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Thermal lensing in high–power ridge–waveguide lasers

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...translating ideas into innovation

Outline

- motivation and laser structure
- experimental results
- theoretical model
- simulation results
- conclusions

Motivation

- fundamental–spatial mode diode lasers with an output power in the 1–W range of interest for a variety of applications
- requires narrow lateral waveguide defined by small effective index step to cut–off higher order modes
- at higher output power appearance of instabilities like
  - kinks in light–current characteristics
  - beam steering
  - appearance of higher order modes
- possible reasons:
  - carrier–induced index suppression
  - thermal lensing
  - spatial hole burning

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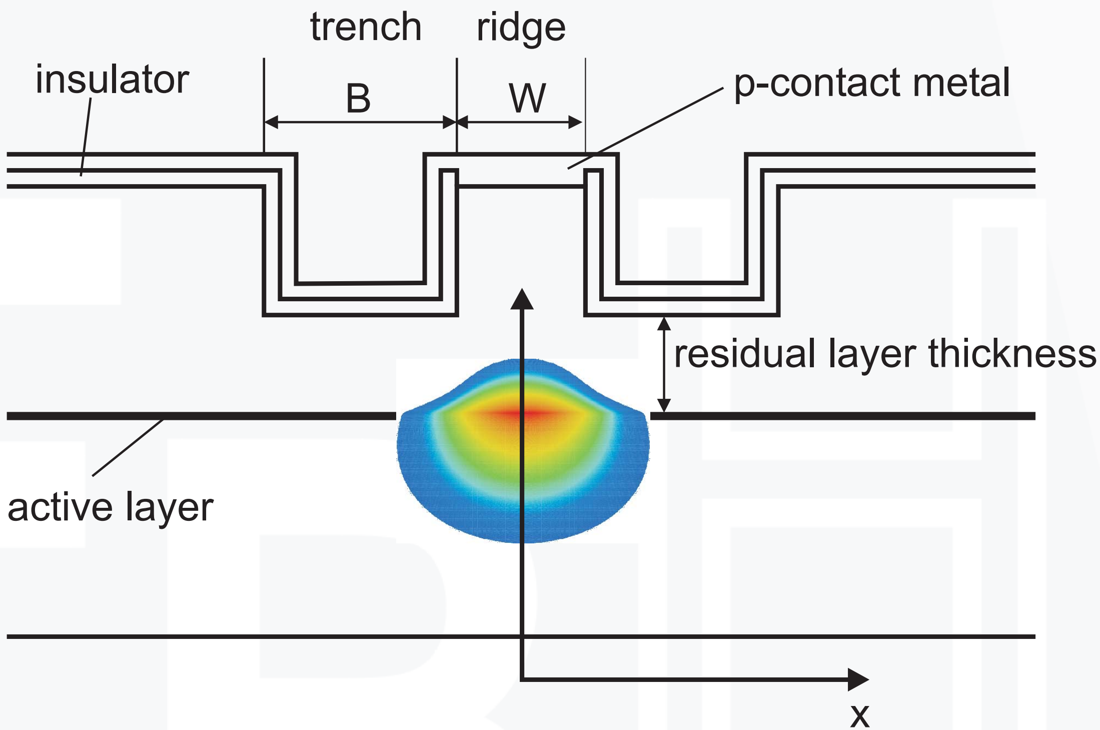
Schematic cross–sectional view of RW devices



- finite trench width $\Longrightarrow$ radiation leaks into the outer high-index regions
- radiation loss rises with mode number $\Longrightarrow$ stabilization of 0th order mode
- anti–index guiding $\Longrightarrow$ sensitive to thermal lensing effect

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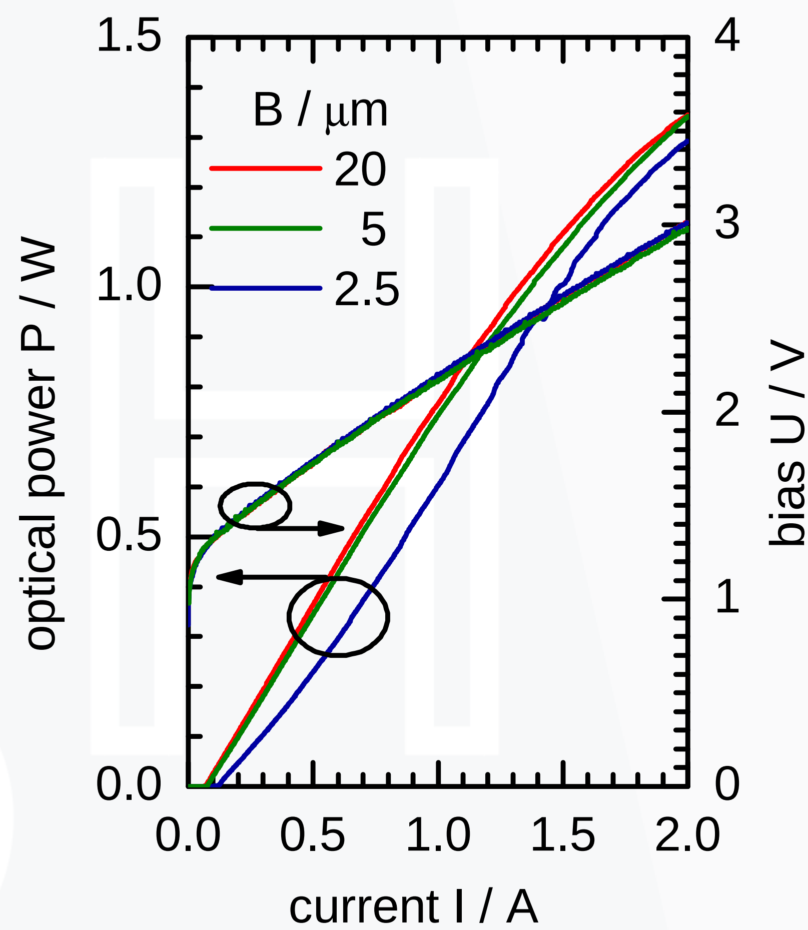
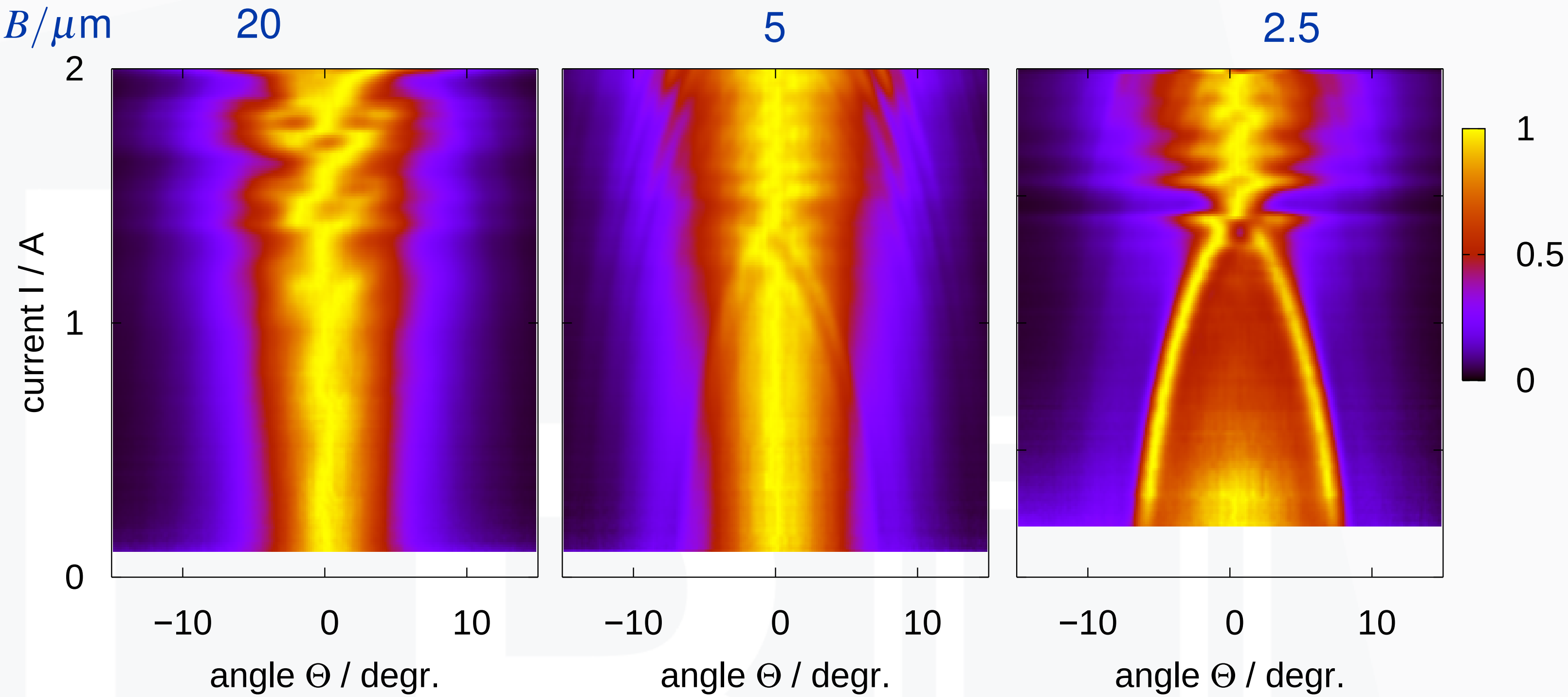
Experimental light–current characteristics

- cavity length $L = 3.9$ mm
- ridge width $W = 2.8\ \mu$m
- emission wavelength around $\lambda = 1064$ nm
- output power $P > 1.3$ W at $I = 2$ A
- only small difference in the characteristics for trench widths $B = 20\ \mu$m and $B = 5\ \mu$m
- strong increase of threshold current and decrease of slope efficiency slightly above threshold for $B = 2.5\ \mu$m



Experimental lateral far–field intensity profiles



- strong dependence of far–field profiles on trench width
- $B = 5\ \mu$m: much more stable far–field compared to $B = 20\ \mu$m
- $B = 2.5\ \mu$m: double peaked far–field, peaks joining around $I = 1.4$ A

Theoretical model: Optics

effective index method for calculating lateral field profile $\Phi(x)$ and complex propagation constant β

$$\frac{d^2\Phi}{dx^2} = \left[\beta^2 - k_0^2\varepsilon_{\text{eff}}(x)\right]\Phi(x)$$

boundary conditions

$$\frac{d\Phi}{dx}\Big|_{x=0} = 0 \quad \text{(even modes)}$$

$$\lim_{x\longrightarrow\infty}\Phi(x) \propto \mathrm{e}^{-i\sqrt{k_0^2\varepsilon_{\text{eff}}(x_c)-\beta^2}\,x} \quad \text{with} \quad \mathrm{Re}\sqrt{k_0^2\varepsilon_{\text{eff}}(x_c)-\beta^2} > 0$$

(outgoing wave)

far field

$$S_{\text{FF}}(\Theta) = \left|\int_0^\infty \Phi(x)\mathrm{e}^{k_0\sin(\Theta)x}\,dx\right|^2$$

Complex effective dielectric function

$$\varepsilon_{\text{eff}}(x) = 2n_{\text{eff},0}\left[\frac{n_{\text{eff},0}}{2} + \Delta n_{\text{eff}}(x) + \Delta n_N(x) + \Delta n_T(x) + i\frac{g_{\text{eff}}(x)}{2k_0}\right]$$

background effective index	$n_{\text{eff},0}$	
built–in effective index step	$\Delta n_{\text{eff}}(x)$	step–wise constant
carrier–density dependent part	$\Delta n_N(x) = \Gamma_{\text{AZ}}\frac{\partial n}{\partial N}N < 0$	step–wise constant
temperature dependent part	$\Delta n_T(x) = \frac{\partial n}{\partial T}T(I,x) > 0$	
effective gain	$g_{\text{eff}}(N)$	step–wise constant

In the model, ε_{eff} depends on current only via temperature T.

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Theoretical model: Heat I

effective heat conduction equation for lateral relative temperature profile $T(x)$ (temperature difference to heat sink temperature)

$$\kappa \frac{d^2 T}{dx^2} = -q(x) + \gamma T(x)$$

boundary conditions

$$\frac{dT}{dx}|_{x=0} = 0 \quad \text{and} \quad \lim_{x \to \infty} T(x) = 0$$

dissipated power density within active stripe obtained from experimental light-voltage-current $P - U - I$ characteristics

$$q(I) = \frac{U(I)I - P(I)}{dWL}$$

Theoretical model: Heat II

temperature relaxation parameter γ determined from the condition

$$\frac{2}{W}\int_0^{W/2} T(x,I_0)\,dx \quad = \quad \left[\frac{\partial\lambda}{\partial T}\right]^{-1} [\lambda(I_0)-\lambda(0)]$$

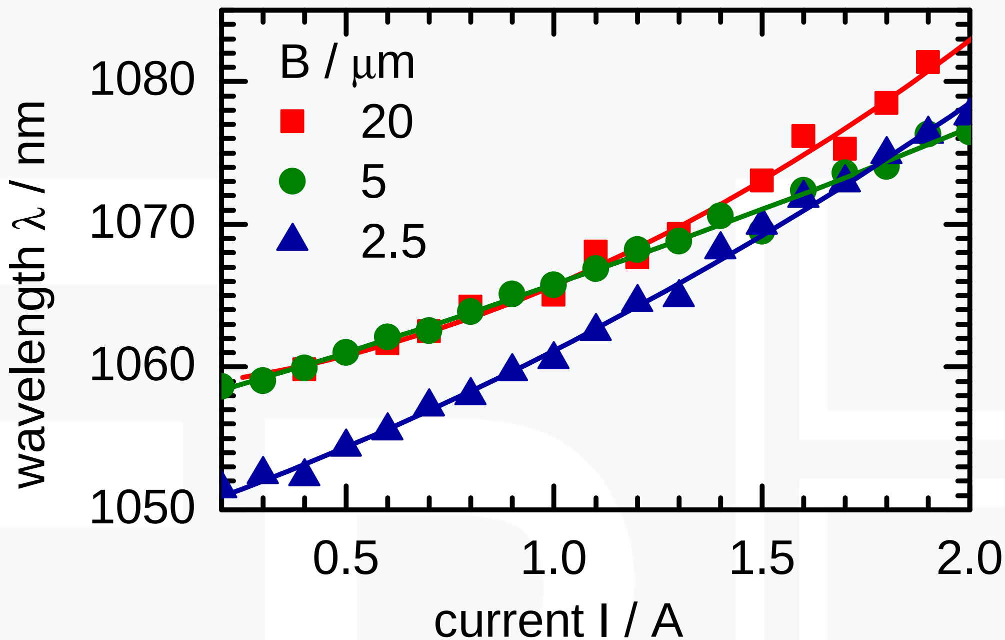
calculated average temperature within the active stripe

temperature rise determined from the experimental wavelength shift

dependence of emission wavelength on injection current

$$\lambda(I) = a + bI + cI^2$$

Experimental wavelength–current characteristics



parameters of $\lambda(I)$ and γ determined at $I_0 = 1$ A

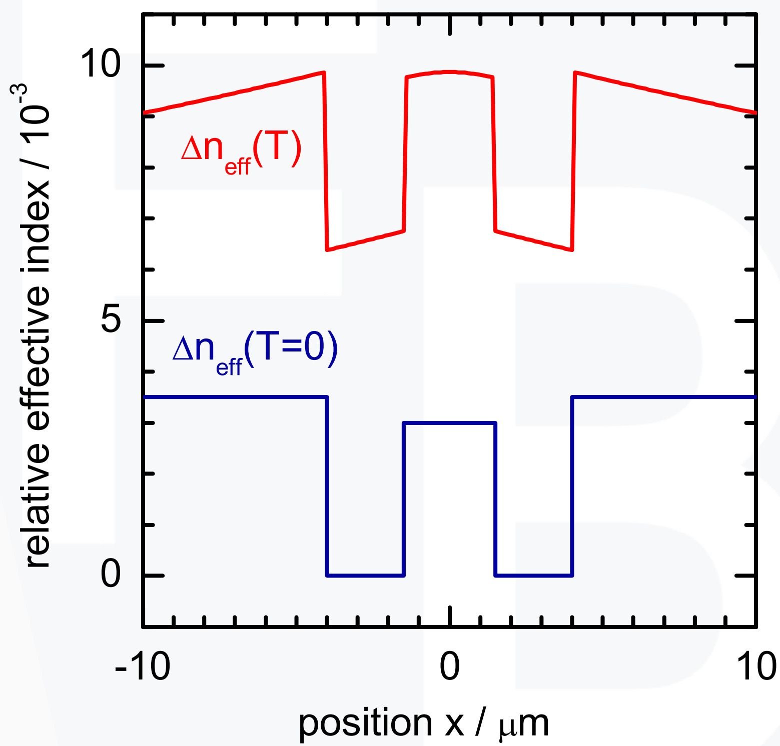
B / μm	a / nm	b / nmA^{-1}	c / nmA^{-2}	γ / 10^{11}KW^{-1}m^{-2}
20	1058.4	2.4	4.9	1.9
5	1056.7	8.2	0.9	1.2
2.5	1048.9	9.8	2.5	0.8

Model parameters

parameter	value
d	2 μm
W	3 μm
L	3900 μm
κ	160 WK^{-1}m^{-1}
$\frac{\partial n}{\partial T}$	2.5$\times$10^{-4} K^{-1}
$\frac{\partial \lambda}{\partial T}$	0.45 nmK^{-1}
$n_{\text{eff},0}$	3.33
Δn_{eff}	ridge: 3.5$\times 10^{-3}$
	trench: 0
	outside: 3.5$\times 10^{-3}$
Δn_N	ridge: -5$\times 10^{-4}$
	trench: 0
	outside: 0
g_{eff}	ridge: 20 cm^{-1}
	trench: 0
	outside: -20 cm^{-1}

Model parameters

effective-index profiles without and with heating: anti– vs. real–index guiding



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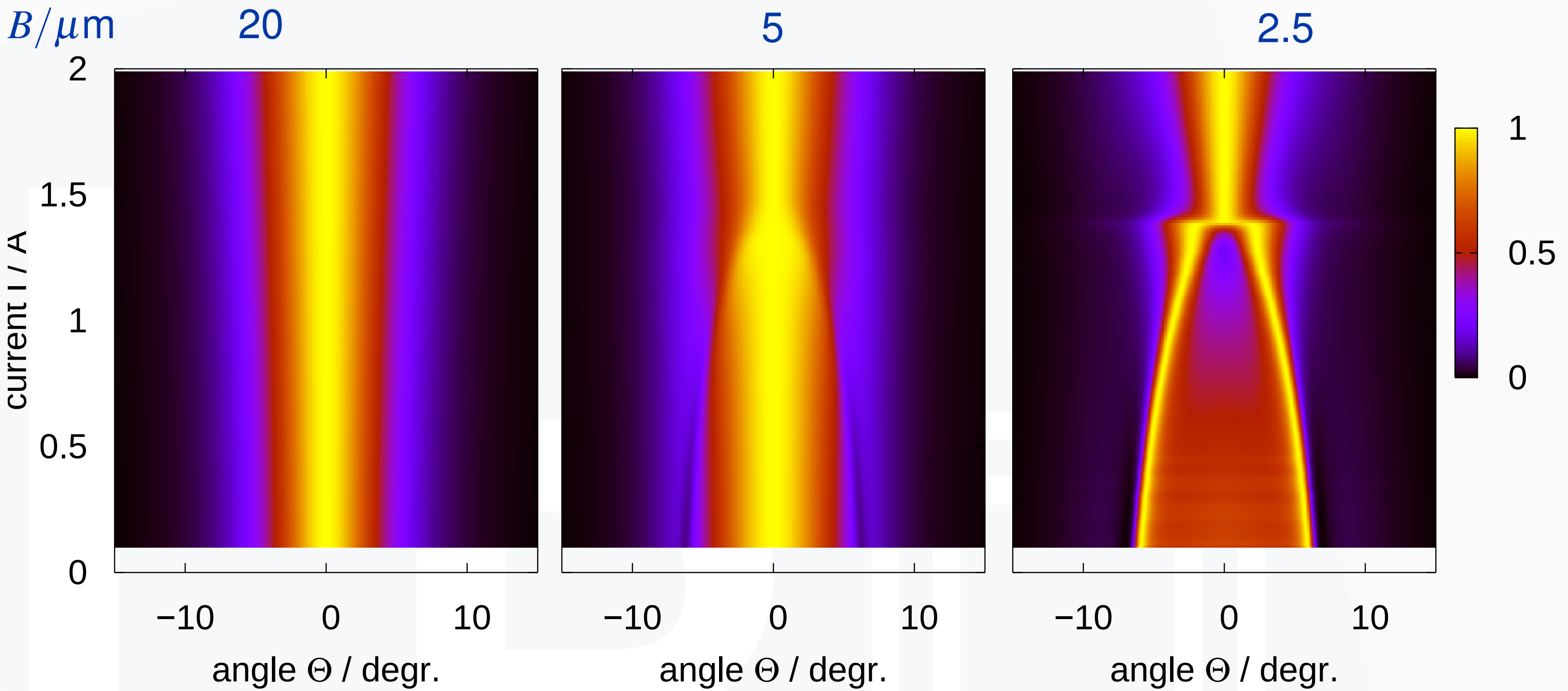
Calculated lateral far–field intensity profiles



- same dependence on trench width and current as measured
- $B = 2.5\ \mu$m: far–field peaks joining at $I = 1.4$ A due to thermal lensing

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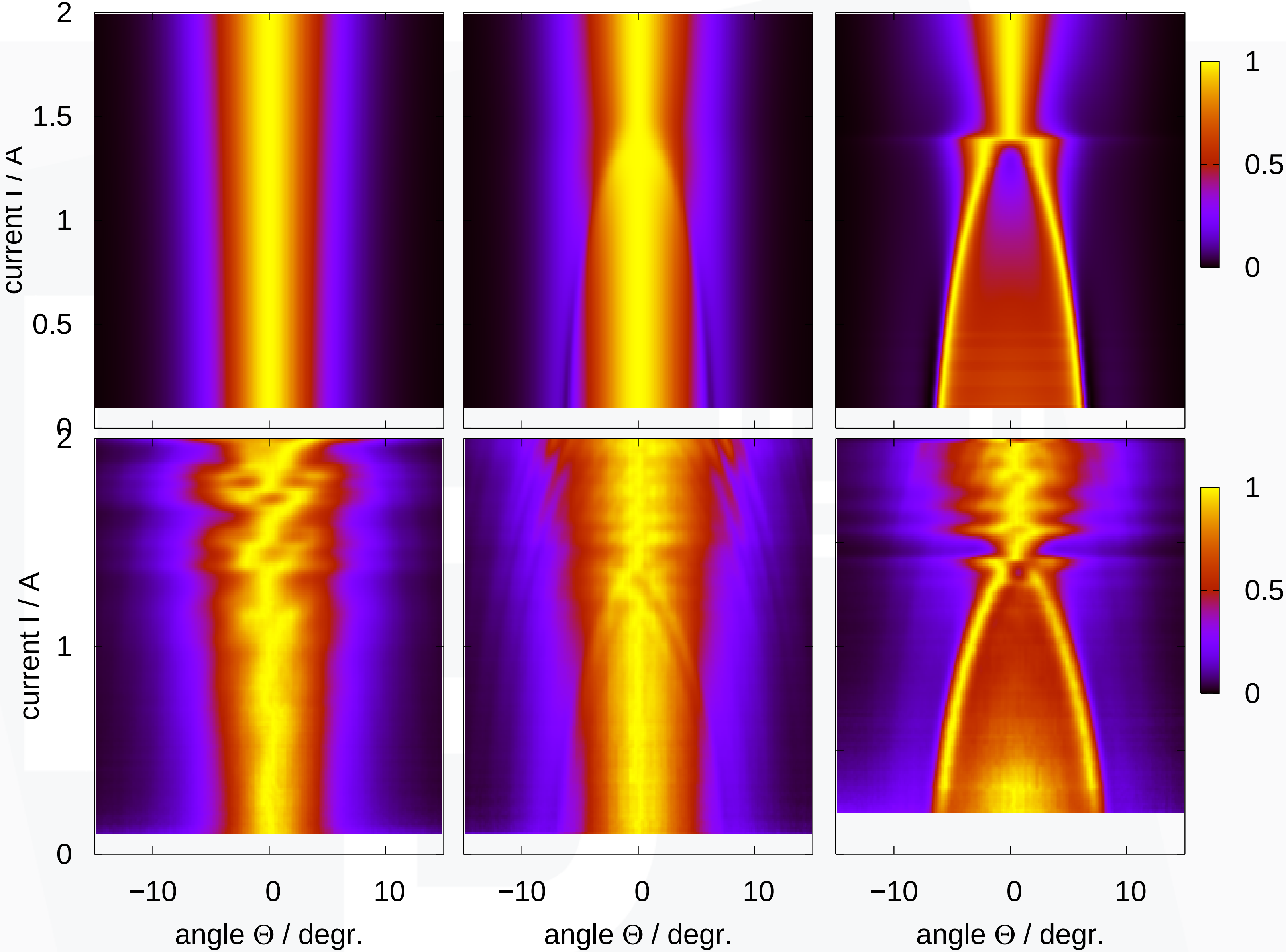
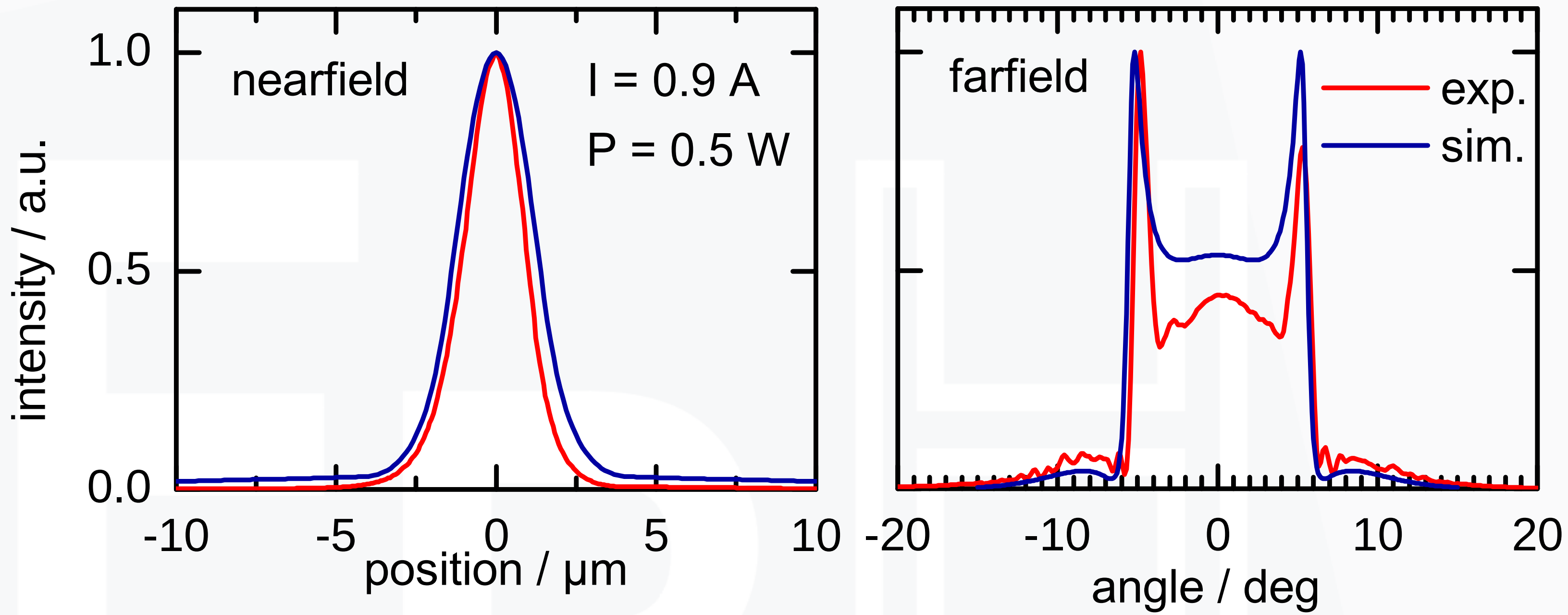


Measured and calculated near– and far–field profiles



- good agreement for both near– and far– field profiles despite the simple model used
- parameters and model o.k.

Conclusions

- thermal lensing contributes significantly to lateral waveguiding in high–power narrow–stripe lasers
- for $P > 1$ W thermal lensing governs lateral waveguiding
  - associated with pronounced far–field instabilities visible in the experimental profiles as current is varied
  - possibly caused by coherent superposition of fundamental and higher order modes
- very stable far–field for trench width $B = 5\ \mu$m
- minimization of thermal–lensing effect crucial for increase of fundamental-spatial mode output power