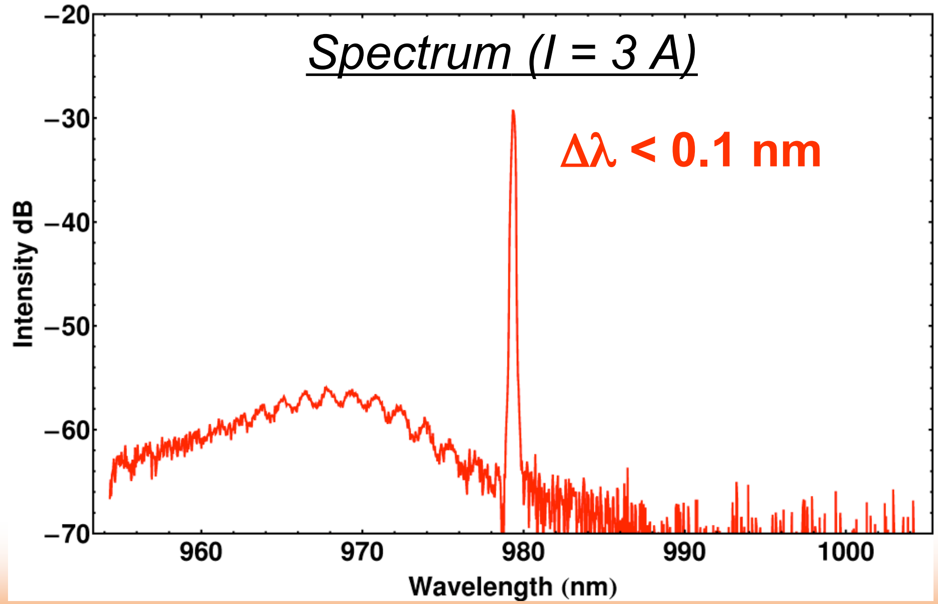
corresponds to one of the lobe in the out-of-phase array supermode

Output beam on the symmetric lobe

Angular filtering with 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

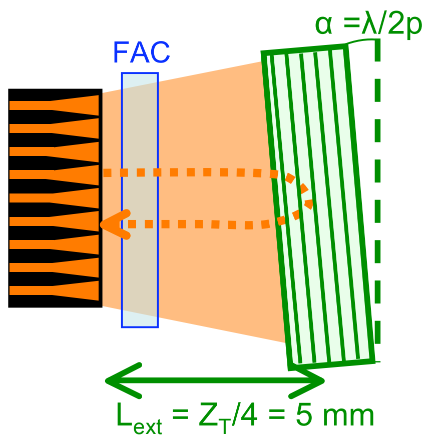
Paboeuf et al, CLEO Europe (2009)

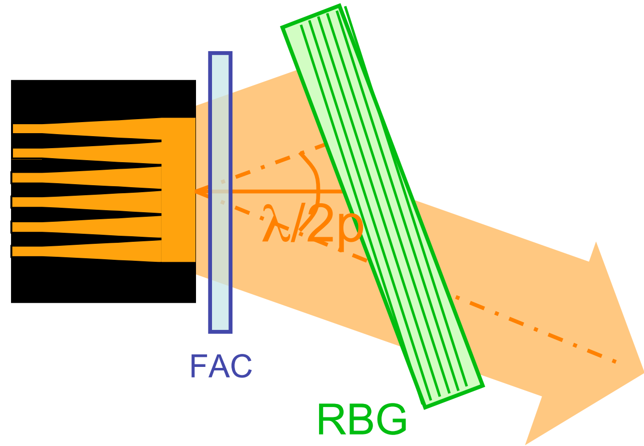
Summary

-Numerical model to predict the modal properties of the extended-cavity diode laser bars

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

Talbot cavity vs Intracavity angular filtering :





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

scalable to high output powers

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

well-adapted to high filling factor arrays
(reduced number of peaks in the far-field)

Outlooks

- Increase of the output power with high-power tapered laser bars
- Conversion of the in-phase supermode far-field profile in a Gaussian profile with phase diffraction gratings : ~80% conversion efficiency expected.

Talbot cavity