

Rare earth doped non-oxide glasses for mid-IR fiber lasers

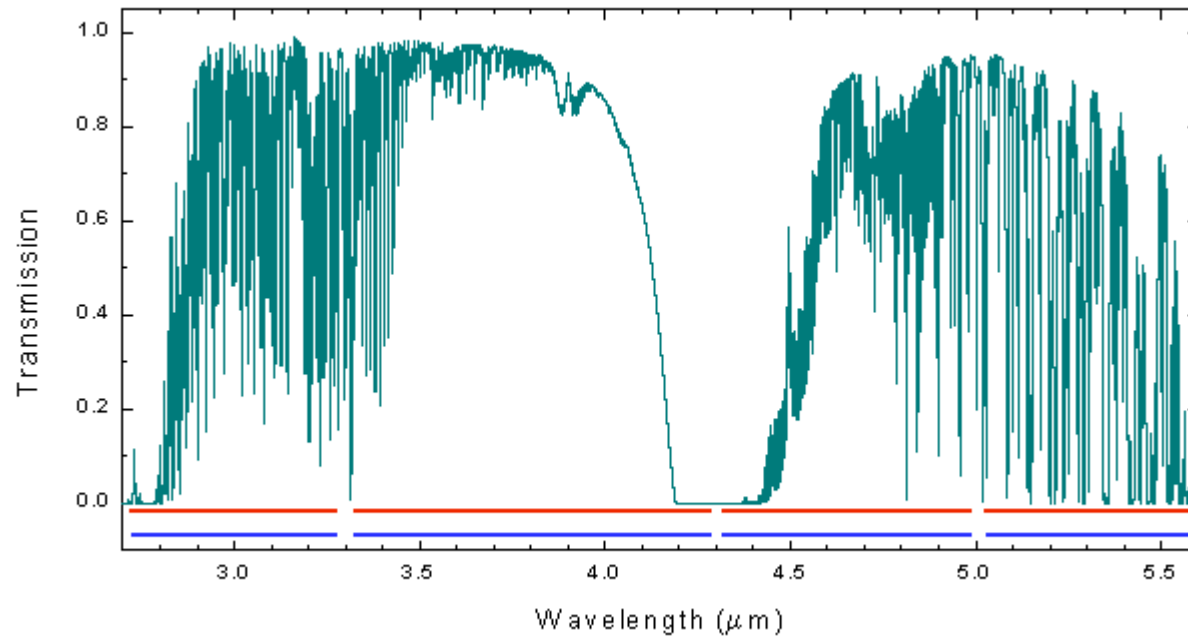
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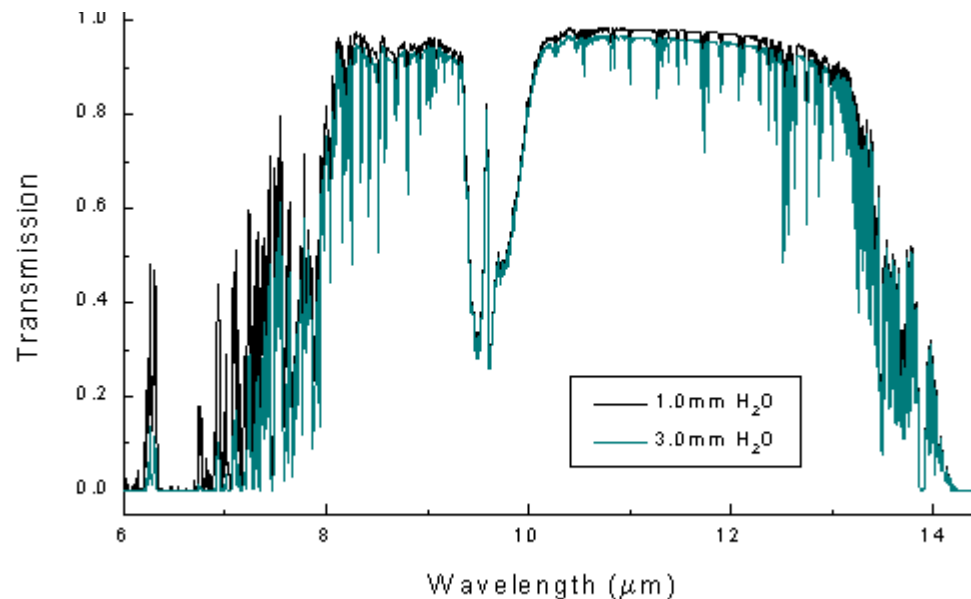
Outline:

1. Overview of mid-IR rare earth transitions
 - need for non-oxide glass host
2. Nonradiative relaxation
 - theory and experiment
3. Fiber lasers demonstrated to date
4. Fiber laser modeling
 - cascade lasing to avoid bottlenecking
 - include fiber attenuation loss

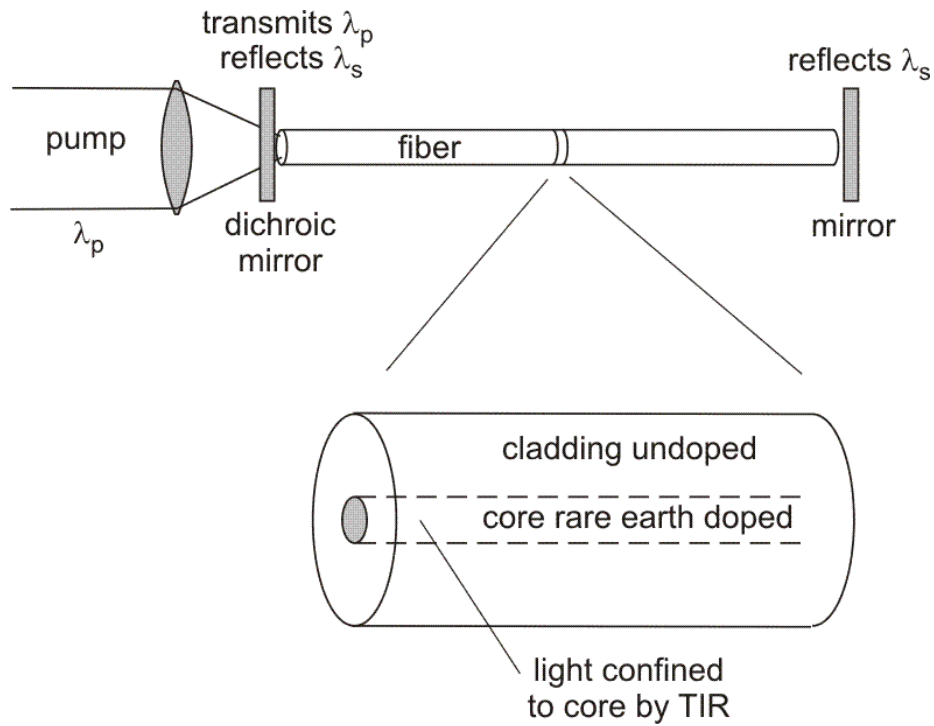
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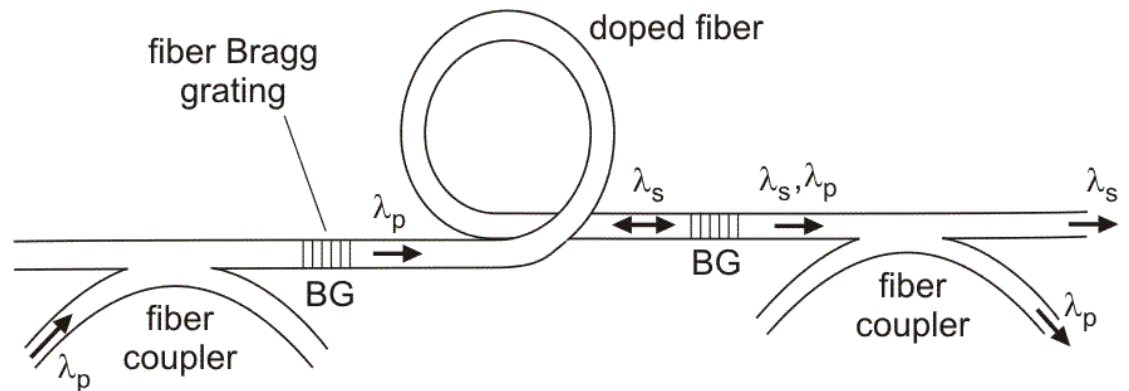
Atmospheric
transmission spectra
above Mauna Kea

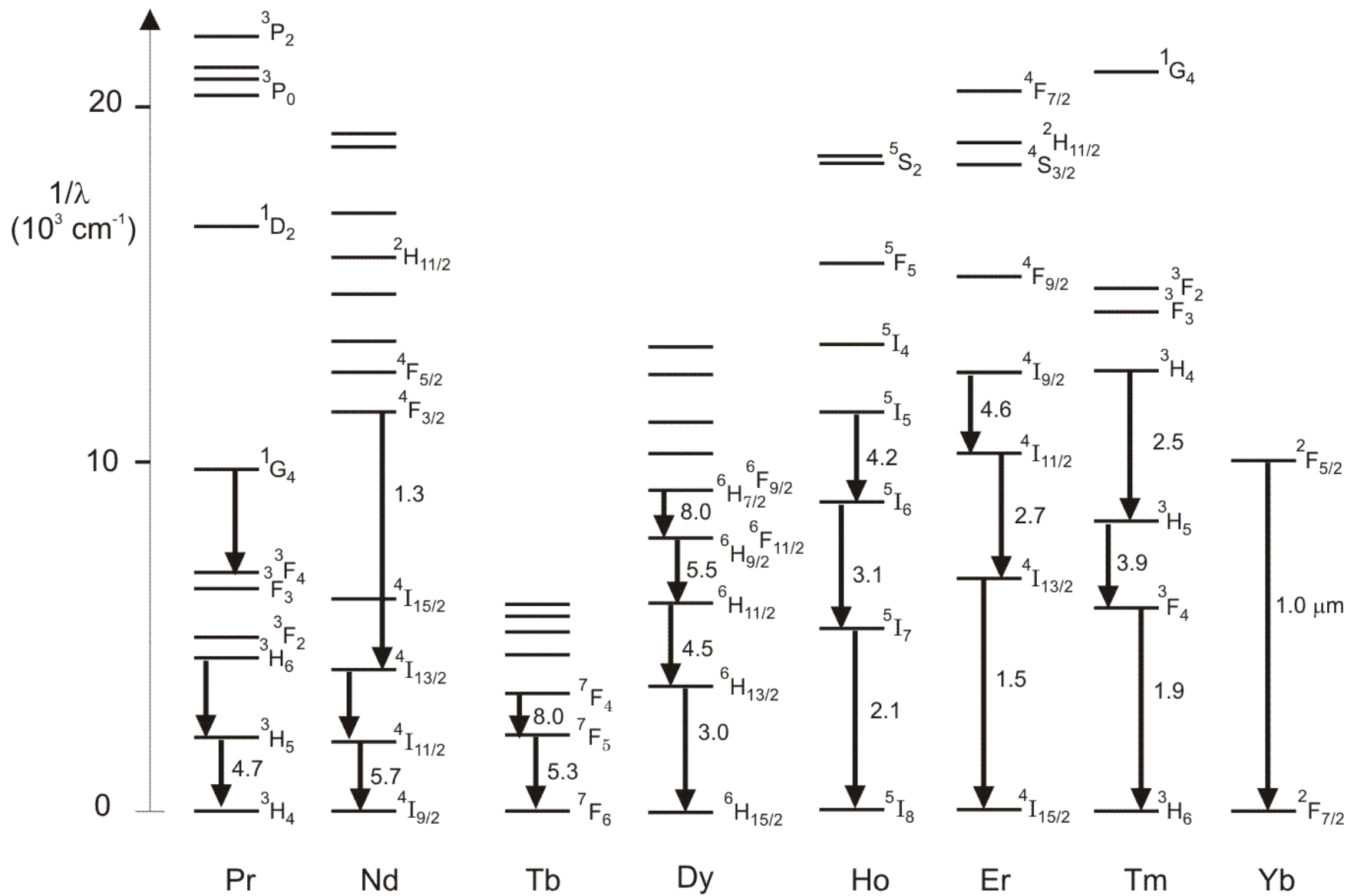


Note: For IRCM
avoid 4.2-4.5 μm
and 9.4-10 μm



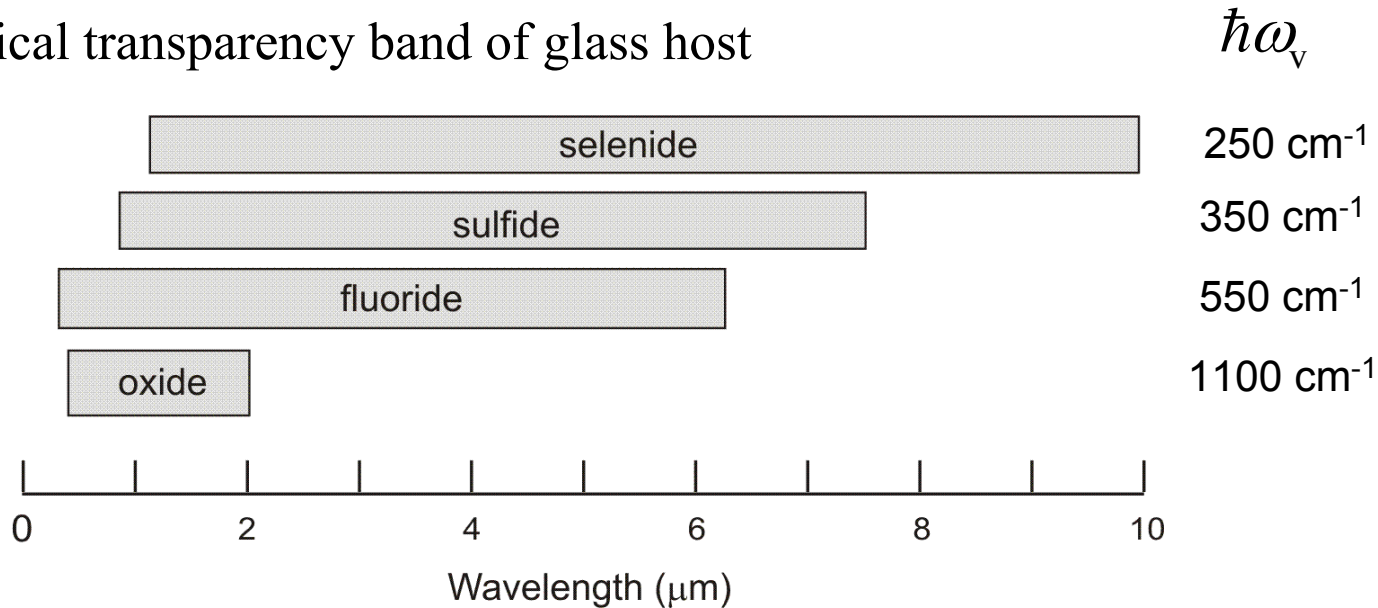
Fiber laser schemes



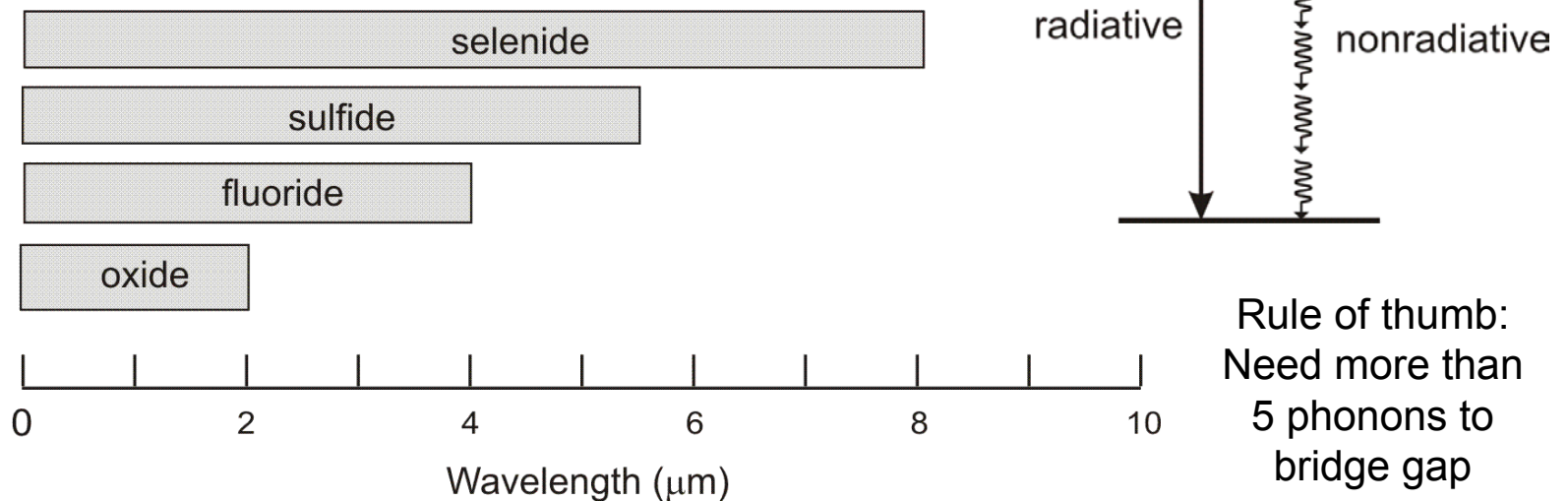


Upper limit on transition wavelength set by:

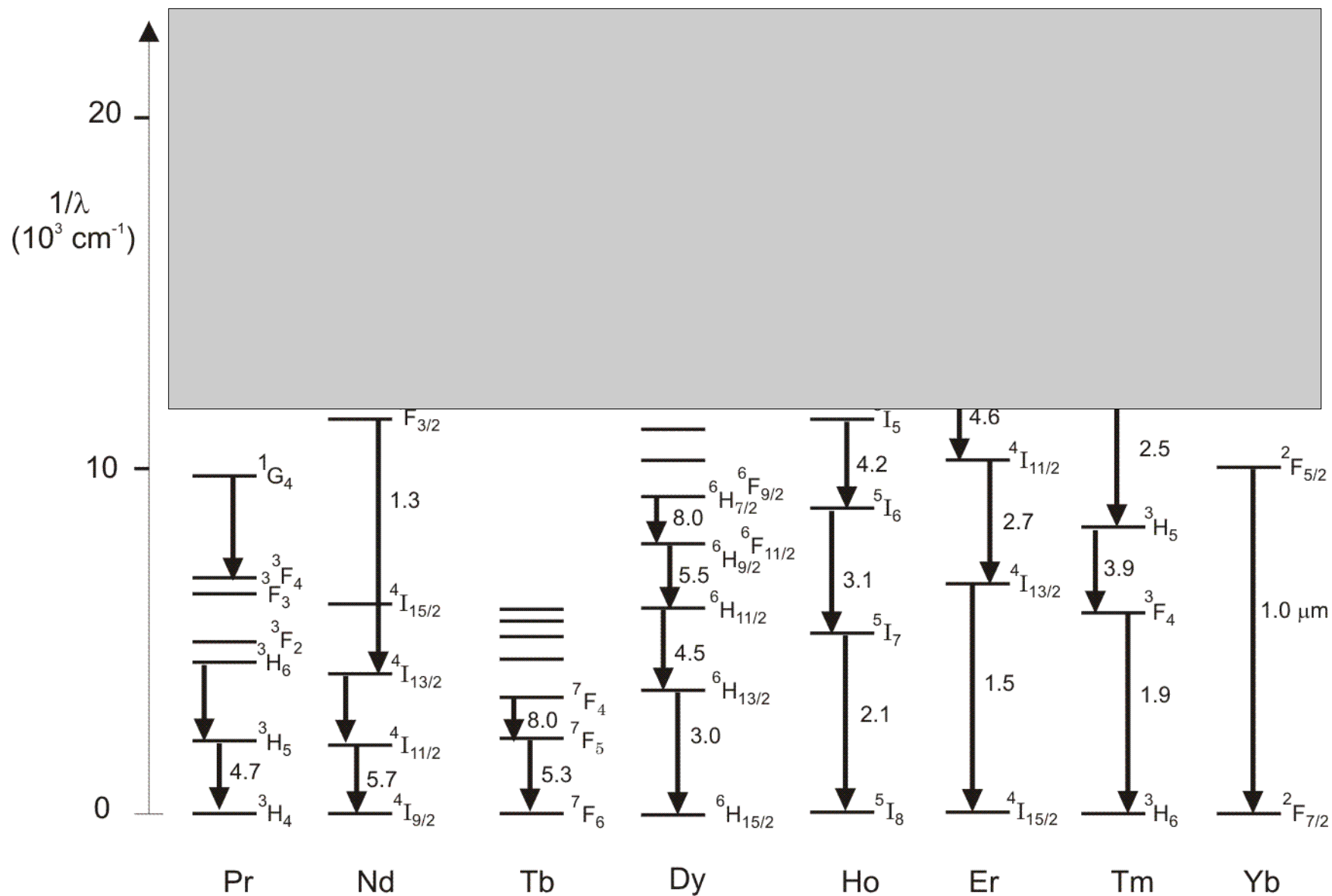
➤ Optical transparency band of glass host



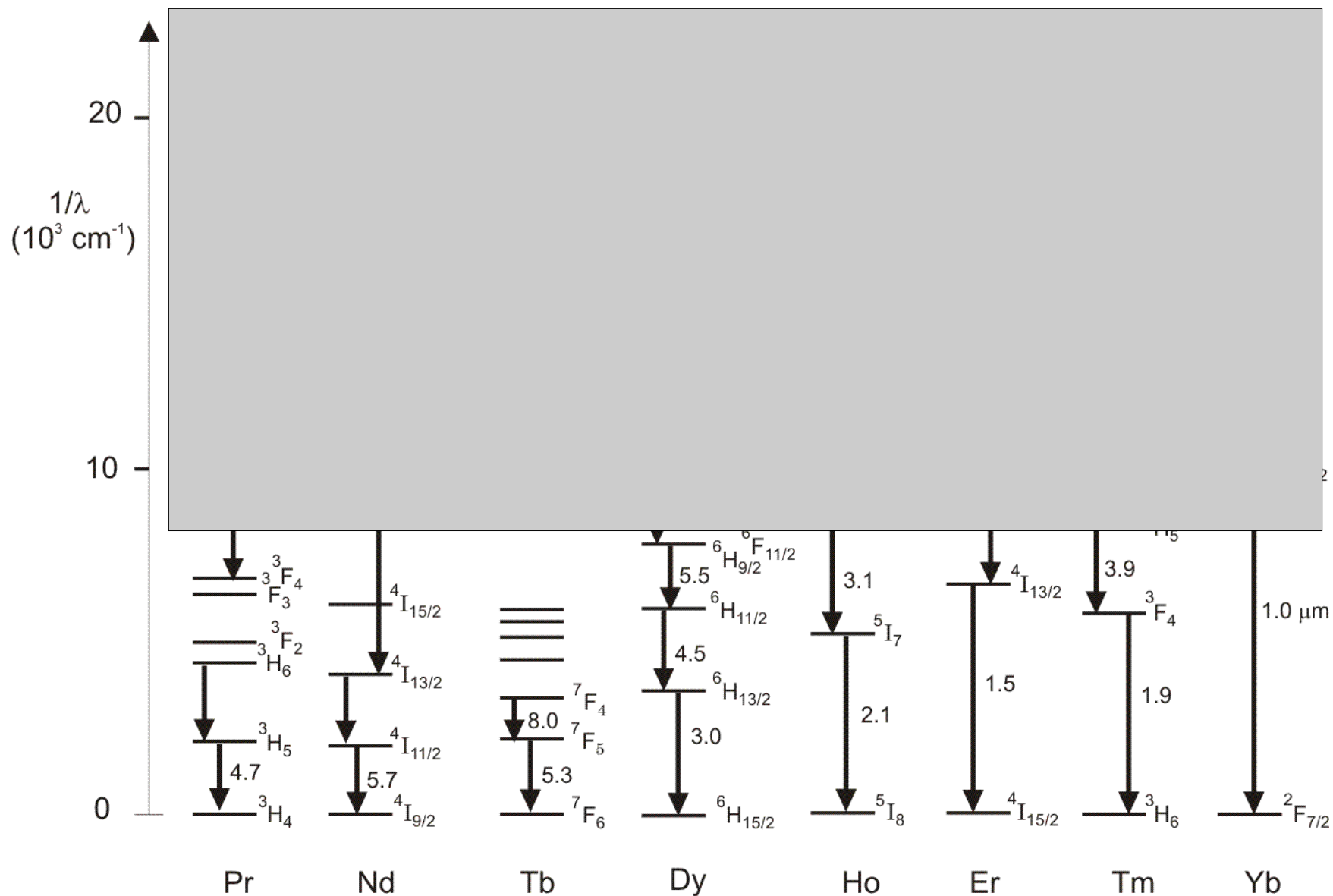
➤ Nonradiative quenching of upper laser level

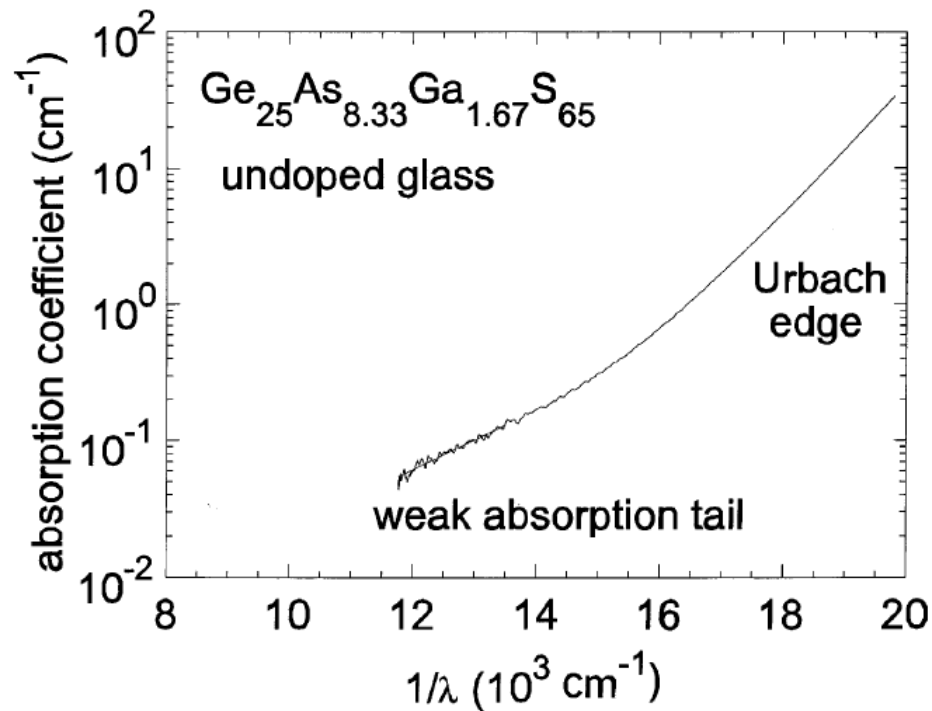


Sulfide glass host



Selenide glass host

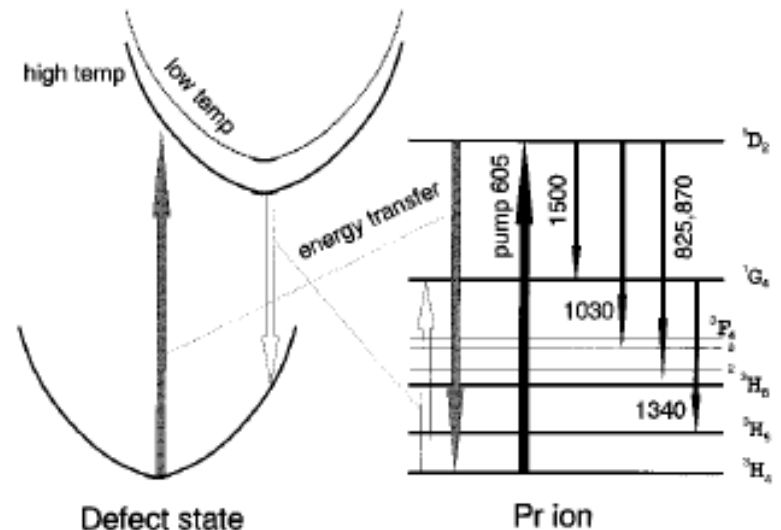




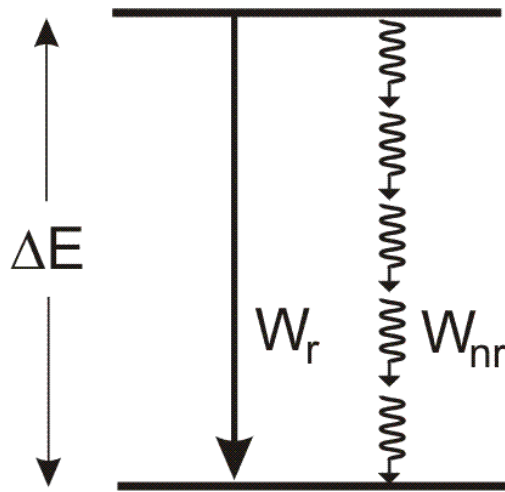
- Definition of band gap is somewhat arbitrary
- Can take $\alpha \sim 1 \text{ cm}^{-1}$ as measure of band edge
- Still absorption well below band edge due to defect states

- Energy can be transferred between rare earth and glass defect state

Quimby and Aitken, J. Appl. Phys. **82**, 3992 (1997)



Nonradiative relaxation: does the energy gap law work in chalcogenide glasses?



$$W_{\text{mp}}(T) = B[1 + n(T)]^p e^{-\alpha \Delta E} \quad \text{multiphonon relaxation rate}$$

$$n(T) = [e^{\hbar\omega/kT} - 1]^{-1} \quad \text{thermally generated phonons per mode}$$

$$p = \Delta E / \hbar\omega$$

number of phonons
needed to bridge gap

At finite temperature T:

$$W_{\text{mp}}(T) = B e^{-\alpha' \Delta E}$$

where

$$\alpha' \equiv \alpha - \frac{\ln(1 + n)}{\hbar\omega}$$

reduced logarithmic
slope at finite T

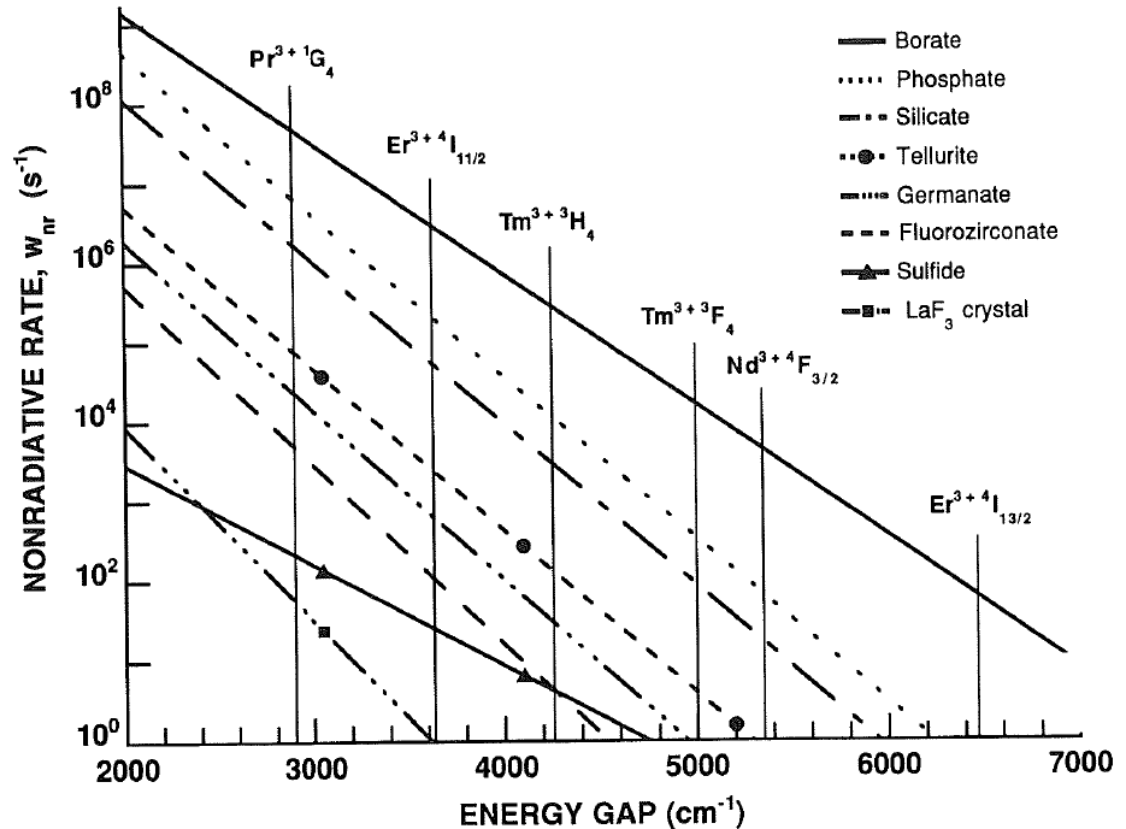
Verifying the energy gap law experimentally

Determine nonradiative rate from:

- Calculated radiative rate
 - Judd-Ofelt analysis or
 - reciprocity relation
- Measured total rate
 - fluorescence lifetime

$$1/\tau = W_r + W_{nr}$$

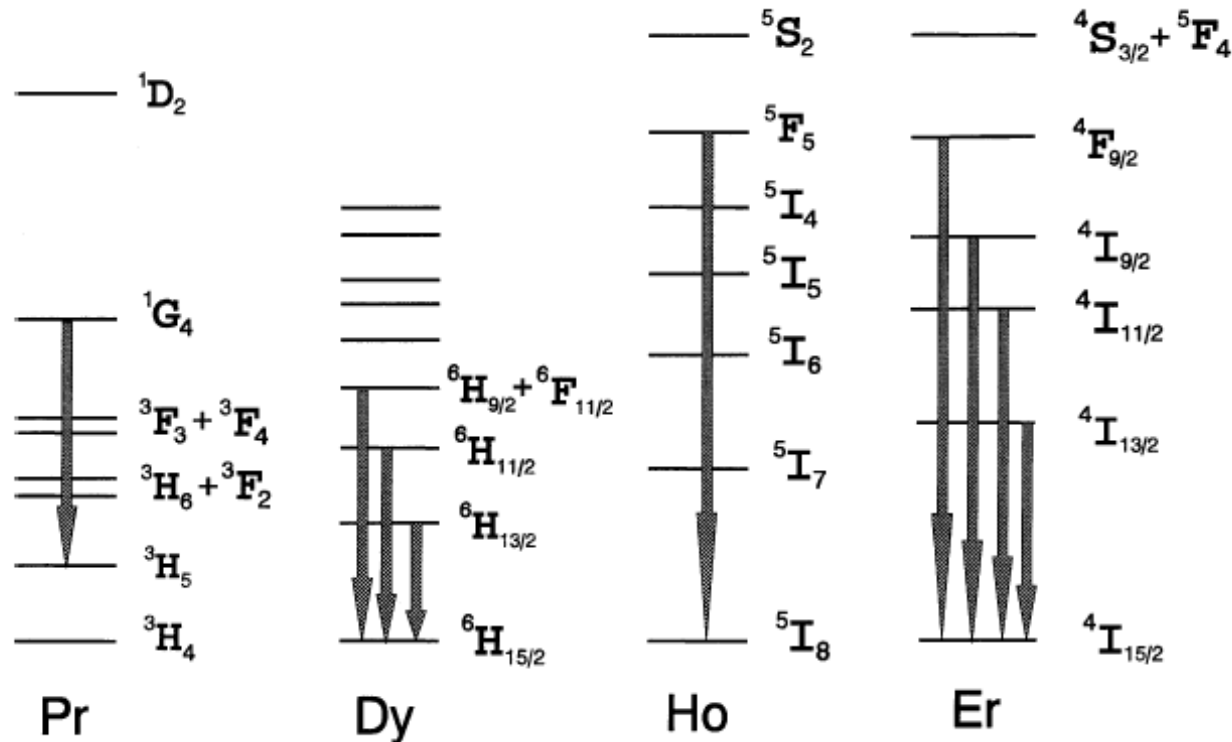
- sulfide glass appears anomalous in this plot (parameters from Reisfeld)
- question: are the nonradiative rates at large energy gap influenced by additional nonradiative processes?



from Miniscalco, in *Rare Earth Doped Fiber Lasers and Amplifiers*, ed. M.J.F. Digonnet (Marcel Dekker 1993)

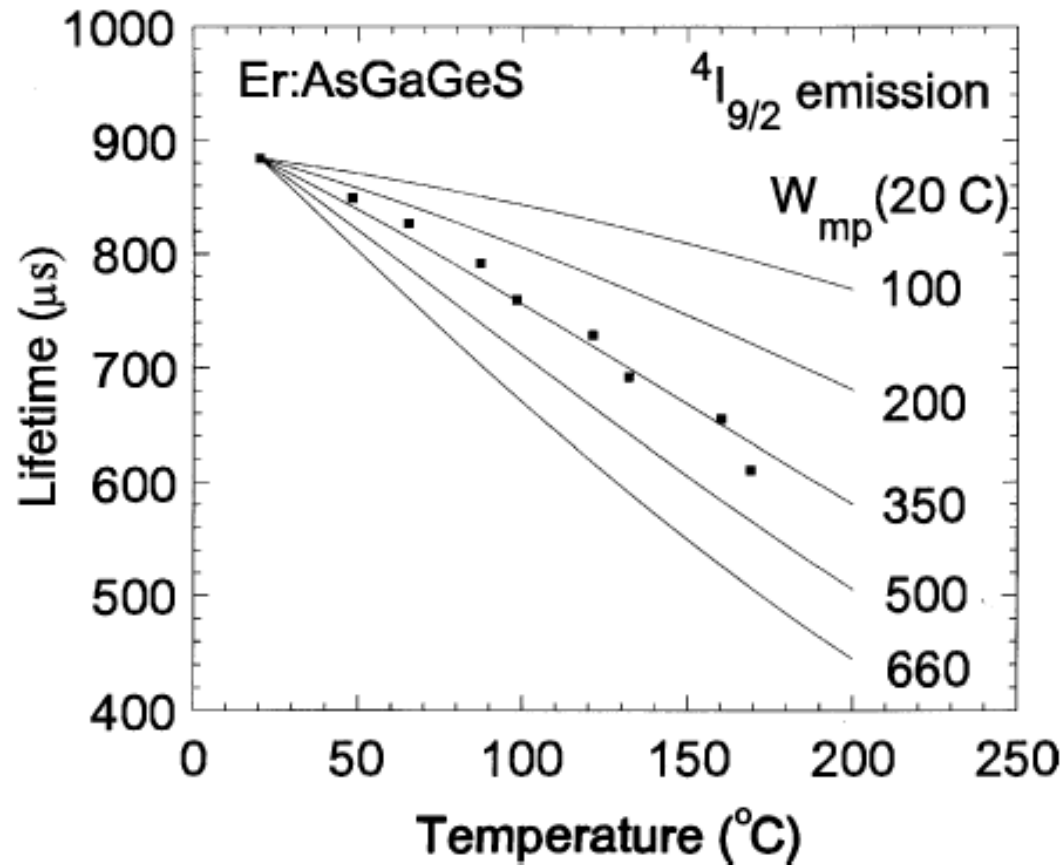
$$\frac{1}{\tau} = W_r + W_{mp} + W_{other}$$

Experimental determination of energy gap law parameters



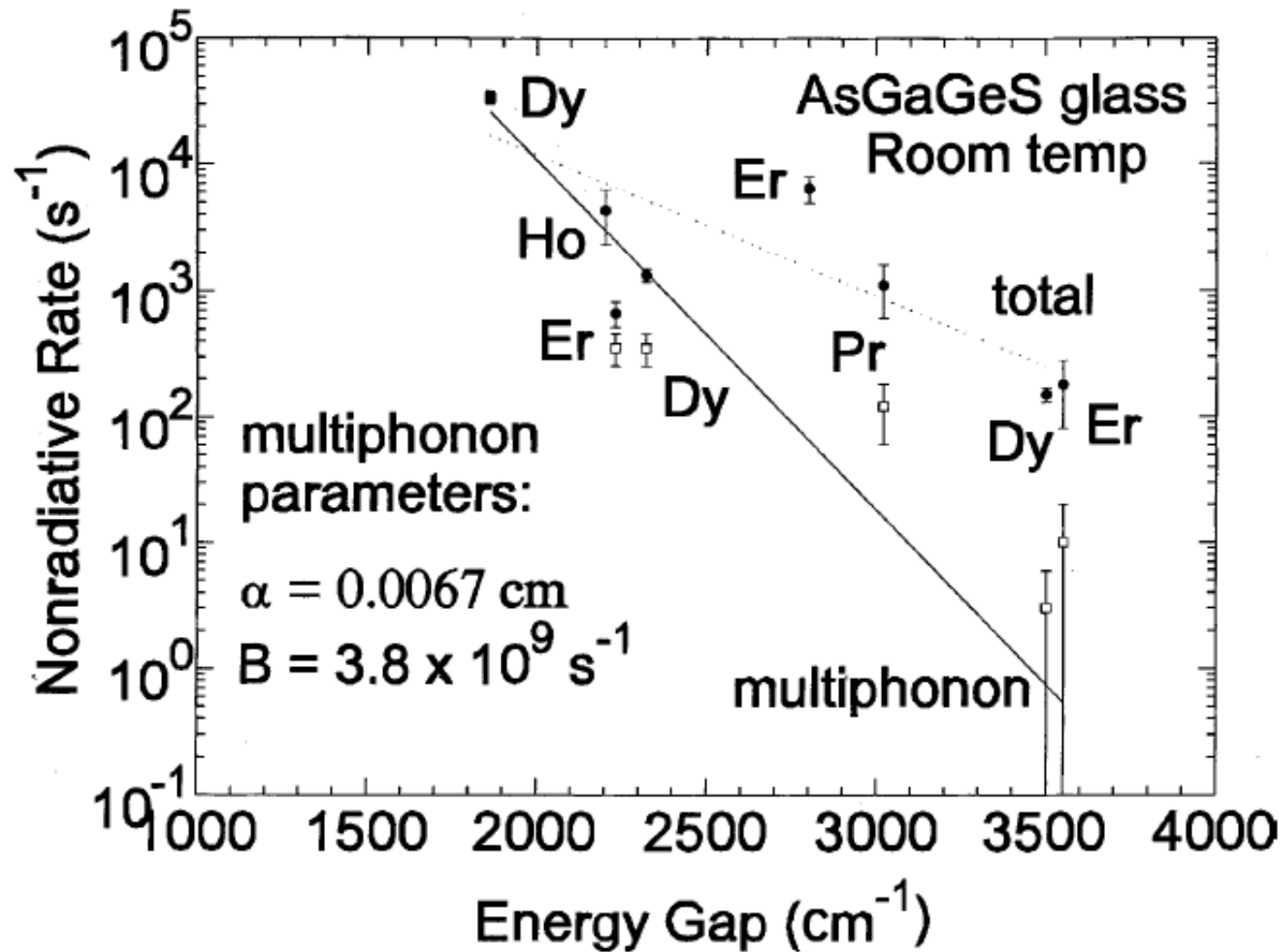
1. Measure absorption spectra, do Judd-Ofelt analysis
2. Calculate all radiative decay rates
3. Measure fluorescence lifetimes for above transitions
4. Determine total nonradiative rate from $W_{nr} = 1/\tau - W_r$
5. Vary temperature to determine the true multiphonon rate

Example variation of fluorescence lifetime with temperature



$$W_{mp}(T) = W_{mp}(20^{\circ}) \left[\frac{1 + n(T)}{1 + n(20^{\circ})} \right]^p$$

treat $W_{mp}(20^{\circ})$ as adjustable parameter to fit to the data



● total nonradiative decay rate

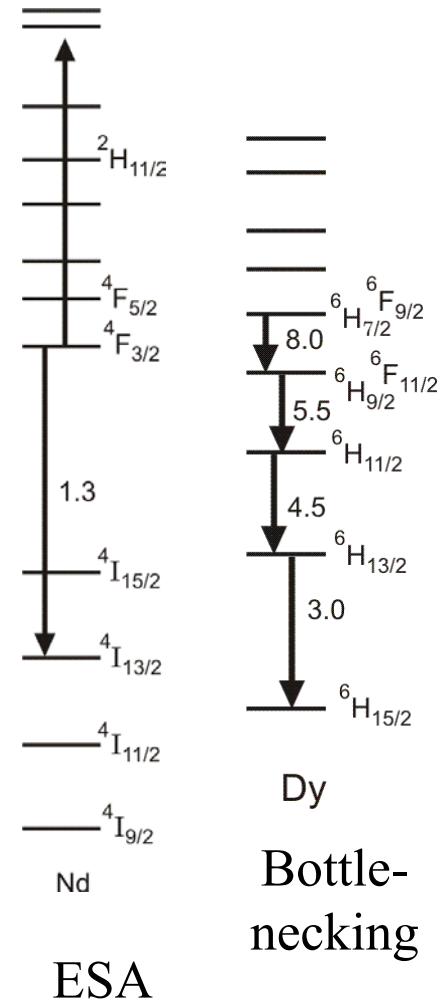
□ multiphonon decay rate

Origin of extra nonradiative decay

1. Is this real or experimental artifact?
 - Error bars are conservative, and difference is outside error bars
 - For ground state transitions use reciprocity as well as Judd-Ofelt
 - For Pr 1G_4 use additional independent method to measure QE
2. Possibly energy transfer to native defects in the glass
 - Mid-gap defect states responsible for photoluminescence, photodarkening, etc.
 - But some transitions (Er $^4I_{13/2} - ^4I_{15/2}$) do not suffer additional nonradiative decay
3. More likely: energy transfer to localized vibrational modes
 - H-S vibrations at 2500 and 3200 cm^{-1}
 - Resonance with several Pr, Dy, Er transitions
 - Er $^4I_{9/2}$ lifetime decreases when H-S concentration > 100 ppm [Moizan, SPIE **6469**, 64690E (2007)]
 - Two classes of doped ions:
 - Ions close enough to H-S to be highly quenched
 - Ions far enough away to be unquenched

Limits on RE-doped chalcogenide fiber laser performance

1. Nonradiative quenching of upper laser level
 - Need to minimize H-S, H-Se, OH content of glass
2. Excited-state absorption may reduce or eliminate gain
 - Gain may still be possible at certain wavelengths
3. Bottle-necking may limit population inversion
 - Co-dope with 2nd RE ions; energy transfer from lower laser level to added RE ion
 - Maintain population inversion by cascade lasing
4. Fiber attenuation may limit round-trip gain
 - Minimize H-S, H-Se, OH content

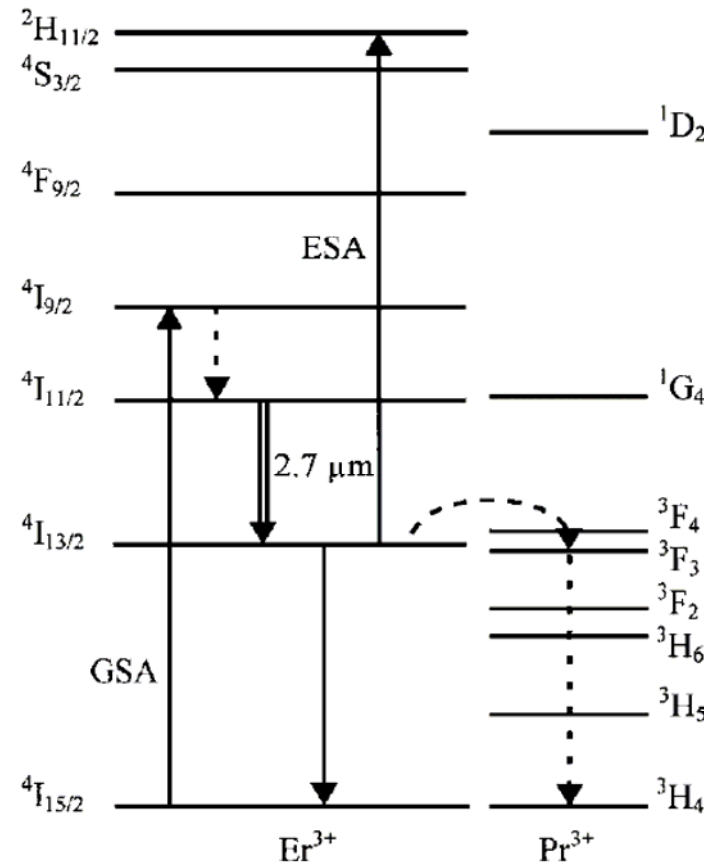


Fiber lasers demonstrated to date

Er:ZBLAN $\lambda = 2.75 \mu\text{m}$

Jackson, SPIE **6453**, 64530B (2007)

- Co-doped with Pr to reduce bottle-necking in $^4I_{13/2}$ level
- Double-clad fiber
- Diode pump at 975 nm
- $P_{\text{out}} \sim 1.7 \text{ W}$ for $P_{\text{pump}} \sim 10 \text{ W}$



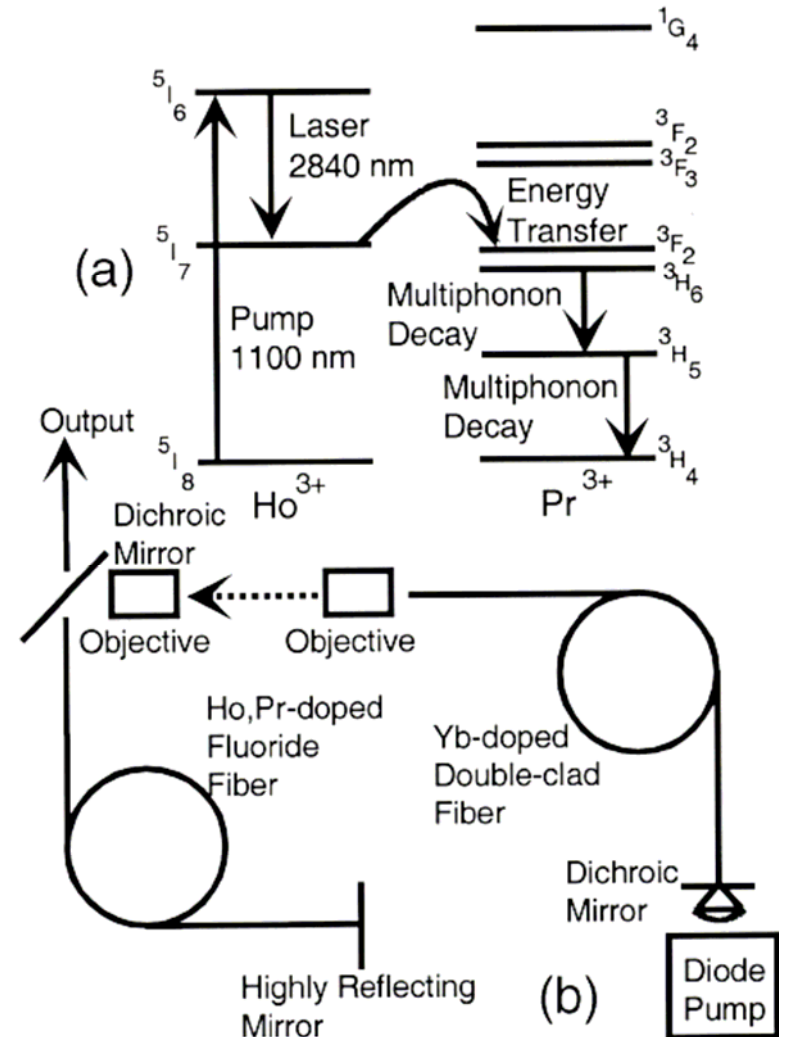
from Jackson et al., Opt. Lett. **24**, 1133 (1999)

Fiber lasers demonstrated to date

Ho:ZBLAN $\lambda = 2.86 \mu\text{m}$

Jackson, SPIE **6453**, 64530B (2007)

- co-doped with Pr to reduce bottle-necking in $^5\text{I}_7$ level
- single-mode fiber
- Yb fiber laser pump at 1100 nm
- $P_{\text{out}} \sim 2.5 \text{ W}$ for $P_{\text{pump}} \sim 9 \text{ W}$
- potentially most efficient $3 \mu\text{m}$ source



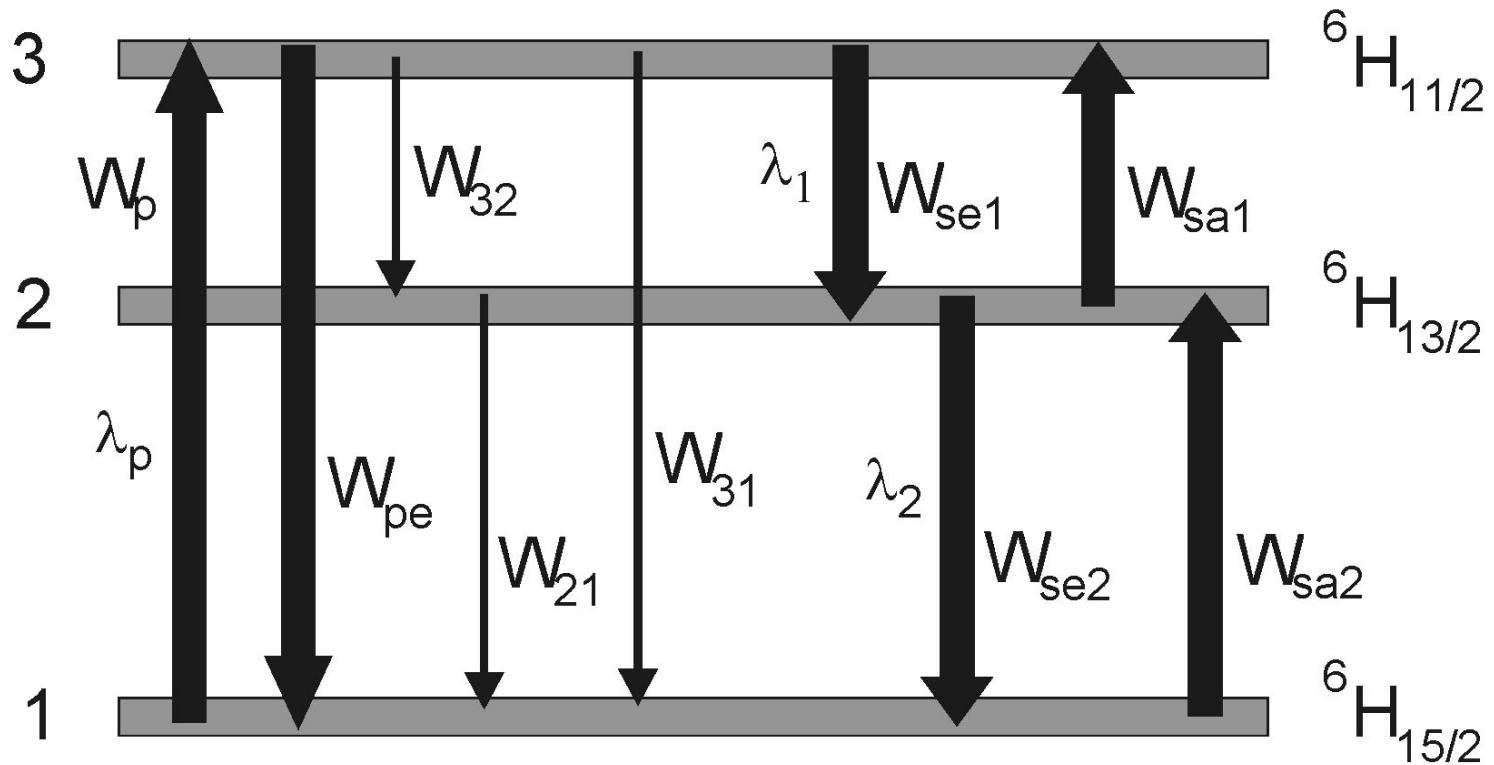
from Jackson et al., Opt. Lett. **29**, 334 (2004)

Fiber lasers demonstrated to date

Beyond 3 μm :still waiting....

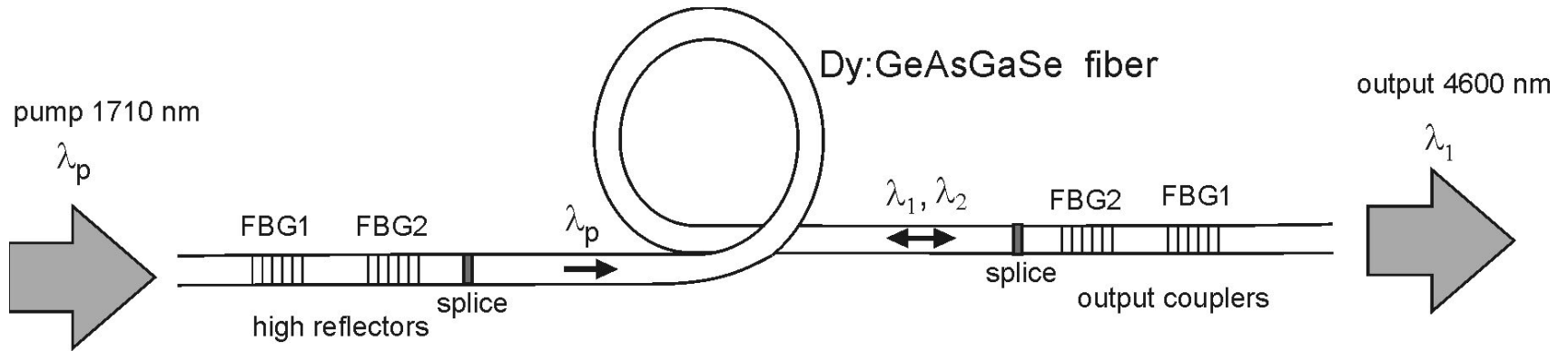
- Wavelength range 4.5 - 4.7 μm of interest
- ${}^6\text{H}_{11/2} \rightarrow {}^6\text{H}_{13/2}$ transition of Dy^{3+} possible candidate
- Need low-phonon energy host (chloride crystal, chalcogenide glass)
- Problem: bottlenecking of population due to long lifetime of lower laser level (${}^6\text{H}_{13/2}$)
- Solution (this work): cascade lasing on the ${}^6\text{H}_{11/2} \rightarrow {}^6\text{H}_{13/2}$ and ${}^6\text{H}_{13/2} \rightarrow {}^6\text{H}_{15/2}$ transitions can serve to effectively depopulate the ${}^6\text{H}_{13/2}$ level

Dy³⁺ lower energy levels



- model includes stimulated emission and absorption between all three levels
- accounts for an arbitrary degree of population saturation

All-fiber scheme for cascade lasing



Fiber Bragg gratings: FBG1: lasing wavelength $\lambda_1 = 4600$ nm
FBG2: idler wavelength $\lambda_2 = 3350$ nm

Model Calculations

$$\frac{dN_3}{dt} = N_1 W_p + N_2 W_{sa1} - N_3 (W_{pe} + W_{se1} + W_3)$$

$$\frac{dN_2}{dt} = N_1 W_{sa2} - N_2 (W_{se2} + W_{sa1} + W_{21}) + N_3 (W_{se1} + W_{32})$$

$$N = N_1 + N_2 + N_3$$

Solve rate equations in steady state for level populations N_1, N_2, N_3

$$\gamma_1(z) = \int_0^a [N_3(r, z) \sigma_{32} - N_2(r, z) \sigma_{23}] \psi_1(r) 2\pi r dr$$

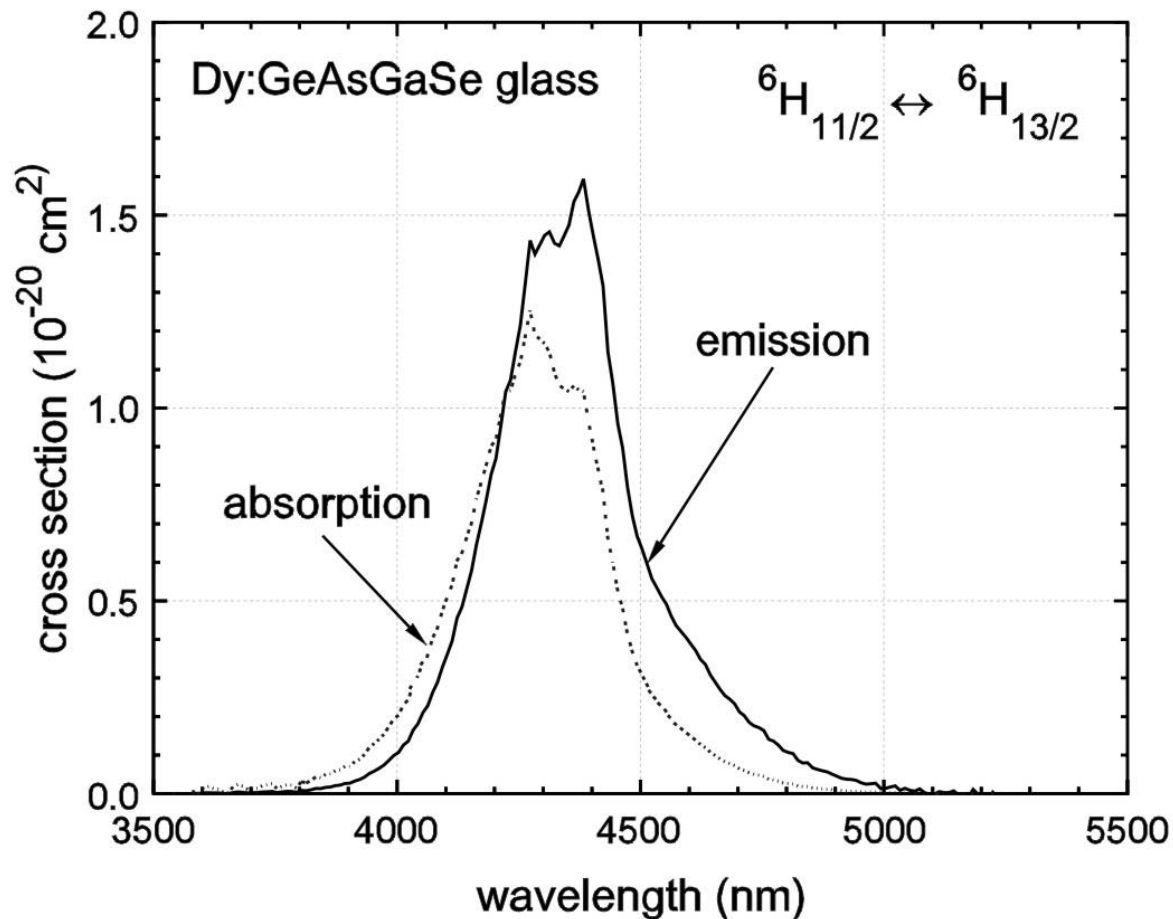
calculate gain/loss coefficients using level populations N_i and light field distribution $\psi(r)$

$$\Delta P_{1+}(z) = \gamma_1(z) P_{1+}(z) \Delta z$$

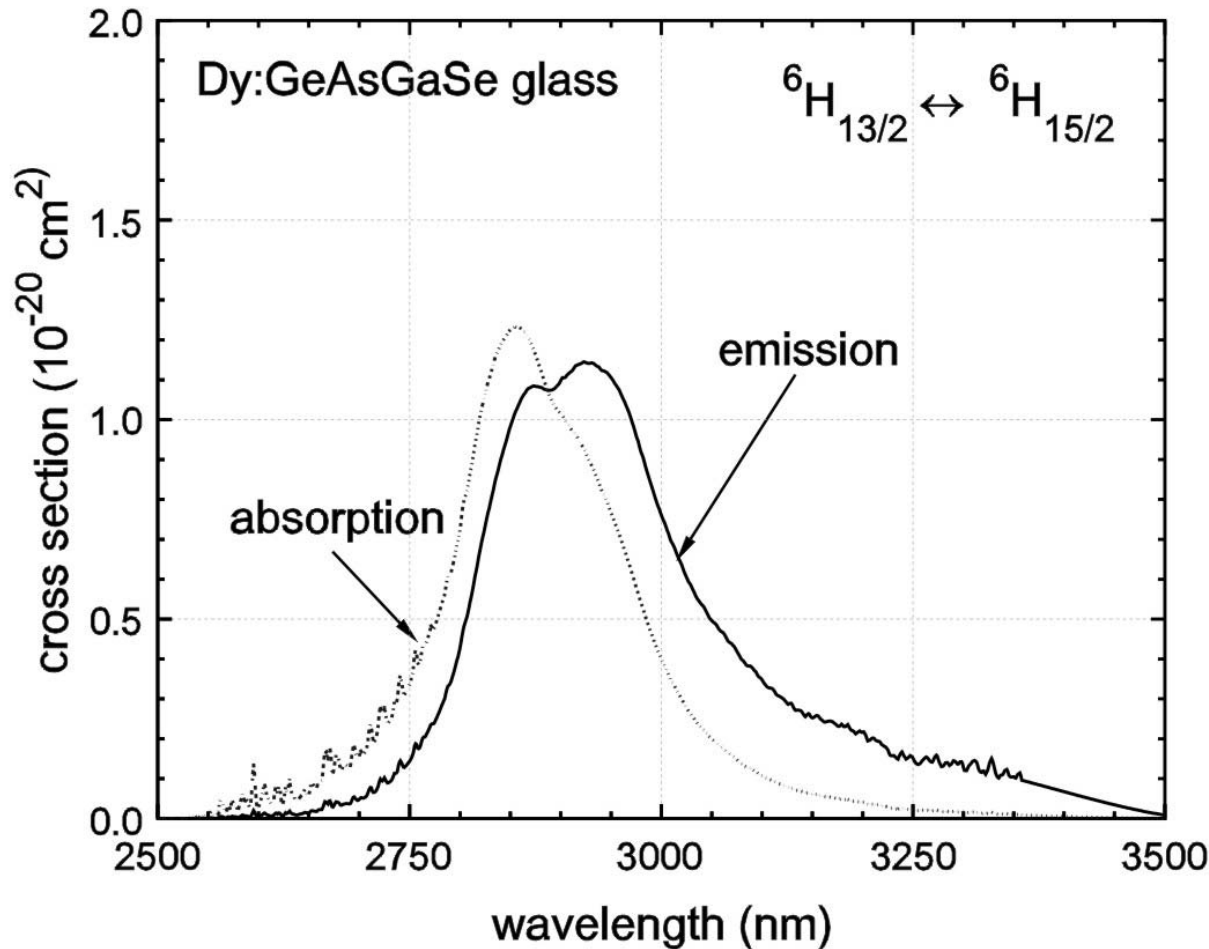
Propagate signal and pump powers back and forth between mirrors until self-consistent solution is obtained

PARAMETERS FOR FIBER LASER MODEL

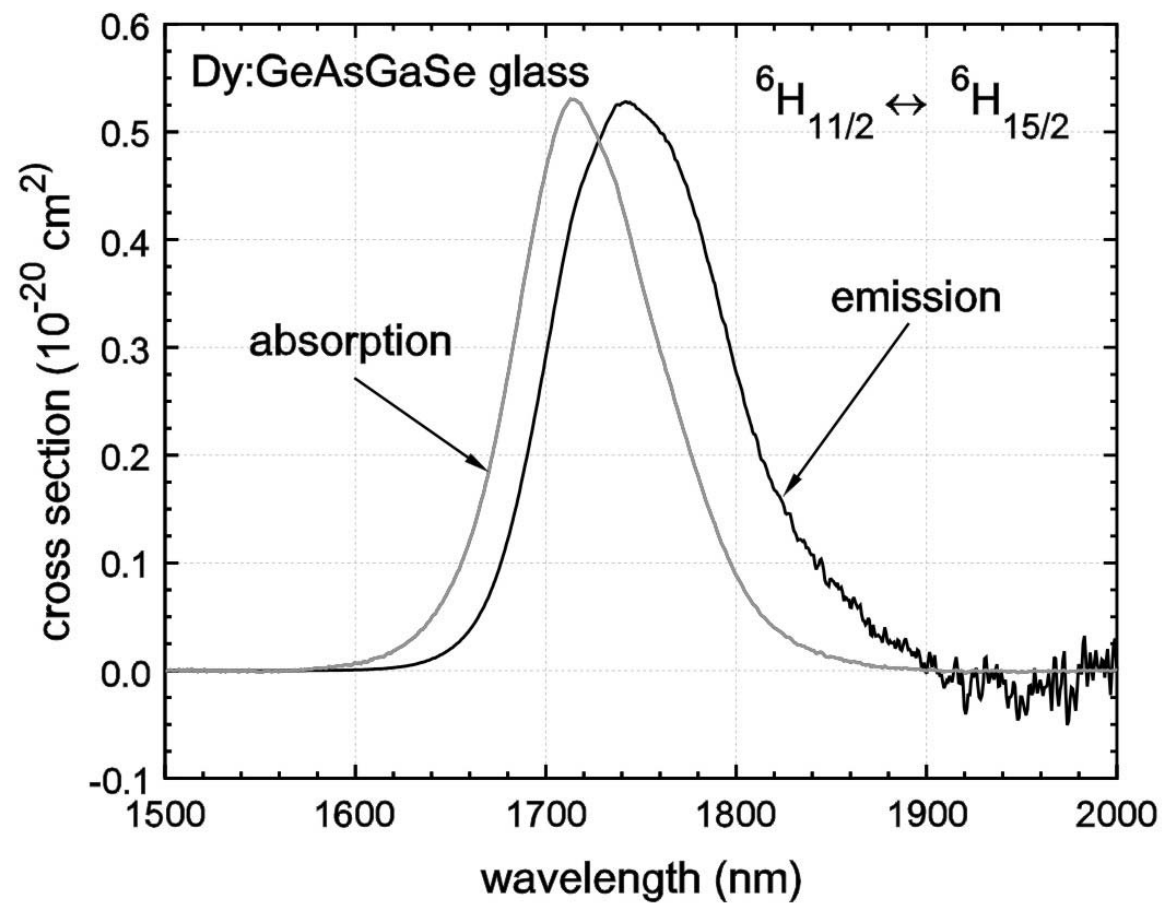
Symbol	Quantity	Value
N	Dy ion density	$7 \times 10^{19} \text{ cm}^{-3}$
a	core radius	$5.5 \text{ }\mu\text{m}$
NA	numerical aperture	0.2
R_{CL}	inner cladding radius	$30 \text{ }\mu\text{m}$
α_2	fiber loss at $3 \text{ }\mu\text{m}$	1 dB/m
τ_3	lifetime of level 3	2 ms
τ_2	lifetime of level 2	5.2 ms
β_{32}	branching ratio for $3 \rightarrow 2$ transition	0.15
$R_{1,\text{out}}$	output coupler reflectivity for λ_1	0.05
$R_{1,\text{HR}}$	high reflector reflectivity for λ_1	1
$R_{2,\text{out}}$	output coupler reflectivity for λ_2	0.9
$R_{2,\text{HR}}$	high reflector reflectivity for λ_2	1
σ_{32}	peak cross section at 4383 nm	$1.59 \times 10^{-20} \text{ cm}^2$
σ_{21}	peak cross section at 2926 nm	$1.14 \times 10^{-20} \text{ cm}^2$
σ_p	absorption cross section at 1710 nm	$0.52 \times 10^{-20} \text{ cm}^2$



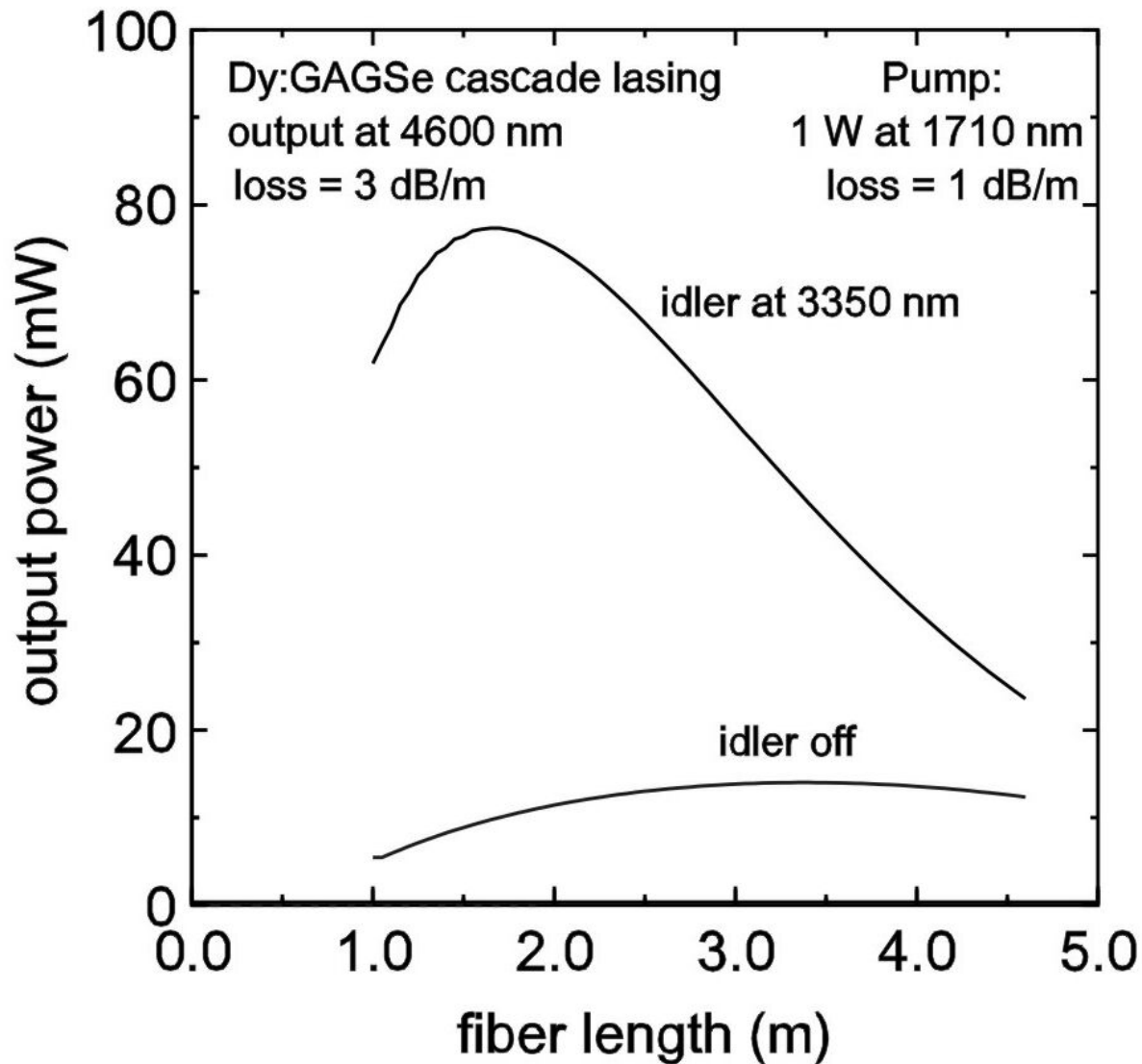
- emission measured from fluorescence
- absolute cross sections scaled to agree with oscillator strength (obtained from Judd-Ofelt analysis)
- absorption spectrum calculated from emission spectrum using reciprocity (McCumber) relation



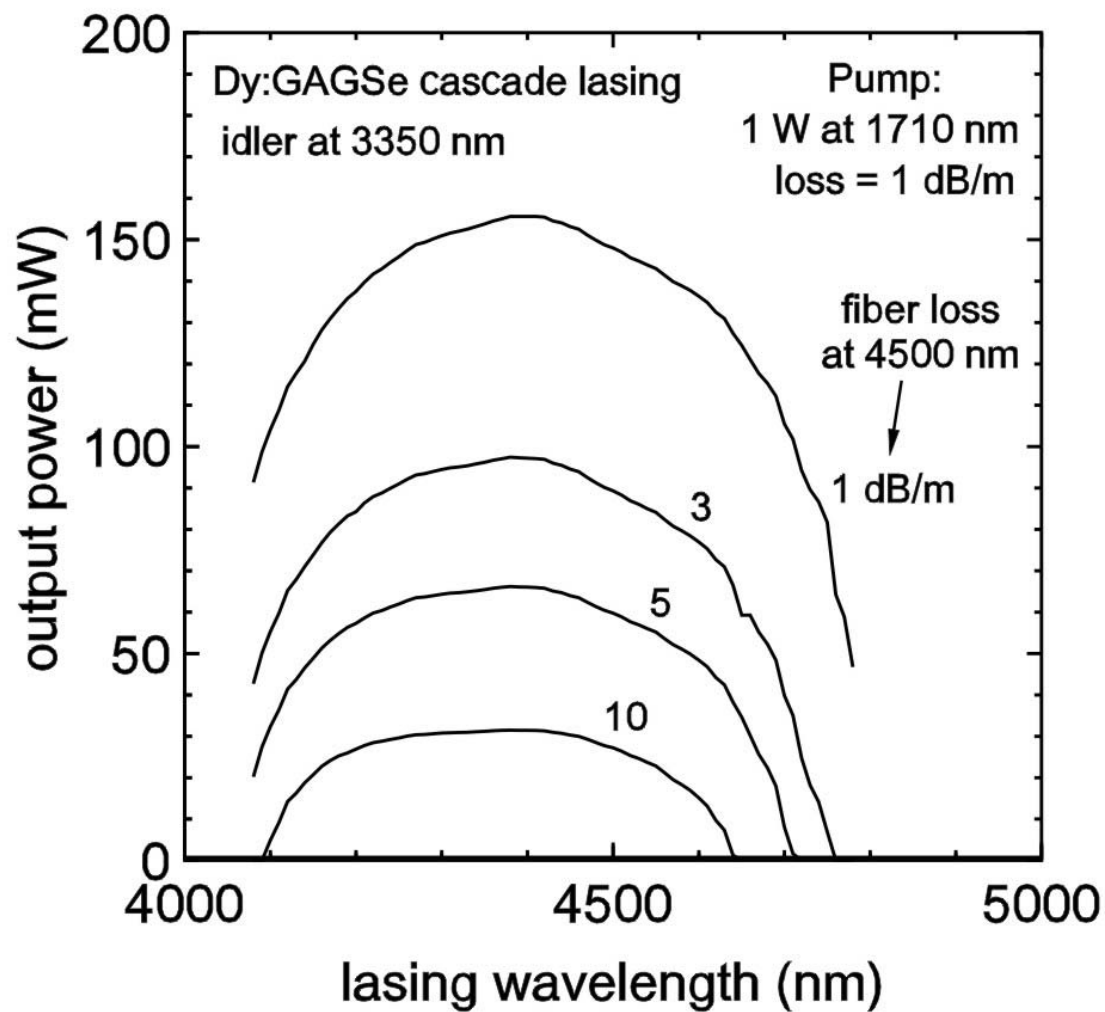
- Optimum idler wavelength is on long-wavelength side of ${}^6\text{H}_{13/2} \rightarrow {}^6\text{H}_{15/2}$ transition (3350 nm)
- This is where $\sigma_{\text{ems}} \gg \sigma_{\text{abs}}$, and level 2 is depleted most efficiently



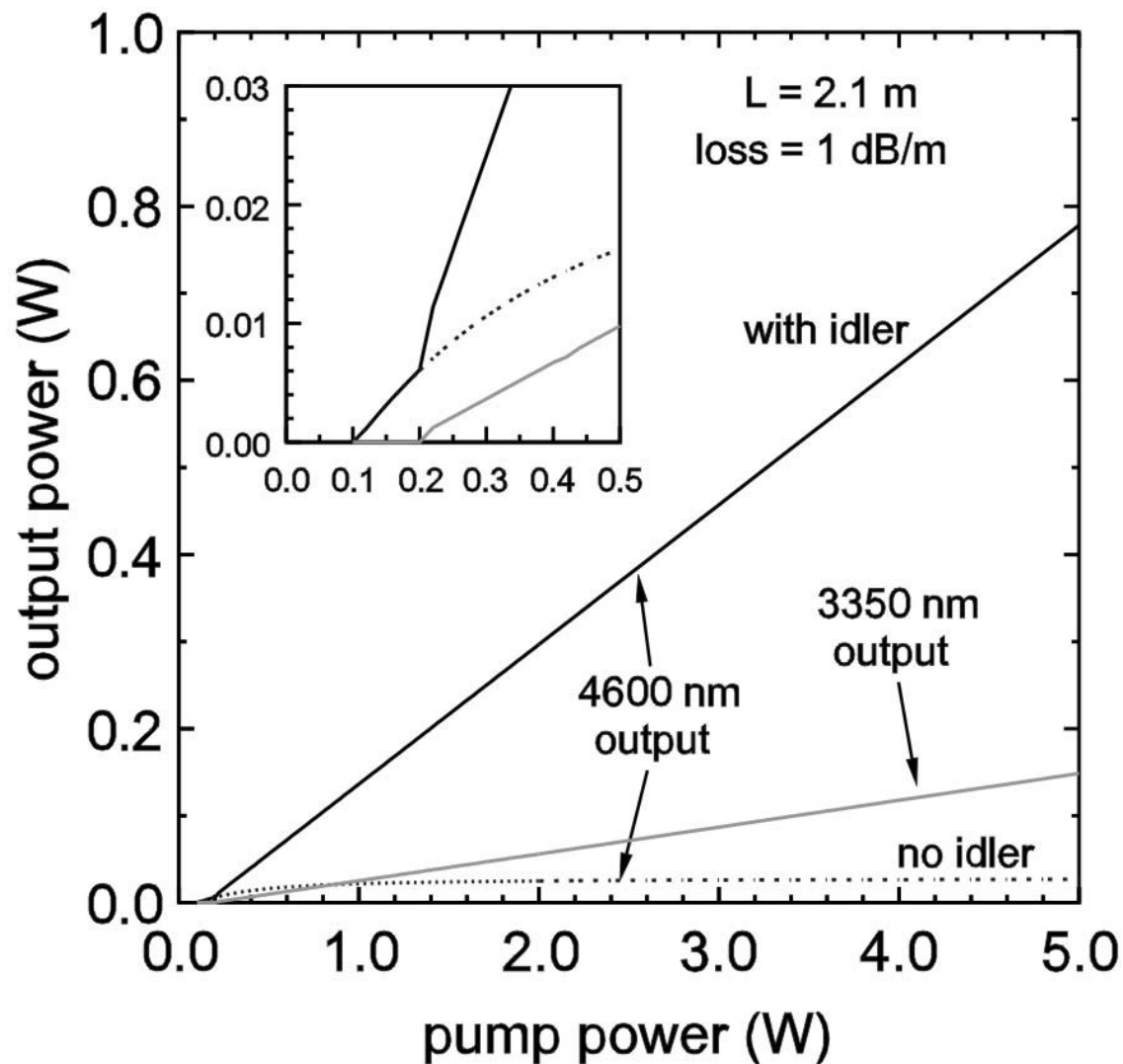
Optimum pump
wavelength is 1710 nm



The idler recycles the excited-state population faster, resulting in increased gain on the 4600 nm transition, and shorter optimum fiber lengths



Efficient lasing from
4200-4600 can be
obtained if the fiber loss
is kept below 3 dB/m



Increase in output power at 4600 nm with simultaneous lasing of idler at 3350 nm is especially large for higher pump power

Summary of Dy fiber laser modeling

- cascade lasing scheme will result in a highly efficient and power-scaleable laser around 4600 nm
- Significant enhancements in efficiency are predicted compared with a traditional single-laser-wavelength scheme
- A key requirement for efficient operation will be fiber losses in the 1-3 dB/m range or smaller.
- high loss in the 4.5 μm region due to HSe impurities may be reduced by special purification techniques [B. Cole et al., *J. Non-Cryst. Solids*, vol. 256&257, pp. 253-259, 1999], and losses in the few dB/m range should be feasible

Conclusions

- Fiber lasers can be designed for efficient operation in the $4 < \lambda < 8 \text{ }\mu\text{m}$ range using rare earth doped chalcogenide glass
- In predicting device performance, caution needed when using multiphonon energy-gap law
- Watt-class fiber lasers at $\sim 3 \text{ }\mu\text{m}$ have been demonstrated using fluoride glass, but no experimental reports yet of rare earth doped chalcogenide glass fiber lasers
- Modeling of a Dy doped selenide fiber laser at $4.6 \text{ }\mu\text{m}$ shows that cascade lasing improves efficiency by preventing bottle-necking in lower laser level
- Fiber attenuation above $\sim 1 \text{ dB/m}$ leads to significantly reduced output power. Need to limit H-Se content of glass.