Diamond – Extreme Material for Nonlinear Optics and Raman Lasers

Presented by:

OSA Laser Systems Technical Group

Technical Group Leadership

OSA Laser Systems Technical Group

Fatima Toor
University of Iowa
Chair

David James Spence
Macquarie University
Vice Co-Chair

Tong Zhou
Thorlabs Inc
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OSA Laser Systems Technical Group

Laser Systems (PL)

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  - Technical Group Newsletter
  - Technical Group Webinars
- OSA CONNECT
- Minorities and Women in OSA (MWOSA)
- Diversity & Inclusion in OSA
- Young Professionals
- Corporate Members
- Optics & Photonics Regions

Laser Systems (PL)

This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications. The group addresses technical issues concerning sources that cover the full spectral range, including: ultraviolet, visible, infrared, terahertz and microwave. Strong overlap with other technical groups that study and develop laser techniques and technologies brings together researchers and engineers to produce sources with unique performance, such as high-power, ultra-short pulses and high coherence.

GROUP LEADERSHIP | UPCOMING MEETINGS | RECENTLY PUBLISHED

Name	Affiliation	Title
Fatima Toor	University of Iowa	Chair
Muhammad Faryad	Lahore University of Management Sciences	Conference Events Officer
Shamsul Arafin	University of California Santa Barbara	Events and Social Media Officer
David James Spence	Macquarie University	Vice Co-Chair
Tong Zhou	Thorlabs Inc	Vice Co-Chair
Austin Joseph Cyphersmith	University of Illinois Urbana-Champaign	Webinar and Social Media Officer

Announcements

Register now for the Laser Systems Technical Group's upcoming webinar on III-nitride nanowire light-emitting diodes grown by molecular beam epitaxy. The webinar, featuring a presentation from Dr. Hieu Nguyen of the New Jersey Institute of Technology, will be held on 27 July 2016 at 12:00 EDT.

Register for the webinar now >>

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Laser Systems Technical Group

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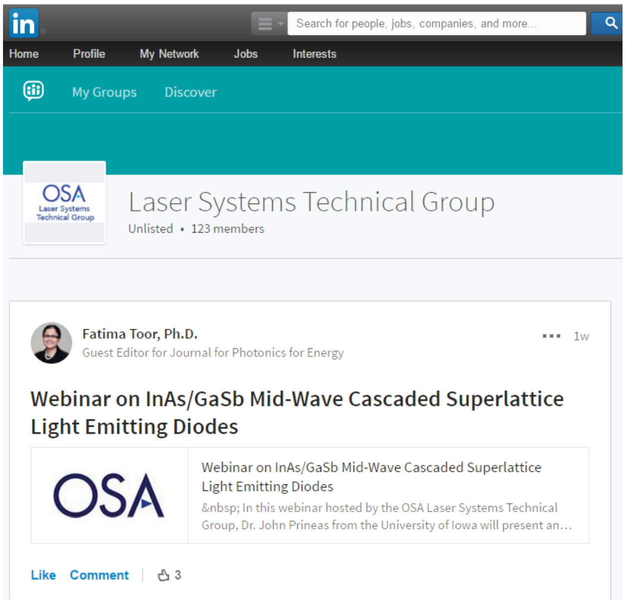
- LinkedIn site (global reach)
- Announce new activities
- Promote interactions
- Complement the OSA Technical Group Member List



Welcome to Today's webinar!

Laser Systems Technical Group

Diamond - Extreme Material for Nonlinear Optics and Raman Lasers

Overview | Speaker(s) | Register

Laser Systems Technical Group

Diamond is an optical material with a suite of properties that are set well apart from most others. Its recent availability in large, high quality, synthesized crystals is bringing forth important opportunities to tackle major challenges in optics. In this webinar hosted by the OSA Laser Systems Technical Group, Dr. Richard Mildren of Macquarie University will provide an introduction to the optical properties of diamond (linear, nonlinear and thermo-optical). Dr. Mildren will then present a detailed description about some of diamond's more outstanding properties and how these are stimulating development of advanced laser-based technologies, such as high power lasers and nonlinear frequency converters.

What You Will Learn in the Webinar:

- Detailed understanding of the contrasting nature of diamond against more familiar optical materials
- Design issues for developing diamond optical devices and in particular diamond lasers
- Features of diamond that are likely to impact on the future development of optics

Who Should Attend the Webinar:

- Research Students
- Researchers
- Professionals in Industry, Government

Richard Mildren, Physics and Astronomy, Macquarie University, Australia

https://research.science.mq.edu.au/diamond/

Diamond - Extreme material for nonlinear optics and Raman lasers

Rich Mildren

rich.mildren@mq.edu.au

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

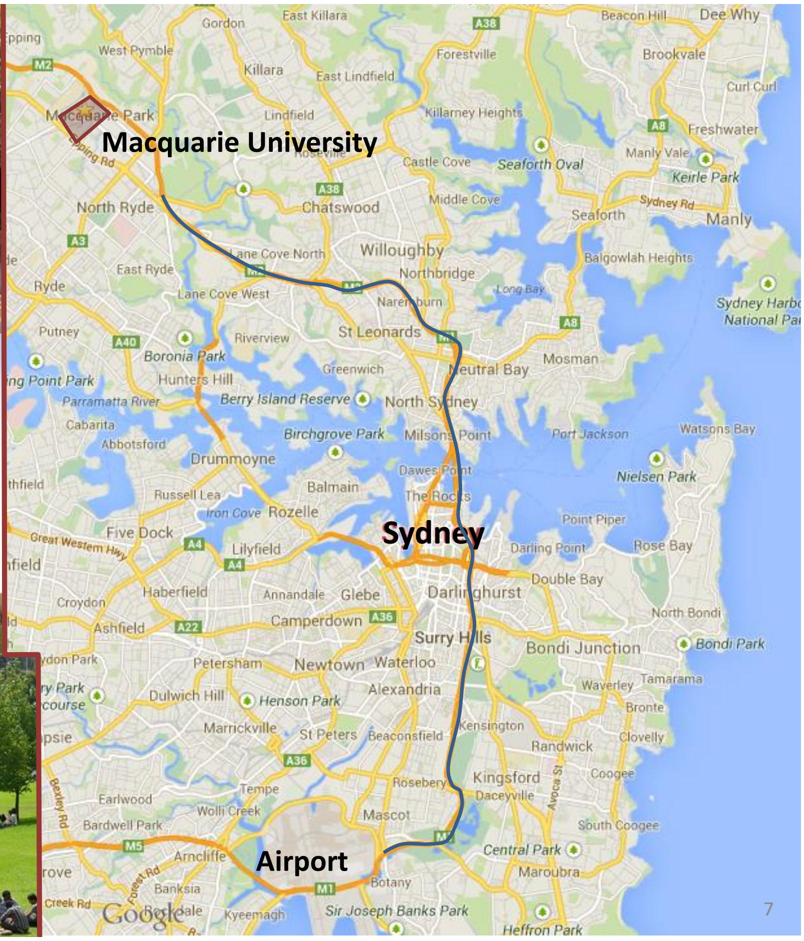
MQ Photonics Research Centre

Department of Physics and Astronomy

Macquarie University, **Sydney, Australia**

MACQUARIE UNIVERSITY

MQ Photonics


Macquarie University
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Manly
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Balmain
Rozelle
Five Dock
Lilyfield
Glebe
Darlinghurst
Surry Hills
Camperdown
Newtown
Waterloo
Alexandria
Bondi Junction
Randwick
Kingsford
Mascot
Botany
Marrickville
Petersham
Ashfield
Double Bay
7

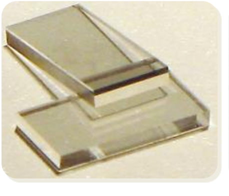
Diamond technologies

Cutting and abrasives

Electrochemistry

Gemstones

Electronics, LEDs and radiation detectors



Linear and nonlinear optics

- *Windows, diffractive elements, waveguides, heat-spreaders*
- *Four-wave mixing*
- *Raman lasers*
- *Nanophotonics*

Opto-mechanics

Thermal Management

Colour Centres

- *Quantum*
- *Magnetometry / Sensing*
- *Bio-imaging*

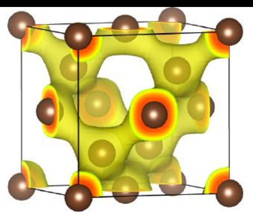
Contents –

1. Optical Properties
   - Linear properties
   - Scattering
   - Nonlinear properties
   - Thermo-optical

2. Properties Summary
   "The good, the bad and the ugly"

3. Applications in Raman lasers

Origins …



Symmetric Lattice	Tightly Bound	Low Atomic Mass	Atomically Dense

Simple spectra	No first-order lattice absorption	Large bandgap	Moderate refractive index	High damage threshold

wide transmission band

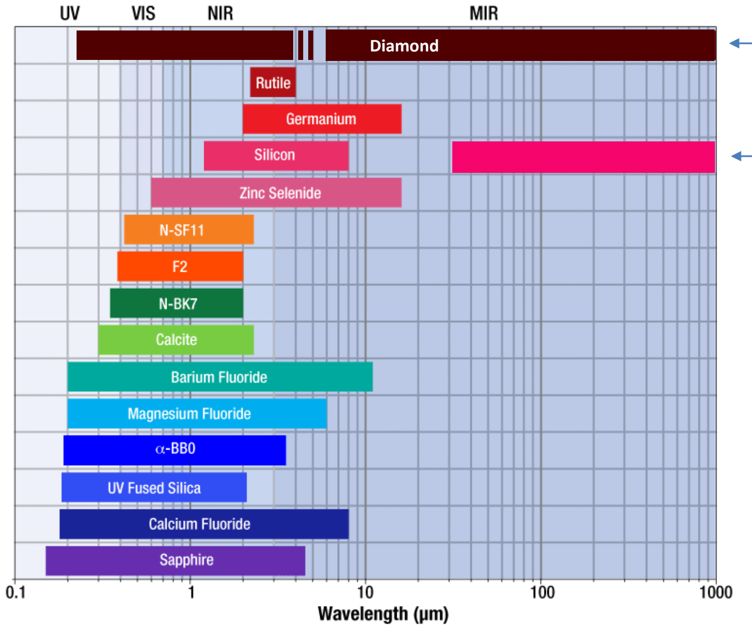
Detailed optical properties depend on subtle effects →

- Electronic band structure
- Phonon dispersion
- Zero point energy
- Anharmonicity
- Surface effects

→ **DEEP PHYSICS ~ MANY POSSIBILITIES**

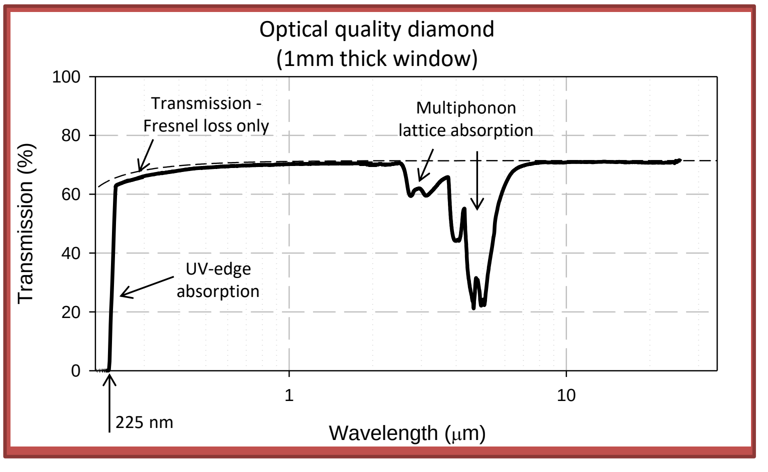
Transmission Range

versus other optical materials

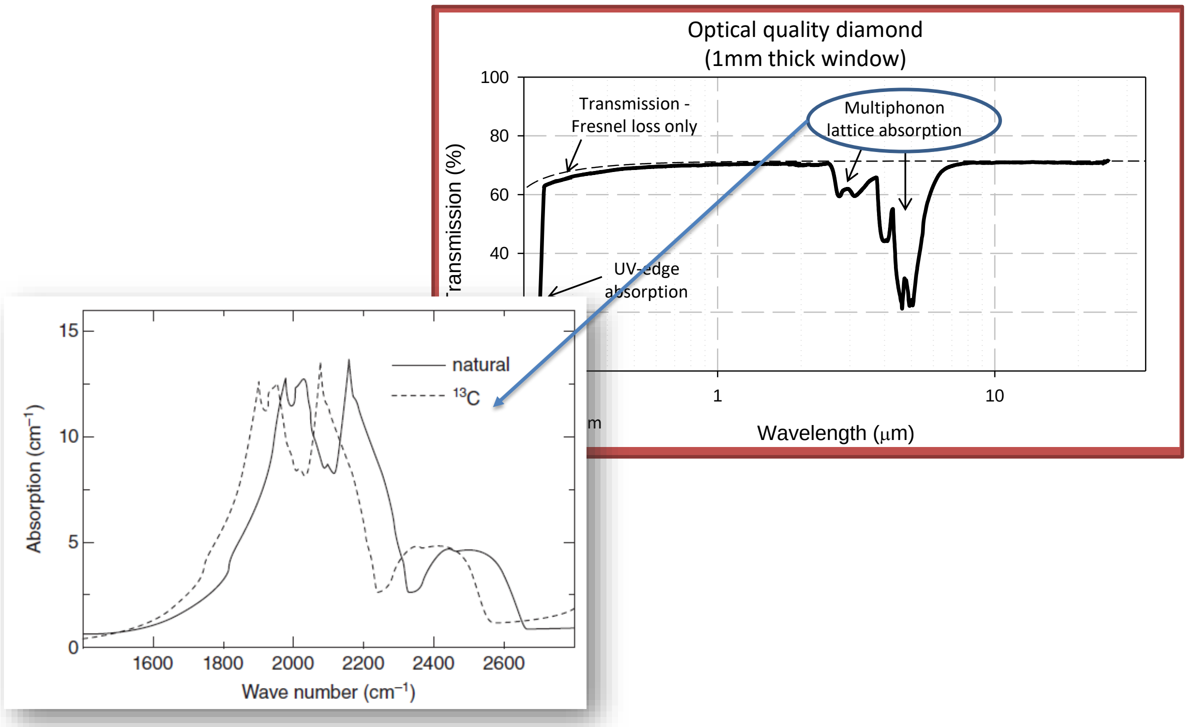


no first-order lattice absorption

Transmission / Absorption



Transmission / Absorption



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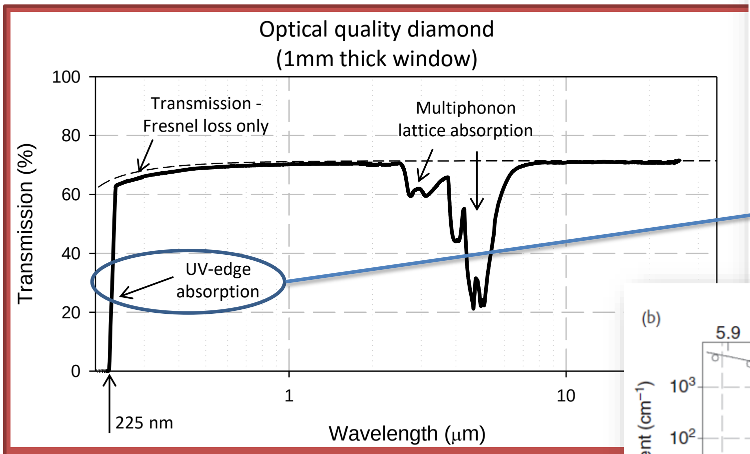
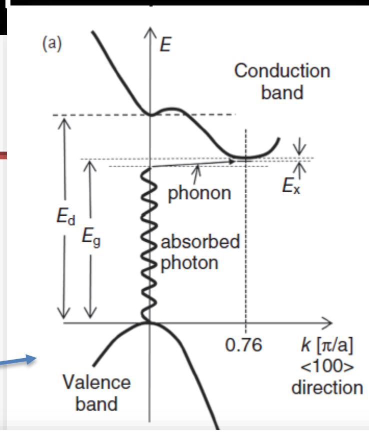
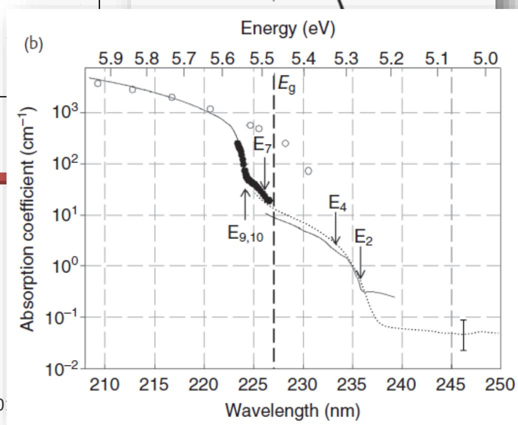
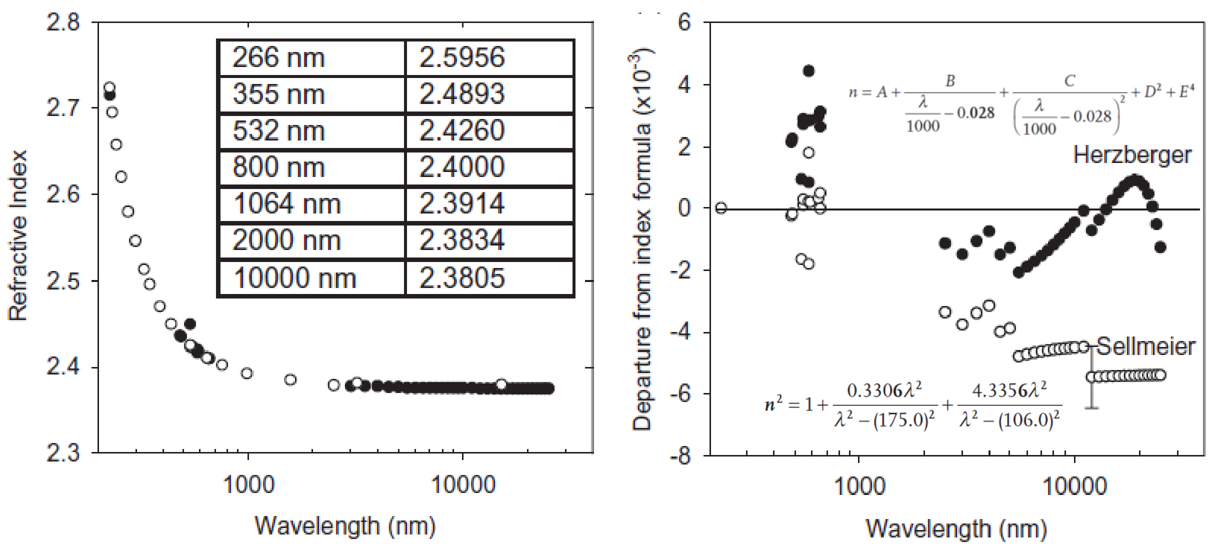
Transmission / Absorption







Refractive index

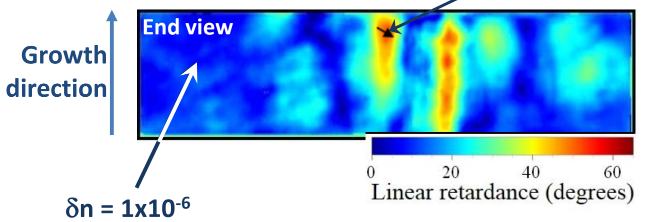


266 nm	2.5956
355 nm	2.4893
532 nm	2.4260
800 nm	2.4000
1064 nm	2.3914
2000 nm	2.3834
10000 nm	2.3805

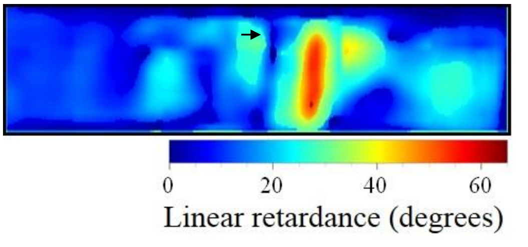
F. Peter, Z. Phys A Hadrons Nucl. **15** (1923)
D.F. Edwards and E. Ochoa JOSA **71**, (1981)

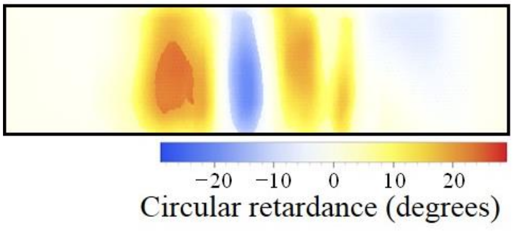
Birefringence in 'laser grade' material

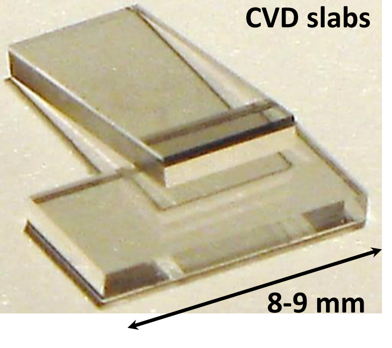
Metripol polarimetry:



Mueller polarimetry:



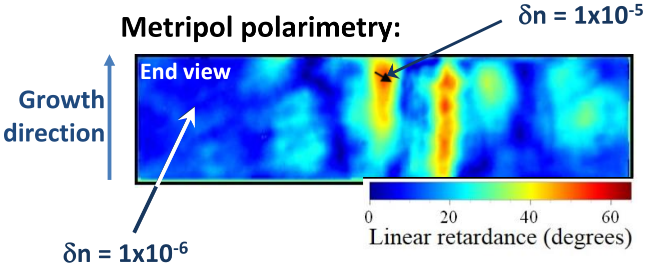




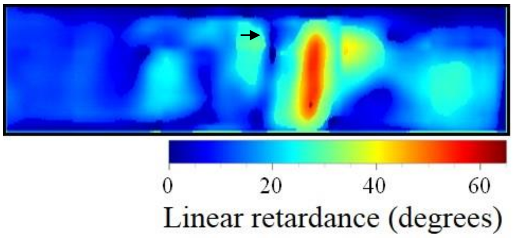
H. Jasbeer, R. Williams, O. Kitzler, A. McKay, S. Sarang R. Mildren, *JOSAB*, ***33*** p56, (2016)

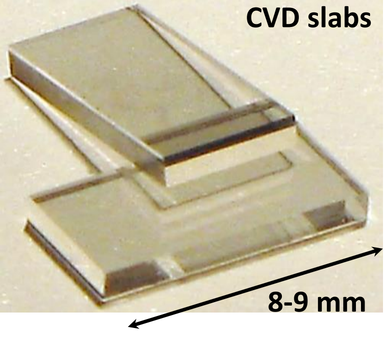
Birefringence in ‘laser grade’ material

Metripol polarimetry:



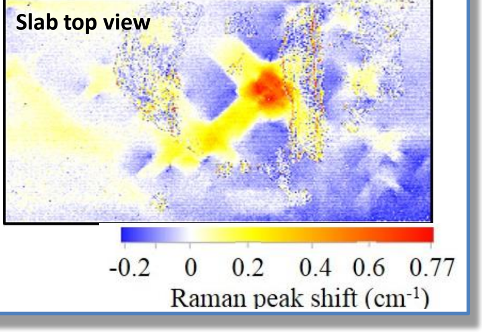
Mueller polarimetry:





Raman microscopy image: top face {100}

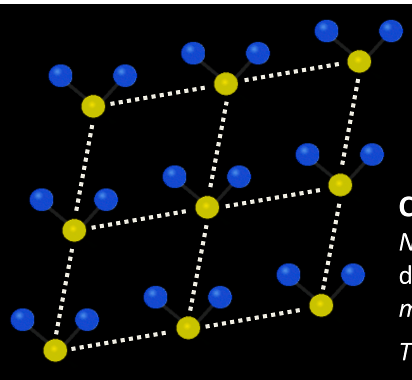
centre Raman frequency:
ω_0 = 1332.3 cm^{-1}



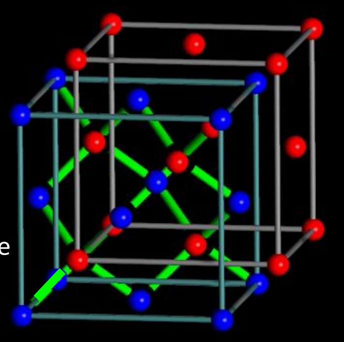
H. Jasbeer, R. Williams, O. Kitzler, A. McKay, S. Sarang R. Mildren, *JOSAB*, **33** p56, (2016)

Scattering – Raman

molecular crystals | **diamond, silicon, germanium**



Critical variables:
N density of scatterers
$d\alpha/dq$ polarizability derivative
m reduced mass
T_2 dephasing time



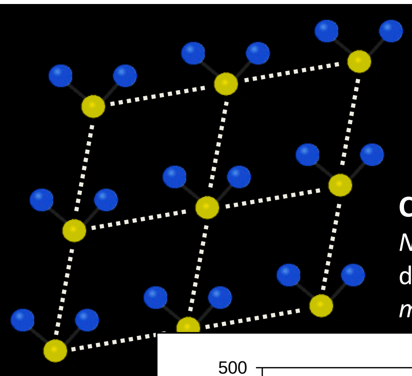
Differential cross-section
$$\frac{d\sigma}{d\Omega} = k.\frac{\omega_s^4}{\omega_R m}\left(\frac{d\alpha}{dq}\right)^2 \qquad k = \frac{\mu_s h}{4\pi\mu_L c^4}$$

Raman gain coefficient
$$g_R = k' \frac{T_2 N}{\omega_s^3}\left(\frac{d\sigma}{d\Omega}\right) \qquad k' = \frac{4\pi^2}{\mu_L \mu_s c^2}$$

Scattering – Raman

molecular crystals

diamond, silicon, germanium

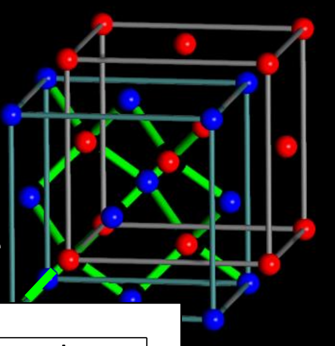


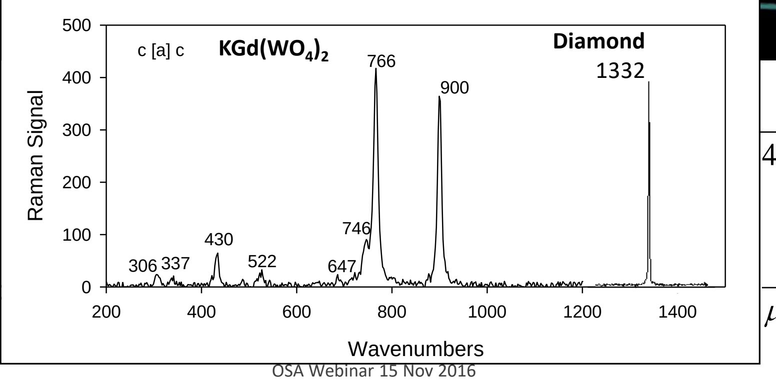
Critical variables:

N density of scatterers

dα/d*q* polarizability derivative

m reduced mass





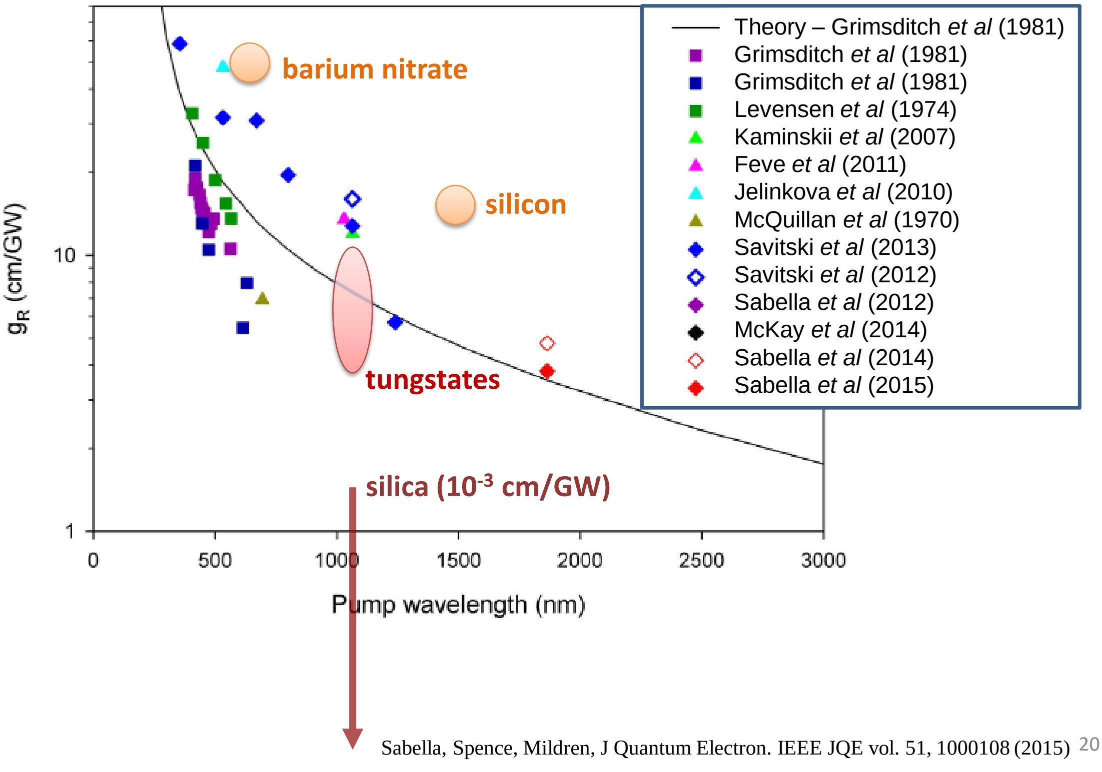
Differential c

$$\frac{\mu_s h}{4\pi\mu_L c^4}$$

Raman gain c

$$\frac{4\pi^2}{\mu_L\mu_s c^2}$$

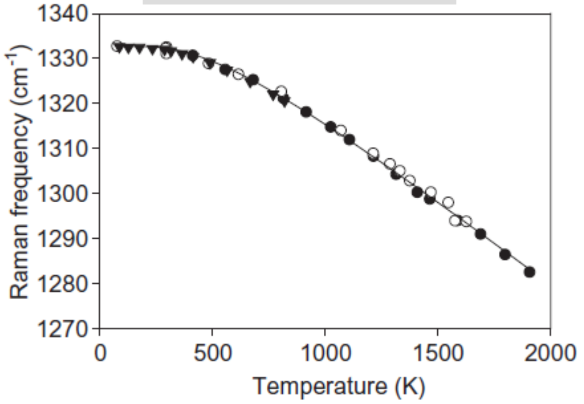
Wavelength dependence of Raman gain



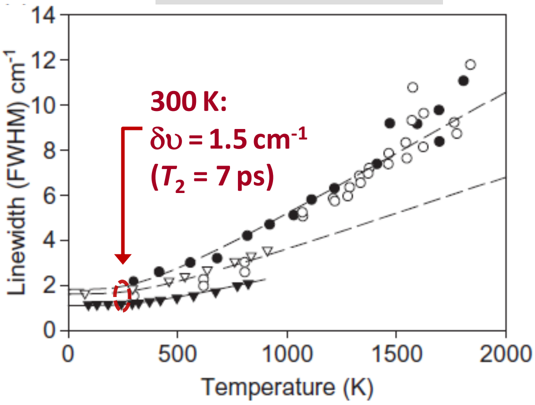
Sabella, Spence, Mildren, J Quantum Electron. IEEE JQE vol. 51, 1000108 (2015) 20

Raman: Temperature and isotopic Purity

Frequency



Linewidth

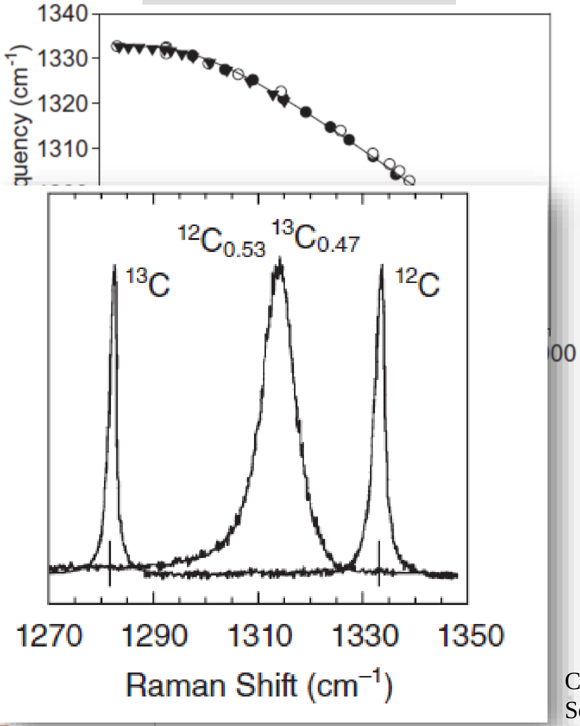


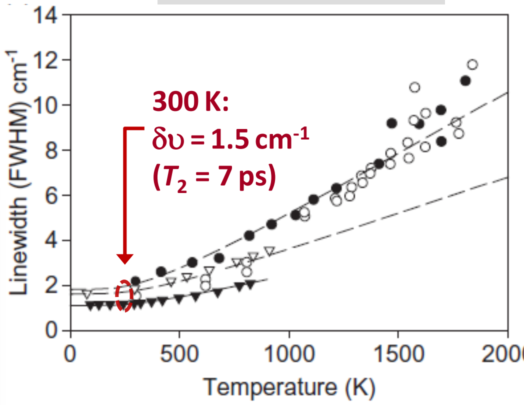
barium nitrate	silicon	diamond
T_2 = 26 ps	~ 6 ps	7 ps

Raman: Temperature and Isotopic Purity

Frequency

Linewidth



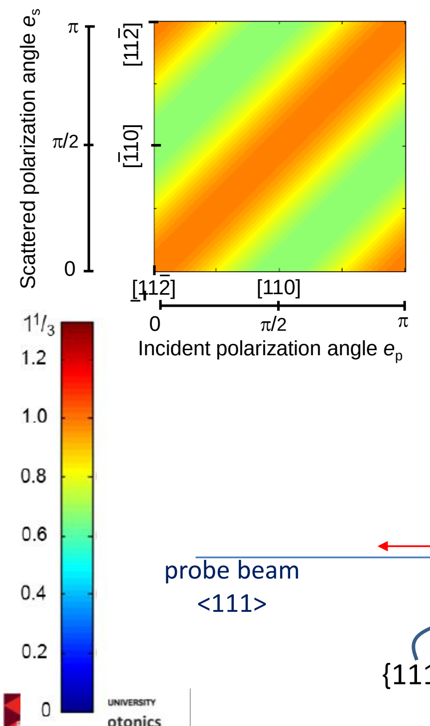


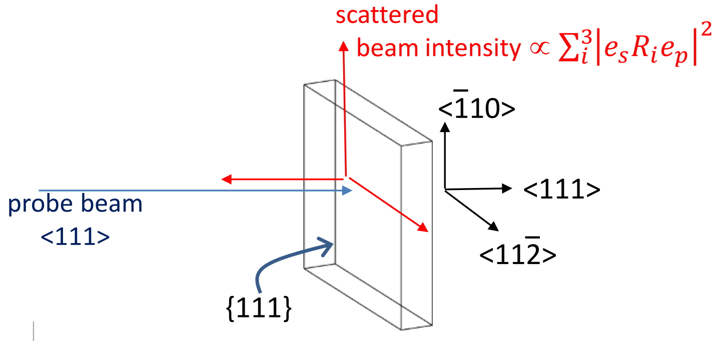
barium nitrate	silicon	diamond
T_2 = 26 ps	~6 ps	7 ps

Cardona & Ruf,
Solid State Commun. 117 (2001)

Raman: Polarization dependence

For / Back
Scatter



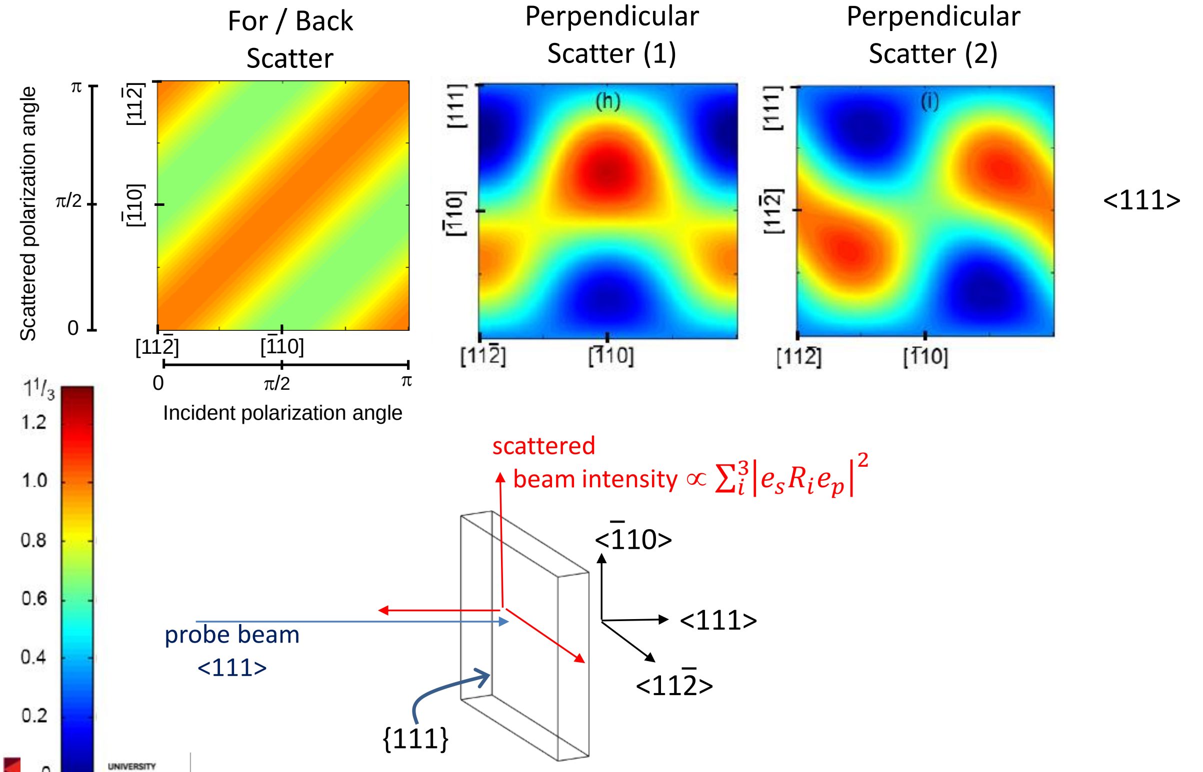


$$R_1 = \begin{bmatrix} 0 & \frac{d}{\sqrt{3}} & \frac{d}{\sqrt{6}} \\ \frac{d}{\sqrt{3}} & \frac{2d}{3} & -\frac{d}{3\sqrt{2}} \\ \frac{d}{\sqrt{6}} & -\frac{d}{3\sqrt{2}} & -\frac{2d}{3} \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0 & \frac{d}{\sqrt{3}} & \frac{d}{\sqrt{6}} \\ \frac{d}{\sqrt{3}} & -\frac{2d}{3} & \frac{d}{3\sqrt{2}} \\ \frac{d}{\sqrt{6}} & \frac{d}{3\sqrt{2}} & \frac{2d}{3} \end{bmatrix}.$$

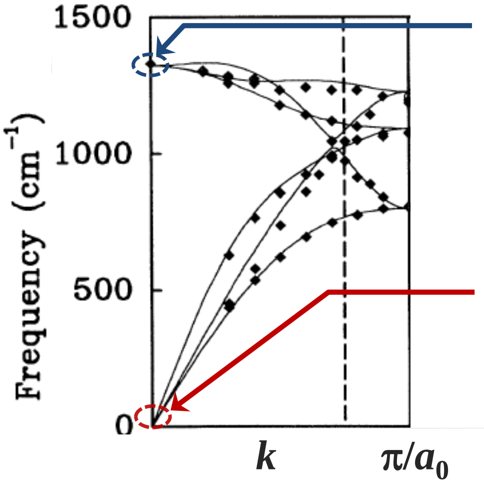
$$R_3 = \begin{bmatrix} d & 0 & 0 \\ 0 & -\frac{d}{3} & \frac{\sqrt{2}d}{3} \\ 0 & \frac{\sqrt{2}d}{3} & -\frac{2d}{3} \end{bmatrix}$$

Polarization dependence



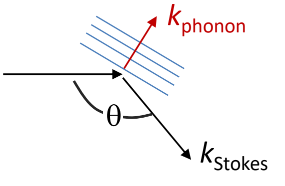
Brillouin scattering

<u>Optical and Acoustic Phonon Branches</u> [Pavone *et al*, PRB, 48 3156 (2003)]



Raman scattering:
Optical branch
ω_R = 1332.3 cm^{-1} (40 THz)

Brillouin scattering:
Acoustic branch
$\omega_B = 2\omega_0 . n v_s / c \, \mathrm{Sin}(\theta/2)$



Brillouin scattering

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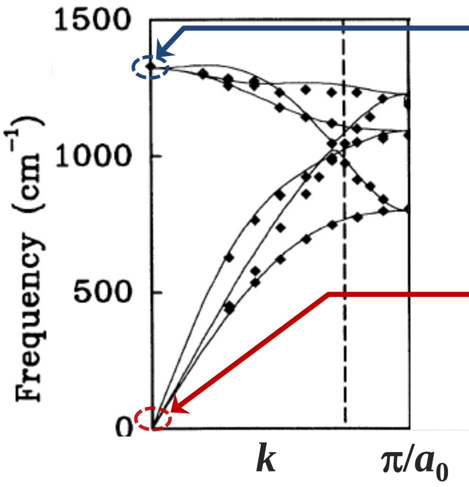

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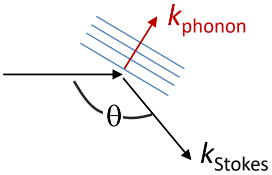
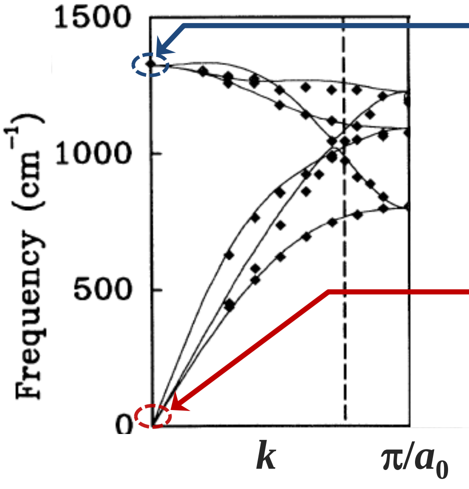


	Glass	Silicon	Diamond
Speed of sound v_s (Longitudinal) [ms^{-1}]	4000-6000	5840	18350
ω_B [GHz] (1500 nm)	8 - 12	26	57

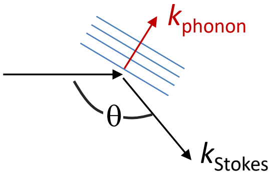
Brillouin scattering

Optical and Acoustic Phonon Branches [Pavone *et al*, PRB, 48 3156 (2003)]



Raman scattering:
Optical branch
ω_R = 1332.3 cm^{-1} (40 THz)

Brillouin scattering:
Acoustic branch
$\omega_B = 2\omega_0.nv_s/c$ Sin(θ/2)



	Glass	Silicon	Diamond
Speed of sound v_s (Longitudinal) [ms^{-1}]	4000-6000	5840	18350
ω_B [GHz] (1500 nm)	8 - 12	26	57
p_{11}	0.13	-0.17	-0.25
P_{12}	0.21	-0.05	0.04
p_{44}	-0.04	-0.05	-0.17

Scattering efficiency
$S \sim p^2n^8$

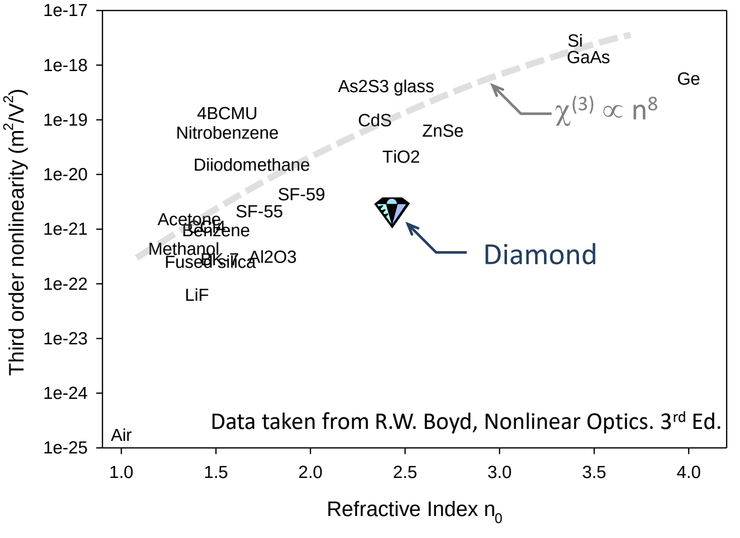
Acousto-optic
$FoM \sim p^2n^6/v_s^3$

SBS gain coefficient
$g_B \sim p^2n^7T_2$

27

Kerr nonlinearity

Comparison with other materials

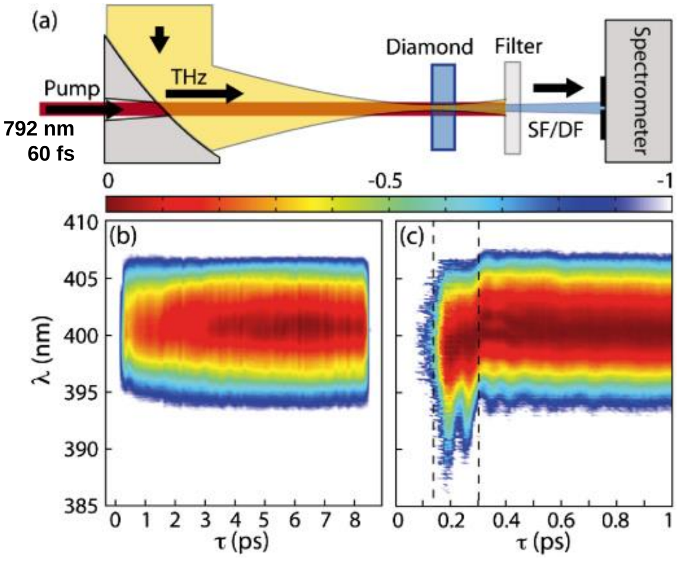


Low Kerr nonlinearity:

- **High critical power for self-focusing = 1-2 MW**
- **Low self-phase modulation**
- **Low four wave-mixing gain**

Sheik-Bahae *et al*, Proc. SPIE, 1624, (1992)
Sheik-Bahae *et al* Proc. SPIE, 2428, (1995)
Zhao *et al*, Chin. Opt. Lett. , 8 (2010)
Kozák *et al*, JOSAB, 142 (2012)

Example: Four wave mixing in diamond

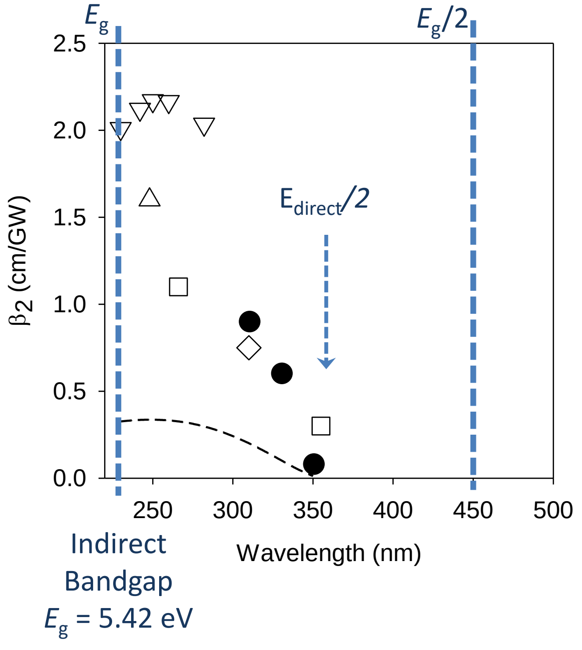


$\omega_{output} = 2\omega_p \pm \omega_{THz}$

Phase-matching achieved for co- and counter- propagating THz beams

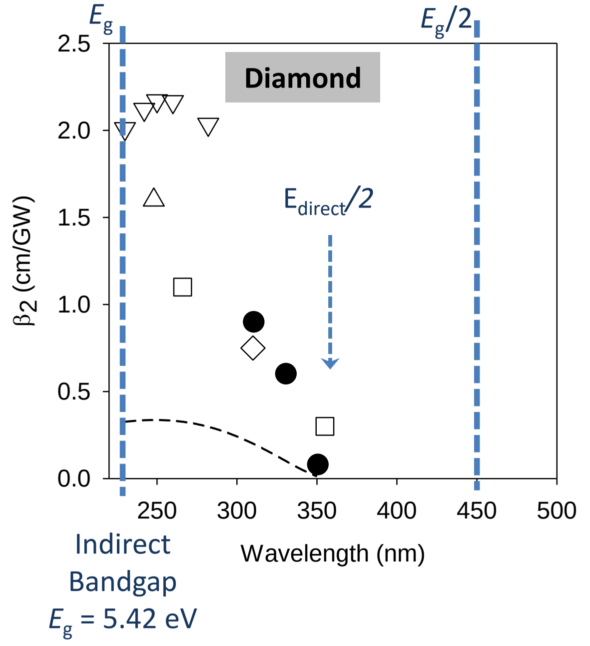
Clerici, et al, *Opt. Lett.* 38, 178-180 (2013)

Two-photon absorption

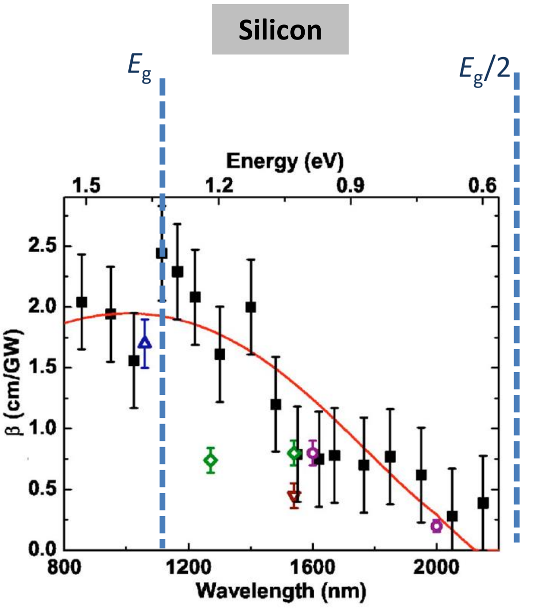


Sheik-Bahae *et al*, Proc. SPIE, **1624**, (1992)
Sheik-Bahae *et al* Proc. SPIE, **2428**, (1995)
Kozák *et al*, JOSAB, **142** (2012)
Preuss and Stuke, Appl. Phys. Lett. , **67** (1995)
Gagarskii and Prikhodko J. Opt. Technol., **75** (2008)

Two-photon absorption

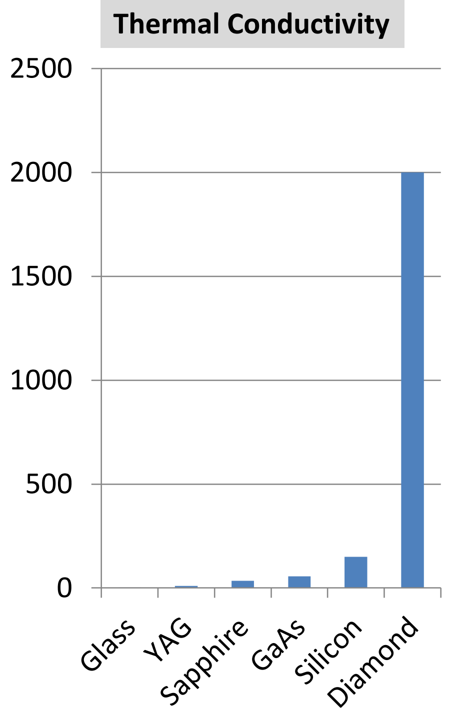


Sheik-Bahae *et al*, Proc. SPIE, **1624**, (1992)
Sheik-Bahae *et al* Proc. SPIE, **2428**, (1995)
Kozák *et al*, JOSAB, **142** (2012)
Preuss and Stuke, Appl. Phys. Lett. , **67** (1995)
Gagarskii and Prikhodko J. Opt. Technol., **75** (2008)



Bristow, *Appl. Phys. Lett.*, **90** 191104 (2004)

Thermo-optic properties

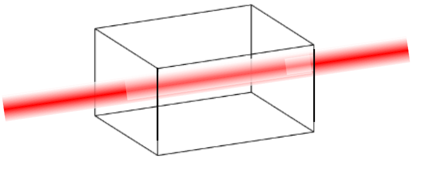


Thermal conductivity	**κ = 2000 W/m.K**
Thermal expansion	**α_T = 1.1 x 10^{-6} /K**
Thermo-optic coeff.	**dn/dT = 16 x 10^{-6} /K**

Thermally-induced lens

$$f^{-1} = \frac{P_{\text{dep}}}{2\pi\kappa\omega_0^2}\left(\frac{dn}{dT} + (n-1)(\nu+1)\alpha_T + n^3\alpha_T C_{r,\phi}\right)$$

Lens strength = *Thermo-optic* + *End-face distortion* + *Stress Birefringence*



$\tau \sim 10^{-5}$ s !!

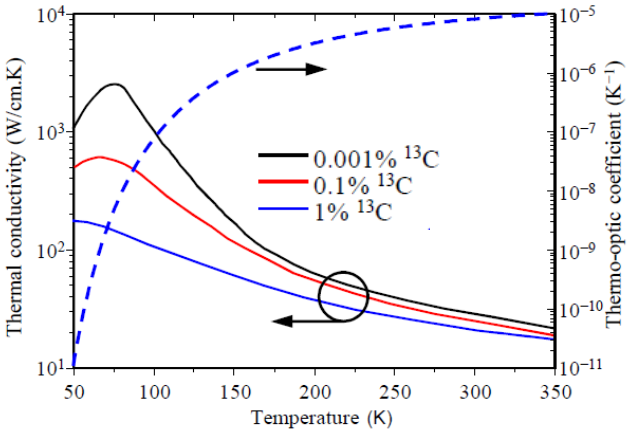
	Key Parameter	Diamond : YAG
Stress fracture limit	κ/α_T	1100:1
Stress birefringence	κ/α_T	1100:1
Crystal distortion	κ/α_T	1100:1
Thermo-optic lens	$\kappa/ {}^{dn}/_{dT}$	85:1

Thermal conductivity (κ)

Thermal expansion coefficient (α_T)

Cryo Cooling: Natural and Enriched diamond

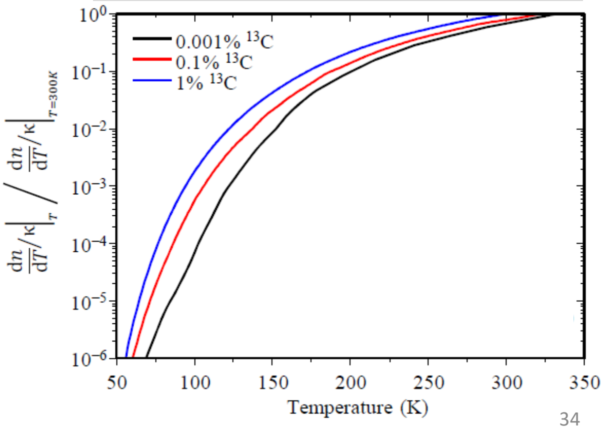
Thermal conductivity κ and d*n*/dT



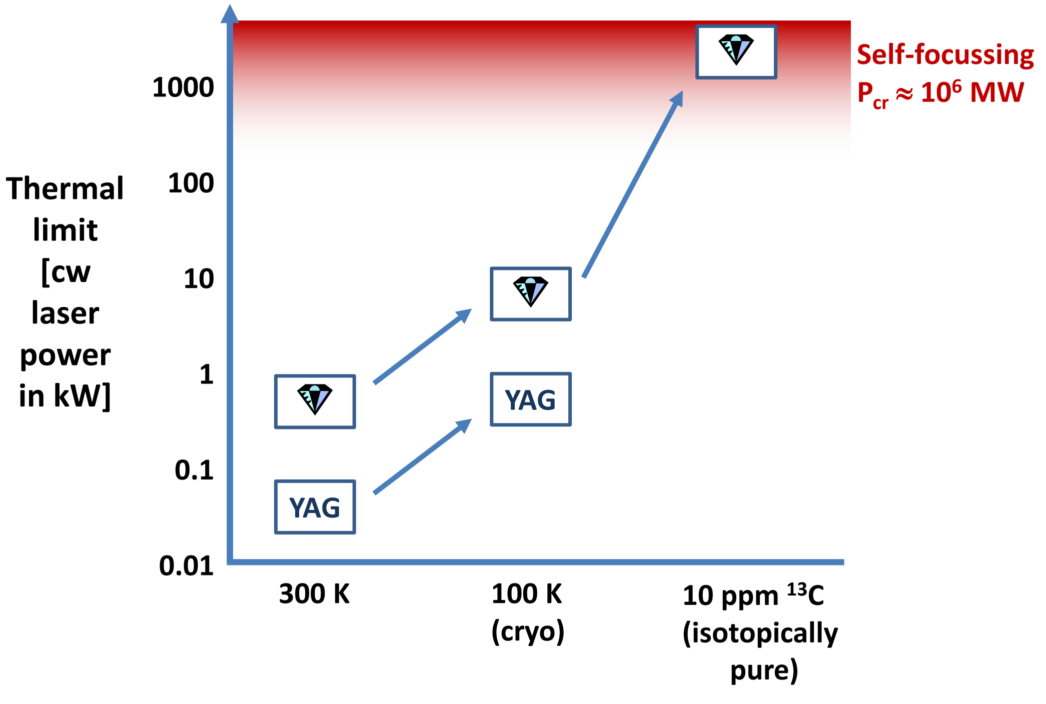
At *T* = 100 K:
10^2 enhancement for natural diamond
10^4 enhancement for enriched 0.001%

Wei et al, *Phys Rev Lett*, 70: 3764 (1993)
Ruf et al, *Phys Rev B*, 62: 16578 (2000)
McKay et al, *Laser and Photonic Reviews* (2016)

Thermal Susceptibility d*n*/dT/κ



Manipulating material properties



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Properties Summary:

Extremely good	"Un-exceptional"	Poor
Transmission range	Refractive index	Mid-infrared transmission (4-6 μm)
Thermal conductivity	Raman gain coeff. (visible and infrared)	Thermo-optic coefficient ($T > 250$K)
UV Raman gain coeff.	Phonon dephasing time	
Brillouin frequency	Photoelastic coefficient	
Low Kerr nonlinearity	Two-photon absorption only strong close to bandgap	
Low optical phonon population at room temperature	Pulsed damage threshold	
CW damage threshold		

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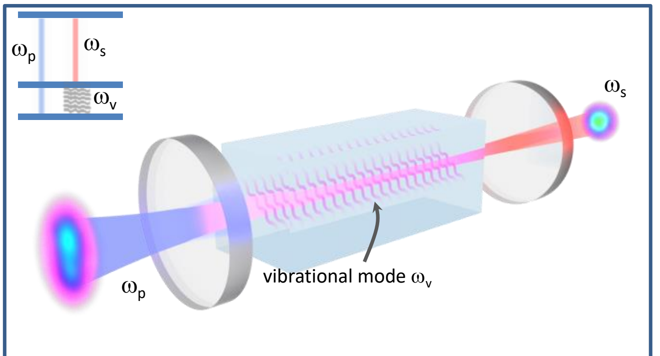
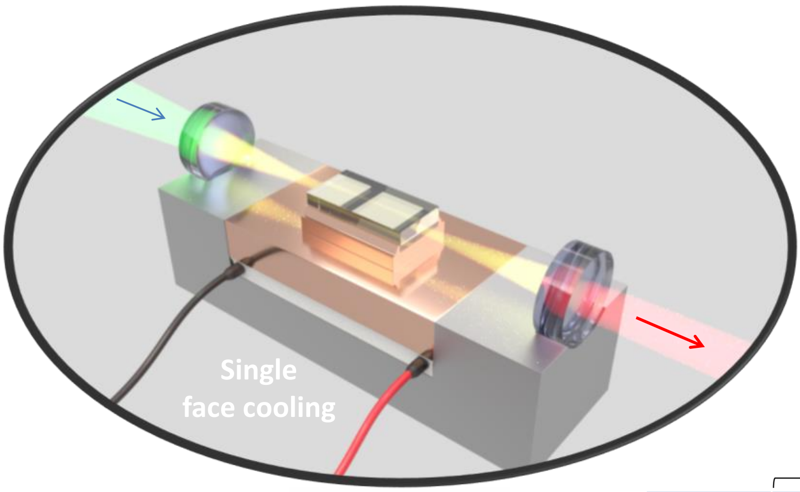
The Raman laser



1962 *(Woodbury, Eckhardt)*

Optical Mixing	Raman Lasers	Fluorescence Lasers
$\chi^{(2)}, \chi^{(3)}$	$\chi^{(3)}$	energy storage in medium
harmonics, anti-/-Stokes	Stokes shift	Stokes shift
phase matched	"auto-phasematched"	incoherent pumping
continuous tuning (OPOs)	beam cleanup	brightness enhancement
aberrations preserved	cascadable	

External Cavity Raman Laser



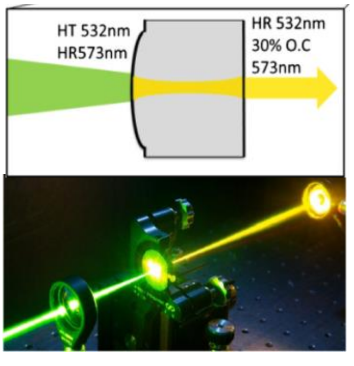
ω_v = 1332 cm^{-1} →

Stokes Order

Wavelengths (nm)

Pump λ	First	Second	Third
266	276	286	298
532	573	620	676
1064	1240	1485	1851

Examples …



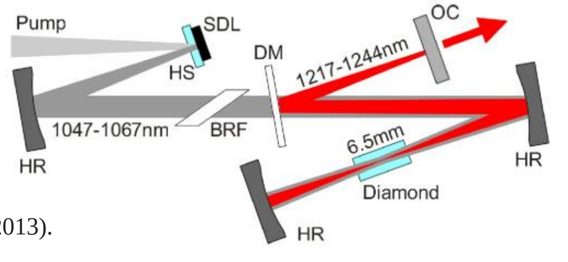
<u>Monolithic External Cavity Raman Laser</u>

- Record efficiency 84%
- 134 mW, 10 kHz, 1.5 ns pulses

Reilly et al, *Opt. Lett*. 40, 930 (2015)

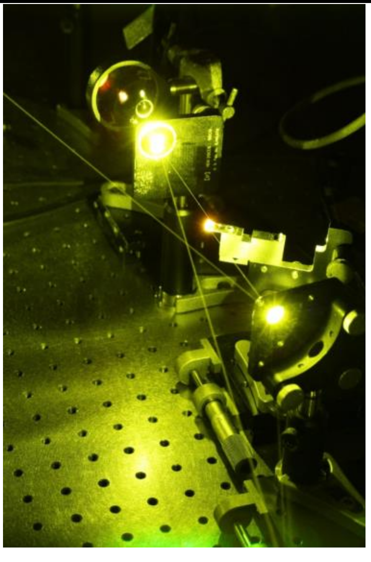
<u>Intracavity CW Raman Laser</u>

- Tunable output via pump tuning
- 4.4 W max, 1217-1244 nm



Parrotta et al, *Opt. Express* 19, 24165 (2011)
IEEE J. Sel. Topics Quantum Electron. 19, 1400108, (2013).

Examples …



Synchronously Pumped, Ultrafast

- 2.2 W, 21 ps, 573 nm

Spence et al, *Opt. Lett.*, vol. 35, 556, (2010).

(25 fs recently demonstrated)

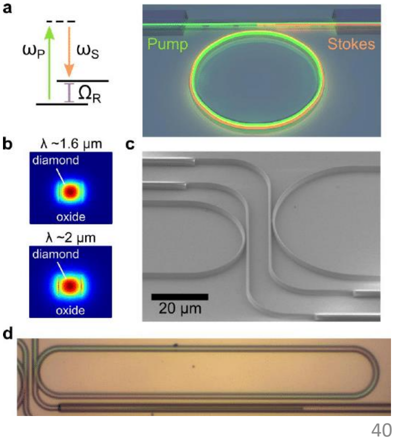
Lin et al, *Opt. Lett.*, *41*, 1861 (2016)

On-Chip Racetrack Resonator

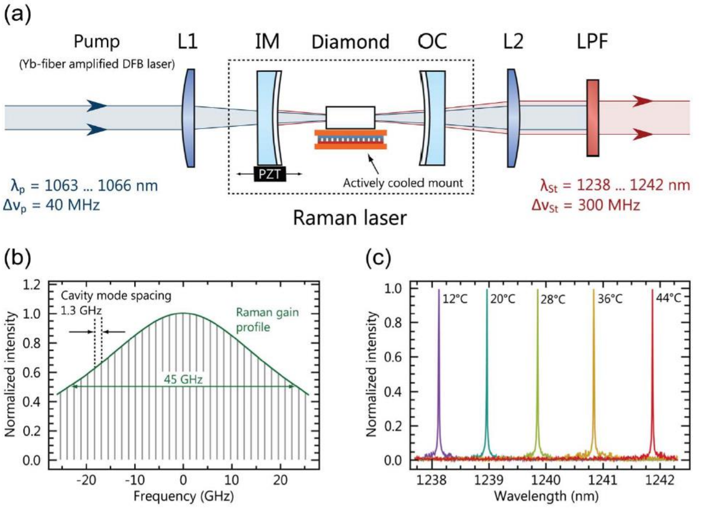
- Tunable output near 2 micron
- 85 mW threshold

(no free carrier absorption)

Latawiec, et al., *Optica*, 2, 11, 924 (2015).



Examples …

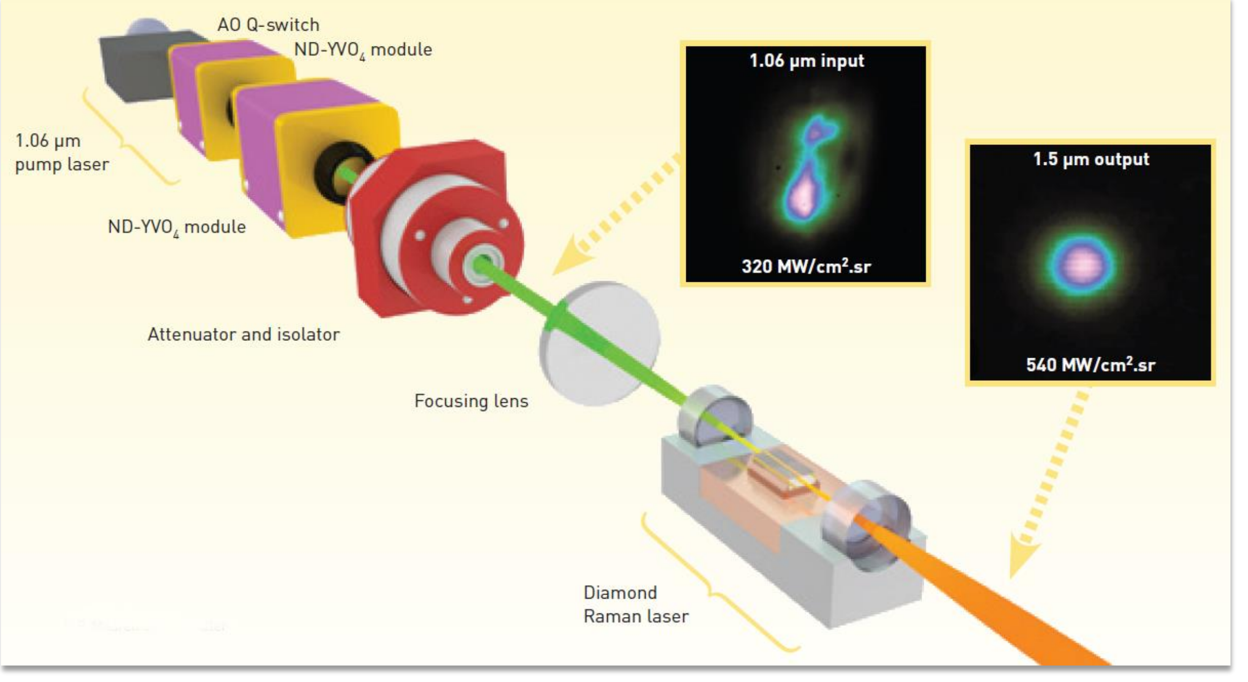


Single longitudinal mode

- Exploits lack of the spatial hole burning in a Raman gain medium
- 3 W, tunable across 1235-1245 nm

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

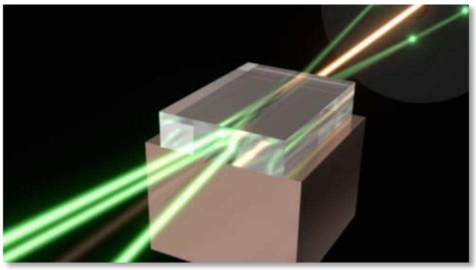
Simultaneous brightness & λ conversion



AM McKay, O Kitzler and RP Mildren, *Laser & Photonics Rev.* 8, (2014)

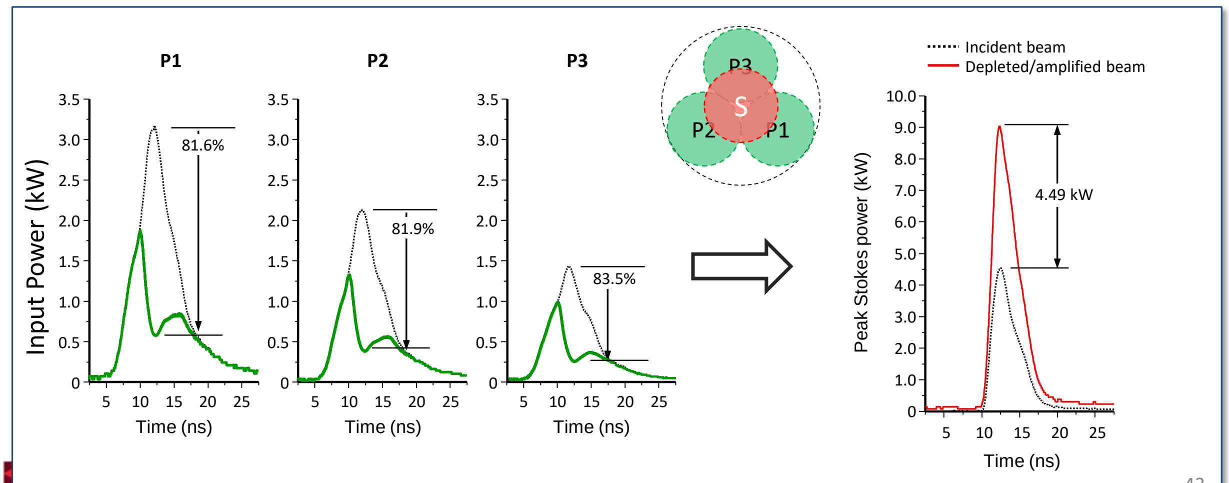
Non-collinear Raman beam combination

In diamond:



$\Delta\omega_R$ = 30 GHz
g_R ~ 10 cm/GW
κ = 2000 W/m.K
=>

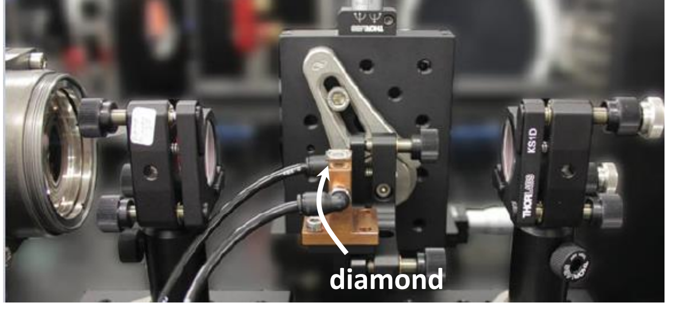
- Multimode, uncorrelated, pumps
- Short interaction lengths
- High average power

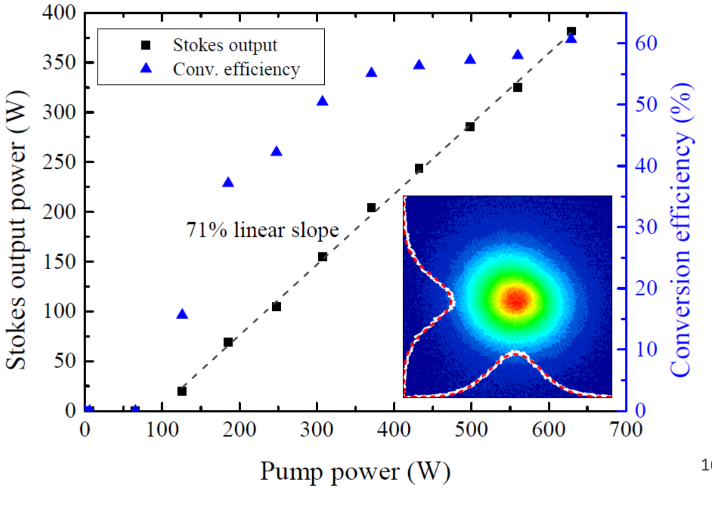


McKay, Coutts, Spence, Mildren , *Laser and Photonics Reviews* (2016)

Fiber laser pumped

Input
1 kW CW
1060 nm
Linewidth 30 GHz
Circular polarization





- 150 W for 5s
- 380 W for 10 ms

(steady-state = 10μs)

Collaborators: J. Nold, M. Strecker and T. Schreiber at the Fraunhofer IOF (Institute of Applied Optics and Precision Engineering), Jena, Germany

R. J. Williams, J. Nold, M. Strecker, O. Kitzler, A. McKay, T. Schreiber, R. P. Mildren, Laser Photon. Rev., **9** p405 (2015)

Review Sources

PHYSICAL REVIEW VOLUME 161, NUMBER 3 15 SEPTEMBER 1967

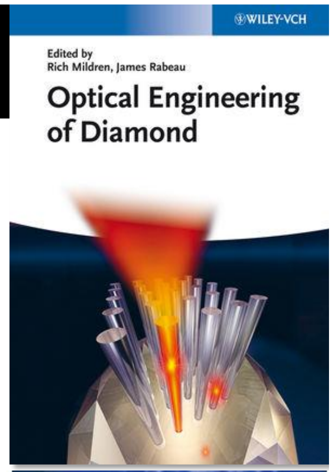
Optical Study of the Electronic Structure of Diamond*

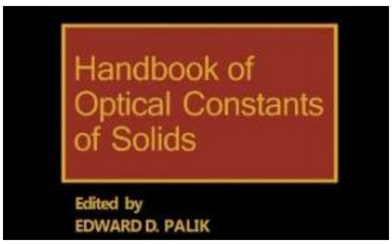
R. A. ROBERTS† AND W. C. WALKER

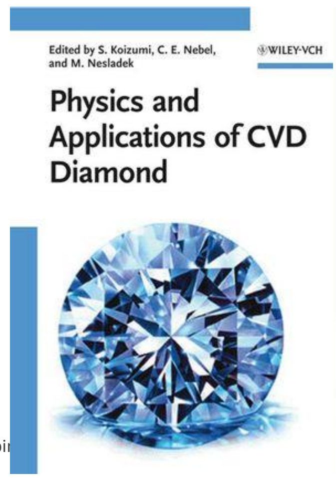
Rep. Prog. Phys., Vol. 42, 1979. Printed in Great Britain

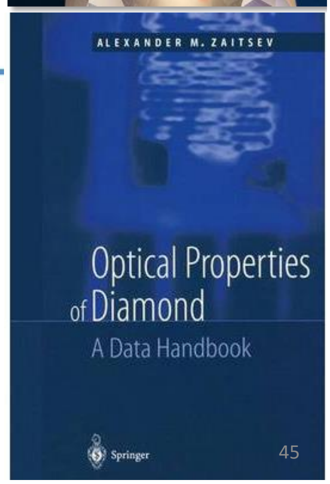
Optical absorption and luminescence in diamond

JOHN WALKER†









Optical properties of diamond

144 / SPIE Vol. 2286

Michael E. Thomas and William J. Tropf

Light Scattering in Solids II

by M. Cardona

Max-Planck-Institut für Festkörperforschung

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Eduardo Granados (SLAC)

Jipeng Lin (M-Squared Lasers)