Coherent beam combining techniques : an introduction

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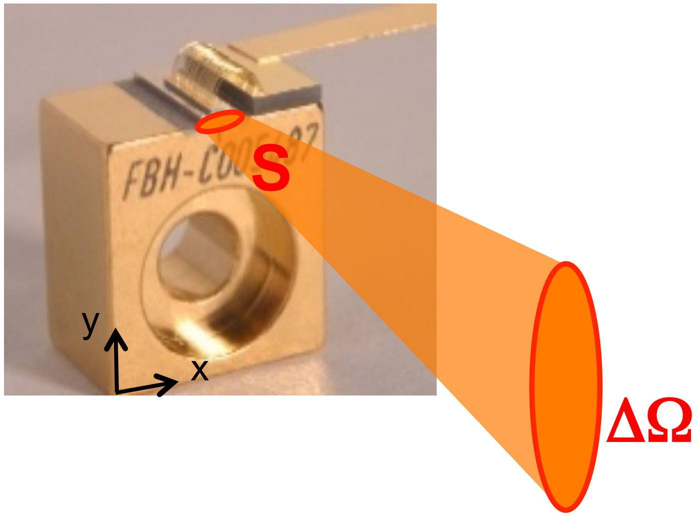
Coherent beam combining of diode lasers:

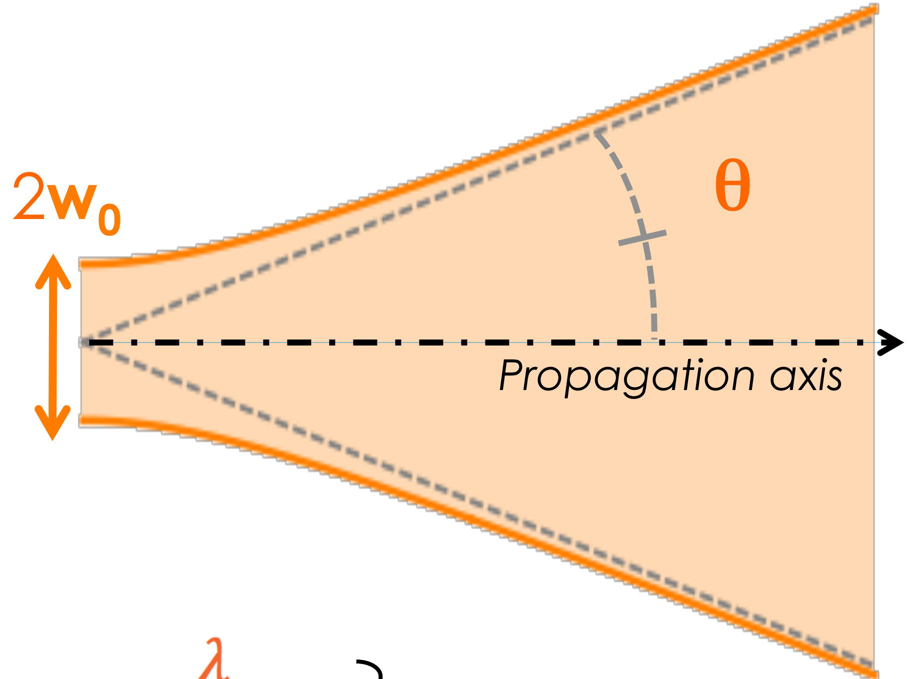
WHY ?	*WARUM ?*
WHAT ?	*WAS?*
HOW ?	*WIE ?*

Outline

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

Laser beam propagation





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

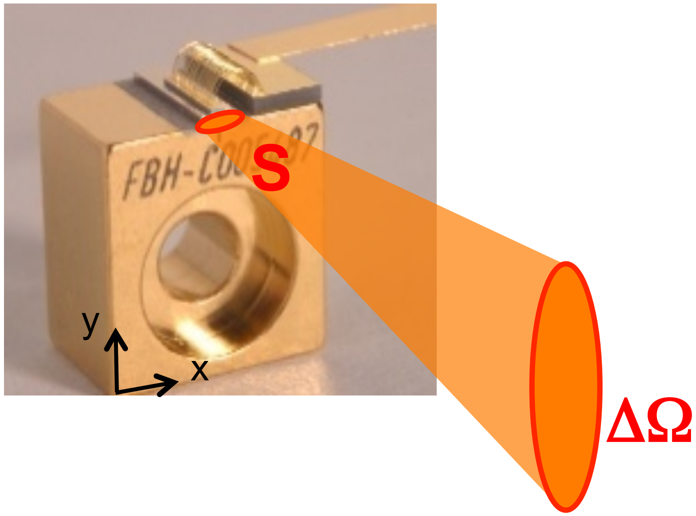
General case : $\theta = M^2 \times \dfrac{\lambda}{\pi w_0}$

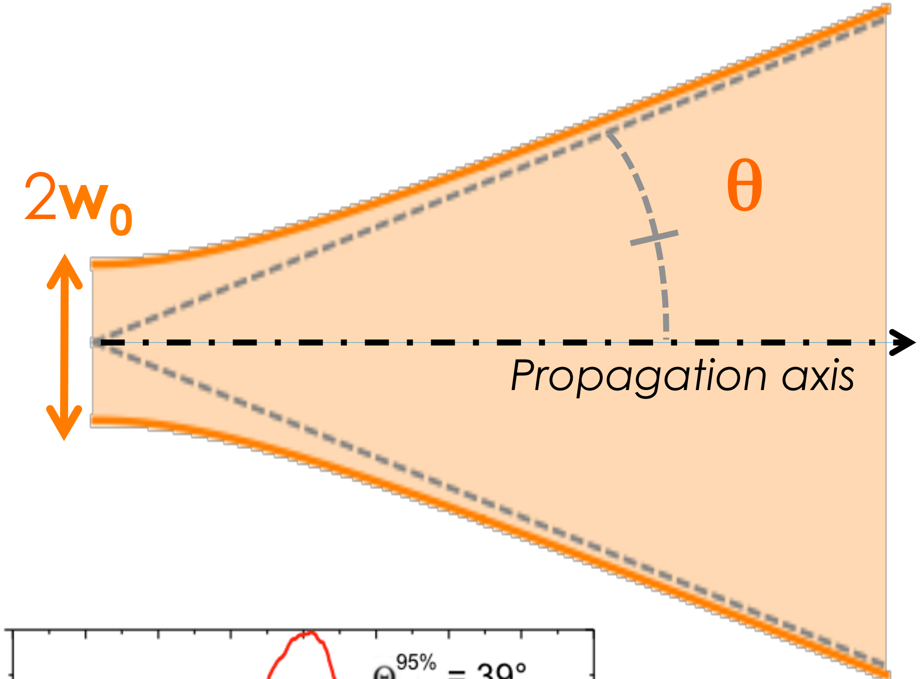
in both x/y axes

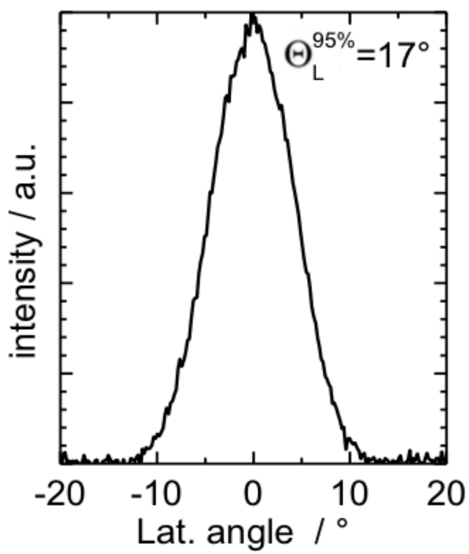
Beam quality parameter

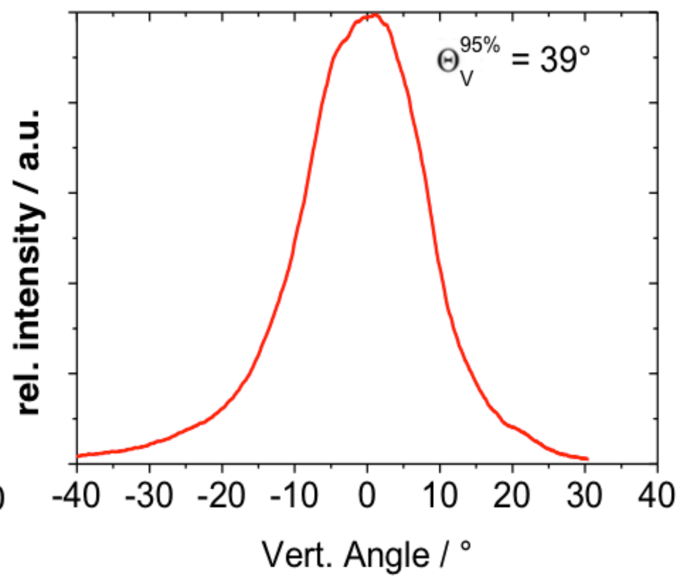
Beam parameter product : $BPP = \theta \times w_0 = M^2 \times \dfrac{\lambda}{\pi} \cong 0.3 \times M^2$ @ λ = 1 µm

Laser beam propagation : diode lasers

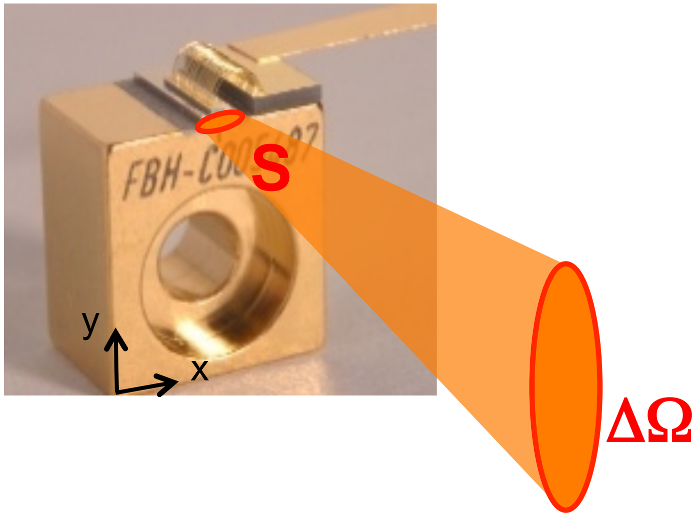








What is the brightness of a laser source ?



→ **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

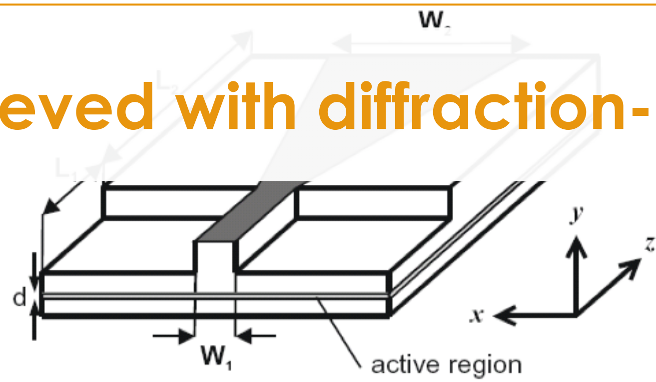
What is the brightness of a laser source ?

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^2_x x M^2_y	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 $MW.cm^{-2}.sr^{-1}$

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

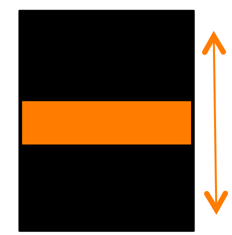
⇒ damages & deterioration of lasers

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

↗ output power

⇒ increase the active volume

⇒ beam quality ↘

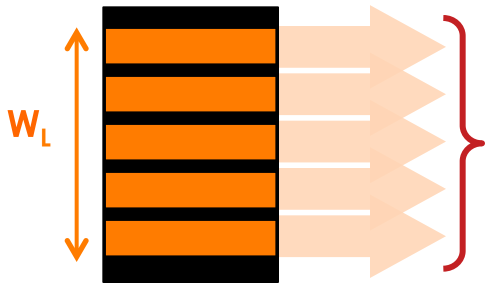


↗ **output power** by **combining** parallel laser sources while maintaining the **beam quality**

= beam combining

Beam combining architectures

- Incoherent (*side-by-side*) combining

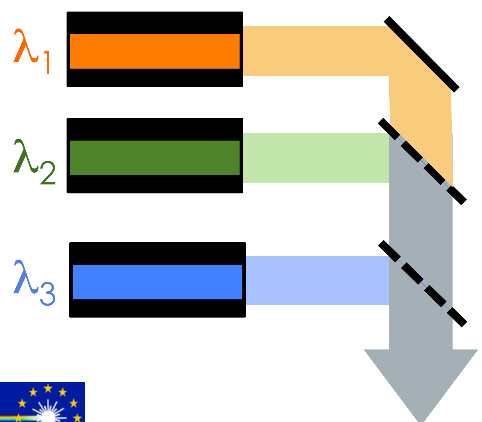


$\nearrow$ W_L but same divergence θ

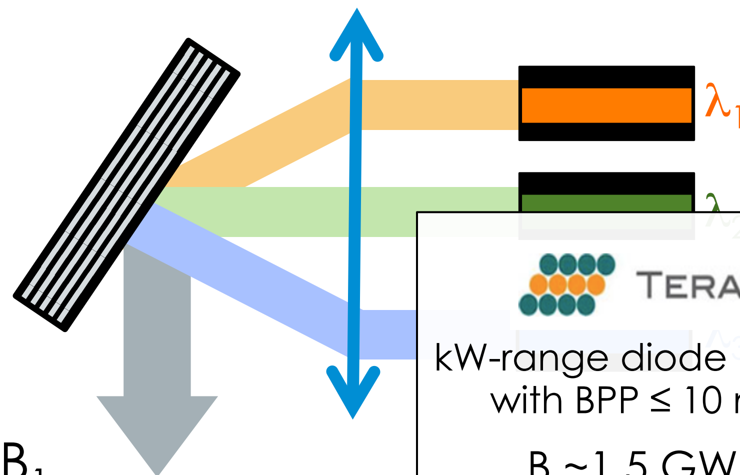
$B_{bar} \leq B_1$

- Spectral beam combining

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



$B_{SC} = N \times B_1$



TERADIODE

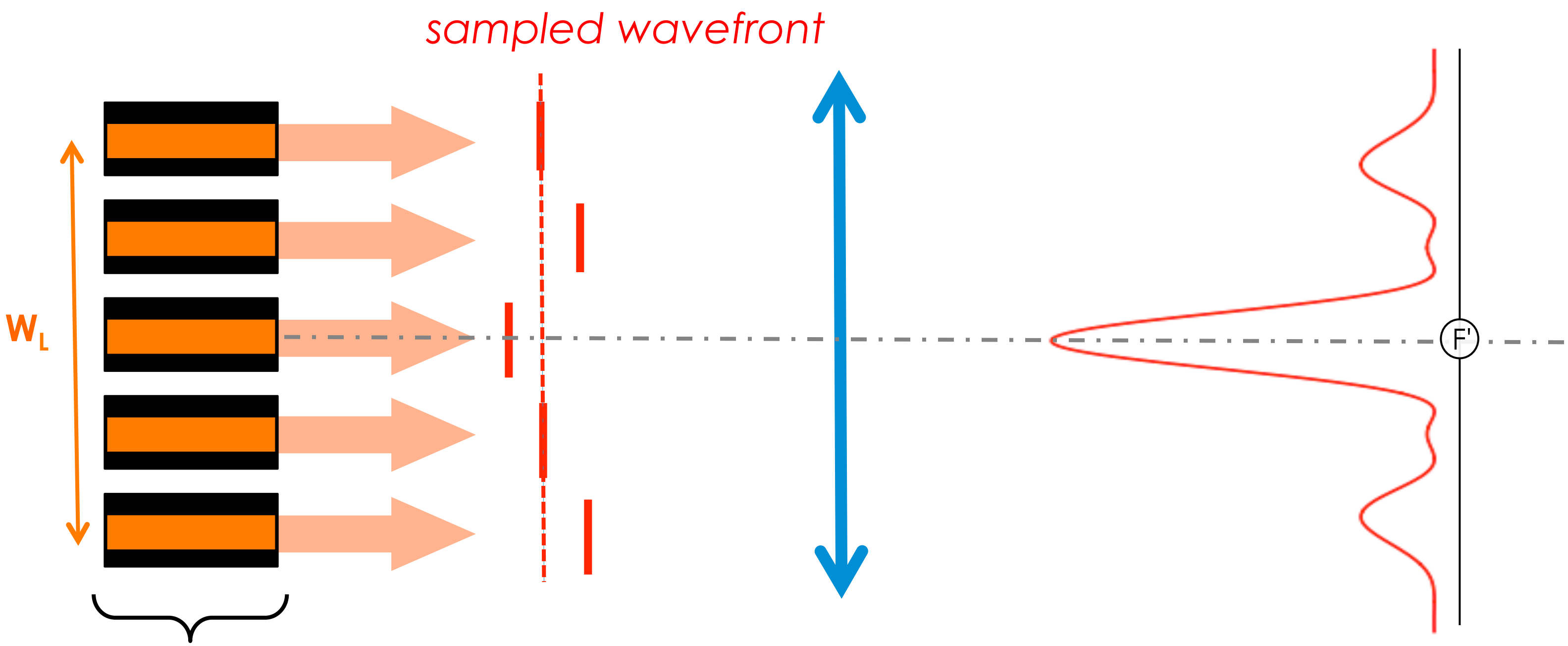
kW-range diode laser systems with BPP ≤ 10 mm.mrad

B ~1.5 GW/cm²/sr

BRIDLE

Coherent Beam Combining

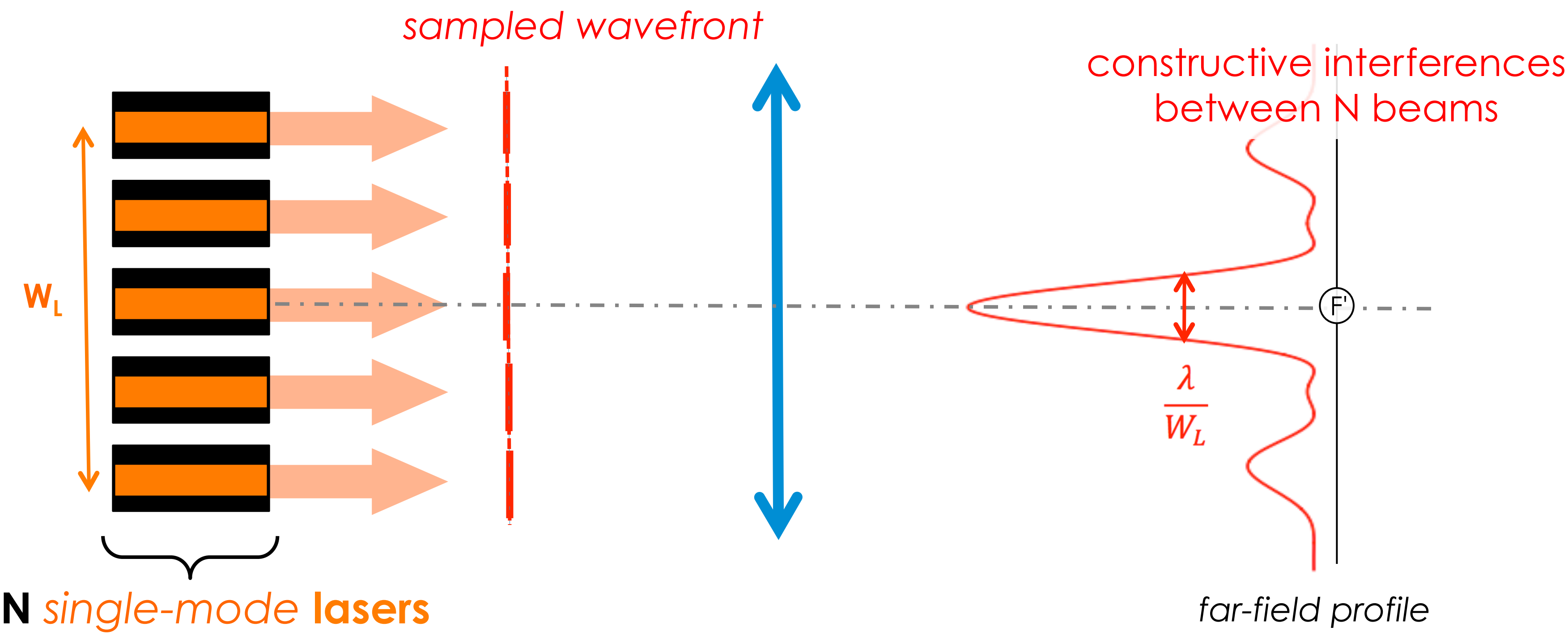
= **constructive superposition** of N laser beams with proper phase relationship



N *single-mode* **lasers**
in parallel
Below damages thresholds
Good beam quality

Coherent Beam Combining

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



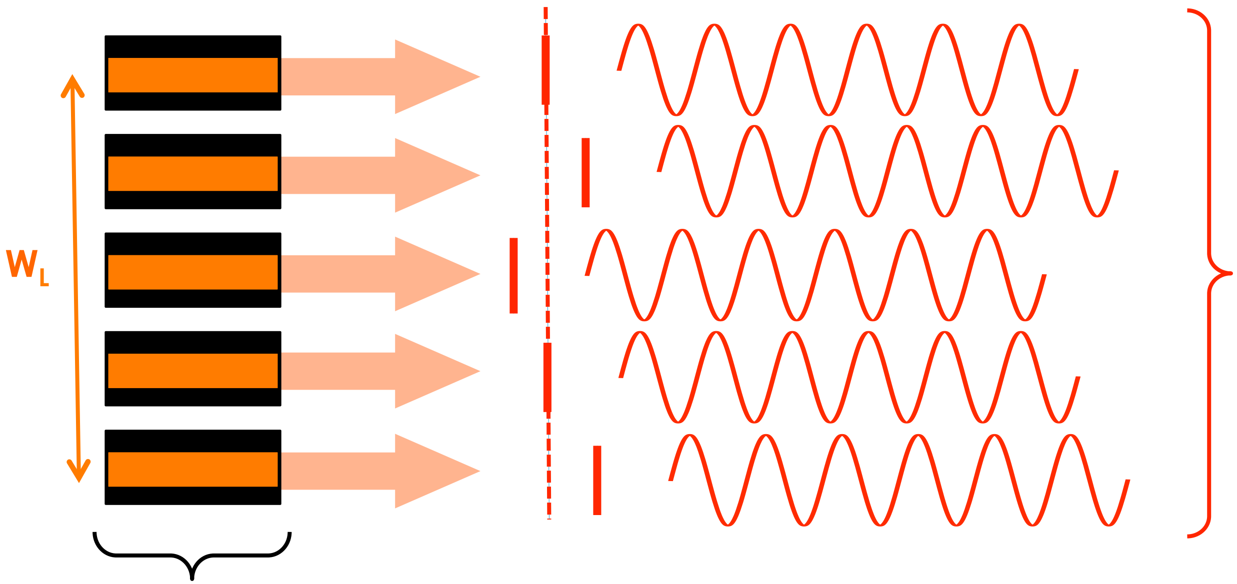
N *single-mode* **lasers**
in parallel
Below damages thresholds
Good beam quality

$$B_{CBC} = \frac{N \times P_1}{\lambda^2 \times M_x^2 M_y^2} = \boldsymbol{N \times B_{single}}$$

↗ output power
↗ emission width W_L & ↘ divergence θ } ⇒ ↗ **spatial brightness** + narrow $\Delta\lambda$

Coherent Beam Combining

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



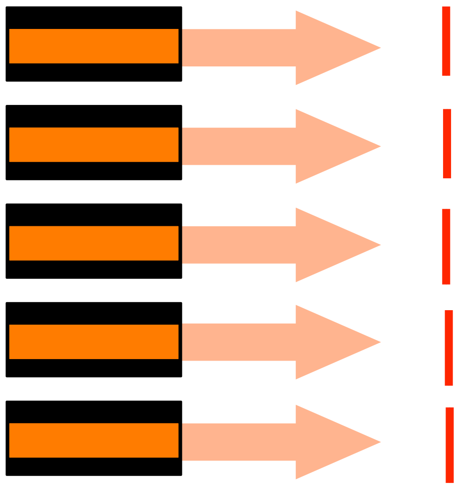
N *single-mode* **lasers in parallel**

Below damages thresholds

Good beam quality

coherent emission = constant phases

Different architectures for CBC



→ <u>MOPA configuration</u>

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

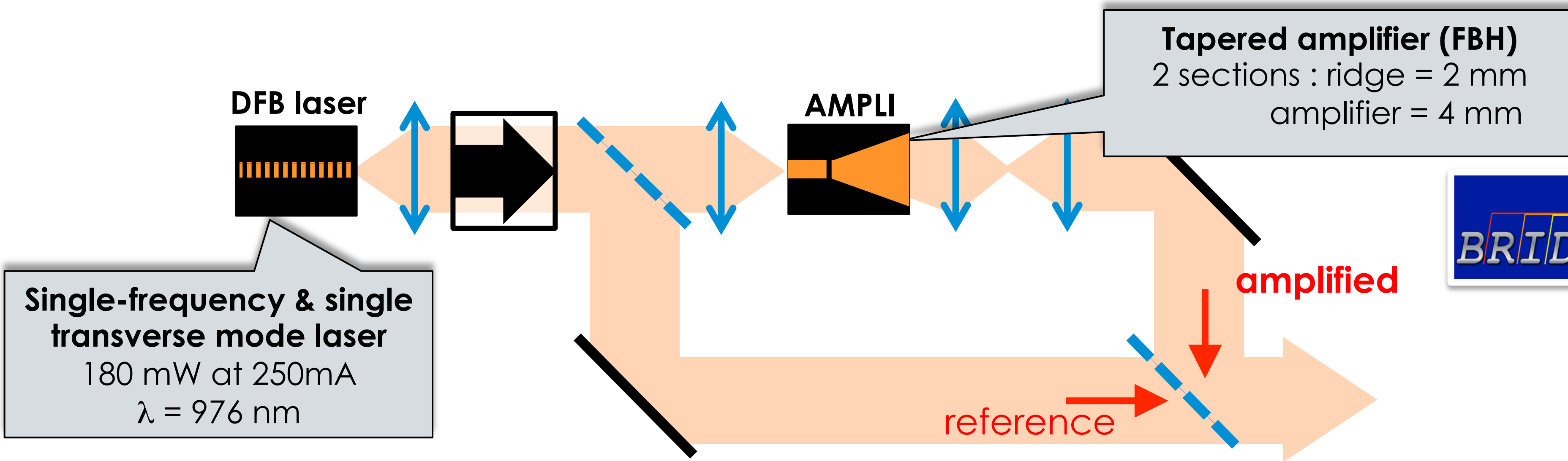
MOPA = Master Oscillator – Power Amplification

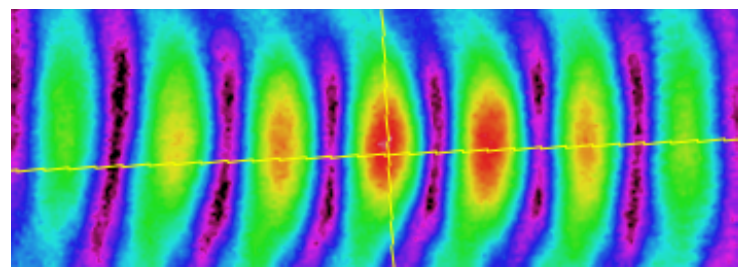
→ <u>Self-organizing lasers</u>

= 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 :





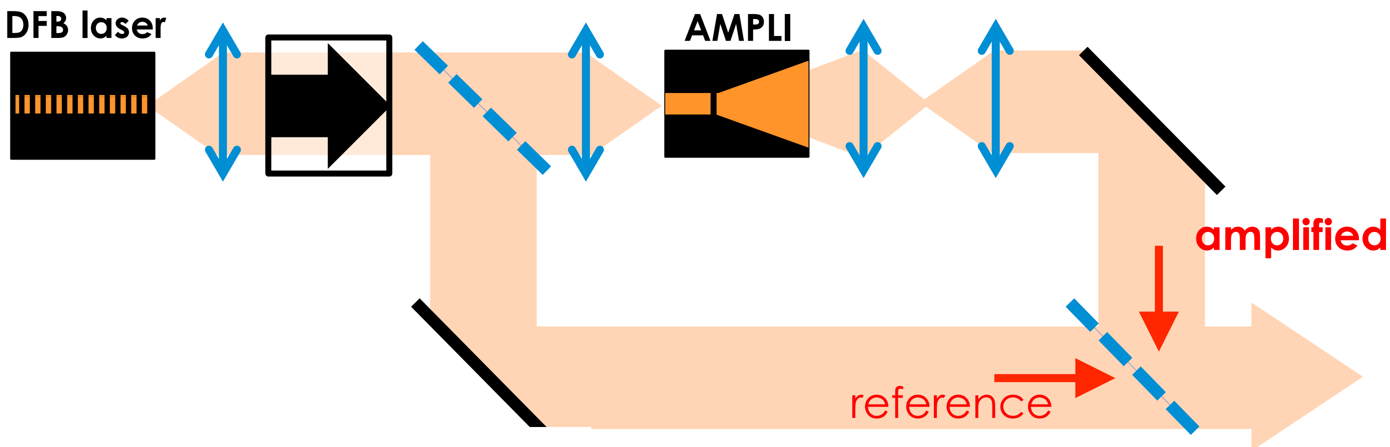
We observe highly-contrasted fringes on the combined port

⇒the seed and amplified beams are phase-locked

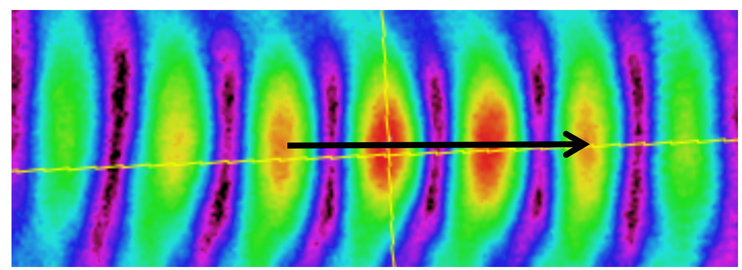
⇒ the coherence between them is ≥ 96 %

Master Oscillator Power Amplification

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



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

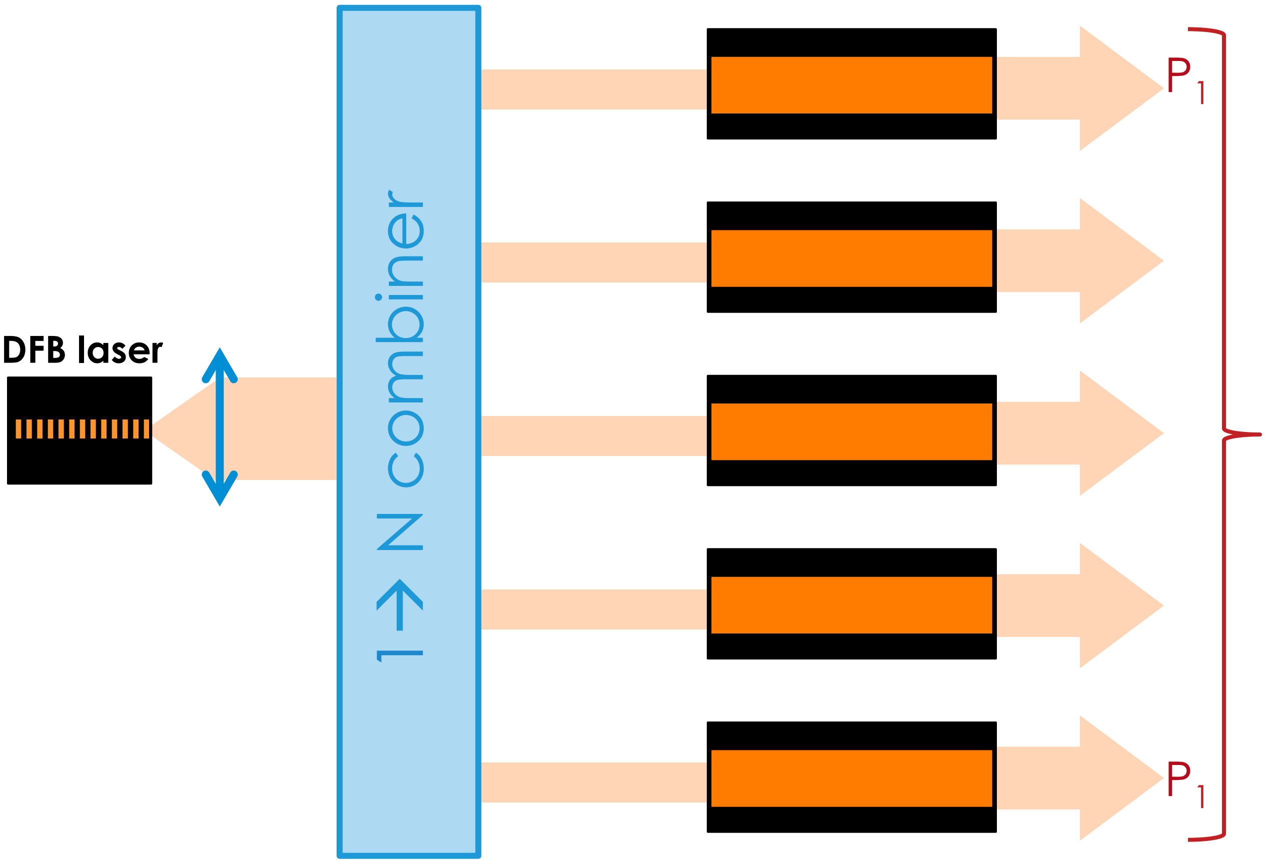


Phase-shift with ridge current

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

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



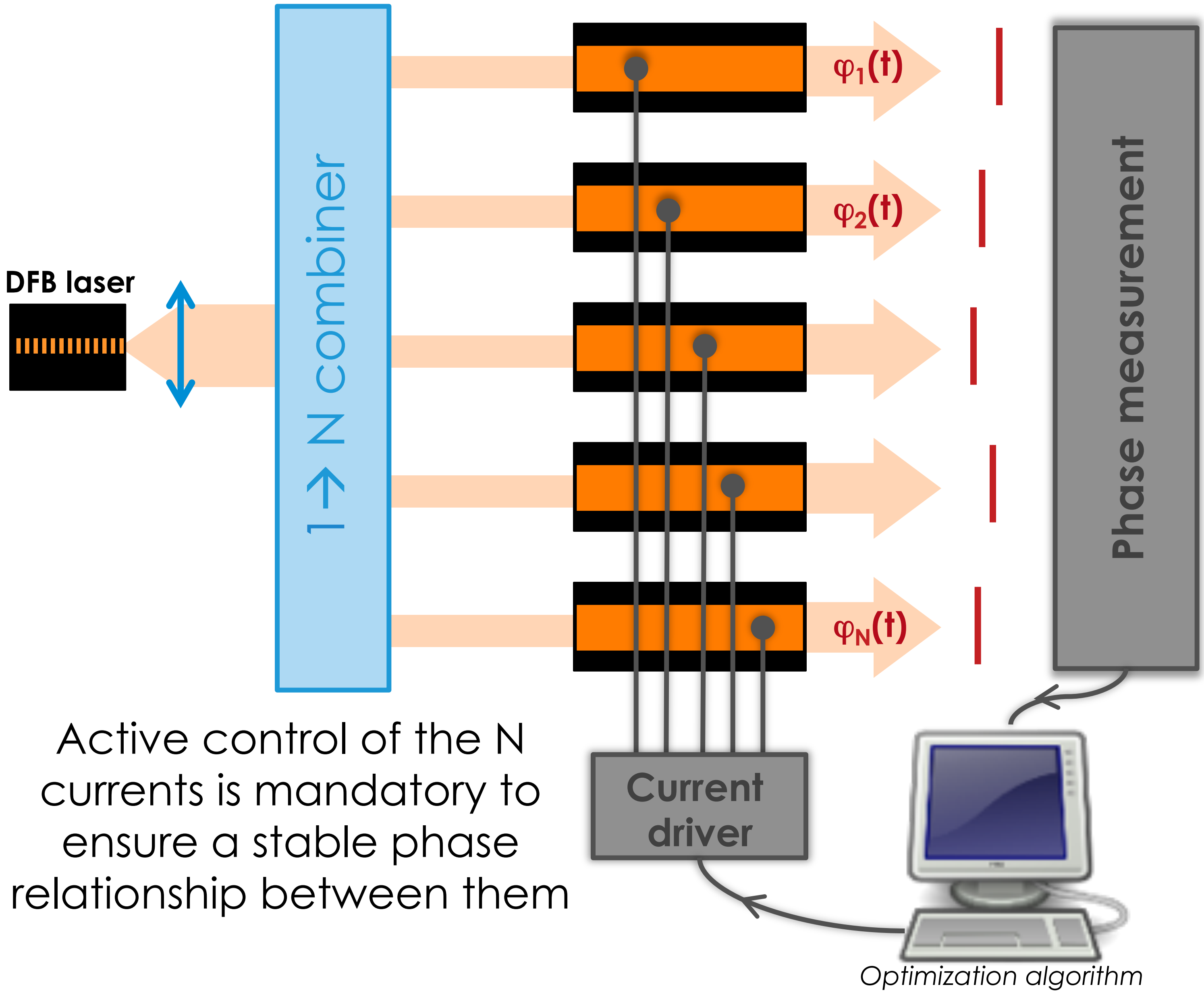
Increase of the total power ∝ N

$P = N \times P_1$

below damage & nonlinearities thresholds for each element

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

Phase-locking in a MOPA architecture



Active control of the N currents is mandatory to ensure a stable phase relationship between them

Active phase-locking of a SCOWL array

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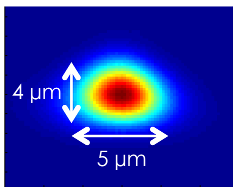
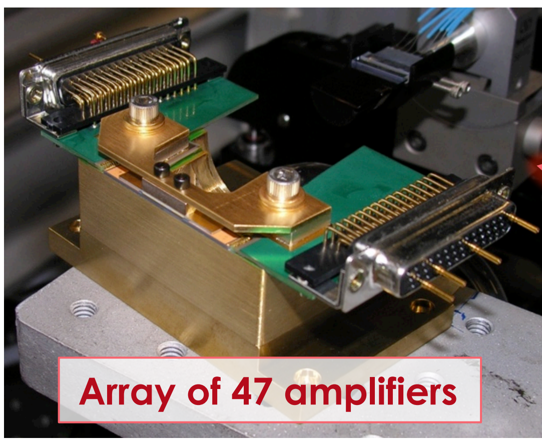
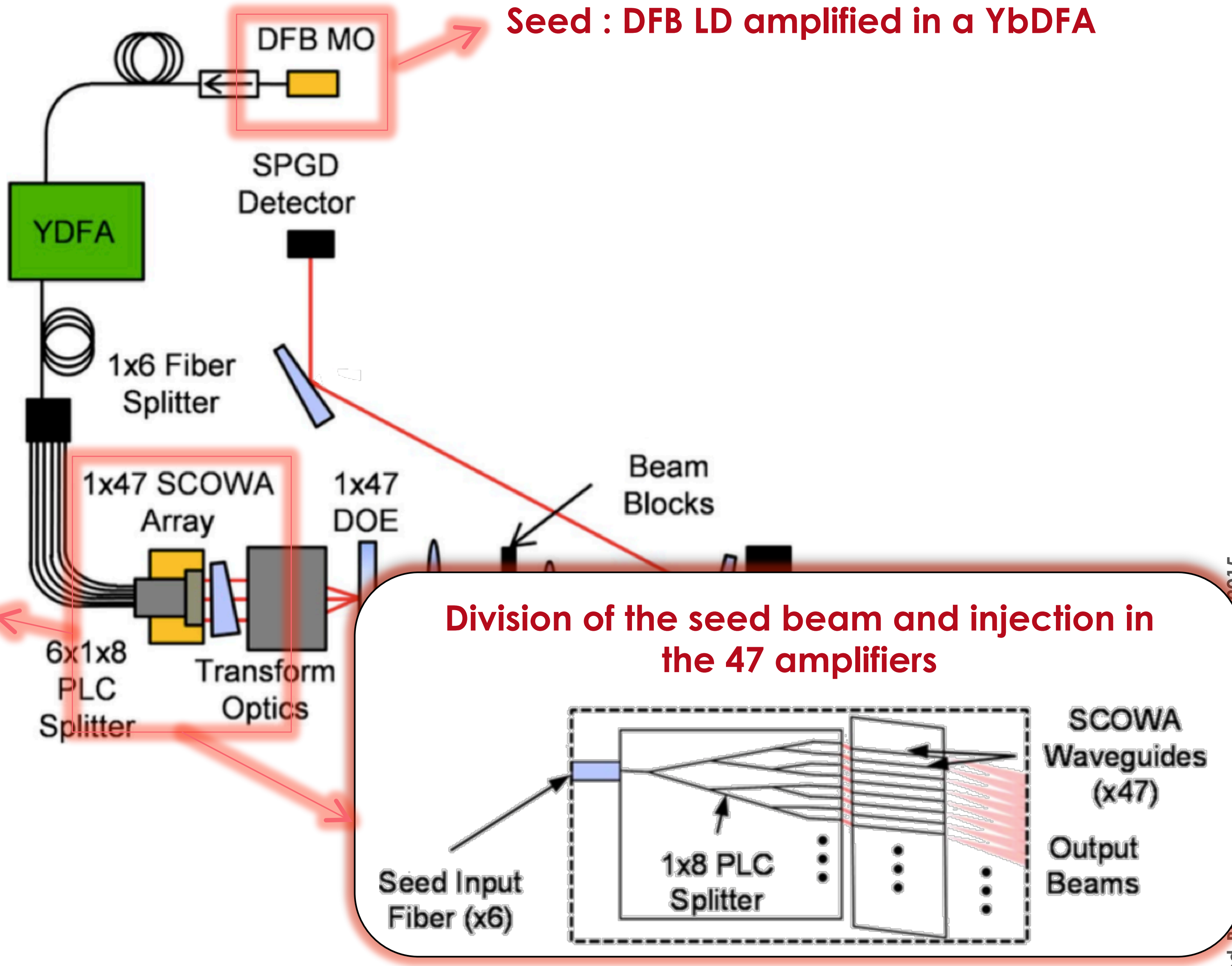
LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Single Element Near Field

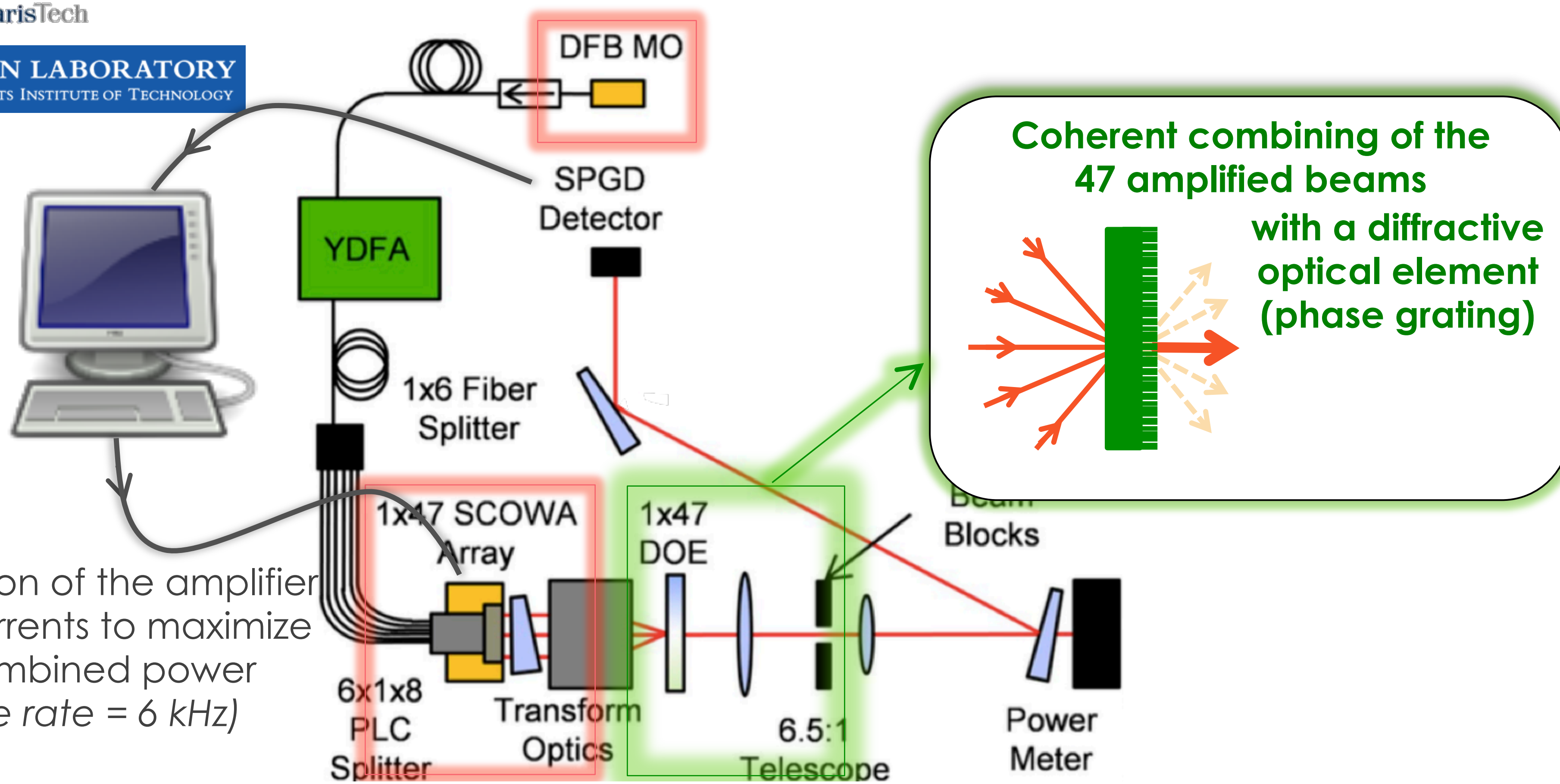






Creedon et al, "High efficiency coherent beam combining of semiconductor optical amplifiers" , Optics Letters **37**, 23 p5006 (2012)

Active phase-locking of a SCOWL array



Optimization of the amplifier driving currents to maximize the combined power *(udate rate = 6 kHz)*

→ Demonstration of the **active phase-locking** & **coherent beam combining** of 47 semiconductor amplifiers

→ **Total output power = 40 W** with η_{CBC} = 87% : B ~ 2.5 GW.cm^{-2}.sr^{-1}

$B_{SC} = 25 \times B_1$

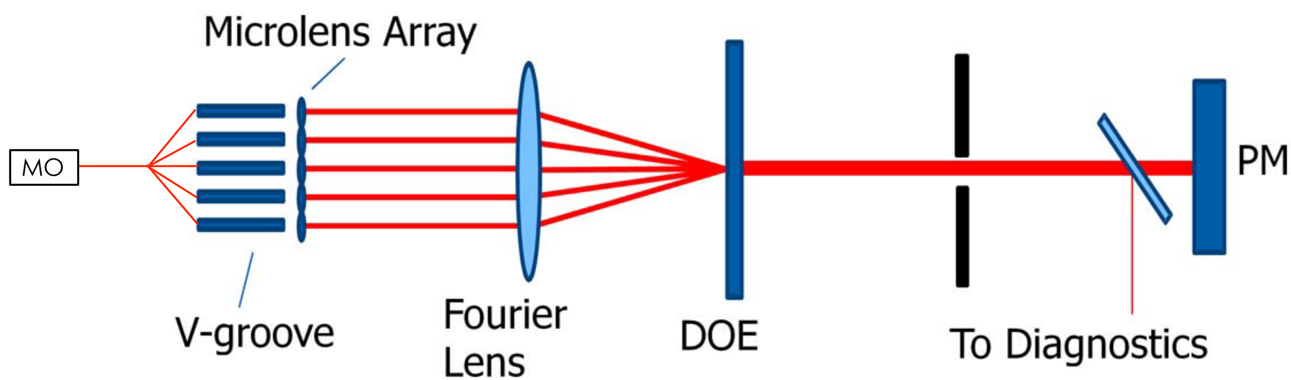
Creedon et al, "High efficiency coherent beam combining of semiconductor optical amplifiers" , Optics Letters **37**, 23 p5006 (2012)

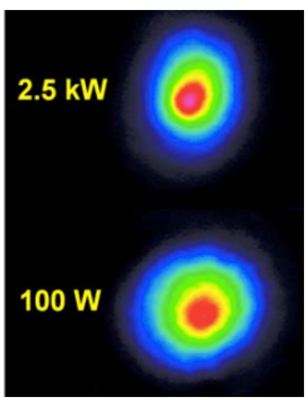
Also with fiber lasers in CW …

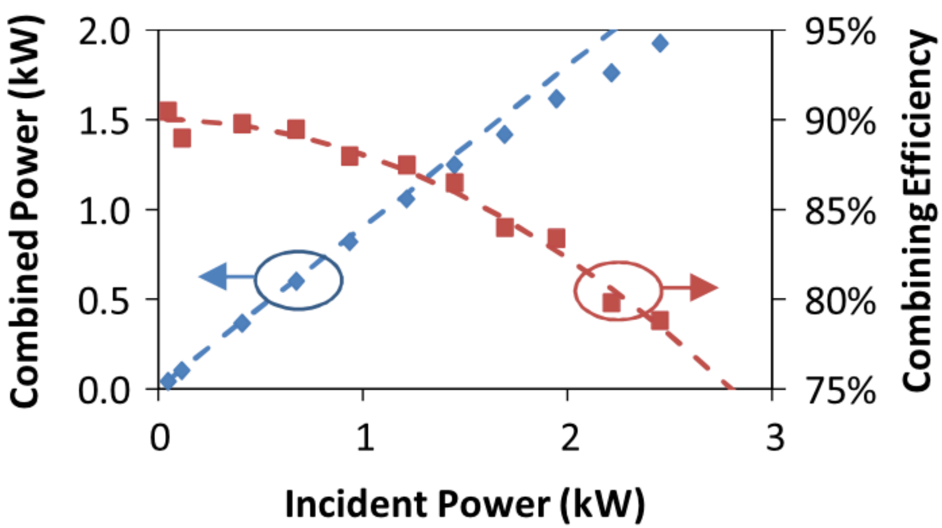
5 x 500 W Yb doped fibers amplifiers : **1.93 kW combined**

79 % efficiency, $M^2 = 1.1$

LOCSET active feedback





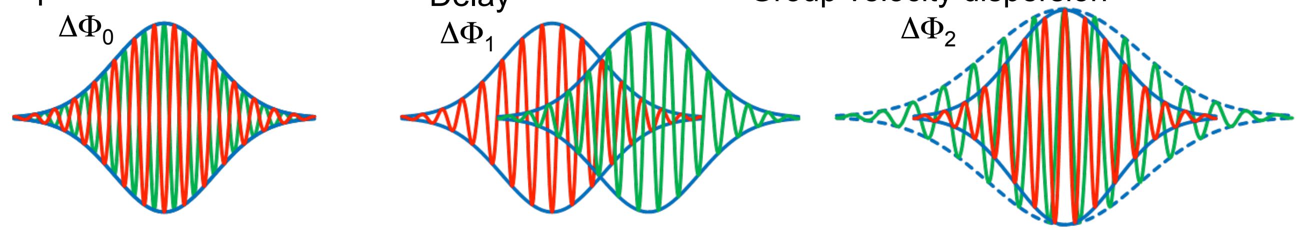


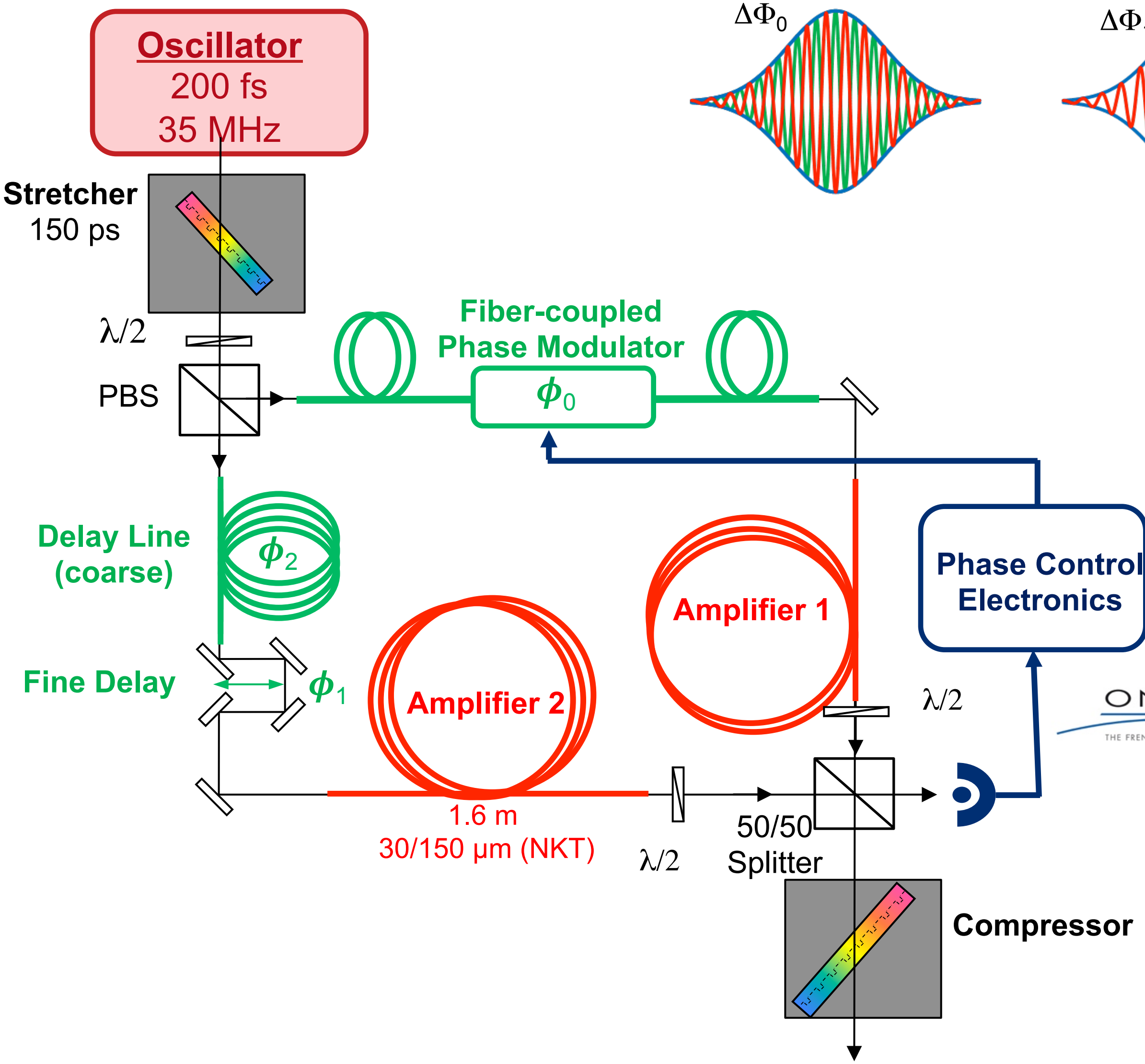
NORTHROP GRUMMAN

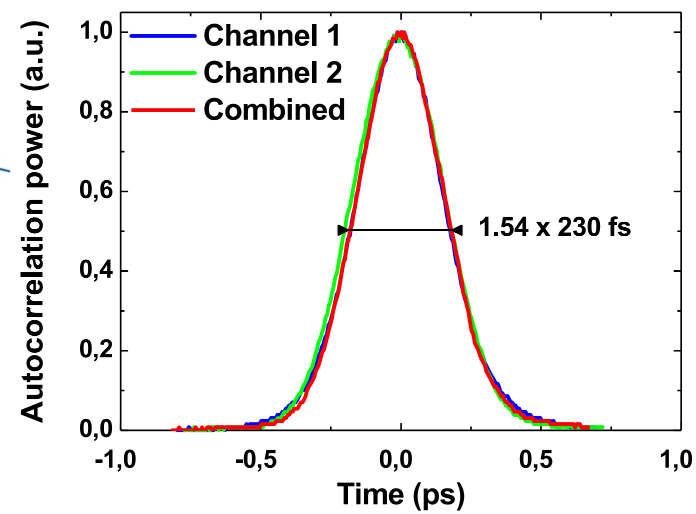
Massachusetts Institute of Technology

Redmond et al., "Diffractive coherent combining of a 2.5 kW fiber laser array into a 1.9 kW Gaussian beam," Opt. Lett. **37**, 2832-2834 (2012)

And even in fs regime



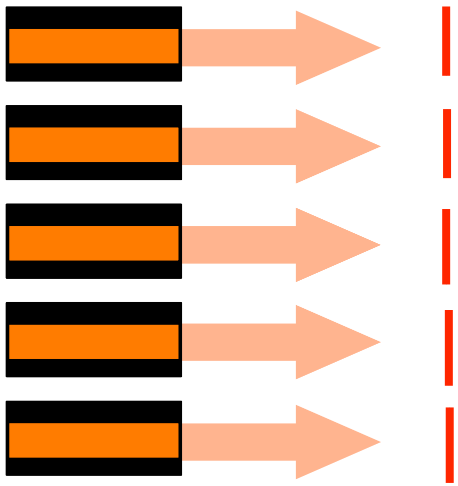




$P_{combined}$ = 1.97 W *(92%)*

L. Daniault et al., "Coherent beam combining of two femtosecond fiber chirped-pulse amplifiers," Opt. Lett. 36, 621-623 (2011)

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

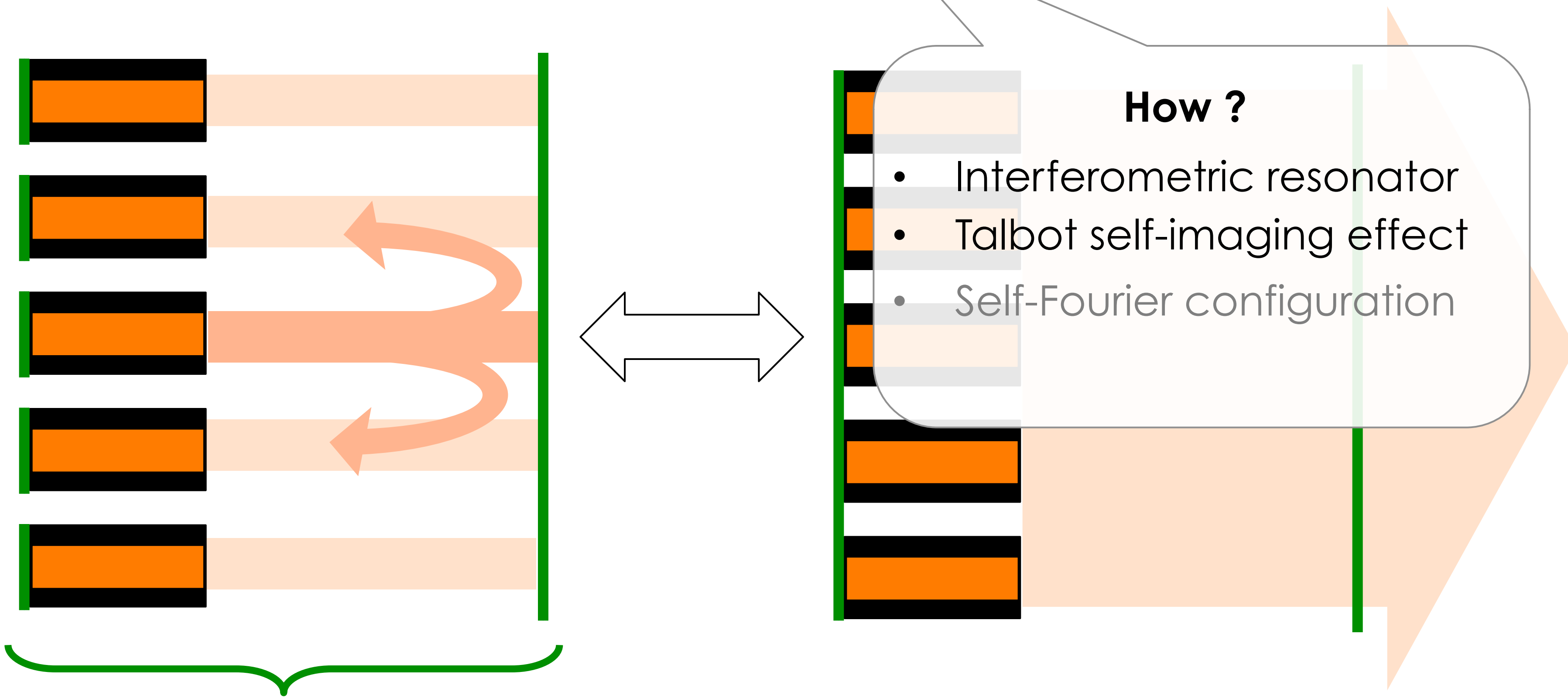
  Diode Laser Arrays, ed. Botez & Scifres (Cambridge Studies in Modern Optics)

- lasers sharing a common external cavity

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



How ?

- Interferometric resonator
- Talbot self-imaging effect
- Self-Fourier configuration

External cavity

The laser array operates as a sampled gain medium in a single cavity

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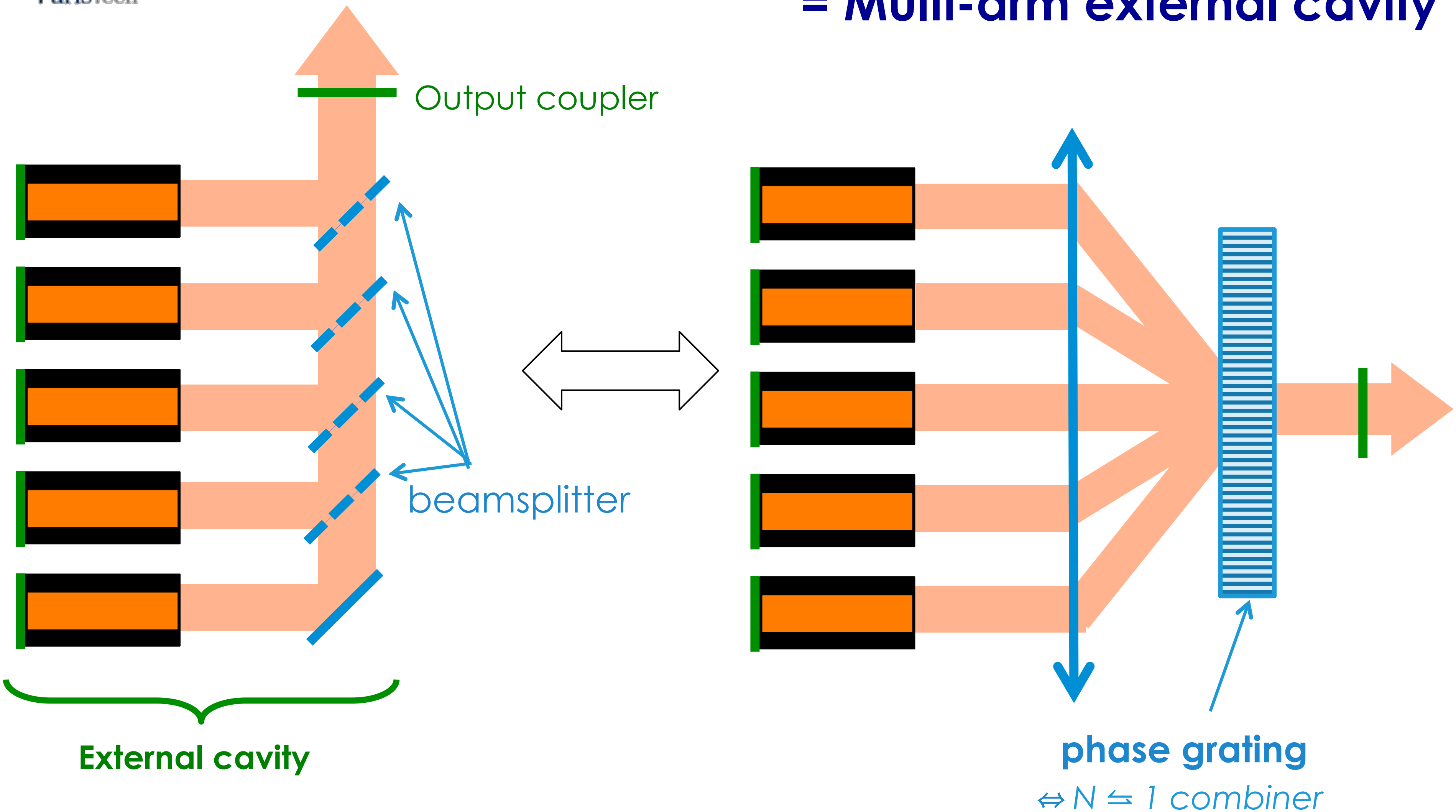
Interferometric resonator

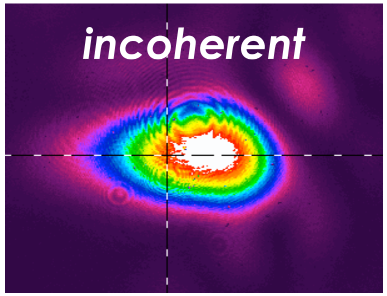
= Multi-arm external cavity

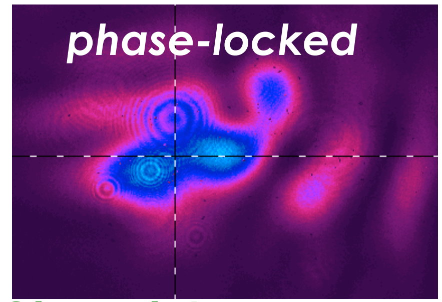


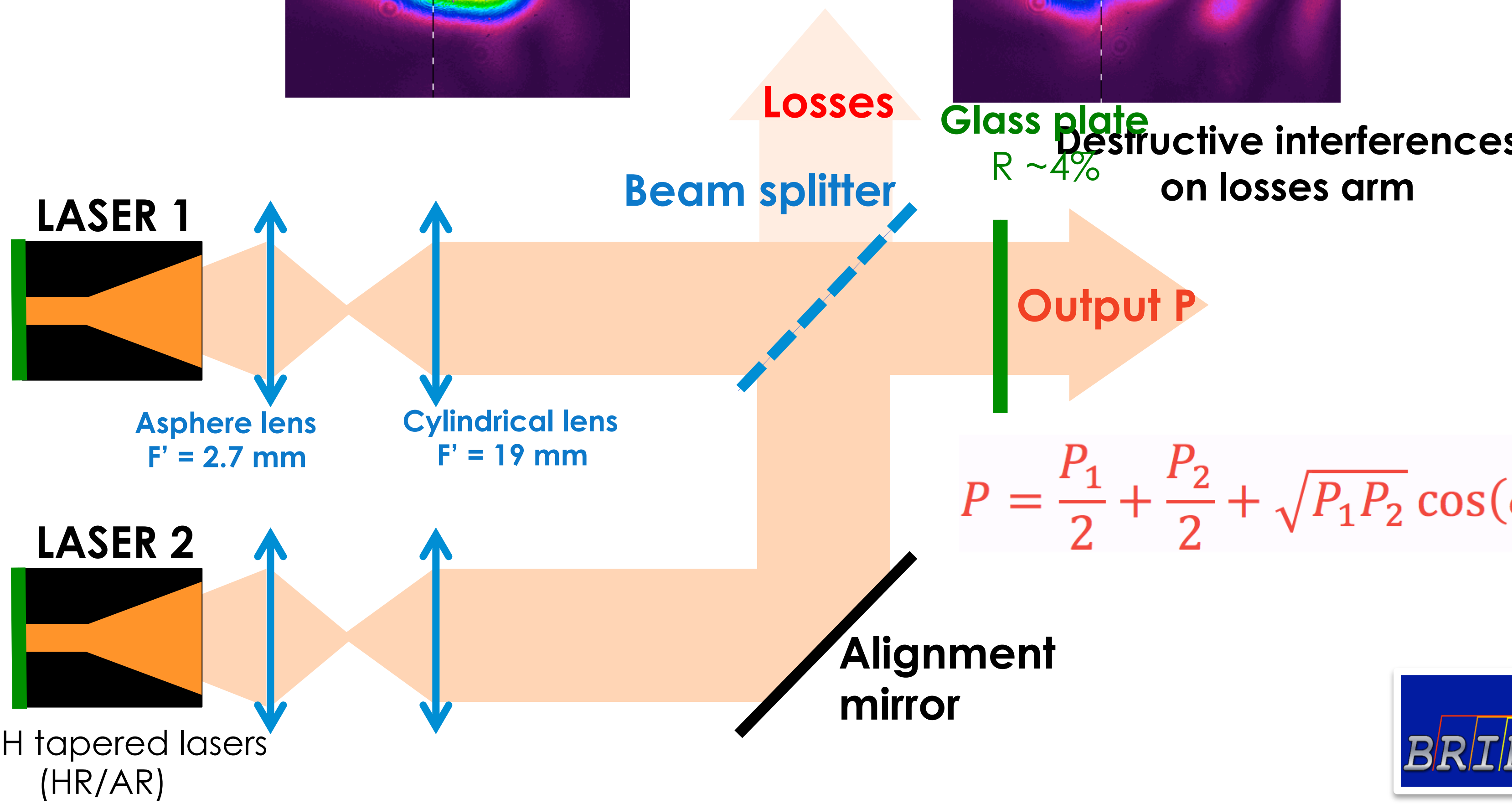
The external cavity favours constructive interferences between the multiple beams.

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



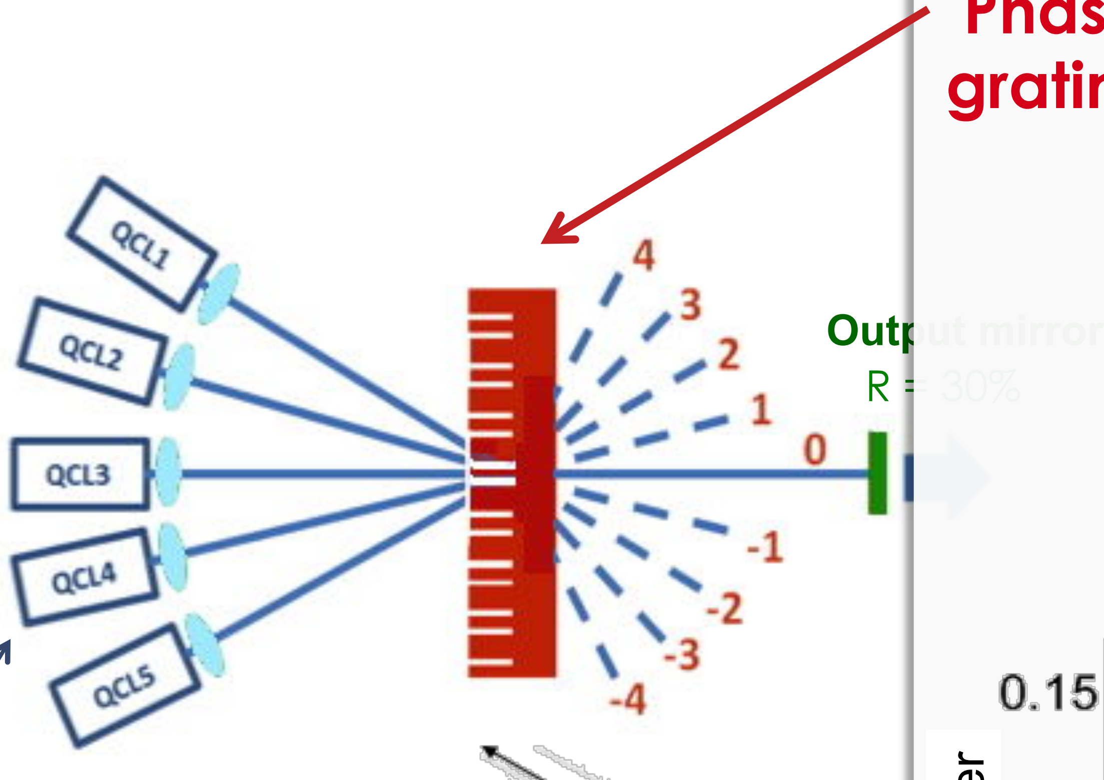


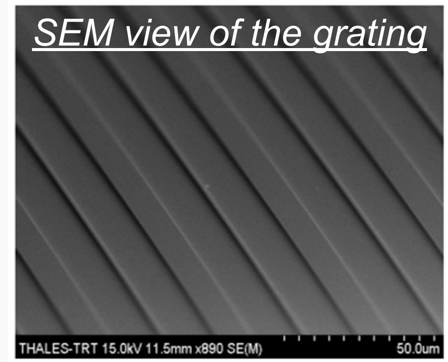


$$P = \frac{P_1}{2} + \frac{P_2}{2} + \sqrt{P_1 P_2}\cos(\varphi_2 - \varphi_1)$$

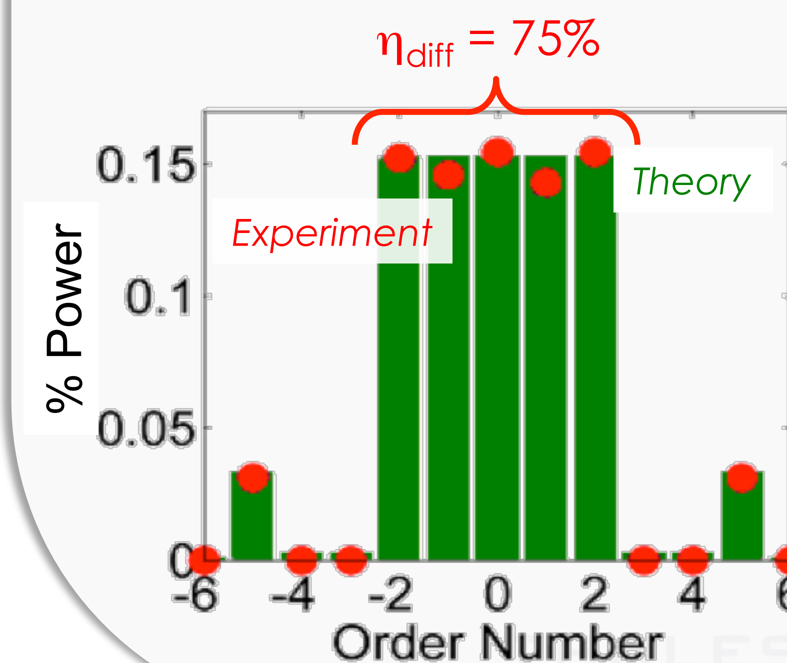
5-arm external cavity

Phase grating





Binary phase grating (0 - π)
1⥦ 5 combiner at λ = 4.65µm
Pitch Λ = 50 µm



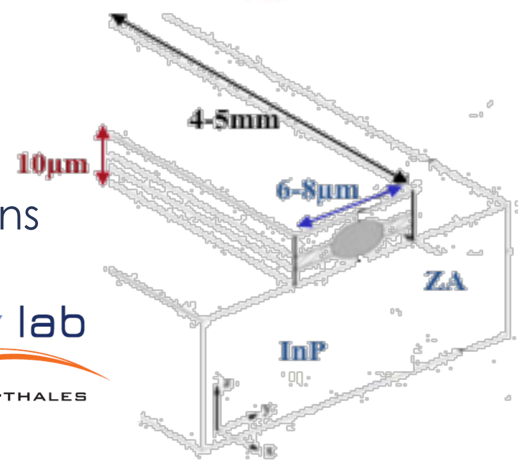
Quantum Cascade Lasers

λ = 4.6 µm

GaInAs/AlInAs active regions

HR / AR (<2%)

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

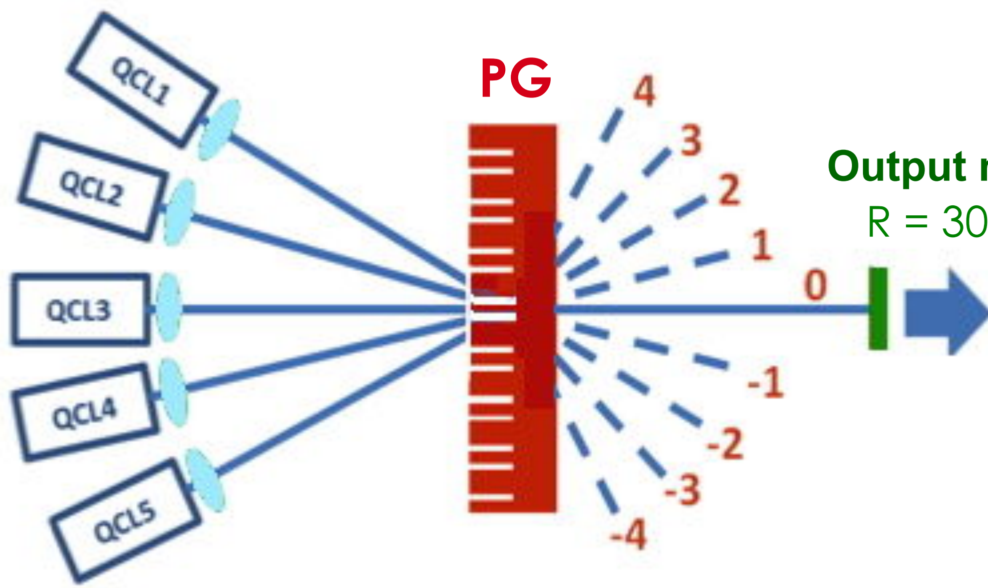


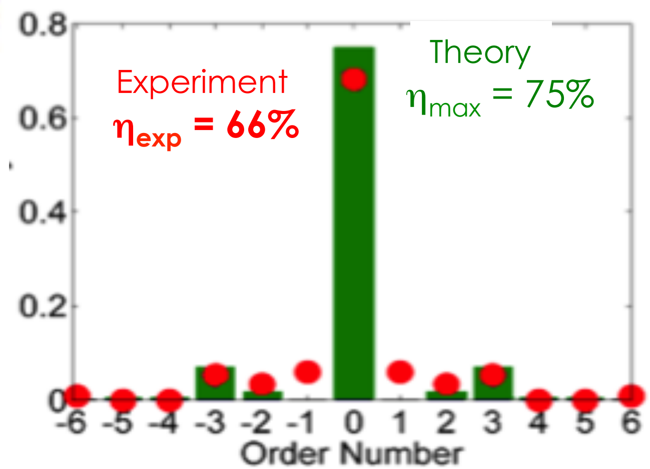
III-V lab
ALCATEL-THALES

G. Bloom *et al*, Optics Letters **36**, 3810 (2011)

5-arm external cavity

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





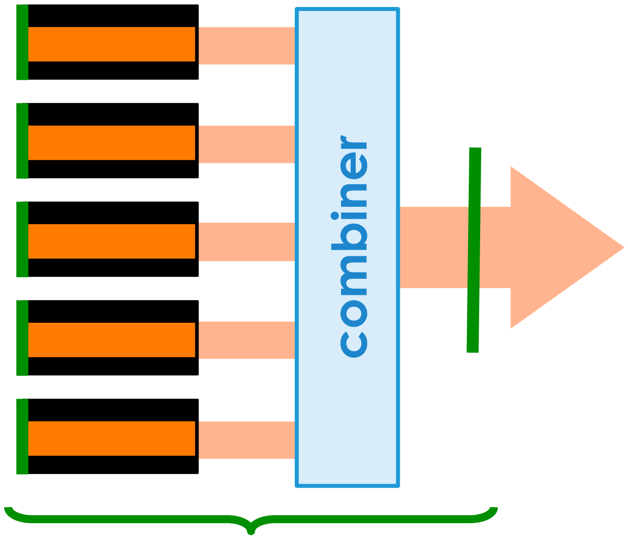
Relative power of the diffraction orders at the output of the external cavity

→ **Coherent beam addition of 5 QCL :**

Combining efficiency = 66%
Output power = 0.5 W
Diffraction-limited beam (M^2<1.6)

G. Bloom *et al*, Optics Letters **36**, 3810 (2011)

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

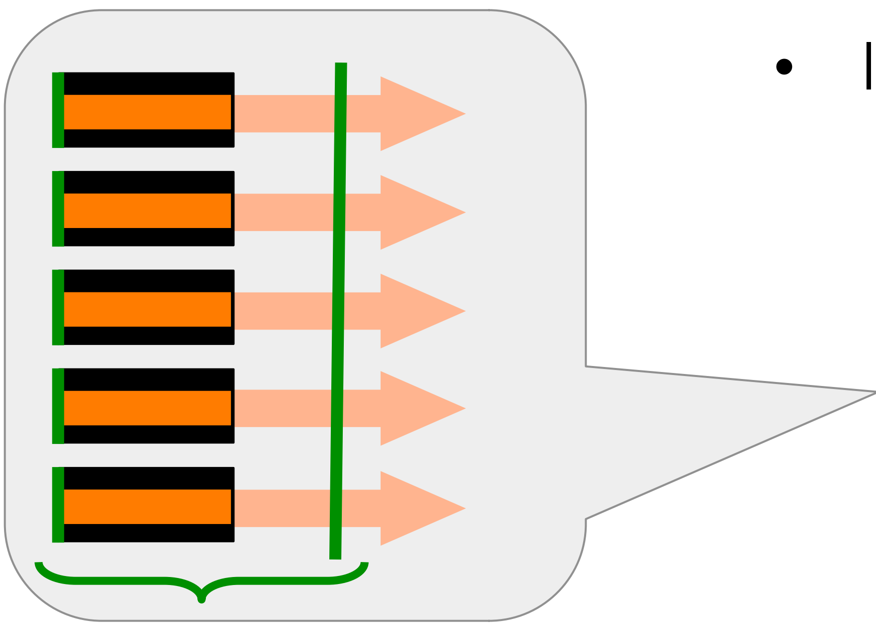
- lasers in a **common external cavity**

Interferometric resonator

⇒ *filled aperture*

Self-imaging cavity : Talbot effect

⇒ *tiled aperture*

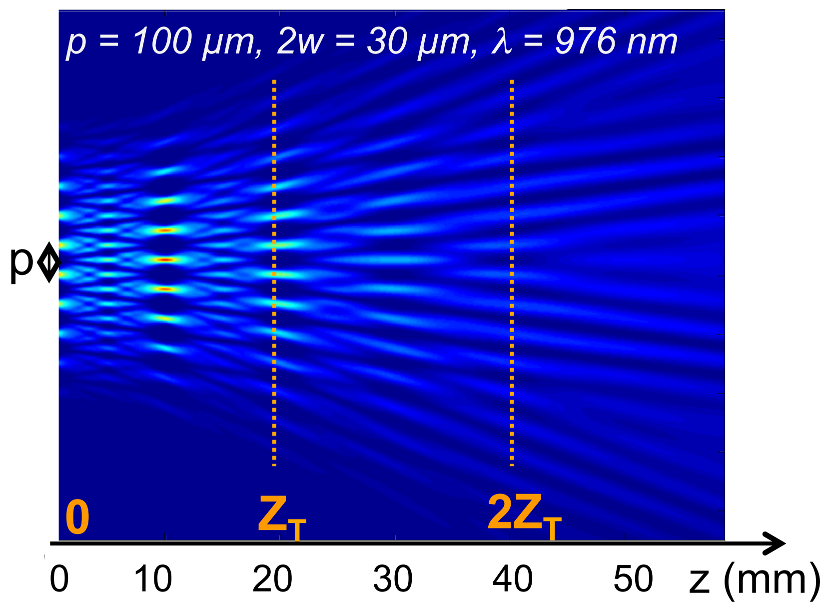


T.Y. Fan, *Laser beam combining for high-power, high-radiance sources*, IEEE JSTQE **11**,3, 567 (2005)

Talbot self-imaging effect

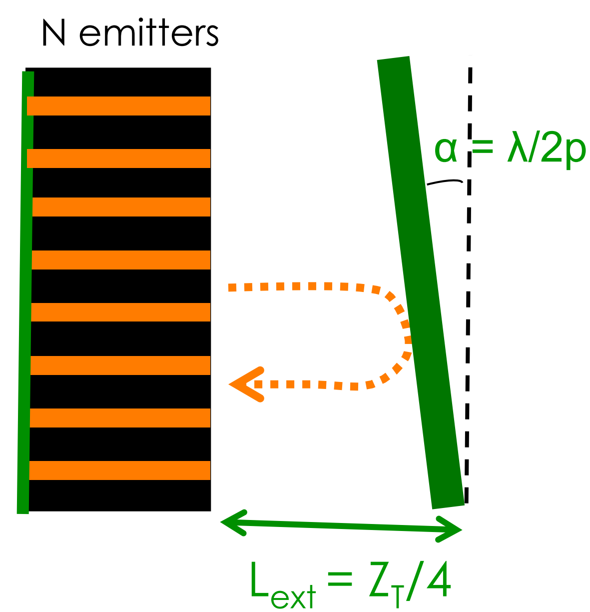
Near-field diffraction effect observed for a grating illuminated by monochromatic light :

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



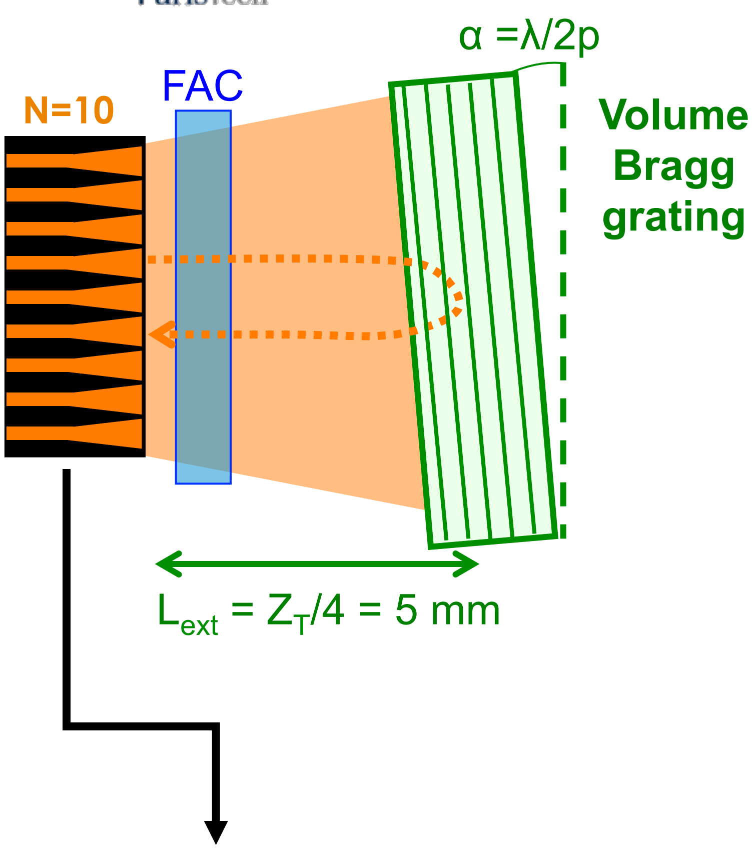
Near-field propagation of 10 in-phase Gaussian lasers, demonstrating the self-imaging Talbot effect.

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

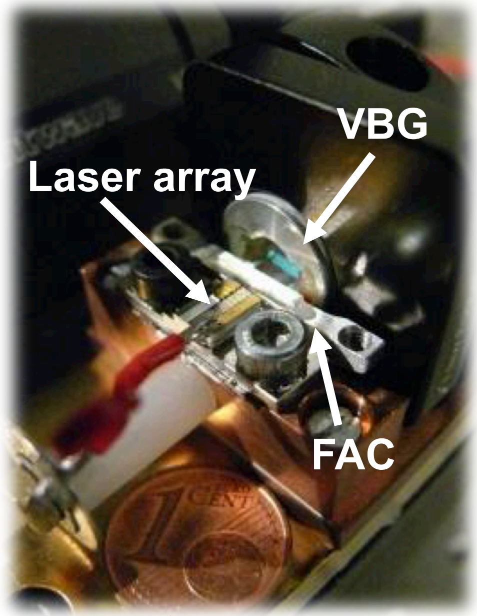
$R_B \cong 40$ %

$\lambda_B = 975.4$ nm, $\Delta\lambda = 0.3$ nm

$\Delta\theta = 2°$ (FWHM)

Array of 10 index-guided tapered emitters

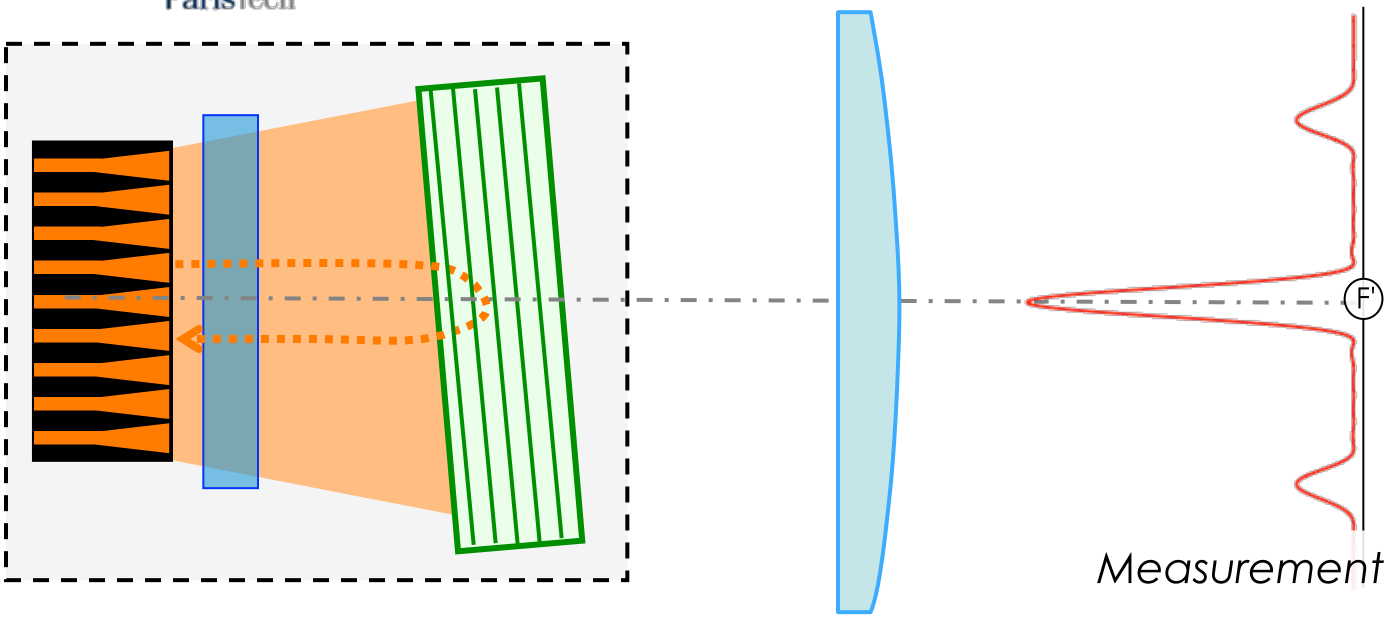
pitch = 100µm, 0.4W/emitter



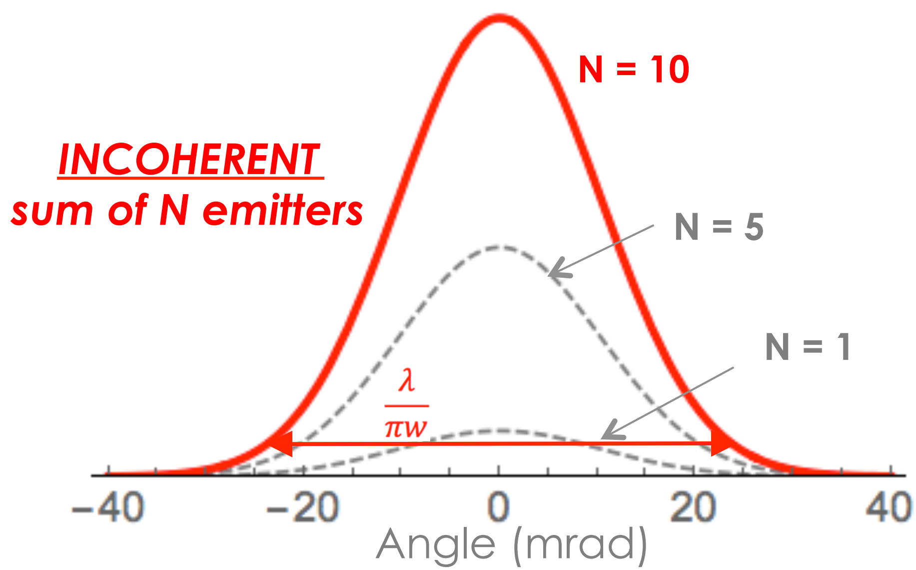
Experimental setup

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

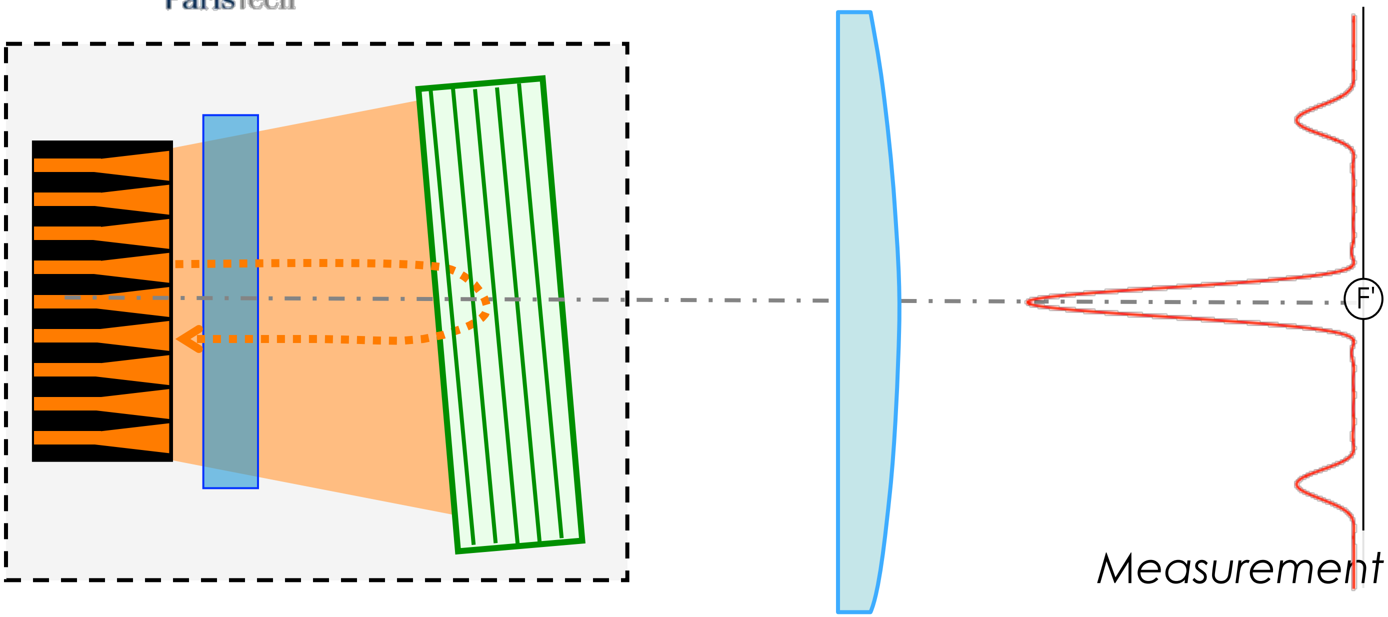
Evaluation of the coherence of the array

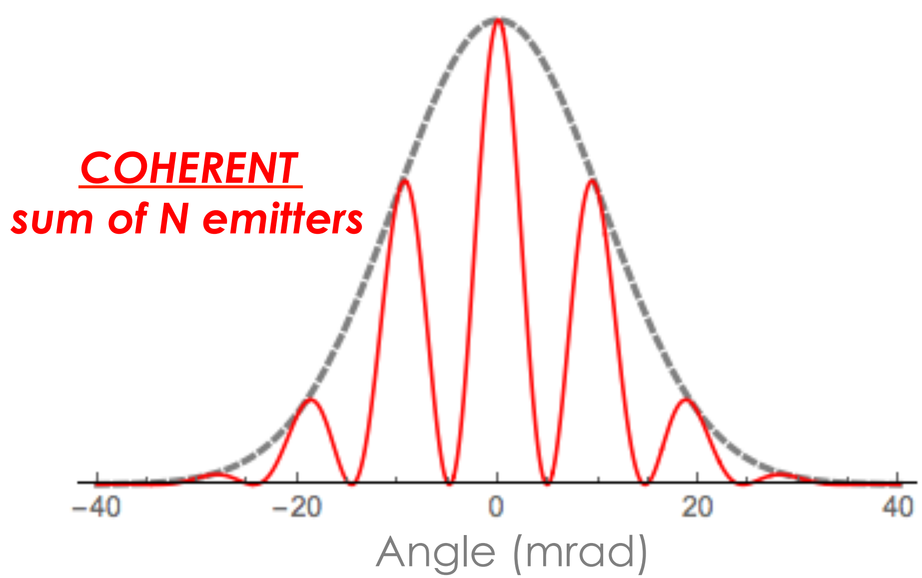


Measurement of the far-field profile

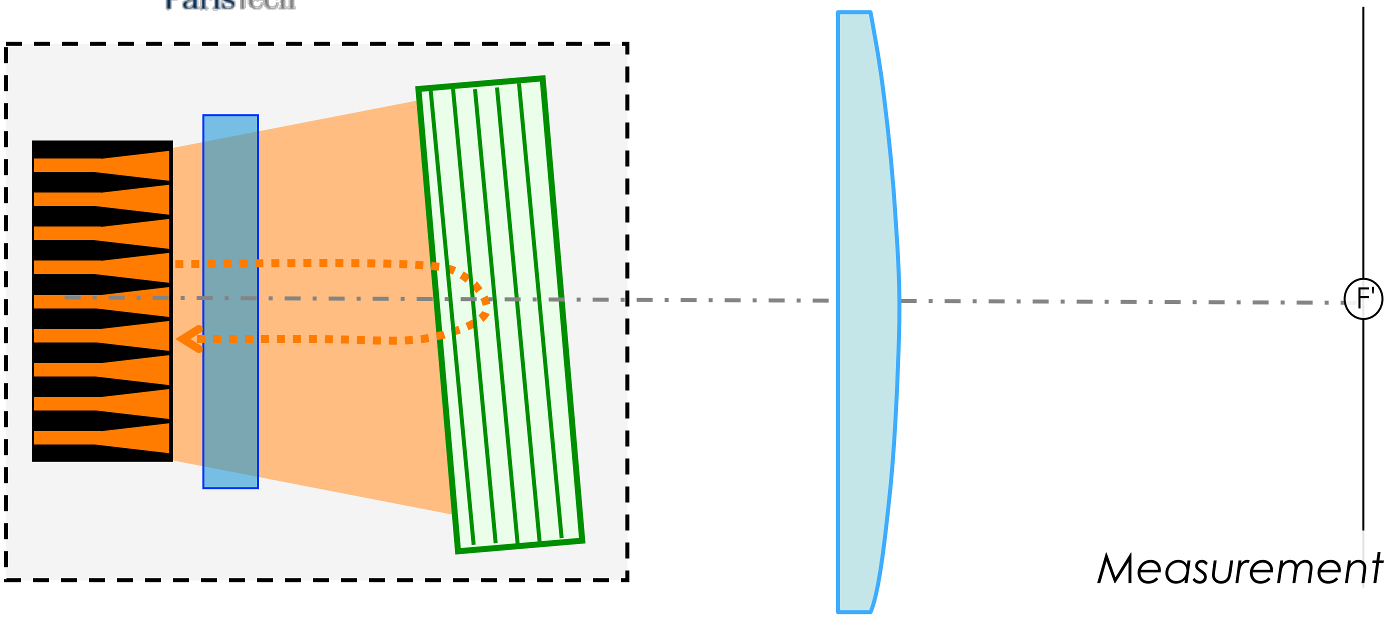


Evaluation of the coherence of the array



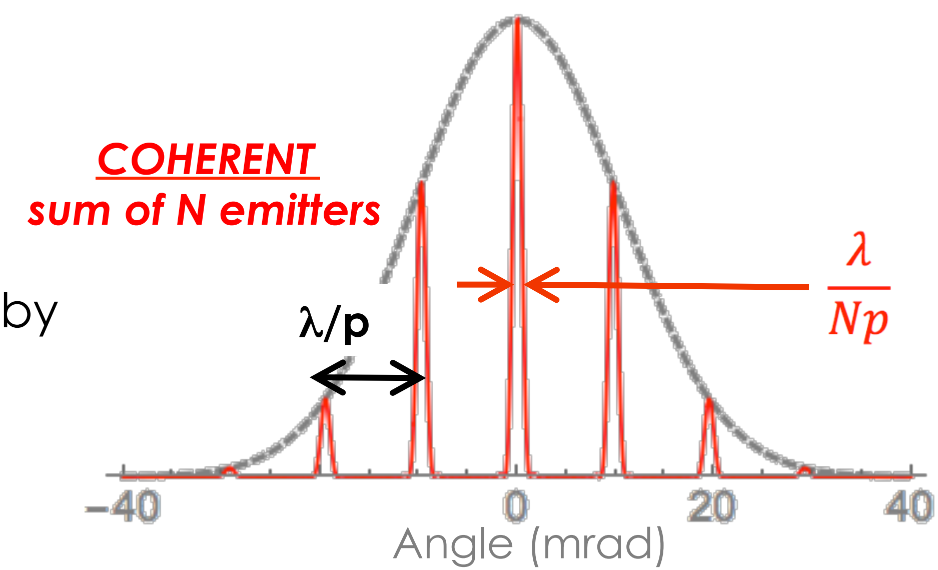


Evaluation of the coherence of the array



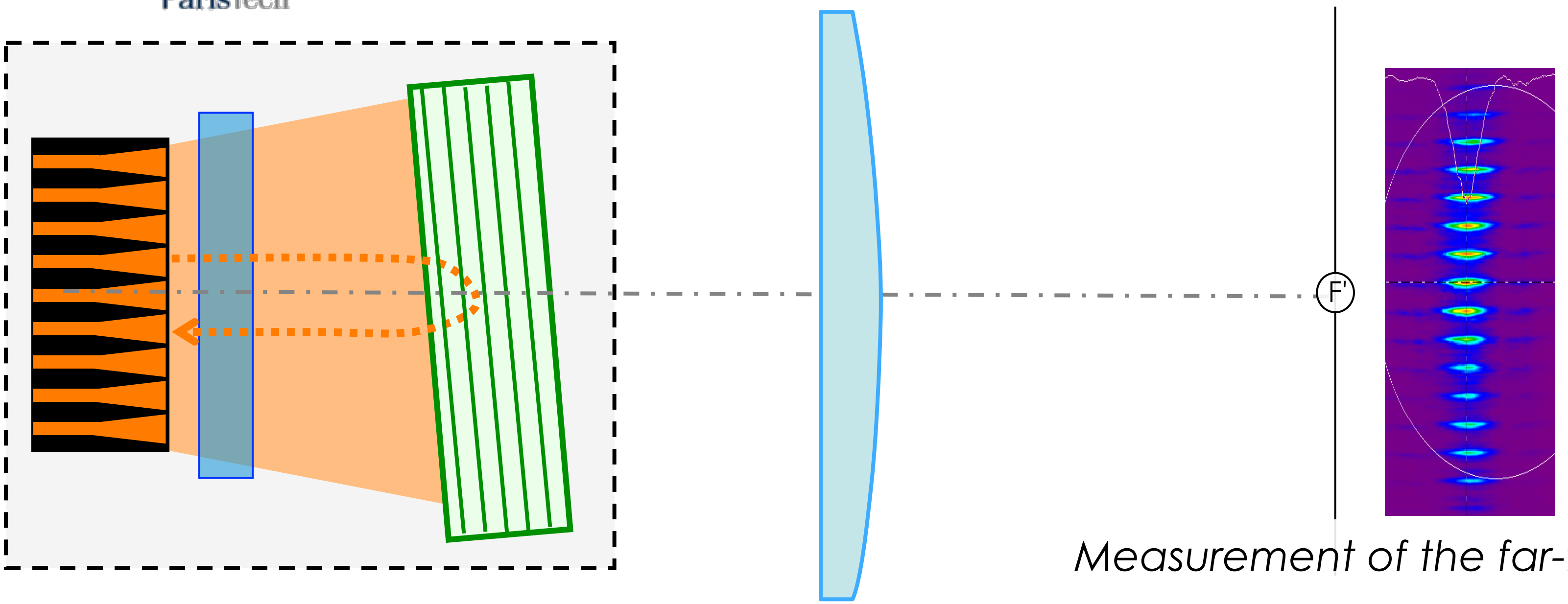
Measurement of the far-field profile

N = 10 in-phase emitters



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

Experimentally …

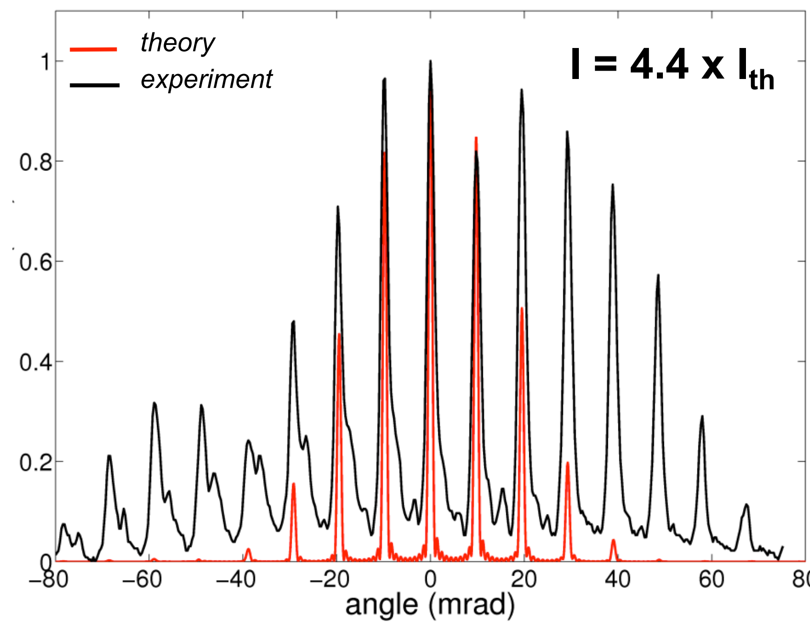


Measurement of the far-field profile

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})

Operation in the in-phase mode
Highly-contrasted fringes in the FF
V ≥ 80%



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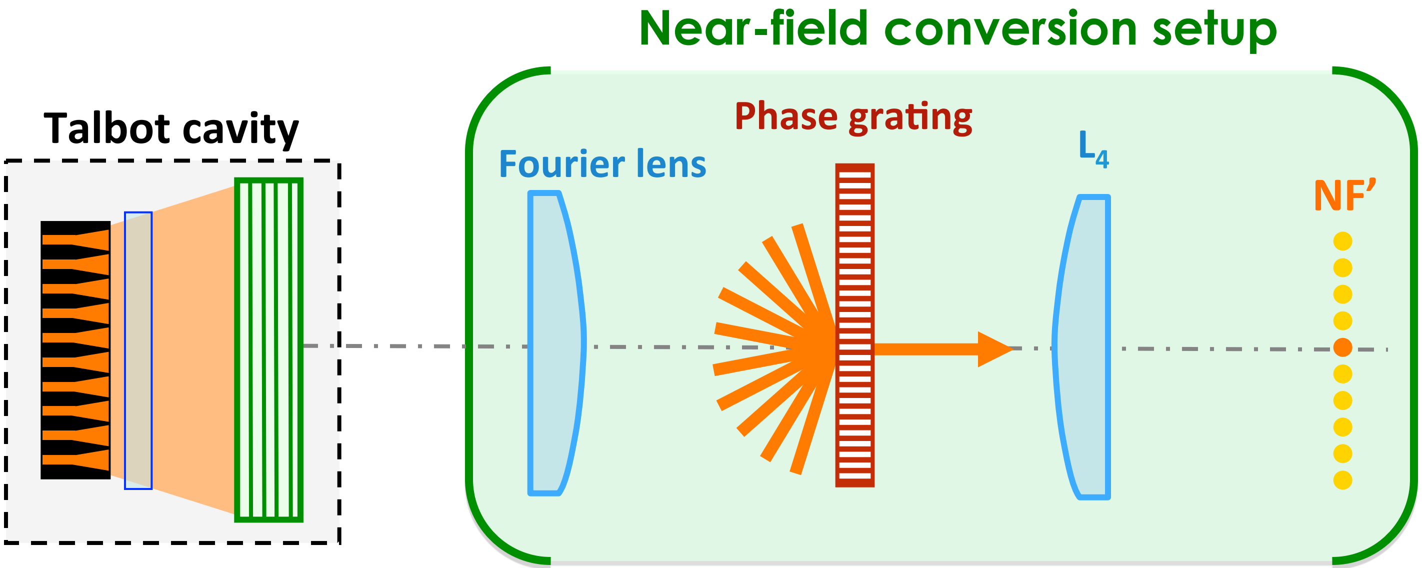
Extracavity coherent superposition



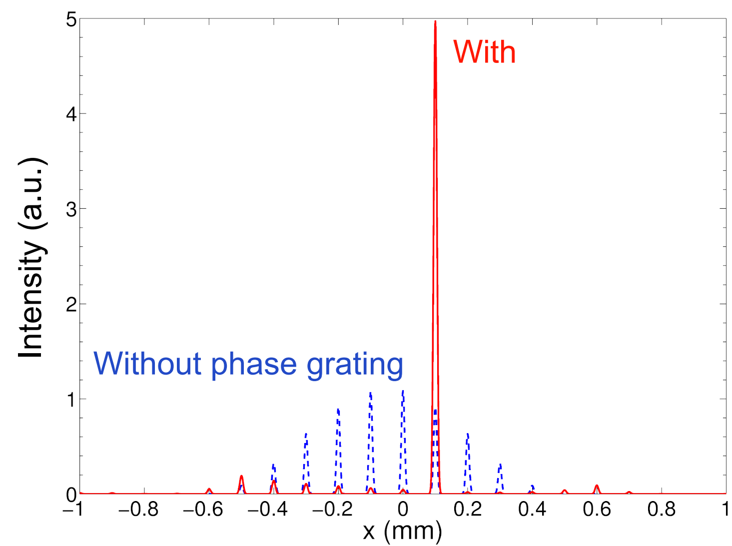
- Passive **phase-locking** of diode lasers in the Talbot external cavity

\+ Passive **conversion** of the complex pattern in a Gaussian-like mode

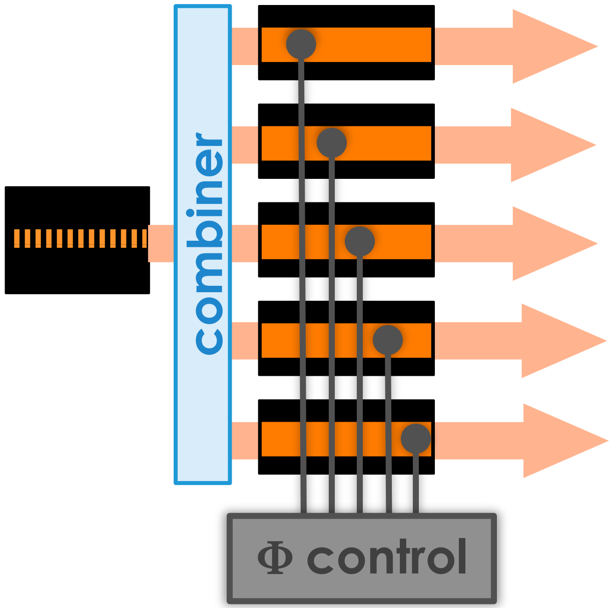
Diffraction of the N = 10 coherent beams on a phase grating within 1 direction

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

Experimental superposition efficiency ≤ 51%



Different architectures for CBC



→ <u>MOPA configuration</u>

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

***Active* electronic feedback**

Linear phase-shift with control

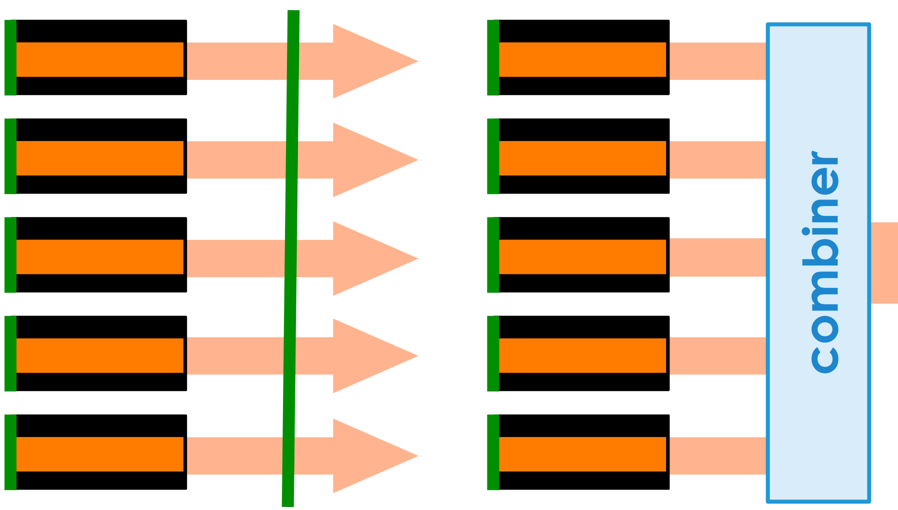
→ <u>Self-organizing lasers</u>

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

lasers in a **common external cavity**

Interferometric resonator

Self-imaging cavity

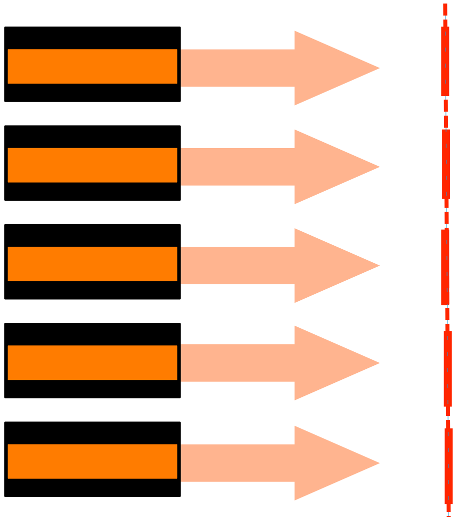


***Passive* optical feedback**

Highly non-linear behavior

<u>Coherent Laser beam combining</u>, ed .Brignon (Wiley – VCH)

Conclusion



- 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 !

BRIDLE

Special thanks to P. Georges, M. Hanna, D. Pabœuf, L. Leveque, G. Schimmel, S. Janicot, I. Doyen

Coherent Laser beam combining, ed .Brignon (Wiley – VCH)