



# Highly efficient blue light generation with high brightness semiconductor lasers

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# Overview

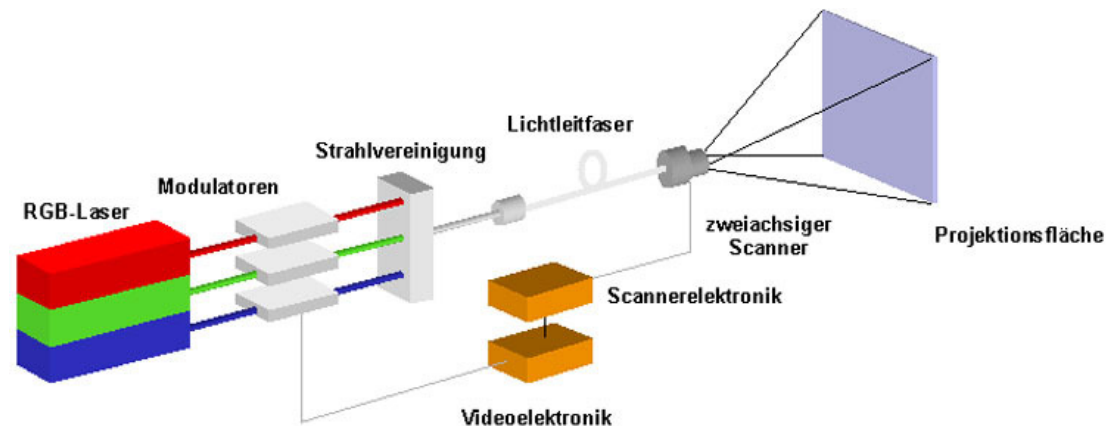
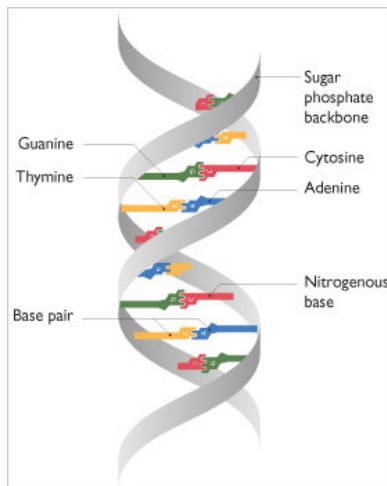


- Motivation
    - Application of blue laser emission
    - Lasers at 488 nm
  - Broad area laser diode
  - V-shaped cavity
    - Experimental results infrared
  - Nonlinear crystal
    - Experimental results SHG
  - Summary
  - Outlook
-

# Motivation



- Applications in the blue-green
  - Spectroscopy
  - Biotechnology
  - Displays
  - Optical data storage



Source: Wellcome Trust Fundation, Jenoptik Laserdisplays, Phillips

# Lasers at 488 nm



- Argon-ion laser
  - Many applications, desired to be replaced
- DPSSL – SHG
  - No lasers at 488 nm
- Fiber lasers
  - 489 nm, low conversion efficiency; Bouchier et. al. Opt. Expr. 13, 6974 (2005)
- OPSL
  - High pump power; Chilla et. al. Proc. SPIE **5332**, 143 (2004)
- Blue diodelasers – GaN
  - Low quantum efficiency; Kojima et. al. Opt. Exp. **15**, 7730 (2007)

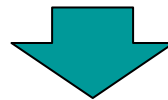


- SHG of infrared diode lasers (976 nm)

# SHG of broad area diode lasers



- RW diode with PPLN
  - 3.6 mW; Birkin et al., Appl. Phys. Lett. **78**, 3172 (2001)
- RW diode FBG with PPLN waveguide
  - 14.8 mW; Ye et al., Opt. Lett. **30**, 73 (2005)
- MOPA with DFB and TA
  - 600 mW; Maiwald, Opt. Lett. **31**, 802 (2006)
  
- Broad area laser diodes (BAL)
  - High output powers, cheap
  - Poor beam quality, broad bandwidth



- BAL in external cavity
  - Increase beam quality and frequency stabilisation

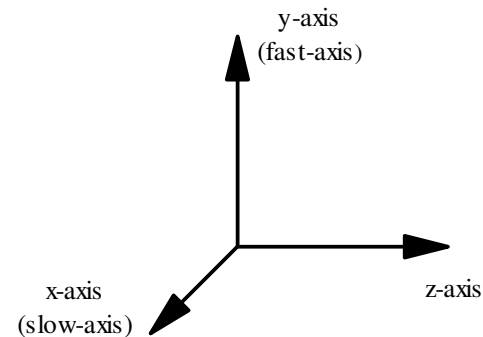
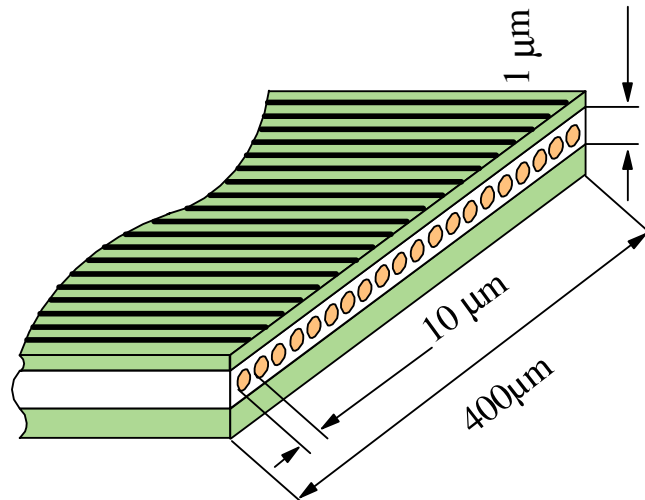
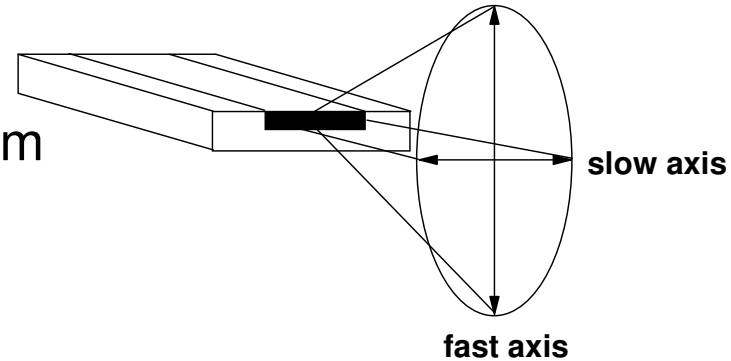


- External cavity-BAL combined with waveguide PP materials

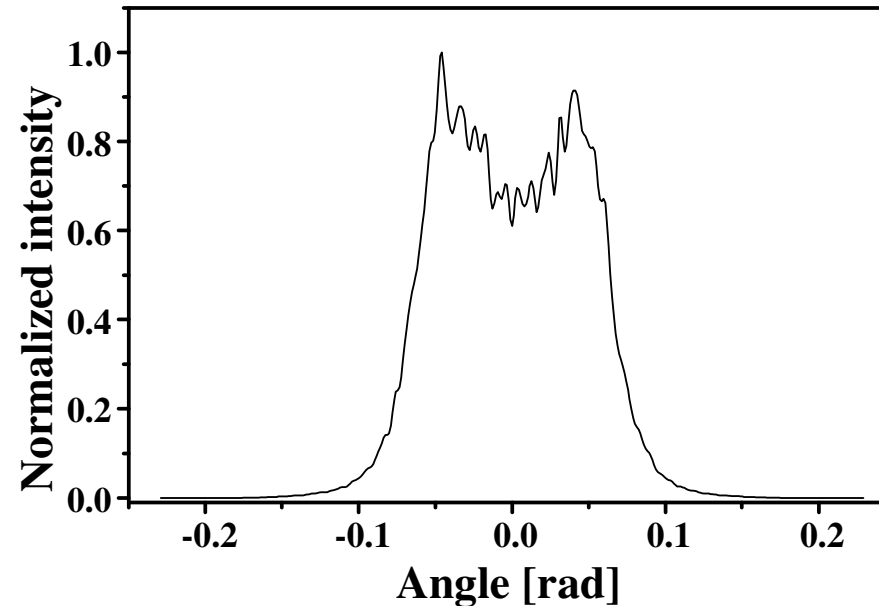
# Broad area laser diode



- M2k 976 nm
  - $P = 2 \text{ W}$
  - $\Delta\lambda = 2 \text{ nm}$
  - Emitting area  $1 \mu\text{m} \times 400 \mu\text{m}$
  - Astigmatic beam
  - $M^2_{\text{slow}} = 60-70$
  - AR – coating ( $R < 10^{-4}$ )
  - Gain guiding (stripe array substructure)

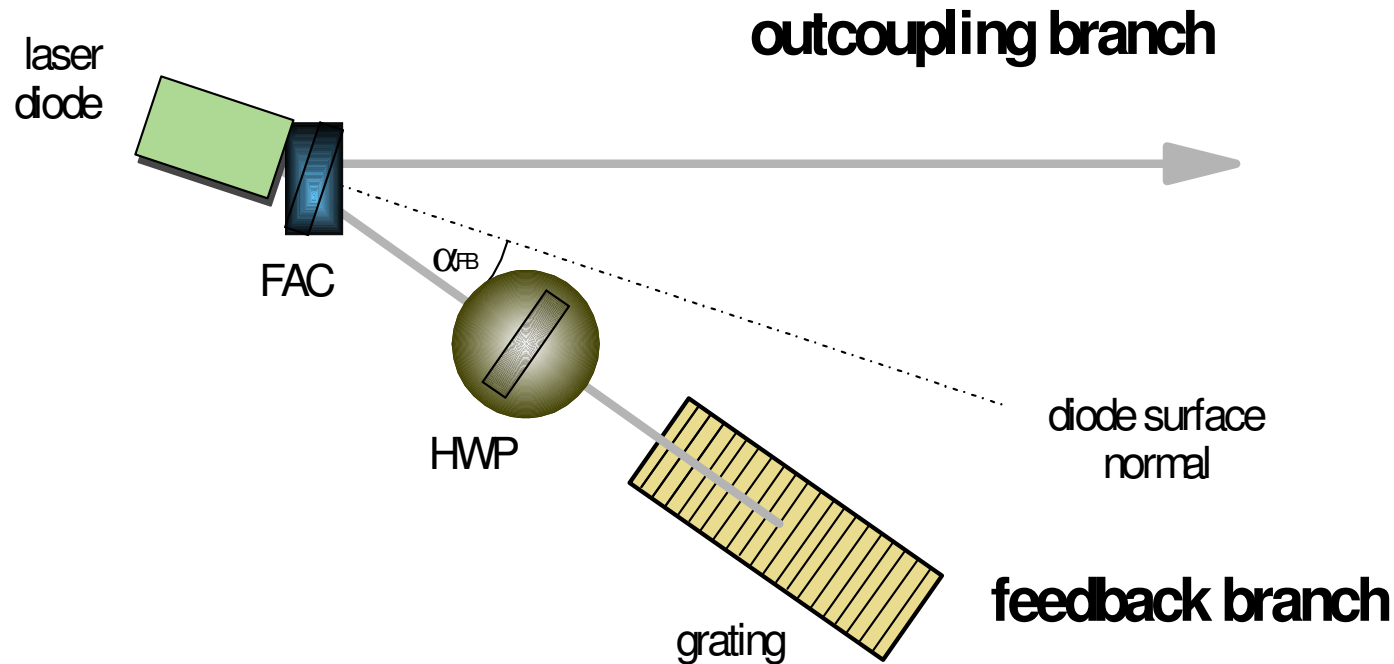


# Broad area laser diode



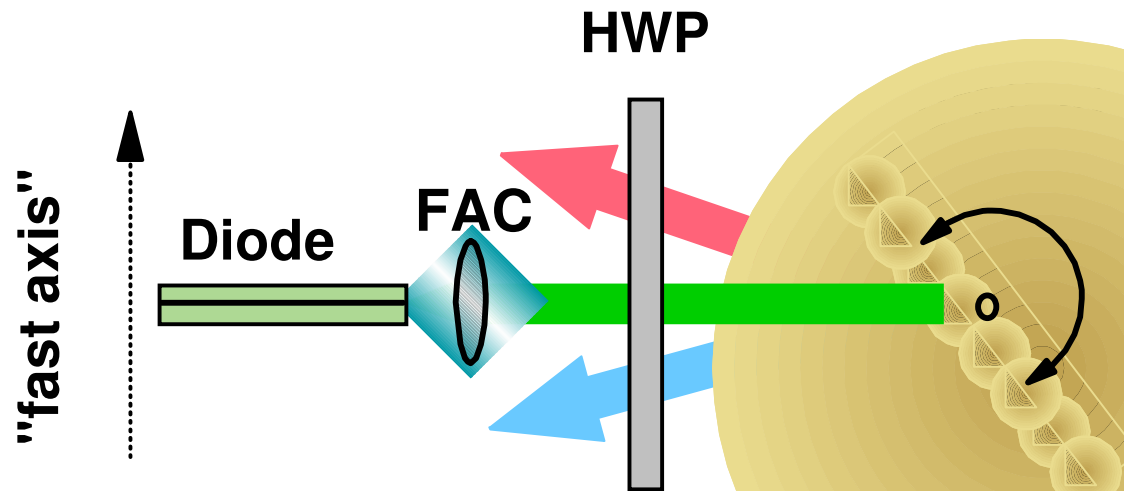
- Farfield pattern of the BAL
  - Double lobe at an angle of 48 mrad
  - Improve beam quality by setting up a V-shaped cavity matching this angle

# Unstable V-shaped cavity



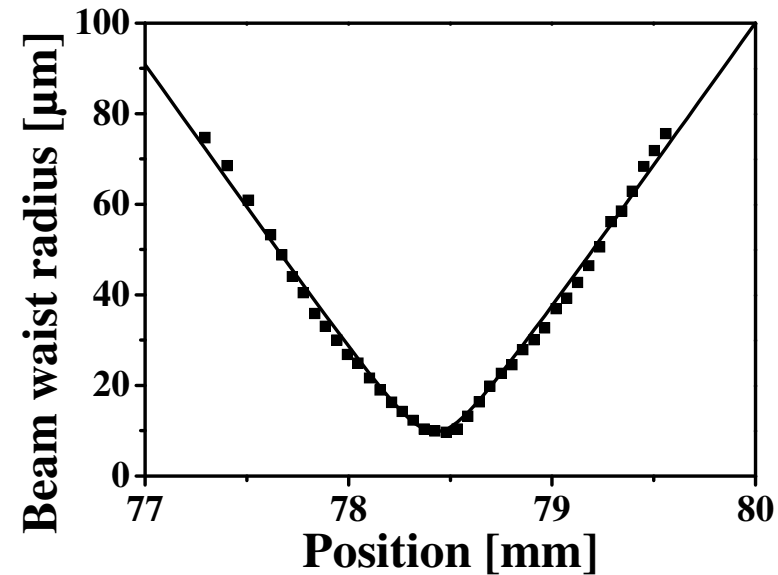
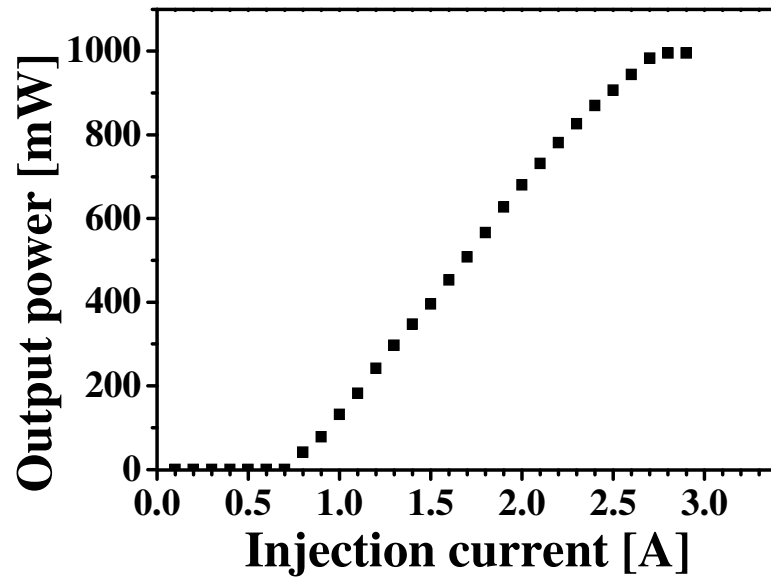
- Cavity consists of only 4 components
  - AR coated laser diode, FAC, HWP, diffraction grating in Littrow configuration
- Grating lines parallel to slow axis (half waveplate)

# Unstable V-shaped cavity



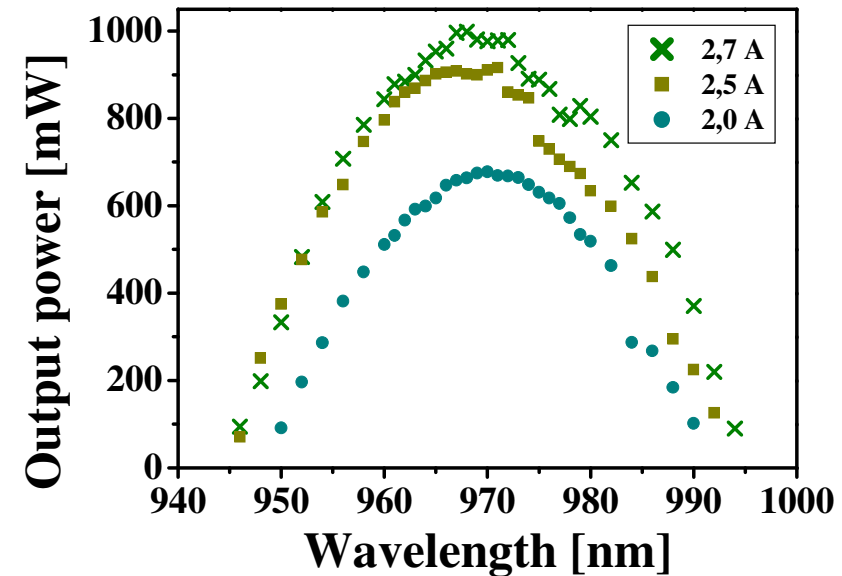
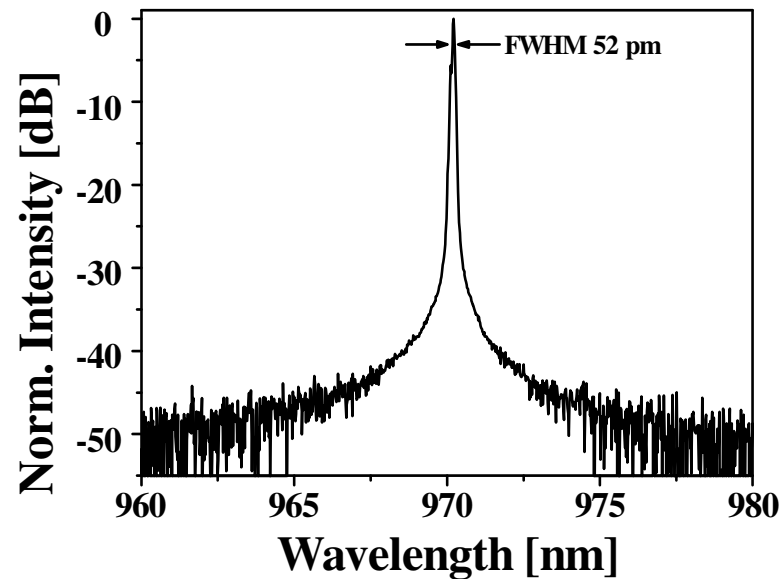
- Frequency selection along the fast axis
- Small aperture of the diode and FAC acts as a monochromator
- tunability

# Experimental results - infrared



- $P = 1 \text{ W}$
- $M^2 < 1.3$  in „slow-axis“
- $M^2 < 1.2$  in „fast-axis“

# Experimental results - infrared



- Band width 50 pm
- Tuning range up to 30 nm (FWHM)

# Summary infrared laser



- Improved beam quality by factor 50
  - $M^2 < 1.3$
- Frequency stabilisation
- Bandwidth narrowing
  - $< 10$  GHz linewidth
- Tunability
  - $> 30$  nm
- High output power
  - 1 W



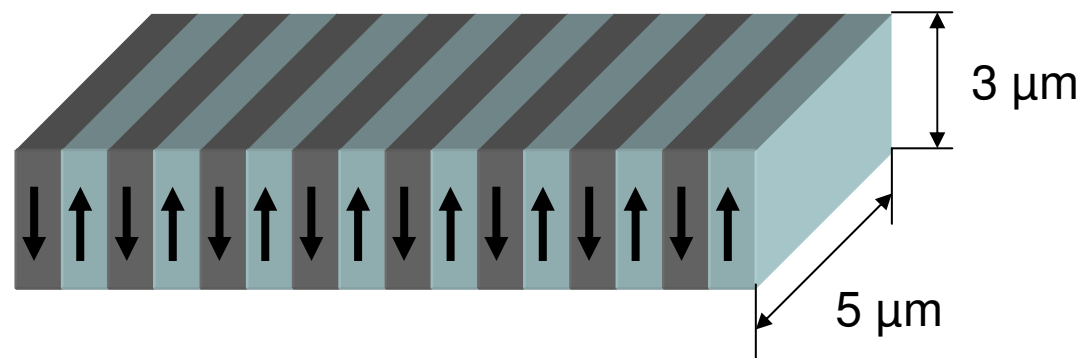
- suitable for nonlinear application



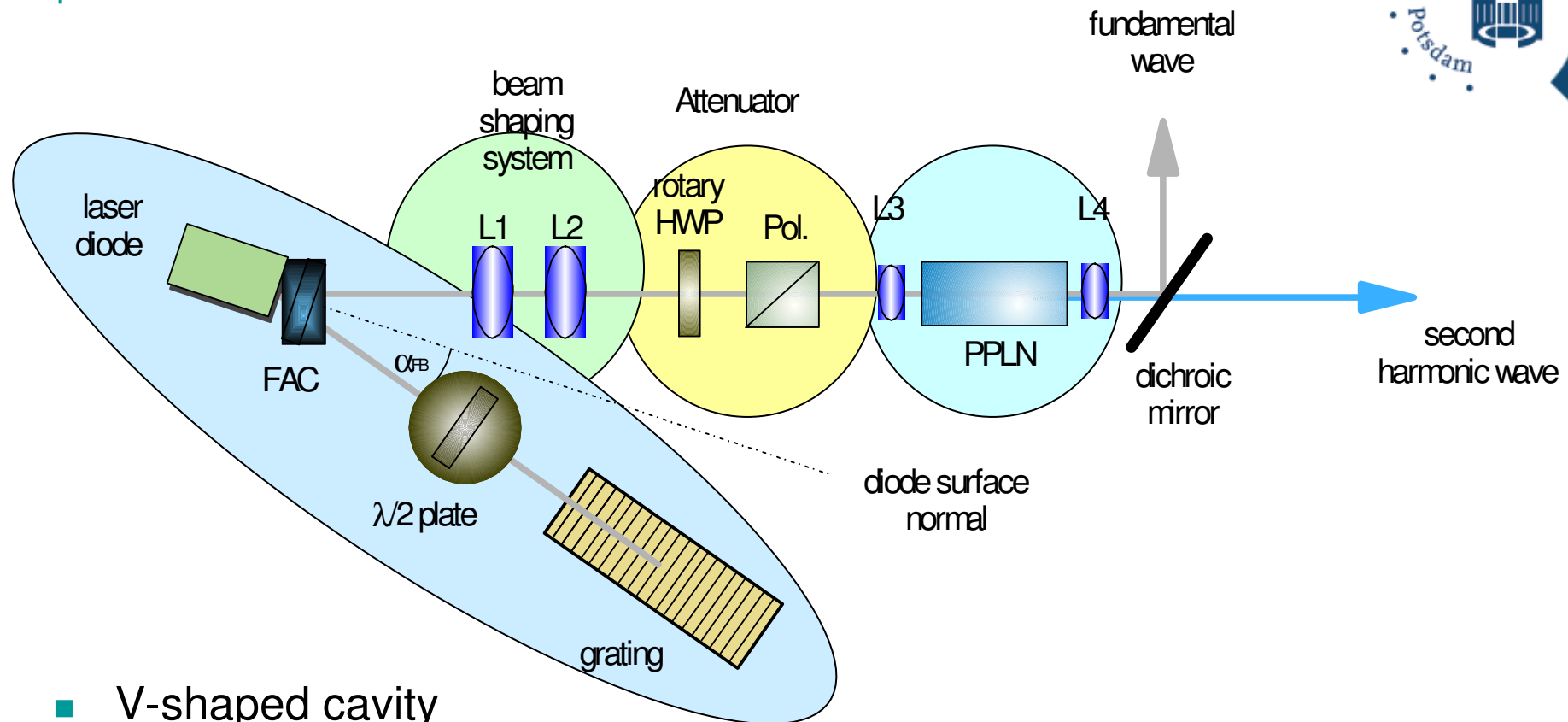
# Nonlinear crystal



- **HC Photonics**
- Periodically poled lithium niobate
- Congruent melt, 3% MgO doping
- Double AR coating 488/976
- 12 mm x 3 mm x 0.5 mm
- 16 waveguide channels
  - 3  $\mu\text{m}$  x 5  $\mu\text{m}$
  - 10 mm length
- QPM grating optimized for SHG 976 nm – 488 nm @ 120°C



# Experimental setup



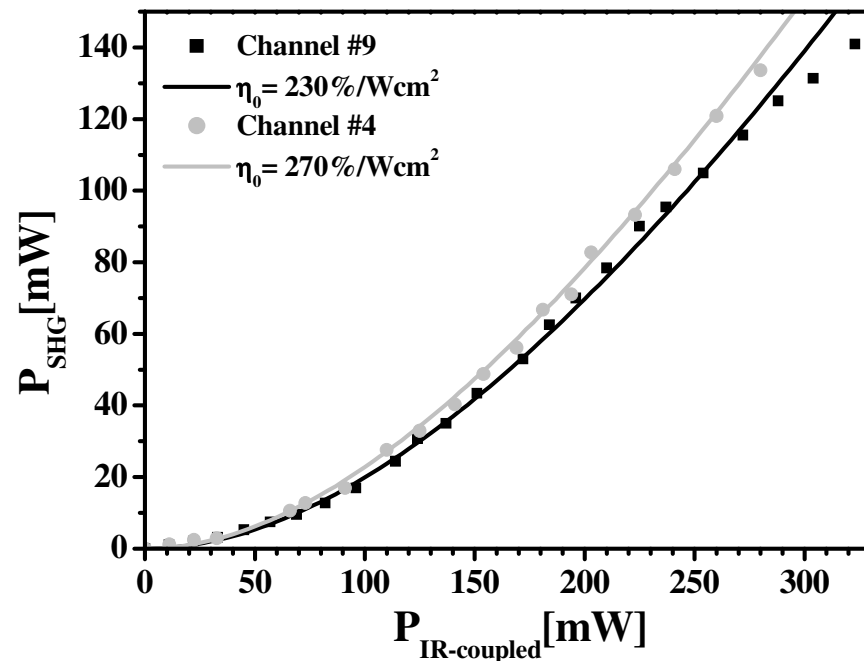
- V-shaped cavity
- Beam shaping lens system (L1, L2) – astigmatic correction
- Attenuator (adjust output power)
- aspherical lenses (L3, L4)
- Size: 150 mm x 200 mm (only 40 mm cavity length)

**Unstable V-shaped cavity**

# Experimental results - SHG

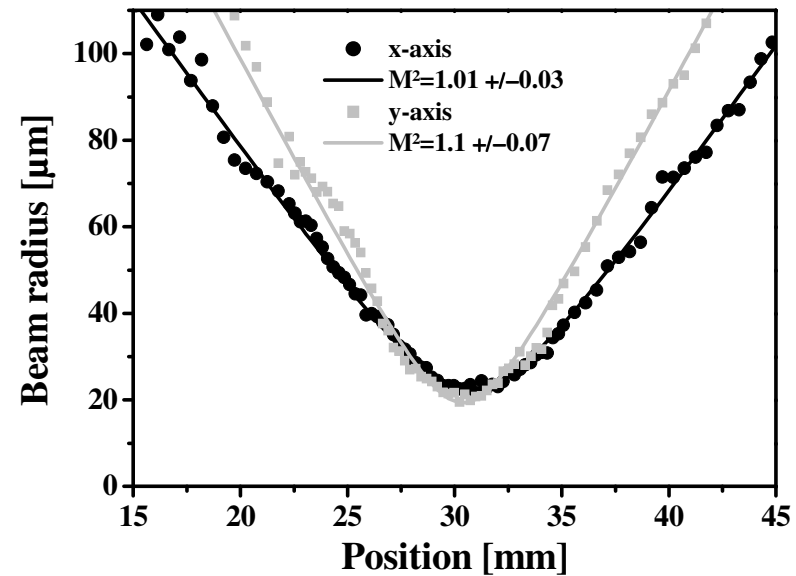
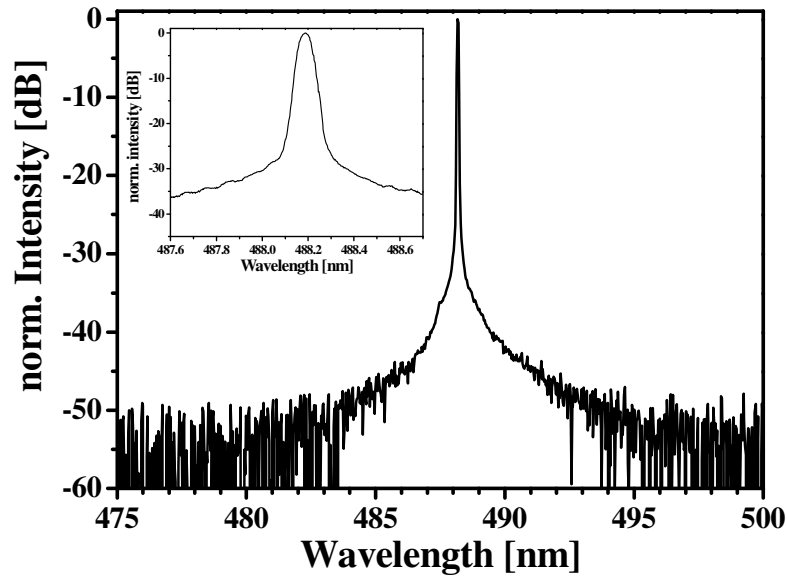


- Fixed injection current  $I = 1.8 \text{ A}$
- $P_{\text{IR}} = 500 \text{ mW}$
- $P_{\text{coupled}} = 320 \text{ mW}$
- Coupling efficiency 64%



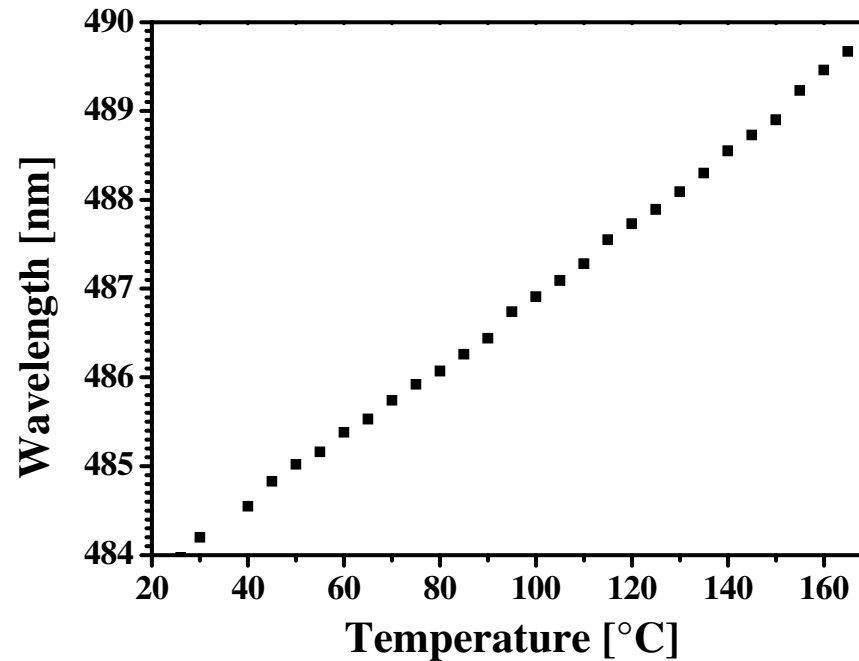
- $P_{\text{SHG}} = 142 \text{ mW}$
- 47 % conversion efficiency
- Normalized conversion efficiency
  - $\eta > 230 \text{ %/Wcm}^2$

# Experimental results - SHG



- Band width 51 pm
- $M^2 < 1.1$  for both axes

# Experimental results - SHG



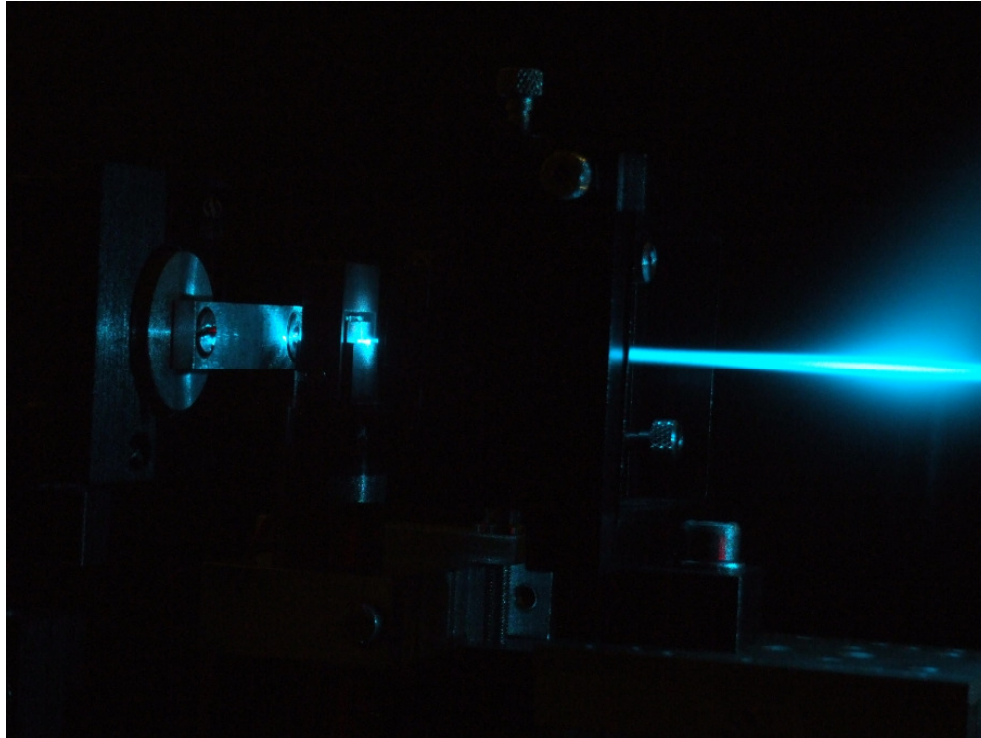
- QPM wavelength
- 5 nm tuning range by changing the crystal temperature

# Summary



- V-shaped unstable cavity 976 nm
    - Beam quality of BAL improved by factor 50
      - $M^2 < 1.3$
    - 1 W tunable light @ 976 nm
      - 30 nm tuning range
      - narrow bandwidth
  - SHG with a PPLN waveguide crystal
    - 142 mW @ 488 nm
      - 47 % conversion efficiency
      - $\eta = 270 \text{ \%}/\text{Wcm}^2$
    - 5 nm tuning range
    - Wall plug efficiency 5.9%
    - Size 150 x 200 mm<sup>2</sup>
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# Outlook - Acknowledgments



- Smaller size
  - Beam shaping optics
- Higher coupling efficiency
  - More infrared incident light
- New external cavity concepts

**Thank you for your attention!**

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