

MODELING OF ABOVE-THRESHOLD SINGLE-MODE OPERATION OF EDGE- EMITTING DIODE LASERS

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OUTLINE

- **Motivation**
- **Numerical model and program package**
- **Antiresonant reflecting optical waveguide laser**
 - ✓ **Characteristics of oscillating mode**
 - ✓ **Higher-order modes**
 - ✓ **Single-mode operation stability**
 - ✓ **Prediction of maximum single-mode power**
- **Conclusions**

Motivation

Around 1 W 0.98- μm -emitting semiconductor lasers required:

- Pumps for rare-earth-doped fiber amplifiers (in fiber-optical communications)
- Free-space communications.
- ❖ Small aperture $\Rightarrow$ mirror-facet degradation; bulk degradation.
- ❖ Larger aperture (8–10 μm) are required.
- ❖ Single-mode regime instability results in degradation in optical beam quality.
- ❖ The mechanisms responsible for this phenomenon : gain spatial hole burning (GSHB) and thermal focusing.
- ❖ 3D description is needed to predict accurately laser limiting characteristics. Our package allows for numerical simulations of optical properties neglecting thermal effects.

Theoretical model

Scalar optical equation for monochromatic wave field

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} + (k_0^2 n^2 - i k_0 g) U = 0$$

1D diffusion equation for carrier number density

$$\frac{\partial^2 Y}{\partial y^2} - \frac{Y}{D\tau_{nr}} - \frac{B}{D} N_{tr} Y^2 - \frac{1}{g_{0N} D\tau_{nr}} (|E_+|^2 + |E_-|^2) g = - \frac{J}{qDdN_{tr}}$$

$$Y = \frac{N}{N_{tr}}, \quad N_{tr} = \frac{1}{2B} \left(-\frac{1}{\tau_{nr}} + \sqrt{\frac{1}{\tau_{nr}^2} + \frac{4BJ_{tr}}{qd}} \right), \quad n = \tilde{n}_0 - \frac{R}{2k} g,$$

$$k_0 = \frac{2\pi}{\lambda}, \quad |E_+|^2 + |E_-|^2 = \frac{I}{I_s}, \quad I_s = \frac{hc}{\lambda} \frac{N_{tr}}{g_{0N} \tau_{nr}}.$$

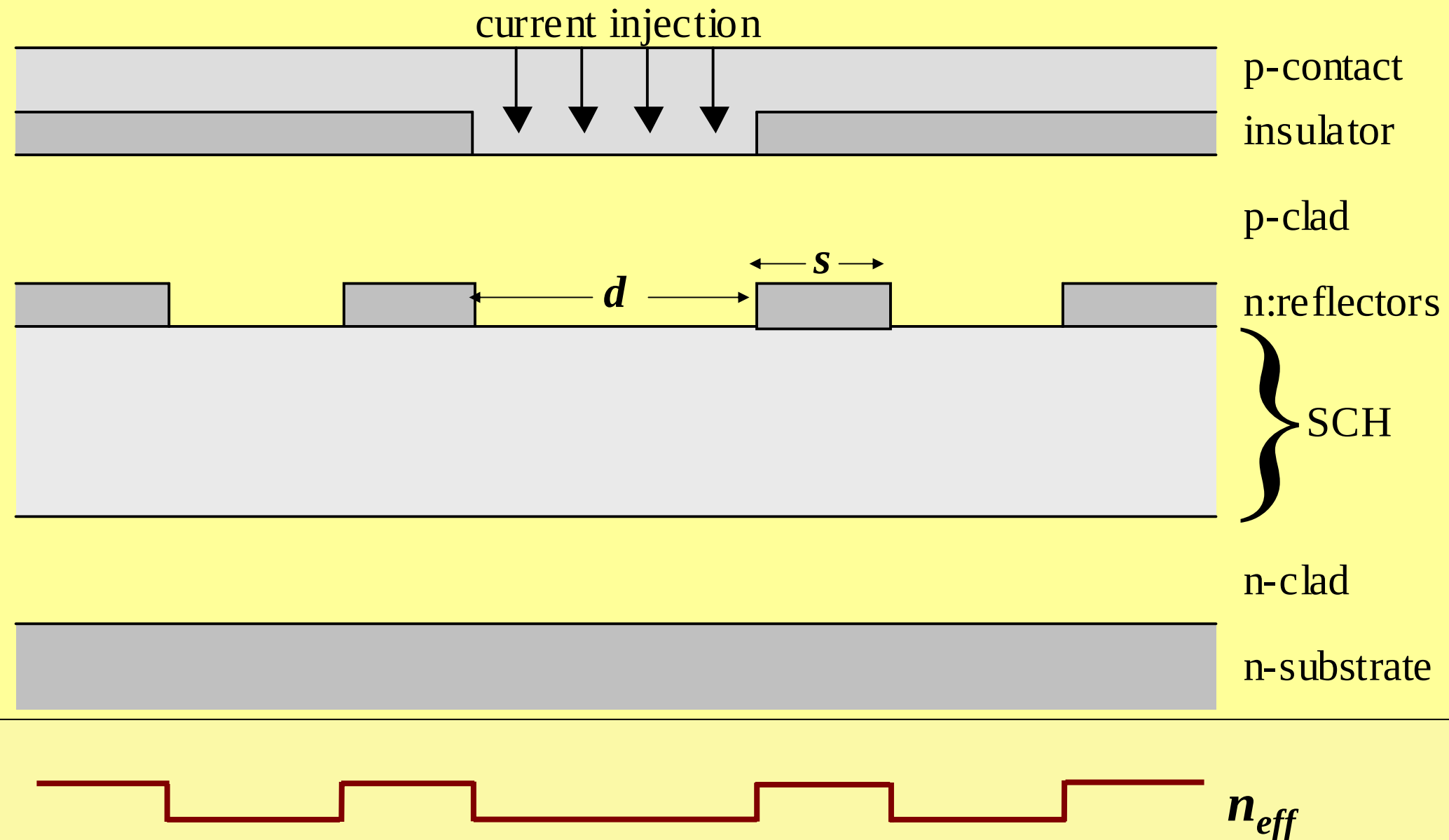
Theoretical model, continuation

Wide-angle Pade approximation is used for counter-propagating waves, E_+ and E_- . Perfectly matched layer is attached to boundaries (W.P. Huang, et al: *IEEE Phot. Techn. Lett.*, 8, 652, 1996). Iteration method is employed to solve the above equations.

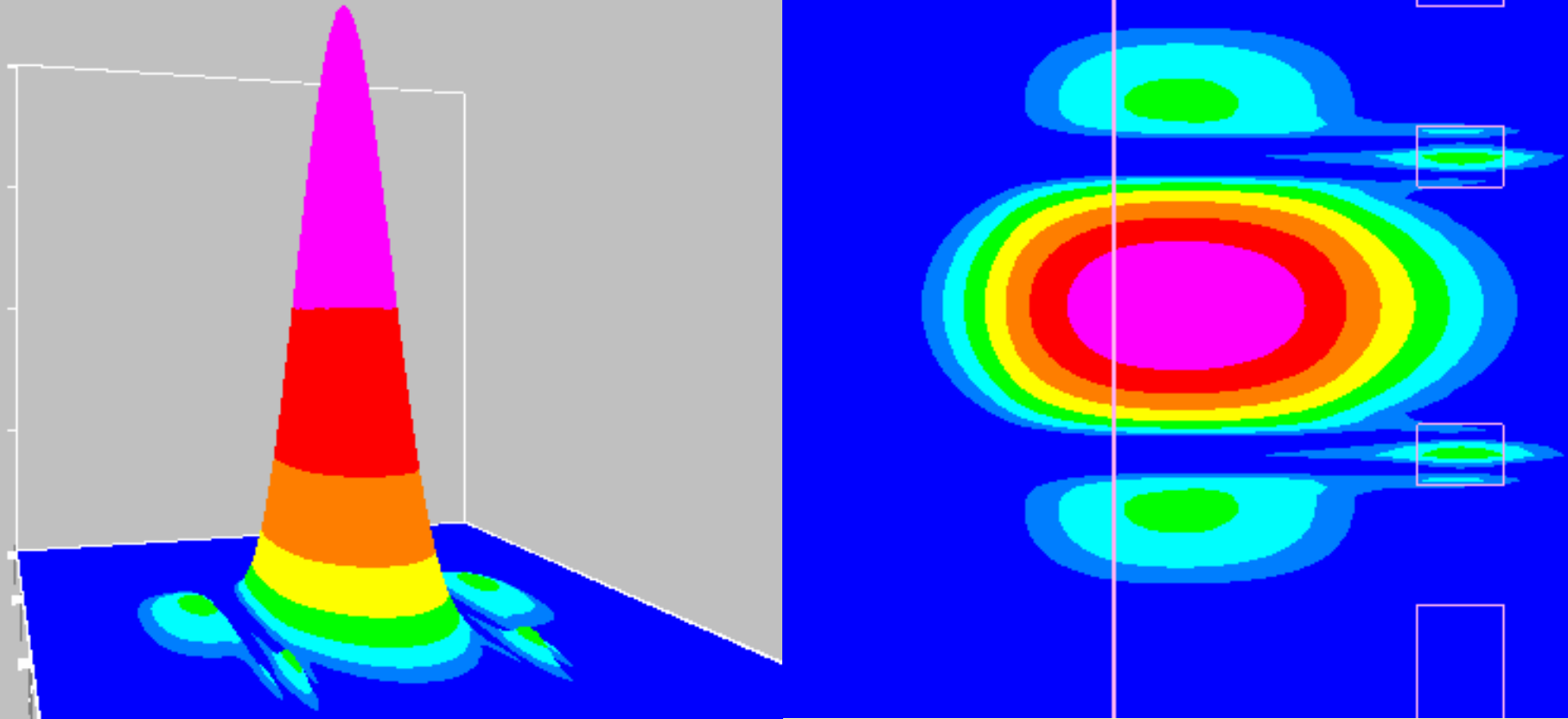
Graphical interface allows for viewing near- and far-field patterns of the oscillating mode in a form of 3D surfaces or contour-plots. Scanning of profiles of mode intensity in an arbitrary cross section in the output plane and in far-field is available.

Further, to evaluate single-mode stability limit, a procedure is developed to calculate 3-5 higher order optical modes taking gain and carrier-induced index depression as they are produced by oscillating mode at a fixed drive level.

Schematic of ARROW device

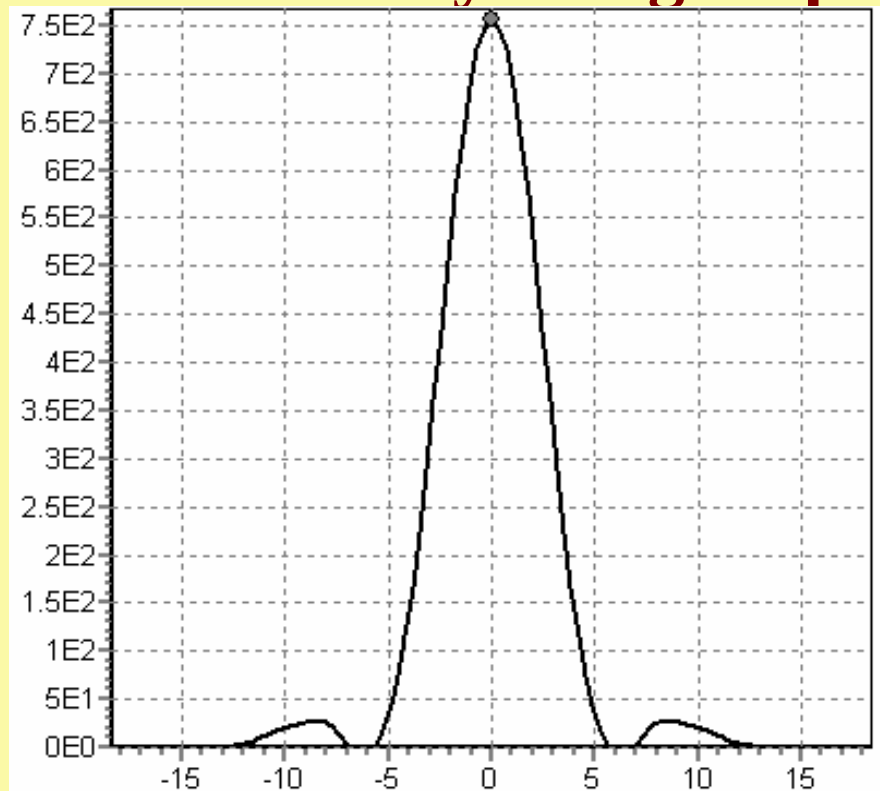


Oscillating mode near-field patterns, $d=10$, $s=2.6\text{ }\mu\text{m}$

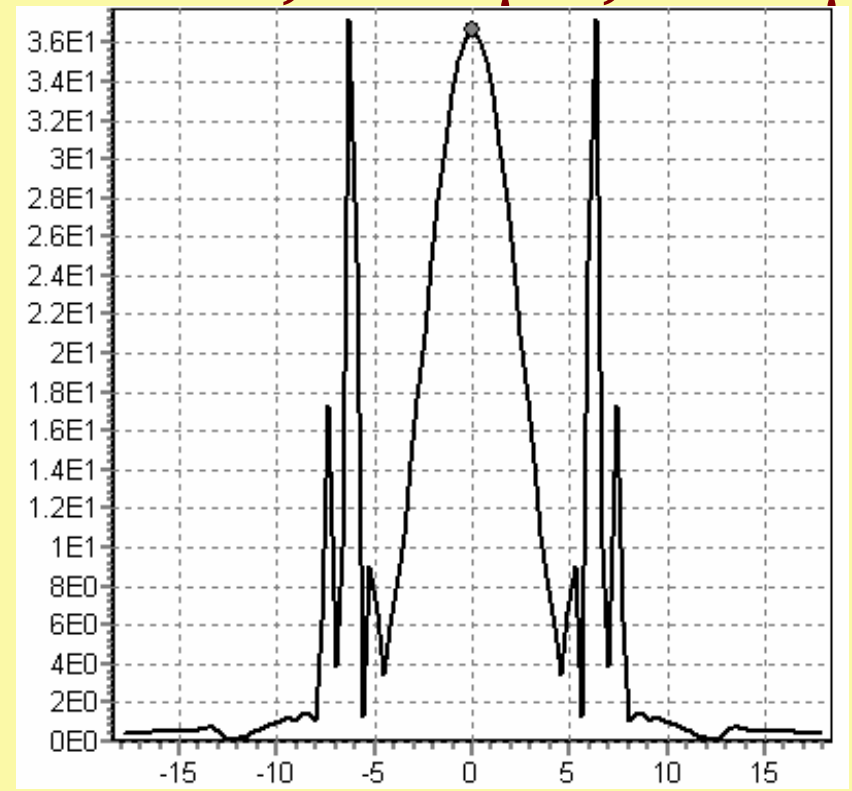


The mode intensity pattern at the output facet for the drive current $I=40.7\text{ }I_{\text{th}}$. Mode 4 in terms of the effective index theory.

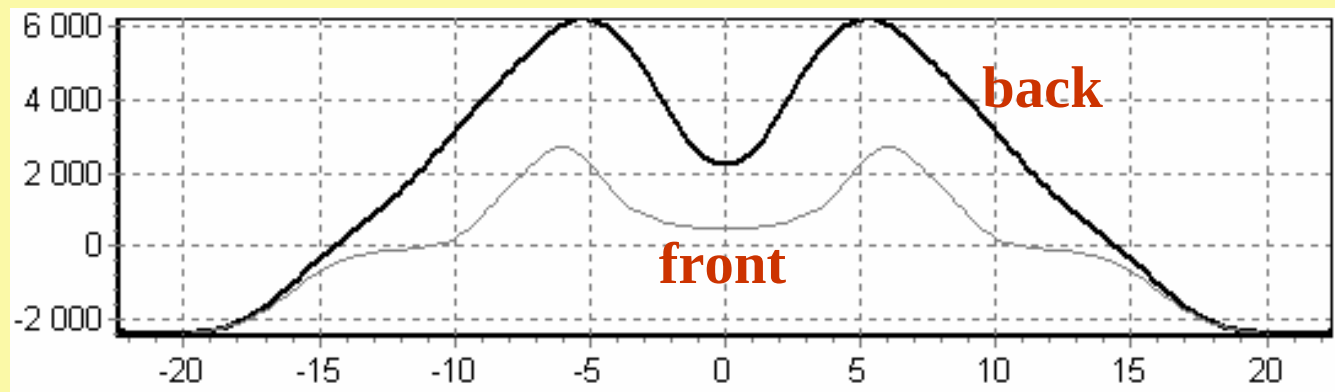
Lateral intensity and gain profiles $L=2\text{ mm}$, $d=10\text{ }\mu\text{m}$, $s=2.6\text{ }\mu\text{m}$



Lateral displacement (μm)

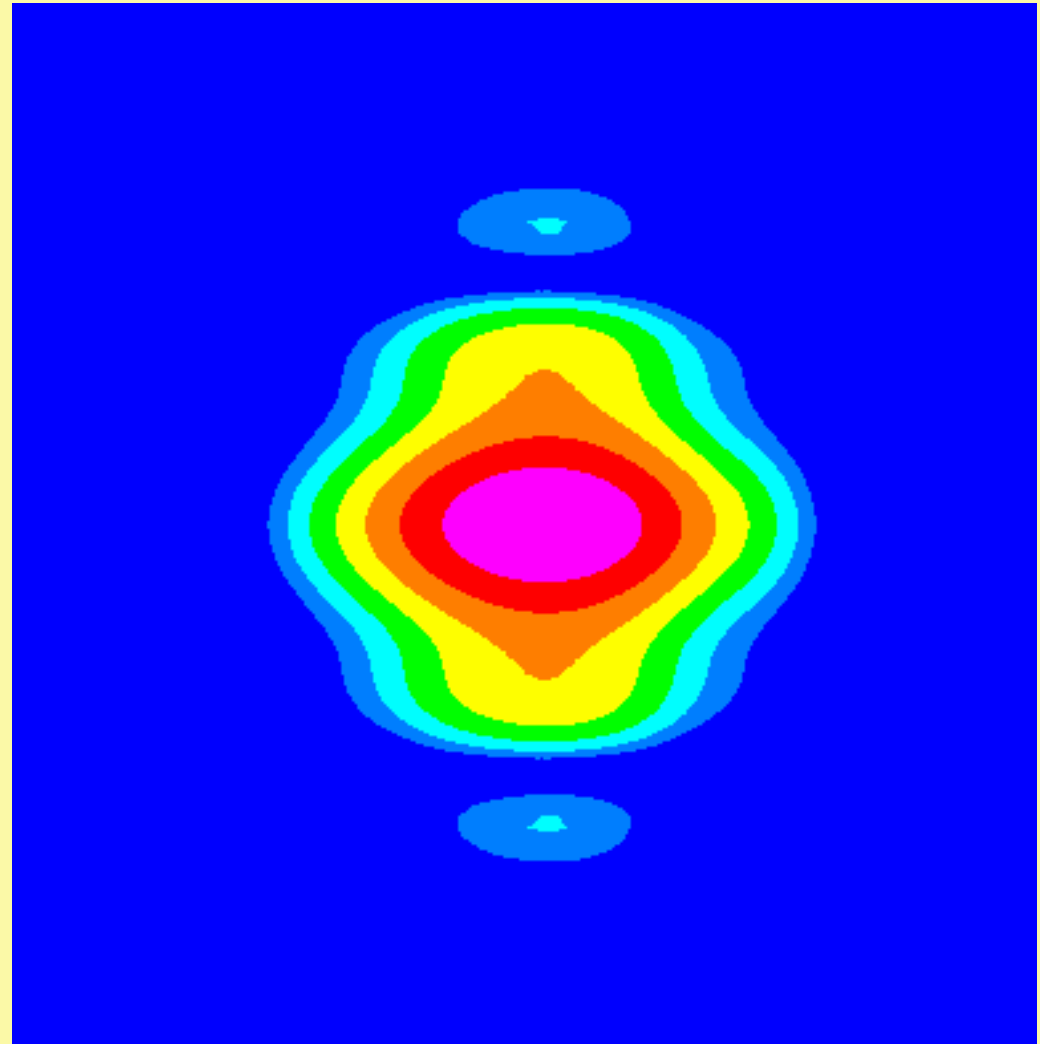
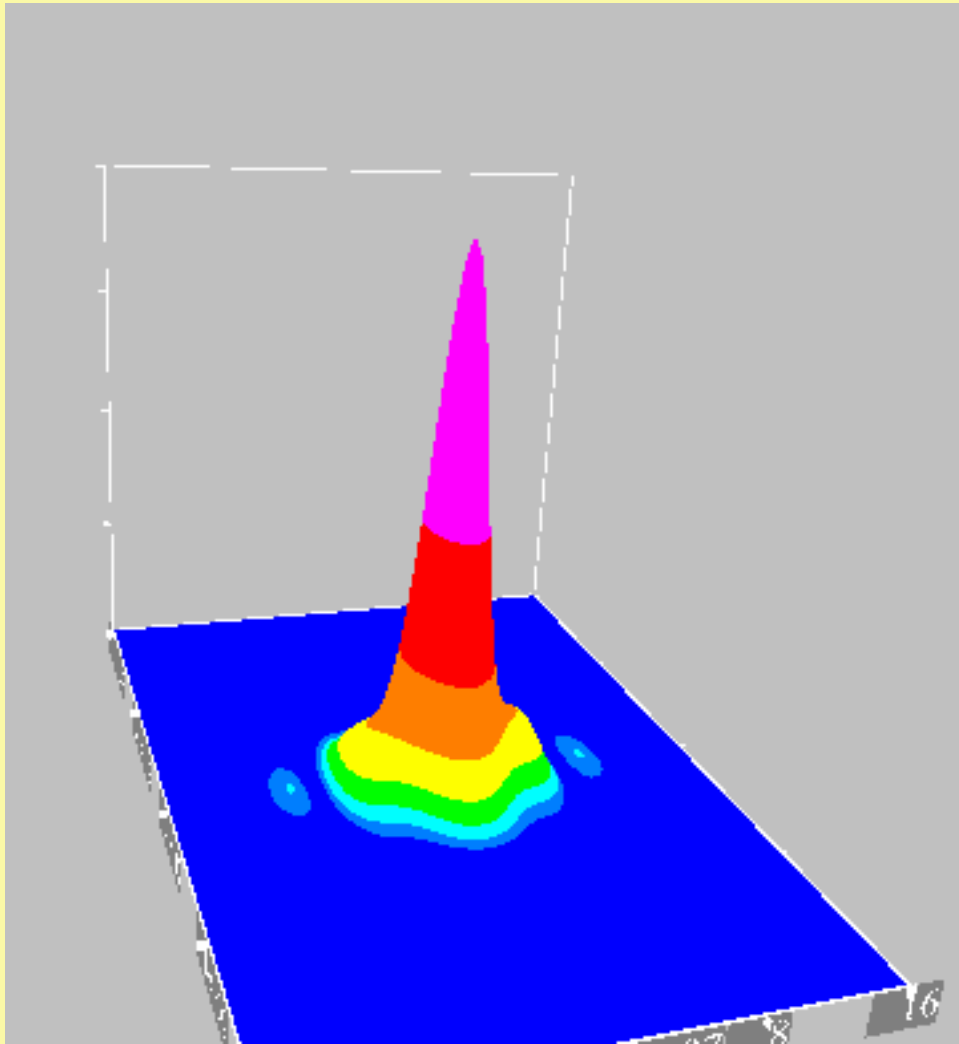


Lateral displacement (μm)

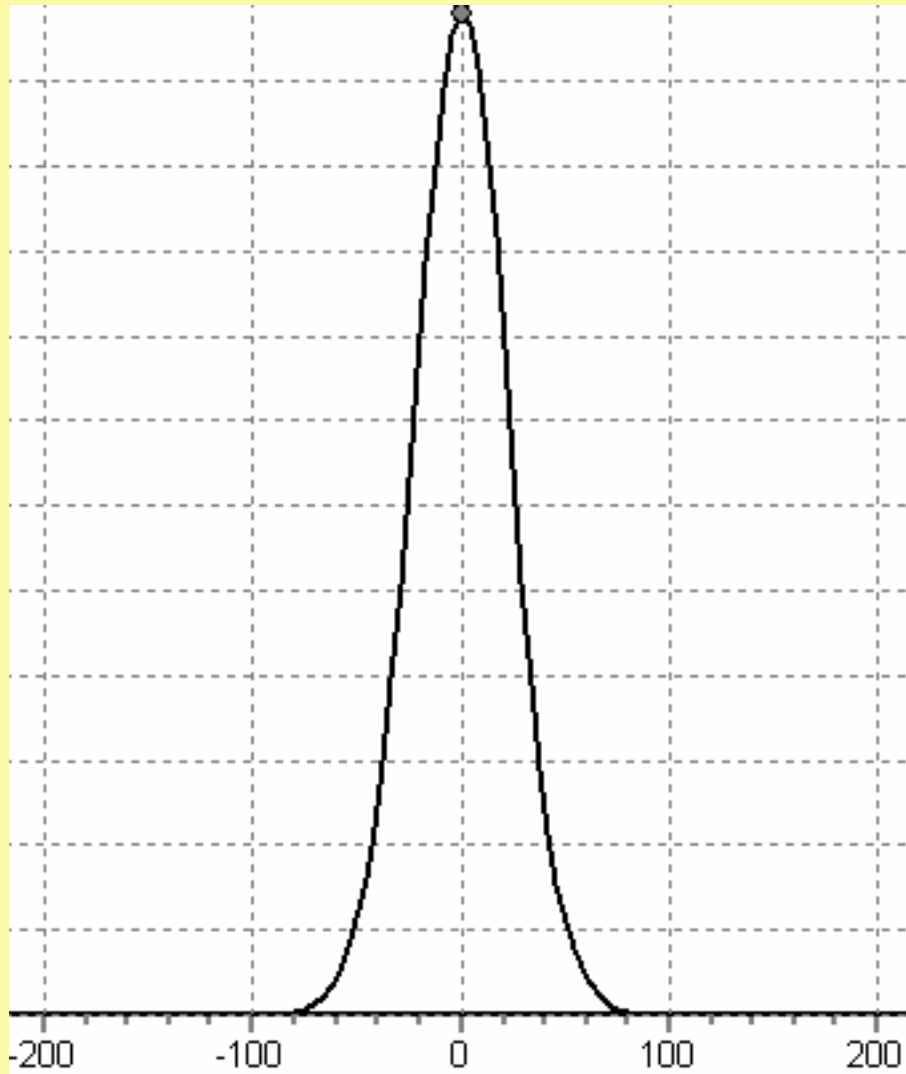


Gain profile in QW at the facets, $I=40.7\text{ }I_{\text{th}}$

Far-field patterns $L=2\text{ mm}$, $d=10\text{ }\mu\text{m}$, $s=2.6\text{ }\mu\text{m}$, $I=40.7\text{ }I_{\text{th}}$.

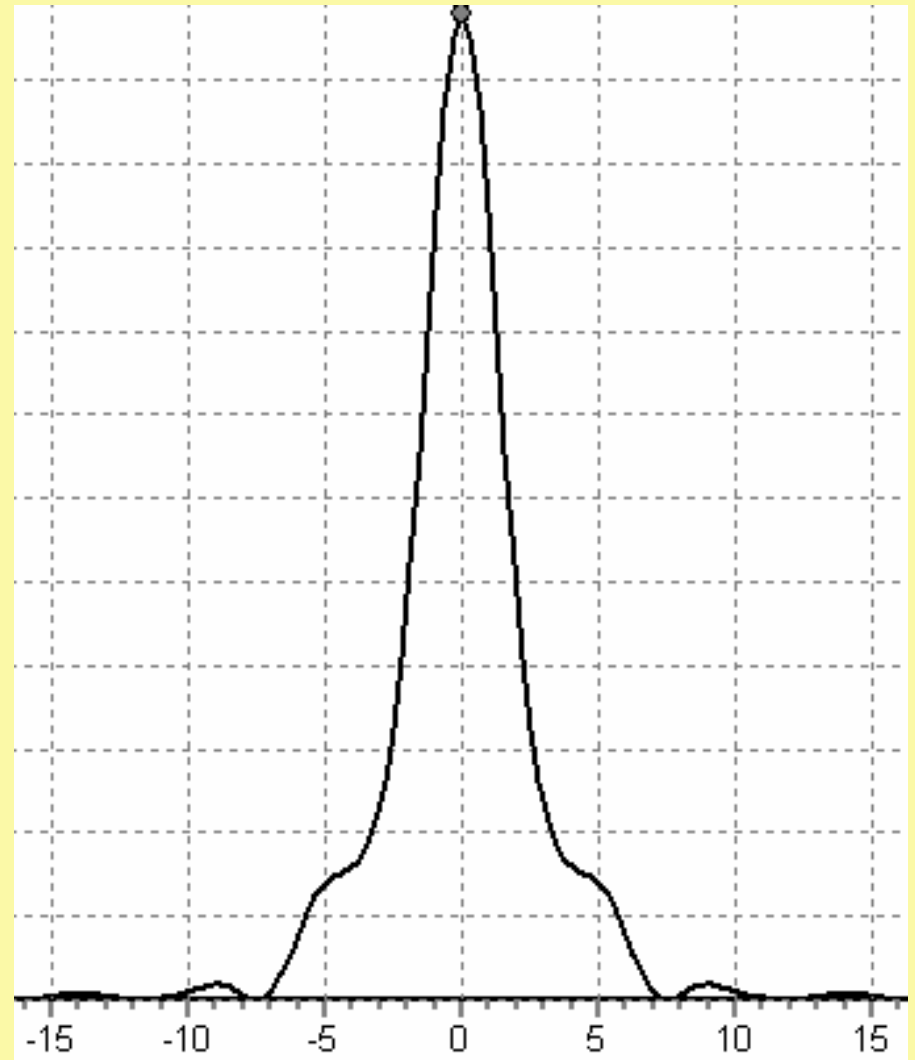


Far-field patterns, $L=2\text{ mm}$, $d=10\text{ }\mu\text{m}$, $s=2.6\text{ }\mu\text{m}$, $I=40.7\text{ }I_{\text{th}}$.



Angle (degrees)

Transverse

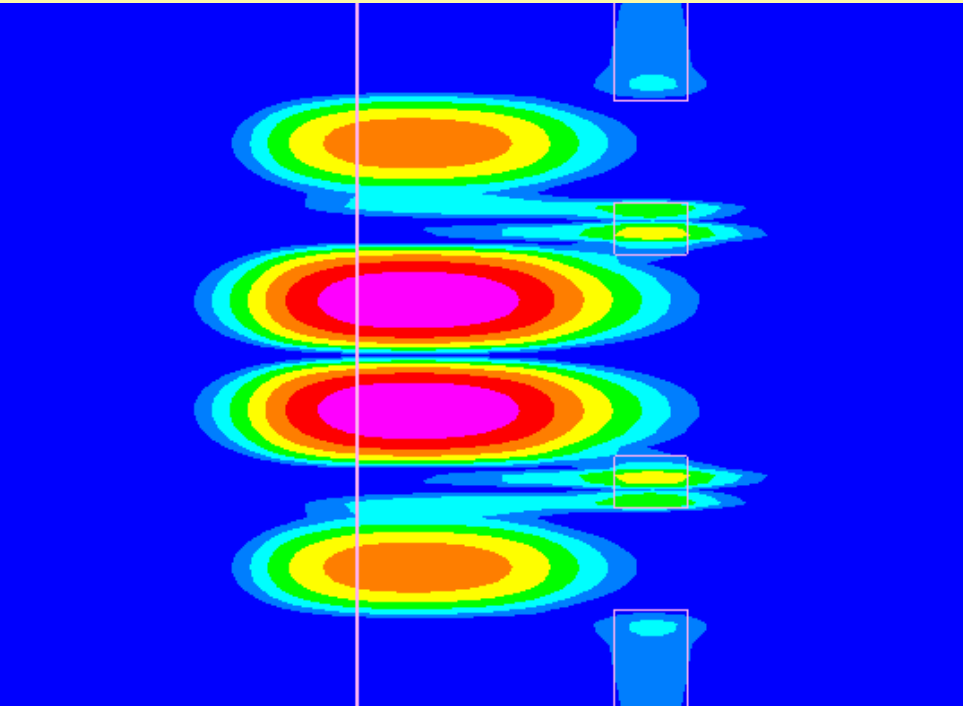


Angle (degrees)

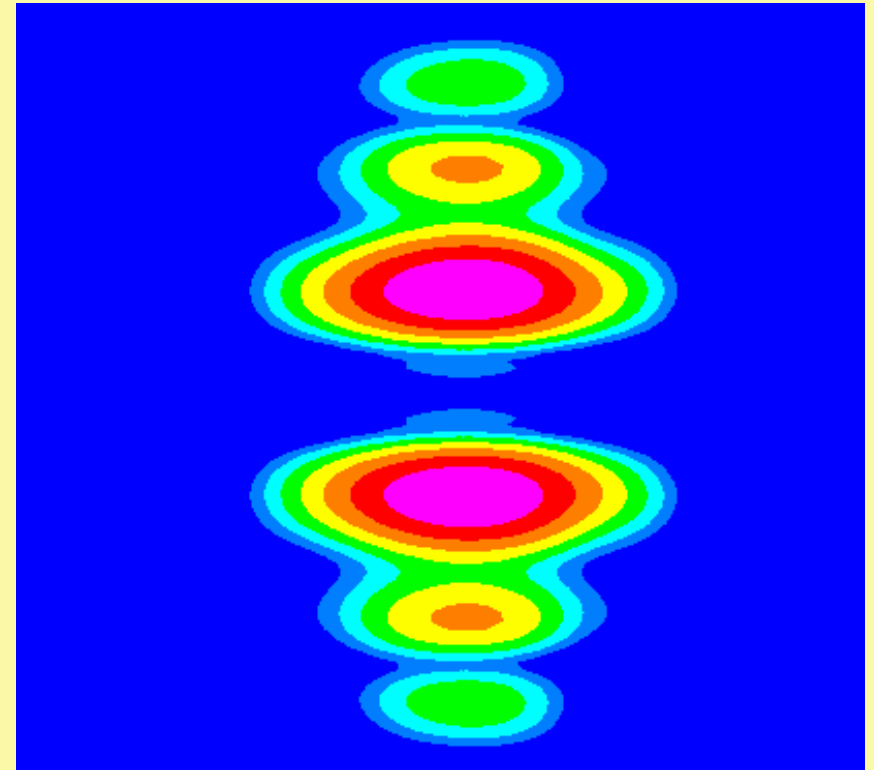
In-plane

Higher-order modes

Higher-order modes were calculated by Arnoldi method (Demmel J. M. *Appl. Numerical Linear Algebra*, 1997 (Philadelphia: SIAM)) allowing for computing a set of optical modes with an accurate gain/loss balance. Gain distribution established under laser action was fixed.



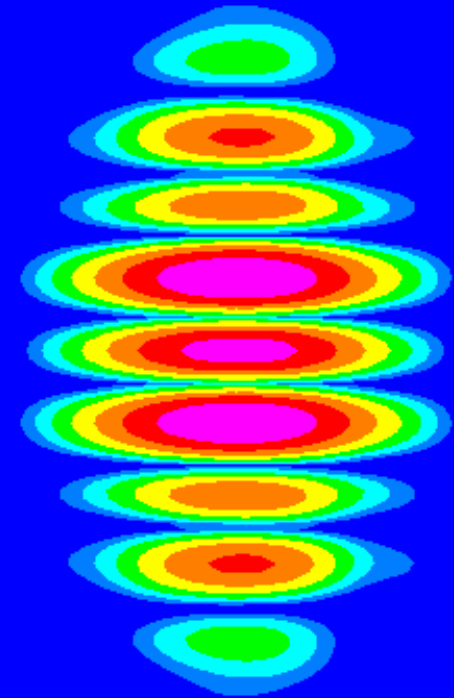
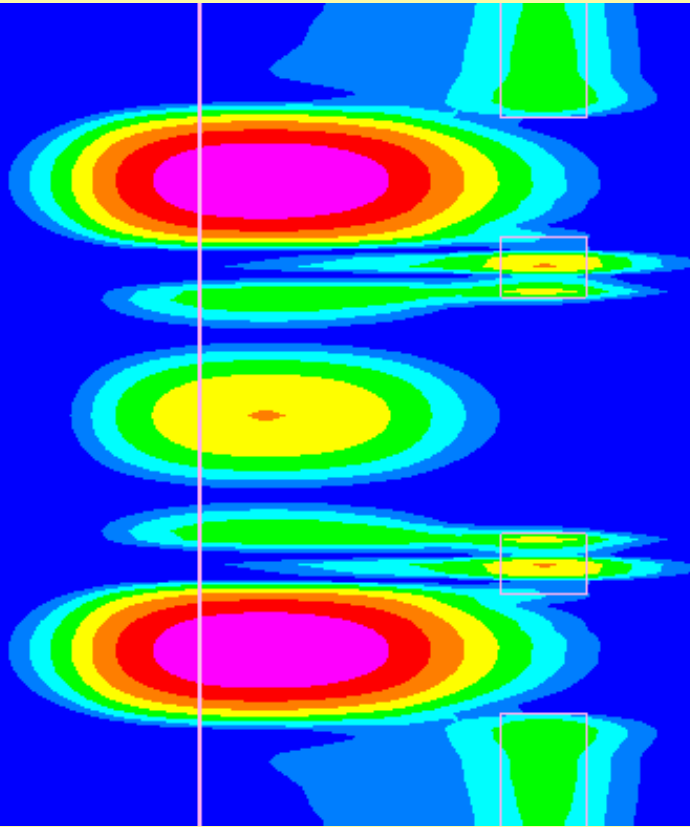
Mode 7 (the EIM terminology) in
the near-field



Far-field mode pattern

$L=2$ mm, $s=2.6$ μm , $d=10$ μm , and $I/I_{\text{th}}=40.7$.

Higher-order modes

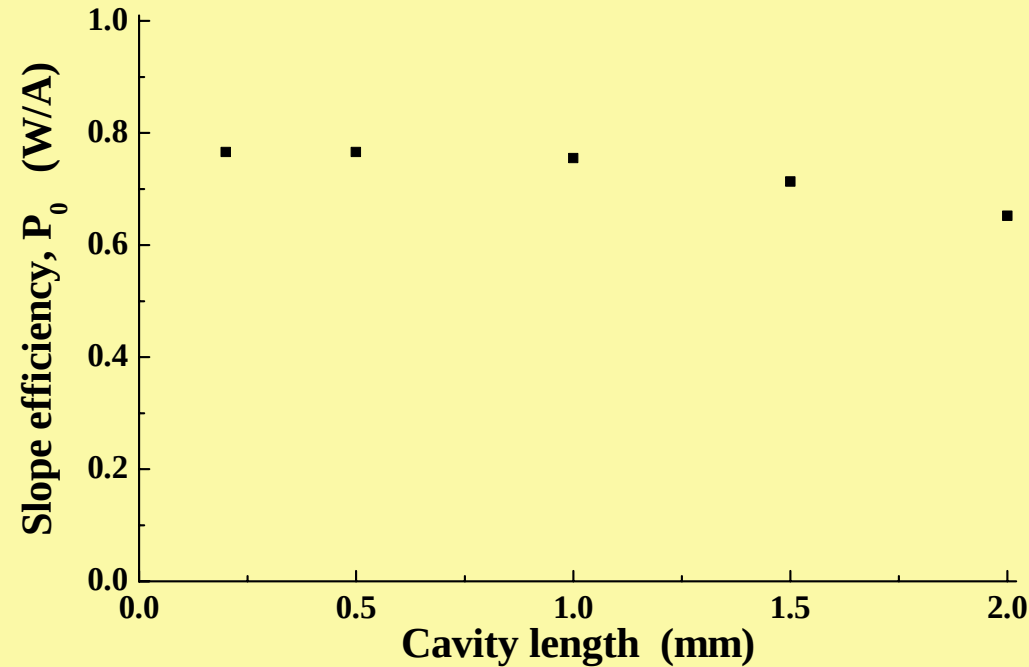
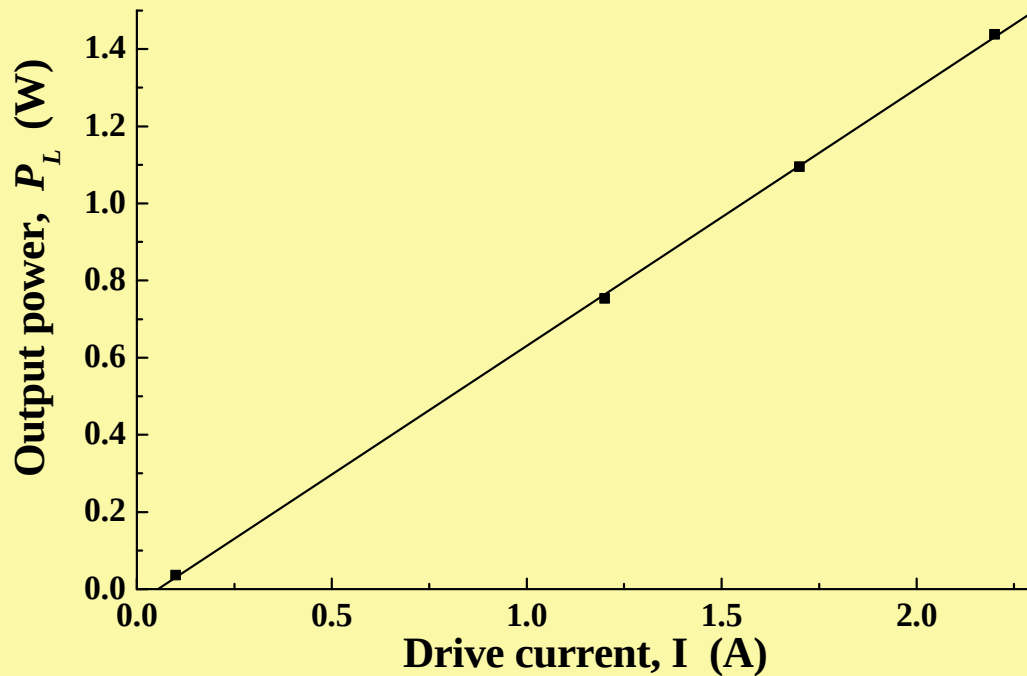


Mode 6 (the EIM terminology) in the
near-field

Far-field mode pattern

$L=2$ mm, $s=2.6$ μm , $d=10$ μm , and $I/I_{\text{th}}=40.7$.

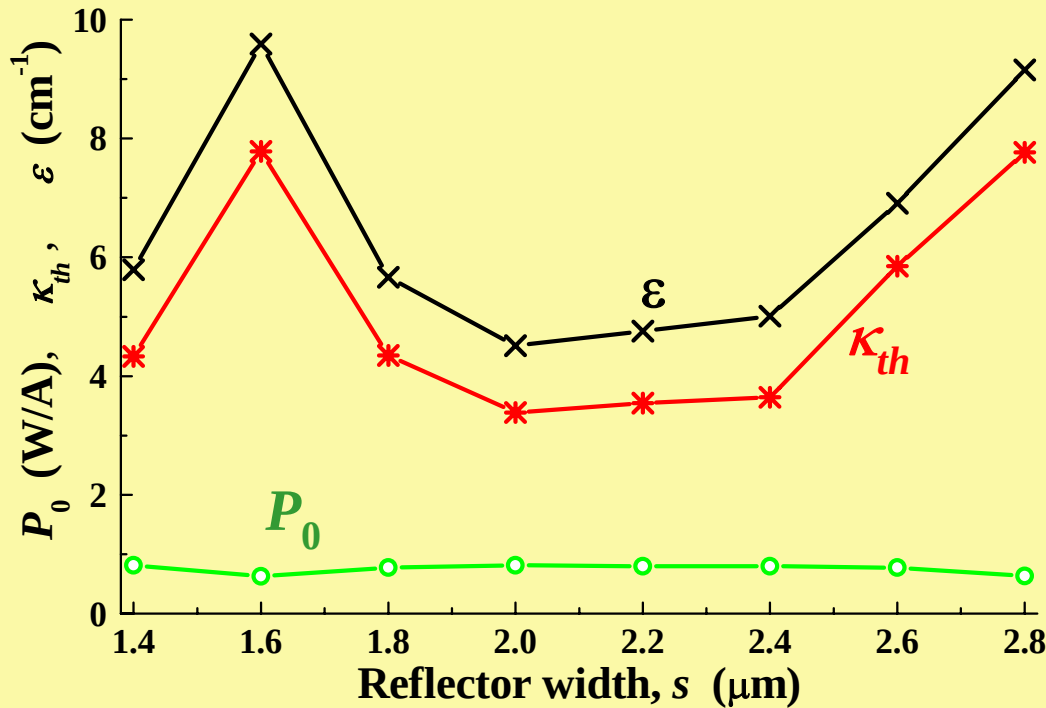
ARROW device, $d=10\text{ }\mu\text{m}$, $s=2.6\text{ }\mu\text{m}$, mode 4



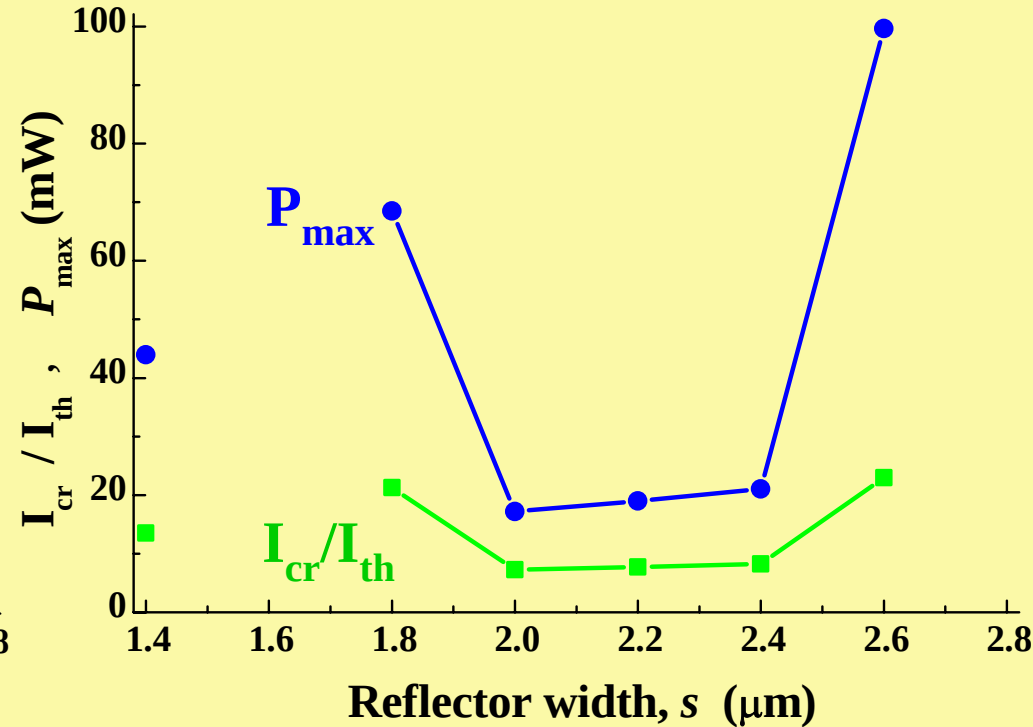
Light-current characteristic, $L=2\text{ mm}$, mirrors with $r_1=0.95$, $r_2=0.01$.

L -dependence of the slope efficiency. Lateral-radiation and bulk absorption losses lead to its diminishing with the device length.

Reflecting waveguide width variation

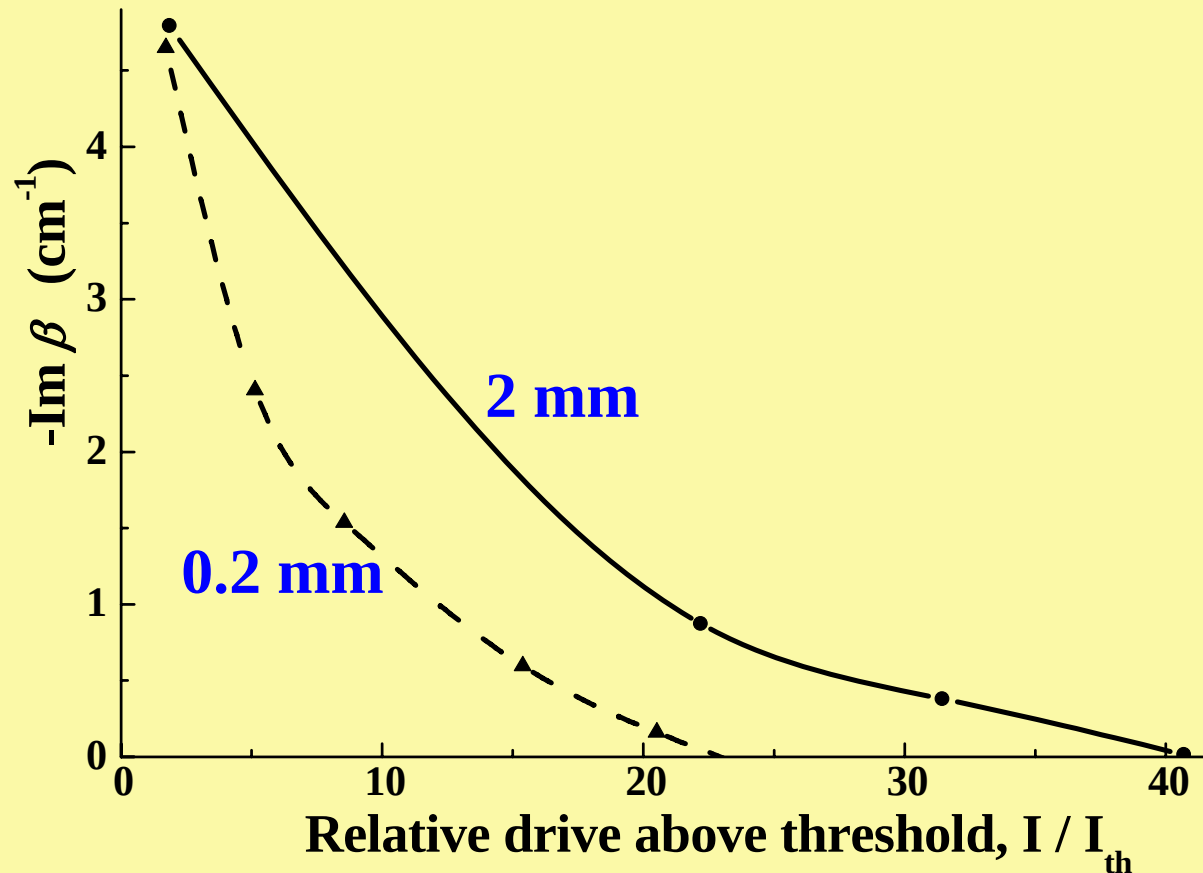


Normalized threshold-current density (in units of the transparency –current density), κ_{th} ; the distributed loss coefficient, ε ; and the slope of L-I characteristic, P_0 , as functions of s when $L=0.2$ mm



Critical relative drive for mode 7 above the threshold of mode 4, I_{cr}/I_{th} and the maximum available single-mode laser power, P_{max} versus the reflecting waveguide width for a device with $L=0.2$ mm.

The imaginary part of the propagation constant, $\text{Im } \beta$, for mode 7 vs. the relative drive above the threshold of mode 4 for short (0.2 mm) and long (2 mm) devices when $s=2.6 \mu\text{m}$.



$\text{Im } \beta$ characterizes decay or growth of wave field after cavity round-trip. Negative values of $\text{Im } \beta$ respond to decay of the field in the cavity. Approaching zero means the lasing onset of this particular mode.

CONCLUSIONS

- A menu-driven 3D computer program is developed for numerical simulations of single-mode diode lasers operating well above threshold
- Besides calculation of non-linear optical modes, the model allows for computing a set of higher-order optical modes operating at the 'frozen' gain and index distributions
- Application of the software for analyzing single-mode operation stability is demonstrated for the antiresonant reflecting optical waveguide diode lasers
- Availability for achieving W-level single-mode power from 10 μm -wide device is predicted