Recent Solutions for Higher-Brightness Laser Sources

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Organisation name: Alcatel-Thales III-V Lab

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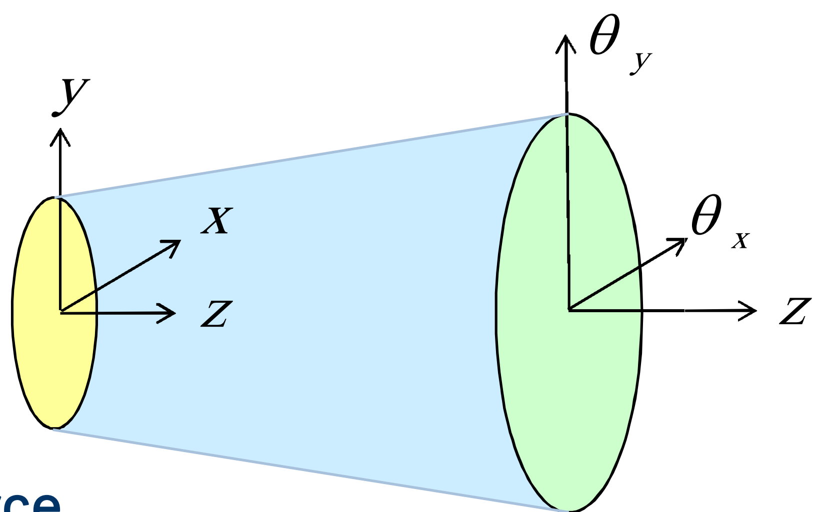
Towards higher-brightness laser sources

- What is brightness?
  - Definition
  - The brightness theorem
- How to measure brightness?
  - ISO and other techniques
- High-brightness Diode lasers
  - The large cavity problem
  - Single mode emitters
  - Multi-mode emitters
- Future trends
- Conclusions

What is brightness?

The diffraction limit

- The beam is a propagating electromagnetic field
- Near- and far-field are linked through the diffraction limit



Source

S

cm²

Solid angle

Ω

sr

Optical throughput or etendue

$$S\Omega \geq \lambda^2$$

$$w_x \theta_x \geq \lambda$$

$$w_y \theta_y \geq \lambda$$

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What is brightness?

- The beam is defined by (here)
  - Its optical power → P (W)
  - Its optical throughput → $S\Omega$ ($cm^2.sr$)
- Brightness is defined by

$$B = \frac{P}{S\Omega} \quad (W.cm^{-2}.sr^{-1})$$

- $M^2 > 1$ is defined by
  - The optical throughput
  - Its lower limit

$$S\Omega \geq \lambda^2 = M^2\lambda^2$$

One common expression of brightness is

$$B = \frac{P}{M^2\lambda^2}$$

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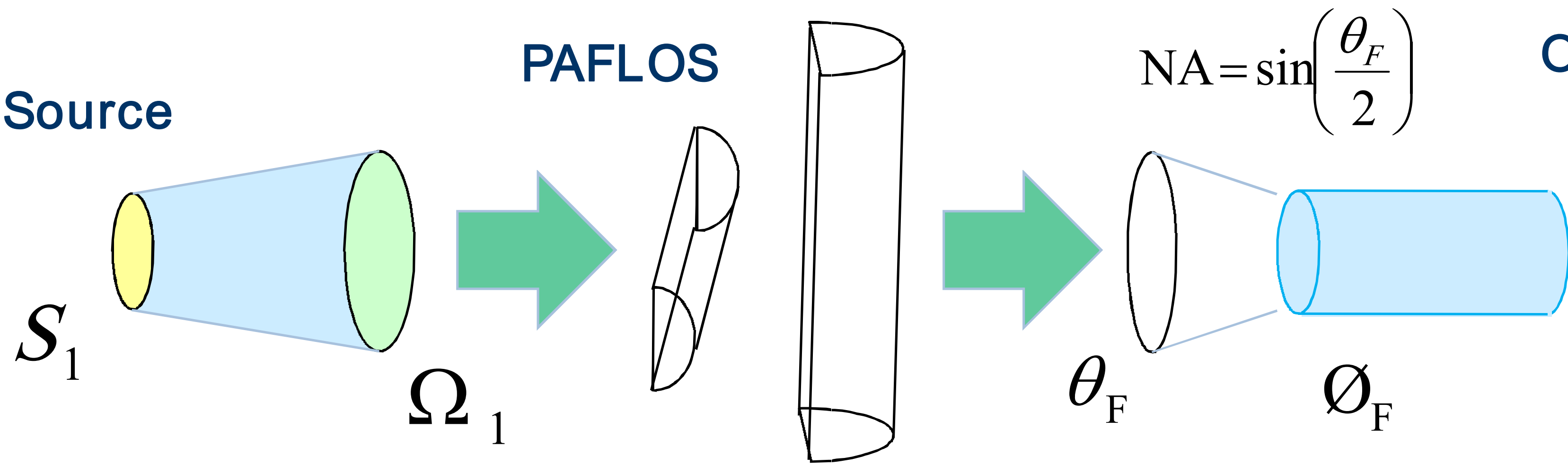
WWW • BRIGHTER • EU

- For fiber coupling
  - Or into any other type of waveguide
- The passive aberration-free lossless optical system
  - PAFLOS
  - Contains only lenses (and/or mirrors)
  - Forms an image of the input beam



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Why is brightness useful?

The brightness theorem

- Also known as "the conservation of brightness"
- PAFLOS systems keep brightness unchanged

$$B_{Fiber} \leq B_{Source}$$

The brightness theorem has important consequences

- For laser research
- Also for fundamental research (How to beat the theorem ?)

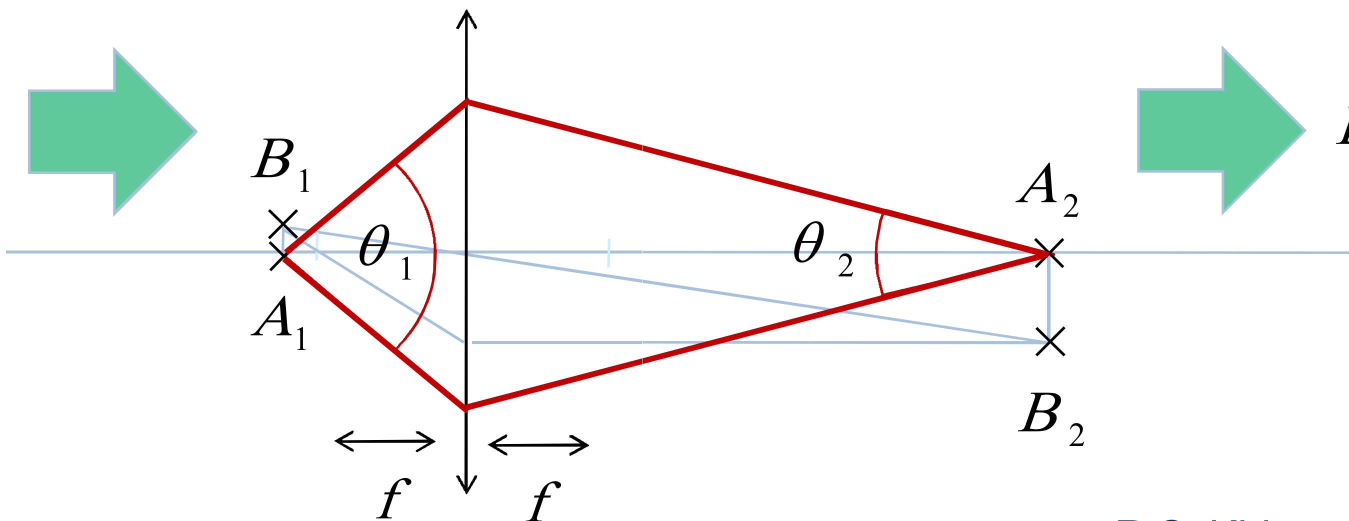
The brightness theorem (demonstration)

- The conservation of brightness
  - One lens
  - 1D geometrical optics

$$P_1 = P_2$$

$$\Omega_1 = A_1 B_1 \theta_1 = \Omega_2 = A_2 B_2 \theta_2$$

All the beam is collected



$$B_1 = B_2$$

- This still holds in physical optics
  - For monochromatic beams

R.S. Kirby
Photonics and Lasers
Whiley Interscience
2006

Why is brightness useful?

- Therefore ...
  - End users
  - Optics manufacturers
  - System integrators

Who are limited by the brightness theorem ...

Ask for more input brightness ...

From laser engineers and laser researchers ...

and join for common research projects

Information Society Technologie

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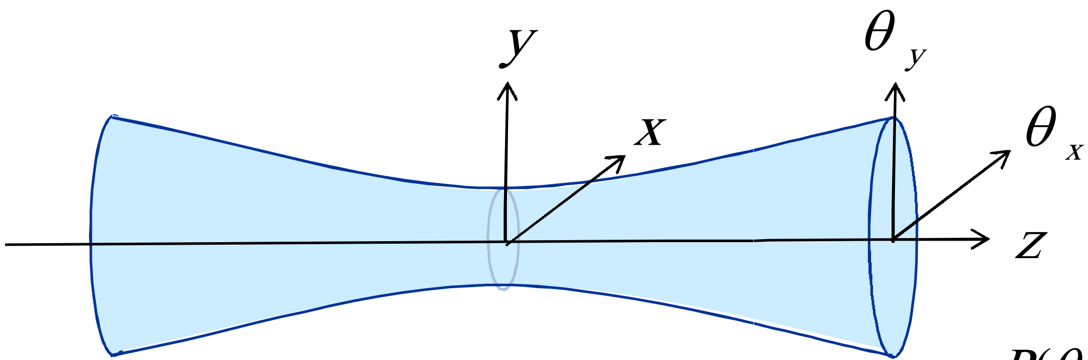
Gaussian beams

Definition

- Gaussian through any transverse cut



far-field

$$P(\theta_x, \theta_y) = \exp\left(-2\pi^2 w_0^2 \frac{\theta_x^2 + \theta_y^2}{\lambda^2}\right)$$

near-field at waist

$$P(x, y) = \exp\left(-2\frac{x^2 + y^2}{w_0^2}\right)$$

Beam quality

- Gaussian beams are diffraction-limited
- $M^2 = 1$

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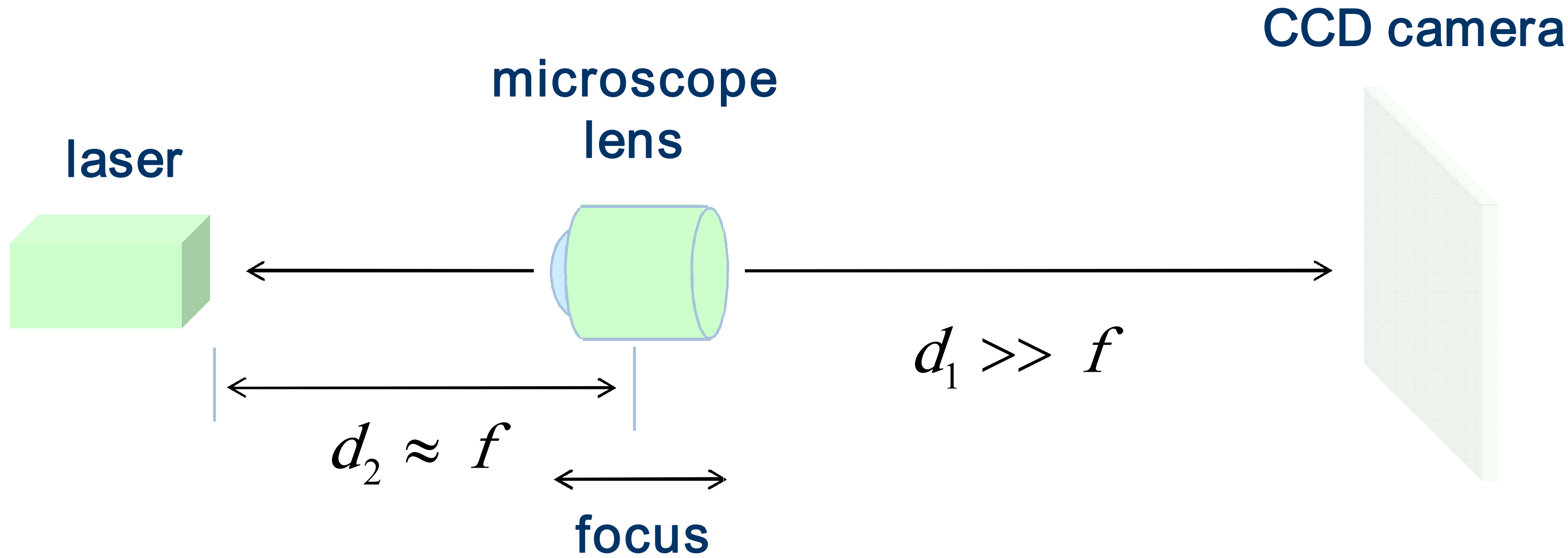
Measuring Gaussian beams

How to measure the near-field at waist

- Install the laser and camera
- Install the lens
- Move the lens and focus on beam waist
- Know the magnification factor

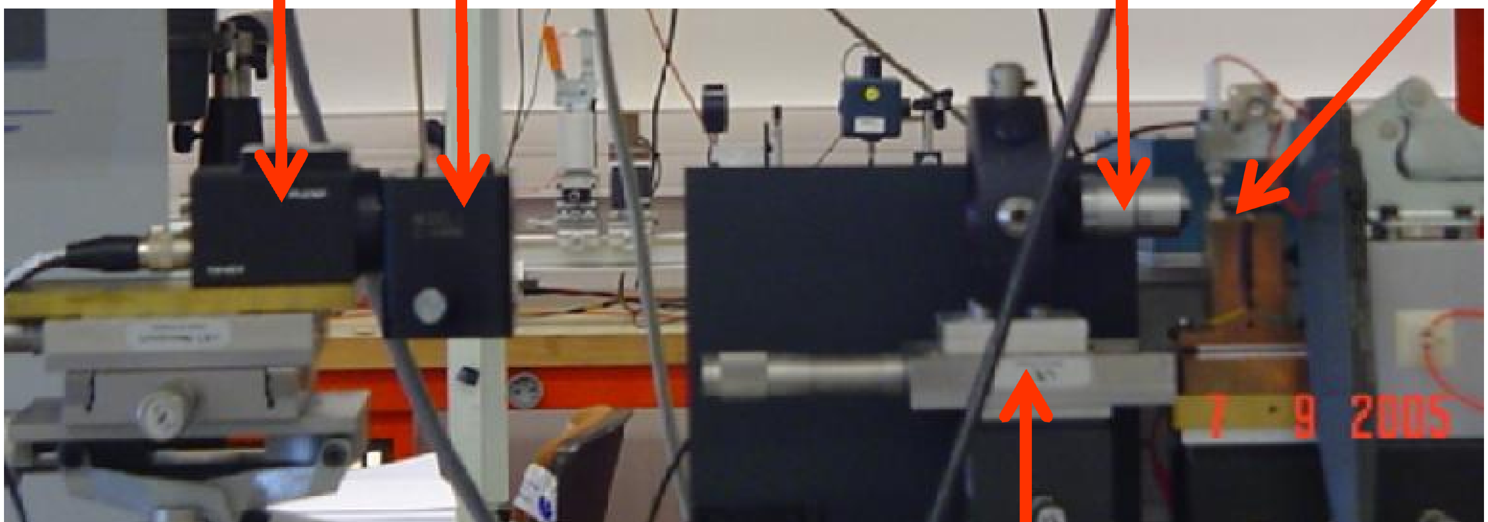
magnification factor

$$MF \approx \frac{d_1}{f}$$



Measuring Gaussian beams

- What does the near-field equipement look like?
  - Setup at III-V Lab



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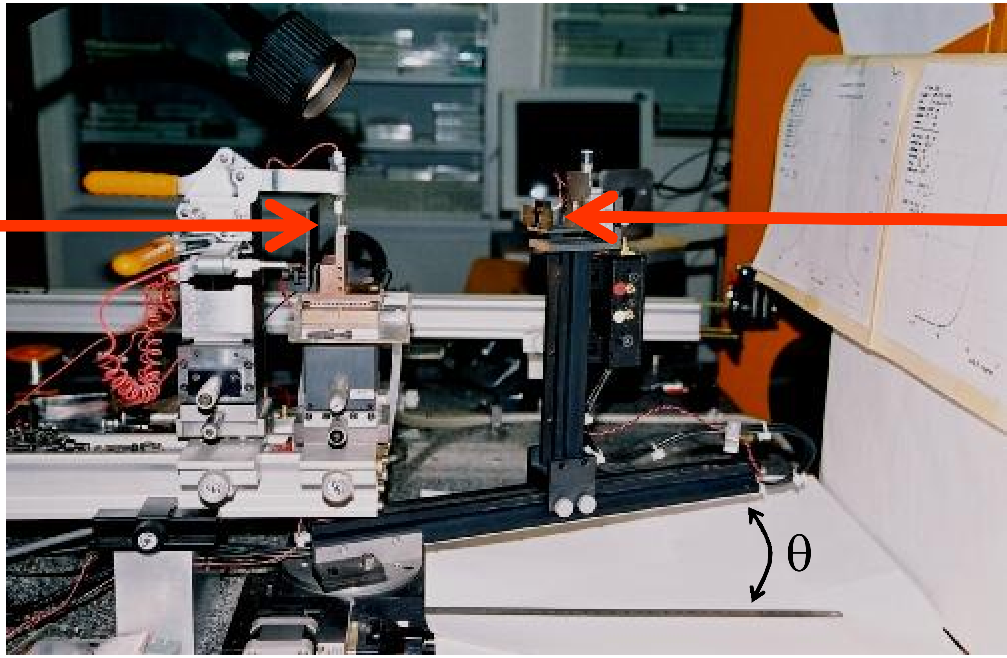
Measuring Gaussian beams

- How to measure the far-field
  - Very simple
  - Rotate a detector around the beam
  - Setup at III-V Lab

arm length must be much longer than

$$Z_r = \pi \frac{w_0^2}{\lambda}$$

diode laser



rotating photodiode

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How to measure brightness?

- Brightness involves three parameters
  - Power
  - Wavelength
  - M^2

$$B = \frac{P}{M^2 \lambda^2}$$ (W.cm^{-2}.sr^{-1})

- How to measure M^2?
  - Two popular techniques presented

- First option: M^2 at $1/e^2$
  - Fast and easy
  - Does not comply with International Standards Organization (ISO)
  - Doe not take all the beam profile into account

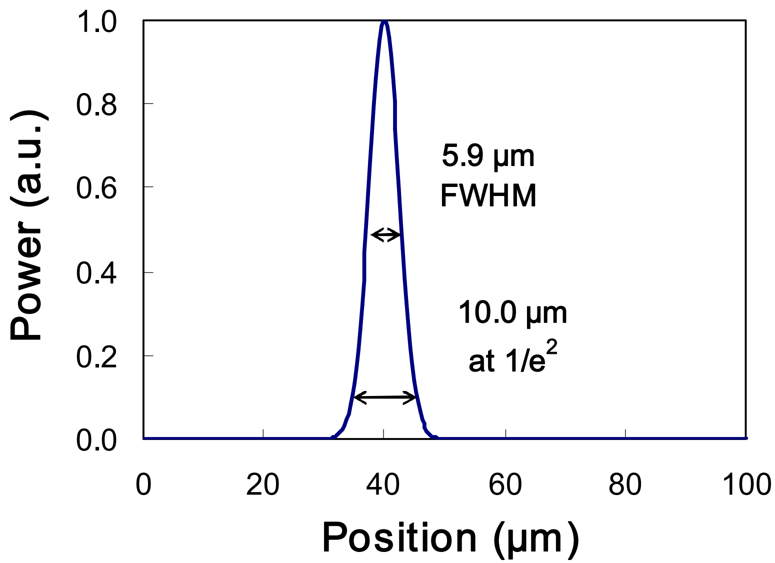
Measuring M^2 at $1/e^2$

- Example with the Gaussian beam
  - Assume perfect beam at 975 nm
  - Simulate near-field at waist
  - Simulate far-field

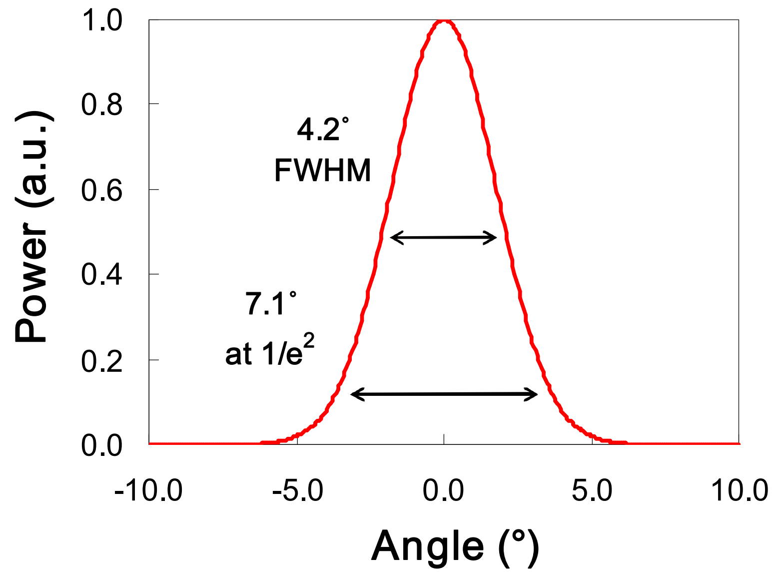
apply formula

$$M^2_{1/e^2} = \frac{\pi}{4\lambda} W_{1/e^2} \Theta_{1/e^2} = 1.0$$

near field at waist



far-field



Measuring M^2 at $1/e^2$

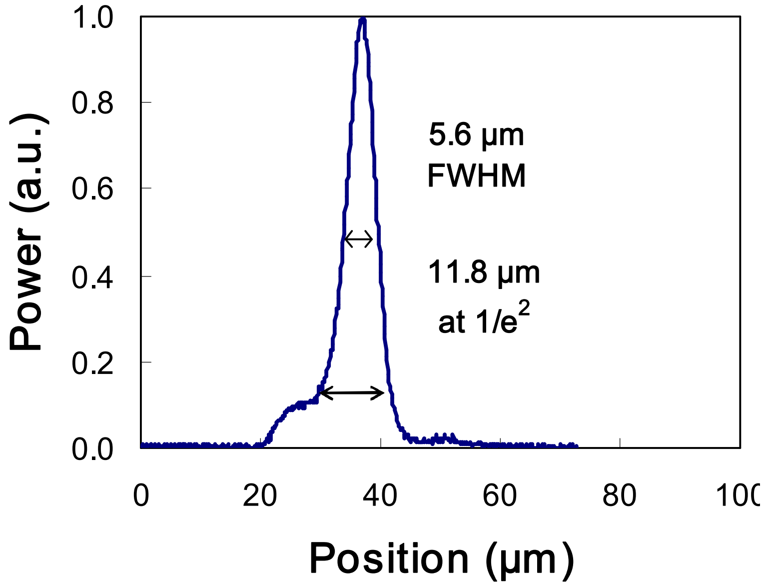
Example with real beam

- Measure actual laser at 975 nm
- Measure near-field at waist
- Measure far-field

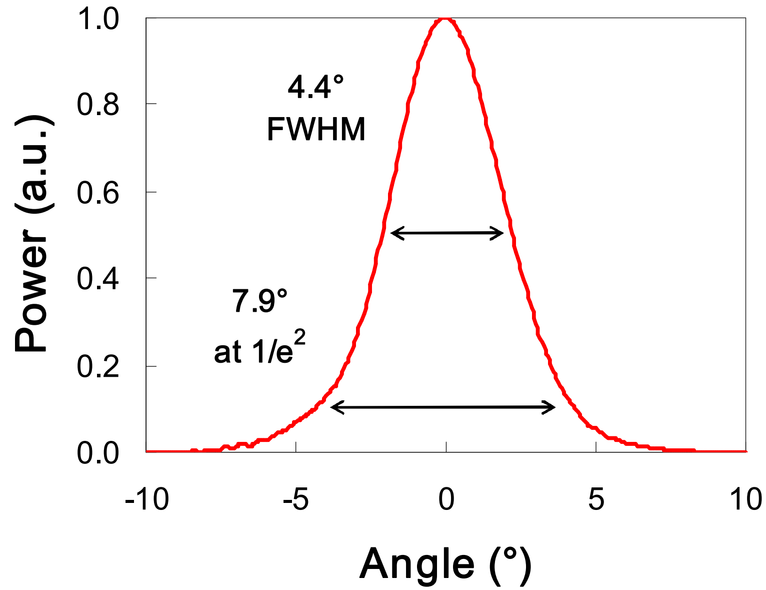
apply formula

$$M^2_{1/e^2} = \frac{\pi}{4\lambda} W_{1/e^2} \Theta_{1/e^2} = 1.3 \pm 0.2$$

near field at waist



far-field



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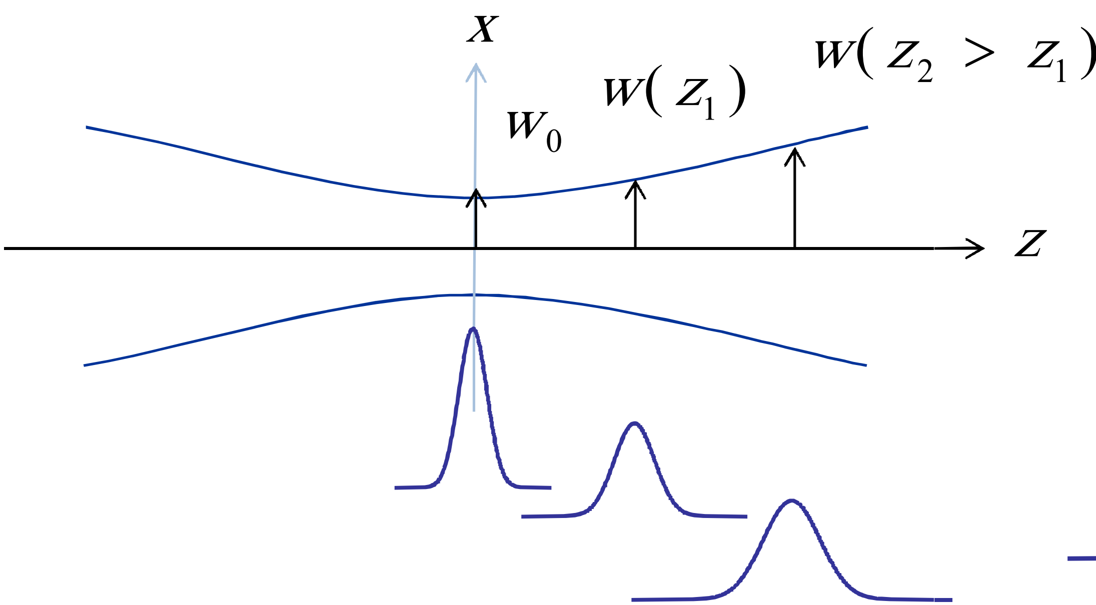
How to measure brightness?

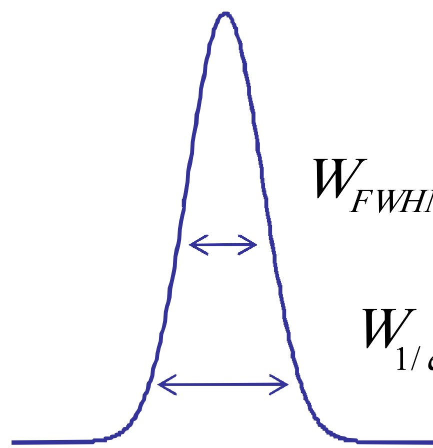
- **Second option: use M^2 according to ISO 11146**
  - International Standard
  - Based on the hyperbolic curve

for Gaussian beams

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

the hyperbolic curve





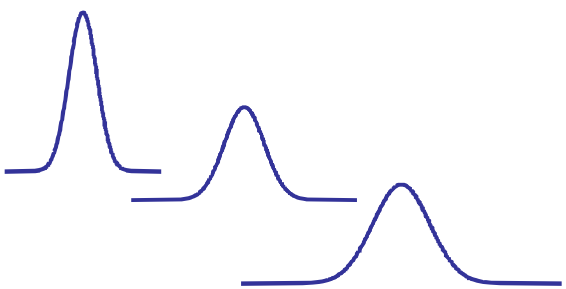
$$W_{FWHM} = \sqrt{2 \ln(2)}\, w(z)$$

$$W_{1/e^2} = 2\, w(z)$$

How to measure brightness?

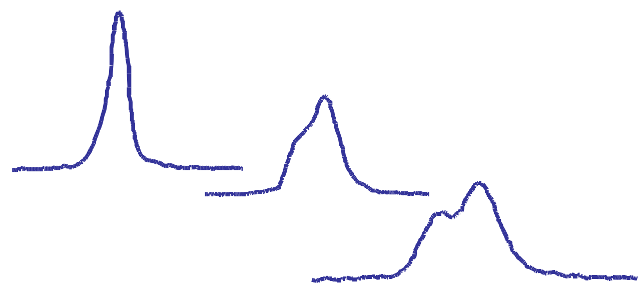
- **How to define the hyperbolic curve of real beams?**
  - Shape changes with diffraction
  - Use standard deviation

Gaussian beams



$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

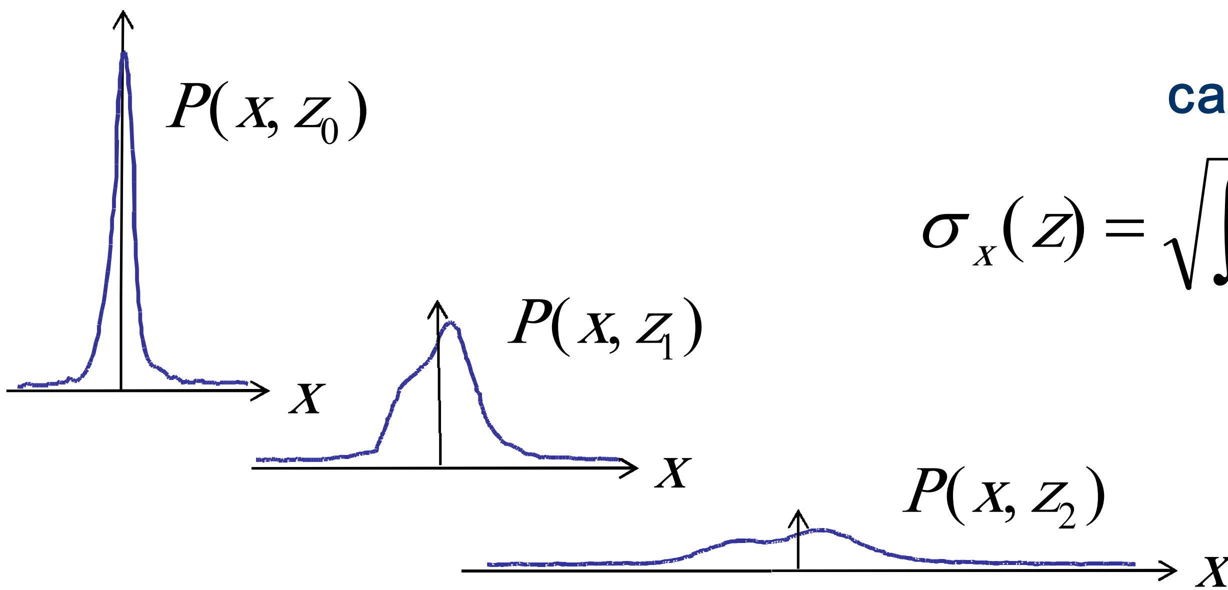
real beams



$$\sigma(z) = \sigma_0 \sqrt{1 + \left(\frac{M_\sigma^2 \lambda z}{\pi w_0^2} \right)^2}$$

How to measure brightness?

- Calculation of the second moment of real beams
  - Integrate
  - Use correct integration window
  - Use low noise acquisition system (SNR>100)
  - Normalise each curve for unit area and zero average <x>



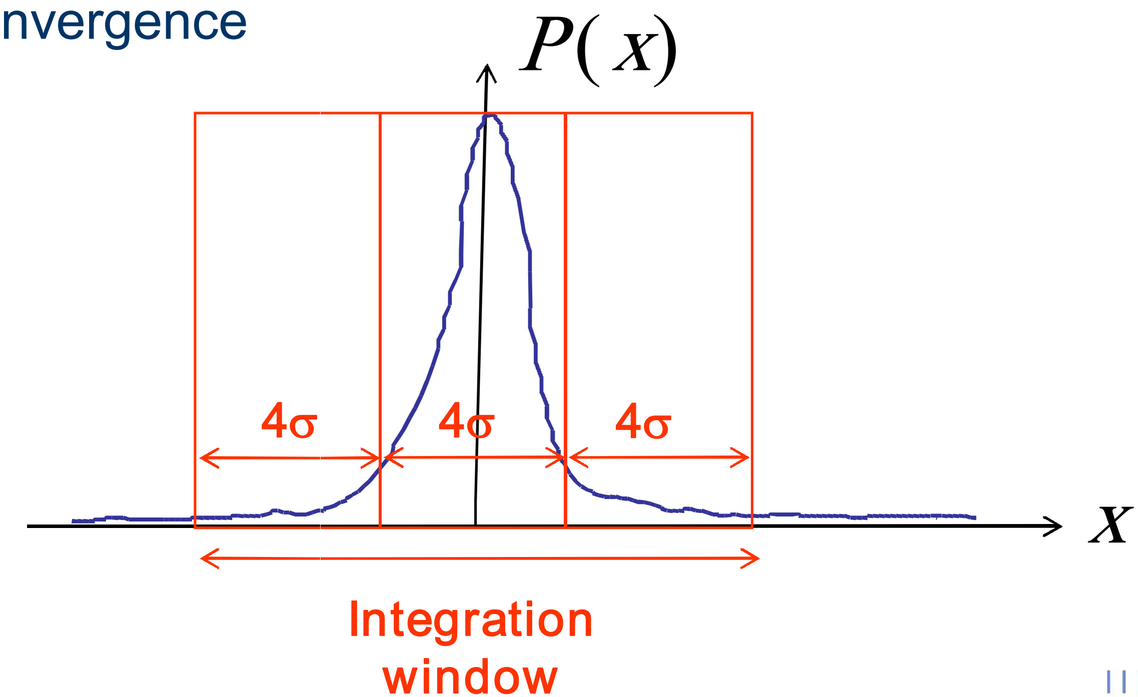
calculate

$$\sigma_x(z) = \sqrt{\int P(x,z)\,x^2\,dx}$$

How to measure brightness?

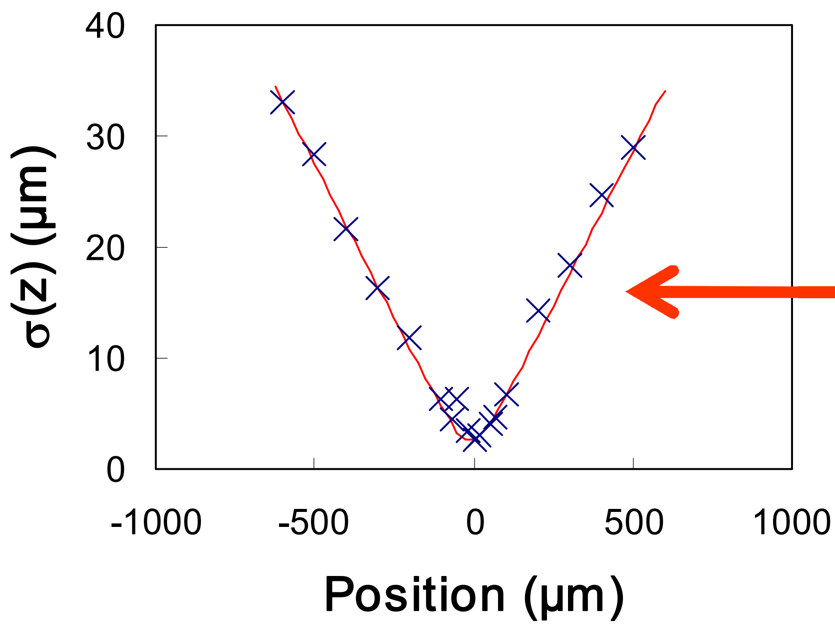
Integration window

- ISO 11146 recommends to use 3 times the beam width (BW) as integration window
- rule of thumb is BW = 4σ true for Gaussian beams
- so that 3 x BW = 12σ
- repeat until convergence



How to measure brightness?

- The Siegman hyperbola
  - σ(z) evolves as an hyperbola along the propagation (z) axis
  - This is proved by A.E. Siegman (from Maxwell equations)
  - See Procs. SPIE Vol. 1224, pp. 11-14 (1990)
  - True for any diode laser beam



actual M² measurement according to ISO

$$\sigma(z) = \sigma_0 \sqrt{1 + \left(\frac{M_\sigma^2 \lambda z}{\pi w_0^2} \right)^2}$$

$$M_\sigma^2 = 1.9 \pm 0.2$$

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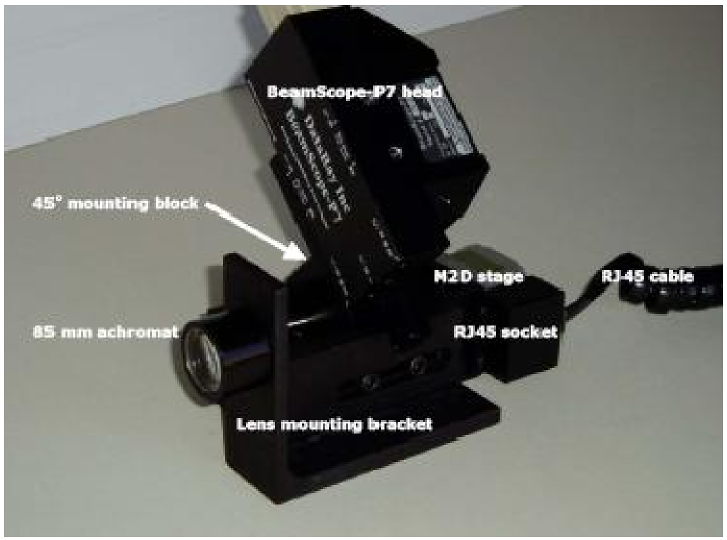
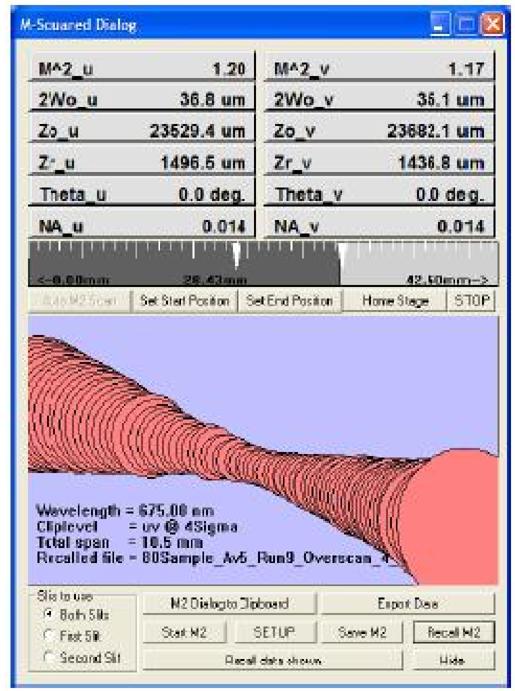
How to measure brightness?

- **The ISO 11146 technique is time consuming!**
  - Unless an automated setup is available ....



automated
z-stage from
Dataray Inc.
and Melles Griot

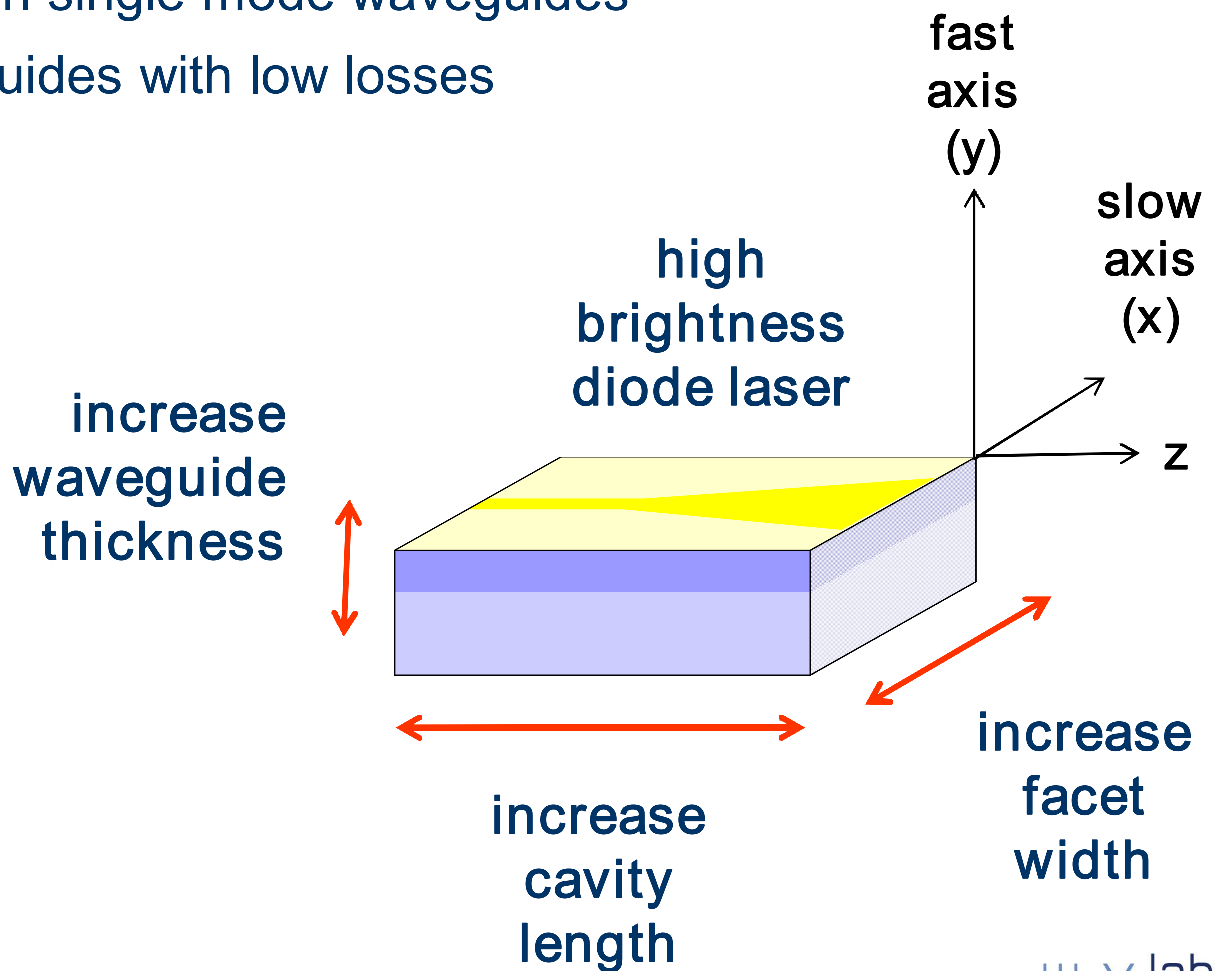


ISO 1146
M^2 extraction

Now let us talk about high-brightness diode lasers!

The large cavity challenge

- Common to high-power photonics
  - **Obtain** large-section single mode waveguides
  - **Obtain** long waveguides with low losses
  - Appears in:
    - diode lasers
    - fiber lasers
    - solid-state lasers
    - large mode area optical fibers
    - large mode area dielectric waveguides



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Catastrophic Optical Damage (COD)

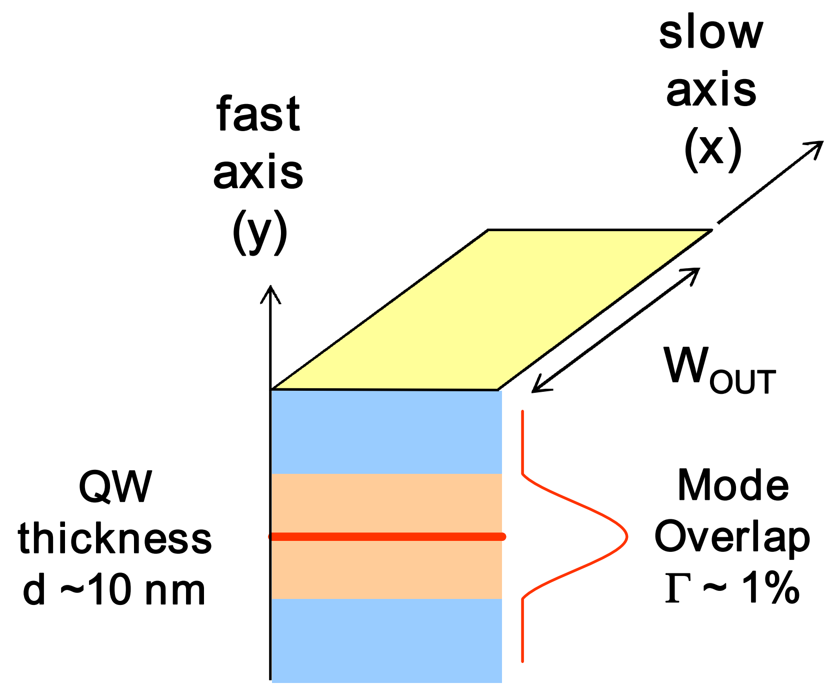
What is COD?

- The facet of the laser is destroyed at high power
- This depends on the material structure and output width of the laser

$$P_{COD} \prec W_{OUT} \times \frac{d}{\Gamma}$$

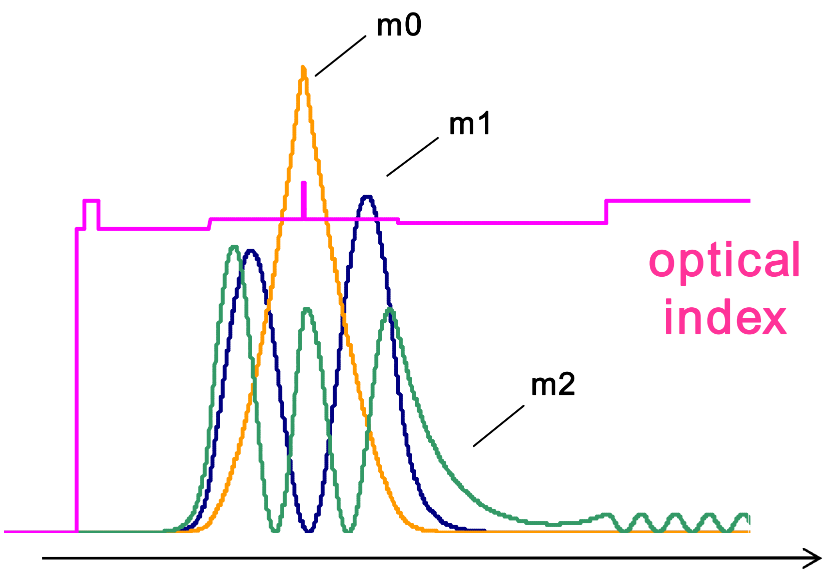
Solutions

- Increase the facet width W_{OUT}
- Structure with higher d/Γ
- Use facet passivation

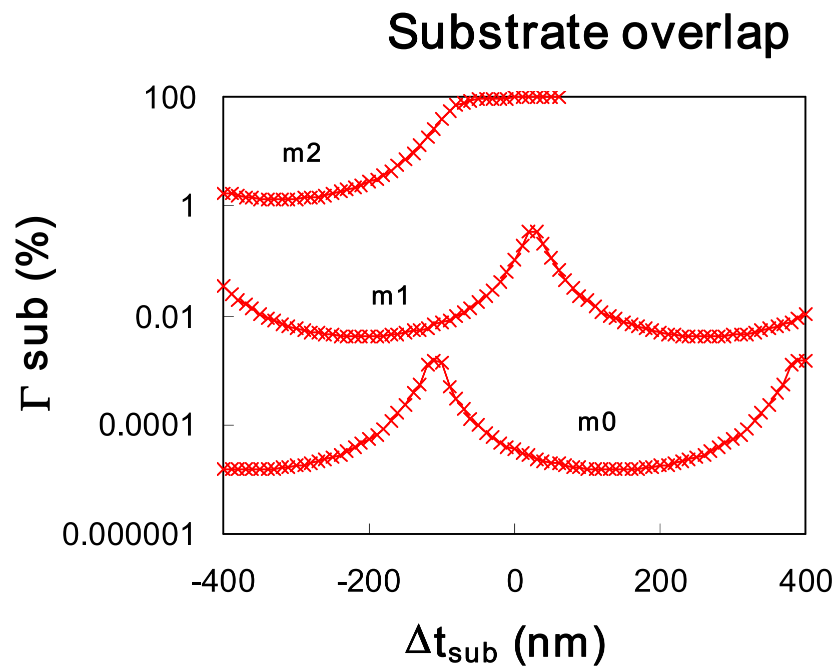


Large spot size structures

- Improving the optical design
  - 1998 - Large Optical Cavity (LOC)
  - 2005 - Super Large Optical Cavity (SLOC)
  - 2008 - High d/Γ asymmetric structures



III-V Lab SLOC design
epitaxial direction



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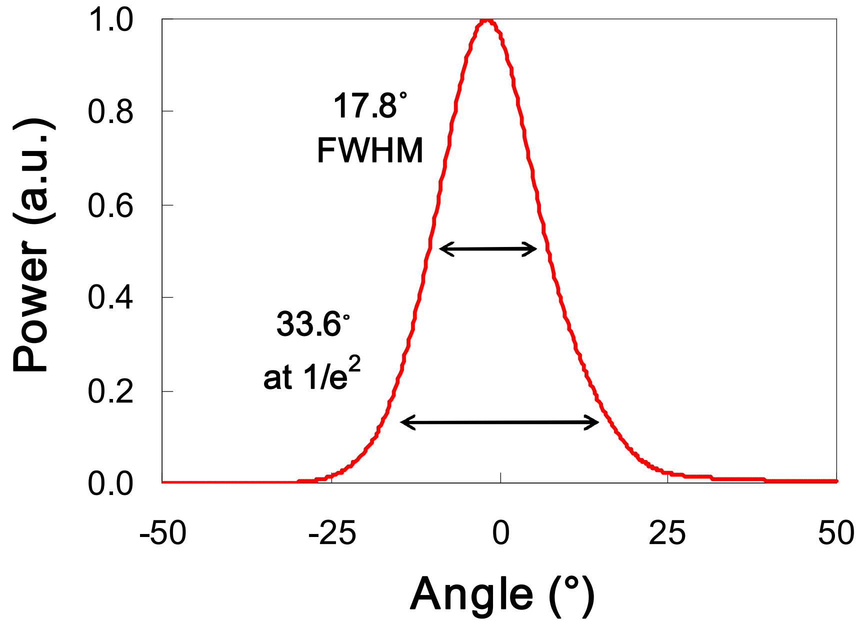
Large spot size structures

- **Reduced fast-axis far-field**
  - Less than 20° FWHM
  - FBH record
    less than 10° FWHM

- **Higher COD values**
  - 100 µm output width
  - FBH more than 15 W CW
  - Intense Photonics record 25 W CW

Measured fast-axis far-field (III-V Lab design)



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The tapered laser

- Large oputput facet width
- Ridge allows for spatial filtering
- Ridge may include Distributed Bragg reflector (DBR) for narrow spectrum
- Increasing use of large spot size structures
- Increasing cavity length allowed by low losses material

Team	Year	Structure	λ (nm)	L_{RW} (mm)	L_{DBR} (mm)	L_{taper} (mm)	θ_{taper} (°)	P (W)	M^2 (no unit)	Brightness ($MW.cm^{-1}.sr^{-1}$)
FBH	2009	LOC	650	0.2		1.8	4	0.7	1.3	127
	2008	SLOC	1060	1	1	4	6	10.0	1.3	685
IAF	2009		1060					9.5	2.0	423
	2005	LOC	975	0.5		3	6	8.0	1.4	601
QPC	2007		1500					1.5		

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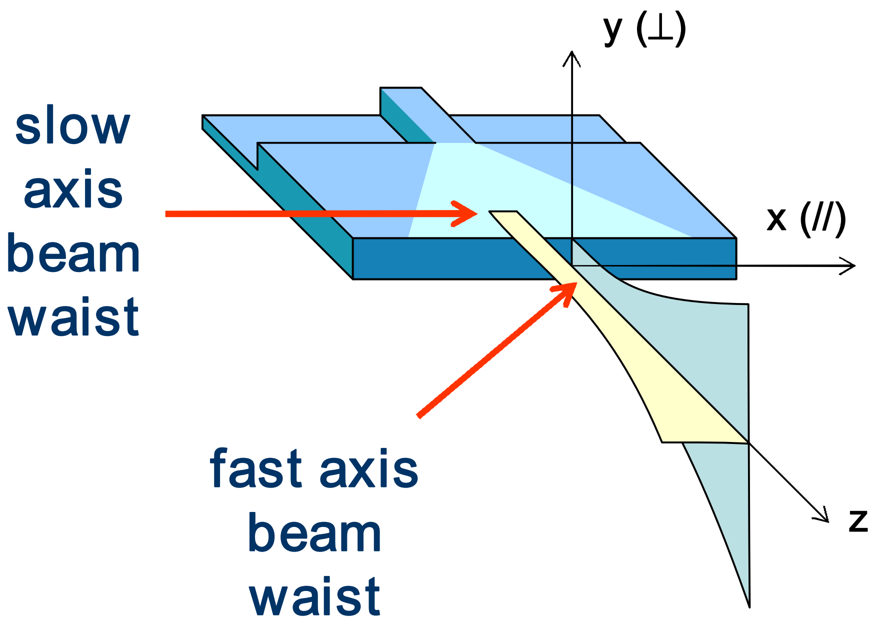
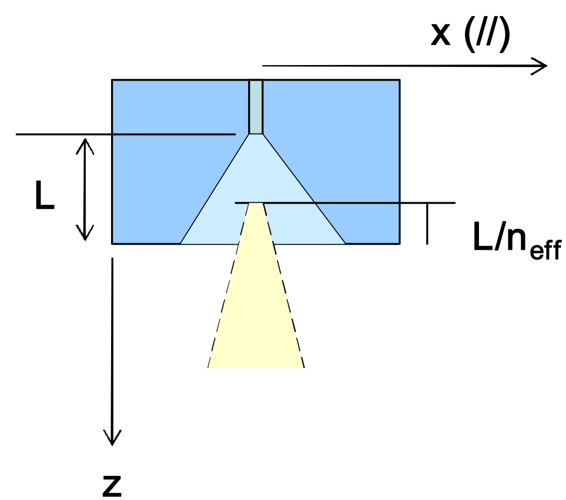
Beam properties of tapered lasers

Astigmatism

- Tapered lasers show astigmatic beams
- Waist location is different in both axes
- Astigmatic beams are more complex for single-mode fiber coupling



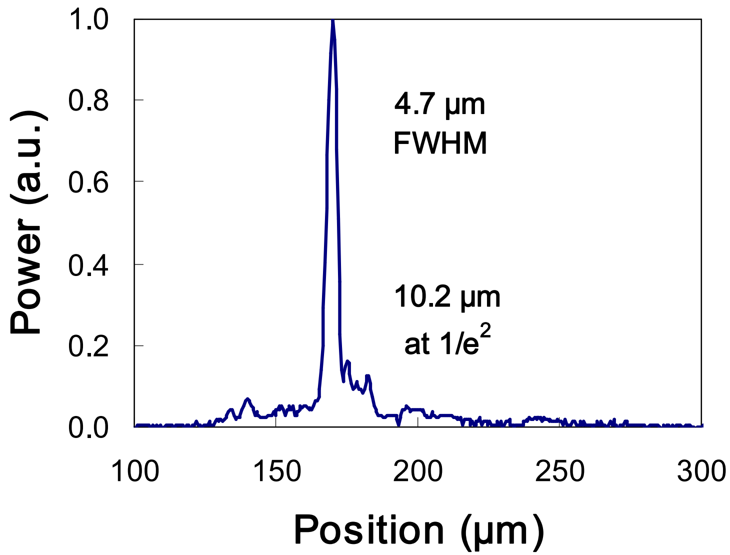


Beam properties of tapered lasers

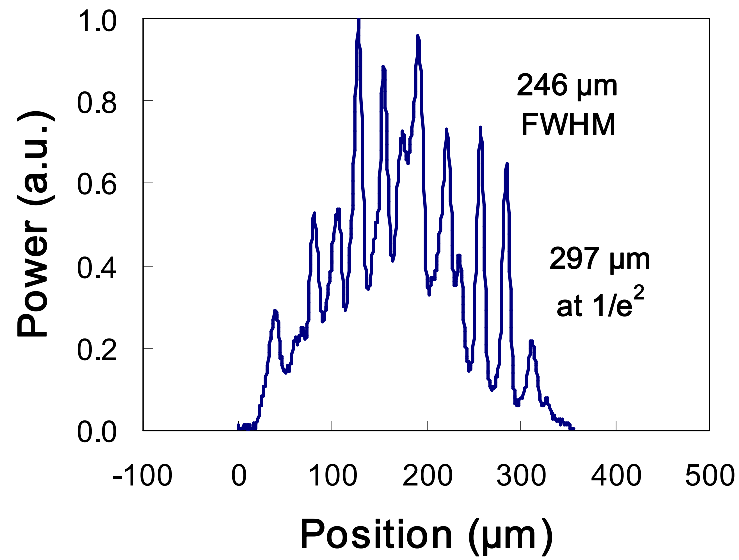
Example of tapered beam with imperfections

- 975 nm tapered laser
- L_{RW} = 0. 5 mm
- L_{taper} = 3 mm
- θ_{taper} = 6°
- 4W CW

near-field
slow axis at waist



near-field
slow axis at facet



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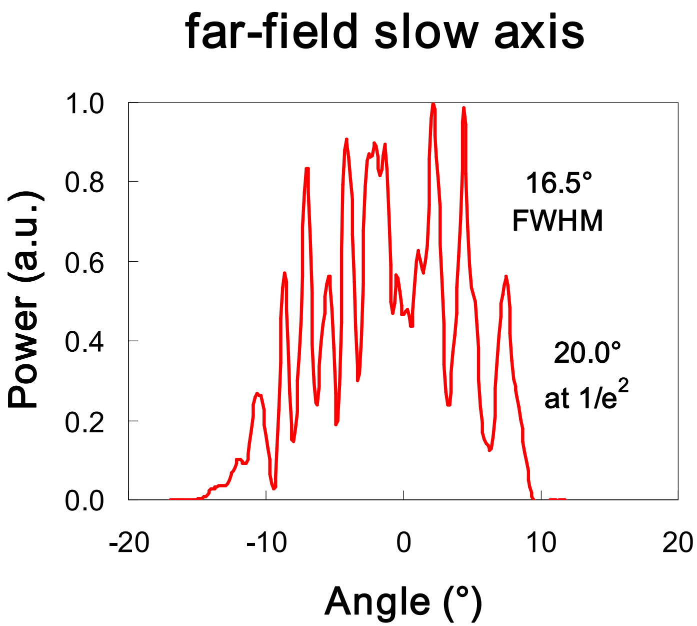

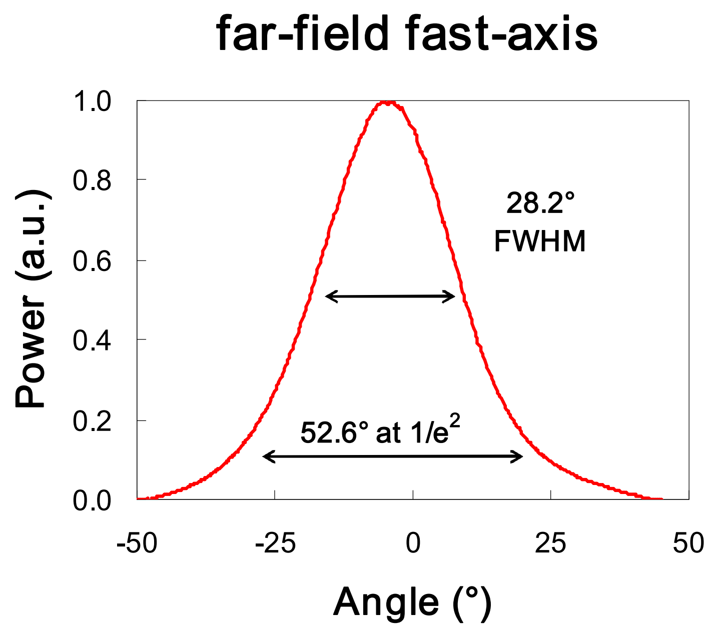

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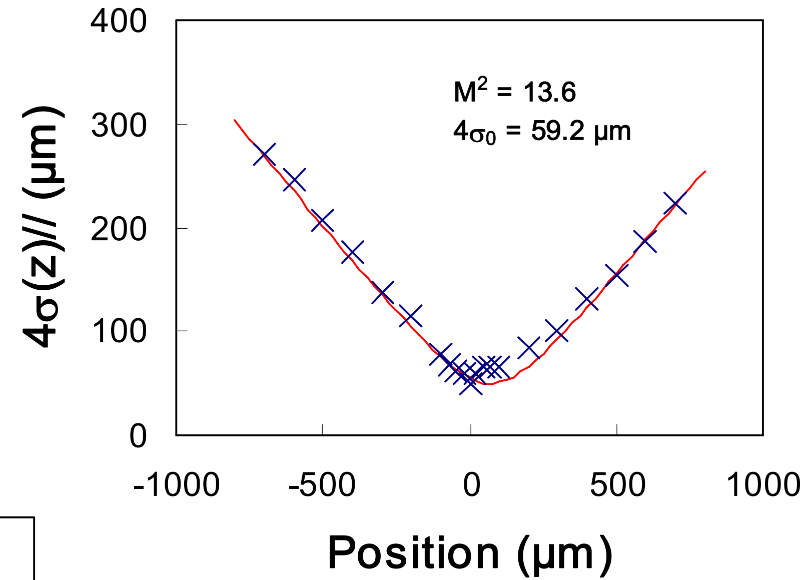
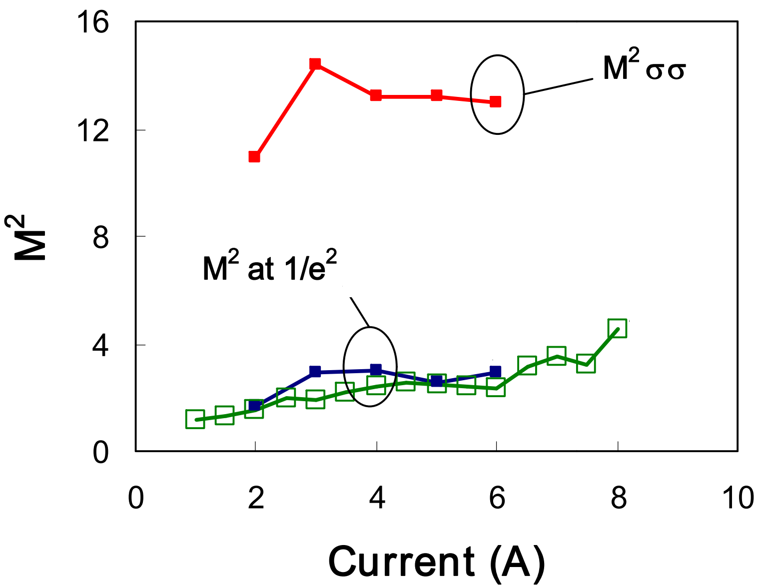
Beam properties of tapered lasers

- M^2 at $1/e^2$ and $M^2\sigma$
  - 975 nm tapered laser
  - L_{RW} = 0. 5 mm
  - L_{taper} = 3 mm
  - θ_{taper} = 6°
  - 4W CW





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Why is brightnes useful?

Single mode fiber coupling (SMF)

- State-of-the-art fiber coupled power is around 2 W
- Coupled power has progressed slower than emitter brightness

1.2 W coupled into SMF
from 1.48 µm
tapered laser
Alcatel
Delepine et al. JSTQE
Vol. 7, n°2
pp. 111-123
(2001)

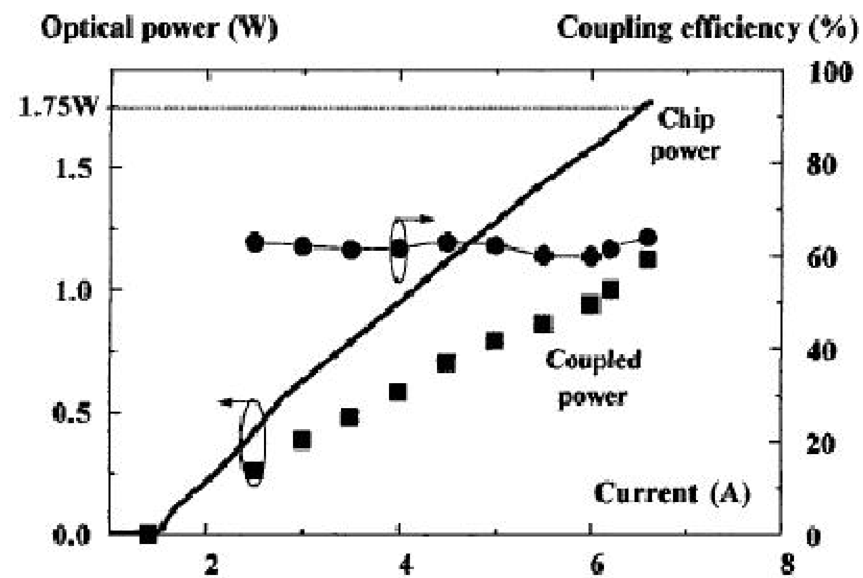

Fig. 22. L–I curves of the laser chip (straight line) and power coupled into SMF (squares), along with coupling efficiency (filled circles).

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Conclusions

- **What is brightness**
  - M^2 relates the optical throughput or etendue to that of diffraction-limited beam
  - M^2 at $1/e^2$ and $M^2\sigma$ techniques were presented and compared
- **The brightness theorem**
  - Higher coupled brightness requires higher input brightness
  - Source of significant laser research
- **Laser source engineering**
  - Is mainly based on the large cavity challenge
  - Requires thicker epitaxy
  - Longer waveguides are possible based on low-loss materials

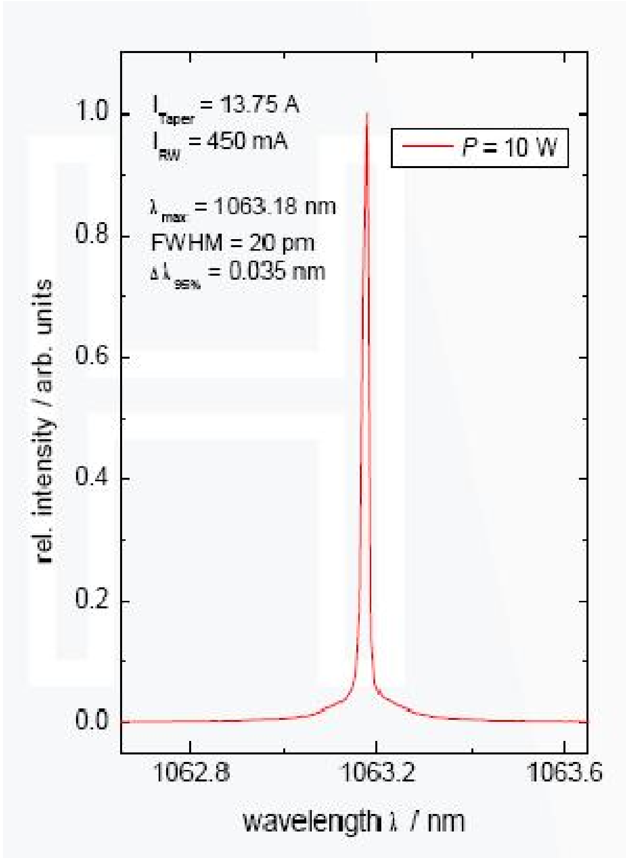
Conclusions

- **State-of-the-art tapered lasers**
  - Tapered lasers deliver 10 W with M^2 of less than 2 near λ = 1 µm
  - Beam limitations include astigmatism and relatively large FF angles
  - Single mode fiber (SMF) coupled power is lower, in the range of 2W

- **Future trends ...**

Need for high spectral brightness

- High spectral brightness lasers are required for
  - Frequency doubling
  - Atom cooling
  - Solid-state pumping on narrow absorption lines
- 1060 nm DBR tapered laser
  - Realised at Ferdinand Braun Institut (FBH)
  - Also developed by US teams
  - Also show improved beam quality



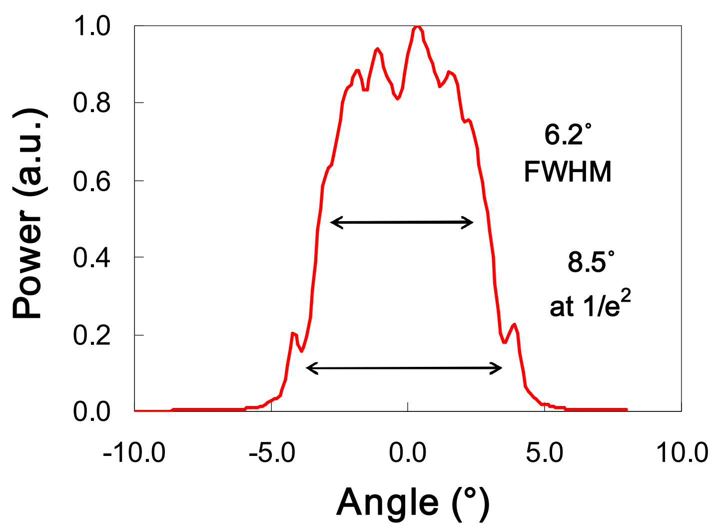
Courtesy FBH
B. Sumpf, K.H. Hasler

Old broad area laser is still a winner ...

New broad-area laser structures

- 25 W CW from 100 µm broad area laser (Intense Photonics)
- Requires high d/Γ
- Offer higher WP efficiency of up to 76% (nLight)
- May be include gratings for less than 1 nm spectral width (Alfalight)
- Offer narrow slow-axis far-field, down to 6° FW @95% (Jenoptik)

III-V Lab uncoated BA laser with narrow slow-axis and 71% max. WP efficiency



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