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Quantum Dot Lasers and New Device Concepts for High-Brightness Applications

Workshop at the World of Photonics Congress and Laser2007 fair

18th June 2007 - Munich

10:30 - 17:00

High Brightness Diode Laser Sources

Cooperation

M.V. Maximov, Yu.M. Shernyakov, I.I. Novikov, S.M.Kuznetsov, L.Ya. Karachinsky, N.Yu. Gordeev, I.P.Soshnikov, Yu.G.Musikhin, N.V.Kryzhanovskaya, and V.A.Shchukin

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R. Duboc, U.Ben-Ami, Dafna Bortman-Arbiv, and A.Sharon

PBC Lasers Ltd., Menlo Park, CA, USA and Kibbutz Einat, Israel

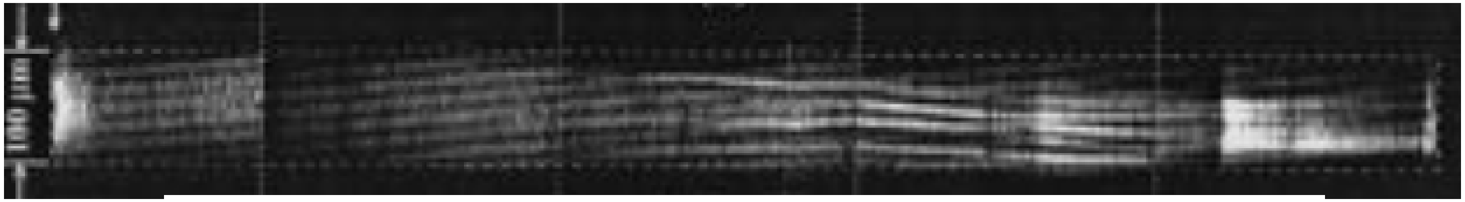
Content

- **Problems of Laser Diodes and Motivation**
- **Quantum Dot Lasers**
- **Photonic Band Crystal (PBC) lasers**
- **1D PBC lasers**
- **2D and 3D PBC Lasers**
- **Conclusion**

Problems of Laser Diodes Limiting Their Market

- **Beam filamentation**

Infrared image of the top of a broad-area gain region illustrating the effect of filamentation.



WELCH: A BRIEF HISTORY OF HIGH-POWER SEMICONDUCTOR LASERS
SDL, Inc., San Jose, CA 95134 USA.
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 6, NOVEMBER/DECEMBER 2000

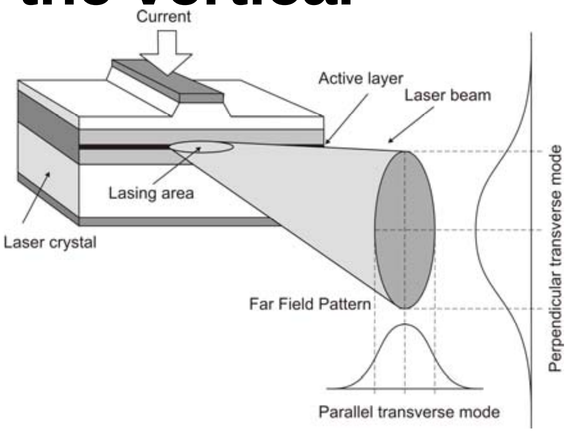
Beams from broad stripes and bars are not focusable

Filaments cause facet degradation

- **Small aperture and divergent beams in the vertical direction**

High power density and facet degradation

Dificult to manipulate and couple the light



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Impact of the Reduced Number of Degrees of Freedom on Laser Performance

United States Patent [19]

Dingle et al.

[54] QUANTUM EFFECTS IN HETEROSTRUCTURE LASERS

[75] Inventors: **Raymond Dingle**, Summit; **Charles Howard Henry**, New Providence, both of N.J.

[73] Assignee: **Bell Telephone Laboratories, Incorporated**, Murray Hill, N.J.

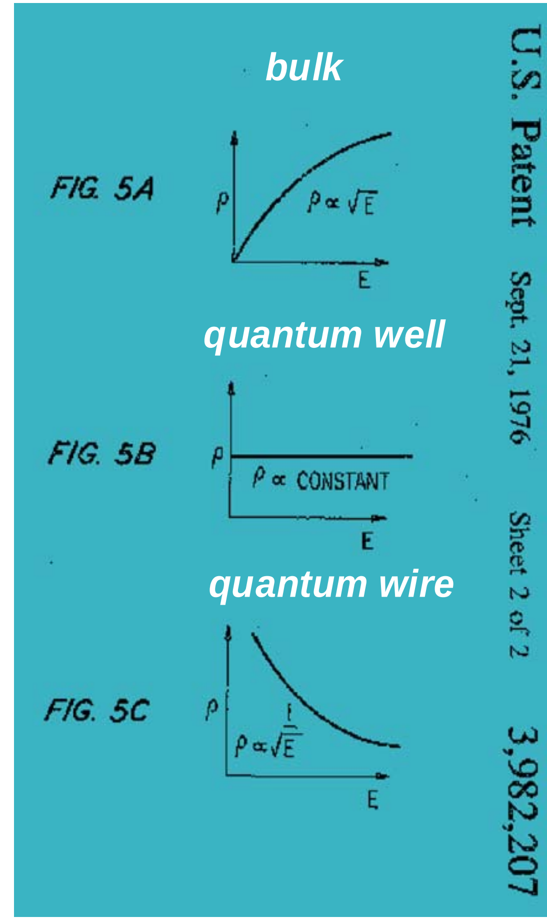
[22] Filed: **Mar. 7, 1975**

[21] Appl. No.: **556,305**

As the number of degrees of freedom is reduced the density of states decreases at high energies. This causes the electrons to occupy the lower energy states and thereby to contribute more effectively to population invention and laser gain.

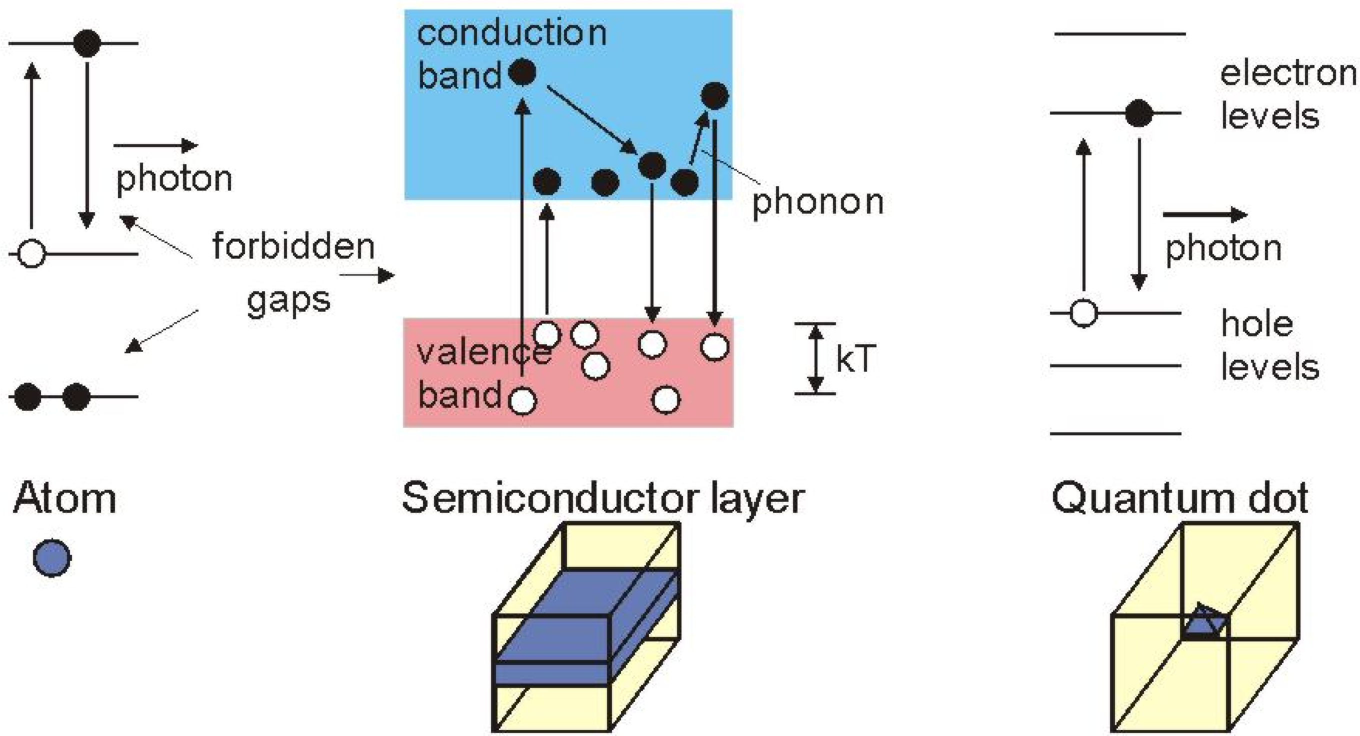
QWs and QWWs: R. Dingle and H. Henry, 1975

Advantage of QDs: Y.Arakawa and H. Sakaki, 1982



Strong modification of the density of states by quantum-size effect

Change of Paradigm: Artificial Atoms vs Layers



Atom	Semiconductor layer	Quantum dot
+ Narrow lines	+ High density	Combines advantages
– Low density	– Thermal broadening	inhomogeneous broadening for arrays of QDs

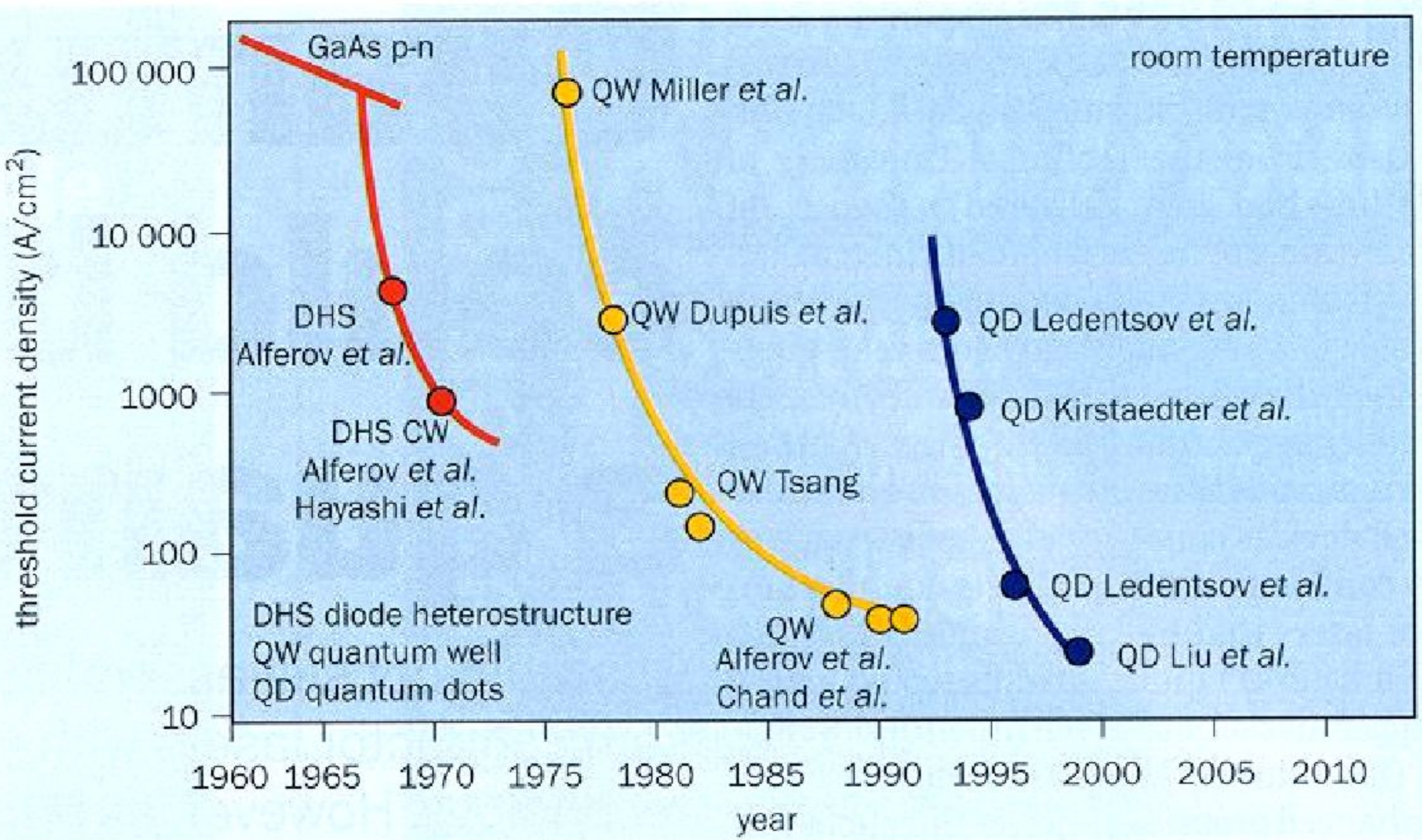
- **Quantum dot: has a discrete atom-like electronic spectrum**
  consists of 1 000 to 100 000 atoms
  may be considered as an artificial atom

History of Heterostructure Lasers

Opto & Laser Europe Issue 74 May 2000

Quantum dots could be set for a quantum leap

34 Quantum dots OLE May 2000

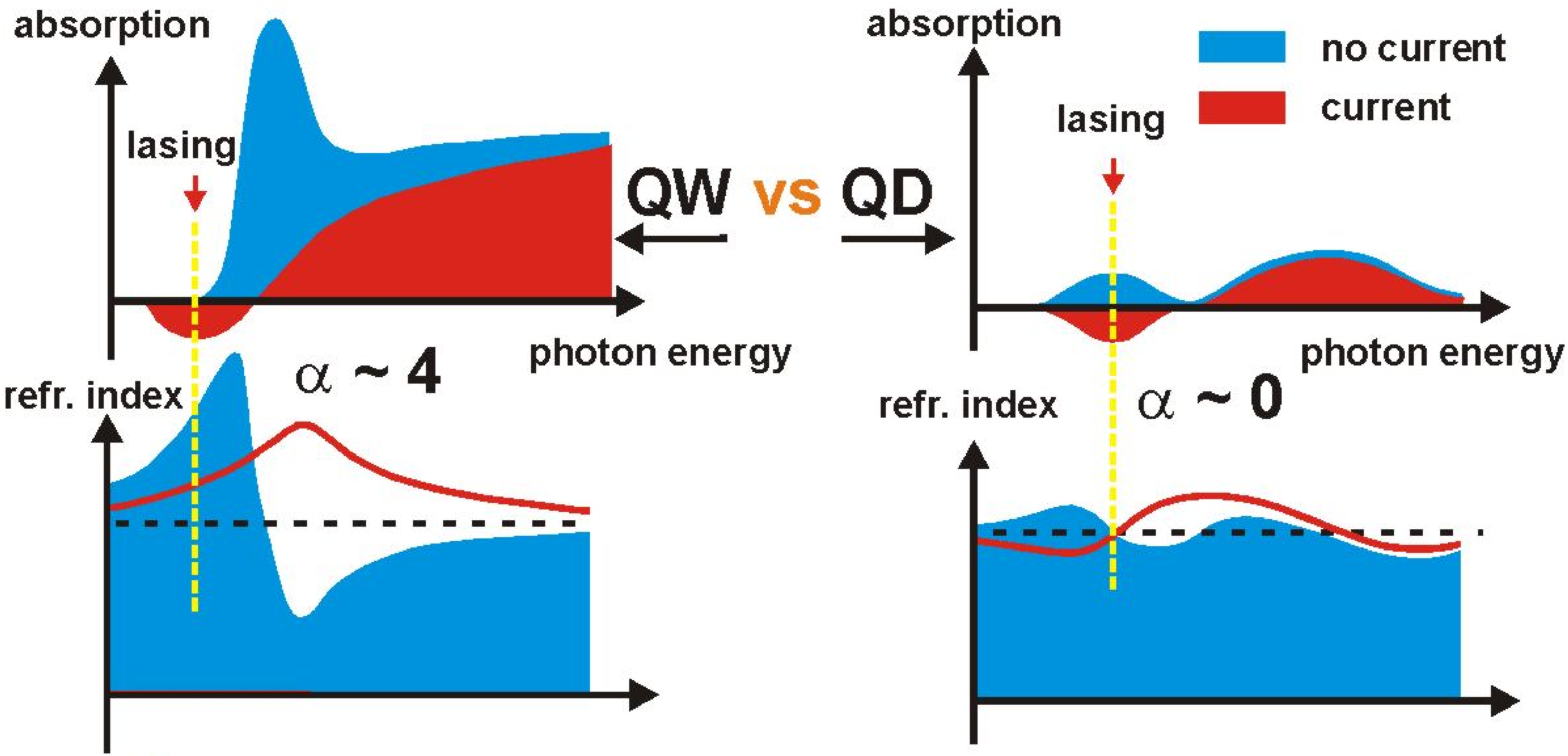


Diode laser progress: the superior gain in quantum-dot devices results in a lower threshold current.

Optical Nonlinearity in Semiconductor Lasers

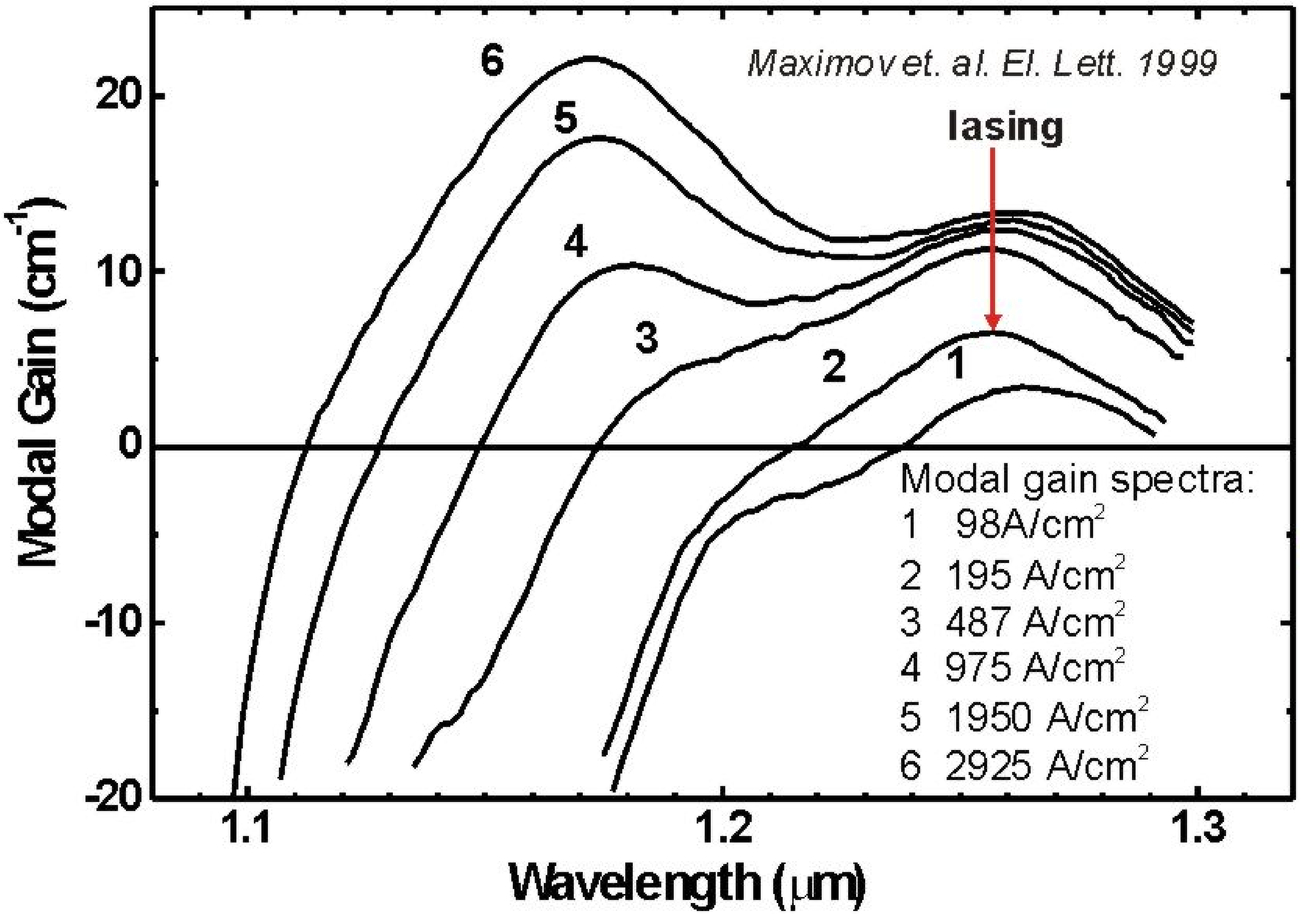
Dielectric susceptibility varies with current injection:

- absorption/gain curve change (light intensity changes)
- refractive index change (wavelength of the FP mode changes)
- a bunch of related effects occur (beam filamentation, etc.)



Elimination of optical nonlinearity in Quantum Dot Laser !

Experiment: Gain Spectrum of the QD Laser



3-fold stacked InAs-GaAs quantum dots

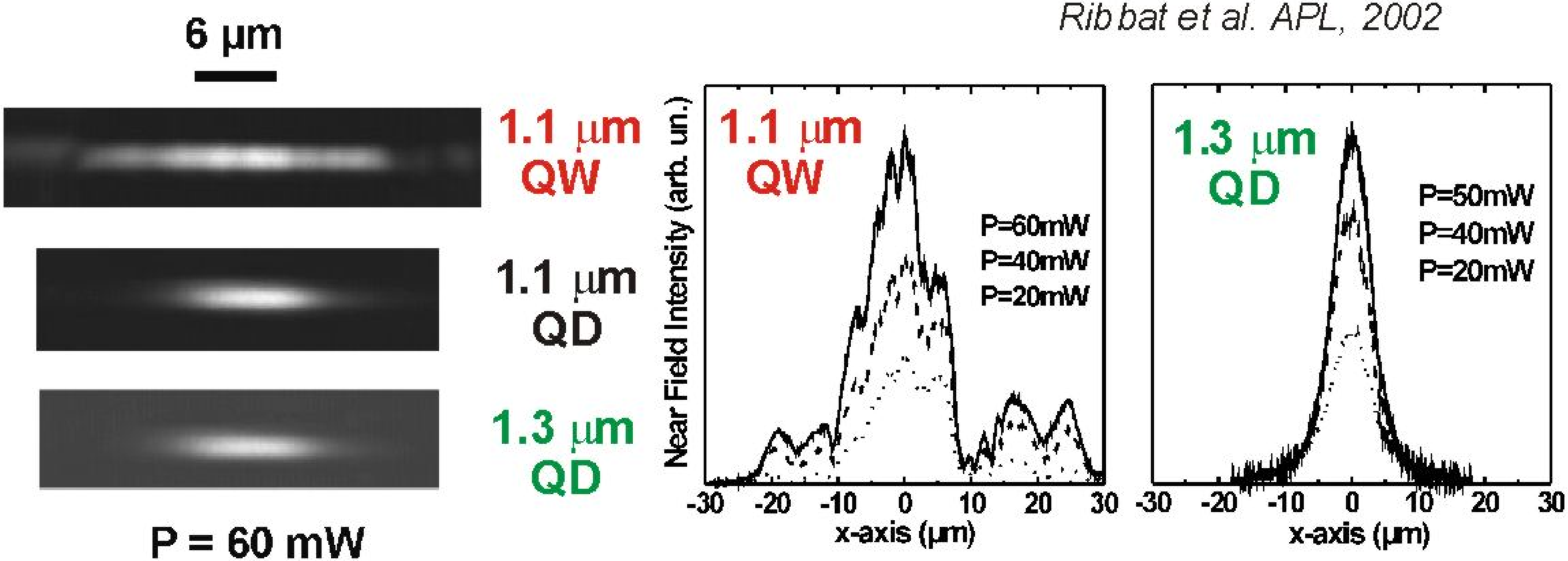
Saturated Modal Gain:

Ground state: 12 cm^{-1}
Excited state: 25 cm^{-1}

- **Gain spectrum in QD media is highly symmetric at threshold !**

Suppression of Beam Filamentation in QDs

Ribbat et al. APL, 2002



- **QW and QD edge-emitting lasers in similar geometry**
- **Complete suppression of beam filamentation in QD laser**

16W CW Operation of as-cleaved QD Lasers

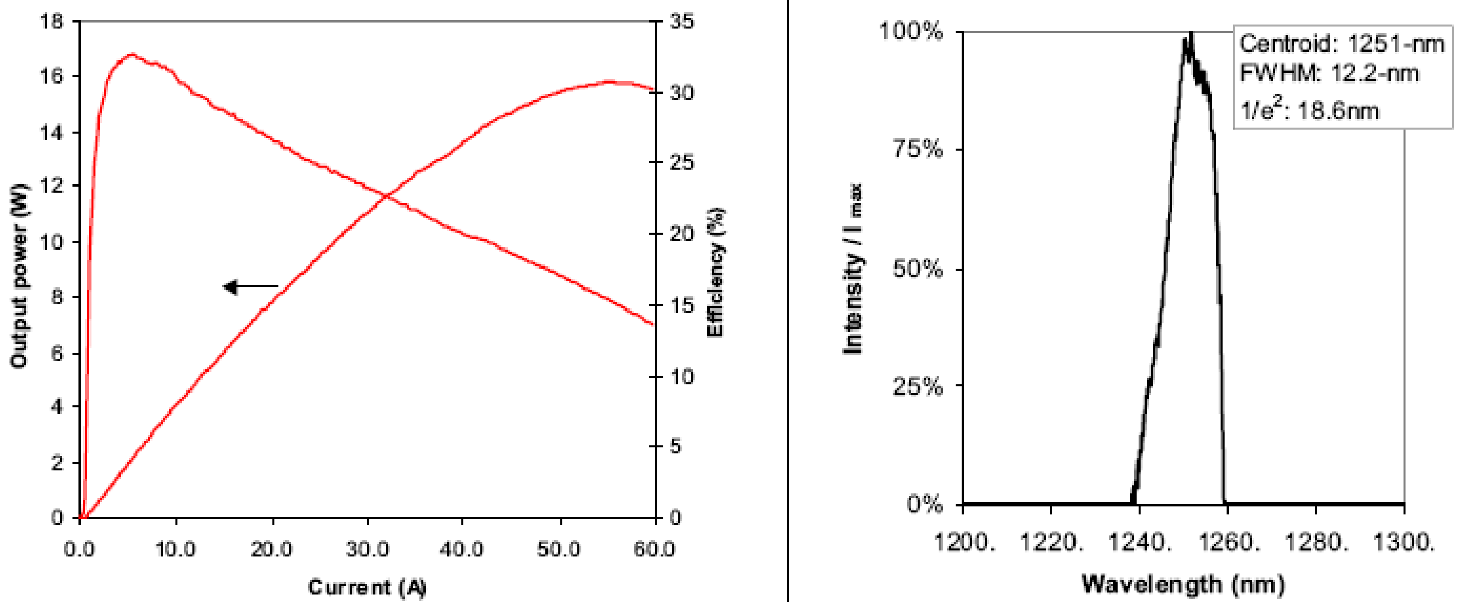


Figure 5: Single emitter 200-µm stripe, 4-mm cavity uncoated quantum dot devices mounted junction down on water-cooled microchannel heatsinks were found to have (Left) total output power from both facets of 16-W, and power conversion of 33% and (right) spectral width at 10-A of 12.2-nm.

nLight Corp, 5408 NE 88[th] Ste, Bldg E, Vancouver, WA, USA 98665

NL Nanosemiconductor GmbH, Josef-von-Fraunhofer Str. 13, 44227 Dortmund, Germany

Princeton University, 70 Prospect Avenue, Princeton, NJ, USA 08540-521

High-Power Diode Laser Technology and Applications V, edited by Mark S. Zediker,
Proc. of SPIE Vol. 6456, 64560E, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.706177

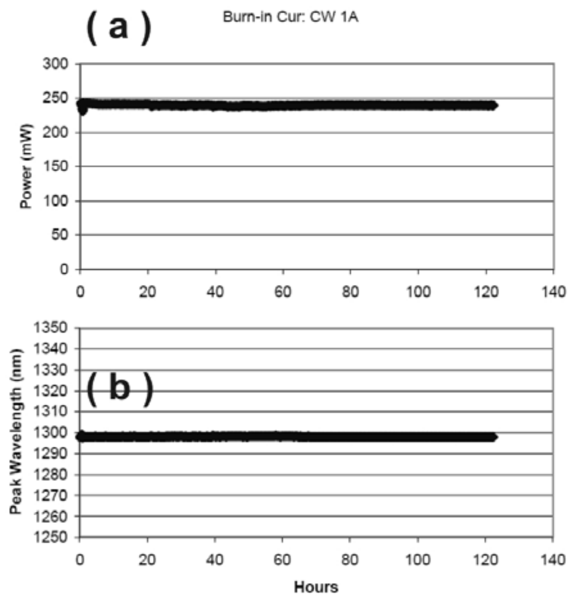
Proc. of SPIE Vol. 6456 64560E-1

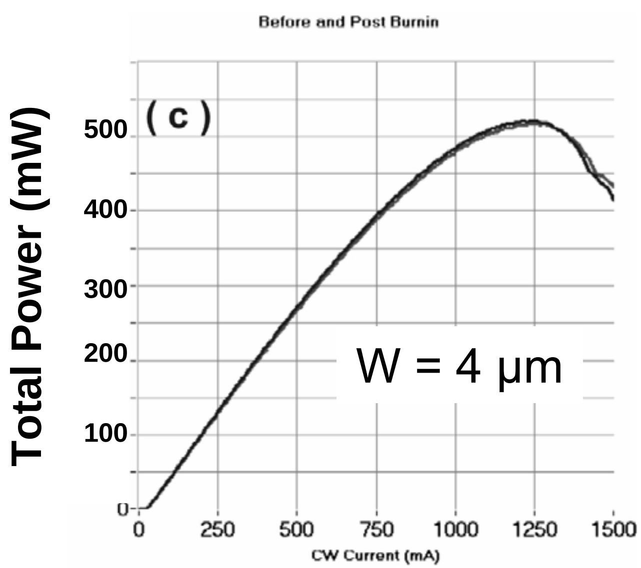
- **No facet degradation up to ultrahigh power**

High-Power Operation of 1.25 – 1.3 µm QD Lasers

Burn-in test at 1 A current for 3mm-long narrow-stripe (4 µm) lasers with uncoated facets.

(a) stability of output power,
(b) stability of the emission wavelength,
(c) Light-current characteristics before/after burn-in tests.

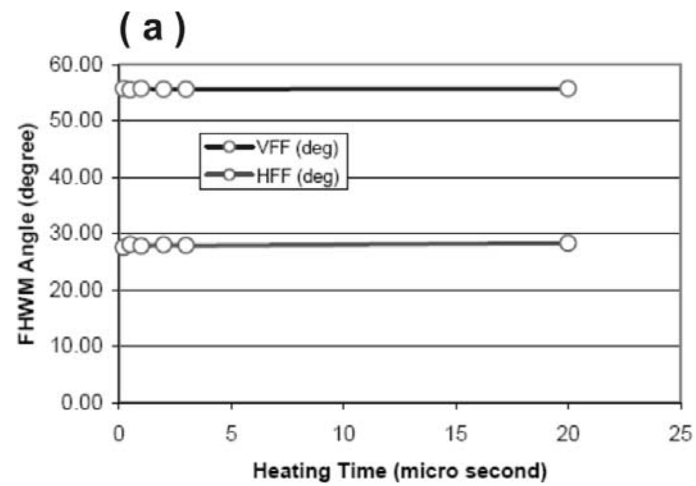




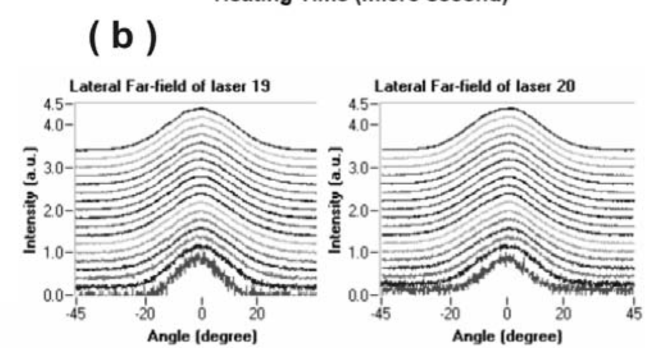
Total cw power limited by thermal roll-over is ~520 mW

Far field stability:

as function of heating time and

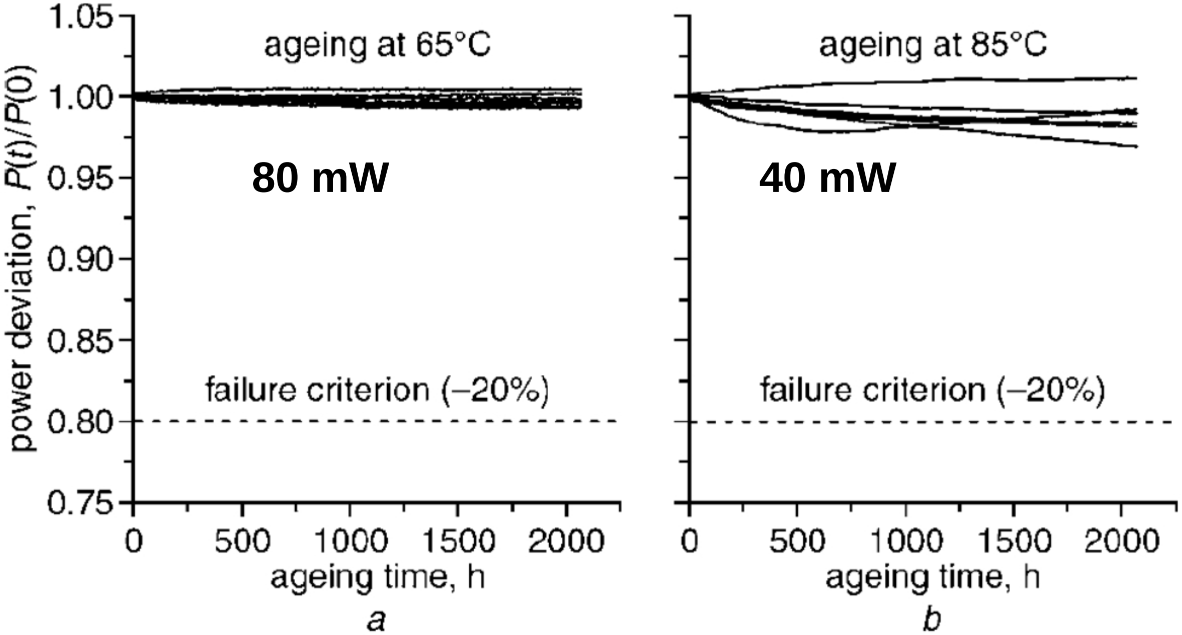


as function of the drive current in the whole range



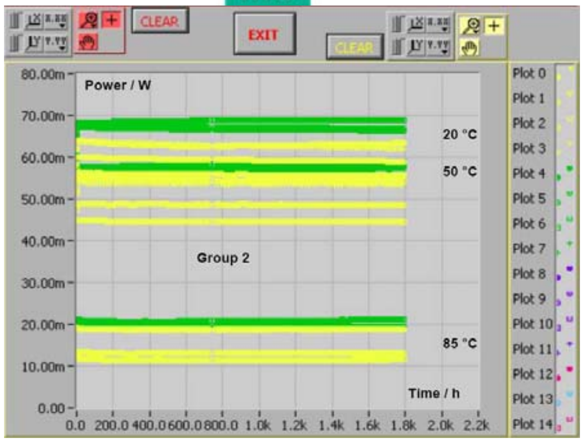
CORNING

High-Power Operation and Degradation Robustness of 1.25 – 1.3 µm QD Lasers



Facet passivation Lumics, Berlin

Degradation test HHI, Berlin



The Arrhenius activation energy E_A of 0.79 eV was extracted

Assuming the temperature of normal operation being 40^{o}C, the median lifetime of QD lasers to be 1.2x10^6 h

- **Lifetime > 10^6 h**

Reliability study of InAs/InGaAs quantum dot diode lasers

I. Krestnikov, D. Livshits, S. Mikhrin, A. Kozhukhov, A. Kovsh, N. Ledentsov and A. Zhukov

ELECTRONICS LETTERS 24th November 2005 Vol. 41 No. 24

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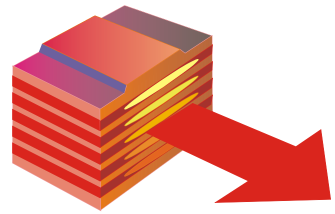
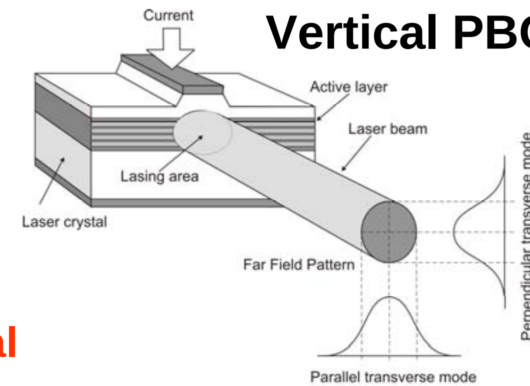
Anticipated PBC Laser Capabilities

(demonstrated: 4 deg. divergence, >1 W single mode, coherently coupled beams)

- **Single mode single stripe PBC emitters (anticipate >3 W CW)**

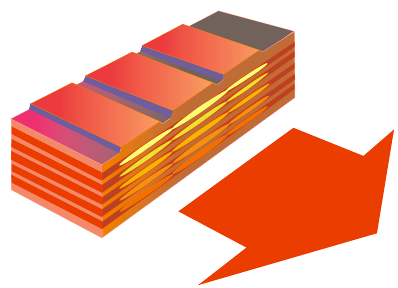


Vertical PBC



Filtering of high-order modes by vertical photonic crystal

- **Single mode coupled PBC stripe emitters (anticipate up to 20 W CW)**



Lateral PBC

Filtering of high-order modes by lateral photonic crystal

- **Large vertical waveguide extension may enable efficient coupling of beams to enable Kwatt single mode beams**

Courtesy of PBC Lasers

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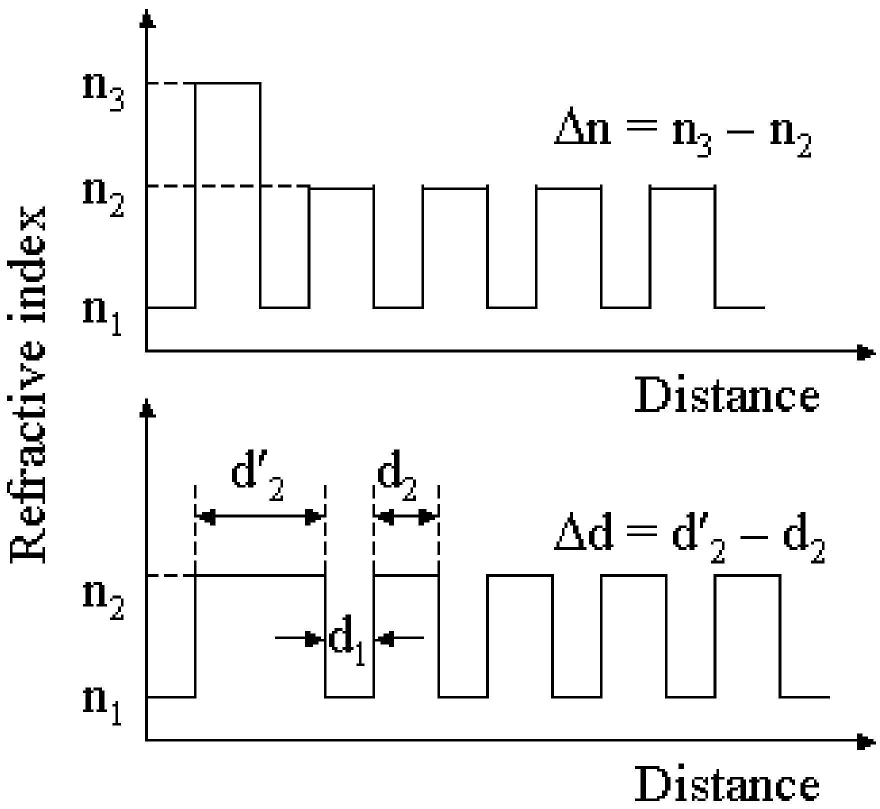
Photonic Bandgap Crystal (PBC) lasers concept

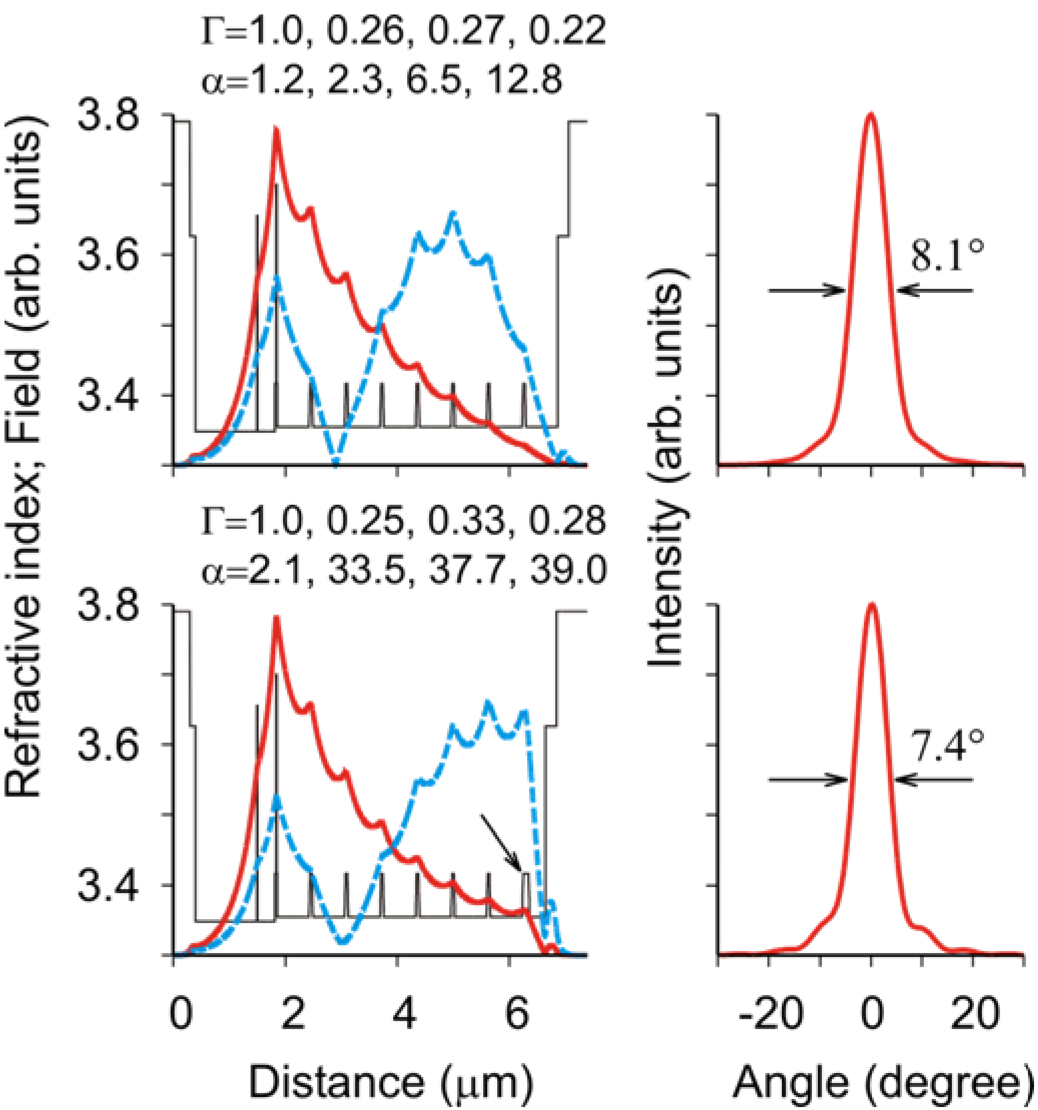


- **Fundamental optical mode is localized by the optical defect and decays away from it**
- **High–order modes are extended over the entire PBC structure**
- **High-order modes may leak into the substrate**

1D Edge-Emitting PBC Laser with an optical defect

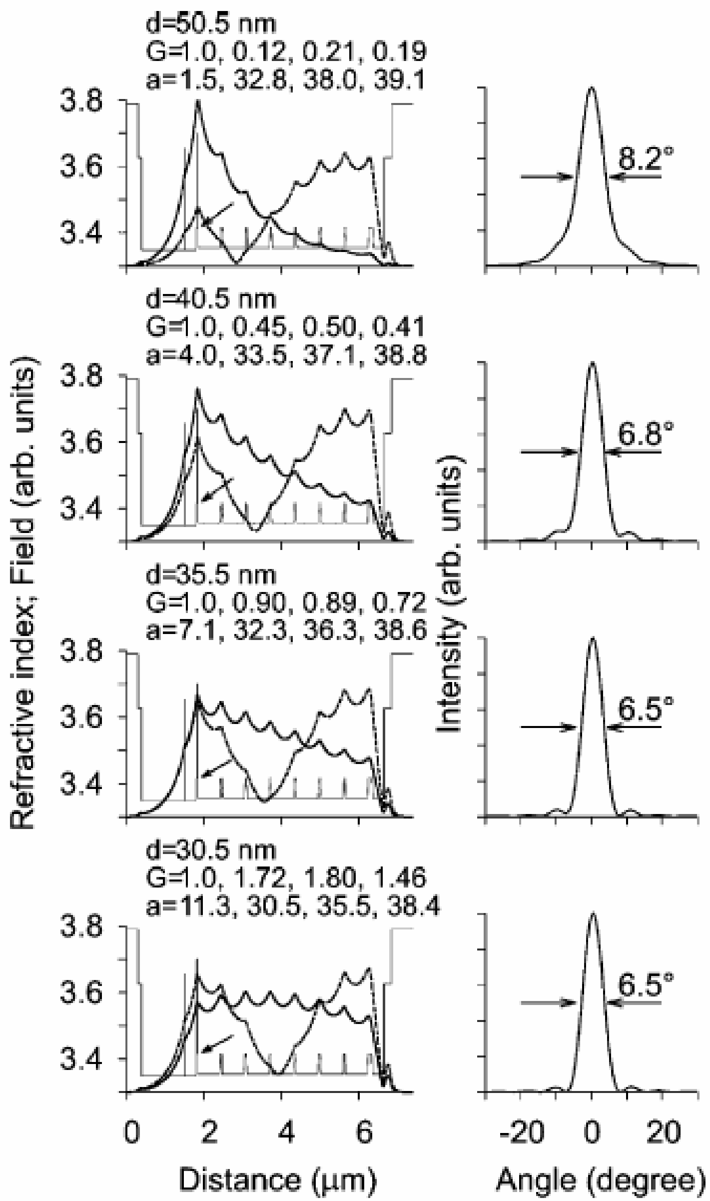
Courtesy of PBC Lasers

Engineering leakage for high order modes



- **Leakage loss may be engineered. It may be order (or orders) of magnitude higher for the excited modes than for the fundamental mode**

Engineering Robustness



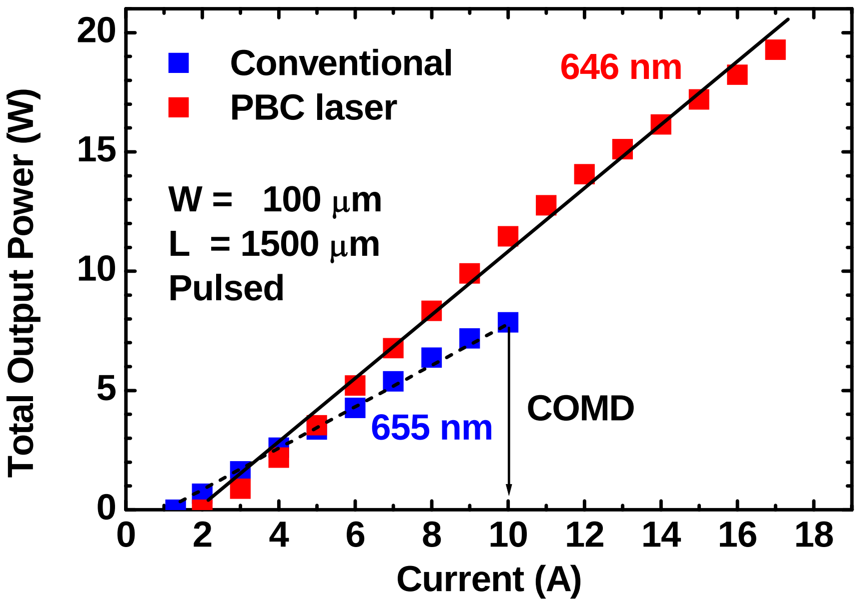
- **Decrease in the thickness of the optical defect from ~50 to 30 nm.**
- **Some narrowing of the beam**
- **No dramatic reduction in the optical confinement factor for the fundamental mode**
- **No dramatic increase in losses for the fundamental mode**

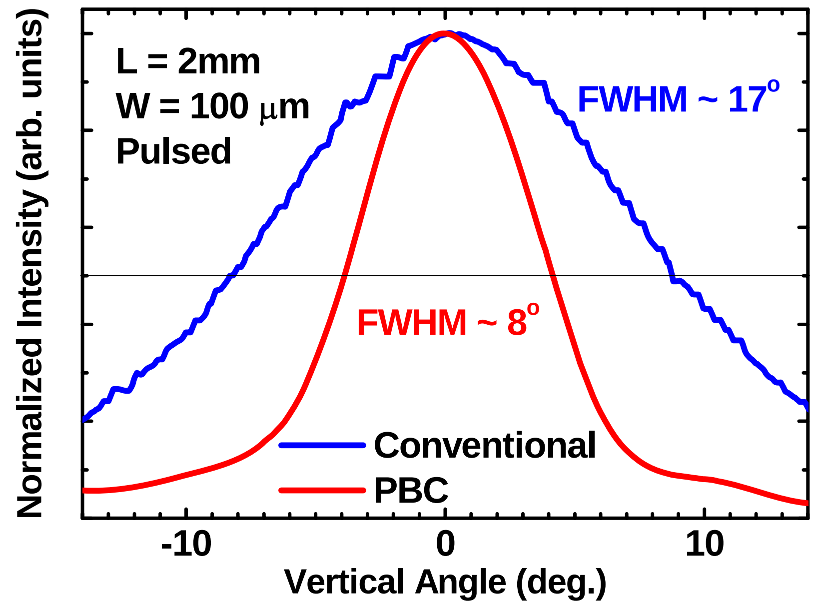
While the change (50 nm to 30 nm) is dramatic !

ROBUST !
Analogue of PC Fiber

Comparison of Generic and PBC Lasers (Pulsed)

IQE growth: 1 to 1 comparison with generic

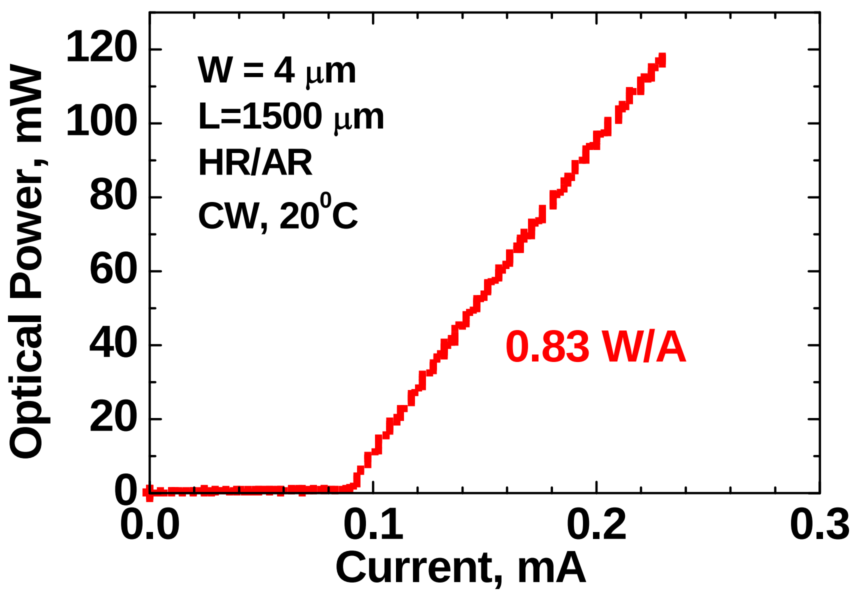


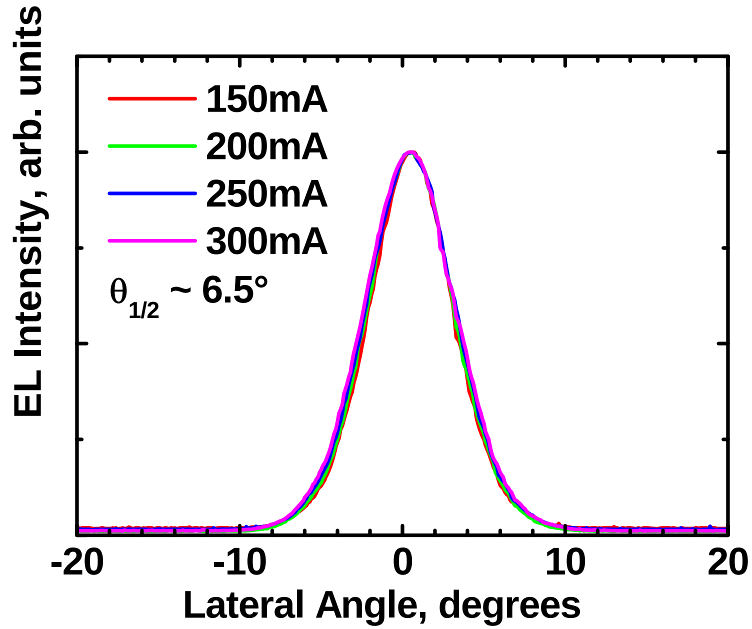


- P_{max} of conventional lasers is < 8 W and limited by COMD
- P_{max} of as-cleaved PBC lasers is ~ 20 W
- FWHM of the vertical far field pattern is 7-8° for PBC laser and 17° for conventional laser

4 μm Single Mode 650 nm CW PBC (~8°x7°) lasers

No passivation/coating of the facets !

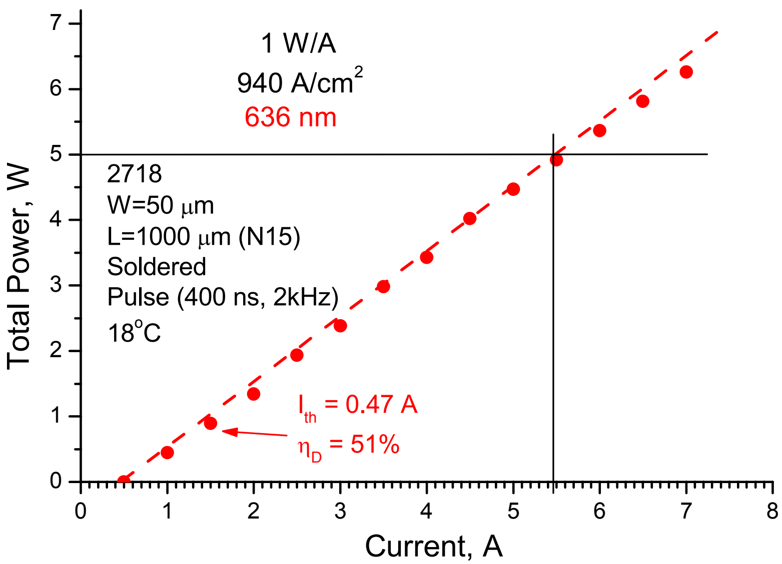




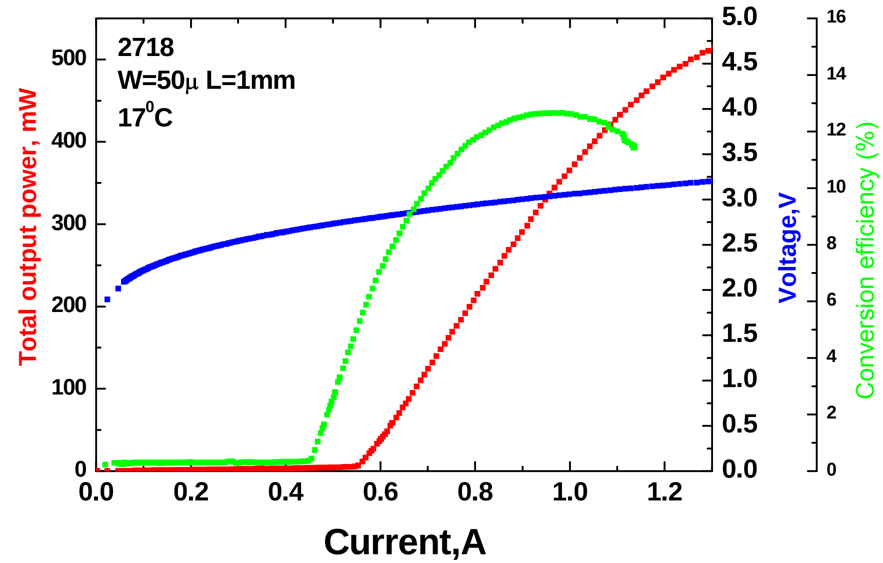
- Single mode operation up to the highest currents applied.
- Maximum CW output optical power is ~ 120 mW and limited by COMD
- Low Aspect ratio ~ 1.2 – 1.4
- No kinks

50 μm single mode 636 nm PBC (~12°) lasers

pulsed

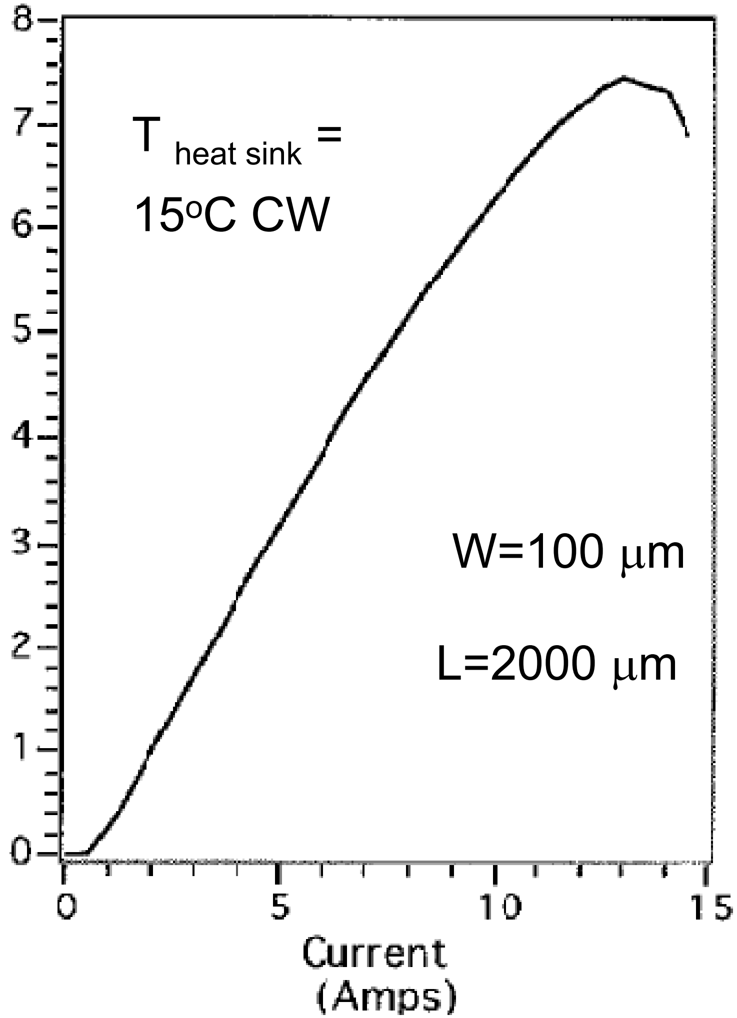


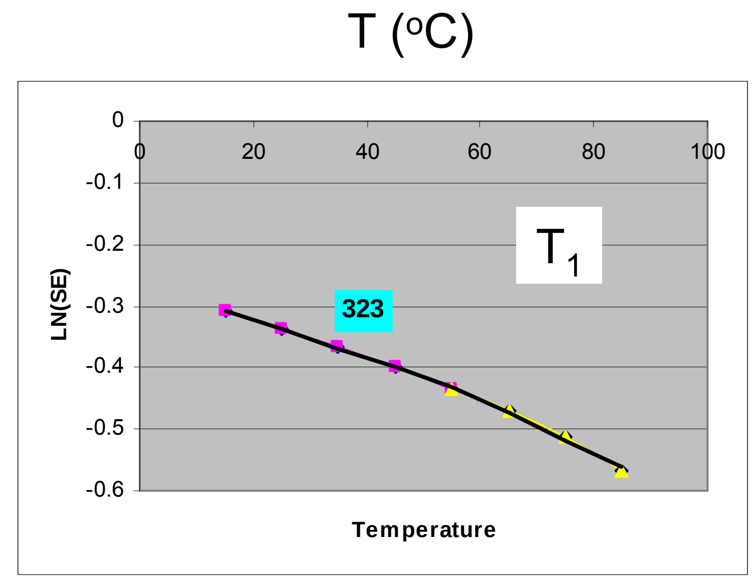
CW



- **Total CW power >500 mW without facet passivation/coating**

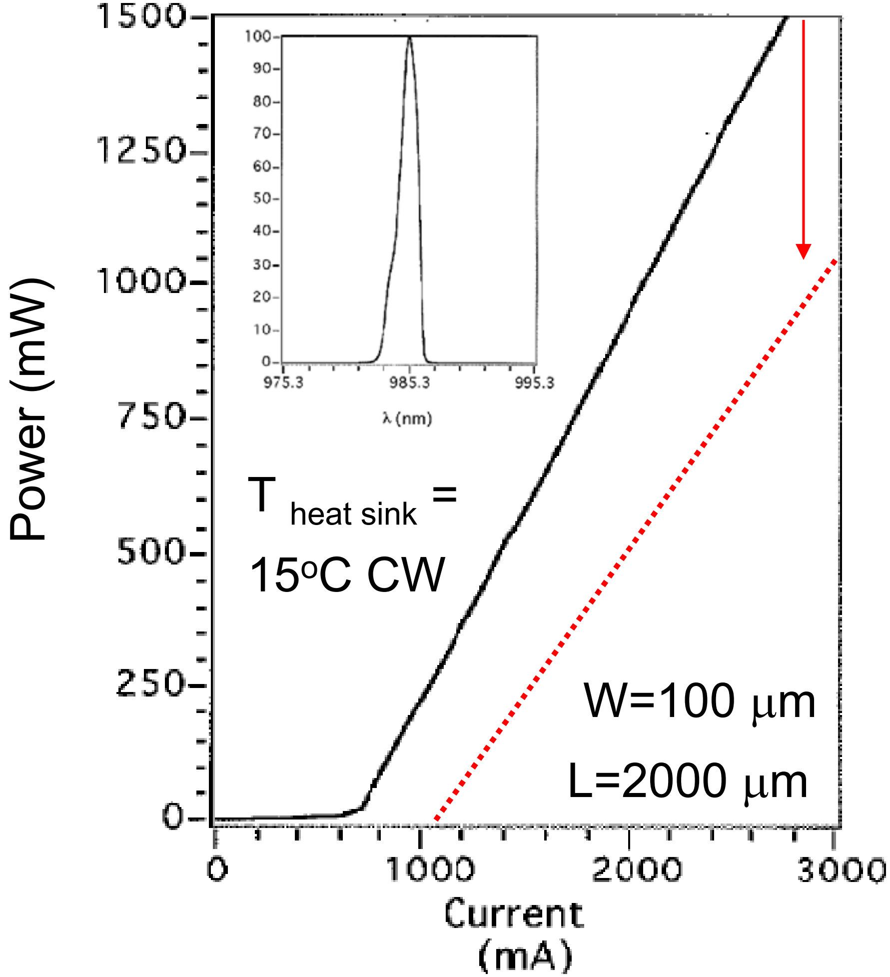
CW 980 nm PBC (~8°) lasers at High Power

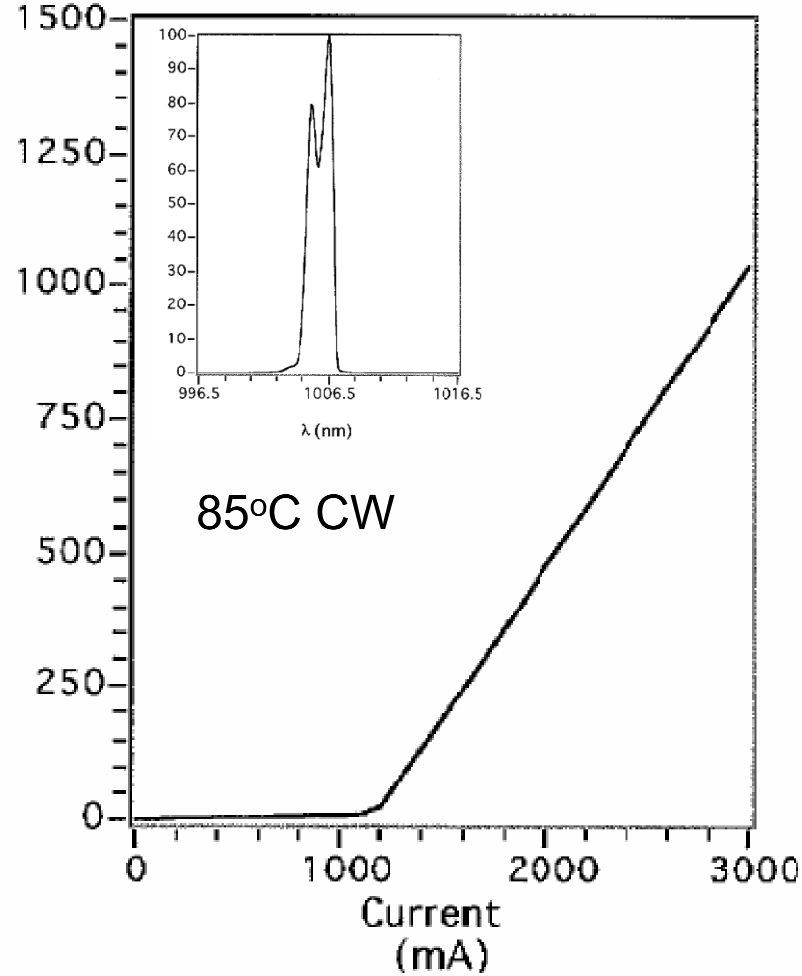




- **7-9 W CW at non-optimized heat sinking**

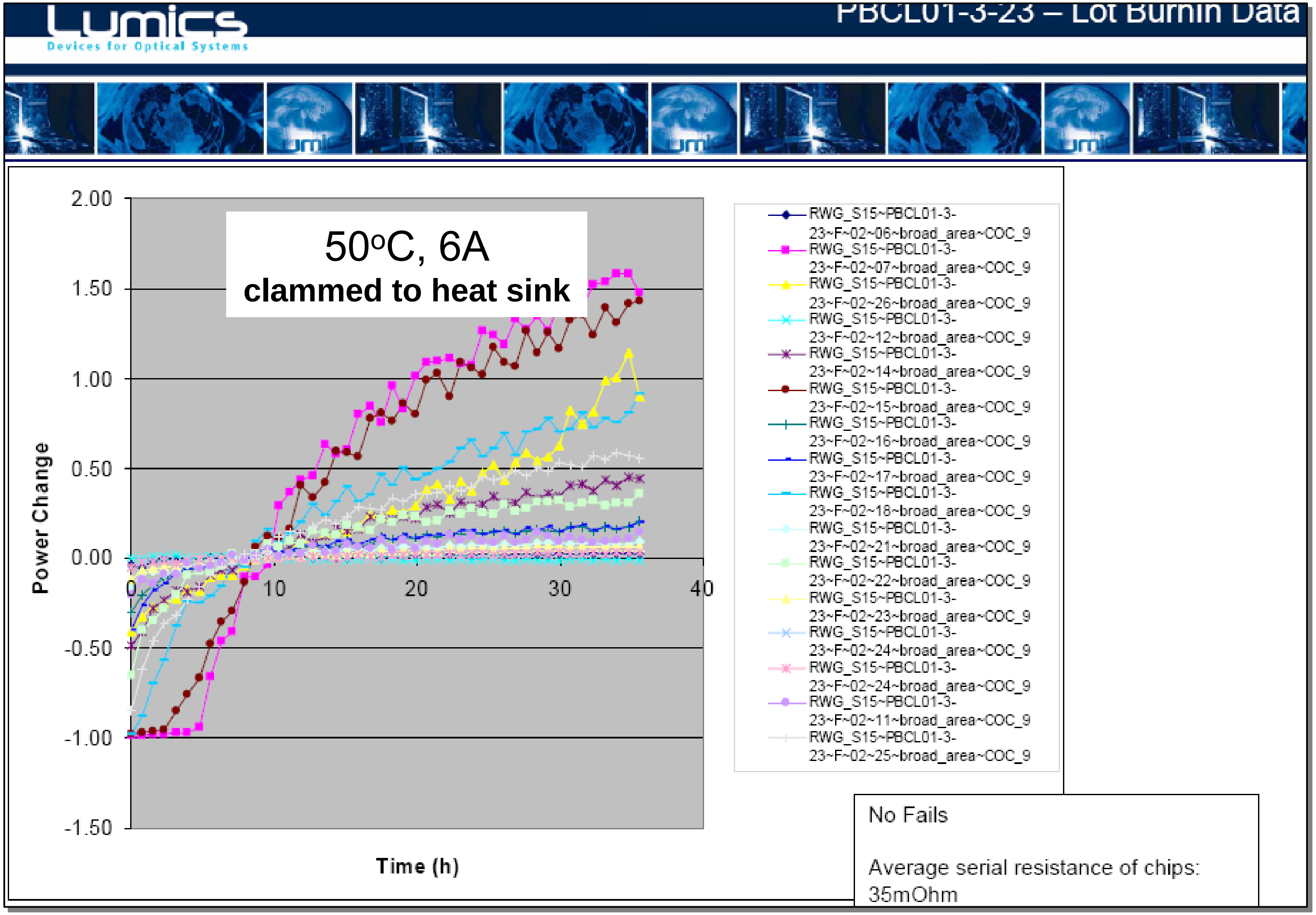
CW 980 nm PBC (~8º) lasers at High Temperature





- **Good CW high-temperature performance**

980 nm PBC Lasers: Reliability



- **Passivated and coated ~100% yield**
- **Zero infant mortality**

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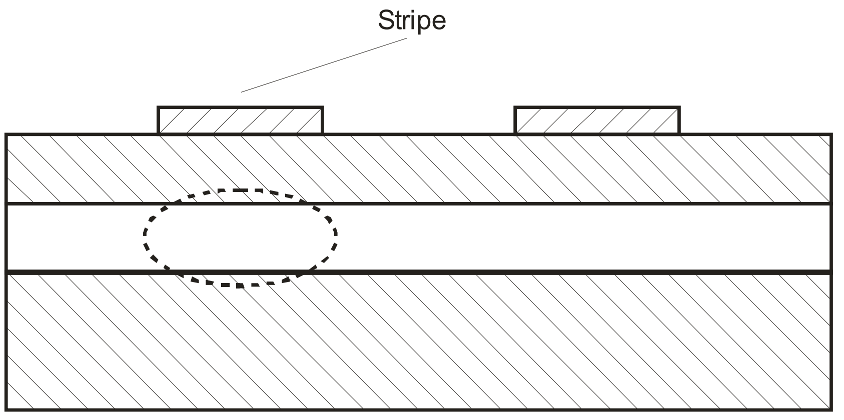
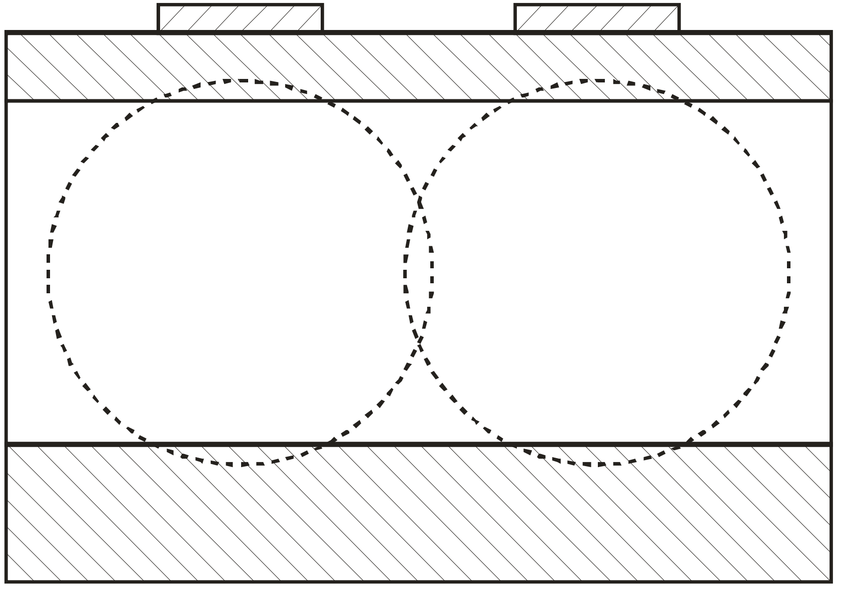
Broad Stripe and Coupled Cavities



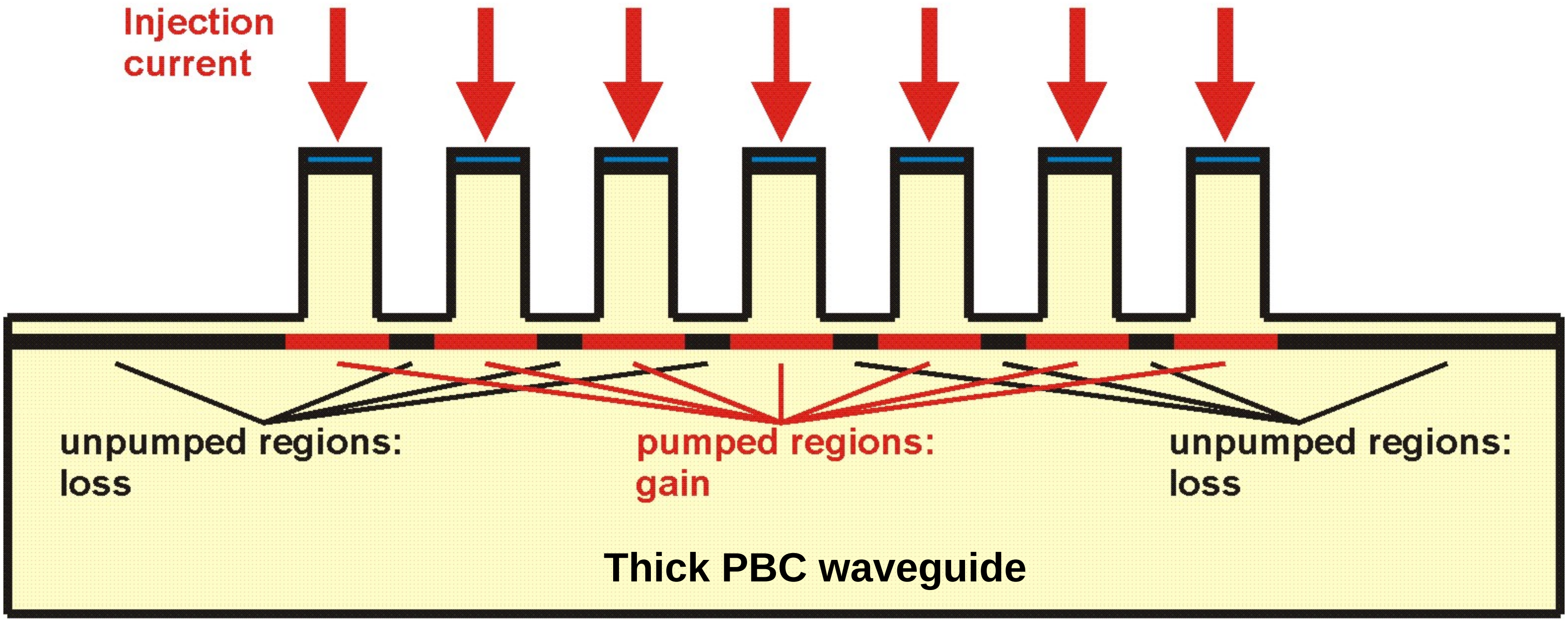
- **Conventional**



- **PBC:**
  - **- single mode to broader stripes**
  - **- multistripe processing keeping strongly coupled field**
  - **- wavelength stabilization is easy**

Courtesy of PBC Lasers

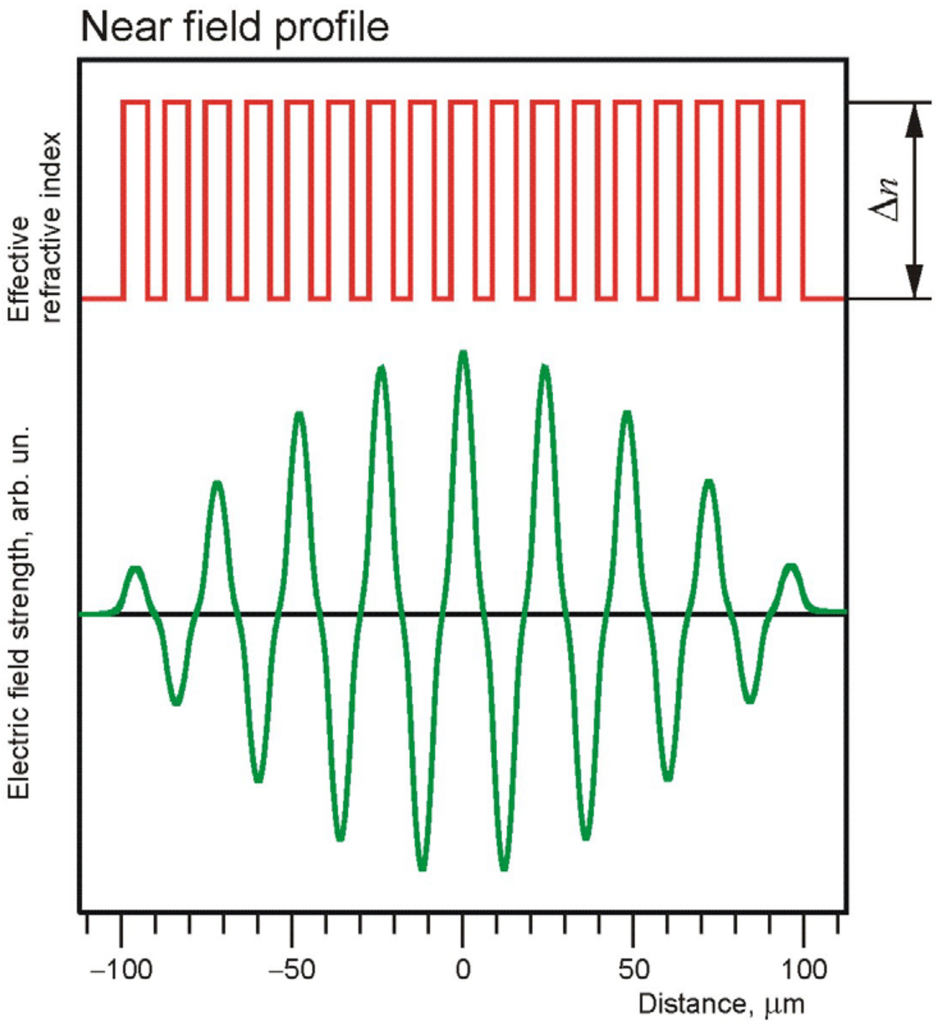
Lateral Photonic Band Crystal: Selection of Modes in Absorption Loss

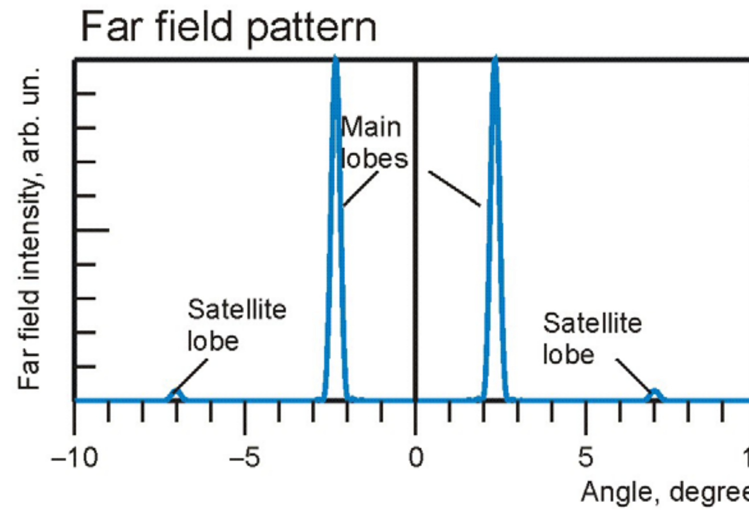


- Lateral mode having nodes in all unpumped regions between stripes has the minimum absorption loss
- Lasing in the lateral mode having minimum absorption loss

Courtesy of PBC Lasers

Oscillating Lateral Mode in Lateral PBC





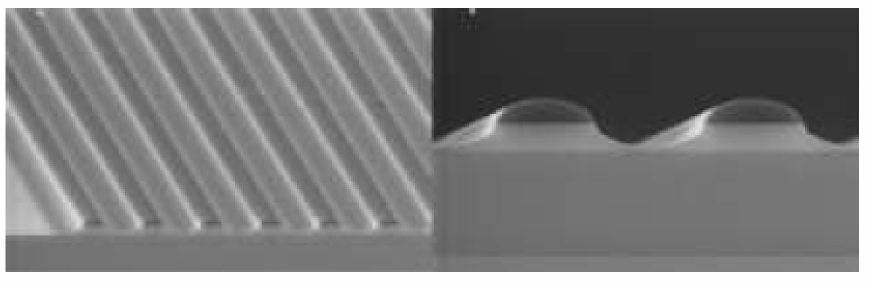
Fitting of refractive index variation in the lateral PBC:

Δn	Relative intensity of satellite lobes in far field pattern
0.01	1:10
0.0023	1:30
Experiment:	1:30

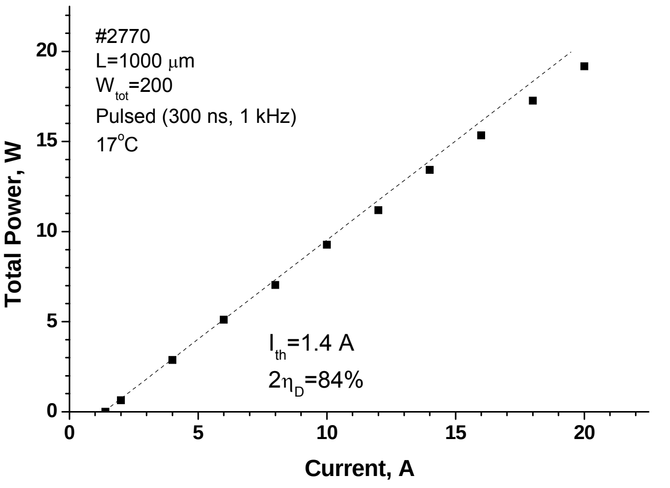
- Fitting of refractive index variation yields Δn = 0.0023

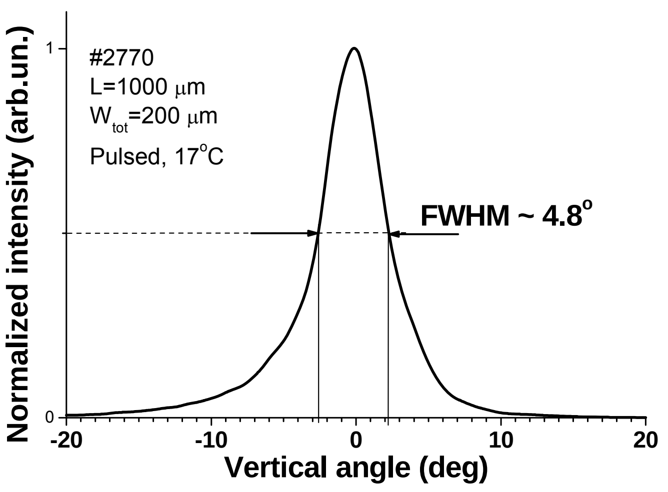
Courtesy of PBC Lasers

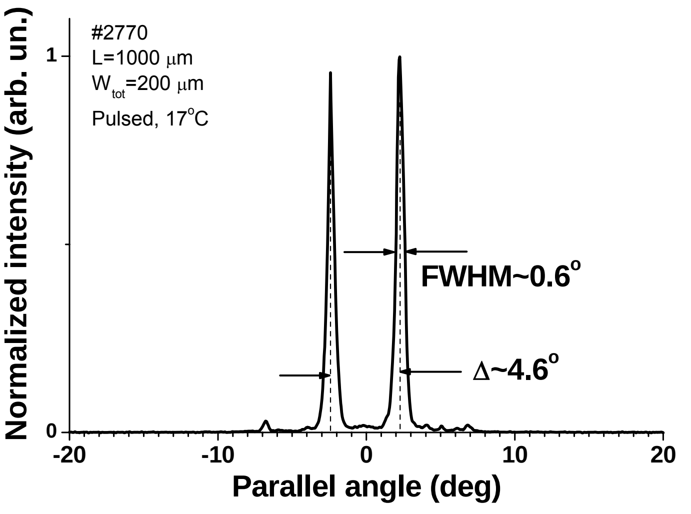
Multistripe PBC Laser: Experiment



17 stripes with a ridge width and a pitch of 7 µm and 12 µm, respectively. 200 µm total width

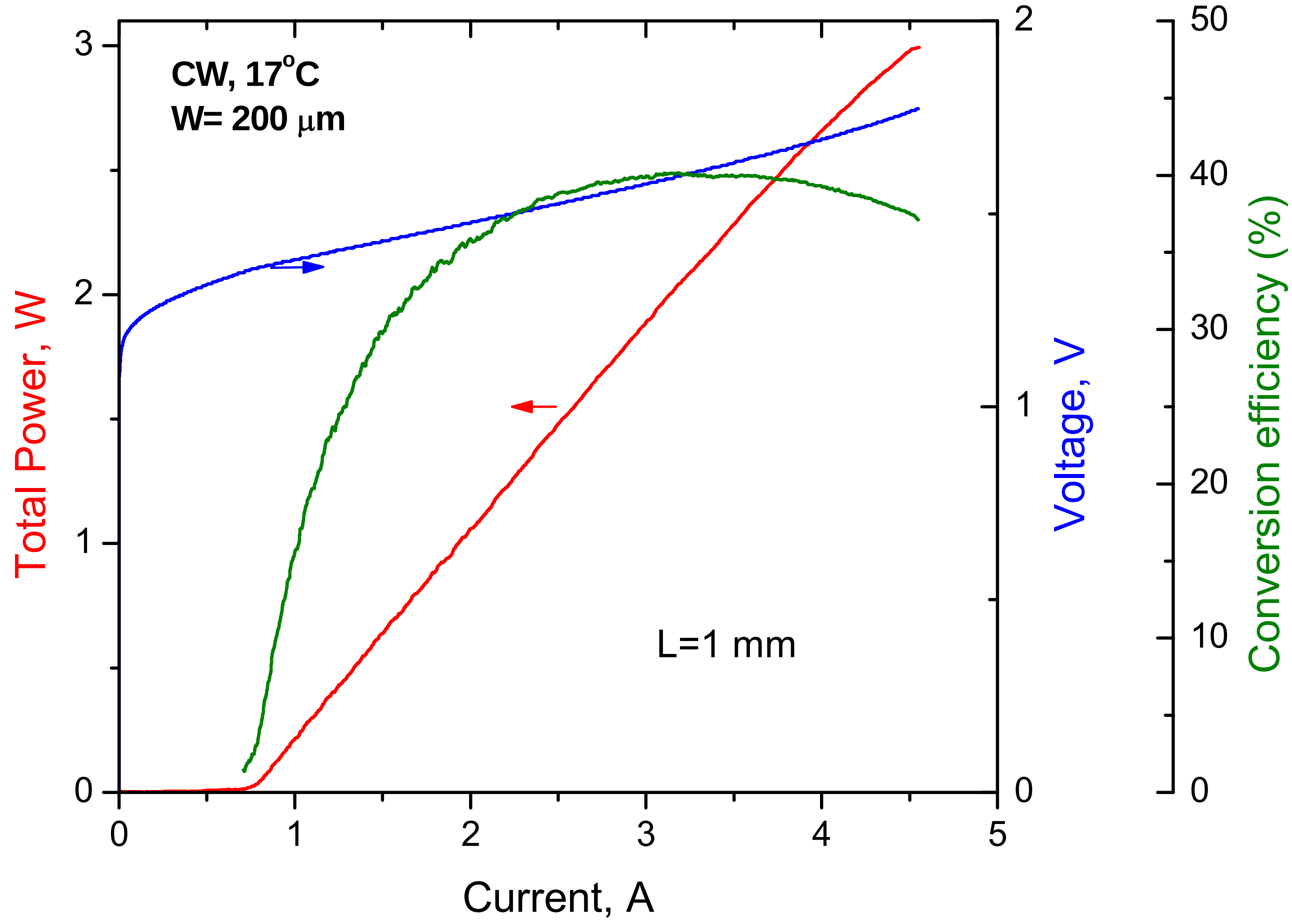






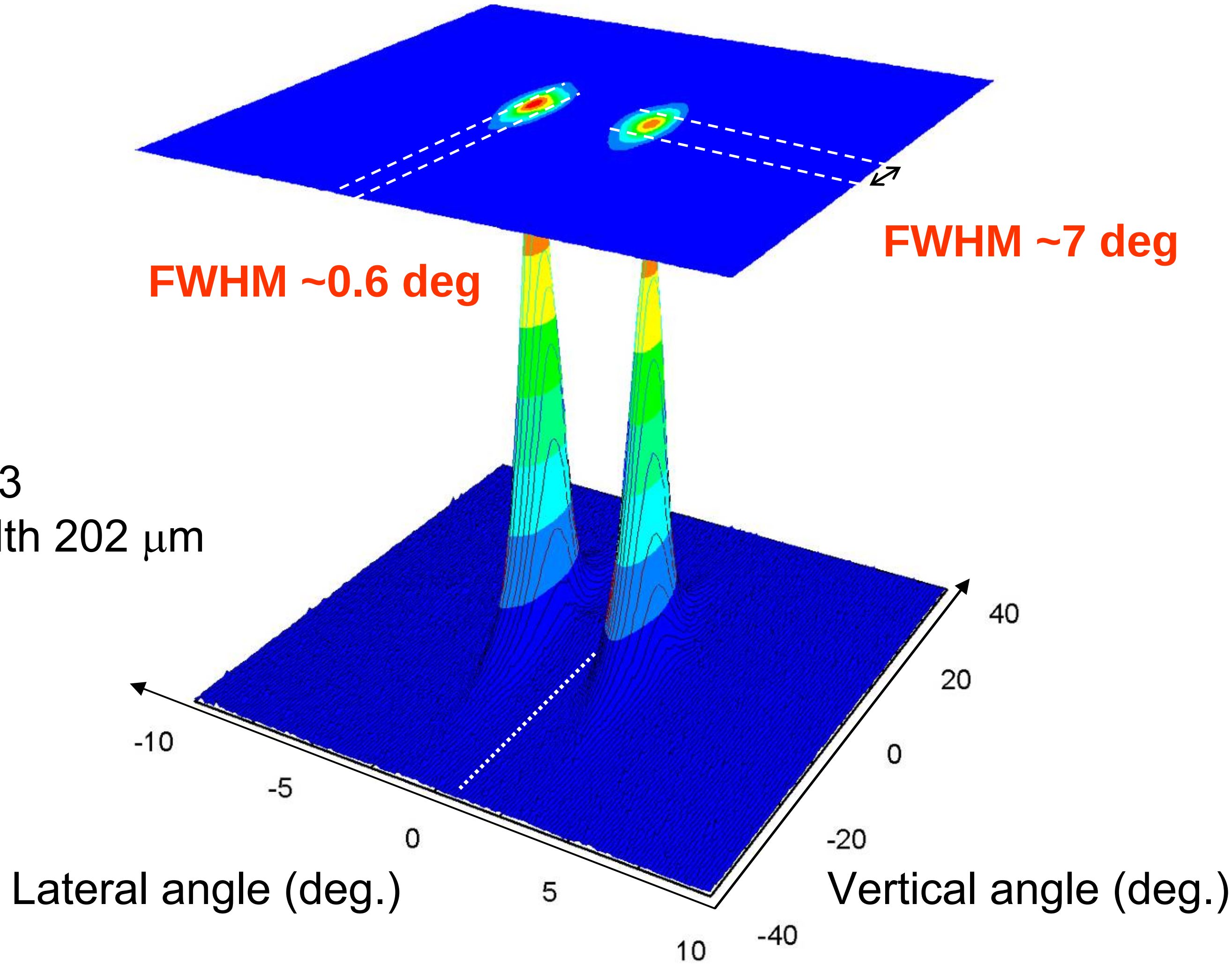
- **Coherent filament-free beam over 200 µm. 980 nm**

Multistripe 7º PBC Laser: CW Experiment



- **Potential for high-performance CW operation**

Multistripe 7º PBC Laser: 2D Far Field (W=202 μm)



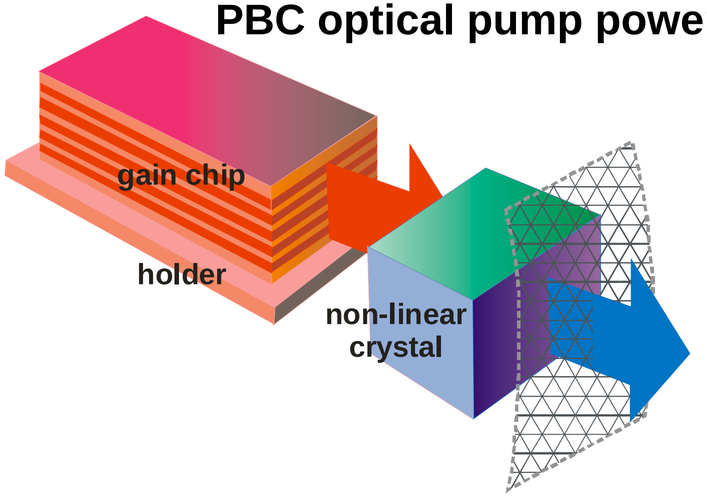
#2768

4 μm x 23
Total width 202 μm
L= 1mm
I = 1A

Potential of Frequency Conversion Using PBC Laser

PBC RGB Module

PBC optical pump power: potential of 10-20W SM in extended cavity

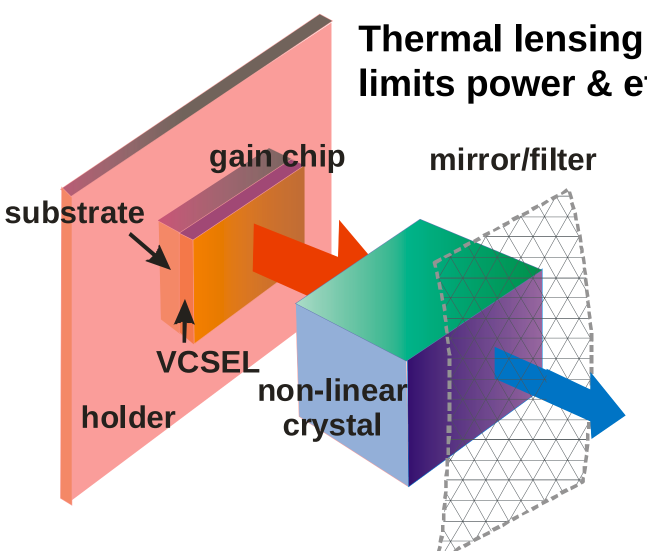


Potential PBC Performance Advantage

- ↑ Laser Intra-Cavity Power density
- ↑ Conversion efficiency
- = 40-1000 X power increase

Surface Emitter with a Large Aperture

Thermal lensing significantly limits power & efficiency



Potential PBC Cost Advantage

- Lower optical parts count
- Required power from minimal # of emitters and non-linear crystals
- <1/5 wafer space; <1/4 crystal volume
- Simpler assembly (lower tolerances)

Courtesy of PBC Lasers

PBC Laser: Publications

Review: Invited Paper

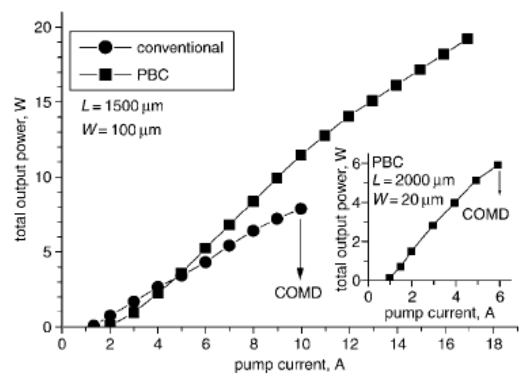
Physics and Simulation of Optoelectronic Devices XIV, edited by Marek Osinski, Fritz Henneberger, Yasuhiko Arakawa, Proc. of SPIE Vol. 6115, 611513, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.661389

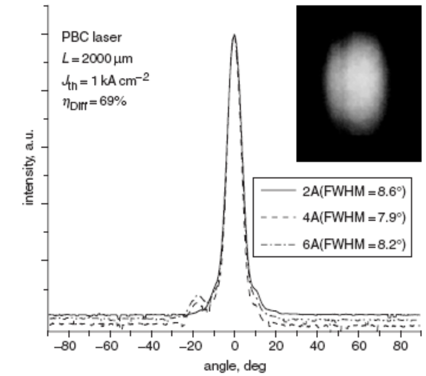
High power GaInP/AlGaInP visible lasers ($\lambda = 646$ nm) with narrow circular shaped far-field pattern

M.V. Maximov, Yu.M. Shernyakov, I.I. Novikov, S.M. Kuznetsov, L.Ya. Karachinsky, N.Yu. Gordeev, V.P. Kalosha, V.A. Shchukin and N.N. Ledentsov

ELECTRONICS LETTERS 23rd June 2005 Vol. 41 No. 13

20W pulsed at 640 nm, W=100 µm





Single mode cw operation of 658 nm AlGaInP lasers based on longitudinal photonic band gap crystal

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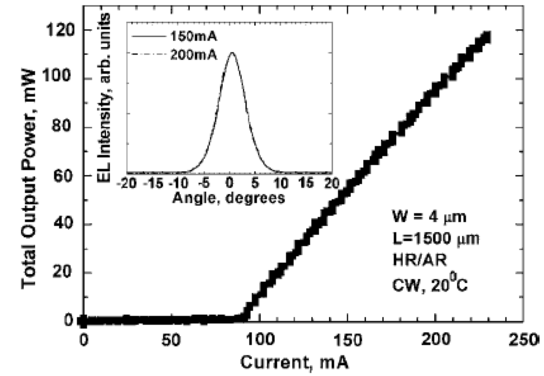
U. Ben-Ami, V. P. Kalosha,[c)] and A. Sharon
V. Mikhelashvili and G. Eisenstein

APPLIED PHYSICS LETTERS 88, 231108 (2006)

120 mW single mode CW at 658 nm, W=4 µm

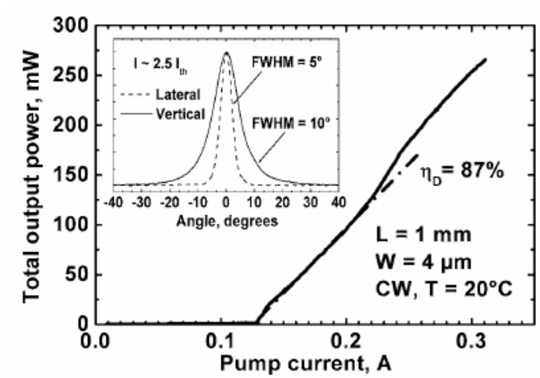


High power GaAs/AlGaAs lasers ($\lambda \sim 850$ nm) with ultranarrow vertical beam divergence

L. Ya. Karachinsky,[a)] I. I. Novikov, Yu. M. Shernyakov, S. M. Kuznetsov, N. Yu. Gordeev, M. V. Maximov, and P. S. Kop'ev
U. Ben-Ami, D. B. Arbiv, and A. Sharon
T. Kettler, K. Posilovic, O. Schulz, V. A. Shchukin,[b)] U. W. Pohl, N. N. Ledentsov,[b)] and D. Bimberg

APPLIED PHYSICS LETTERS 89, 231114 (2006)

250 mW single mode CW at 840 nm, W=4 µm



Content

- Problems of Laser Diodes and Motivation
- Quantum Dot Lasers
- Photonic Band Crystal (PBC) lasers
- 1D PBC lasers
- 2D and 3D PBC Lasers
- **Conclusion**

Conclusion

- **Filamentation problem can be eliminated or reduced by using Quantum Dot active media:**
  - **ultalong expected lifetime >10^6h, 50 mW SM 40^{o}C**
  - **>16W CW without COMD without facet passivation or coating**

- **Photonic Band Crystal (PBC) lasers:**
  - **single mode to broader stripes (higher brightness)**
  - **ultrahigh brightness by lateral field engineering**
  - **reliable**

- **Combining the advantages (QD+PBC) may be important**