Frequency Doubling

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Outline of the talk

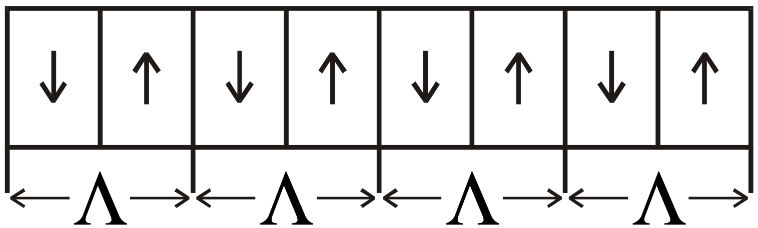
- Quasi phase matching
- Schemes for frequency doubling
- Conversion efficiency
- Focusing
- Acceptance bandwidths
- Single-pass SHG
- External cavity SHG
- Experimental results using different lasers
- Conclusion
- Acknowledgements

Quasi phase matching

- The generated second harmonic is sum of contributions from the entire crystal
- Birefringent phase matching

- Quasi phase matching

  largest nonlinear tensor elements can be used

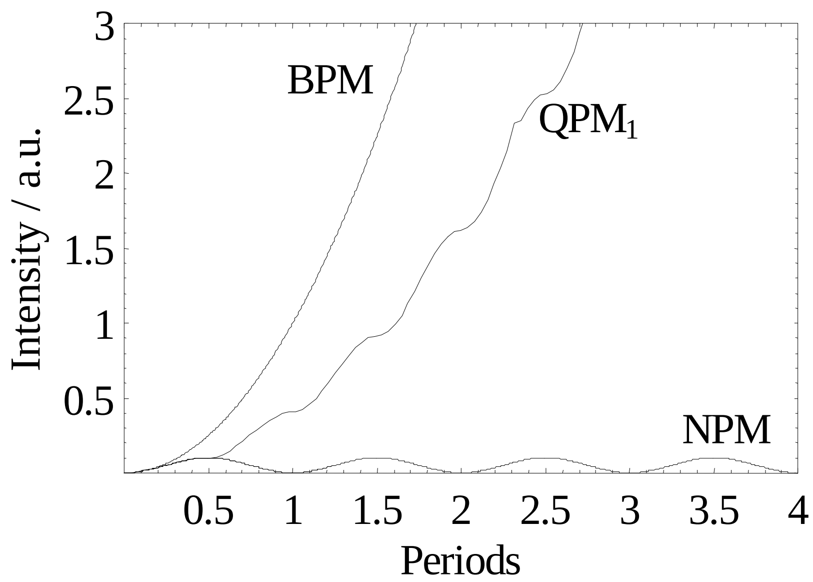


- No phase matching $n_\omega \neq n_{2\omega}$

$$E_{2\omega}(L) \propto \int_0^L E_\omega^2 d(z) \exp\left[i(k_{2\omega} - 2k_\omega)z\right] dz$$

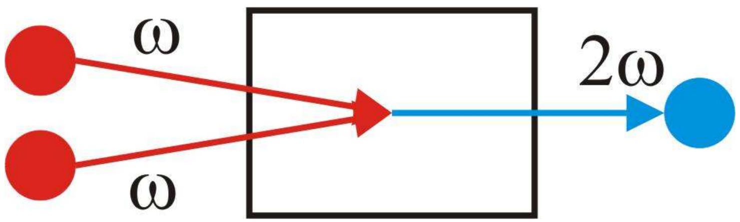
$$\frac{2\pi n_\omega}{\lambda_\omega} + \frac{2\pi n_\omega}{\lambda_\omega} = \frac{2\pi n_{2\omega}}{\lambda_{2\omega}} \Leftrightarrow n_\omega = n_{2\omega}$$

$$k_{2\omega} - 2k_\omega - \frac{2\pi}{\Lambda} = 0 \quad , \quad \Lambda = 2l_c$$

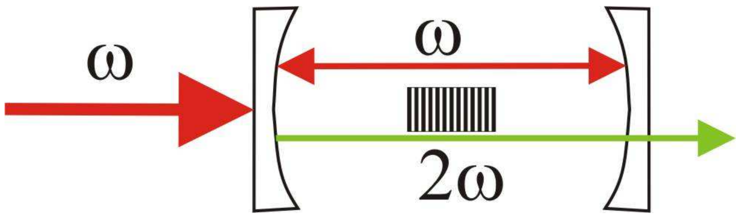


Schemes for frequency doubling

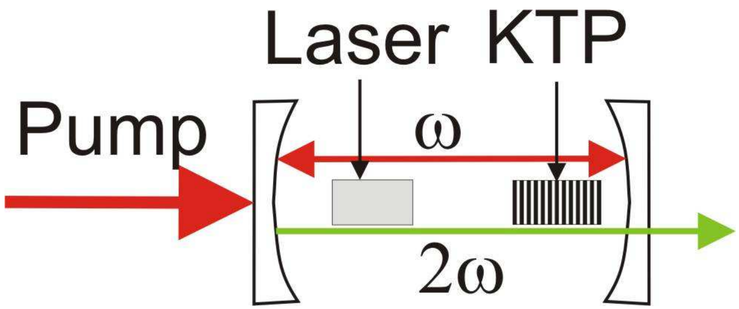
- Single-pass SHG



- External cavity SHG



- Intracavity SHG



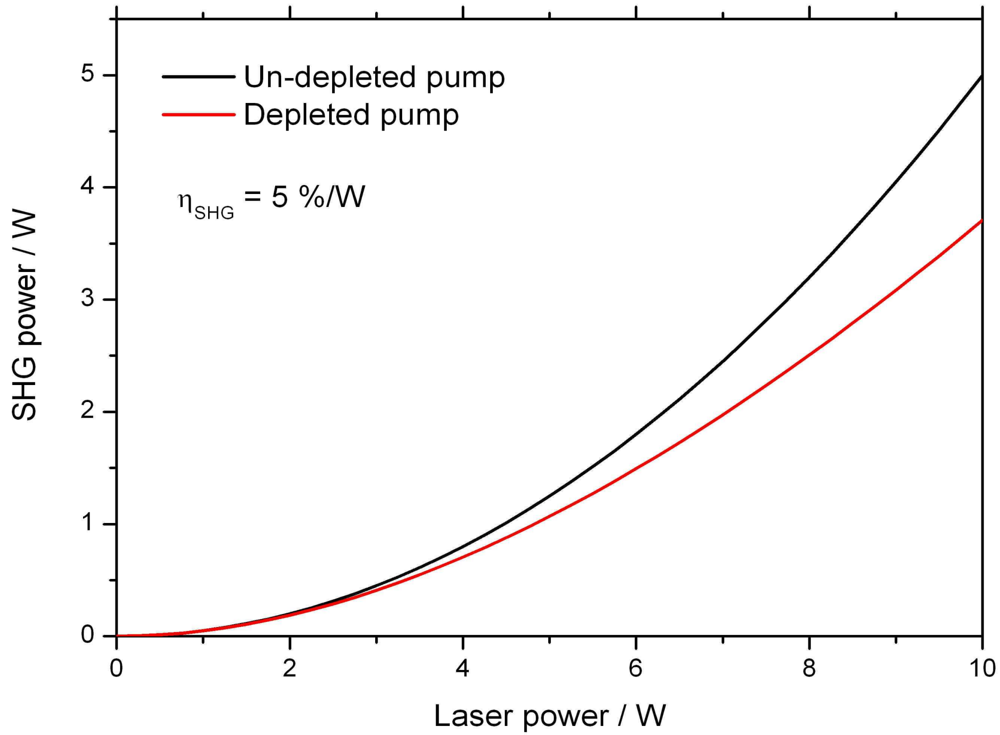
Conversion efficiency

$$P_{2\omega} = \eta_{SHG} P_{\omega}^2$$

$$P_{2\omega} = P_{\omega} \tanh^2 \sqrt{\eta_{SHG} P_{\omega}} \qquad (Including\ \ pump\ depletion)$$

Thermal effects in the nonlinear material will limit the conversion efficiency due to phase mismatch through the crystal.

Common crystals:
LBO, BBO, BiBO, KTP, $LiNbO_3$, PPKTP, PPLN
η_{SHG} = 0.01 – 2 %/W·cm



Focusing – plane waves

$$\eta_{SHG} = \frac{P_{2\omega}}{P_{\omega}} = \frac{2\omega^2 d^2}{n^3 \varepsilon_0 c^3} \cdot \frac{\sin^2\left(\frac{\Delta k l}{2}\right)}{\left(\frac{\Delta k l}{2}\right)^2} \cdot \frac{P_{\omega} l^2}{A} \propto \frac{l^2}{A}$$

For high efficiency

- $\Delta k = 0$
- Small beam area (A) → plane wave analysis not accurate!

A more accurate analysis assumes focused Gaussian beams.

Focusing – Gaussian beams

$$\eta_{SHG} = \frac{P_{2\omega}}{P_\omega} = \frac{2\omega^3 d^2}{\pi n^2 \varepsilon_0 c^4} \cdot h_{BK}(\xi,\sigma) \cdot P_\omega \cdot l \propto l$$

Focusing parameter:

$$\xi = \frac{\lambda L}{2\pi n w_0^2}$$

Normalized phase mismatch:

$$\sigma = z_0 \Delta k$$

SHG focusing function:

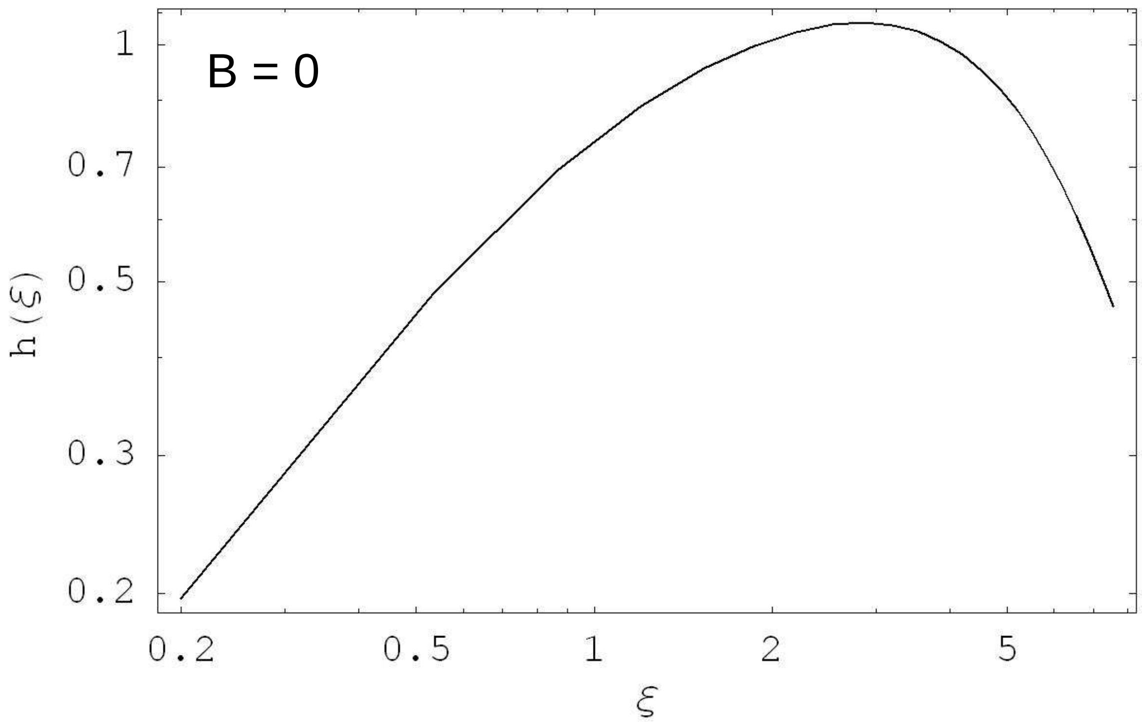
$$h_{BK}(\sigma, B, \kappa, \xi, \mu)$$

Optimized focusing is a tradeoff between
high intensity and ***long interaction length***

[1]*G. D. Boyd and D. A. Kleinman, J. Appl. Phys.* ***39****, 3597, 1968.*

Focusing – Gaussian beams

- Optimal focusing: ξ = 2.84, h = 1.068.
- Confocal focusing: ξ = 1, h = 0.8.
- Weak focusing: ξ << 1; tight focusing: ξ >> 1.
- Note that **Δk ≠ 0**.



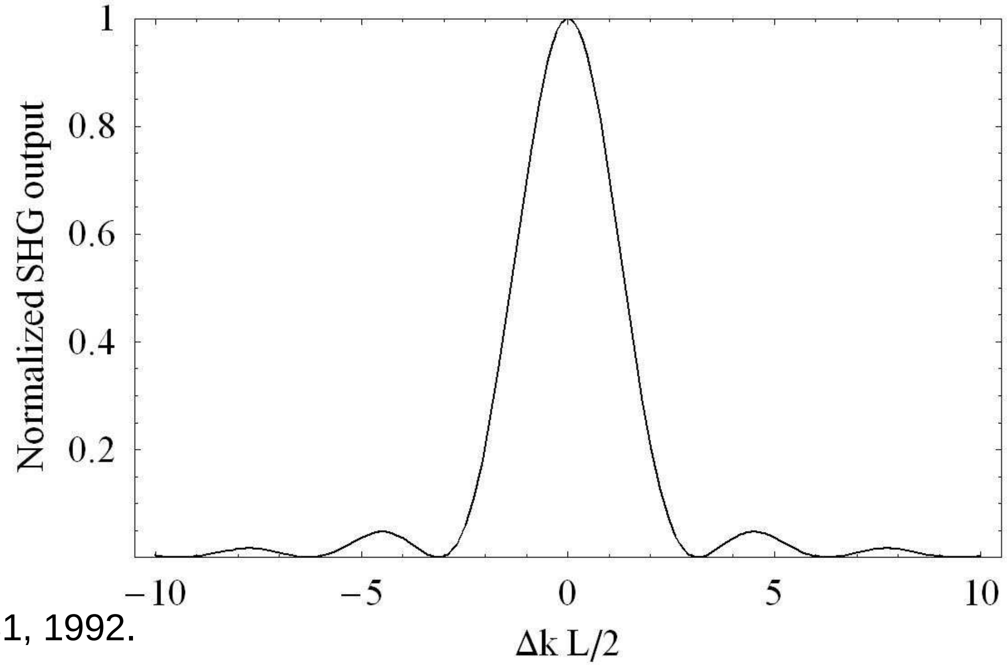
Acceptance bandwidths

The conversion efficiency will depend on the deviation from perfect phase matching. Three parameters will be important –

$$\eta_{SHG} \propto \sin c^2\left(\frac{\Delta k \cdot L}{2}\right) = \frac{\sin^2\left(\frac{\Delta k \cdot L}{2}\right)}{\left(\frac{\Delta k \cdot L}{2}\right)^2}$$

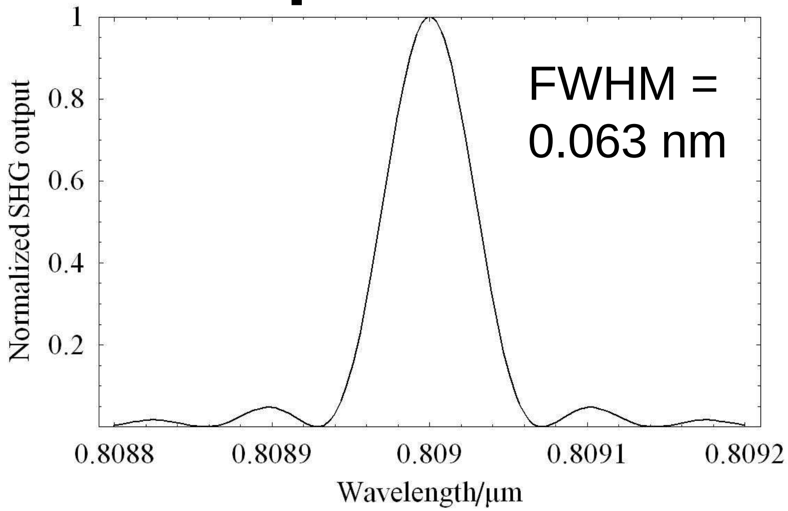
- Wavelength
- Temperature
- Propagation angle

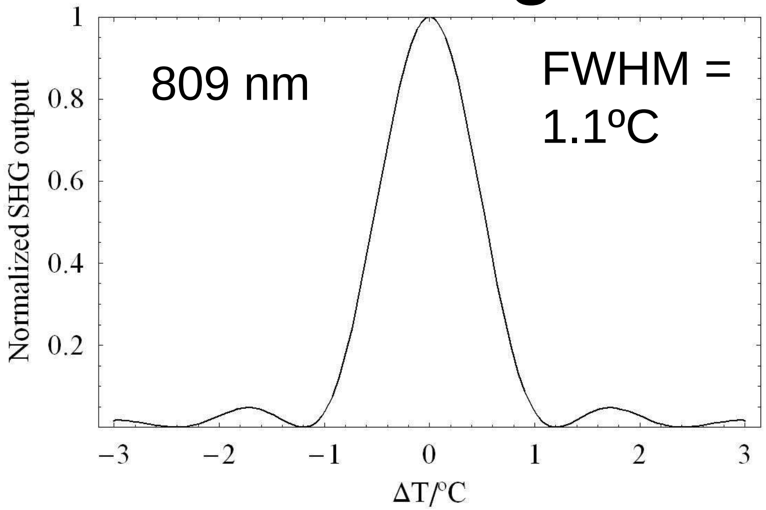
A large deviation from phase matching will strongly reduce conversion efficiency. High power and/or strong thermal effects will alter the acceptance bandwidths.

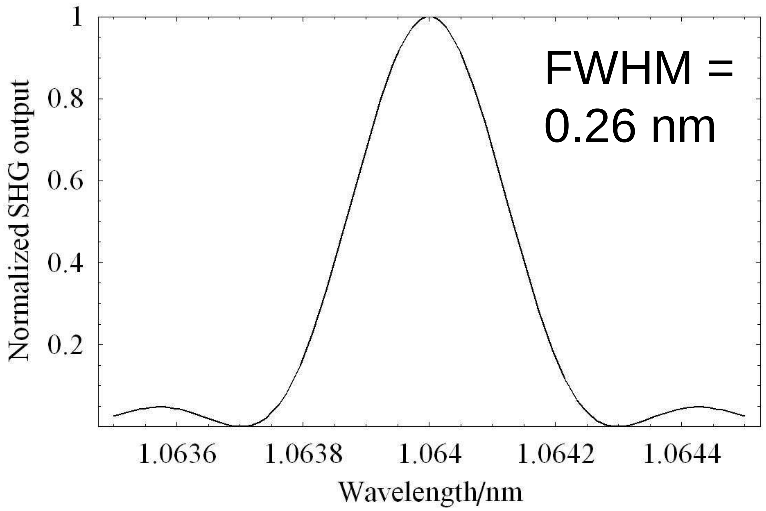


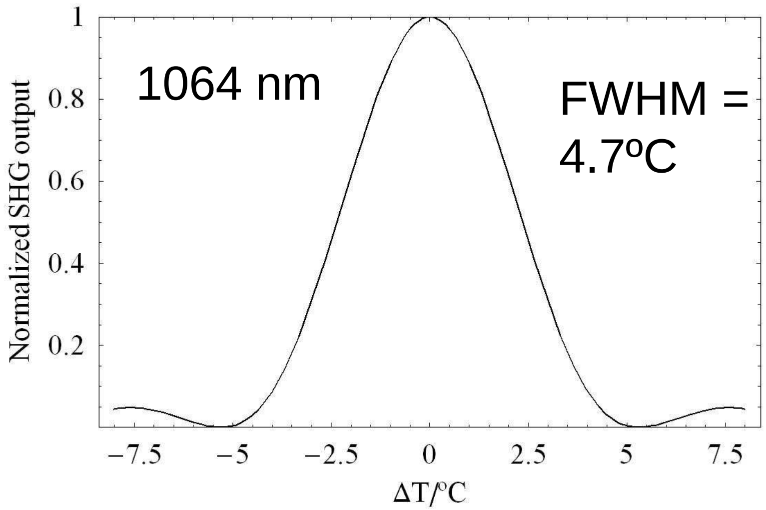
[1]M. M. Fejer *et al*, IEEE J. Quant. Electron. **28**, 2631, 1992.

Acceptance bandwidths – 10 mm long PPKTP

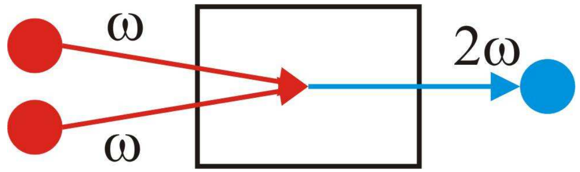




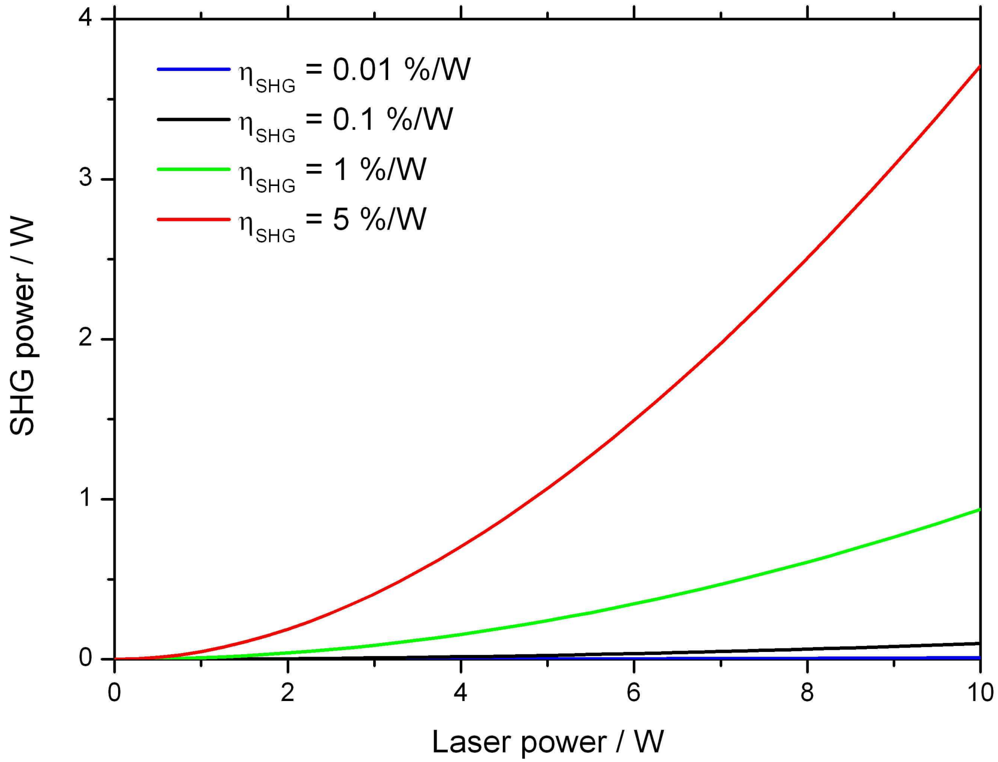




Single-pass SHG

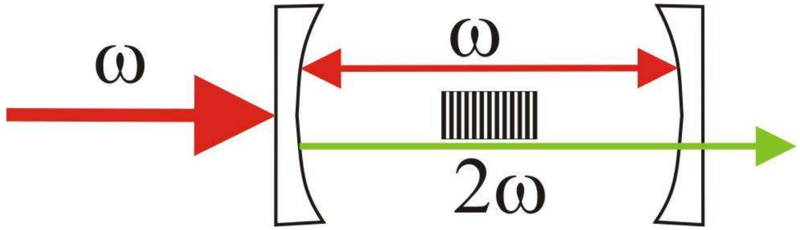


Good single-pass conversion efficiency is achieved using efficient nonlinear materials, optimal focusing and perfect phase matching.



$$P_{2\omega} = P_{\omega} \tanh \sqrt{\eta_{SHG} P_{\omega}}$$

External cavity SHG



- By enhancing the power using a resonant cavity, the SHG power and efficiency can increase dramatically.

$$P_{\omega,circ} = \frac{1-R}{(1-\sqrt{R(1-L)})^2} P_{\omega,in}$$

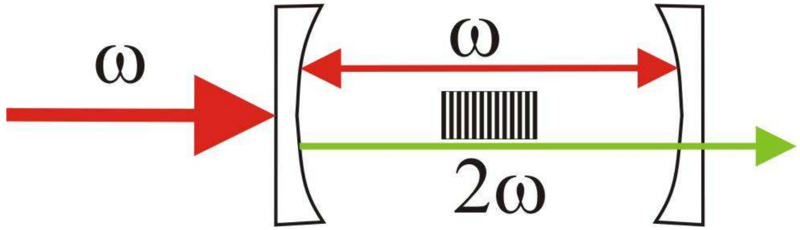
- Assume R = 1 - L = 0.99 →

  P_{circ} = 100 P_{in},

  P_{SHG} = 10000 $P_{SHG,single\text{-}pass}$

- Frequency locking is required to keep the laser at the cavity resonance or vice versa.

External cavity SHG

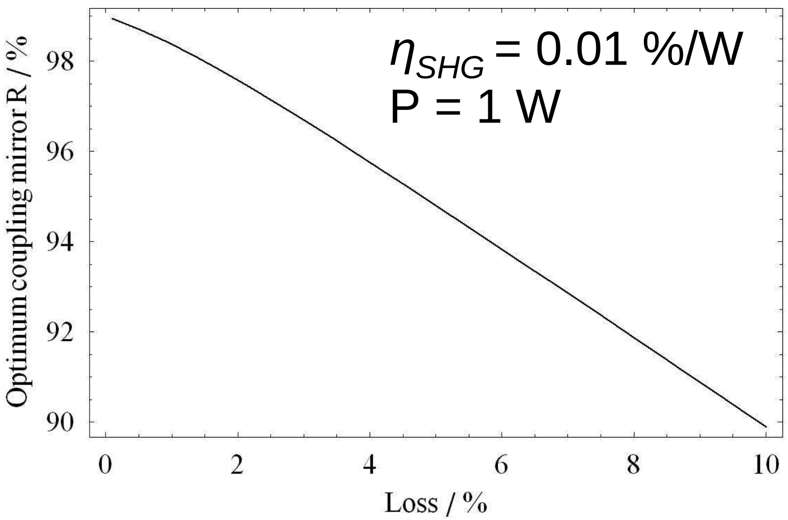


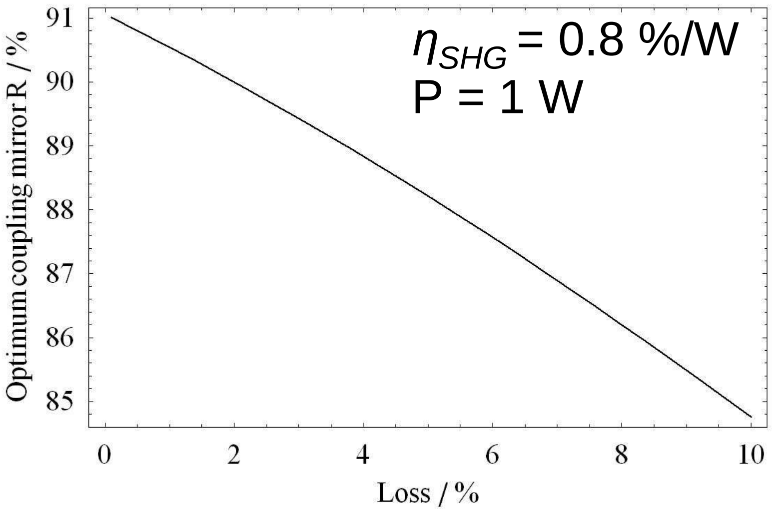
- Optimum coupling mirror depends on non-linearity and losses

$$R_{opt} = 1 - Loss - \sqrt{\frac{Loss^2}{4} + \eta_{SHG} P_\omega^{in}}$$

- Efficiency Γ vs. η_{SHG} and losses

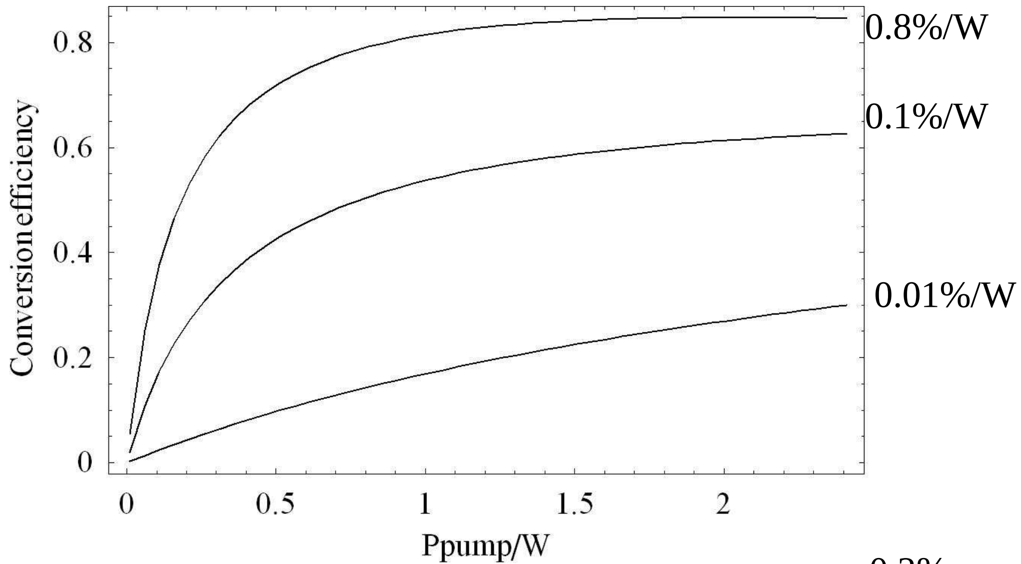
$$\sqrt{\Gamma}\left[2 - \sqrt{R_{input}}\left(2 - Loss - \eta_{SHG}\sqrt{\frac{\Gamma P_\omega^{in}}{\eta_{SHG}}}\right)\right]^2 - 4(1 - R_{input})\sqrt{\eta_{SHG} P_\omega^{in}} = 0$$



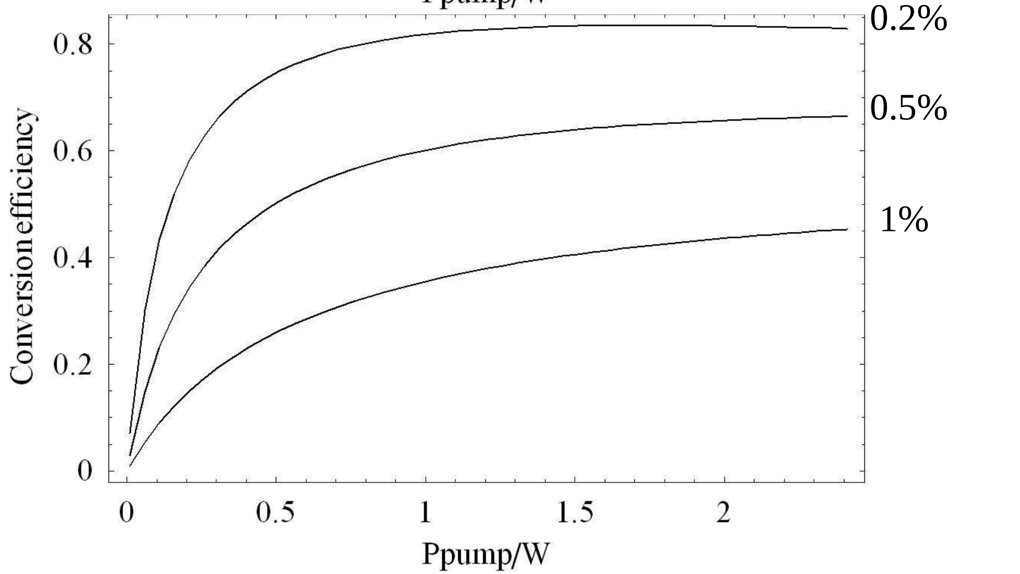


External cavity SHG

Efficiency vs. η_{SHG} in the crystal.
η_{SHG} = 0.01 %/W, 0.1 %/W
and 0.8 %/W.
Losses = 2 %.
Optimized coupling mirror.

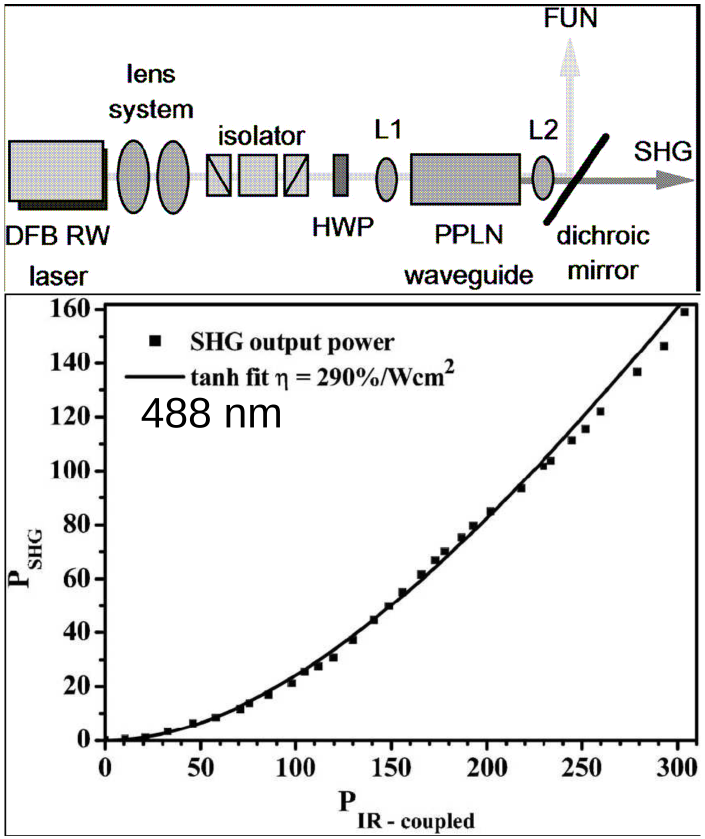


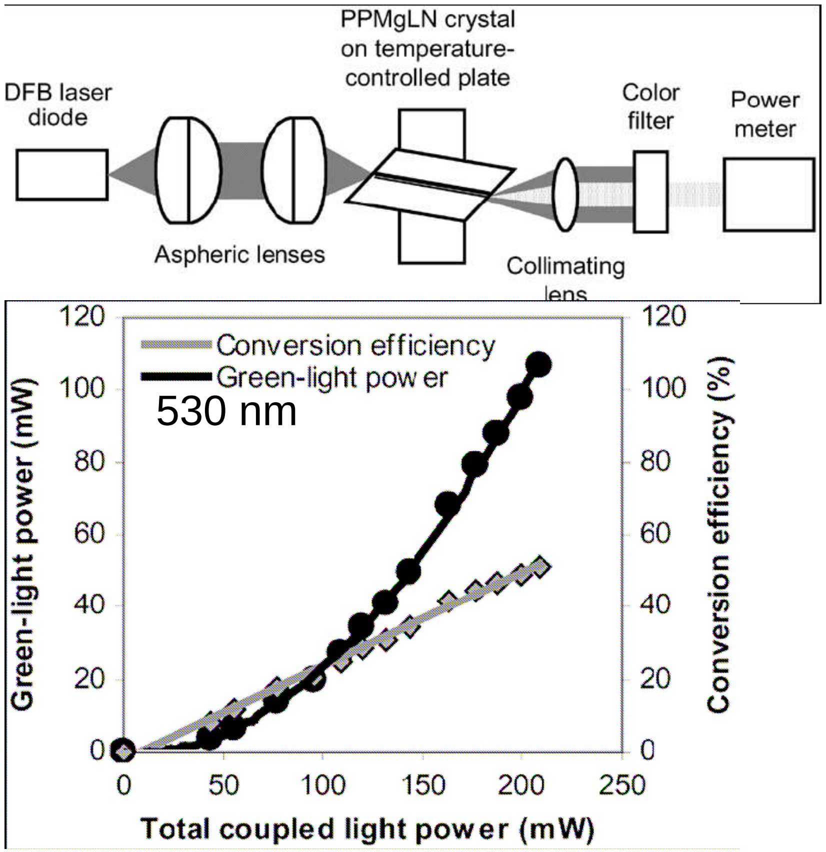
Efficiency vs. losses in the cavity.
η_{SHG} = 0.01 %/W.
Losses = 0.2 %, 0.5 % and 1 %.
R = 99 % coupling mirror.



Experimental results

- SHG of single-mode diode lasers in nonlinear waveguides

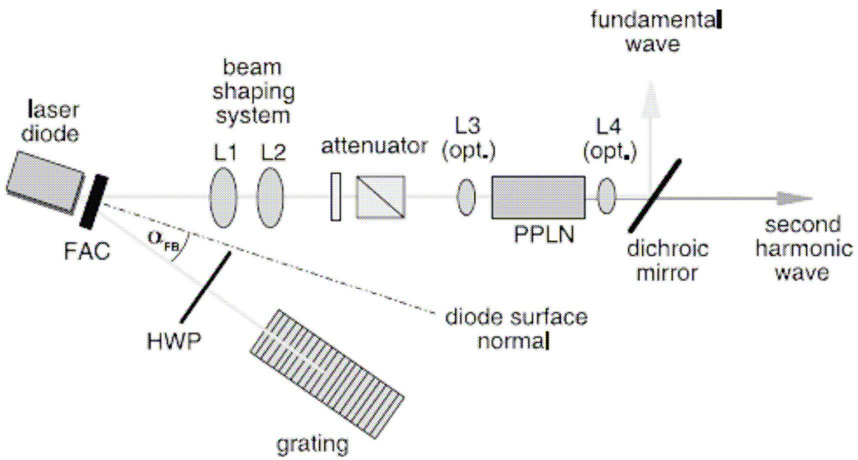


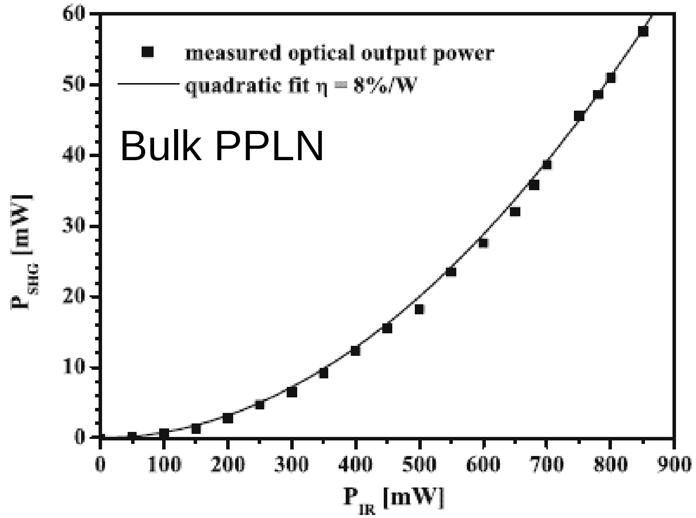


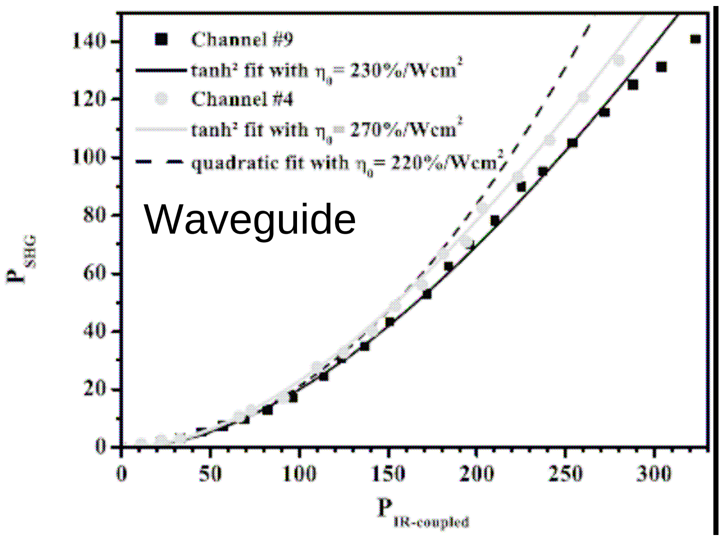
[1]A. Jechow *et al*, Opt. Lett. **32**, 3035, 2007.
[2]H. K. Nguyen *et al*, IEEE Phot. Technol. Lett. **18**, 682, 2006.

Experimental results

- SHG of broad area diode lasers
- 976 nm SHG to 488 nm



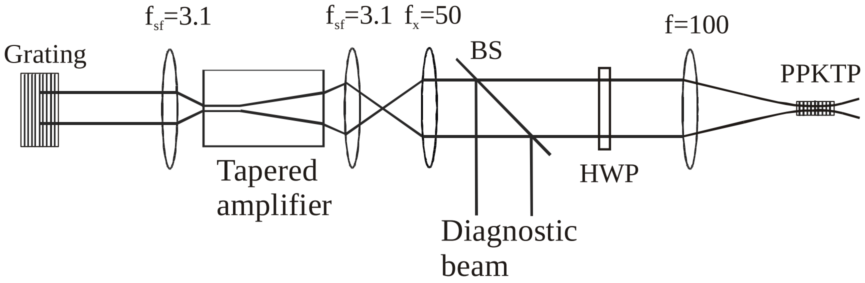


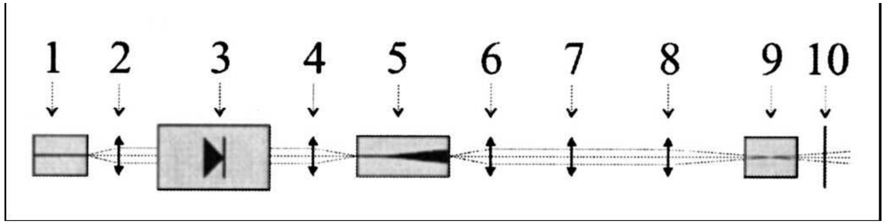


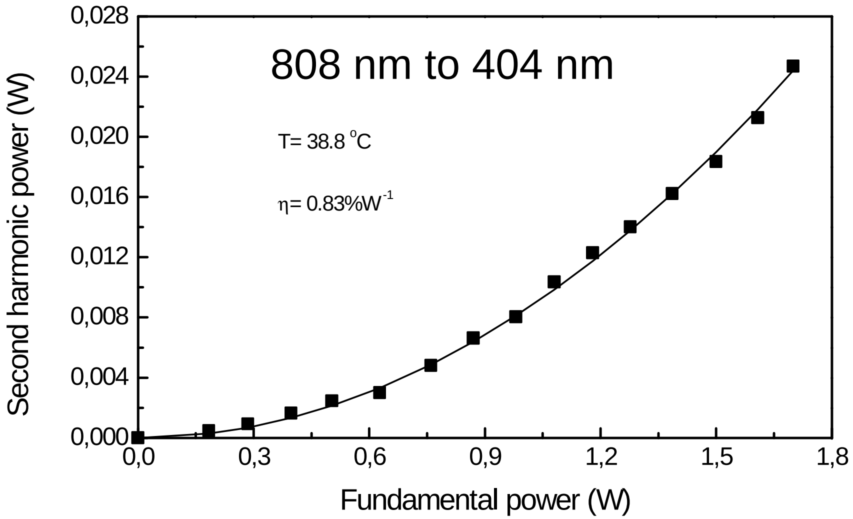
[1]A. Jechow *et al*, Appl. Phys. B, **89**, 507, 2007.

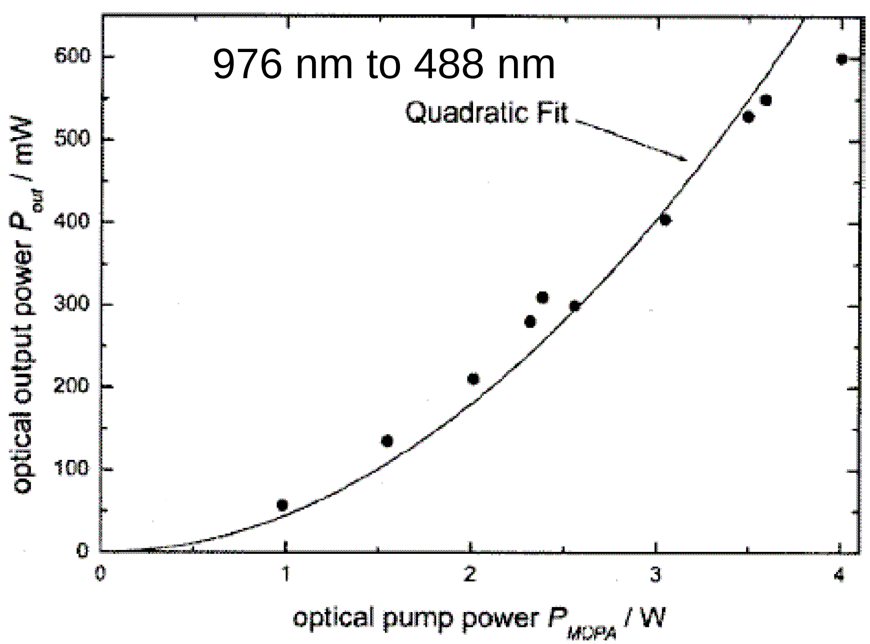
Experimental results

- SHG of tapered lasers – single-pass





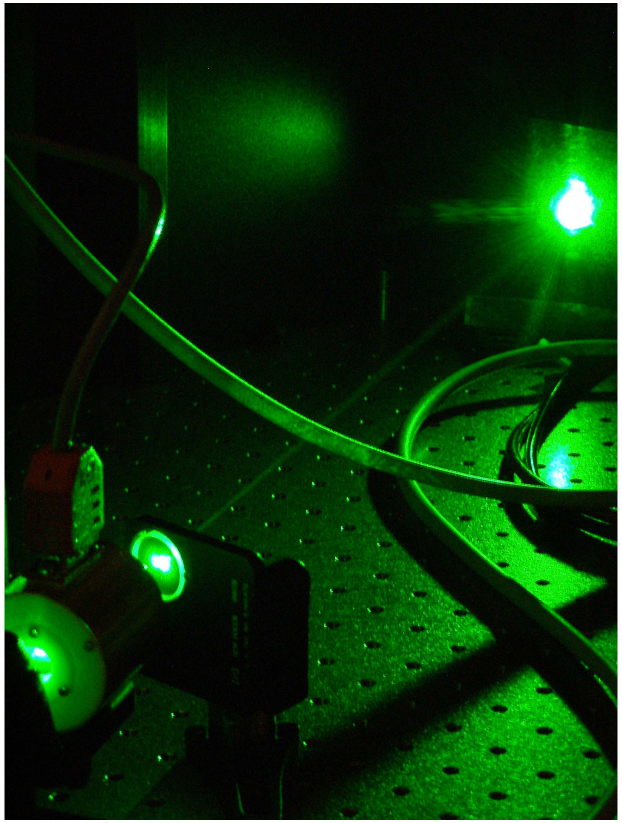


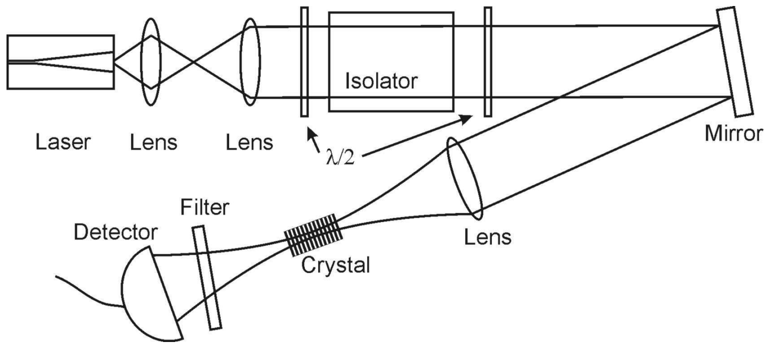


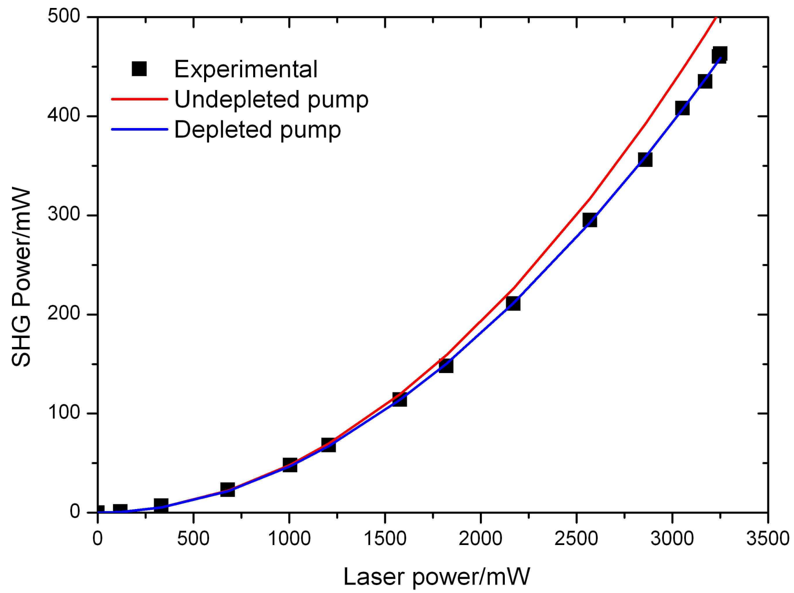
[1]M. Chi *et al*, Opt. Express, **13**, 10589, 2005.
[2]M. Maiwald *et al*, Opt. Lett. **31**, 802, 2006.

Experimental results

- SHG of tapered lasers – single-pass
- 1062 nm DBR tapered laser (FBH)

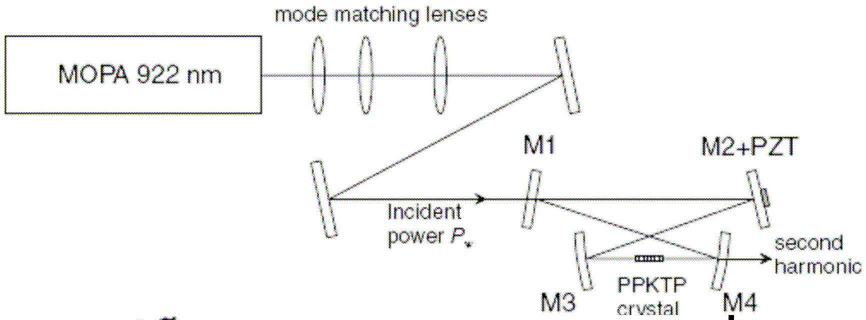


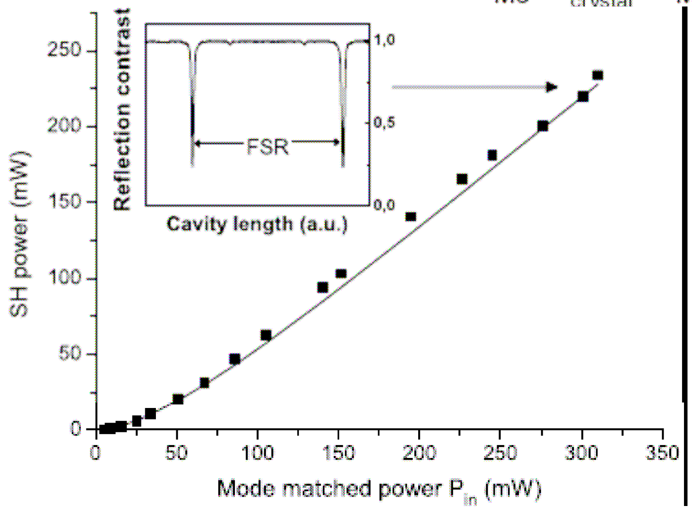


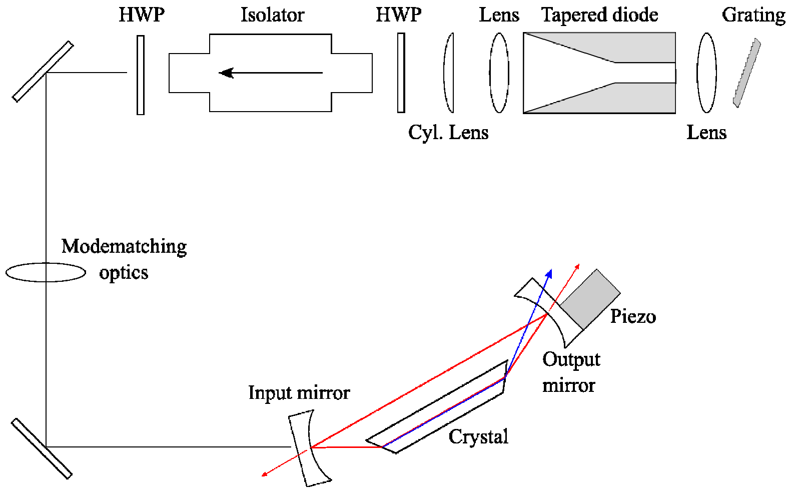


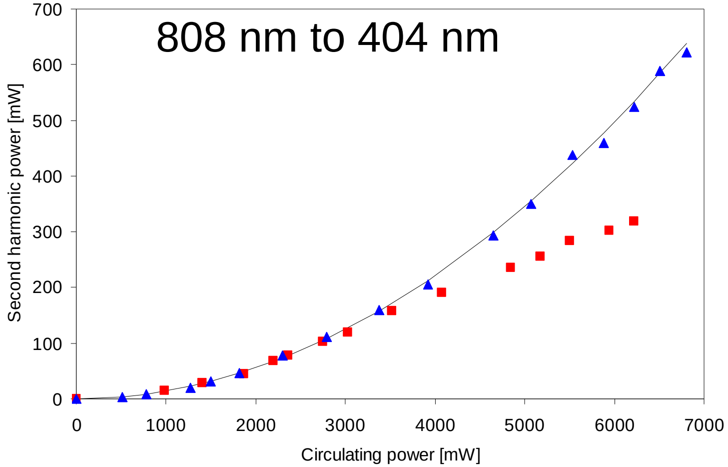
Experimental results

- SHG of tapered lasers – external cavity SHG



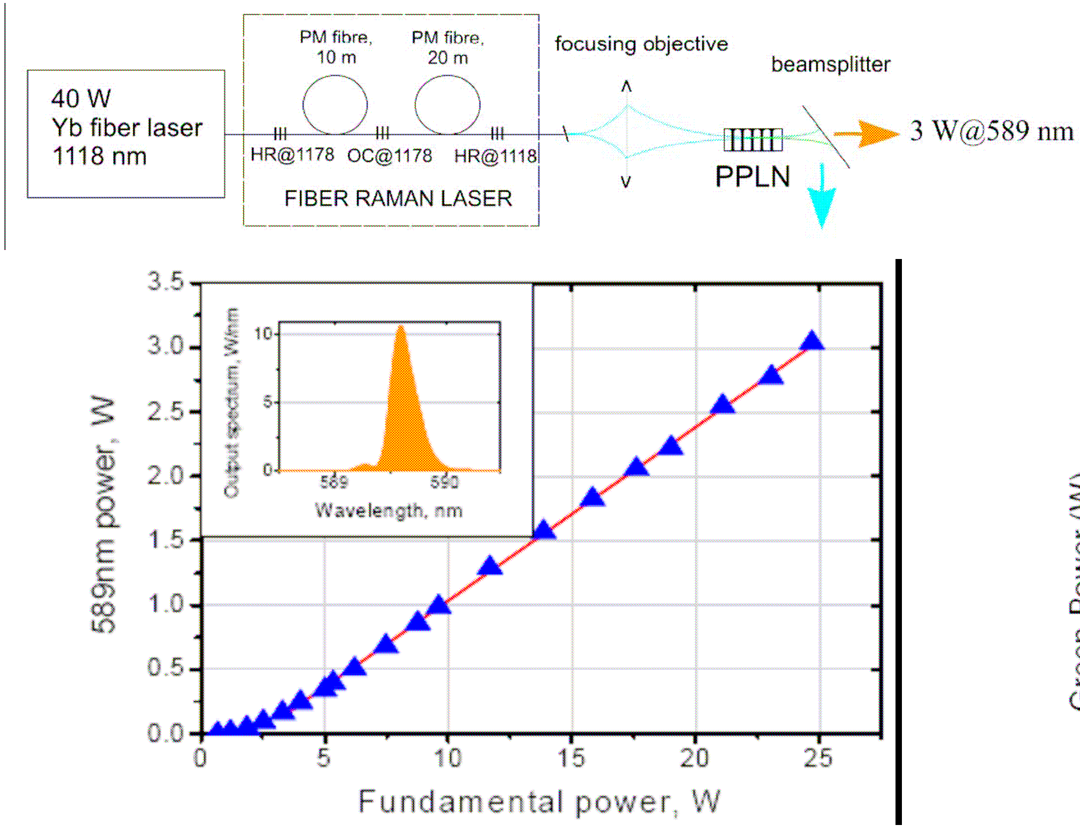


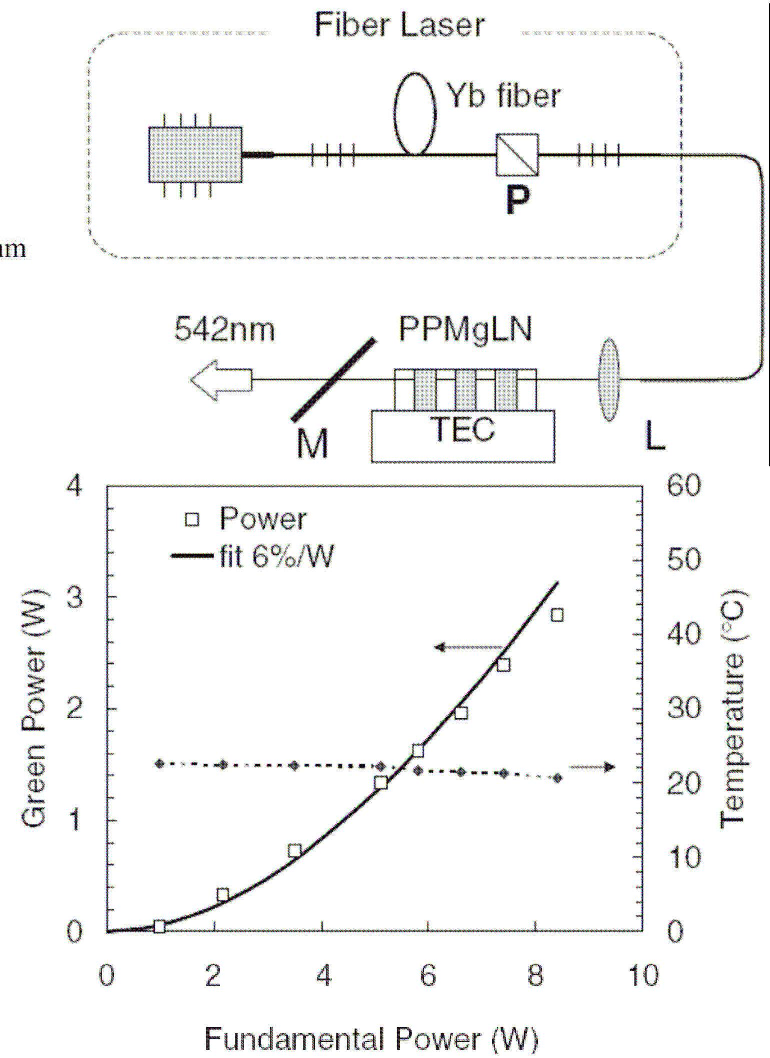




[1]R. Le Targat *et al*, Opt. Com. **247**, 471, 2005.
[2]J. H. Lundeman *et al*, Opt. Express **16**, 2486, 2008.

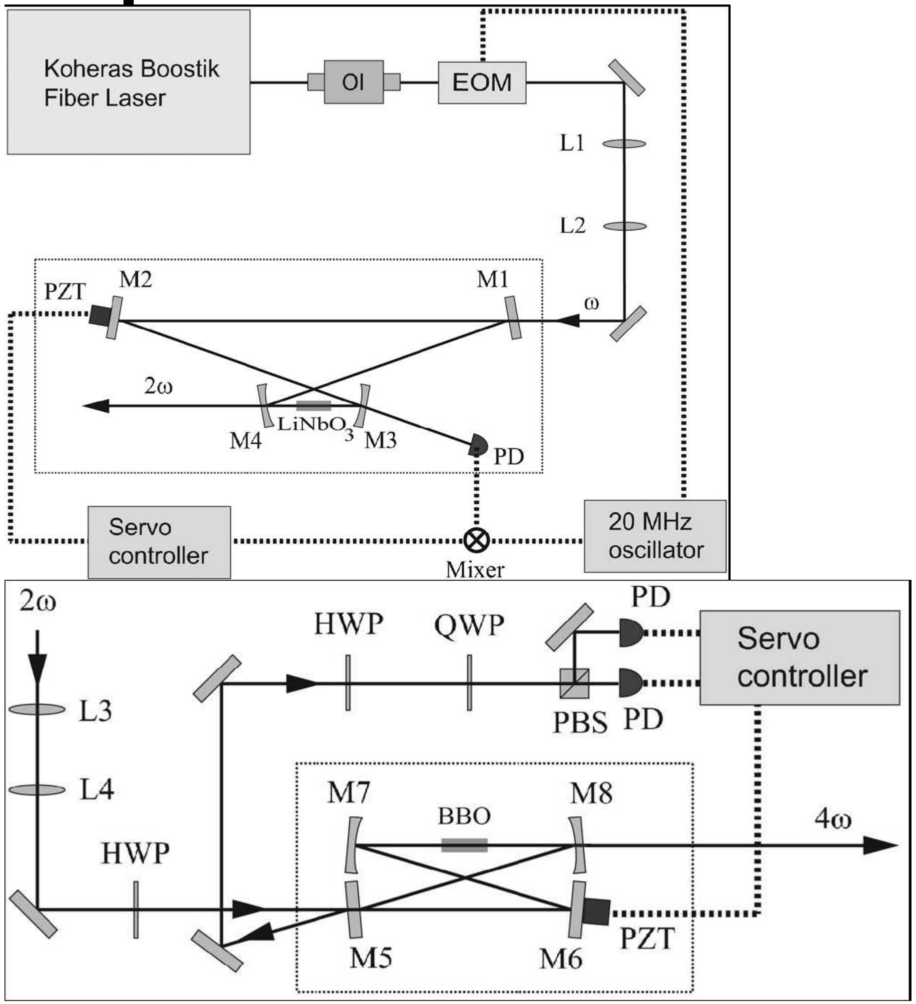
Experimental results

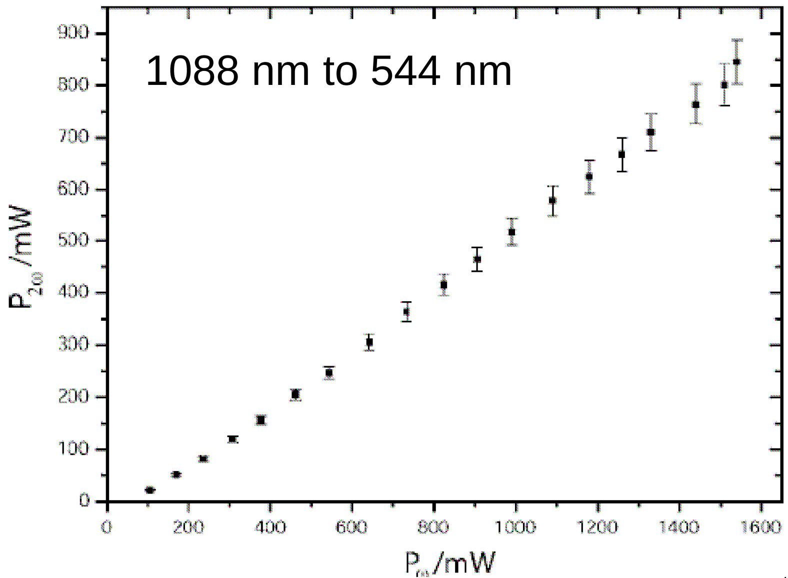


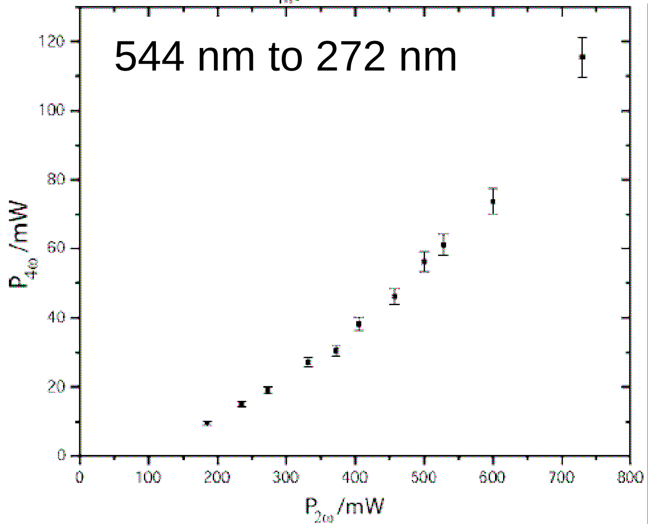


[1]D. Georgiev *et al*, Opt. Express. **13**, 6772, 2005.
[2]H. Furuya *et al*, Jap. J. Appl. Phys. **45**, 6704, 2006.

Experimental results

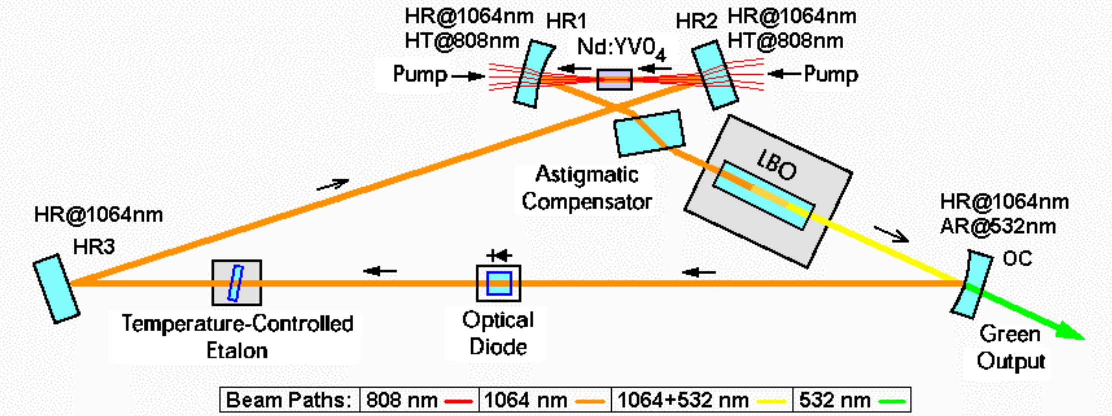




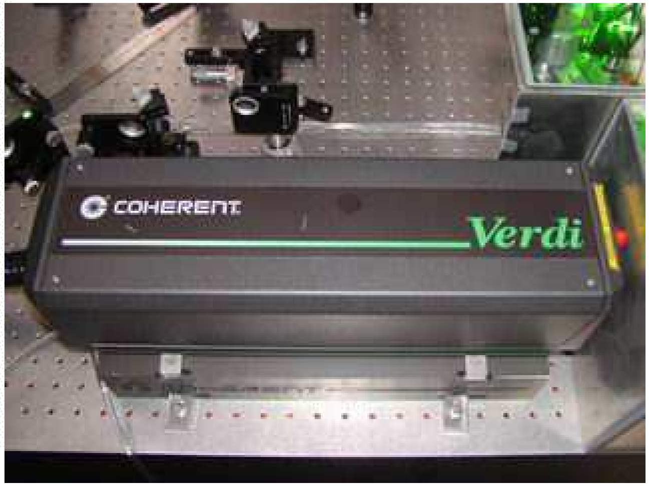


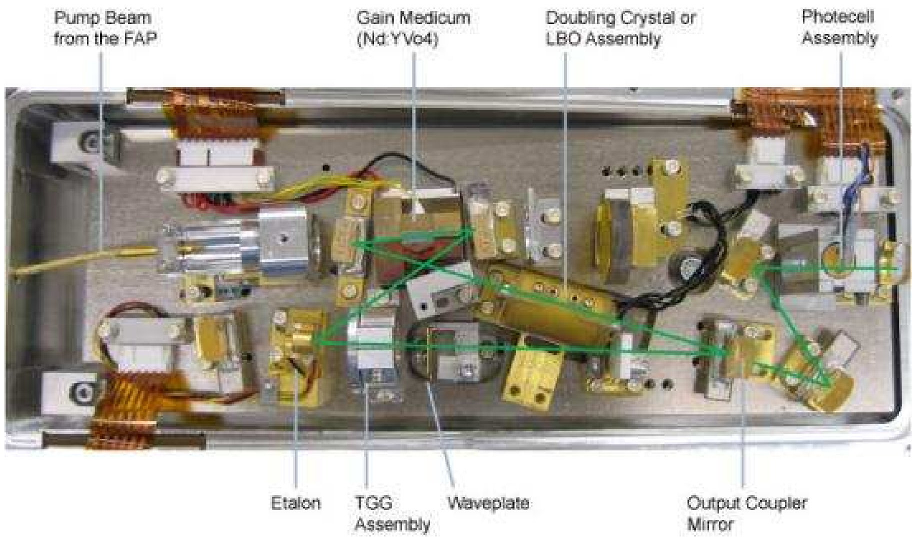
[1]P. Herskind *et al*, Opt. Lett., **32**, 268, 2007.

Experimental results



Ring Cavity Resonator of Coherent, Inc. Verdi Green DPSS Laser





- Up to 18 W single-frequency green light at 532 nm.

Conclusions (I)

- Basic principles for frequency doubling described.
- Good beam quality, low spectral bandwidth and high fundamental laser power is mandatory for obtaining high frequency doubling efficiency.
- There exist an optimum focusing condition where the conversion efficiency is maximized. This optimum condition depends on both the laser and nonlinear crystal. The main parameters are
  - Low/zero walk-off in the nonlinear crystal
  - “Perfect” phase matching
  - Low absorption
  - Focusing optimized to crystal length
  - Location of focus in the center of the nonlinear crystal

Conclusions (II)

- Single-pass frequency doubling is relatively simple to implement but the conversion efficiency is limited.
- External cavity frequency doubling puts more strict requirements on the laser parameters and the setup is more complicated. However, the conversion efficiency can be very high (> 80 %).
- High power diode lasers with good beam quality represent a strong candidate for future visible and UV laser systems based on frequency doubling.

Acknowledgements

Peter E. Andersen, Jesper Holm Lundeman, Mingjun Chi, Birgitte Thestrup, Peter Jensen, Bjarne Sass and Christian Petersen

All partners involved in the experiments.