



Coherent beam combining techniques : an introduction

Gaëlle Lucas-Leclin

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Coherent beam combining techniques : an introduction

Gaëlle LUCAS-LECLIN

Associate Professor

gaelle.lucas-leclin@institutoptique.fr

Laboratoire Charles Fabry

Institut d'Optique, CNRS, Université Paris-Sud 11
(France)

www.lcf.institutoptique.fr



Coherent beam combining of diode lasers:

WHY ?

WHAT ?

HOW ?

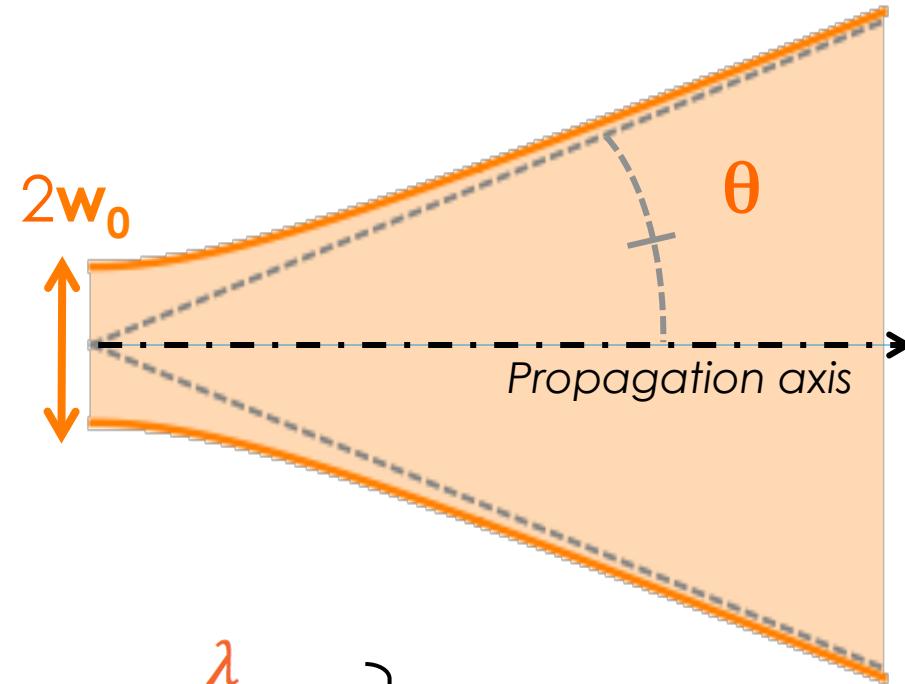
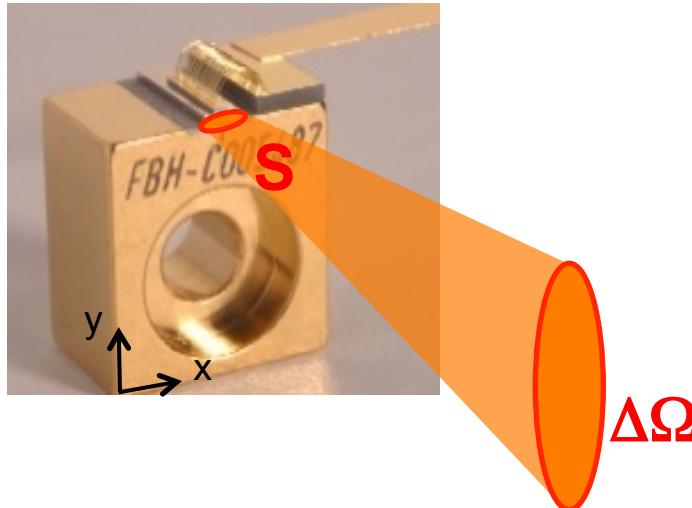
WARUM ?

WAS?

WIE ?

Outline

- **Introduction**
brightness of a laser source
beam combining architectures
- **Coherent beam combining**
active MOPA configuration
self-organising external cavities



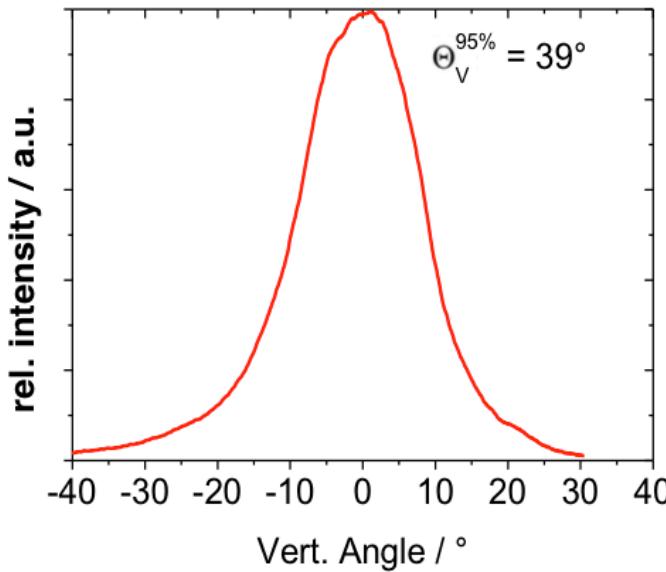
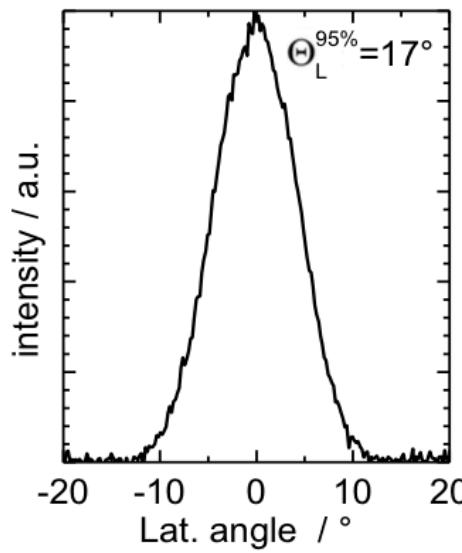
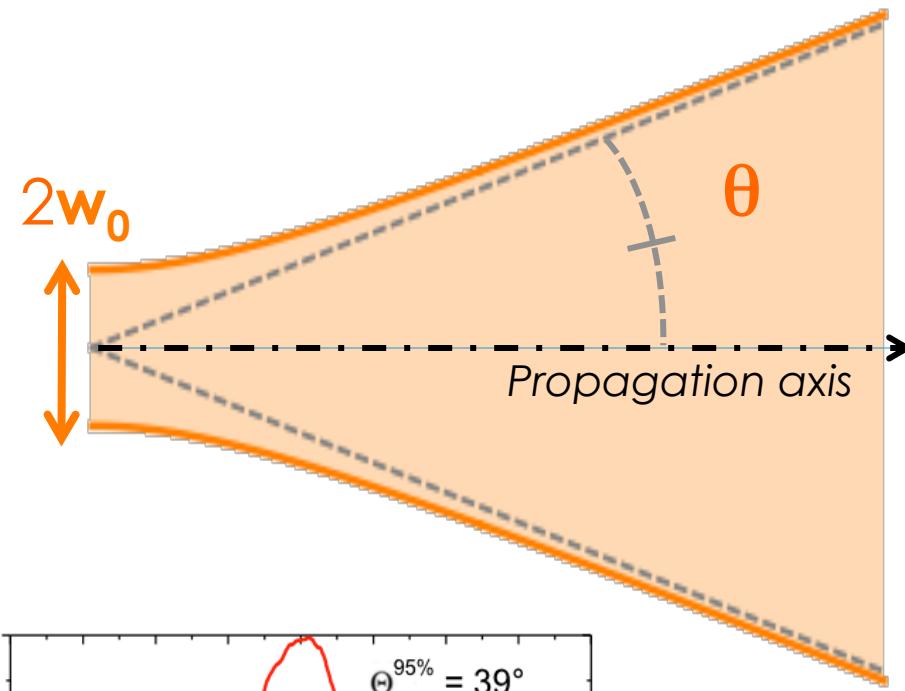
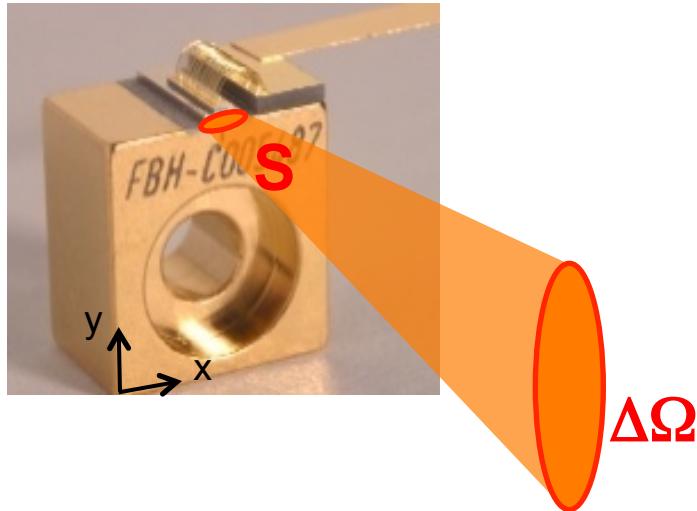
Gaussian diffraction-limited beam : $\theta = \frac{\lambda}{\pi w_0}$

General case : $\theta = M^2 \times \frac{\lambda}{\pi w_0}$

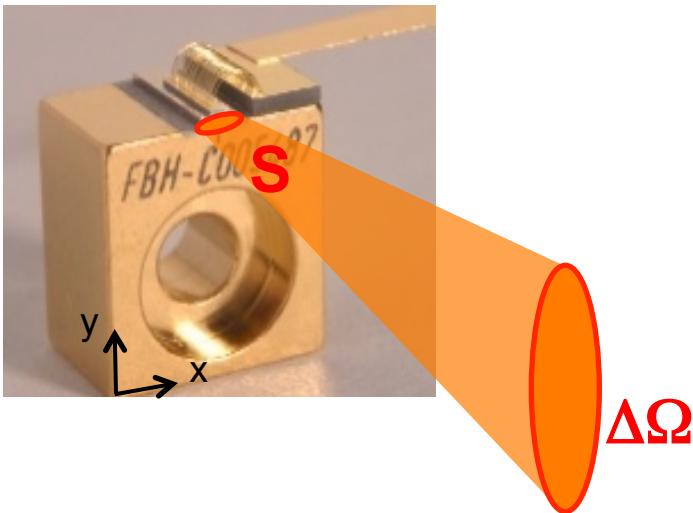
Beam quality parameter

Beam parameter product : $BPP = \theta \times w_0 = M^2 \times \frac{\lambda}{\pi} \cong 0.3 \times M^2$ @ $\lambda = 1 \mu\text{m}$

Laser beam propagation : diode lasers



What is the brightness of a laser source ?



→ The brighter the better ...

Brightness =

measurement of the power and beam quality of a laser source

$$B = \frac{P}{S_{em} \times \Delta\Omega} = \frac{P}{\lambda^2 \times M_x^2 M_y^2}$$

[unit : W.m⁻².sr⁻¹]

↔ ability to focus a high power on a small area with a low NA

What is the brightness of a laser source ?

Brightness =

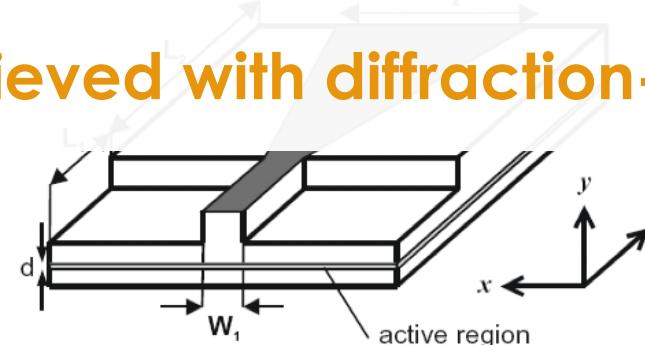
measurement of the power and beam quality of a laser source

$$B = \frac{P}{\lambda^2 \times M_x^2 M_y^2}$$

State-of-the-art	Power	$M_x^2 \times M_y^2$	Brightness
Single-mode LD ^(a)	1 W	1	100 MW.cm ⁻² .sr ⁻¹
Broad area LD ^(b)	7 W	1 x 6	110 MW.cm ⁻² .sr ⁻¹
Tapered LD ^(c)	12 W	1 x 1.2	1000 MW.cm ⁻² .sr ⁻¹

w.

Highest brightness achieved with diffraction-limited laser sources



- (a) SCOWL – Donnelly et al, IEEE JQE 39, 2 (2003)
- (b) P. Crump, BRIDLE
- (c) Fiebig et al. Elec. Lett, 44, p1253 (2008)

What limits the brightness ?

↗ output power of single-mode devices

⇒ increase the power density on facets

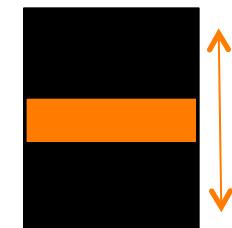
⇒ damages & deterioration of lasers

$$B = \frac{P}{\lambda^2 \times M_x^2 M_y^2}$$

↗ output power

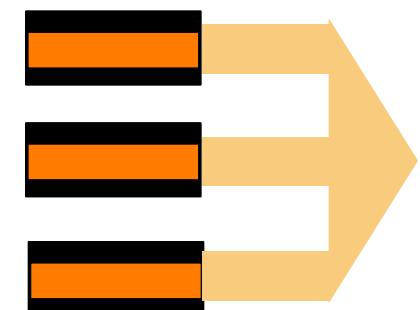
⇒ increase the active volume

⇒ beam quality ↓

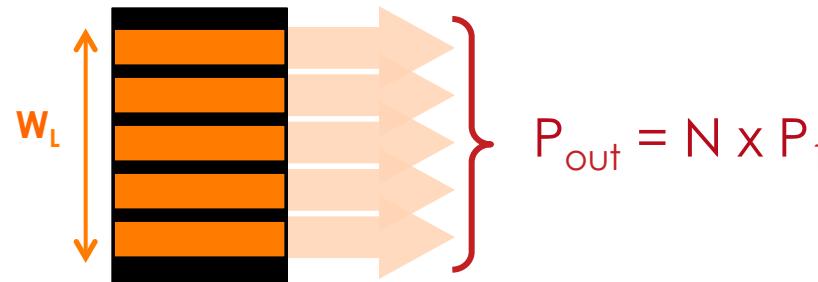


↗ output power by **combining** parallel laser sources while maintaining the **beam quality**

= beam combining



- Incoherent (side-by-side) combining

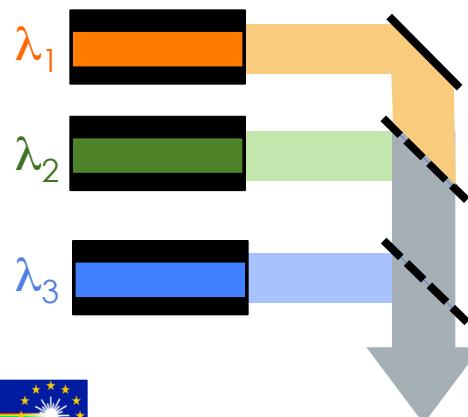


↗ W_L but same divergence θ

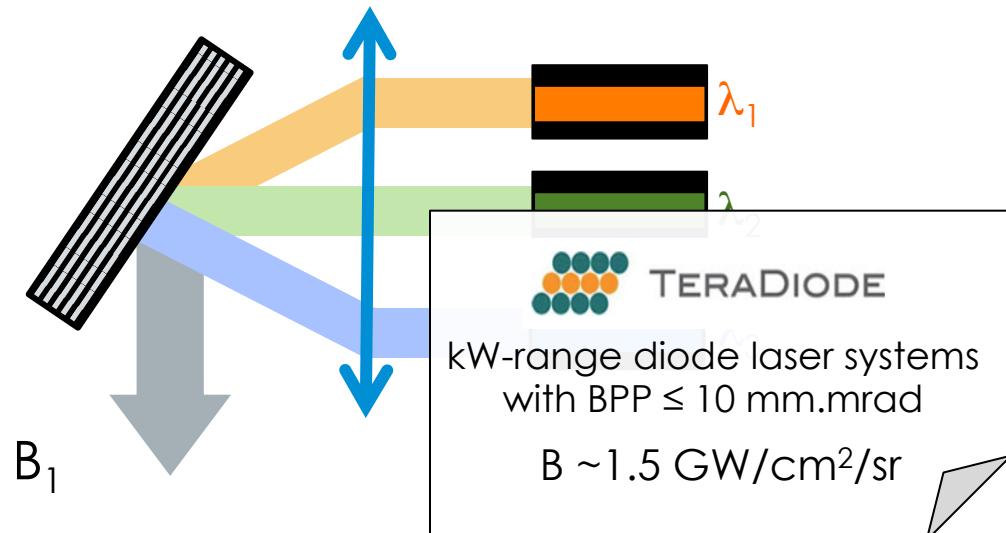
$$B_{\text{bar}} \leq B_1$$

- Spectral beam combining

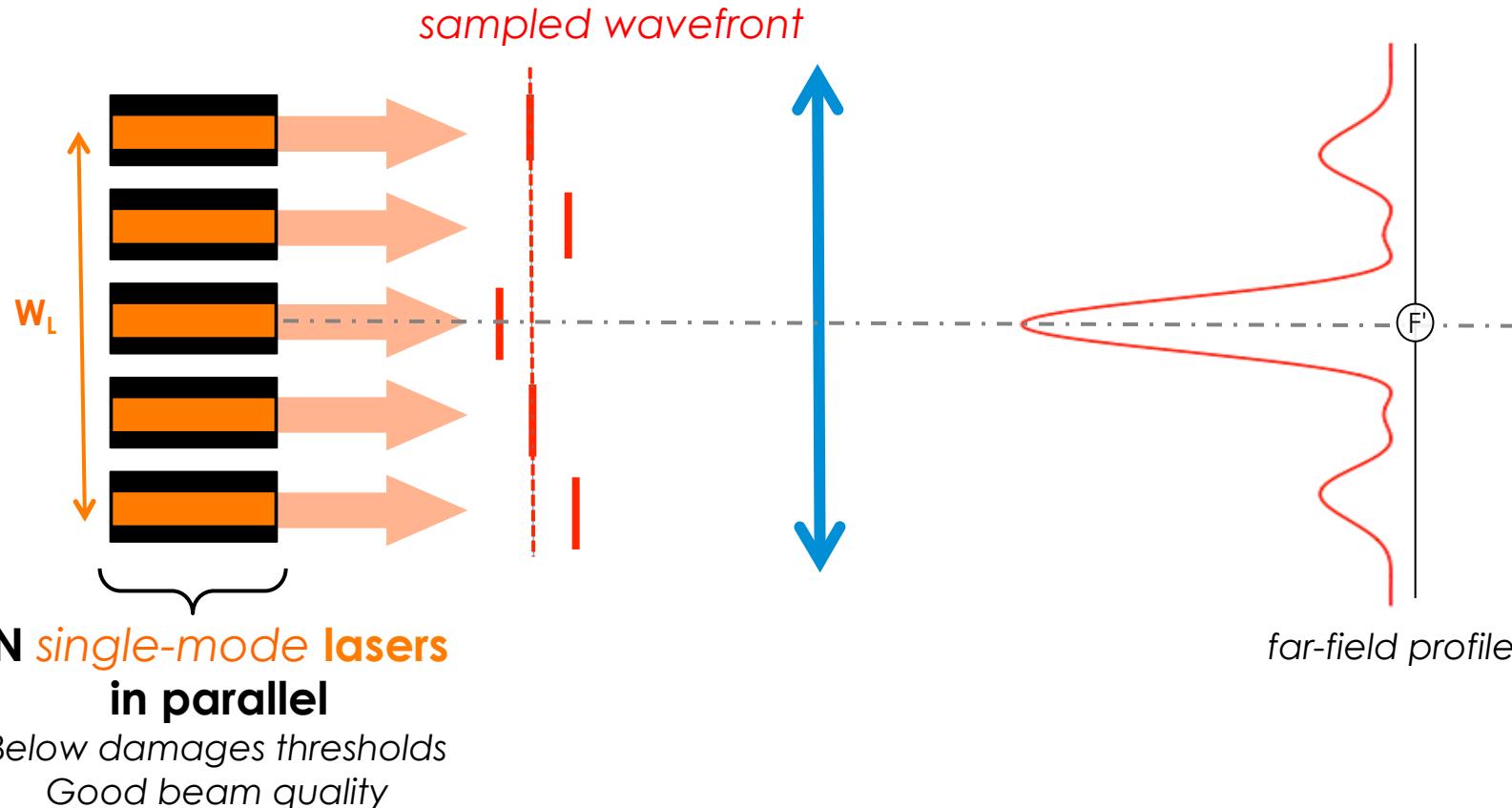
= superposition of \neq laser lines with grating / dichroïc mirrors / vol Bragg gratings



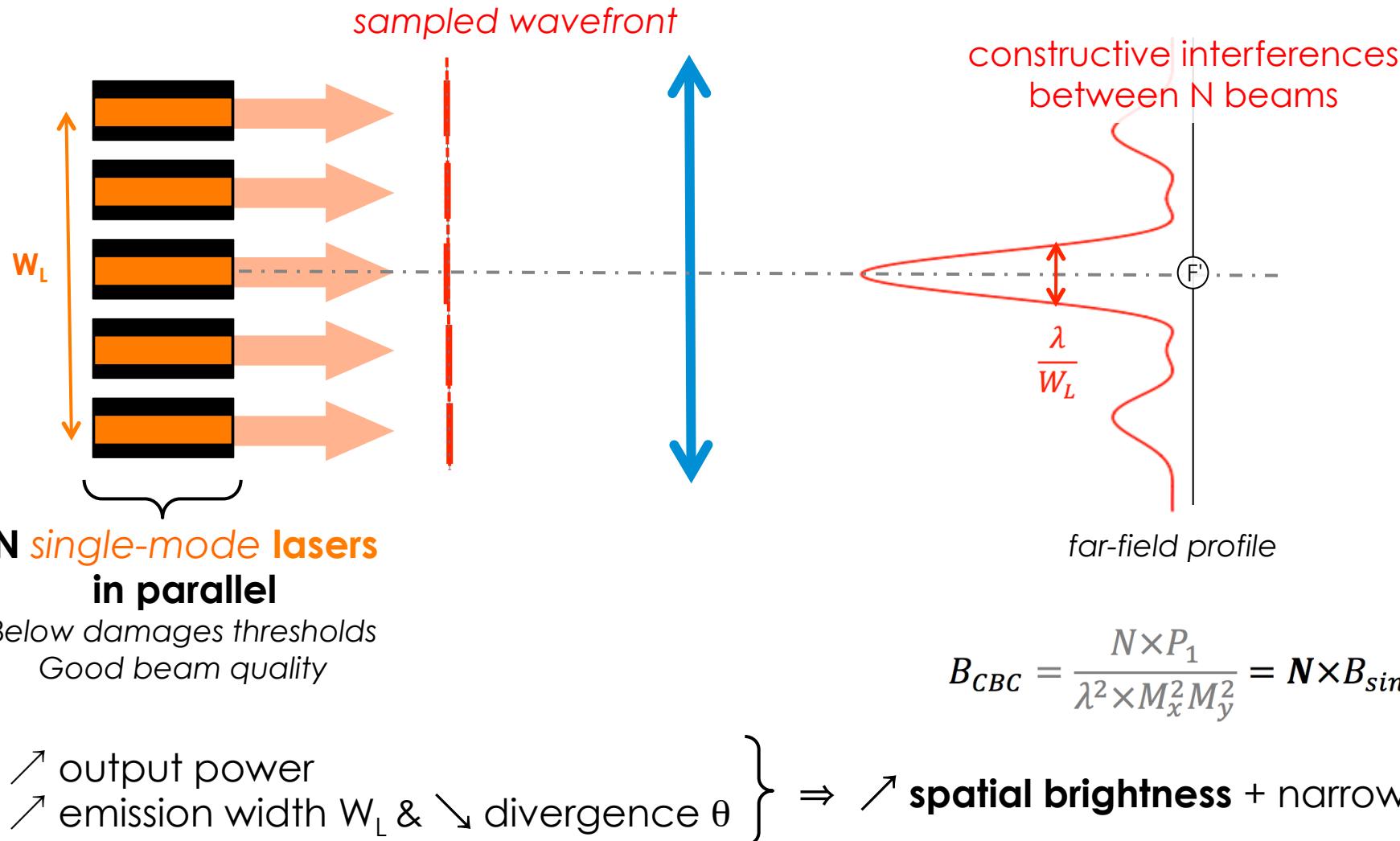
$$B_{\text{SC}} = N \times B_1$$



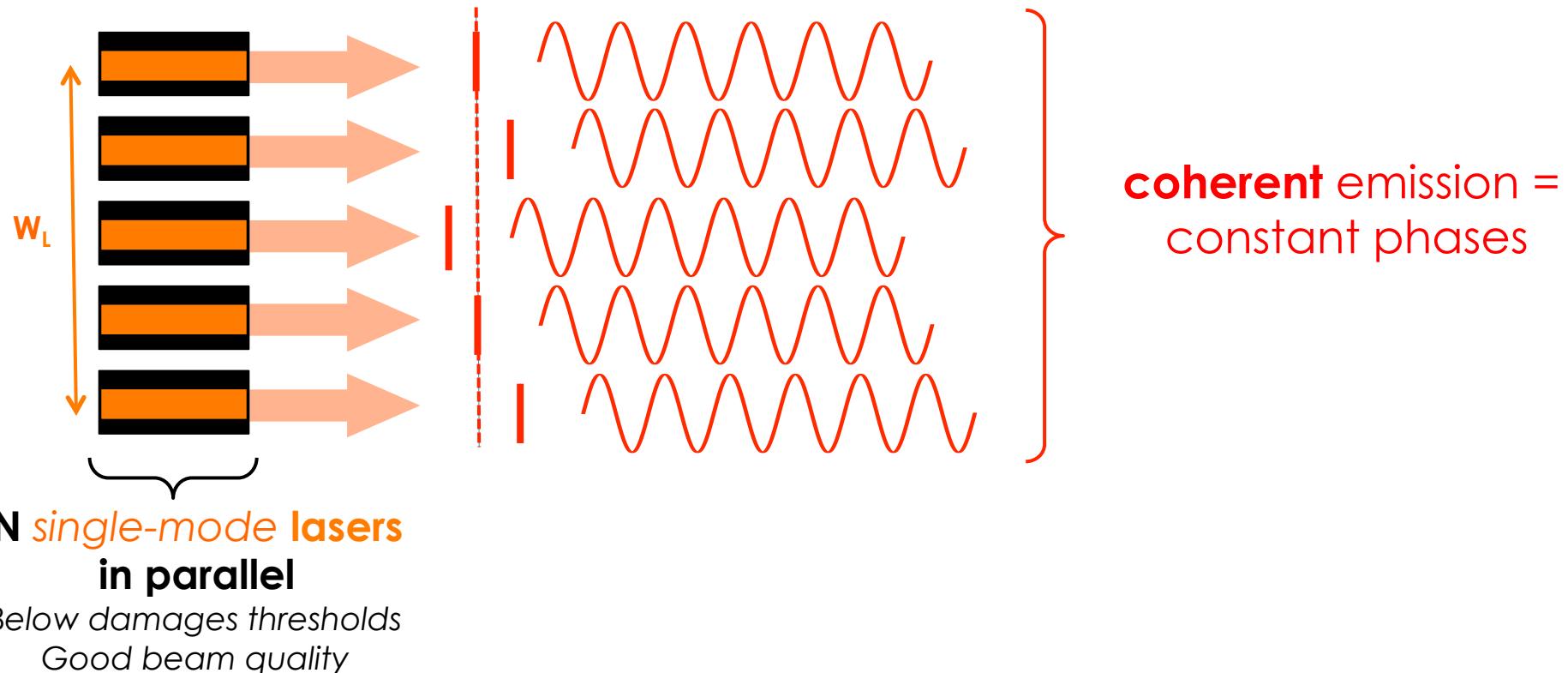
= **constructive superposition** of N laser beams with proper phase relationship



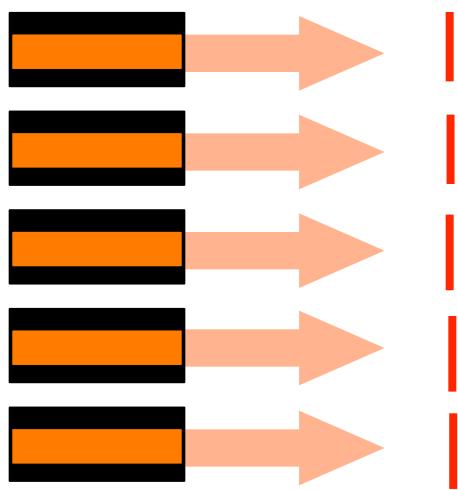
= **constructive superposition** of N laser beams with proper phase relationship



= **constructive superposition** of N laser beams with proper phase relationship



Different architectures for CBC



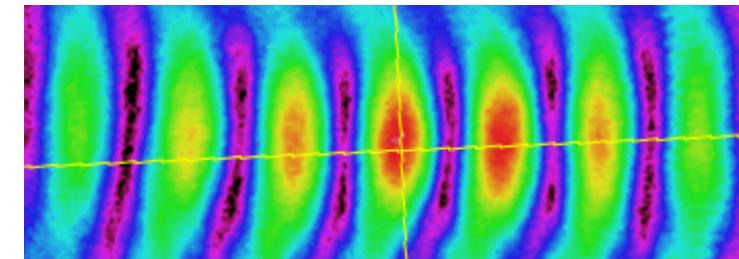
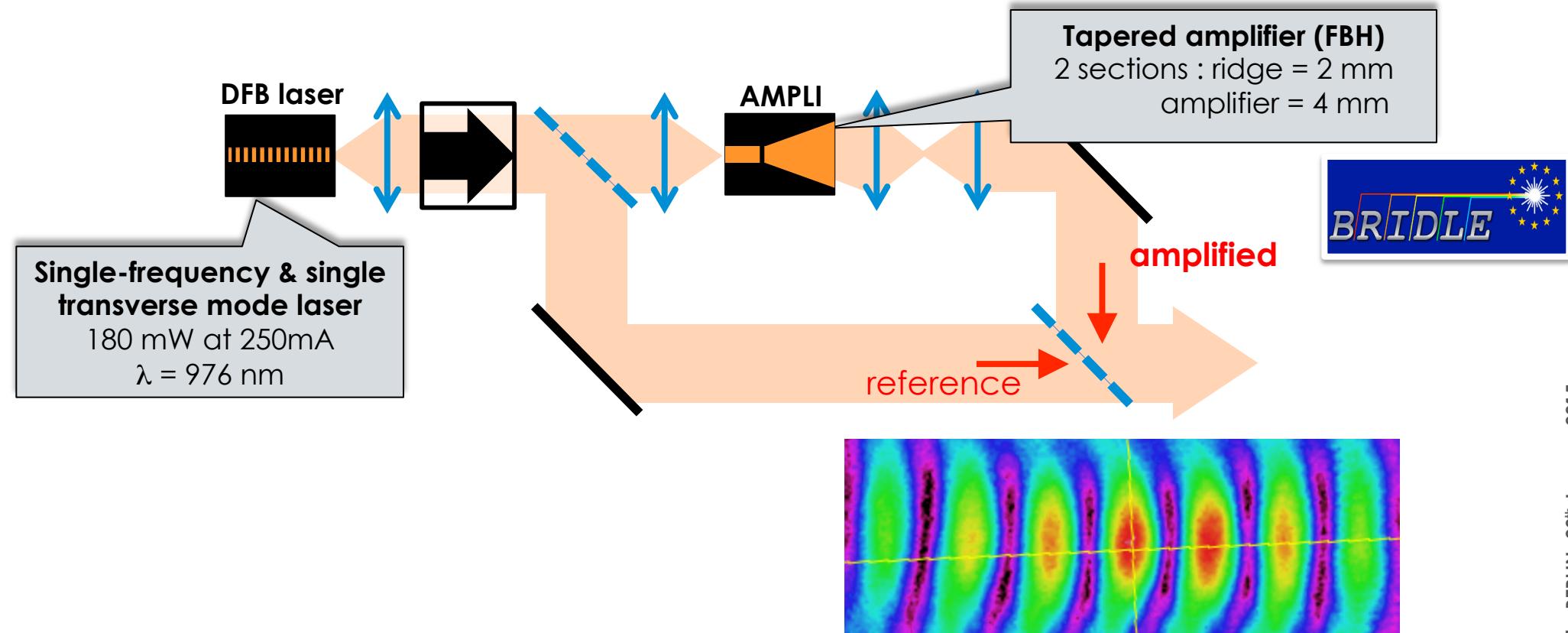
→ MOPA configuration
= **parallel amplification** of one seed
laser in N **amplifiers**

MOPA = Master Oscillator – Power Amplification

→ Self-organizing lasers
= spontaneous operation in the
phase-locked regime of N **lasers**

Master Oscillator Power Amplification

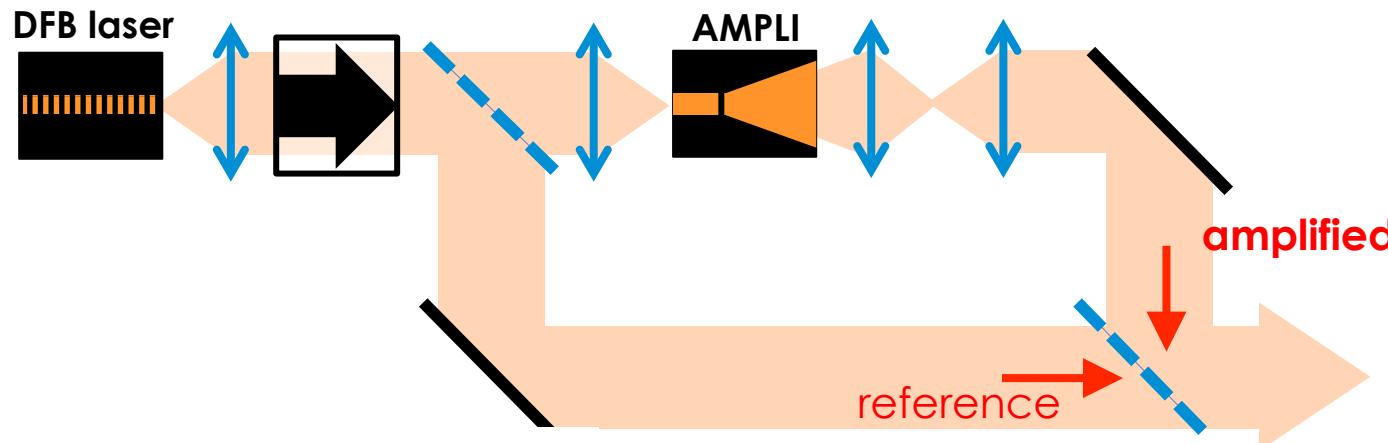
Demonstration of the amplification of a single-frequency laser beam in a tapered amplifier in a Mach-Zehnder interferometer configuration :



We observe highly-contrasted fringes on the combined port
 ⇒ the seed and amplified beams are phase-locked
 ⇒ the coherence between them is $\geq 96\%$

Master Oscillator Power Amplification

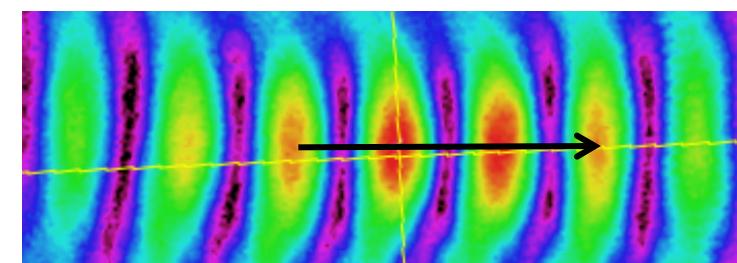
Demonstration of the amplification of a single-frequency laser beam in a tapered amplifier in a Mach-Zehnder interferometer configuration :



$$\varphi_{AMPLI}(I, T^\circ) = \frac{2\pi}{\lambda} n_{opt} L_{AMPLI}(I, T^\circ)$$

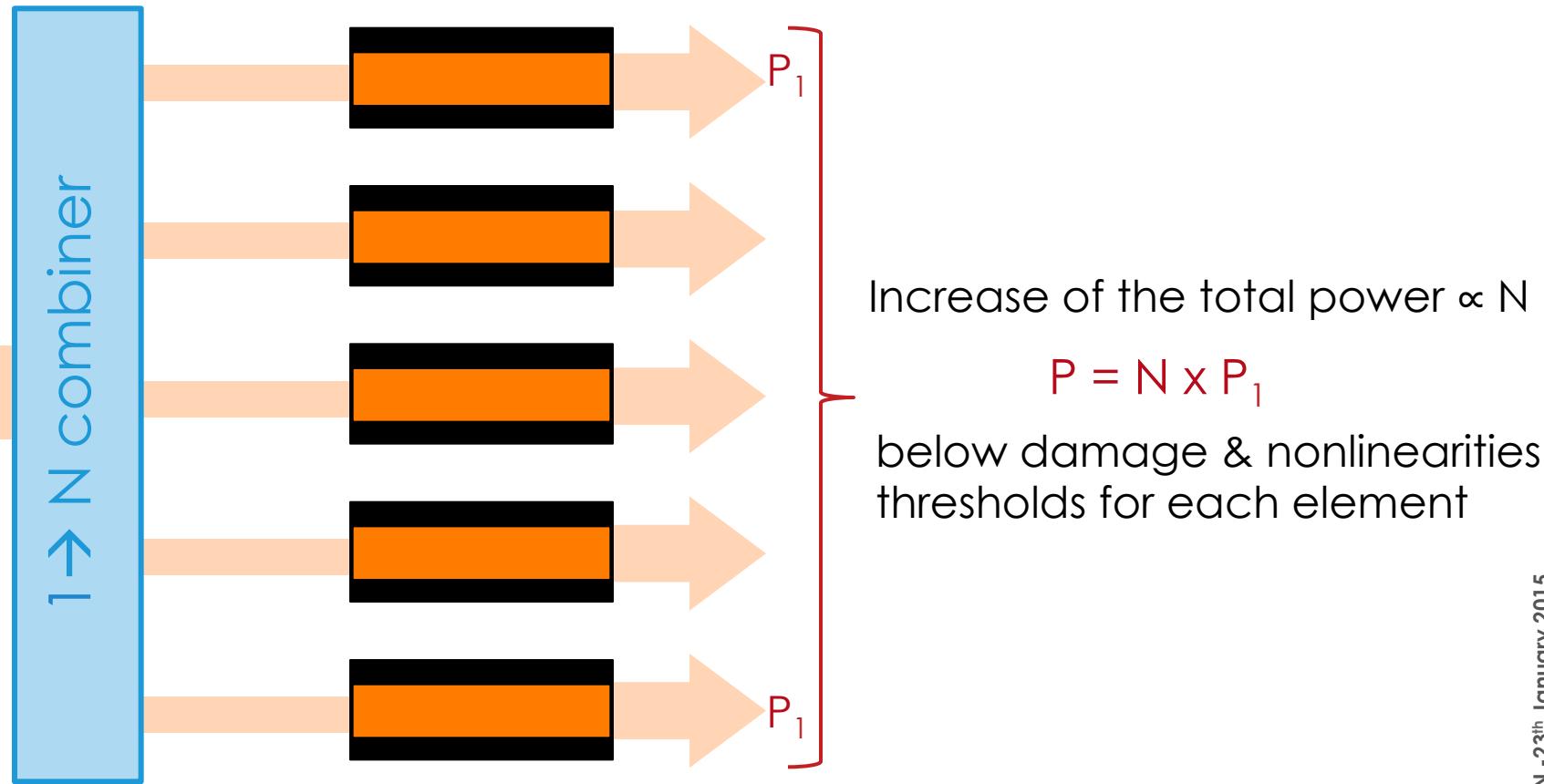
Phase-shift with ridge current

$$\frac{\Delta \varphi_{AMPLI}}{\Delta I_{ridge}} \cong 0.025 - 0.037 \text{ } \pi/\text{mA}$$



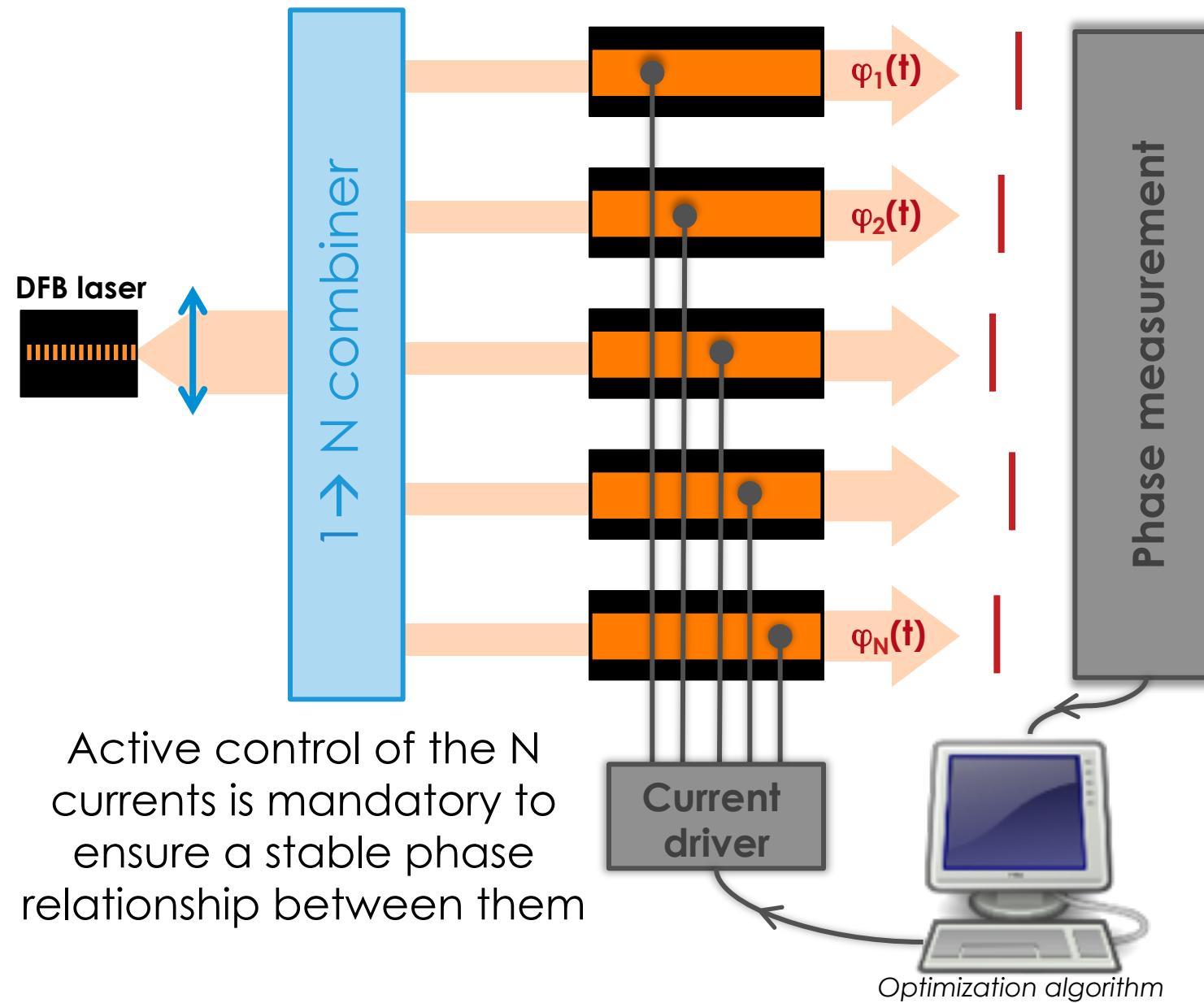
The fringes shift with the currents in the ridge & taper section, because of thermally-induced change of the optical path in the amplifier

Phase-locking in a MOPA architecture



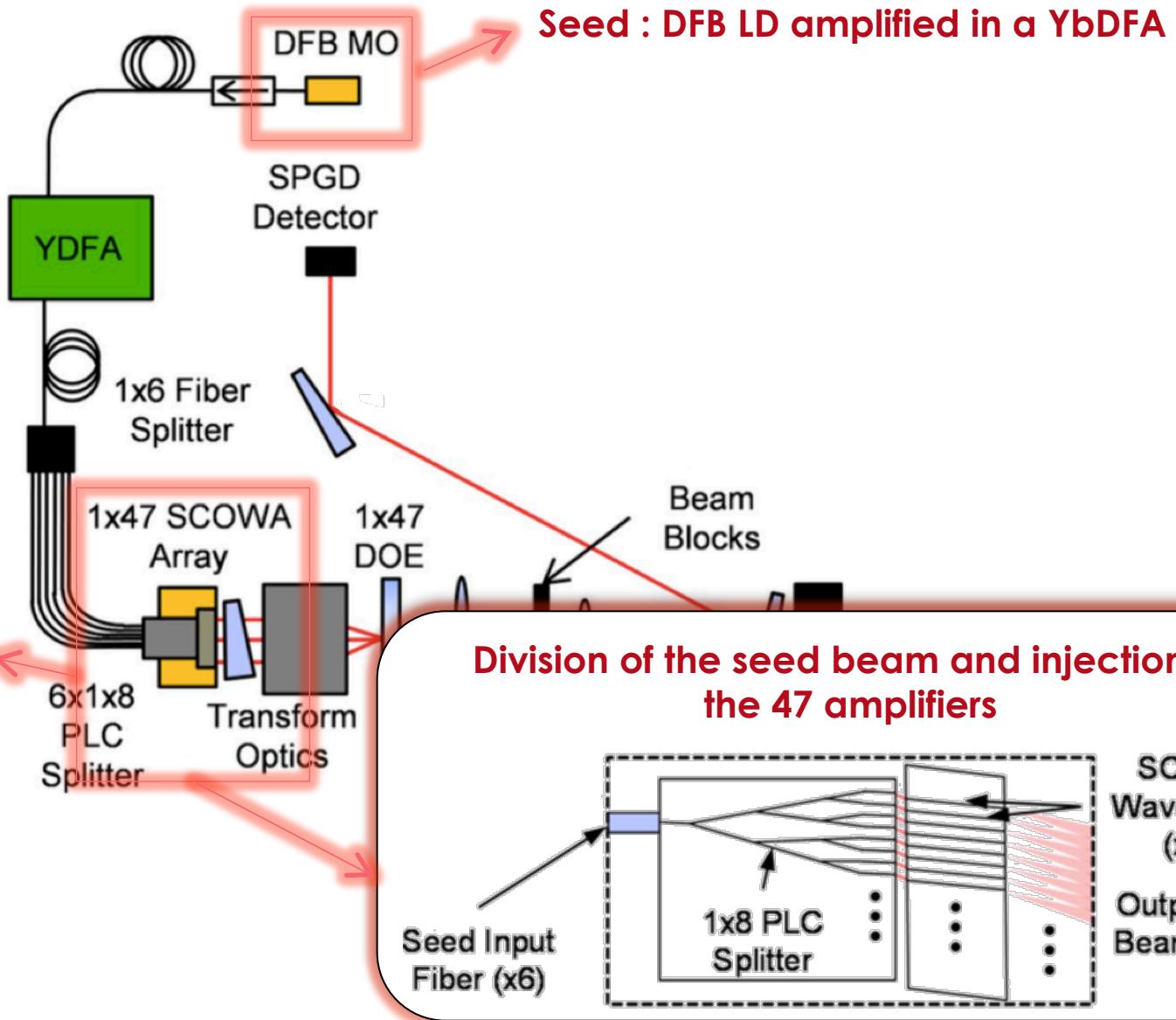
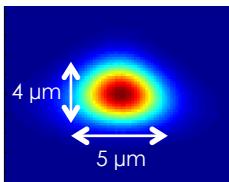
= Amplification of a single-frequency laser beam in multiple amplifiers in //

Phase-locking in a MOPA architecture



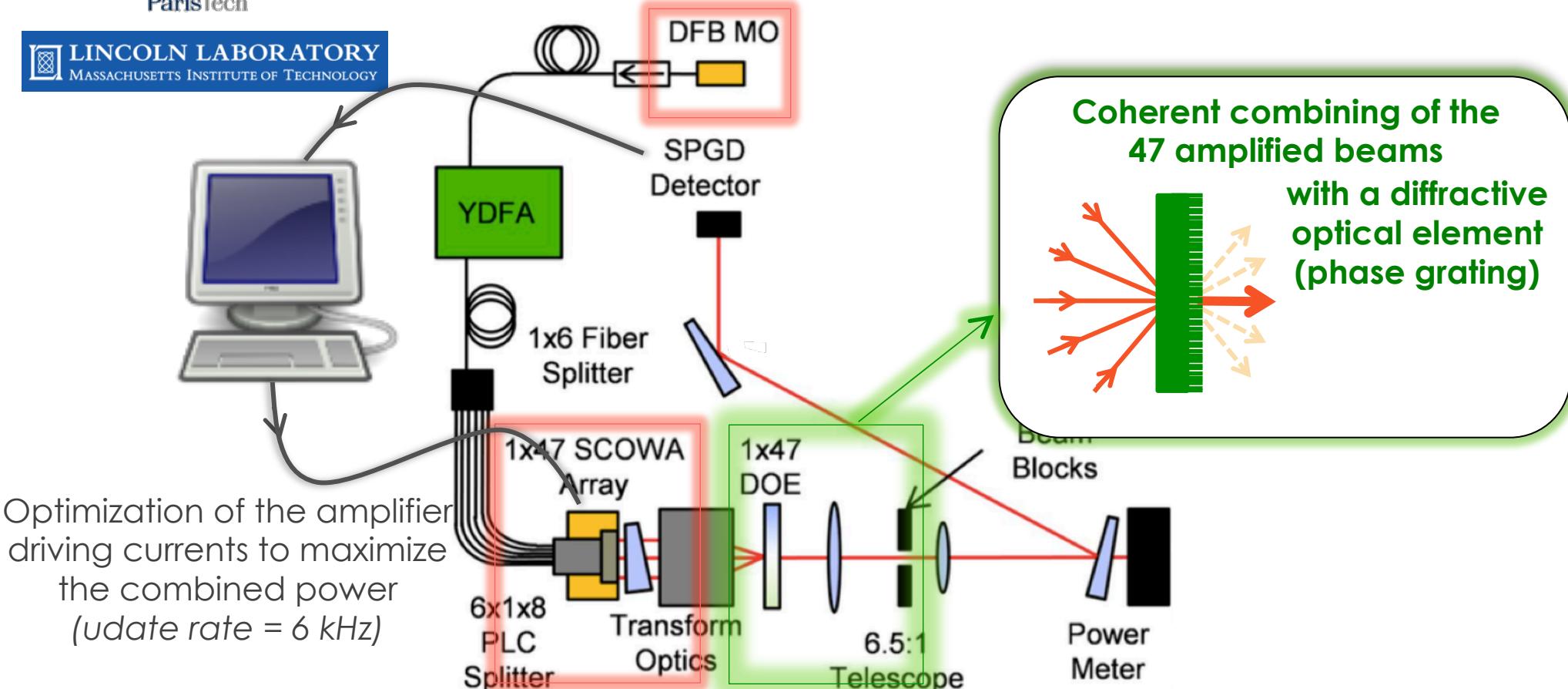
Active phase-locking of a SCOWL array

Single Element
Near Field



Active phase-locking of a SCOWL array

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



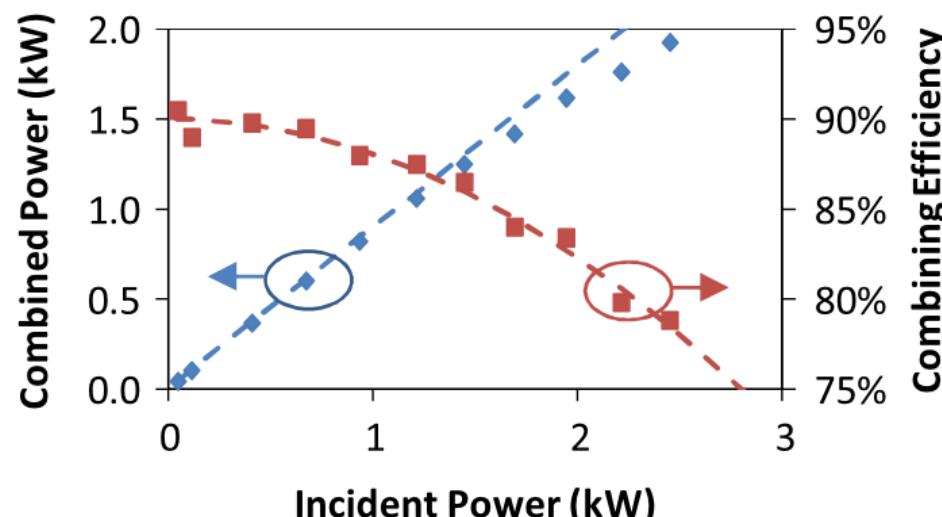
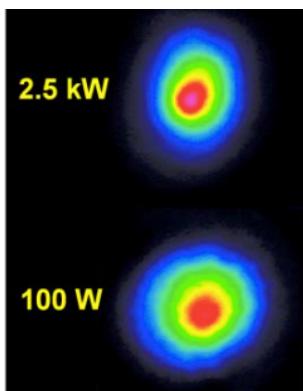
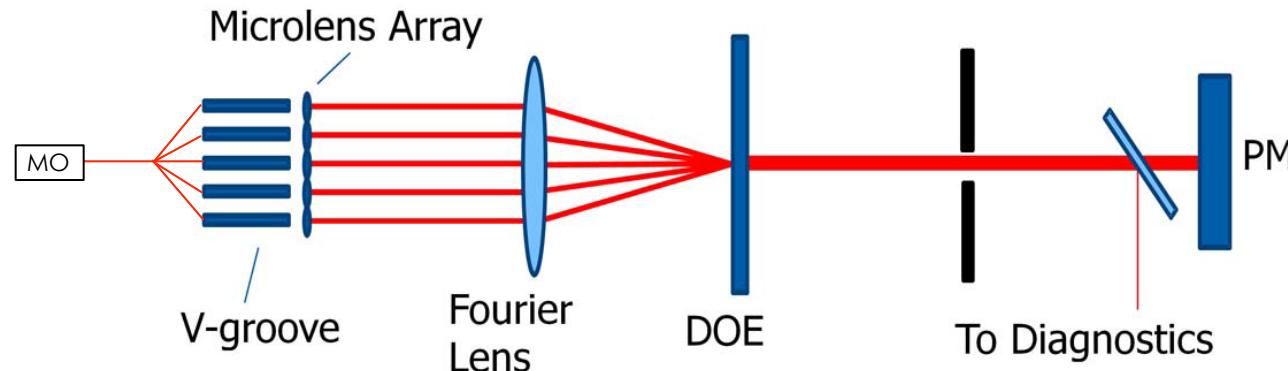
- Demonstration of the **active phase-locking & coherent beam combining** of 47 semiconductor amplifiers
- **Total output power = 40 W** with $\eta_{\text{CBC}} = 87\%$: $B \sim 2.5 \text{ GW.cm}^{-2}.\text{sr}^{-1}$

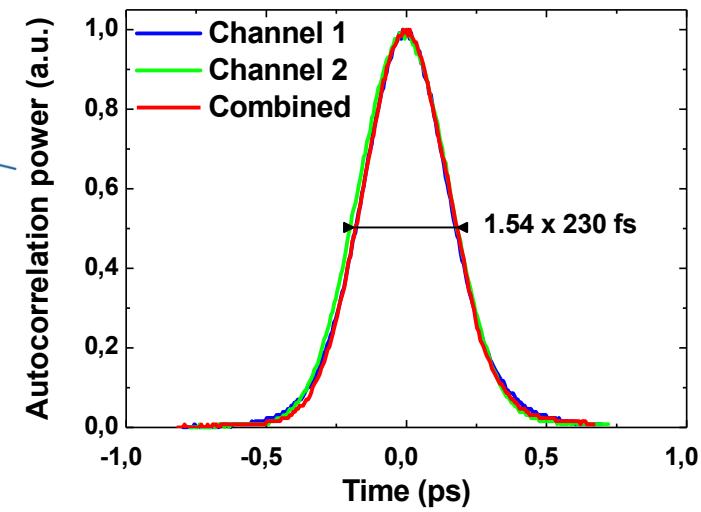
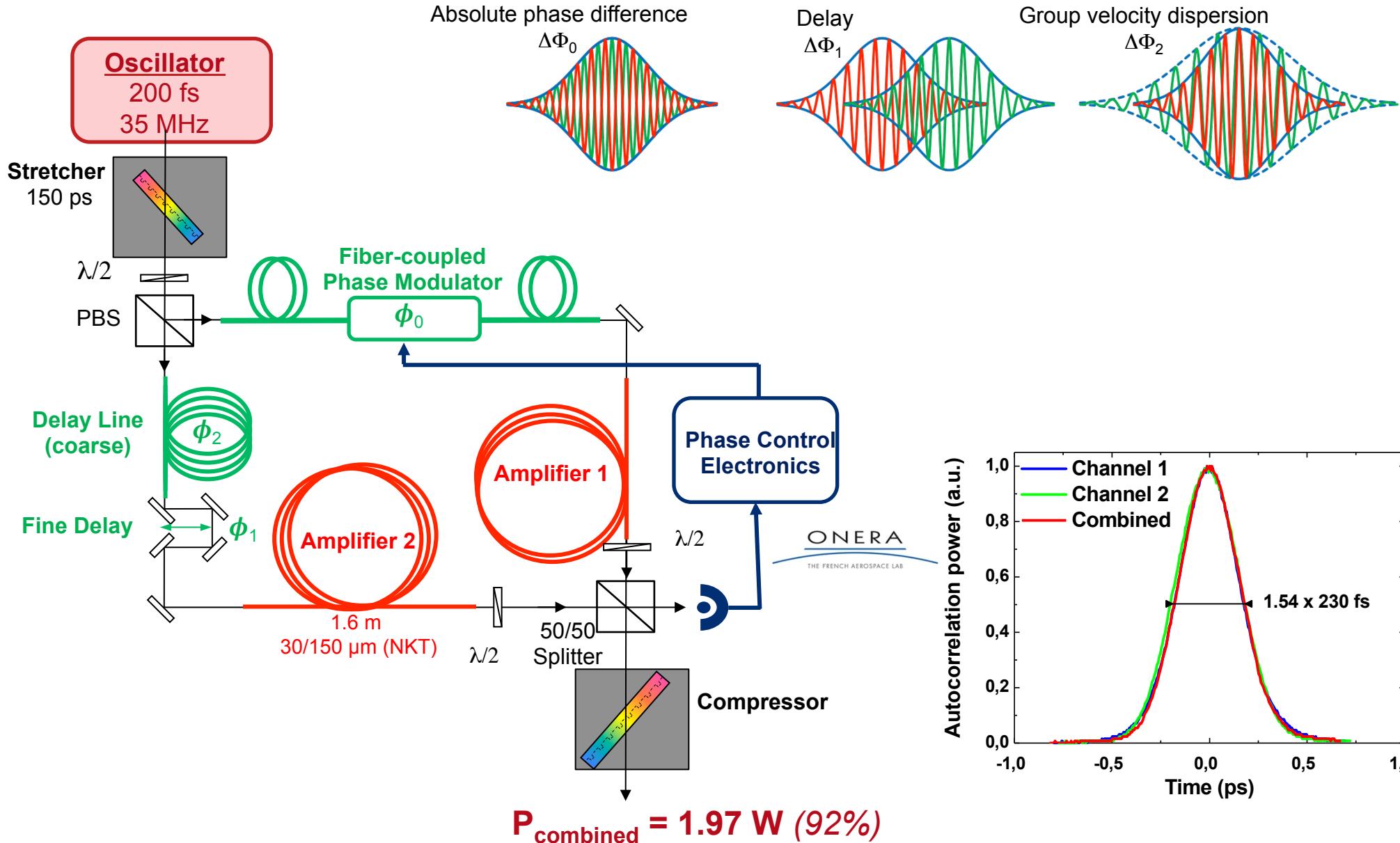
$$B_{\text{SC}} = 25 \times B_1$$

5 x 500 W Yb doped fibers amplifiers : 1.93 kW combined

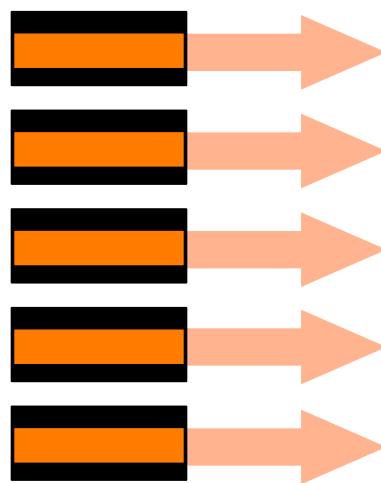
79 % efficiency, $M^2 = 1.1$

LOCSET active feedback





Different architectures for CBC



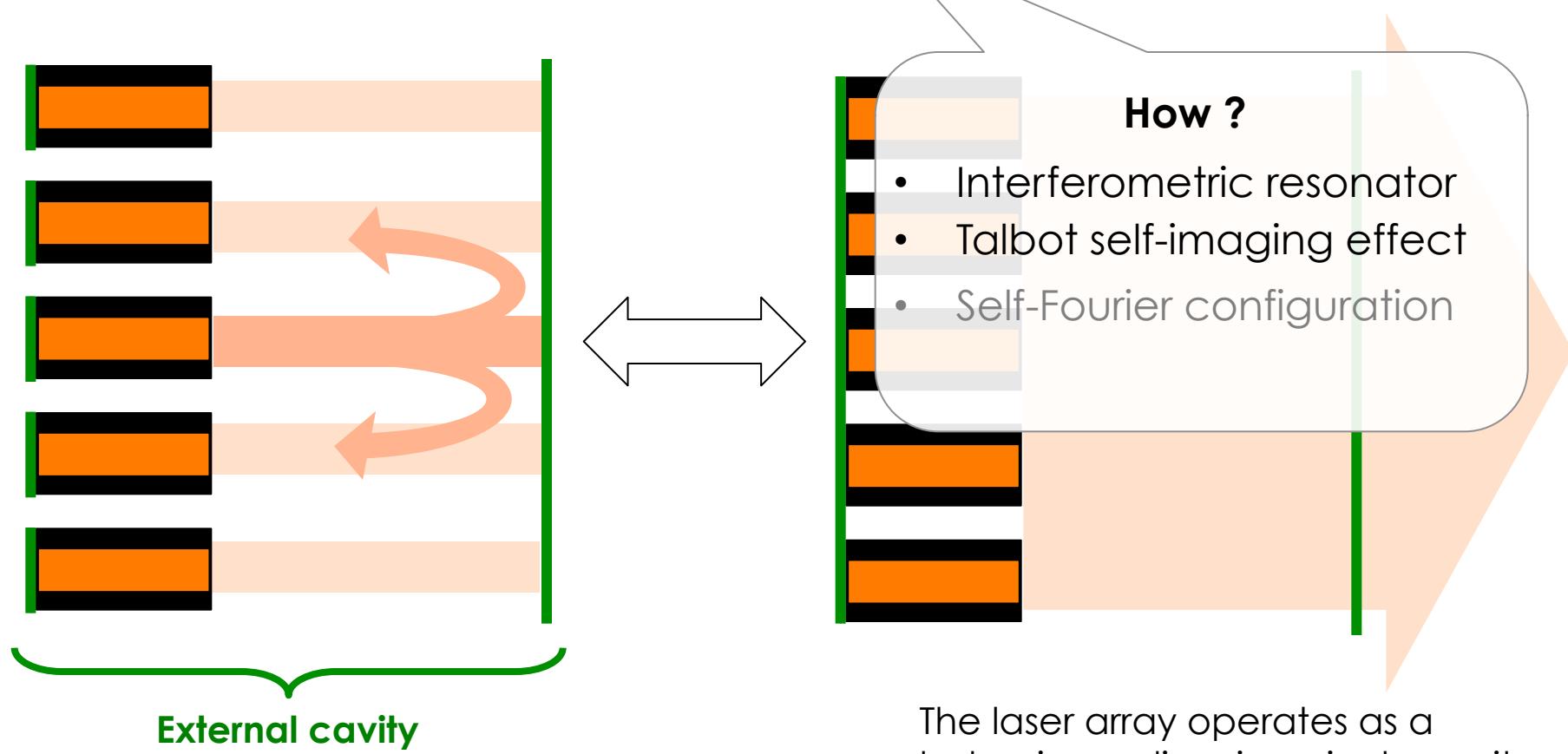
→ MOPA configuration
= **parallel amplification** of one seed
laser in N amplifiers

→ Self-organizing lasers
= spontaneous operation in the
phase-locked regime of N **lasers**

- phase-locked laser array
evanescent coupling between
adjacent emitters
Diode Laser Arrays, ed. Botez & Scifres
(Cambridge Studies in Modern Optics)
- lasers sharing a common external cavity

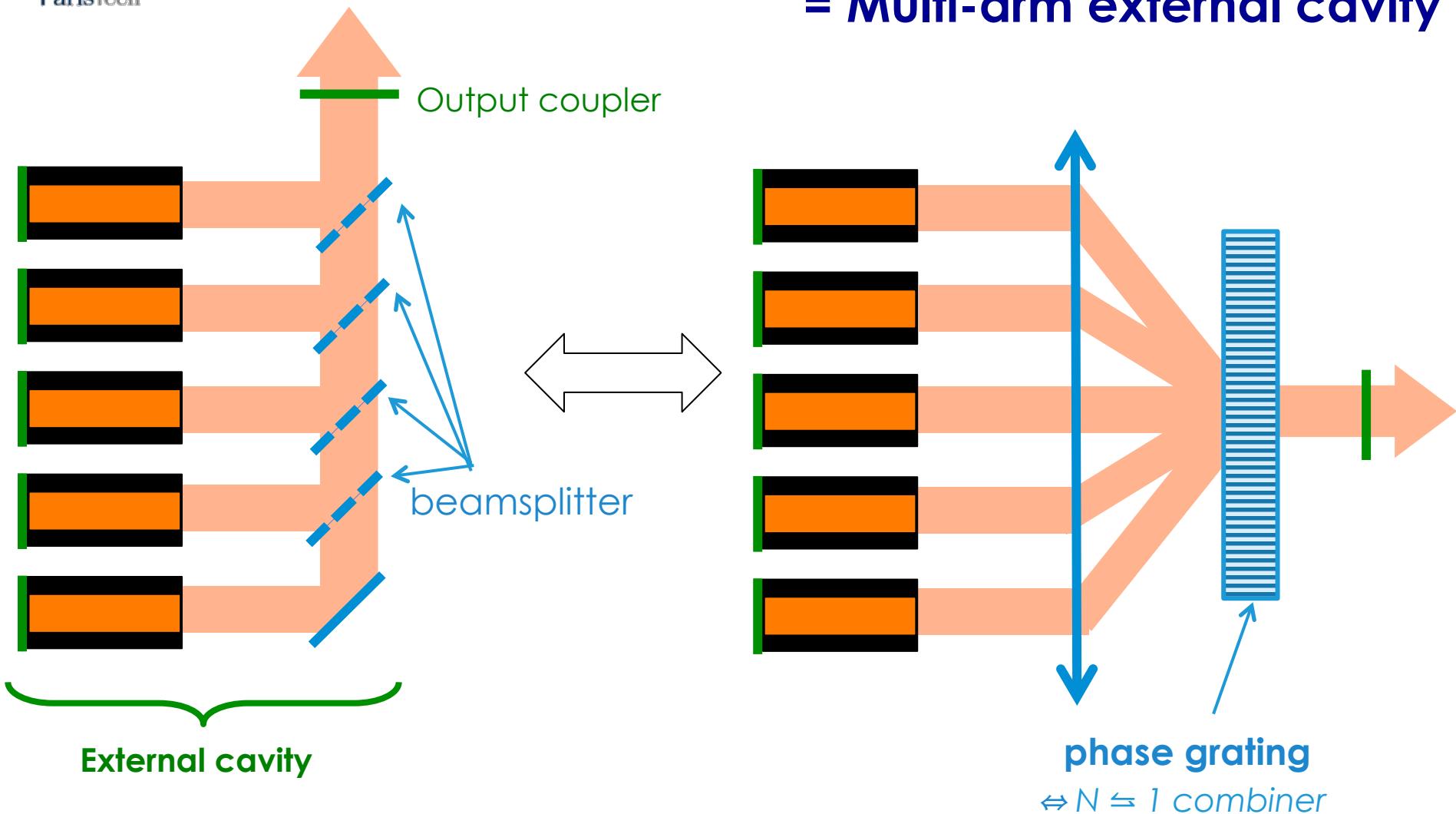
The external cavity is designed to favour the **collective operation** of the emitters by inducing a **coupling** between them.

⇒ light from one emitter is reflected into the others



Interferometric resonator

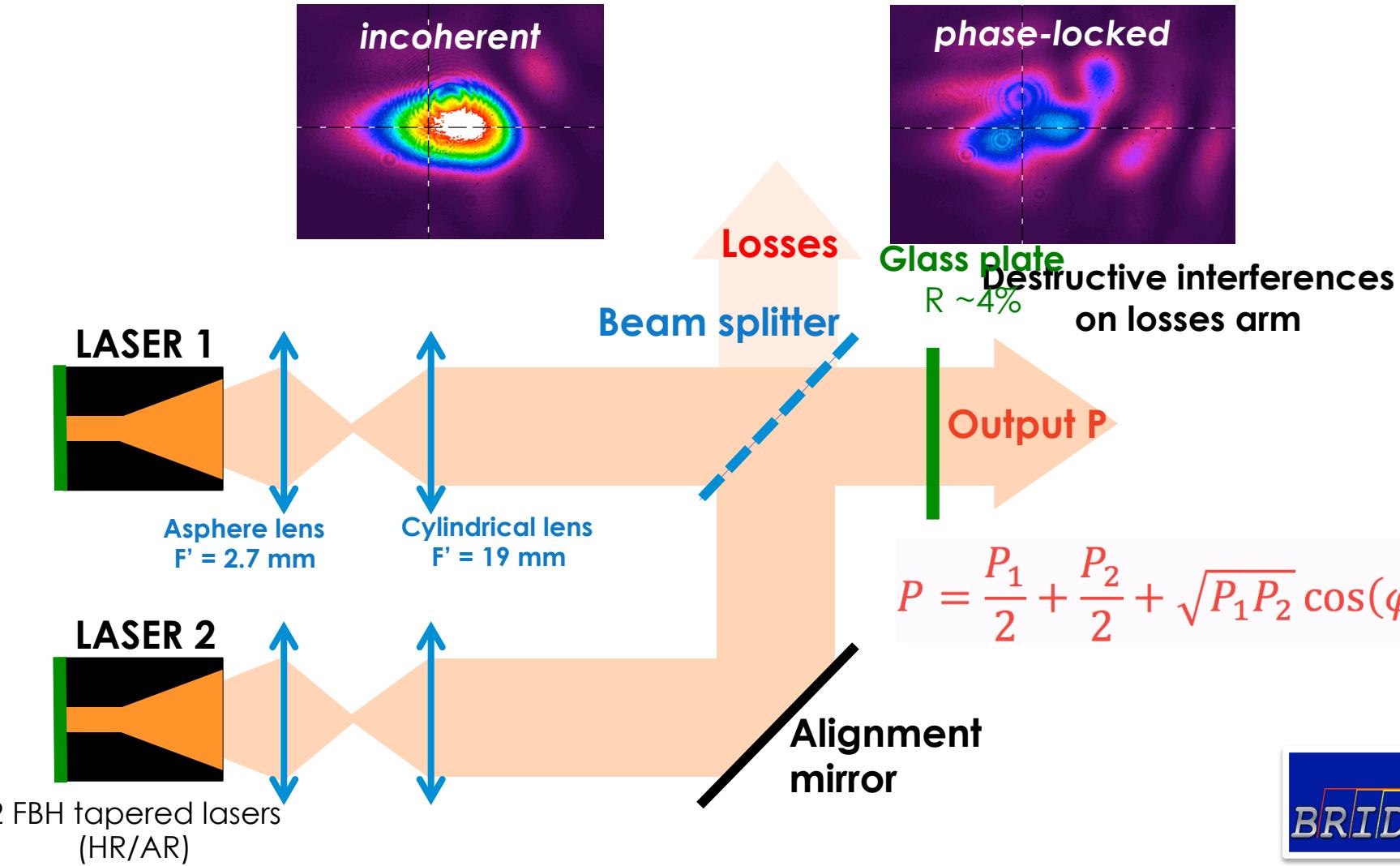
= Multi-arm external cavity



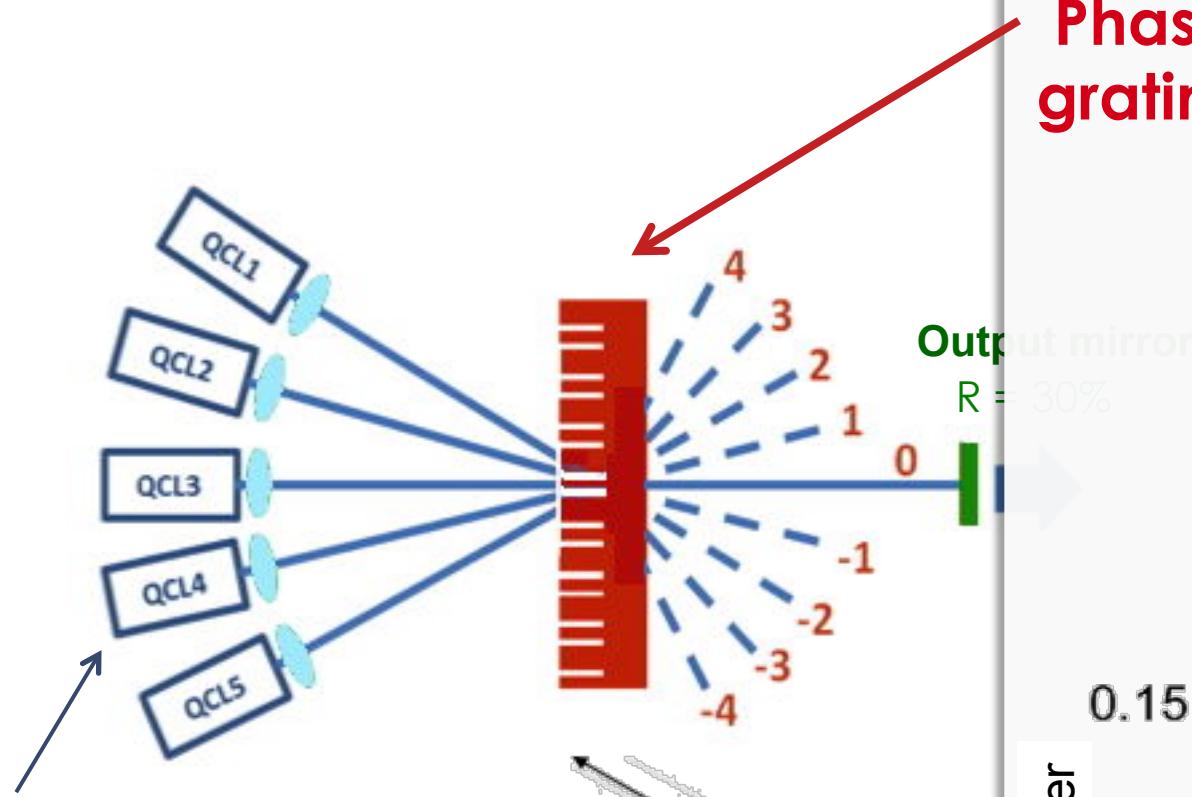
The external cavity favours constructive interferences between the multiple beams.

Michelson cavity : 2-arm interferometer

Minimum losses in the laser cavity for constructive interferences on BS in the P arm : **passive phase-locking & coherent combining** of the two lasers



5-arm external cavity

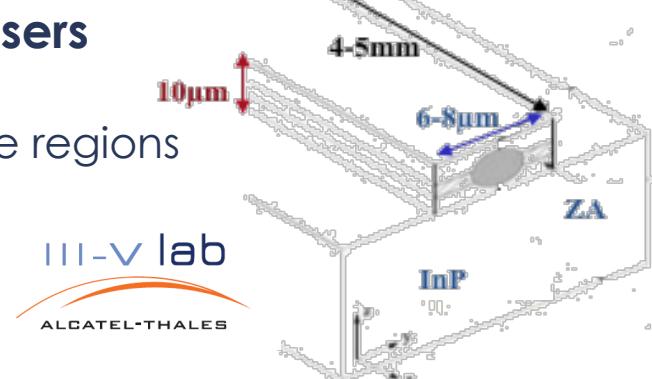


Quantum Cascade Lasers

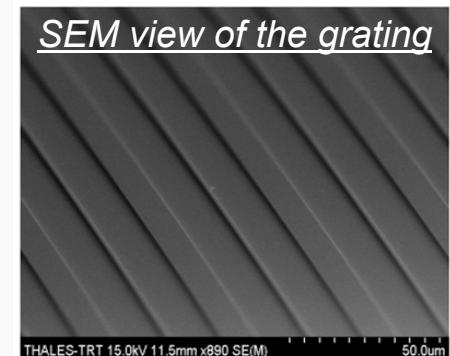
$\lambda = 4.6 \mu\text{m}$

GalnAs/AlInAs active regions
HR / AR (<2%)

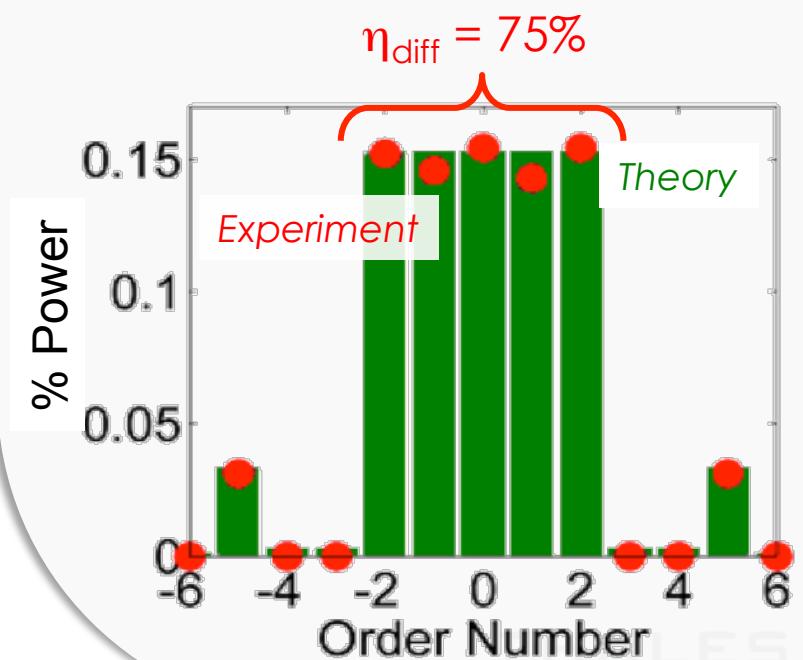
$M^2_y \leq 1.2, M^2_z \leq 1.5$



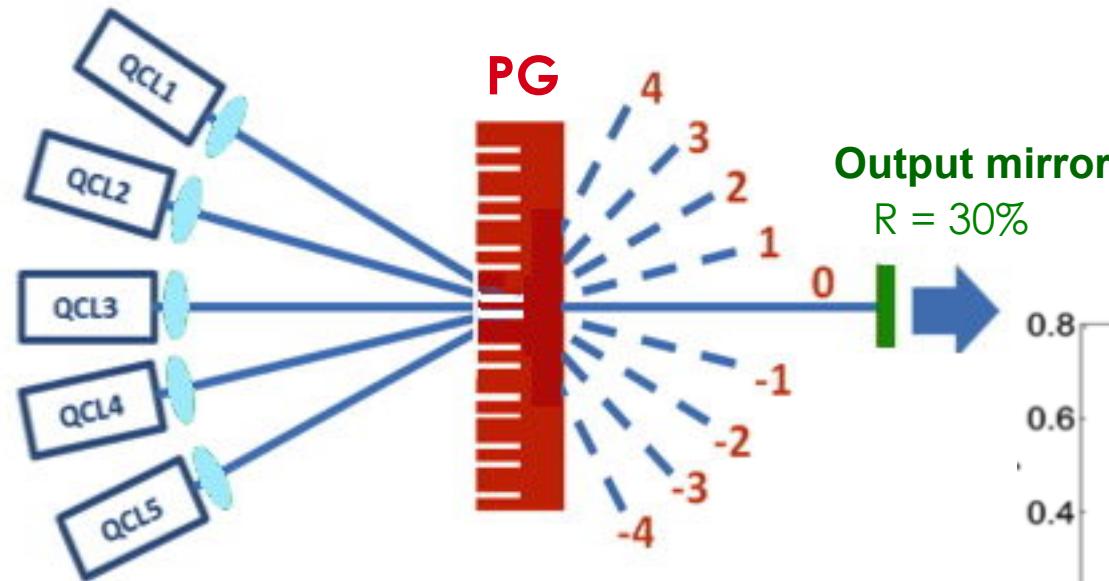
Phase grating



Binary phase grating ($0 - \pi$)
1≤ 5 combiner at $\lambda = 4.65 \mu\text{m}$
Pitch $\Lambda = 50 \mu\text{m}$



Minimum losses in the laser cavity for constructive interferences in the 0th order of the PG : **passive phase-locking & coherent combining**

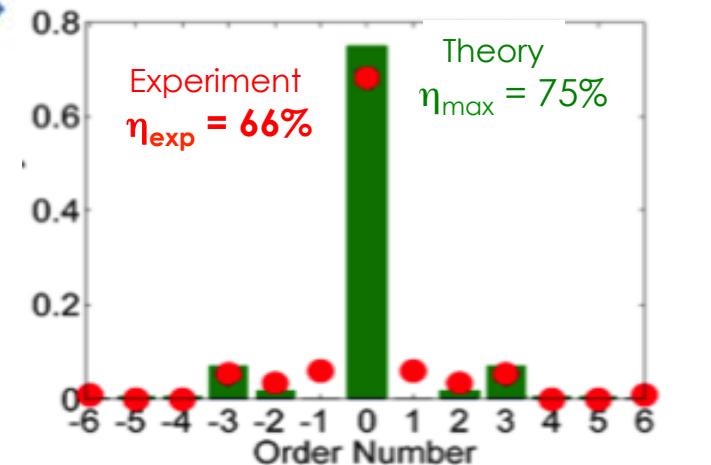


→ Coherent beam addition of 5 QCL :

Combining efficiency = 66%

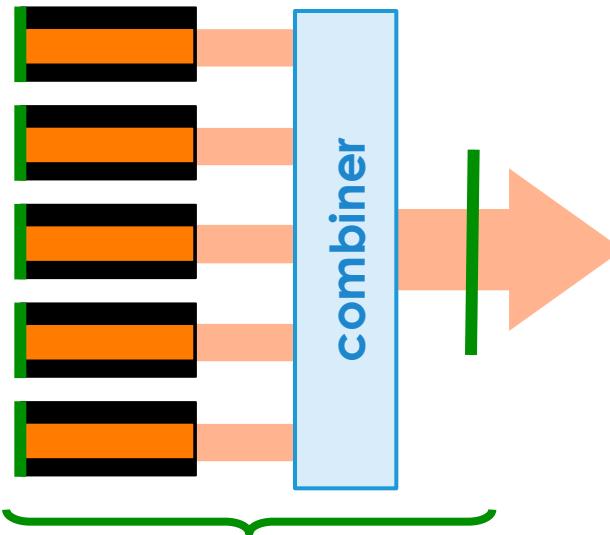
Output power = 0.5 W

Diffraction-limited beam ($M^2 < 1.6$)



Relative power of the diffraction orders at the output of the external cavity

Different architectures for CBC

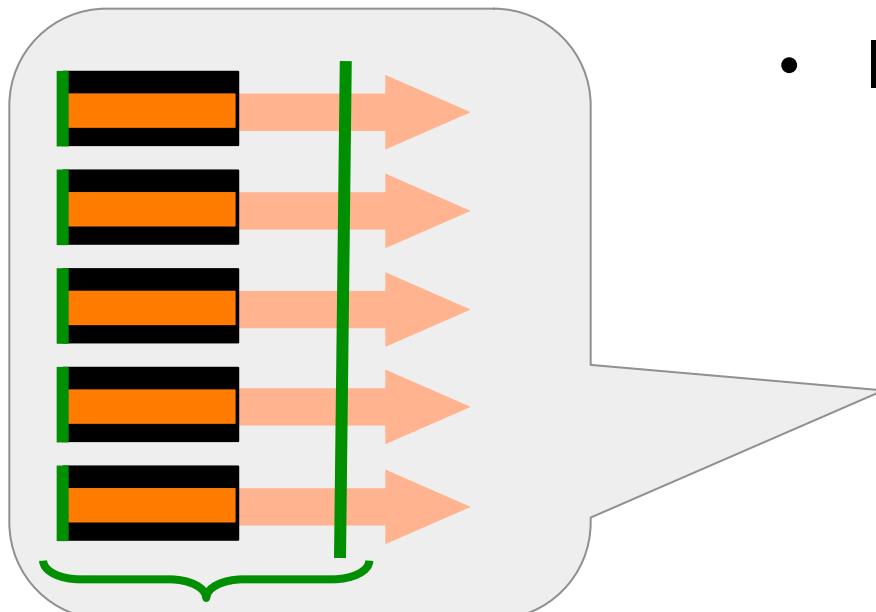


→ MOPA configuration
 = **parallel amplification** of one seed
 laser in N amplifiers

→ Self-organizing lasers
 = spontaneous operation in the
 phase-locked regime of N **lasers**

- lasers in a **common external cavity**

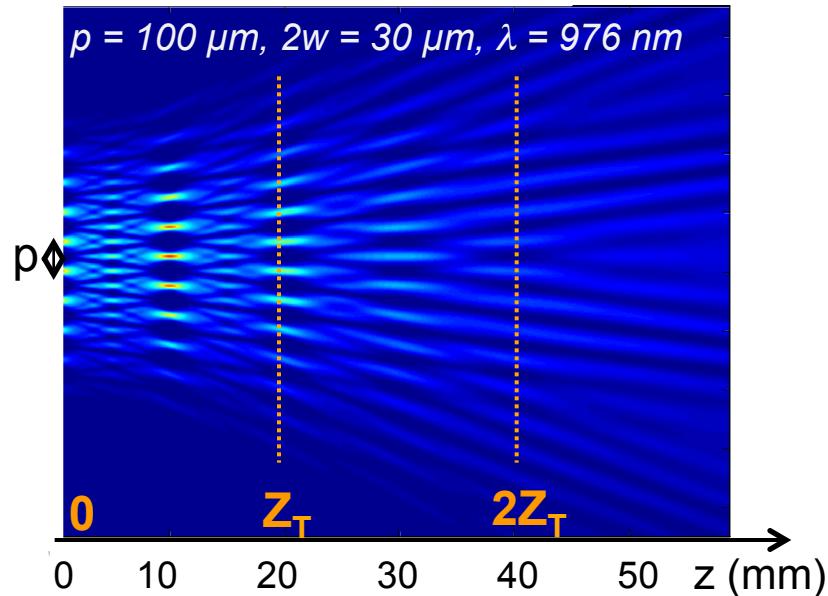
Interferometric resonator
 ⇒ *filled aperture*



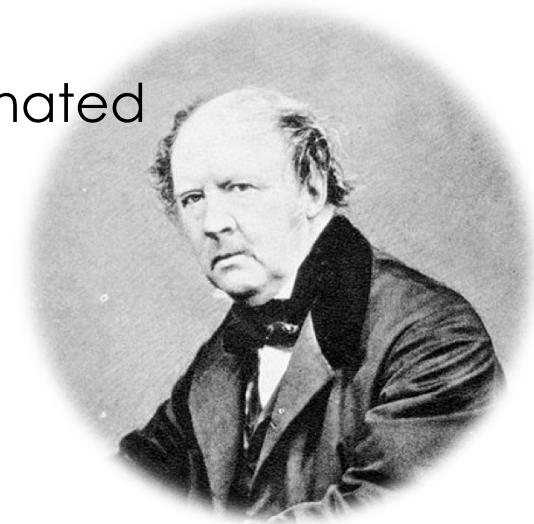
Self-imaging cavity : Talbot effect
 ⇒ *tiled aperture*

Near-field diffraction effect observed for a grating illuminated by monochromatic light :

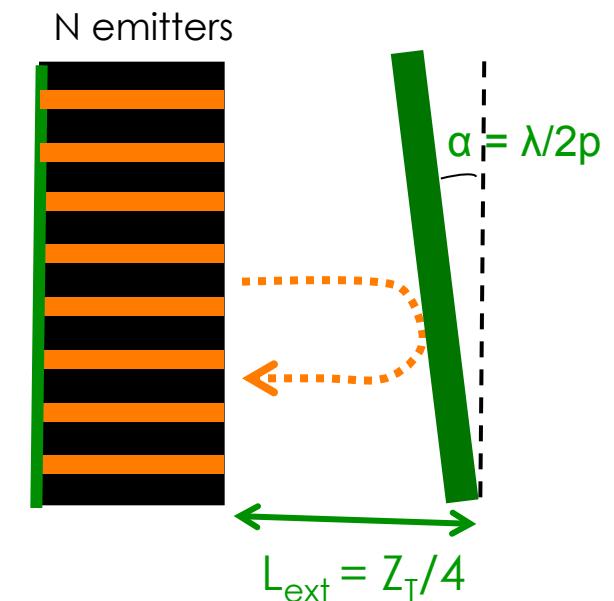
→ self-images (E, φ) at multiples of $\frac{Z_T}{2} = \frac{p^2}{\lambda}$



Near-field propagation of 10 in-phase Gaussian lasers, demonstrating the self-imaging Talbot effect.

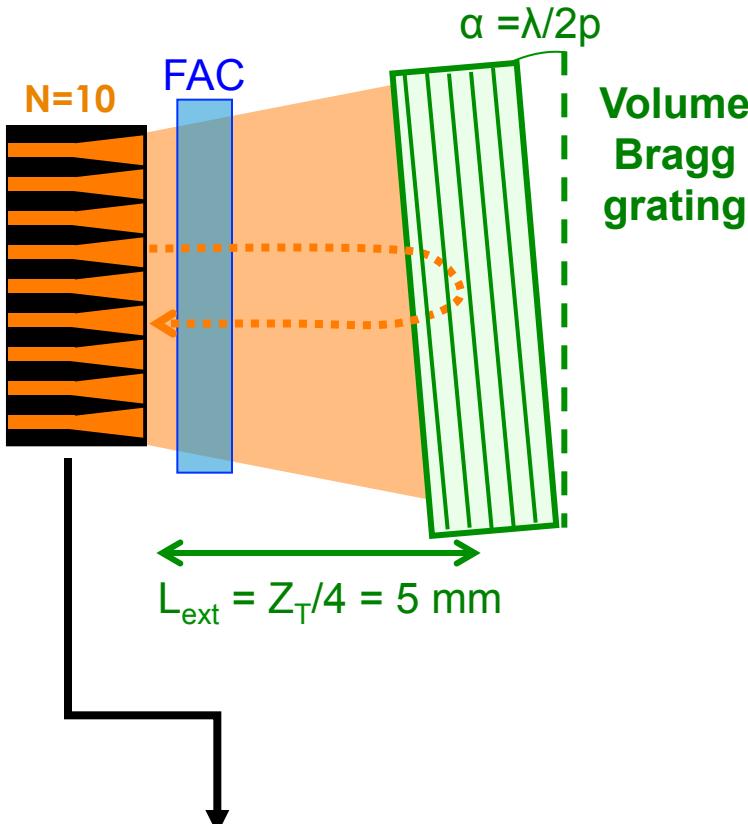


W. H. F. Talbot
"Facts relating to optical science"
Philos. Mag. 9 (1836)



⇒ effect used in an external cavity to maximize the coupling between emitters : maximum back reflection of light for $L_{ext} = Z_T/4$

Passive phase-locking in a Talbot cavity

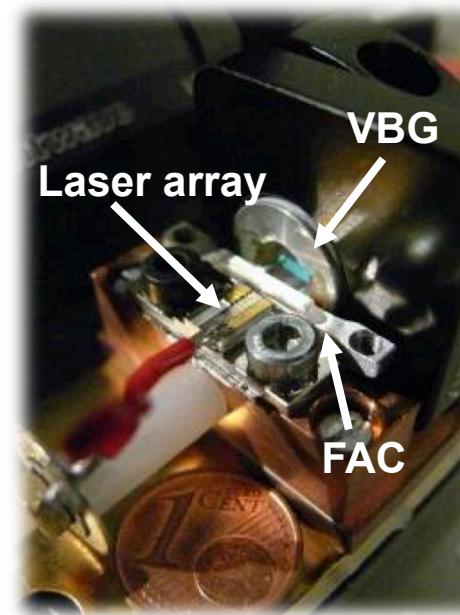


→ Output coupler with angular + spectral selectivity

$$\begin{aligned} R_B &\approx 40\% \\ \lambda_B &= 975.4 \text{ nm}, \Delta\lambda = 0.3 \text{ nm} \\ \Delta\theta &= 2^\circ \text{ (FWHM)} \end{aligned}$$

Array of 10 index-guided tapered emitters
pitch = $100\mu\text{m}$, 0.4W/emitter

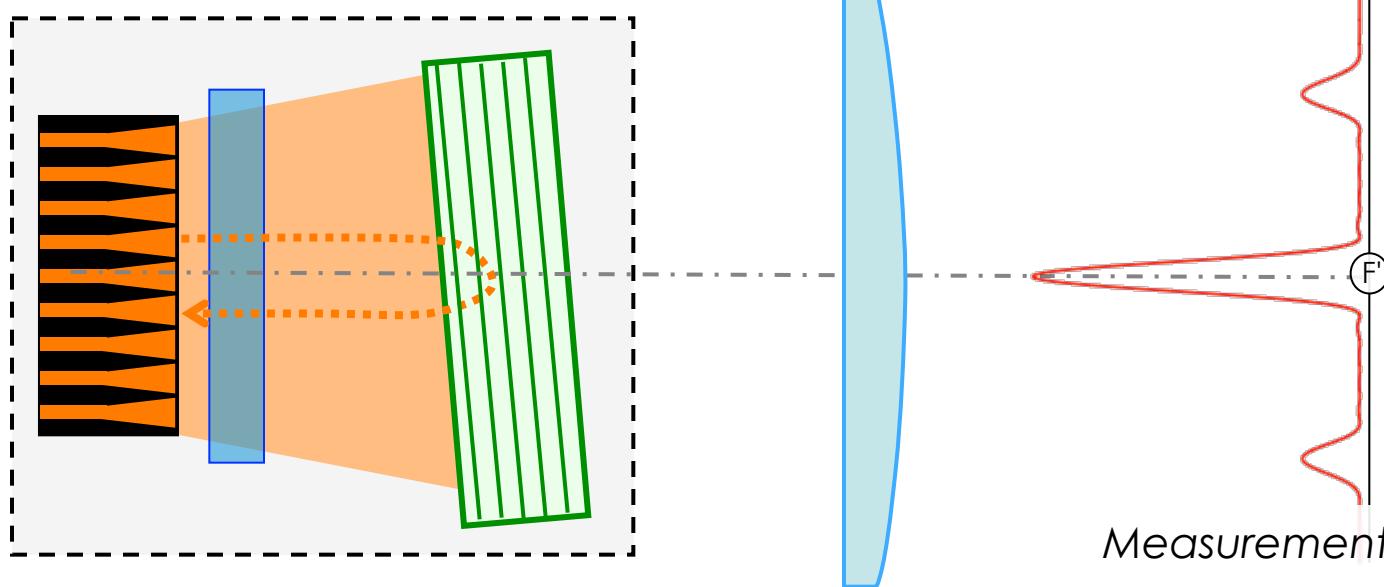
III-V lab
ALCATEL-THALES



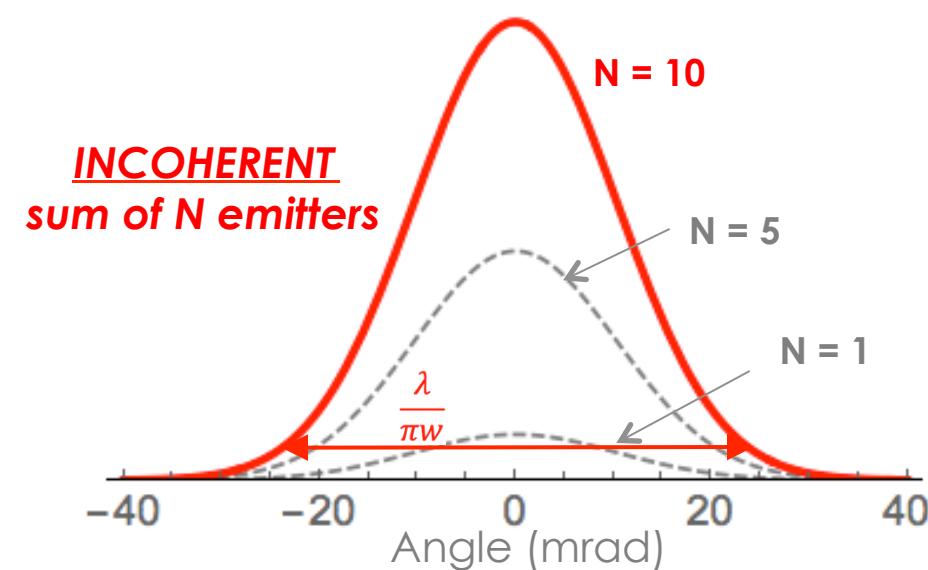
Experimental setup

Evaluation of the coherence of the array

WWW • ★ ★
BRIGHTER • EU
★ ★ ★ ★

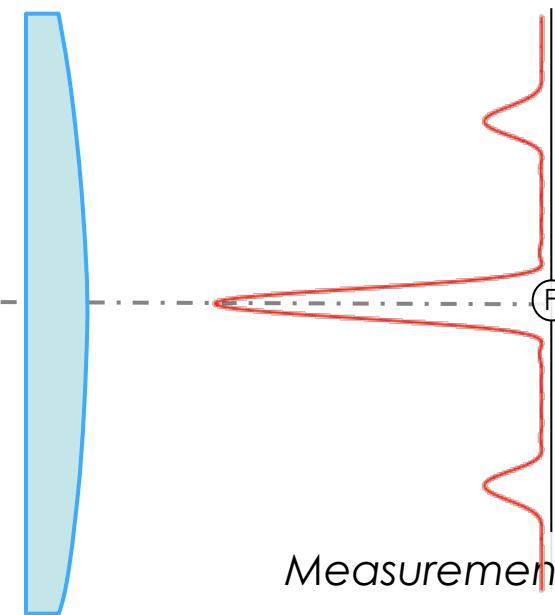
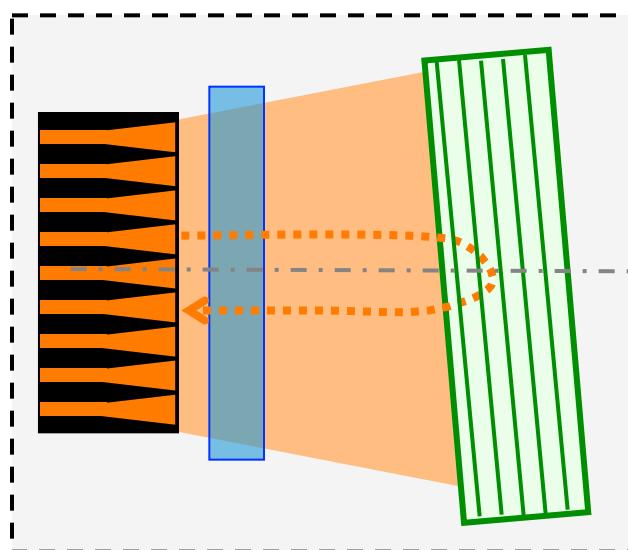


Measurement of the far-field profile



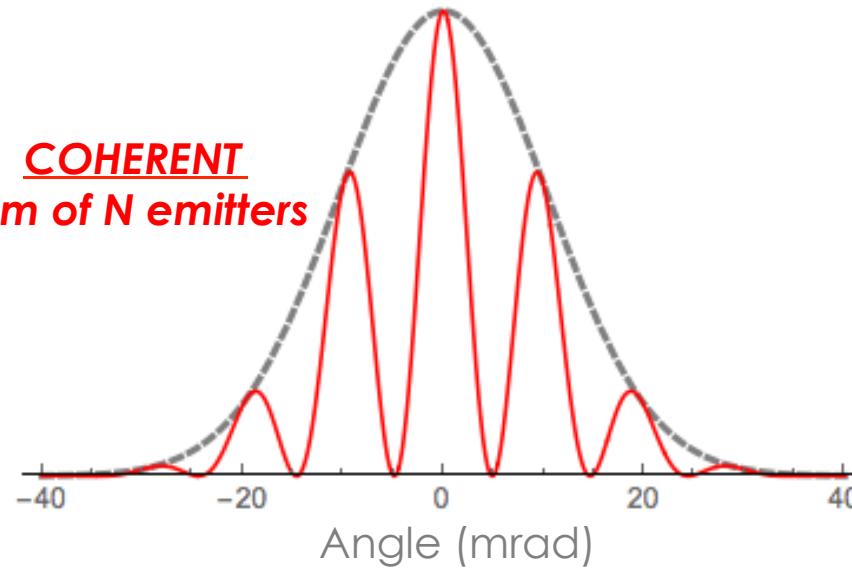
Evaluation of the coherence of the array

WWW • ★ ★
BRIGHTER • EU
★ ★ ★ ★

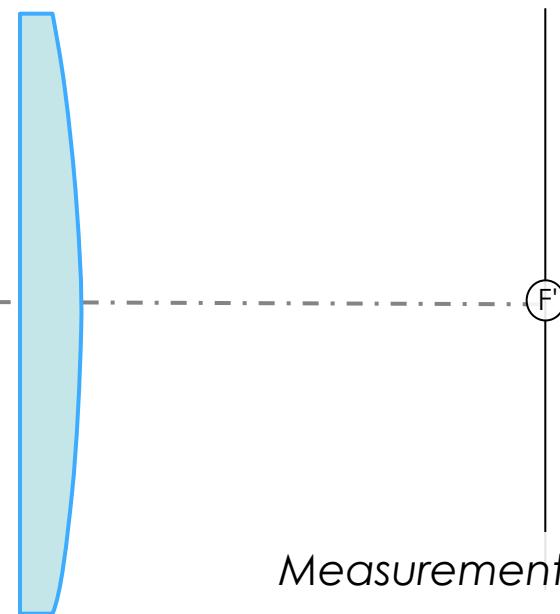
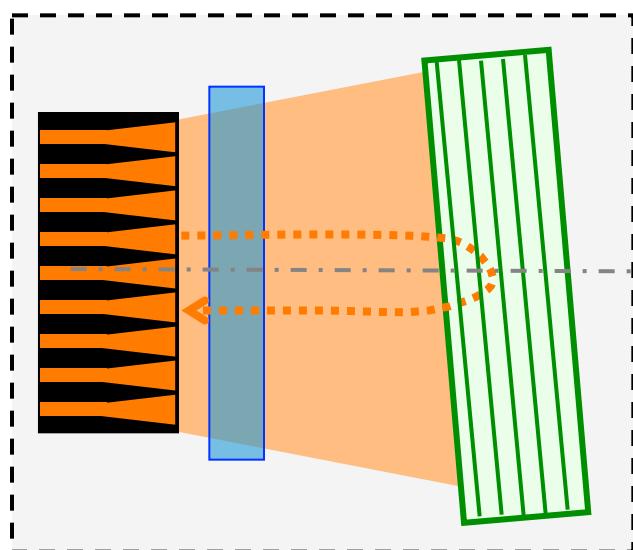


$N = 2$ in-phase emitters

COHERENT
sum of N emitters

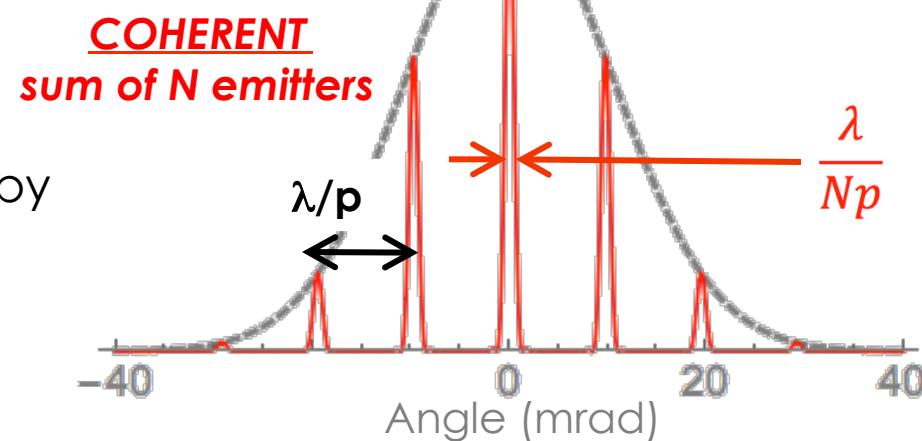


Evaluation of the coherence of the array

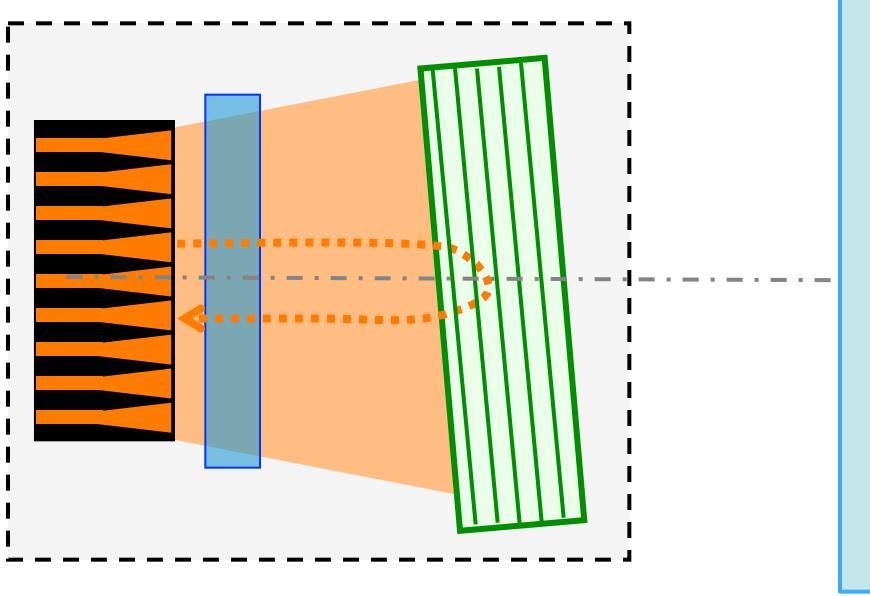


Measurement of the far-field profile

N = 10 in-phase emitters



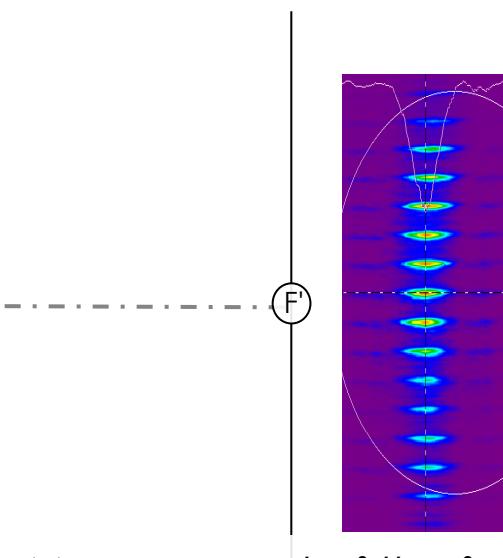
→ Coherent operation is evidenced by
regularly spaced
& narrow peaks
in the FF profile



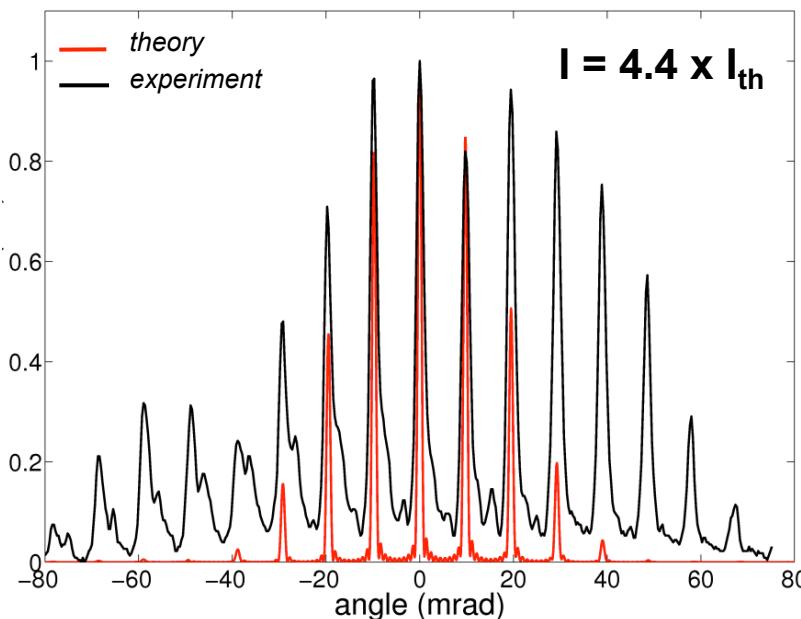
Spectral locking of each laser diodes
Narrow linewidth ($\Delta\lambda < 0.1 \text{ nm}$)

Laser threshold $I_{\text{th}} = 0.9 \text{ A}$
 $P_{\text{max}} = 1.7 \text{ W} @ 4 \text{ A } (4 \times I_{\text{th}})$

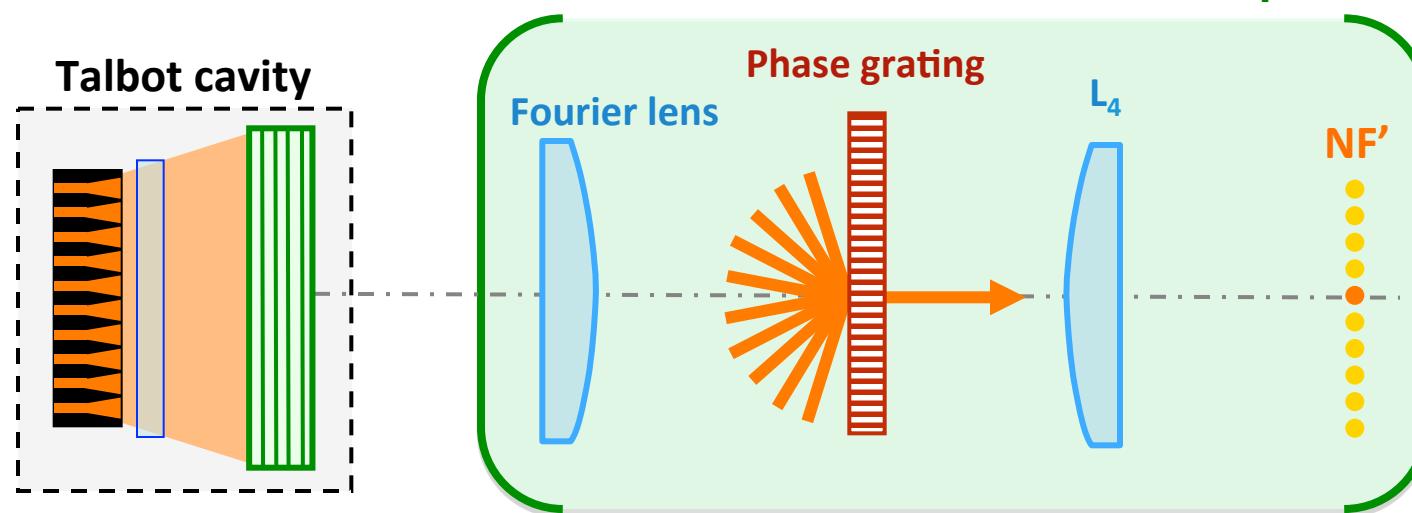
Operation in the in-phase mode
Highly-contrasted fringes in the FF
 $V \geq 80\%$



Measurement of the far-field profile



Extracavity coherent superposition

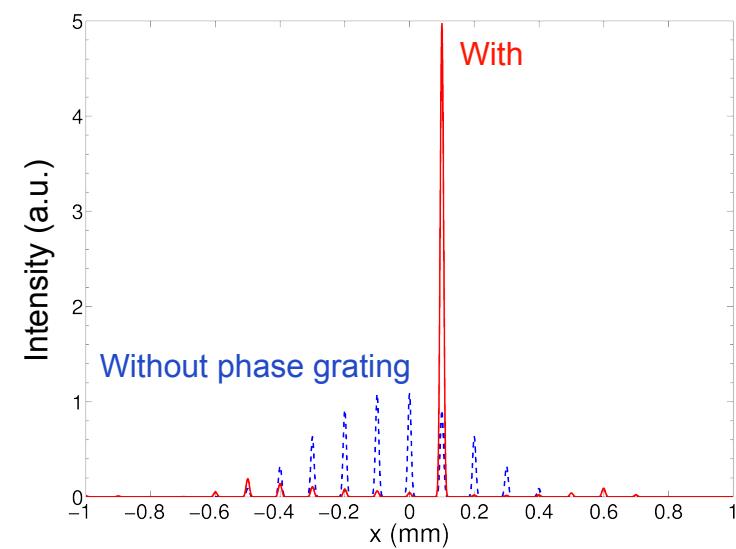


- Passive **phase-locking** of diode lasers in the Talbot external cavity
- + Passive **conversion** of the complex pattern in a Gaussian-like mode

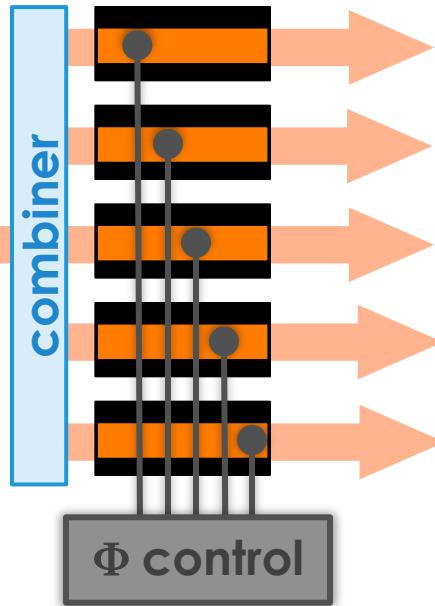
Diffraction of the $N = 10$ coherent beams on a phase grating within 1 direction

⇒ **coherent superposition** of the emitters in the near-field plane NF'

Experimental superposition efficiency $\leq 51\%$



Different architectures for CBC



→ MOPA configuration

= **parallel amplification** of one seed laser in N **amplifiers**

Active electronic feedback

Linear phase-shift with control

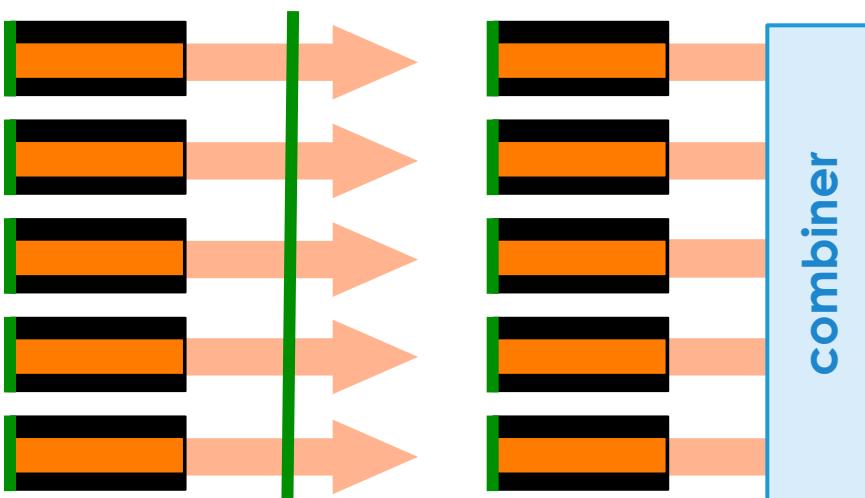
→ Self-organizing lasers

= spontaneous operation in the phase-locked regime of N **lasers**

lasers in a **common external cavity**

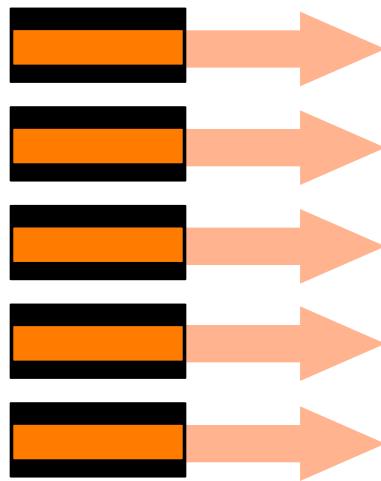
Interferometric resonator

Self-imaging cavity



Passive optical feedback

Highly non-linear behavior



- New interest in coherent beam combining techniques in the laser community (fiber, solid-state, diodes ...)
- Better understanding of the limits
- High-brightness CBC laser sources have been demonstrated
- Scaling to large number of emitters is still challenging.
- Active vs passive ? Electronic vs optic ?
- Detailed analysis of the physics of passively phase-locked lasers still needed.
- Careful design & optimization of the CBC architecture in regard with the devices.
- New results in BRIDLE expected !



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