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MACQUARIE University

Progress in diamond Raman lasers for sodium beacon applications

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http://web.science.mq.edu.au/groups/diamond/

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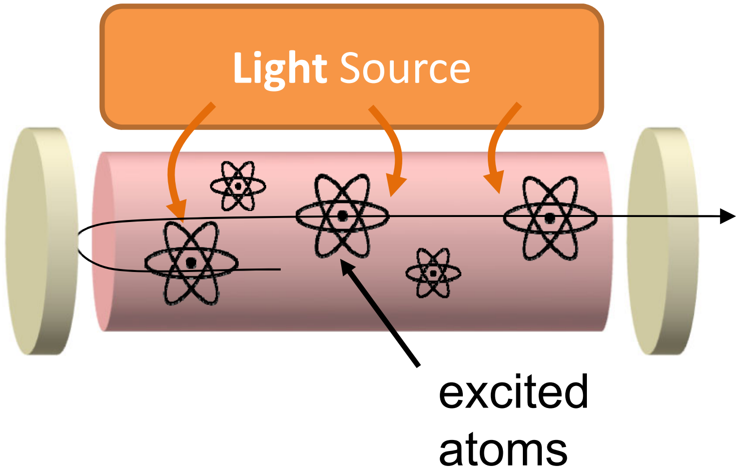
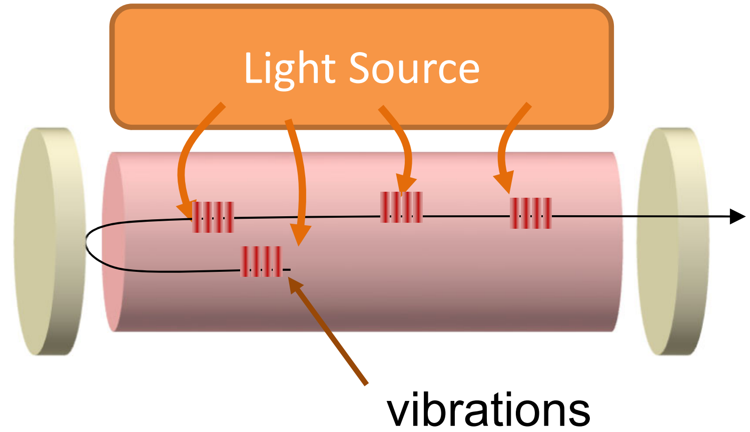
1. **Intro to *diamond Raman lasers* – what are they?**
2. **Single frequency operation**
3. **589 nm and 330 nm**
4. **Conclusion / Future directions**

Inversion lasers vs Raman lasers

Inversion



Raman



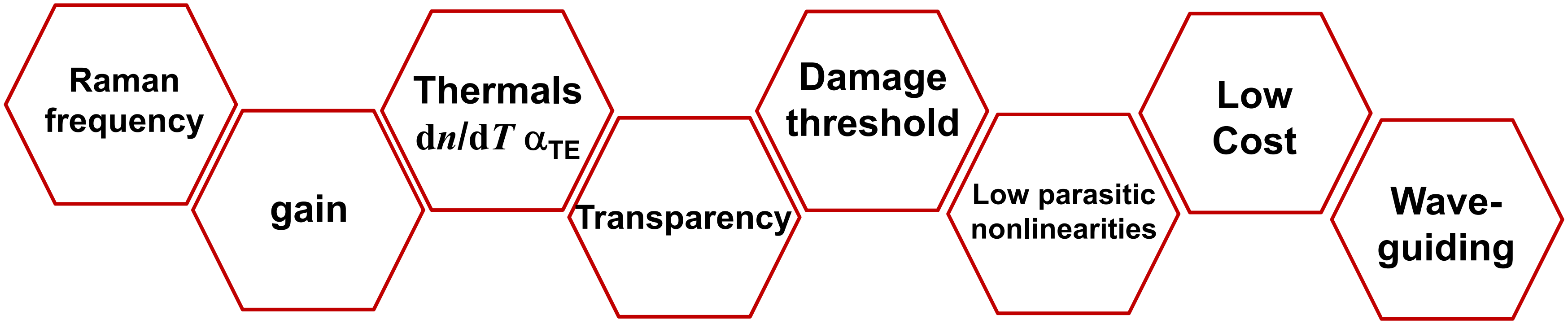
- Greater wavelength range
- Coherent output
- BUT Raman is a weak effect - need to pump hard or have long gain lengths

TOPTICA APPROACH:

- High power
- Easy to add a repump line
- Fiber based

M. Enderlein and W.G. Kaenders, Optik & Photonik 11, (2016): 31-35.

Raman materials

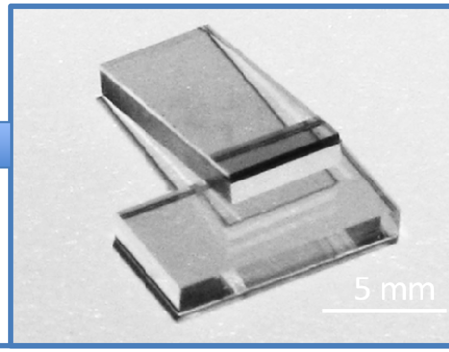


Some standout materials:

	Plusses +	Minuses -
Glasses (SiO_2, GeO, P_2O_5)	Low cost fibers, high damage threshold, transparency	Low g and ω_v, high parasitic nonlinearities in fiber form
Metal-WO_4, YVO_4, Metal-MoO_4, etc.	High gain, moderate damage threshold, good transparency	Waveguiding is challenging Complex Raman spectra Poor heat handling
Diamond, silicon	High gain, excellent thermals Simple Raman spectra	Diamond – immature fabrication Si – high parasitic nonlinearities

Diamond Raman lasers

Raman Lasers



Inversion Lasers

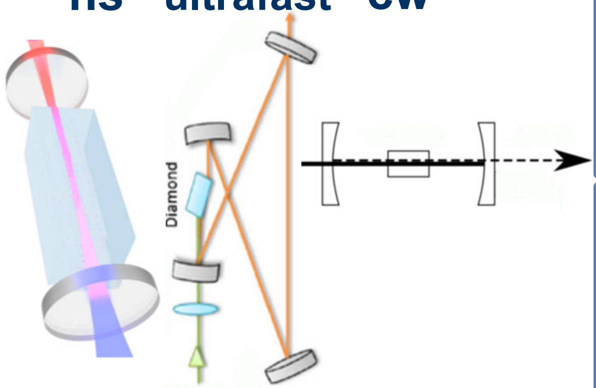
Rand, S. C., *et al* "Visible color-center laser in diamond." *Opt. Lett.* 10, (1985): 481-483.

A. Savvin, A. Dormidonov, E. Smetanina, V. Mitrokhin, E. Lipatov, D. Genin, S. Potanin, A. Yelisseyev, V. Vins, Nat. Commun. 12, (2021): 7118.

- High thermal conductivity
- High Raman gain
- Wide transmission

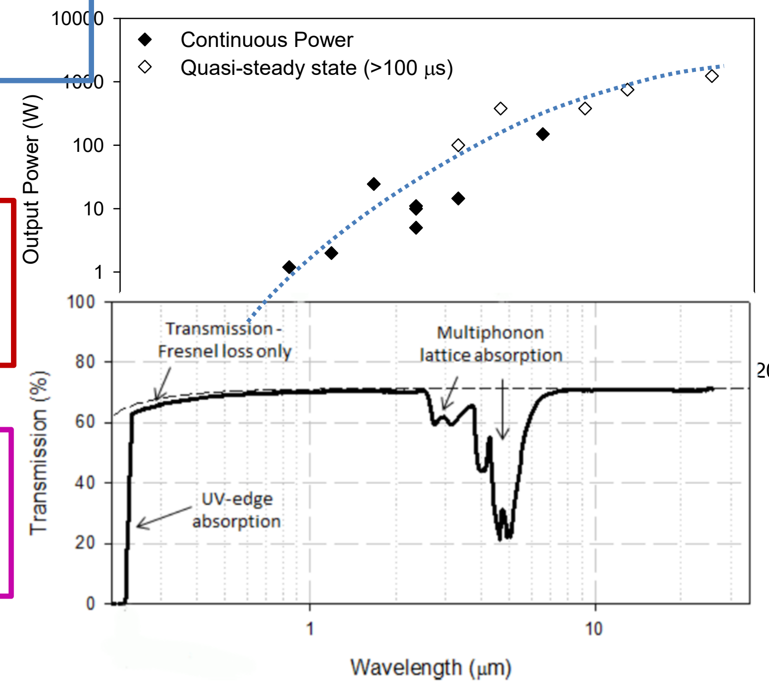
Efficient Gain Switched Lasers

ns ultrafast cw

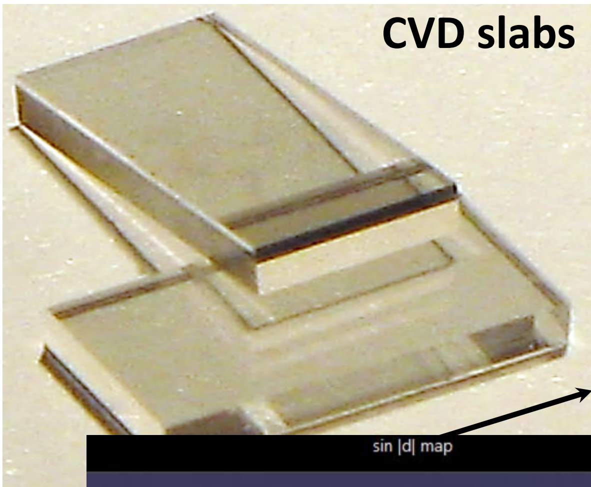


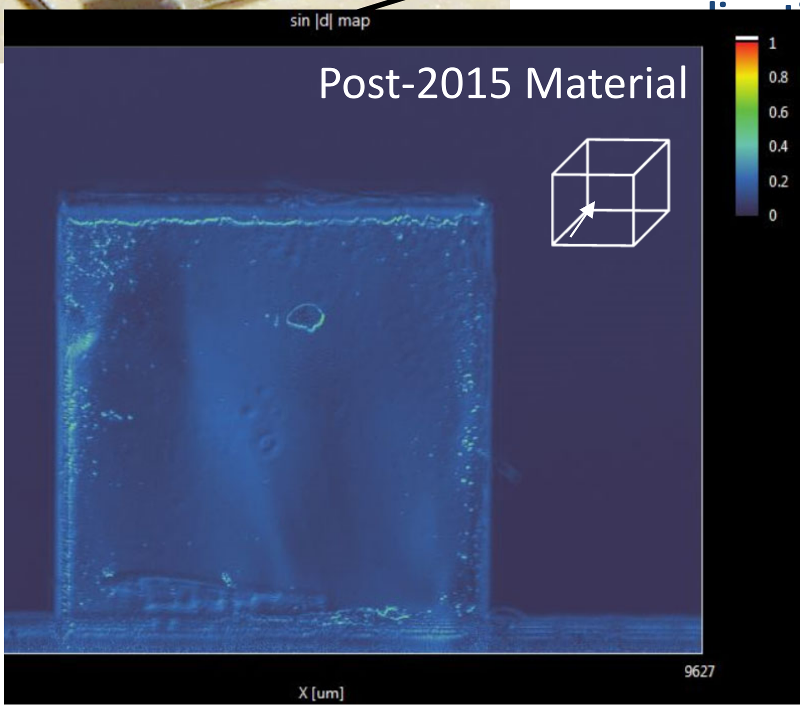
High Average Power

Deep UV
to
Mid-infrared



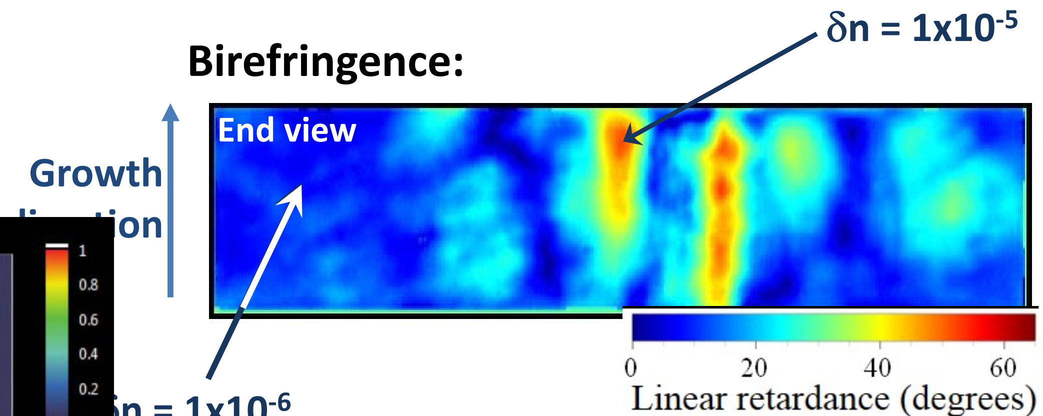
‘Laser grade’ material



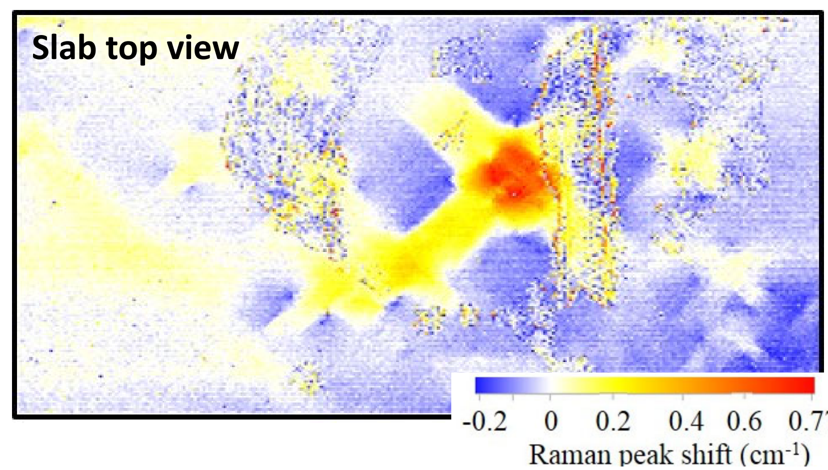


Absorption < 0.15 %/cm (1.06 μm)

Birefringence:

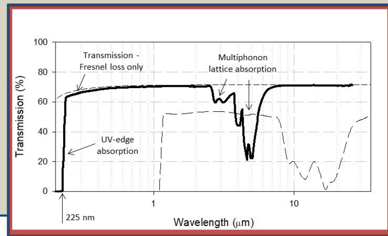


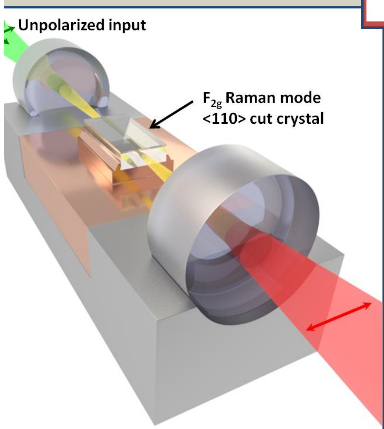
man
ncy:
cm^{-1}

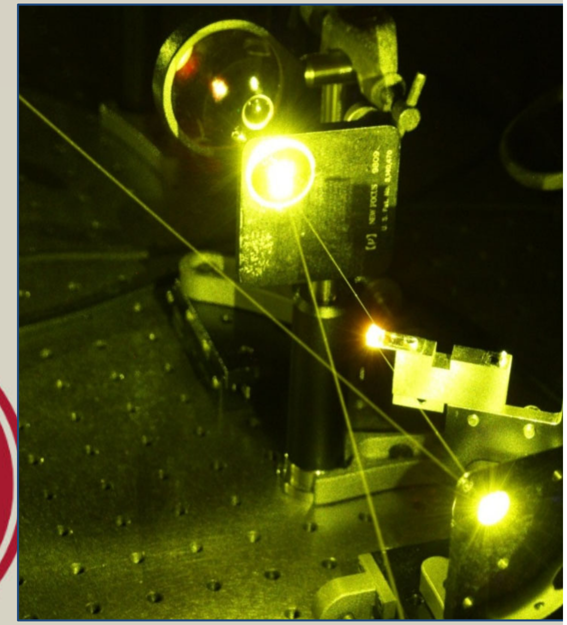


H. Jasbeer, R. Williams, O. Kitzler, A. McKay, S. Sarang R. Mildren, *JOSAB, 33* p56, (2016)

Diamond Raman laser research directions







UV to Mid-infrared

Polarization Conversion

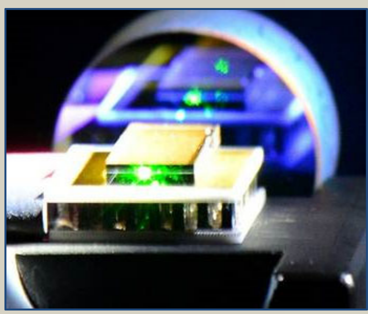
Ultrafast

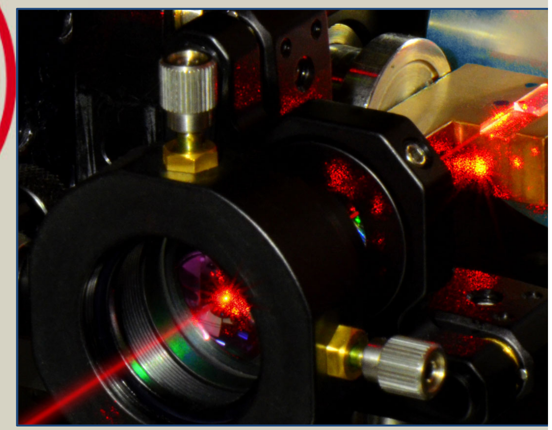
Raman

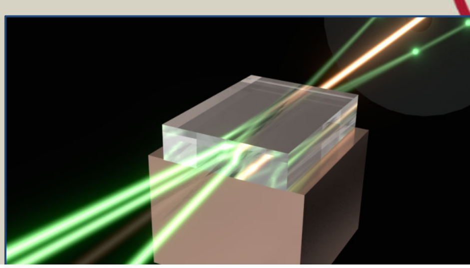
High Power

Single Frequency

Beam Combination





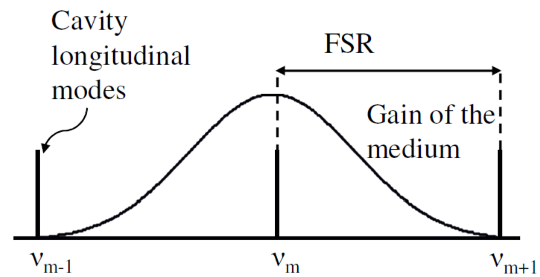


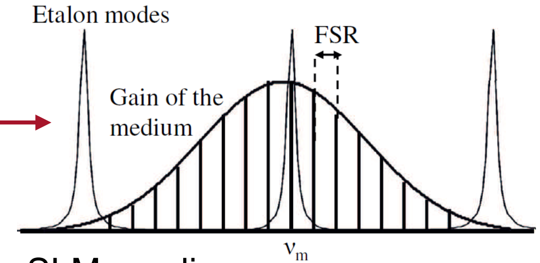
48 papers, 5 patents

Enforcing a single frequency in Raman Lasers

SLM Methods:

- ❑ H_2 Raman laser[1]
  - *Short cavity, cavity mode spacing > Raman gain linewidth*
- ❑ Silicon Raman laser[2]
  - *Unknown longitudinal-mode suppression*
- ❑ Raman Distributed Feedback Fiber Laser[3]
  - *Short cavity, π phase-shifted FBG*
- ❑ Nd:YVO_4 self-Raman laser[4]
  - *Low temperature, cavity mode spacing > Raman gain linewidth*
- ❑ Intracavity $BaWO_4$ Raman laser[5]
  - *F-P etalons*
- ❑ CH_4 Raman laser[6]
  - *SLM pump, SLM Raman seed*
- ❑ Raman fiber amplifier (RFAs)[7]
  - *SLM Raman seed, backward pumping*



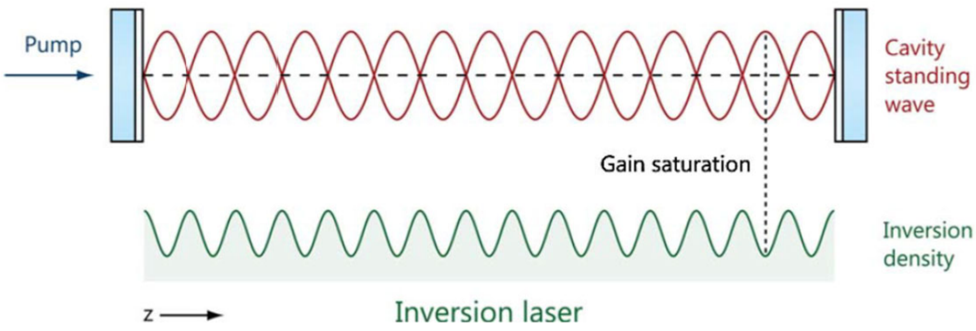


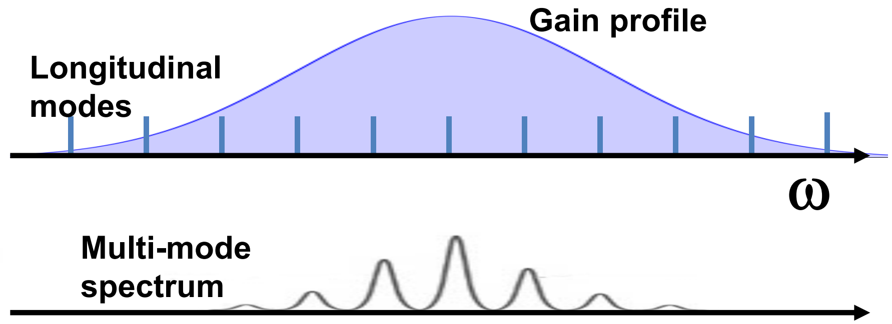
Injection SLM seeding

[1] Lei S. Meng, Peter A. Roos, and John L. Carlsten, "Continuous-wave rotational Raman laser in H_2," Opt. Lett. 27, 1226-1228 (2002)
[2] H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang, and M. Paniccia, "A continuous wave Raman silicon laser," Nature 433(7027), 725 (2005).
[3] Jindan Shi, Shaif-ul Alam, and Morten Ibsen, "Highly efficient Raman distributed feedback fibre lasers," Opt. Express 20, 5082-5091 (2012).
[4] C. Y. Lee, C. C. Chang, et al., "Cryogenically monolithic self-Raman lasers: observation of single-longitudinal-mode operation," Opt. Lett. 40, 1996-1999 (2015).
[5] Z. Liu, S. Men, et al., "Single-frequency Nd:GGG/BaWO4 Raman laser emitting at 1178.3 nm," In CLEO: Science and Innovations, pp. SM3M–3 (2016).
[6] S. M. Spuler and S. D.Mayor, "Raman shifter optimized for lidar at a 1.5 m wavelength," Applied optics 46(15), 2990 (2007).
[7] Y Feng, Taylor, D. Bonaccini Calia, Optics Express vol. 17, 23678, (2009)

Spatial hole burning

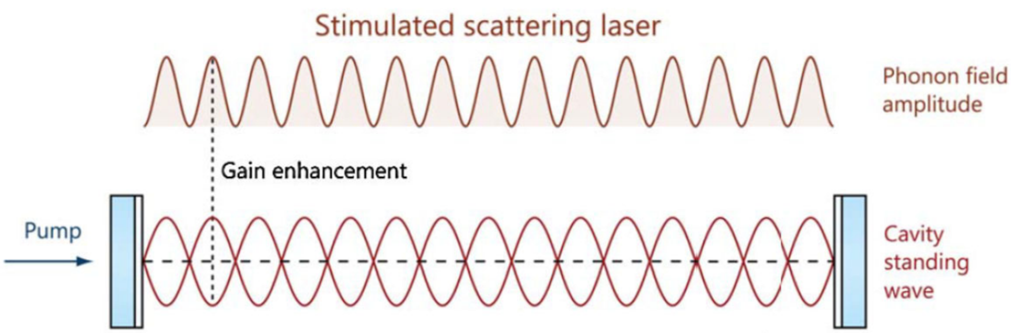
Inversion lasers: Spatial hole burning destabilizes single frequency output:





….complicates design (ring cavities, etalons, gain medium near mirror, etc)

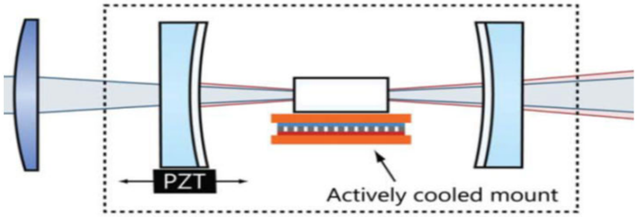
In **stimulated scattering lasers** → no energy storage → **no spatial hole burning**



- Simplifies design

Lux et al, Optica, vol. 3, 876, (2016).

Single frequency operation in diamond

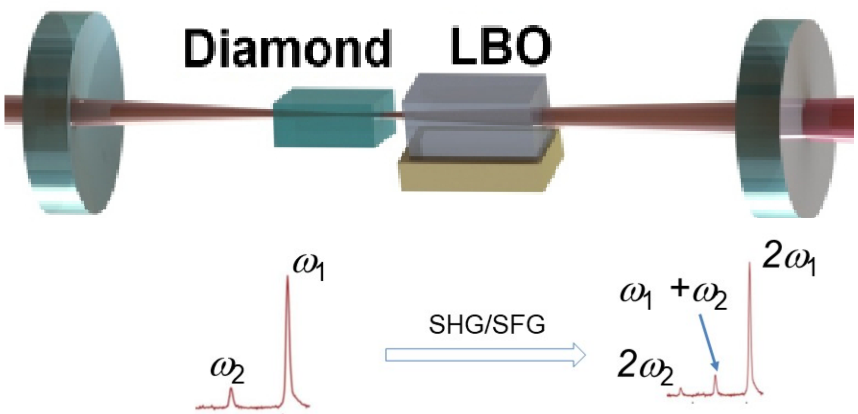


Simple standing wave cavity

- Up to a few watts
- Eg. at 1240 nm

Lux et al, Optica, vol. 3, 876, (2016)

<u>Additional mode competition via intracavity $\chi^{(2)}$:</u>



$$\frac{\text{loss of mode}\,\omega_1}{\text{loss of mode}\,\omega_2} = \frac{kI(\omega_1) + 2kI(\omega_2)}{kI(\omega_2) + 2kI(\omega_1)} \xrightarrow{I(\omega_1) >> I(\omega_2)} \frac{1}{2}$$

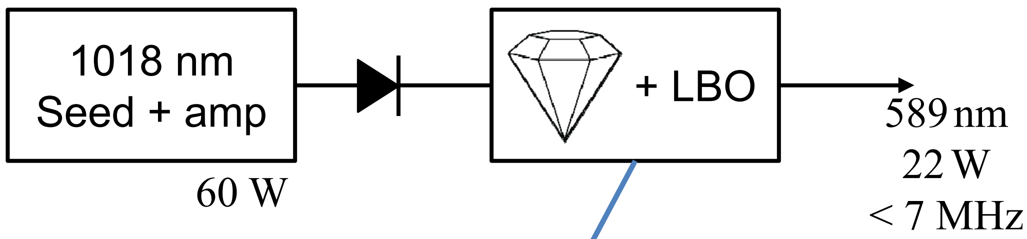
- *Martin, Clarkson & Hanna, Opt. Lett.* ***22*** *375 (1997)*

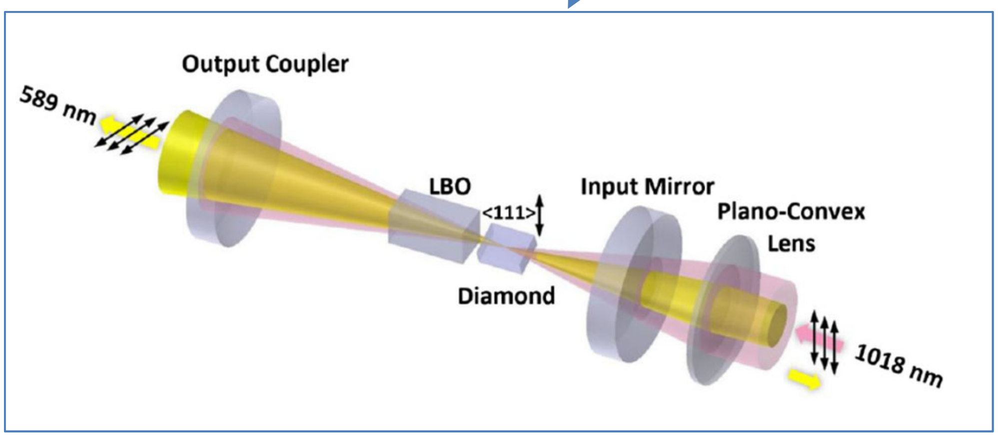
- Much higher power
- 30 W SLM
- Visible output (620 nm)

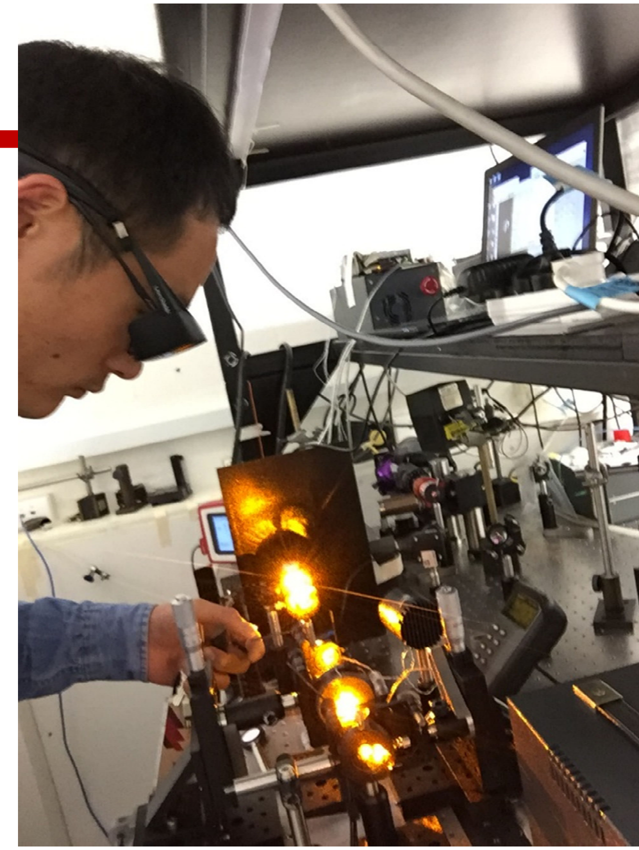
Jasbeer, et al, Opt. Express ***26,*** *1930 (2018)*
Yang, et al Opt. Lett. (2019)

Targeting 589 nm

Using a Yb^{3+}-doped 1018 nm fiber laser pump:





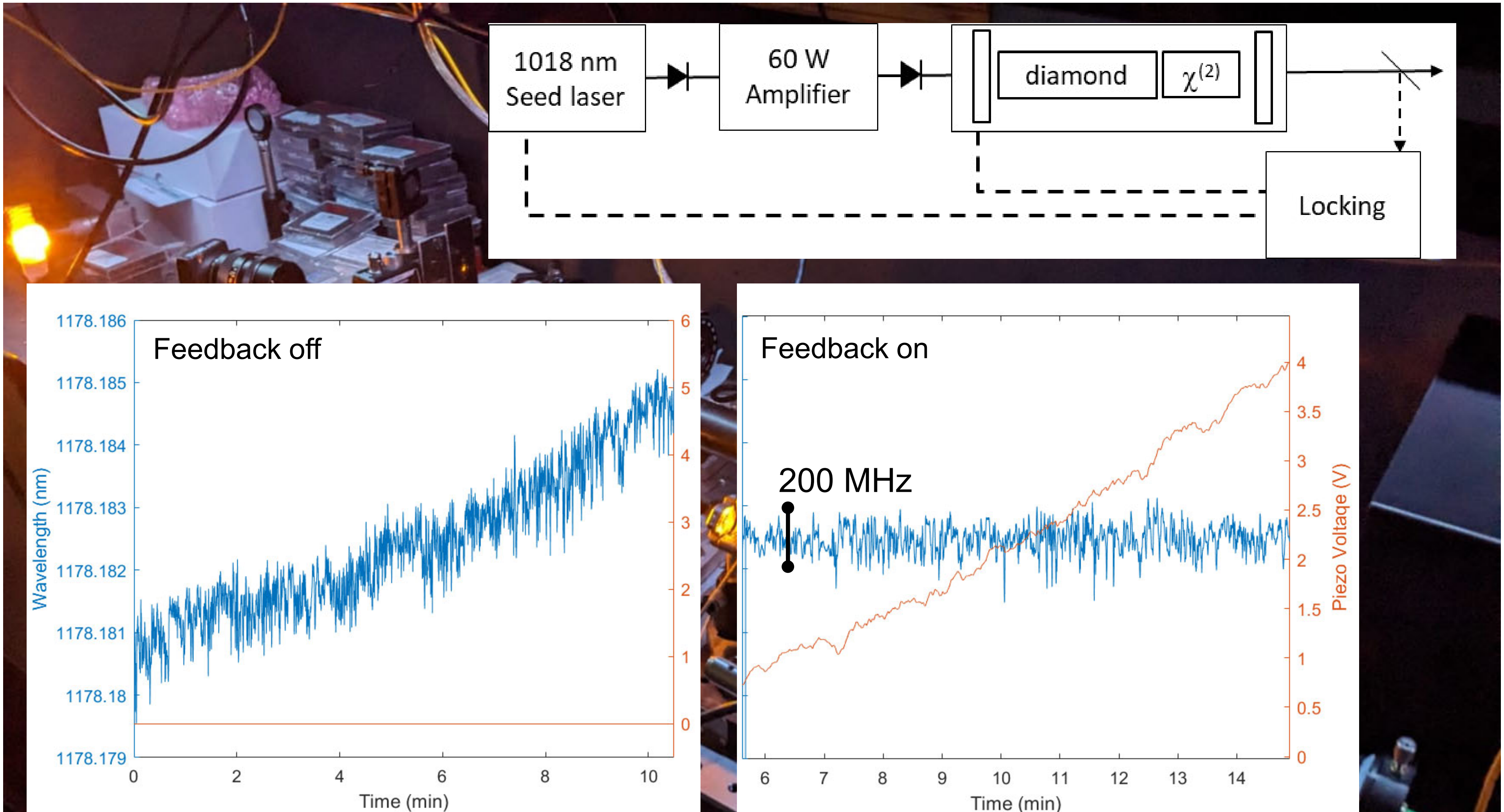


Features:

- Builds on Yb fiber technology
- Tunable from 588 – 620 nm
- Extend to the UV

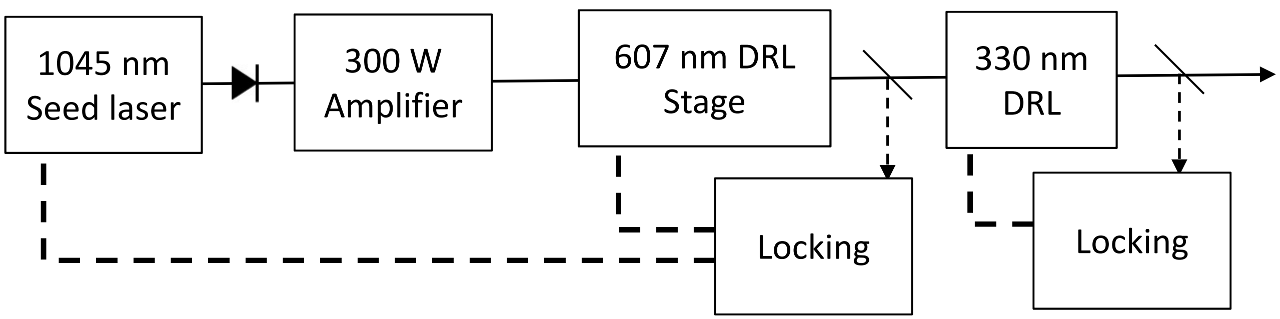
X. Yang et al, Opt. Lett. 45, 1898. (2000); Opt. Express. 29(18), 29449 (2021)

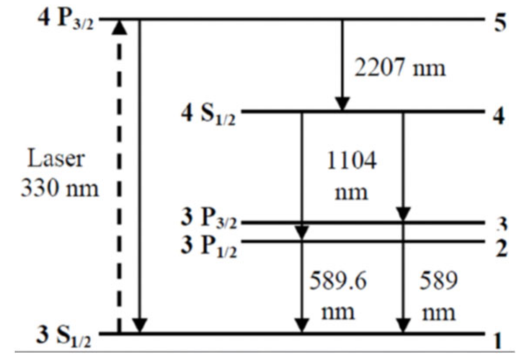
Locking and linewidth

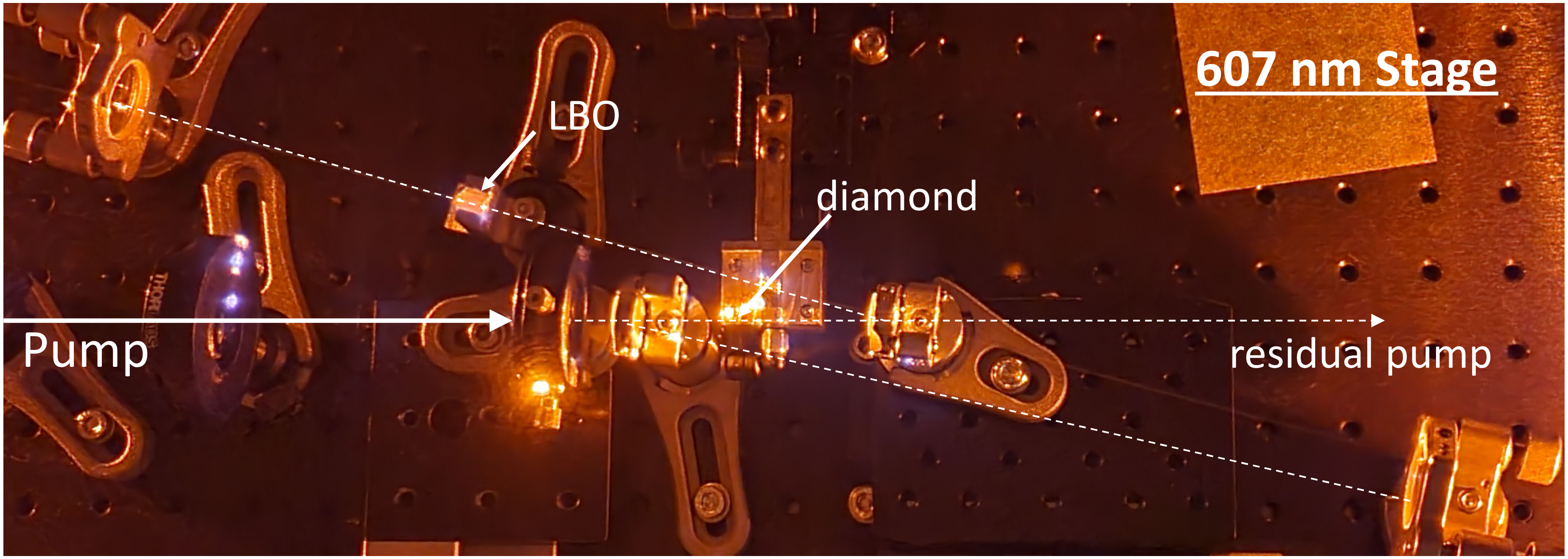


- Early results - un-optimized
- 3 W level
- Linewidth 8 MHz (effective), < kHz (intrinsic)

330 nm laser (polychromatic guide stars)



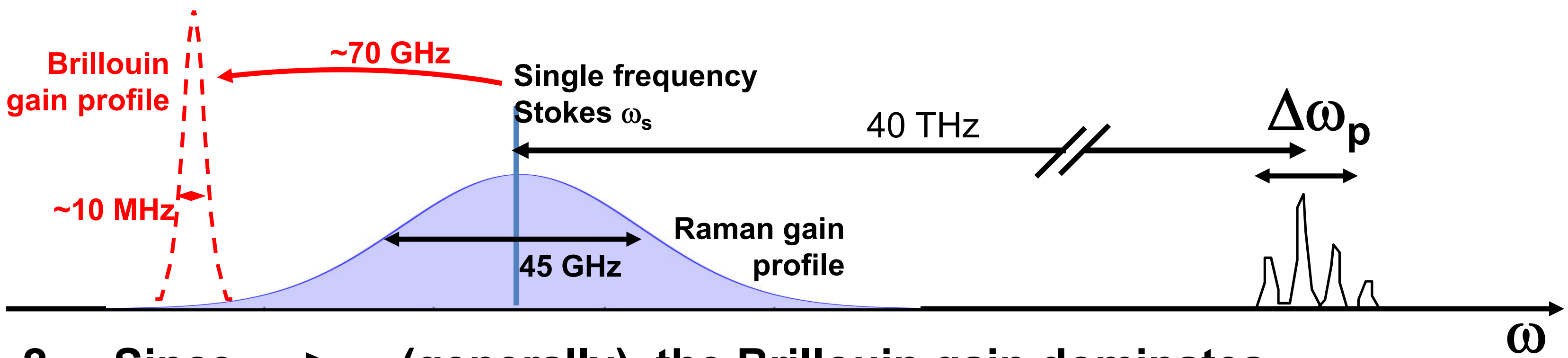




- Design avoids high power isolator
- 25 W so far, mode is unstable

Power limit - The SBS Problem

1. **Stimulated Brillouin scattering (SBS)**



2. **Since $g_B > g_R$ (generally), the Brillouin gain dominates**
3. **Brillouin lasing spoils efficiency and degrades spectrum**

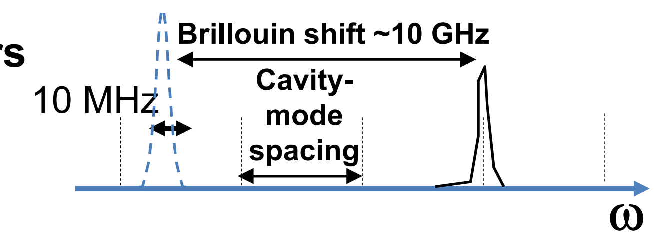
<u>Mitigations</u>

Raman fiber lasers

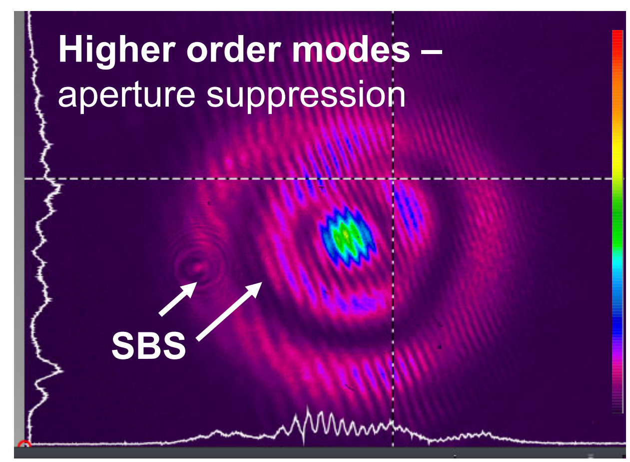
– strain and/or temperature gradients

Crystal Raman lasers

– cavity suppression



- etalon suppression (*M. Heinzig, et al p. PC124050I. SPIE, 2023.*)



Summary

1. **Diamond Raman lasers**
   - Generic high power laser technology with large λ reach
   - Single frequency (if you do it right)
   - SBS mitigations are different from Raman fibers

2. **Current status**
   - 22 W single frequency 589 nm
   - 25 W at 607 nm (first stage to 330 nm)
   - Locking has been achieved recently

3. **Current projects**
   - Aiming for 100 W at 589 nm
   - 10 W at 330 nm
   - (Pulsed guidestars for pulse tracking)