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Tapered Laser Design: Part 1

Efficiency of diode lasers: Basics and principles of optimisation

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...translating ideas into innovation

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Outline

- Introduction
- Theoretical considerations
- Material parameter
- Design issues
- Example of diode laser structure
- Outlook

Introduction I

Benefits of high conversion efficiency

- Energy saving
  - high power laser systems (cost, climate!)
  - military (DARPA: SHEDS, ADHELS… 100kW power laser system)
  - mobile, handheld laser systems
- Lower temperature rise of the active region
  - reduced defect mobility ⇒ improved reliability
  - reduced thermo-mechanical stress in pulsed operation
  - reduced impact on lateral index profile ⇒ stable beam quality
  - reduced shift of wavelength
- Higher output power
- Simpler, low cost mounting schemes

Introduction II

Applications

- Laser bars for optical pumping of solid state lasers
  - 9xx nm ⇒ Yb – doped fibre and disk lasers
  - 808 nm ⇒ Nd - doped solid state lasers
- Medical applications (handheld systems)
- High brightness diode lasers (fibre amplifier, visible sources...)

Introduction III

State of the art

- Several groups have reported on high efficiency laser bars (alfalight, nLight, JDSU, OSRAM, DILAS, JenOptik...)
  - Maximum values ≈ 75% @ 70W , 9xx nm
- Output power up to 1000W from a single bar
  - JenOptik, Spectra physics...

- Chip (mounted chip): conversion efficiency
- Laser system: Wall plug efficiency

At 100 W optical output power

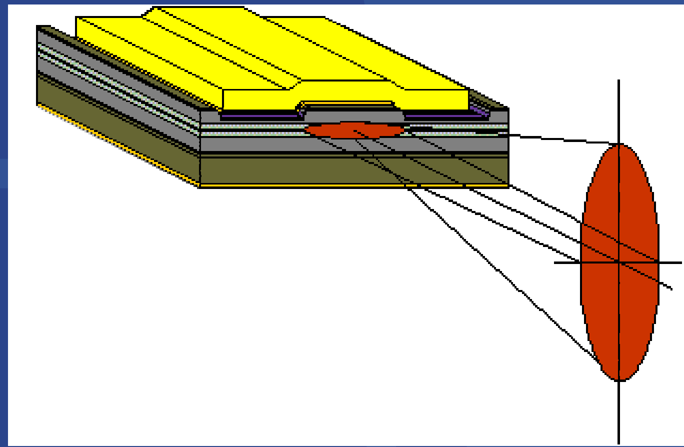
50 % → 100 W waste heat

75 % → 33 W waste heat

Diode lasers: basics

- Optical gain by carrier injection
- Optical resonator by waveguide structure, contact windows and cleaved mirrors
- Power current characteristics*
- Slope *

*thermal effects neglected



$$P = \eta_d \cdot \left(I - I_{th} \right)$$

$$\eta_d = \frac{\hbar \cdot \omega}{q} \cdot \eta_i \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

Conversion efficiency: basics

Definition of conversion efficiency

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

- Internal efficiency
- Excess current level
- Pumping loss by excess voltage
- Relation mirror loss to internal + mirror loss

There exist a maximum value of conversion efficiency, due to increase of U_{op} with I_{op} (series resistance, generation of Joule heat)

Conversion efficiency: internal efficiency

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

Internal efficiency = generated lasing photons / injected carriers

- **Losses by**
  - **carrier leakage**
    - insufficient barrier height (red emitting lasers, design)
    - deep levels waveguide layers (material quality)
  - **nonradiative recombination**
    - quality of interface layers
    - Deep levels caused by defects or impurities in QW
- **Characterisation by carrier lifetime**
  spontaneous recombination / stimulated recombination
- **Best values for 9xx nm lasers** $\eta_i \geq$ **0.95** **(red emitting 0.8 … 0.9)**

Conversion efficiency: threshold current

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

- **Excess current level**
  - **Low threshold current**
    - Highly strained SQW – devices
    - Small area devices
    - Optical confinement
    - Barrier height
- **Limit of excess current level**
  - **maximum reliable power**
    - Facet load
    - Thermal limitations (series resistance)
- **Typical operating currents about 10x I_{th} ➔ $\eta_{th} \geq$ 0.9 (red emitting 0.8)**

Conversion efficiency: voltage

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

- **Pumping loss by excess voltage**
  - **barriers of layer structure,**
  - **Series resistance**
    - doping level,
    - Material and material quality
- **Loss increases with current**
- **Typical values (BA-devices)** $\eta_v \geq$ **0.9** **(red emitting 0.8)**

Conversion efficiency: optical loss

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

- **Internal resonator optical loss**
  - **Absorption by carriers**
    - Doping
    - Carrier density in QW
  - **Optical leakage (waveguide design)**
  - **scattering**
- **Relation mirror loss to internal + mirror loss** $\eta_{ol} \geq 0.9$

Conversion efficiency

$$\eta_c = \frac{P_{op}}{U_{op} \cdot I_{op}} = \eta_i \cdot \frac{I_{op} - I_{th}}{I_{op}} \cdot \frac{\hbar\omega}{q \cdot \left(V_d + I_{op} \cdot R_s\right)} \cdot \frac{\alpha_m}{\alpha_m + \alpha_i}$$

- Internal efficiency > 0.95
- Excess current level > 0.9
- Pumping loss by excess voltage > 0.9
- mirror loss to internal + mirror loss > 0.9

$\eta_c \geq 0.95 \cdot 0.9 \cdot 0.9 \cdot 0.9 \approx 0.7$

(red emitting $\eta_c \geq 0.8 \cdot 0.8 \cdot 0.8 \cdot 0.9 \approx 0.46$)

Thermal effects

Thermal resistance (low, but not zero) $\Rightarrow$ increase of T_j in operation

- Empirical implementation of thermal impact on threshold and slope

$$P_{op} = \eta_d \cdot \exp\left(- \frac{R_{th} \cdot \left[I_{op} \left(V_d + I_{op} \cdot R_s \right) - P_{op} \right]}{T_1} \right) \cdot \left(I_{op} - I_{th} \cdot \exp\left(\frac{R_{th} \cdot \left[I_{op} \left(V_d + I_{op} \cdot R_s \right) - P_{op} \right]}{T_0} \right) \right)$$

- T_0 increases threshold
- T_1 decreases slope efficiency

- T_0 depends on QW – design + barrier height
- T_1 depends on barrier height (carrier leakage above threshold)
- R_{th} depends on footprint, layer thickness and material
- Equation only empirical,
  however helps in determination of most efficient design issues

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Design issues for high efficiency

Common criteria

- **material quality**
- **Total layer thickness as small as possible**

Optimising

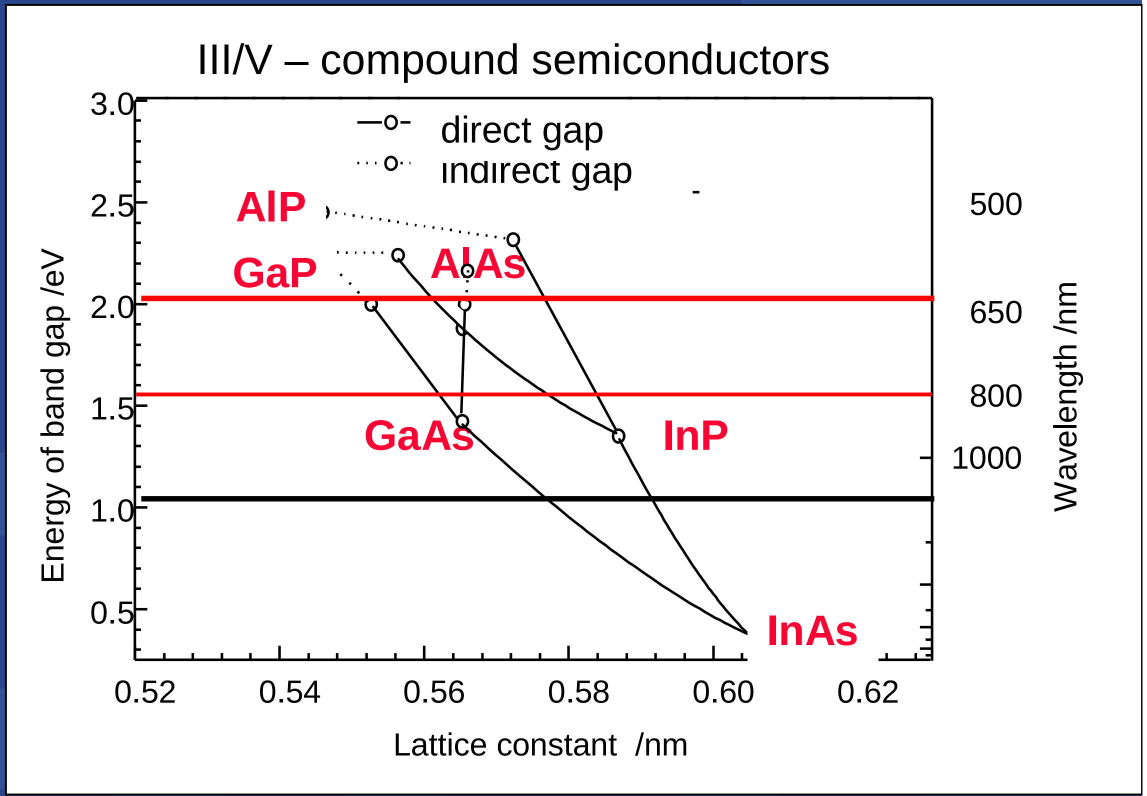
- **Doping profile**
  - absorption loss versus series resistance
- **Active region**
  - low threshold current density (SQW) versus T_0 and T_1 + external efficiency
- **Waveguide design**
  - high optical confinement versus beam quality (+ higher order modes)
- **Resonator quality (length + reflectivity)**
  - low R_s and R_{th} versus threshold current (+ external efficiency)
- **Barrier height**
  - high T_0 an T_1 versus material quality (voltage and series resistance)

GaAs based HPDL 650nm – 1150nm

Binary crystals
⇒ substrates
GaAs

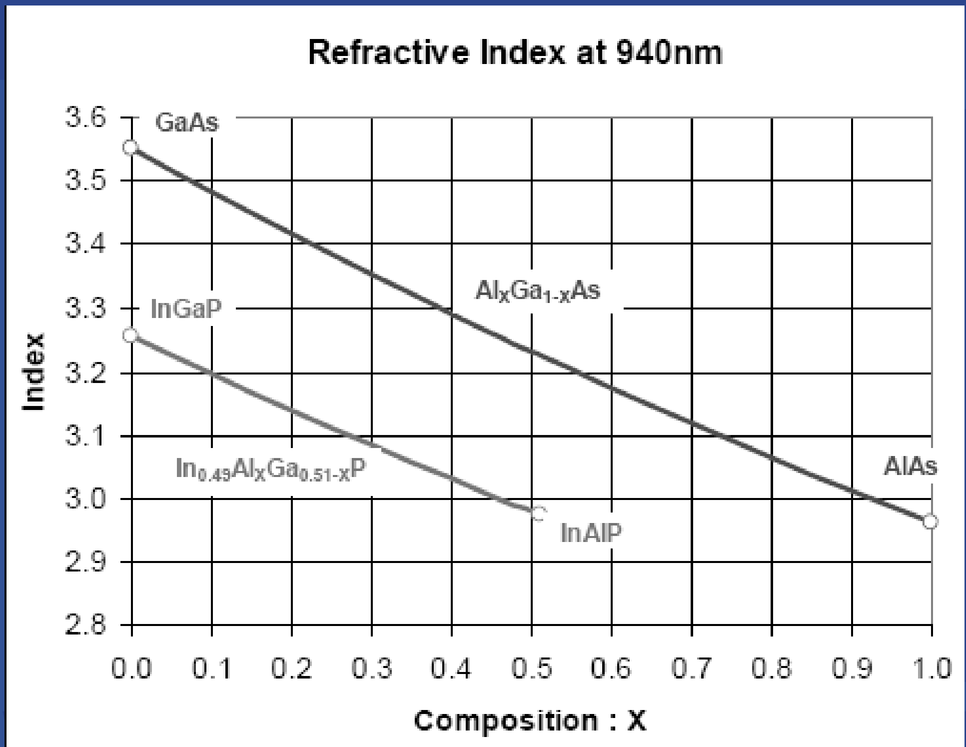
Lattice matched layers
⇒
waveguide structure
InGaAsP, AlGaAs

Pseudomorphic layers
⇒ active regions
thickness 10nm QW
strain 2%
InGaP, GaAsP,
InGaAs



Landscape of epitaxial layer design

Material parameters for design I

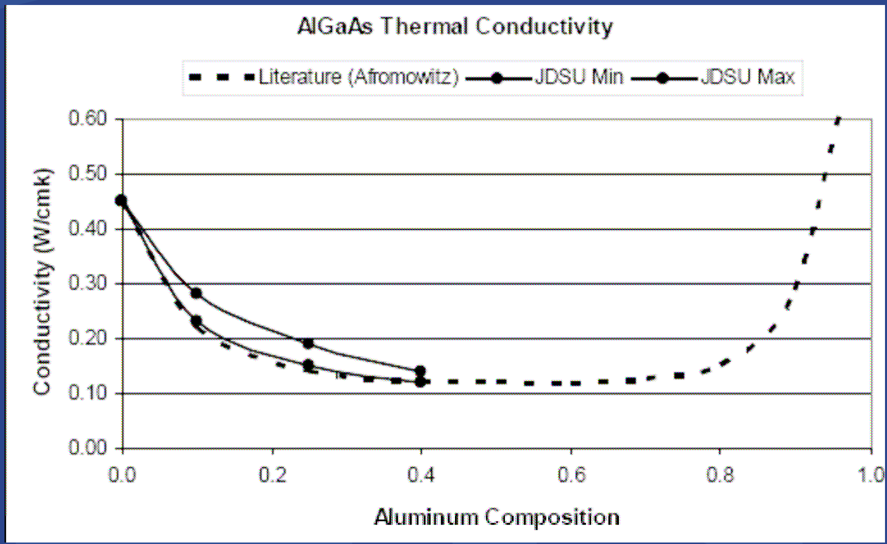


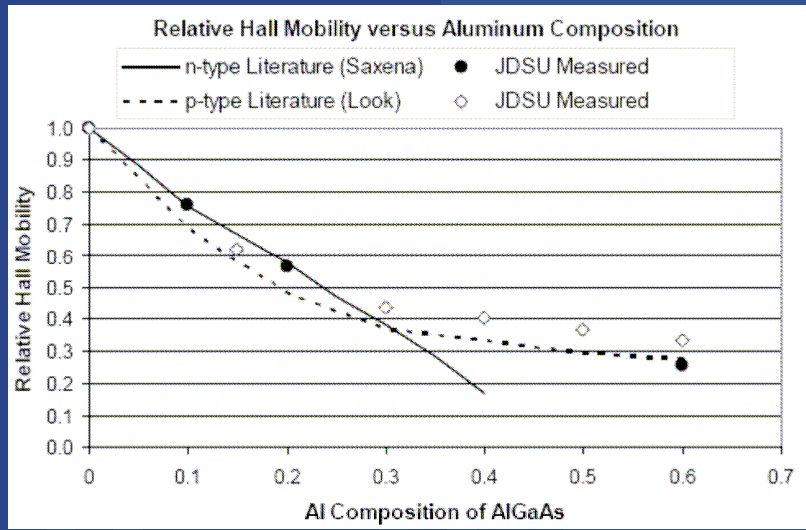
Profile of refractive index required for desired waveguiding properties has to be adjusted by composition profile

$\Delta N \approx 0.15$ sufficient

$\Rightarrow \Delta x \geq 0.2$

Material parameters for design II





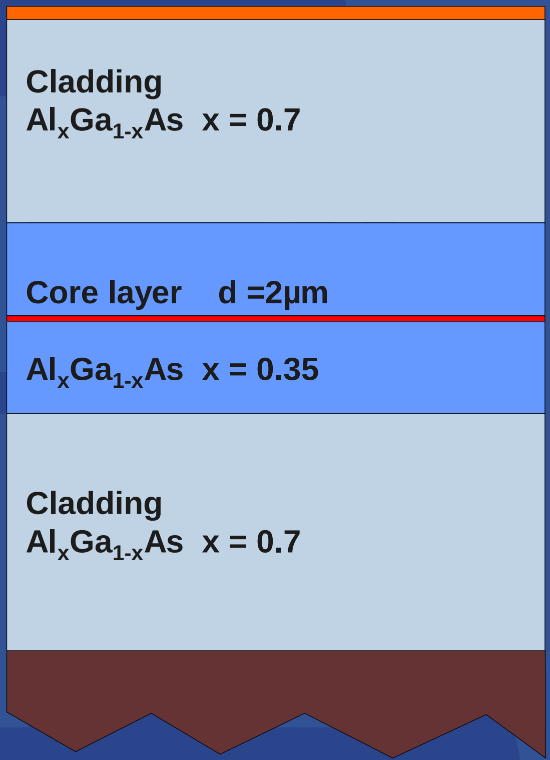
- Low x values favoured for high thermal and electrical conductivity (but low barrier height to QW, ⇒ wavelength >1000nm)
- Medium x values results in bad thermal and electrical conductivity, but highest barriers (common used)
- High x values ⇒ again good thermal conductivity, but difficult due to strain, oxygen and carbon uptake, oxidation

Way to highly efficient diode lasers

- Exact solutions require:
  Solving a complex mathematical problem with a lot of parameters
  - Calculation of threshold current, slope efficiency, T_0, T_1, R_s
  - Scanning different QW, waveguide designs, doping profils …
- One point solution
- practical way
  - Experience ➔ design rules
  - experimental data
  - playing with simple equations or simulation tools
  - additional parameters determined by
    - Technology
    - Reliability
    - Economy

Example: 940nm laser bars layer structure

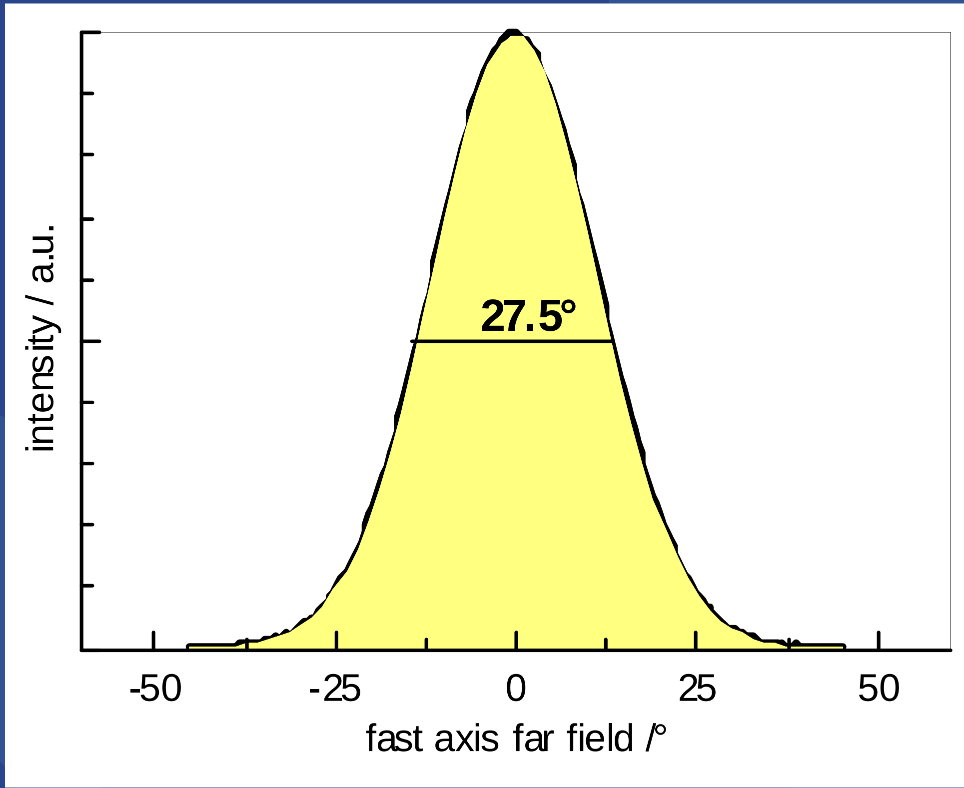
- InGaAs SQW embedded in GaAsP spacer layers and AlGaAs waveguide structure
- Broad waveguide 2µm core with large difference in refractive index between core and cladding
  - Good confinement of the optical mode
  - Optimising thickness of cladding
  - Optimising doping profile



940nm laser bars: properties of layer structure I

Vertical far field

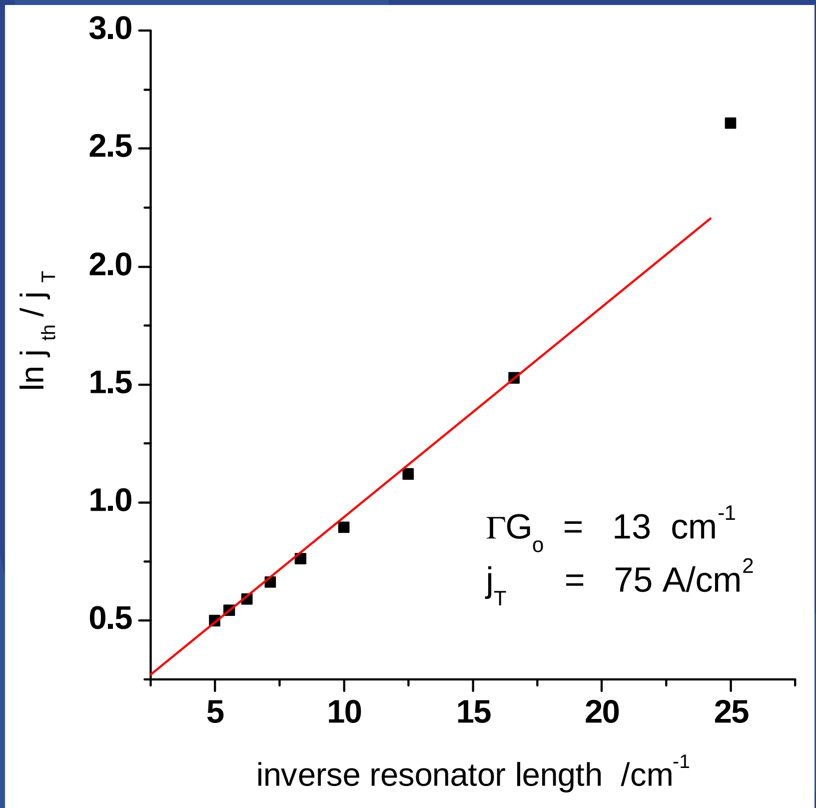
- Nearly perfect Gaussian intensity distribution
  - 27.5° FWHM
  - 47° 95% power
  - 60° 99% power

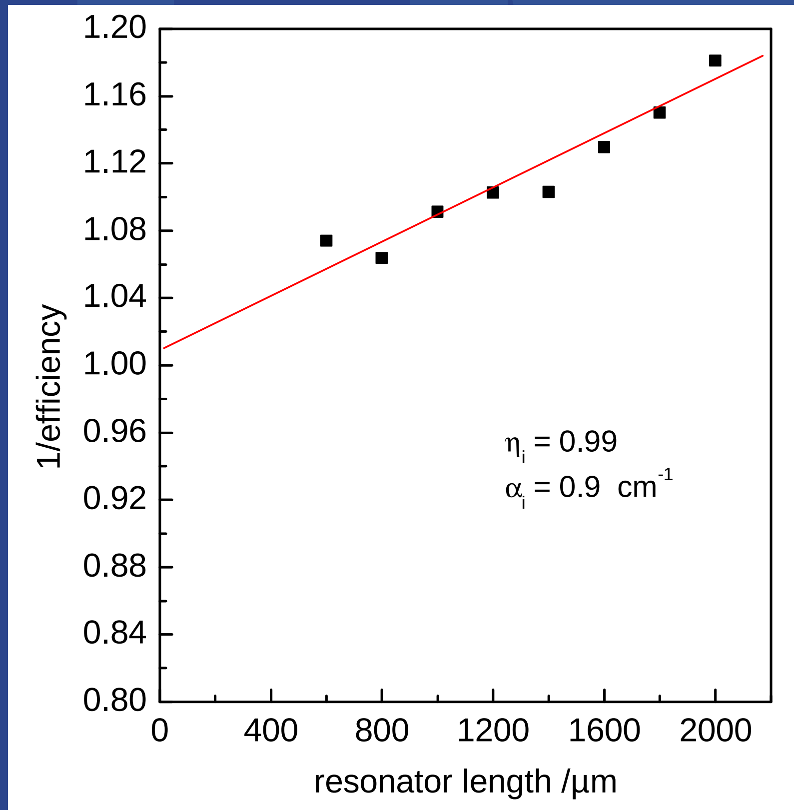


940nm laser bars: properties of layer structure II

Results of length dependence of threshold and efficiency

- Measured in pulsed mode using unmounted chips (1µs, 5kHz)
- L = 600µm … 2000µm





⇒ excellent fits possible

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940nm laser bars: characteristic parameters of layer structure

Parameter	value	unit
Transparency current density	75	Acm^{-2}
Modal gain coefficient	13	cm^{-1}
Threshold current density L = 1000µm	184	Acm^{-2}
Internal efficiency	99	%
Internal loss	0.9	cm^{-1}
Slope efficiency L=1000µm	91	%

Expected values for 1cm bar 30% filling, L = 1.5mm
- **6...7 A threshold current**
- **90% slope efficiency**

70 W laser bar at 940nm: parameters for simulation

1cm laser bar, 19 emitter, 150µm stripe width, 1.5mm resonator length
Values based on "standard" InGaAs/AlGaAs material at FBH
(results of pulsed measurements)

Parameter	Default value	range		unit
Threshold current	7.5			A
Slope efficiency	1.15	1.10	1.25	W/A
Diffusion voltage	1.32			V
Series resistance	2	1	2.5	mOhm
Thermal resistance	1	0.2	1.4	K/W
T_0	180	120	210	K
T_1	1000			K

$$P_{op} = \eta_d \cdot \exp\left(-\frac{R_{th} \cdot \left[I_{op}\left(V_d + I_{op} \cdot R_s\right) - P_{op}\right]}{T_1}\right) \cdot \left(I_{op} - I_{th} \cdot \exp\left(\frac{R_{th} \cdot \left[I_{op}\left(V_d + I_{op} \cdot R_s\right) - P_{op}\right]}{T_0}\right)\right)$$

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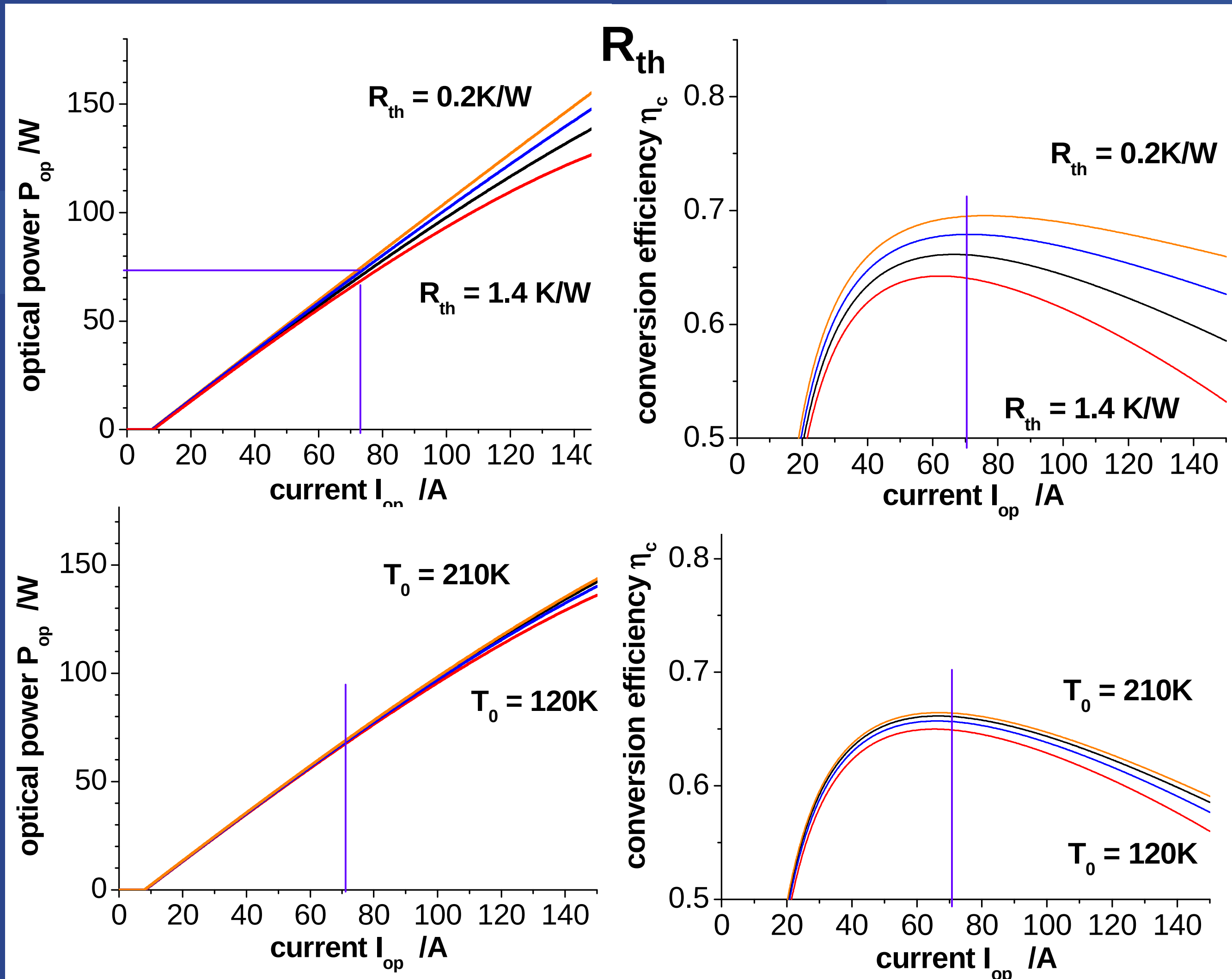
Simulation of P/I and efficiency of 940nm laser bars I

R_{th}
$\Rightarrow P_{op}$ small
η_c large

T_0
$\Rightarrow P_{op}$ small
η_c small

Black curves
= default values



Simulation of P/I and efficiency of 940nm laser bars II

η_d

$\Rightarrow$ P_{op} large

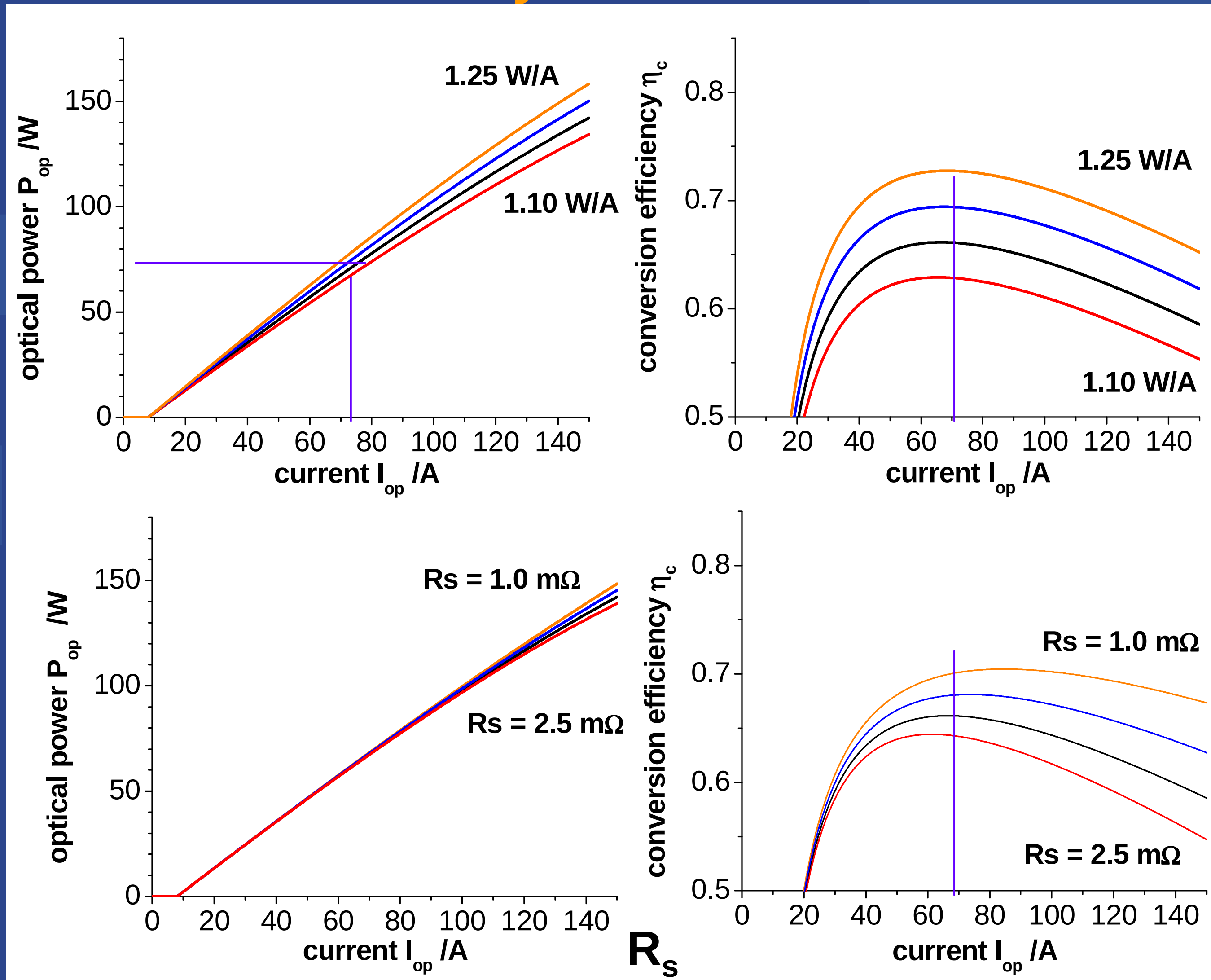
η_c large

R_s

$\Rightarrow$ P_{op} small

η_c large

Black curves = default values



Simulation of 940nm laser bars: results

- 70% conversion efficiency possible with “slight” improvement of “default“ parameters
- Slope efficiency and series resistance most crucial issue
  - Careful design of doping profile
  - Selection and quality of layer material
  - Optimised reflectivity
- T_0, T_1 important only at very high output power
- Threshold current ≤ 7.5A
- Thermal resistance about 1K/W (mounting schemes)

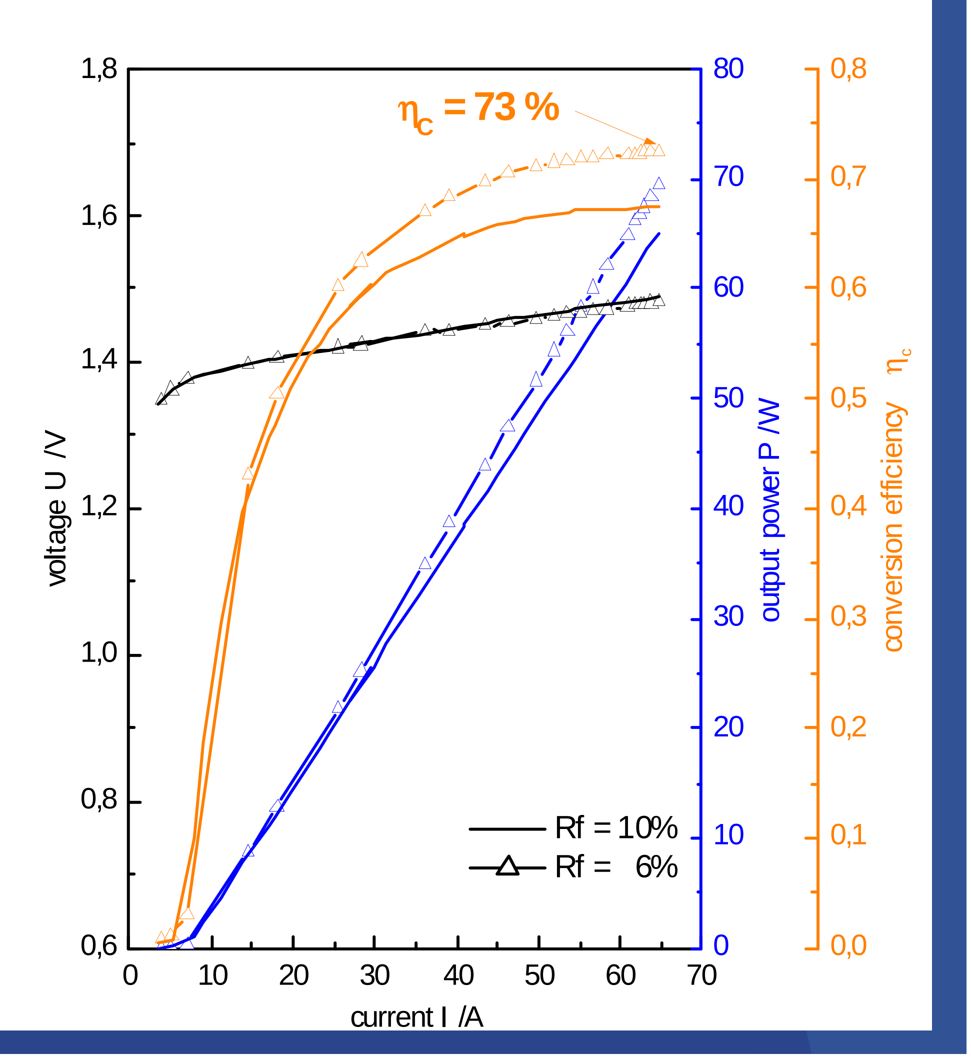
PUI characteristics of 940nm laser bars

CW operation T = 25°C
up to 65A

Two bars different AR coating
R_f = 10% and R_f = 6%

- threshold current
  I_{th} = 7.2A ⇒ I_{th} = 7.4 A
- conversion efficiency
  68% ⇒ 73%

Optimised design
⇒
> 70% efficiency



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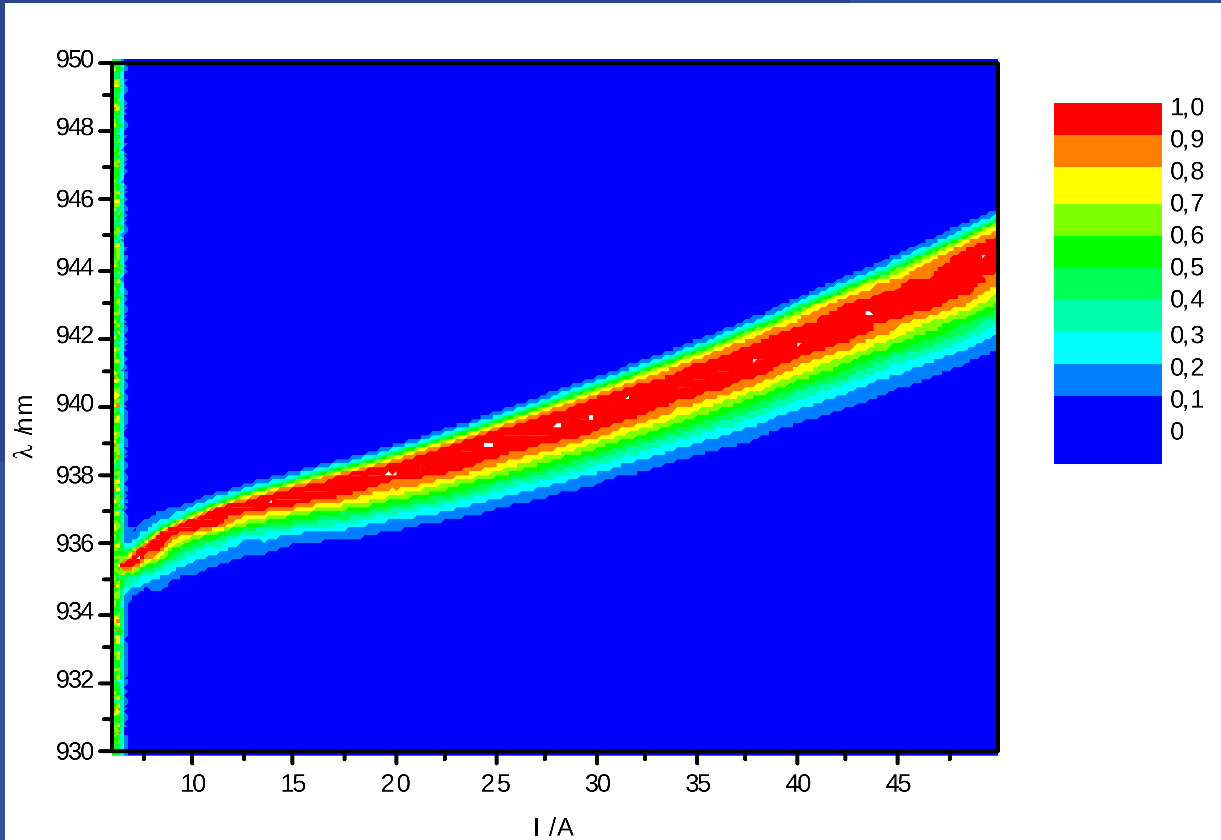
Spectral behavior of 940nm laser bar

- **wavelength**
  $\lambda \approx$ 940nm
- **spectral width**
  $\Delta\lambda \approx$ 2nm
- **thermal λ - shift**
  $\Rightarrow$
  R_{th} = 1.3K/W



CW operation measured up to 50A
T = 25°C

Parameters of 940nm laser bars

1cm laser bar
19 emitter, 150µm stripe width, 1.5mm resonator length

Comparison of “default values” with achieved results

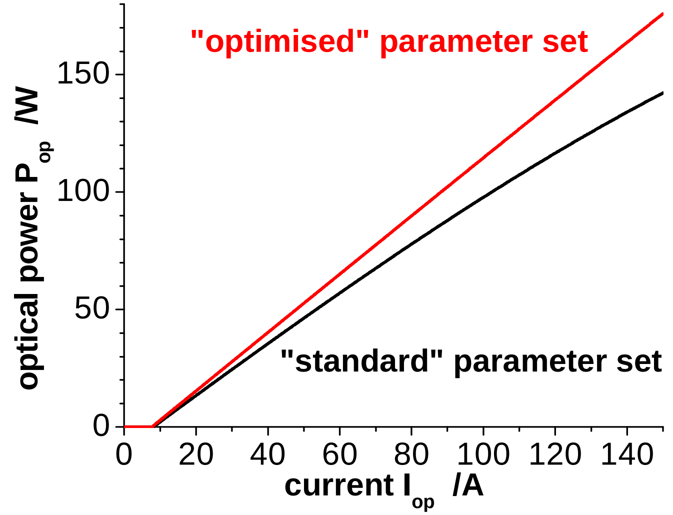
Parameter	Default value	achieved	unit
Threshold current	7.5	7.4	A
Slope efficiency	1.15	1.20	W/A
Diffusion voltage	1.32	1.33	V
Series resistance	2.0	1.6	mOhm
Thermal resistance	1.0	1.3	K/W
T_0	180	190	K
T_1	1000	1000	K

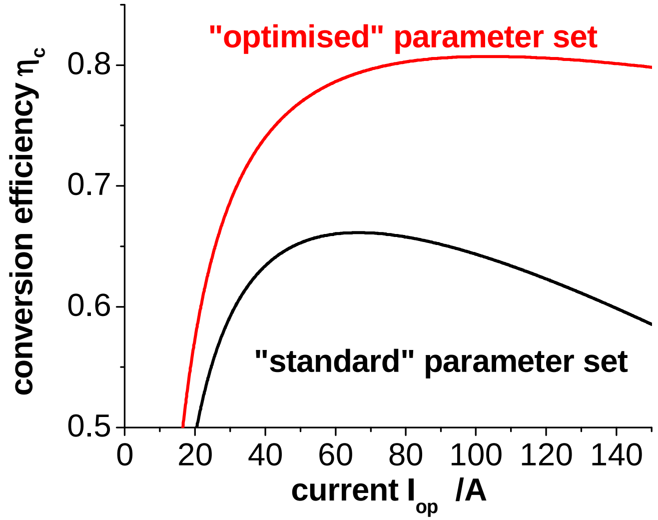
Outlook

- Higher efficiencies strongly reduce the amount of waste heat
  - 70% → 80% factor of 1.7 !!
- Simulation using “best values”
  ⇒ 80% conversion efficiency

Way to “best values”

- Reduction of layer thickness stronger optical confinement
  - Lower series resistance +
  - Higher divergence and facet load -
- “better” material
  - Lower Al-content +
  - Lower barrier height (longer wavelength!?) -





Literature

textbooks

- R. Diehl, (Ed.)
  “High Power Diode Lasers” 2000 Topics in Applied Physics Vol. 78
  chap. 5
- Bachmann, Loosen, Poprawe (Eds.)
  “High Power Diode Lasers”, 2007 Springer Science and business,
  chap. 2

papers

- Proceedings of SPIE
  “High power diode laser Technology and Applications V”
  Volume 6456, 2007, paper 64560C, 64650G, 64560L

Acknowledgment

The author thanks many colleagues of the FBH for stimulating discussions on efficiency of diode lasers.

Tapered Laser Design: Part 2

High-Power High-Brightness Tapered Diode Lasers and Amplifiers

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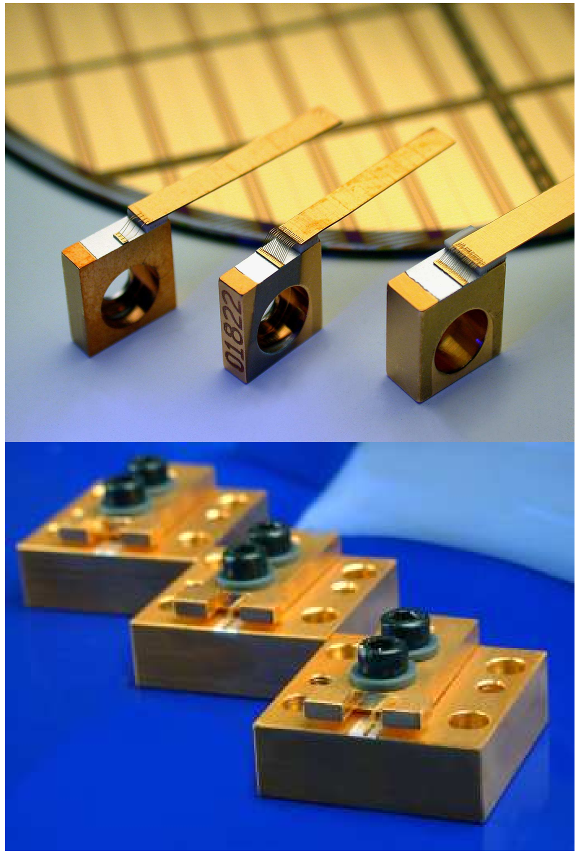
Outline

Principle design of a tapered laser
Designing a tapered laser ...

... for high beam quality
... for high output power
... for a stable astigmatism

(3) Tapered amplifiers in external cavity setup
(4) Summary



Principle Design

of a

Tapered Laser

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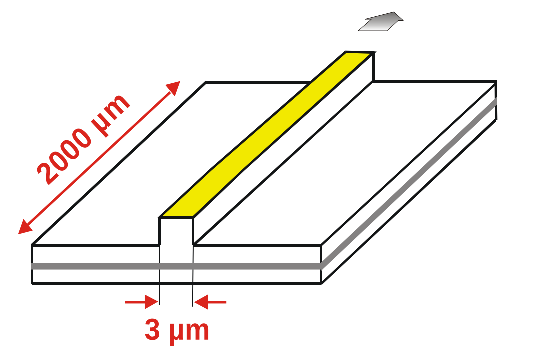
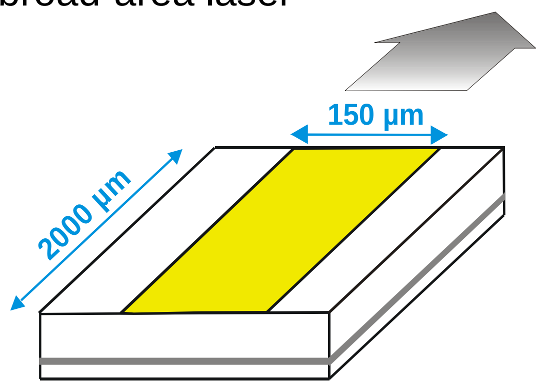
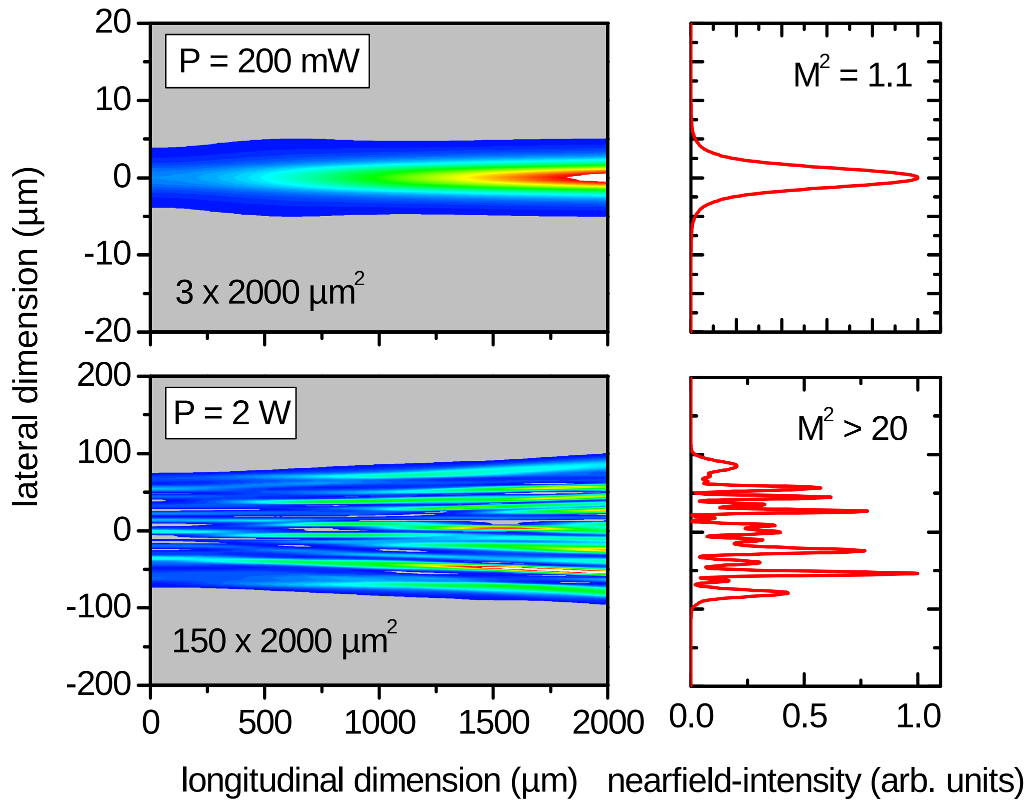
Principle design of a tapered laser – common diode lasers

ridge laser

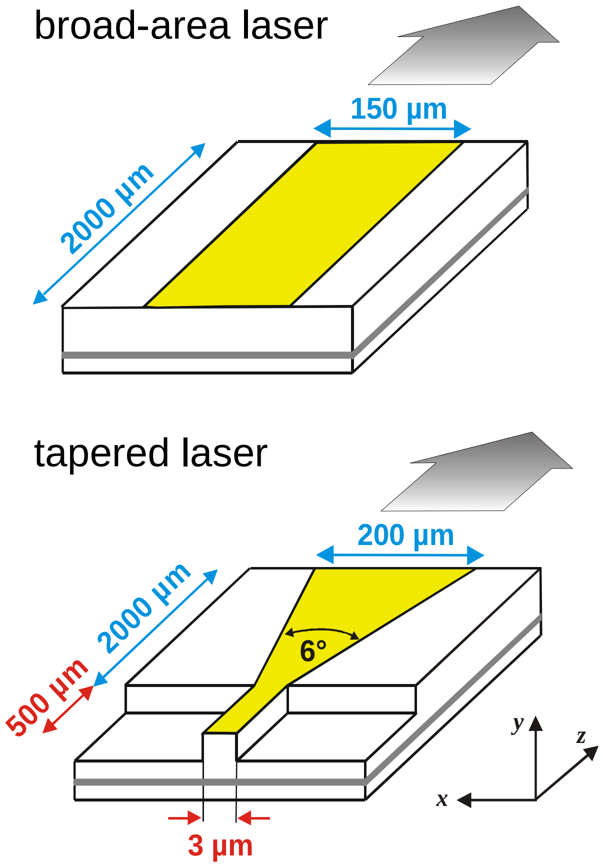


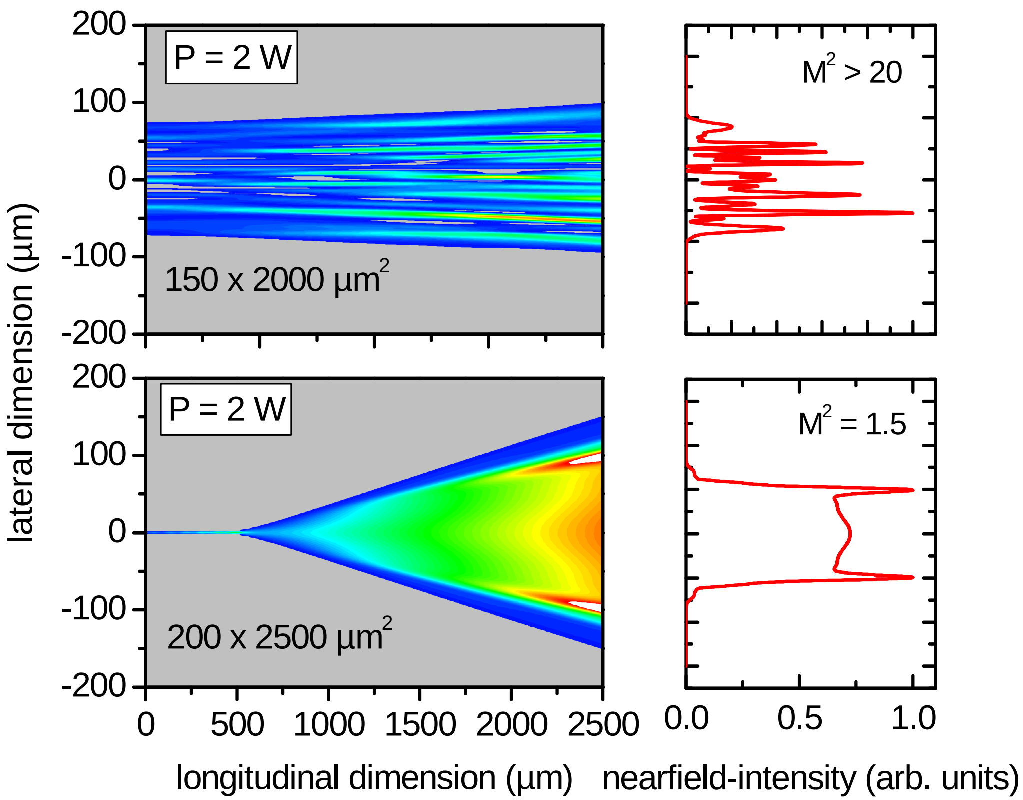
broad-area laser



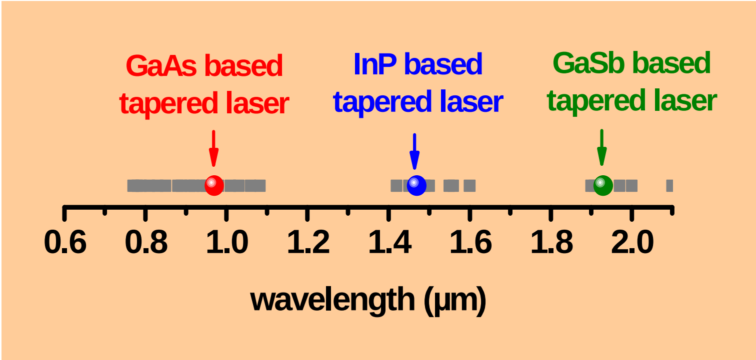


Principle design of a tapered laser – tapered laser design



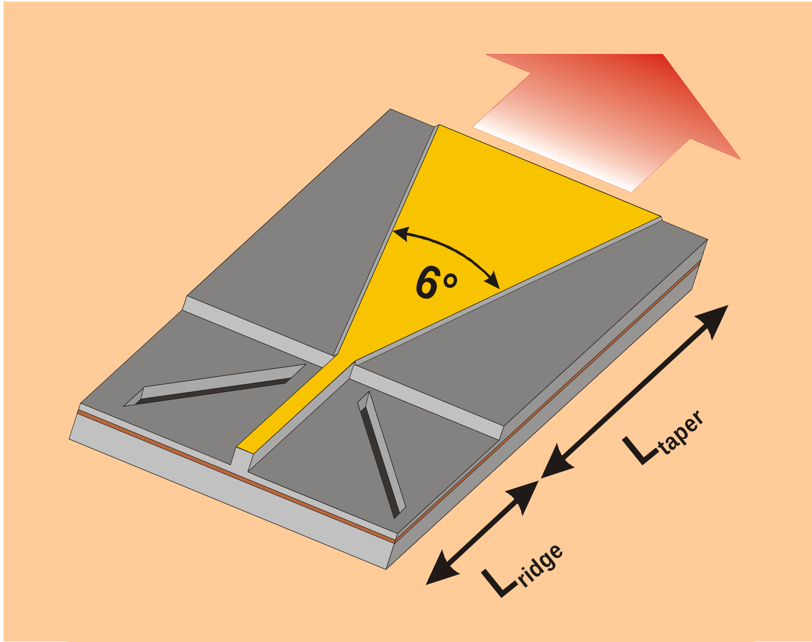


Principle design of a tapered laser – processing tapered lasers



Good epitaxial layer sequences needed with:

- low internal losses
- high conversion efficiency



Processing :

- index guided ridge section
- gain guided taper section
- optical lithography and chemical etching
- etching height of ridge crucial
- HR and AR coating on the facets

Designing

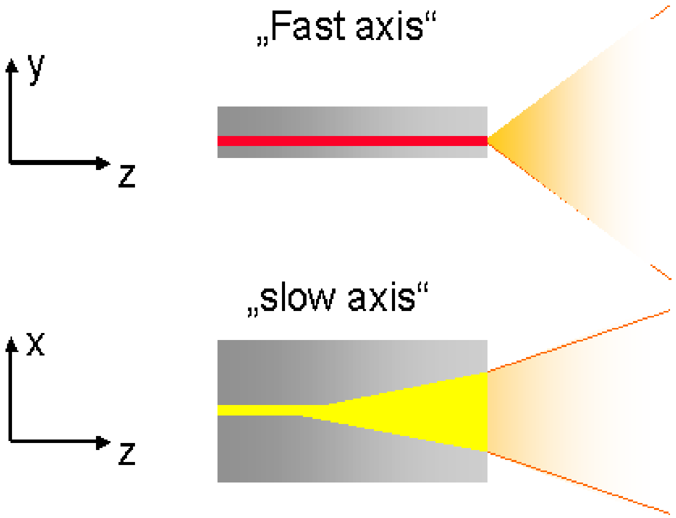
a

Tapered Laser

Designing a tapered laser for high brightness

Brightness of a tapered laser is described by:[1]

$$B \approx \frac{P}{\lambda_0^2 M_{fast}^2 M_{slow}^2}$$



The brightness of a tapered laser diode can be improved by:

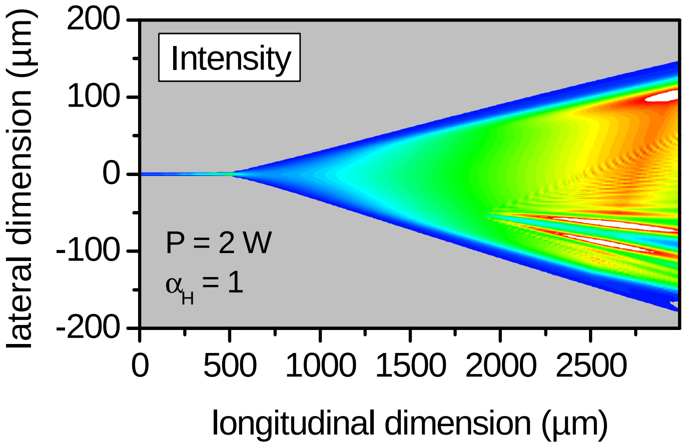
⇨ increase of beam quality
⇨ increase of output power

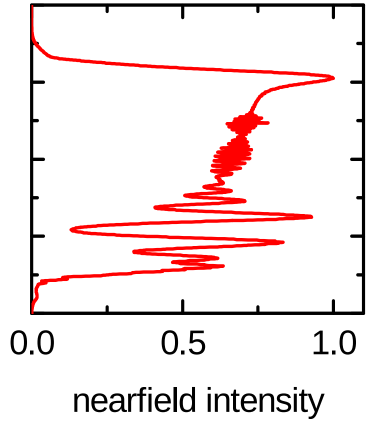
[1] J.N. Walpole, Opt. And Quant. Electr. 28, 623 (1996)

Beam Quality – thermal induced filamentation effect

Filamentation effect induced by local wave guides

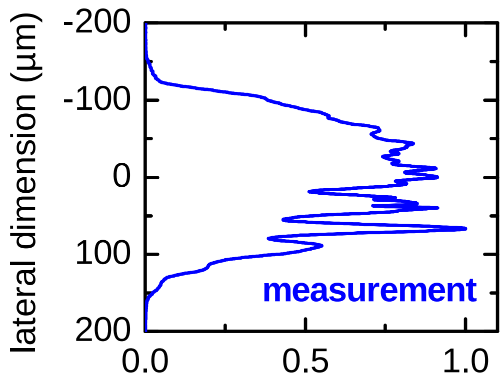
⇨ self focussing
⇨ „hot spot"





Methods to avoid filamentation effect:

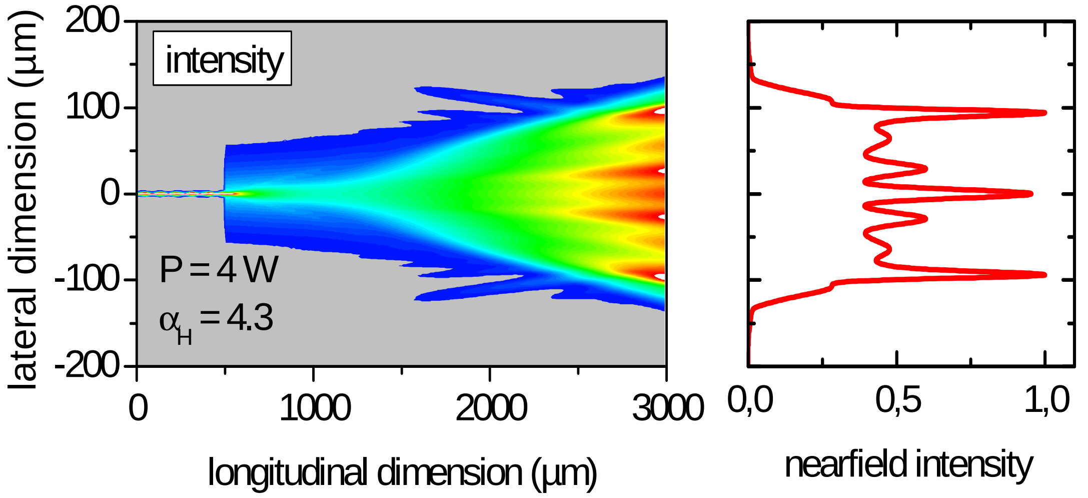
- homogenious soldering of diodes
- good heat dissipation



Beam Quality – carrier induced filamentation effect

Filamentation effect through local intensity fluctuations

The filamentations depend on the overall losses of tapered diode lasers.



description: [1]

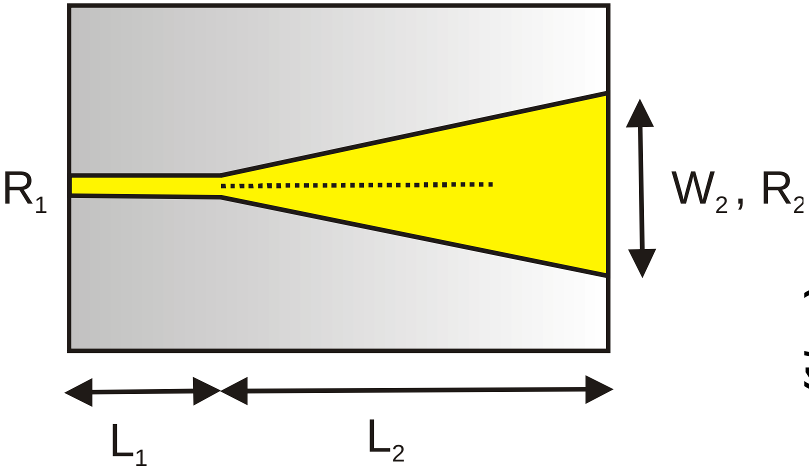
sinusoidal perturbations of carriers and fields

$$P = \frac{2\pi}{\sqrt{\frac{\alpha_H (I_0/I_s)\alpha_{tot} k_0}{1+I_0/I_s}}}$$

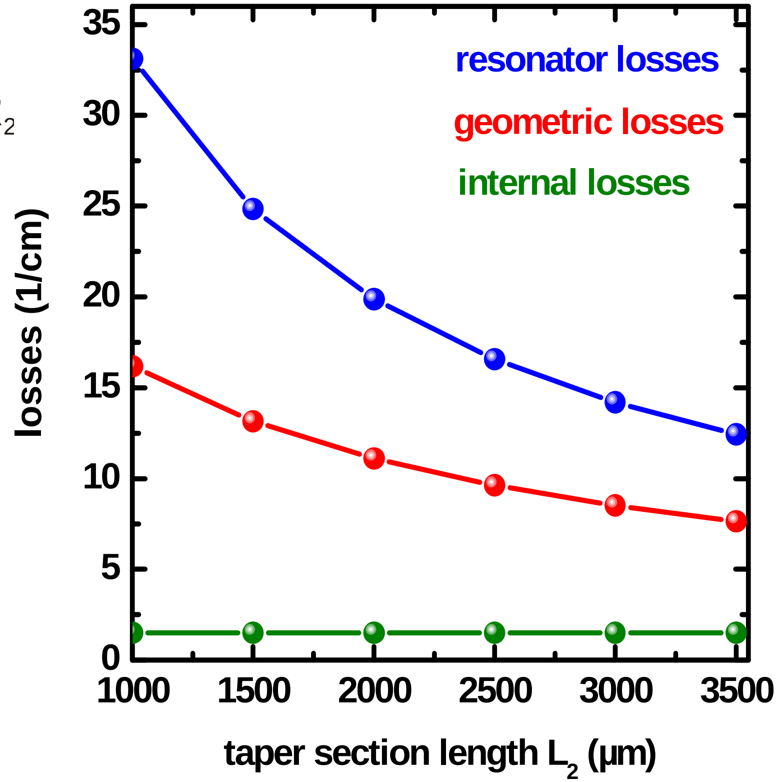
$$g_{max} = \frac{\left(\sqrt{\alpha_H^2+1}-1\right)}{2}\frac{I_0/I_s}{1+\left(I_0/I_s\right)}\alpha_{tot}$$

[1] G.C. Dente, J.Quantum Electr., Vol. 37, 2001

Beam Quality – additional losses of tapered diode lasers



$$\alpha_{tot} = \alpha_i - \frac{1}{2(L_1+L_2)}\ln[R_1R_2] - \frac{1}{2(L_1+L_2)}\ln\left[\frac{w_1^2 n_{eff}}{4L_2\lambda_0}\right]$$

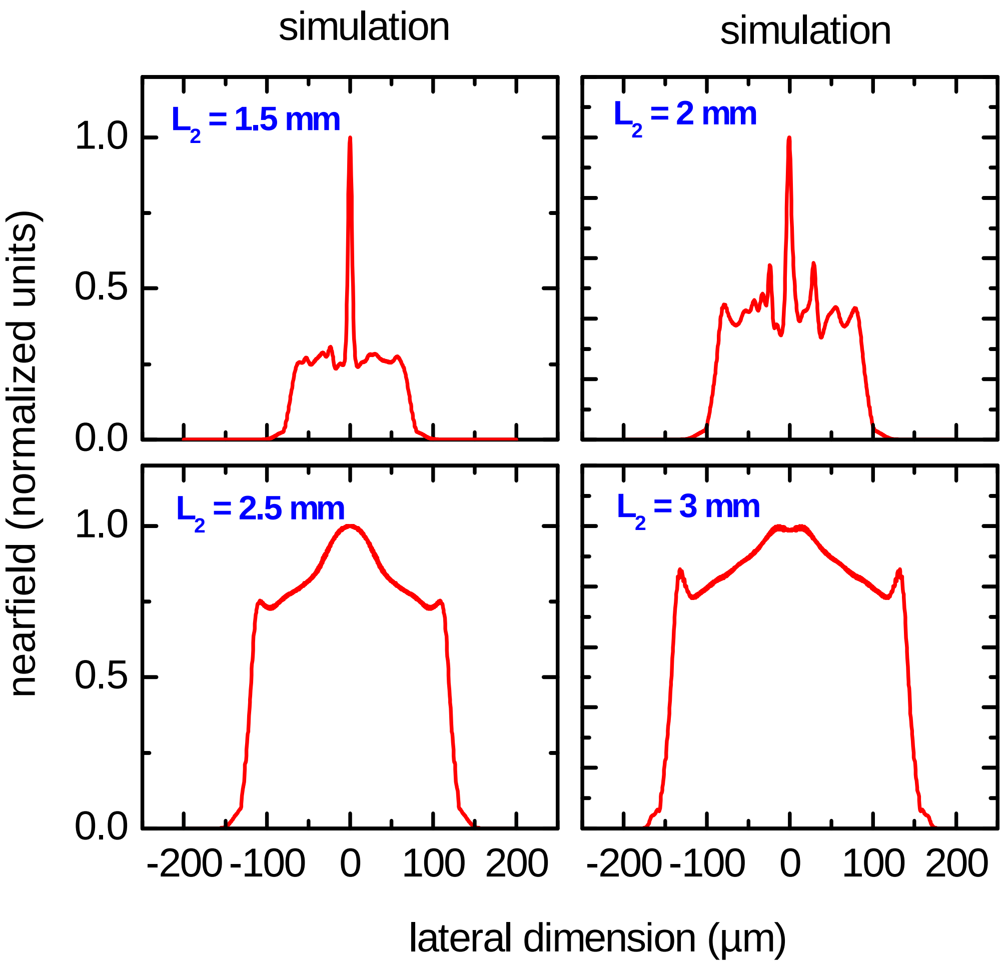


Beam Quality – nearfields

type	**RTL 976 nm**
ridge section:	**500 µm**
Simulation:	**L_2 varied** **$\alpha_H = 3$** **P = 4 W**

$$R_{2,\mathrm{eff}} = R_2 \frac{b_1^2 n_{eff}}{4 L_{Trapez} \lambda}$$

Filament density and ~ height decrease with longer taper section lengths.



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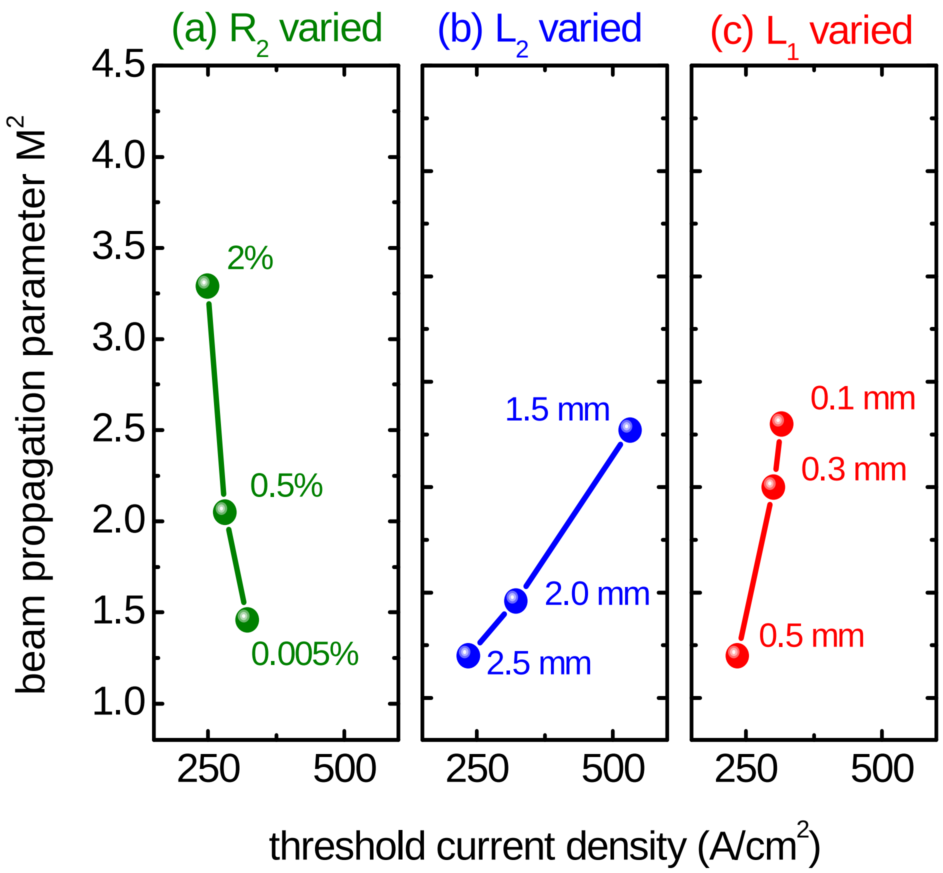
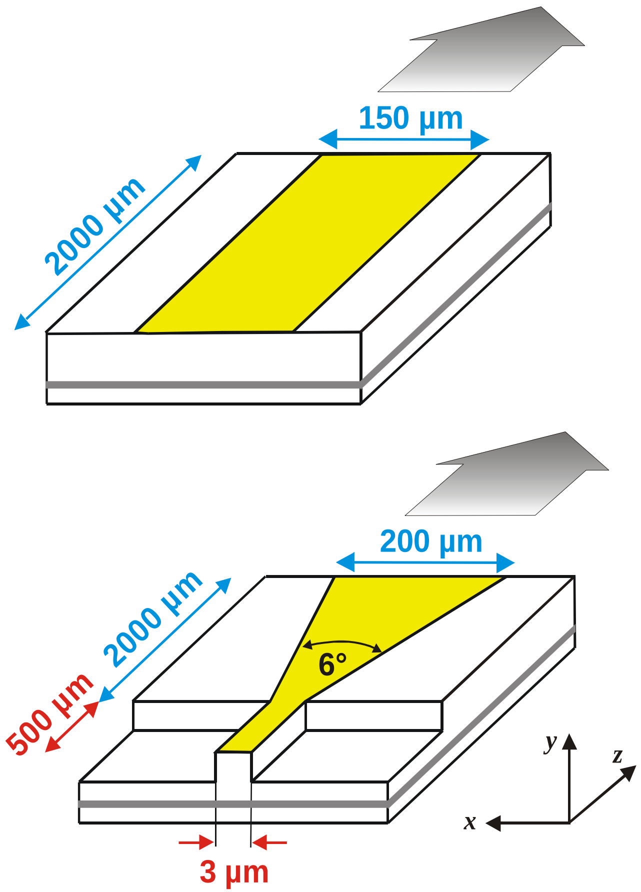
Beam Quality – beam propagation parameter M^2

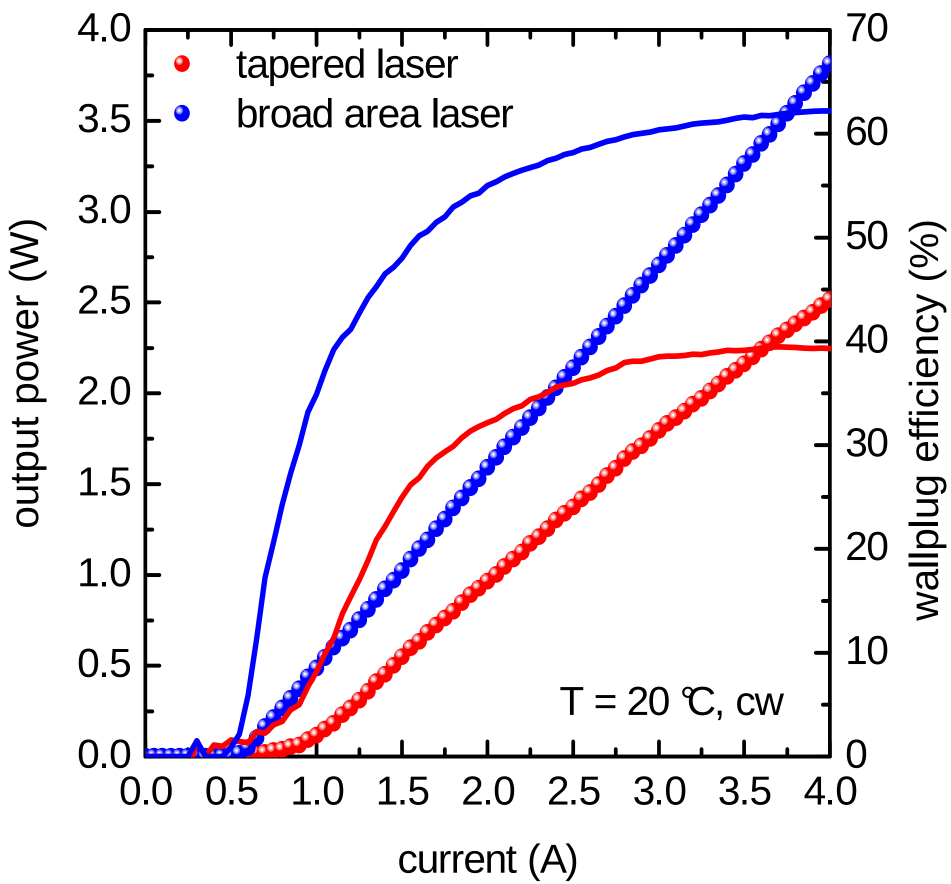
type	RTL 976 nm
ridge section:	100 .. 500 µm
taper section:	1.5 .. 2.5 mm
mounting:	p-side down
experiment:	20 °C, cw P = 2 W

type	M^2
theory (gaussian)	1
ridge laser	< 1.3
tapered laser	< 1.7
broad-area laser	> 20



Output Power – comparison between broad-area and tapered lasers





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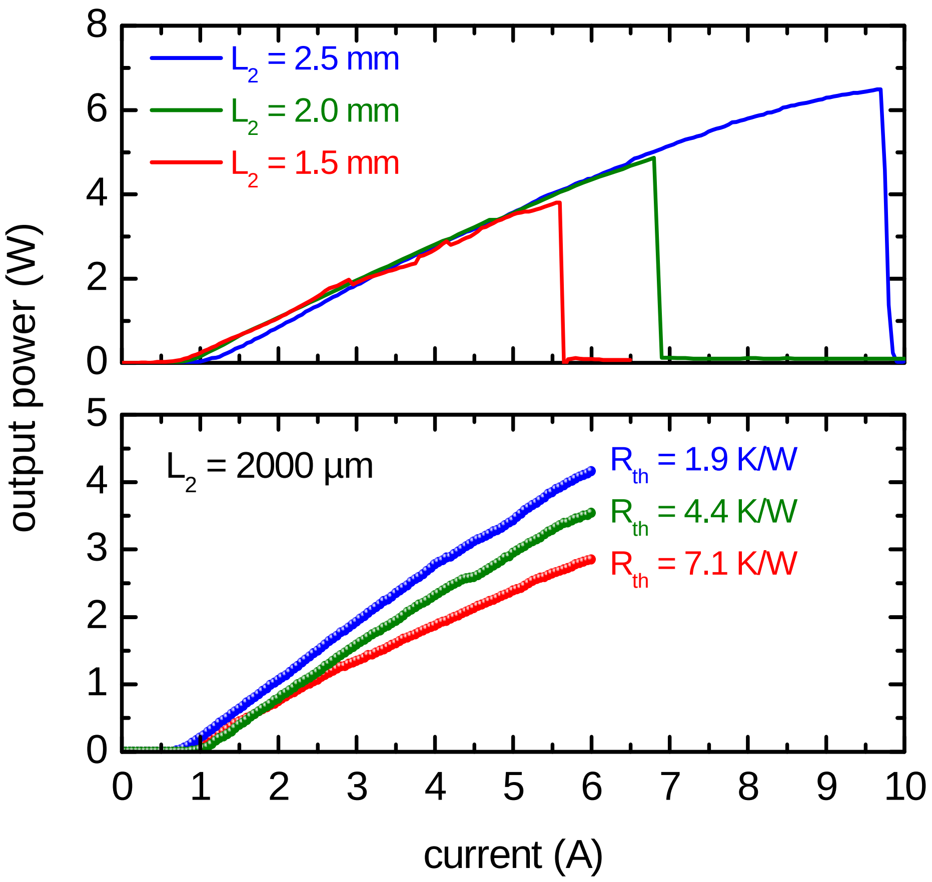
Output Power – how can we increase the output power ?

type	**RTL 976 nm**
ridge section:	**500 µm**
experiment:	**20 °C, cw**
mounting:	**different copper blocks**

- $COMD_{cw}$ = 2.5 MW/cm^2

  => longer taper section length

- The output power has been increased by 42% only by using different copper blocks.



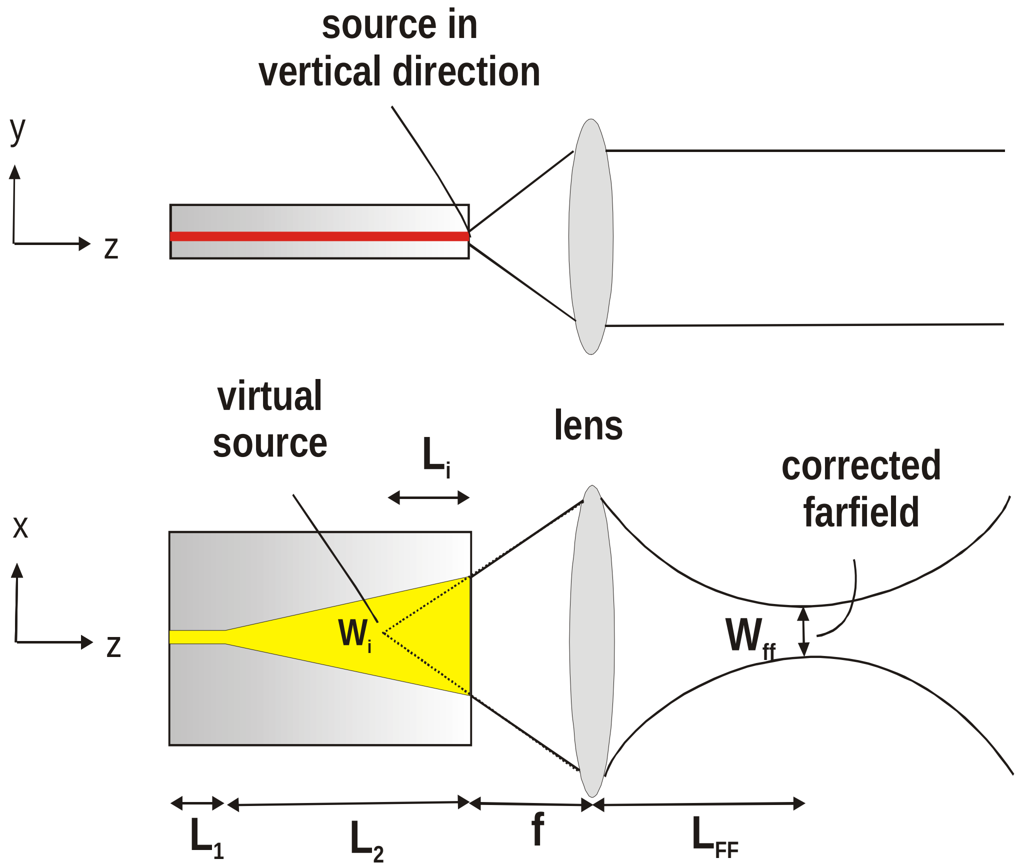
Astigmatism – definition

The astigmatism depends on the temperature and on the carrier density.

$$L_i(\mathrm{n,T}) = \frac{L_2}{n_{eff}(n,T)}$$

The position of the corrected farfield is a measure for the astigmatism

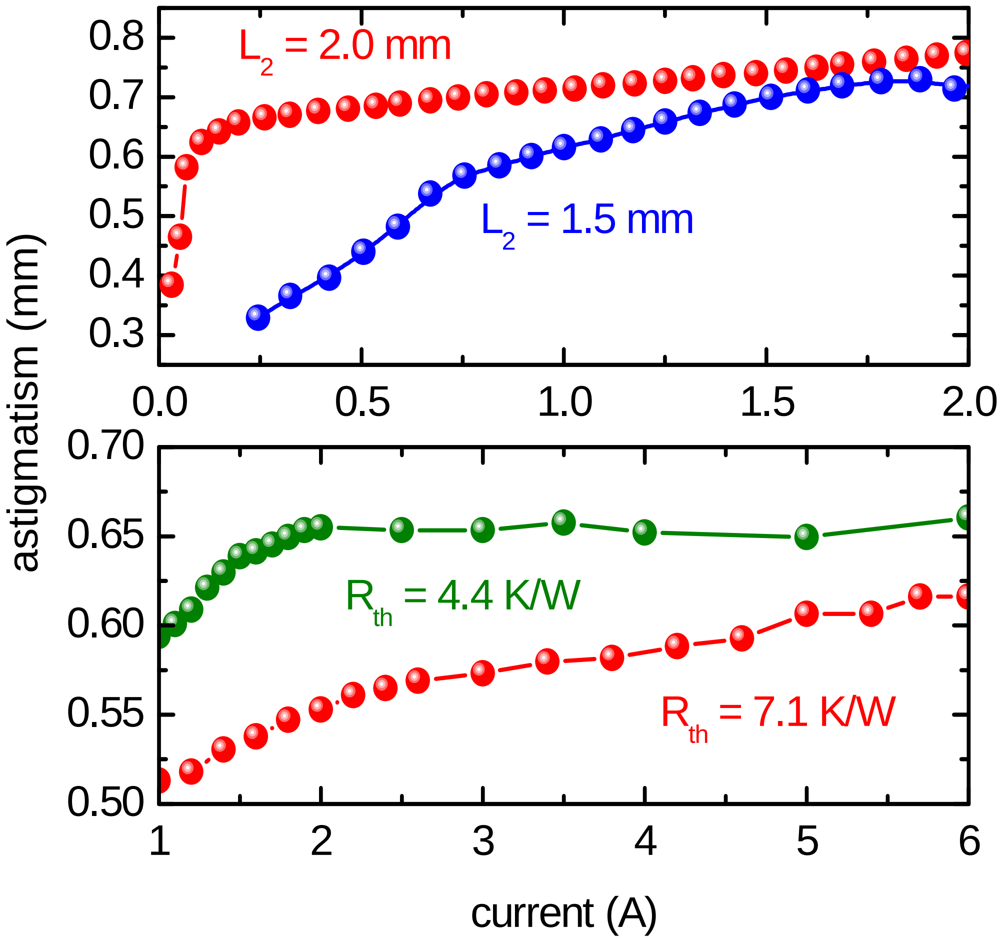
$$L_i(\mathrm{n,T}) = \frac{f^2}{L_{FF} - f}$$



Astigmatism – dependence on resonator design

type	**RTL 976 nm**
ridge section:	**varied**
taper section:	**varied**
mounting:	**p-side down**
experiment:	**20 °C, cw**

- The astigmatism depends on the resonator design.
- The astigmatism for GaAs tapered lasers is mainly temperature driven.



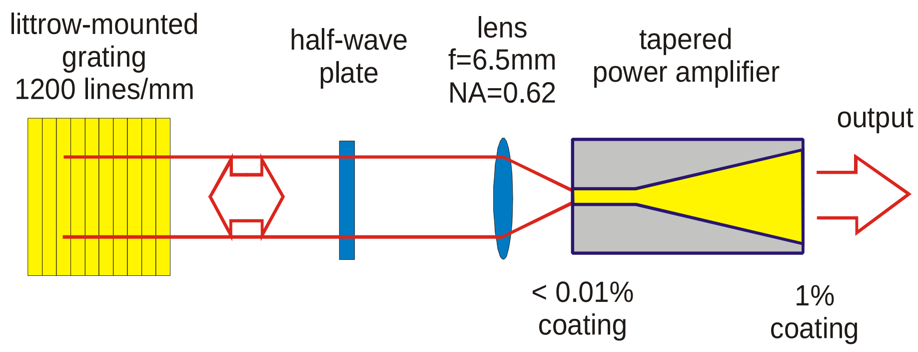
Tapered Amplifiers

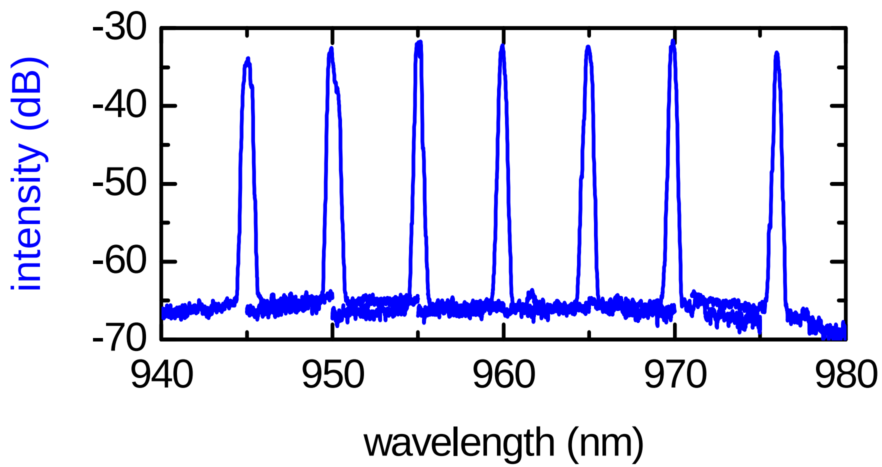
in external resonator configuration

at 975 nm

Tapered amplifiers – definition

type	RTL 976 nm
ridge section:	500 µm
taper section:	2000 µm
mounting:	p-side down
external cavity:	Littrow-configuration





Application examples:

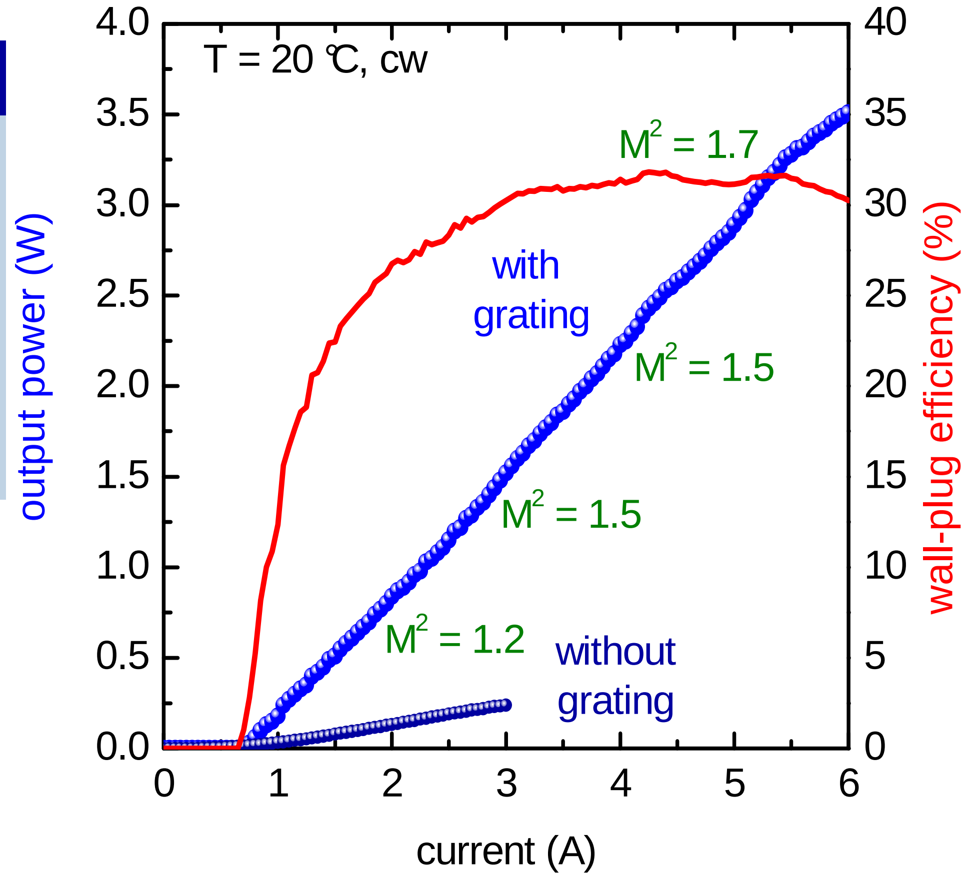
- absorption spectroscopy
- THz spectroscopy
- optical traps
- non-linear frequency doupling

Tapered amplifiers – output power in cw mode

type	RTL 976 nm
ridge section:	500 µm
taper section:	2000 µm
mounting:	p-side down
experiment:	20 °C, cw

More than 3.5 W of output power in cw mode.

I_{th} = 0.83 A
s.e. = 0.70 W/A
η_{max} = 32%



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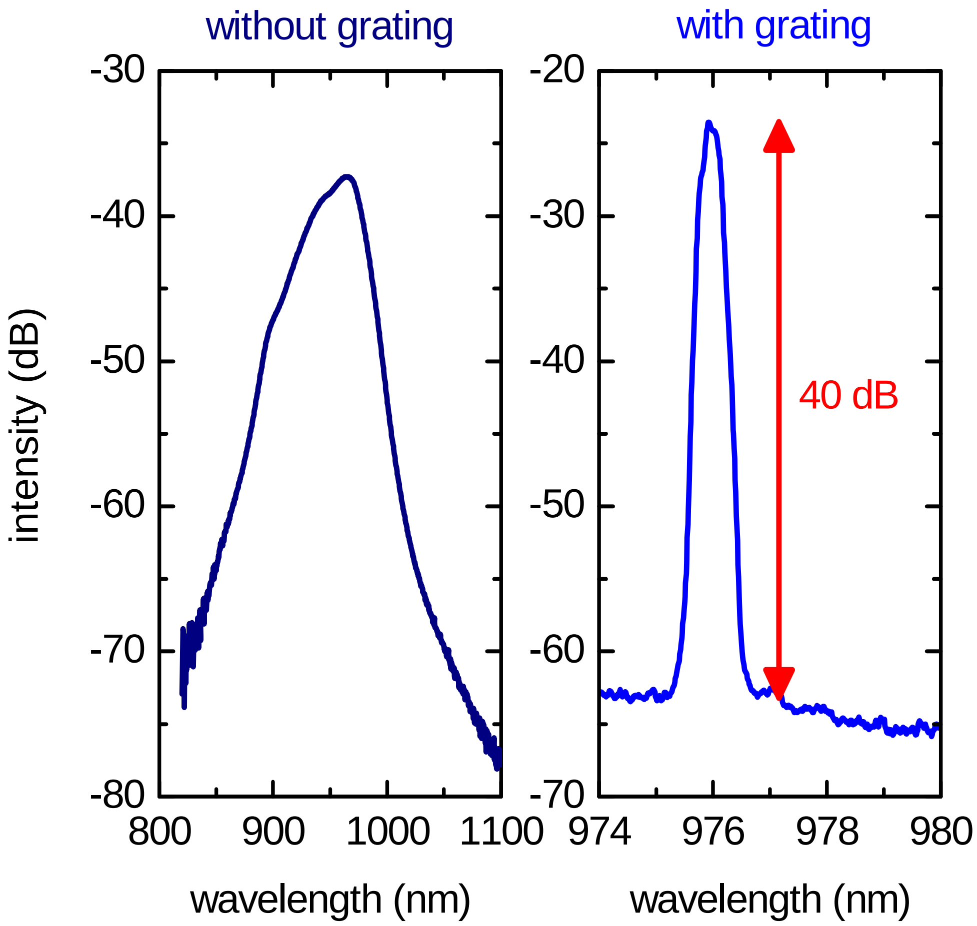
Tapered amplifiers – spectral behaviour

type	RTL 976 nm
ridge section:	500 µm
taper section:	2000 µm
mounting:	p-side down
experiment:	20 ℃, cw

- 46 nm tunable range (FWHM) between 934 nm and 980 nm

- sidemode suppression of 40 dB (@ 976 nm)



Summary

A reduction of the thermal resistance and longer taper section lengths lead to ...

- a better beam quality
- a higher output power
- a stable astigmatism

=> a higher brightness