Diamond Color Center Laser for Sodium Guide Star

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Ideal Sodium Guide Star Laser

- Tuned to 589.0 nm
  - D2 transition of Na
  - Highest oscillator strength
- Bandwidth of 1-3 GHz
  - 1 GHz matches Doppler broadened fine structure F=2 peak
  - 3 GHz includes F=1 transition
- Continuous Wave
  - Avoids saturation of sodium (I_{sat}=64 W/m^2)
  - Most efficient use of laser power
- High Power
  - 8-10 Watts
- M^2=1 (perfect beam quality)
  - Production of smallest possible guide star
- Polarized
  - Convert to circular polarization for optical pumping enhancement

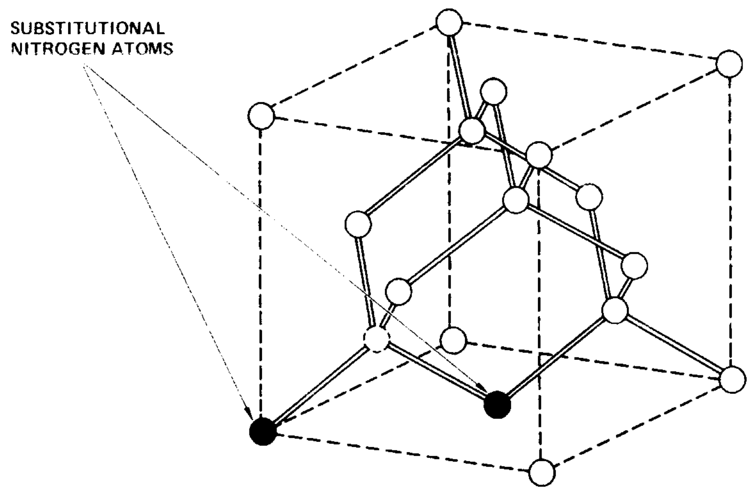
Primary Sodium Guide Star Laser Candidates

Concept	Advantages	Disadvantages
Ar^{+}-pumped commercial dye	• Lases CW • Broadly tunable • Homogeneously broadened	• Difficult to maintain • Large footprint • Power limited 3-4 W
Doubled Nd:YAG pumped dye MOPA	• High power (20 W)	• Pulsed - inefficient use of power • Very large footprint • Very Expensive
Sum frequency	• Sum generates 589 nm • Moderate power (8 W) • Small footprint	• Pulsed - inefficient use of power • Very narrow tuning range • Difficult history with operation
Doubled Raman-shifted Nd:YAG	• Can be tuned to 589 nm • Good beam quality	• Pulsed - inefficient use of power • Previous experiments power limited • Issues with SBS at high power • Must thermally tune Nd:YAG (-50 C) for efficient wavelength matching
Doubled LiF-F_2^- color center	• Easily tunable to 589 nm • Good beam quality	• Pulsed - inefficient use of power • Previous experiments power limited • Concerns of thermal stability

Advantages of H3 Color Center Guide Star Laser

- Direct lasing at 589.0 and 589.6 nm sodium lines
  - No frequency conversion required
  - No pulsing necessary to enhance nonlinear processes
- CW operation
  - Highest temporal efficiency in guide star generation
- Homogeneously broadened
  - Improved conversion efficiency to desired wavelength
  - Controllable lasing bandwidth allows for efficient spectral matching
- Commercially available high-power CW pump lasers
  - 488 nm line of Ar^+ laser - 20 Watts
  - Recent development of 473 nm solid state lasers approaching 1 Watt
- Superior power scalability
  - Highest known thermal conductivity (4-5 times Cu)
    - Promotes extremely rapid heat removal
    - Thwarts thermal lensing and birefringence
  - Extremely high thermal shock parameter (300 times higher than sapphire)
  - Extremely small thermal index change parameter ($<10^{-6}$/K)

Diamond H3 Color Centers



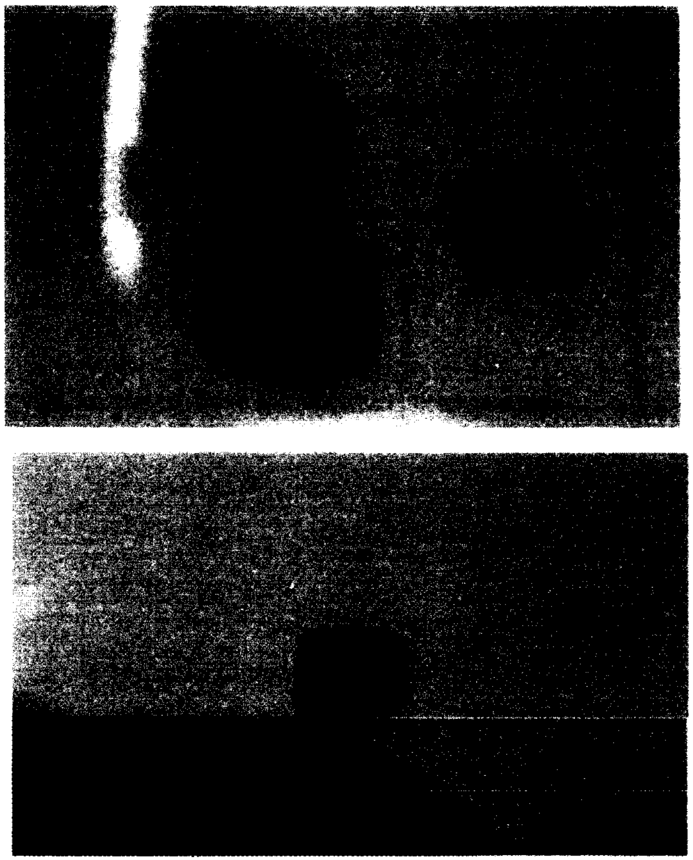
Carbon Atoms in Diamond Lattice

- Naturally occurring color center, giving diamond a yellow hue
- Can be induced in diamonds with proper nitrogen concentration by electron beam irradiation followed by high temperature (900C) anneal.
- H3 centers are long-term stable at temperatures over 800 C
- Excited state lifetime does not degrade out to 500C

H3 Color Center Laser History

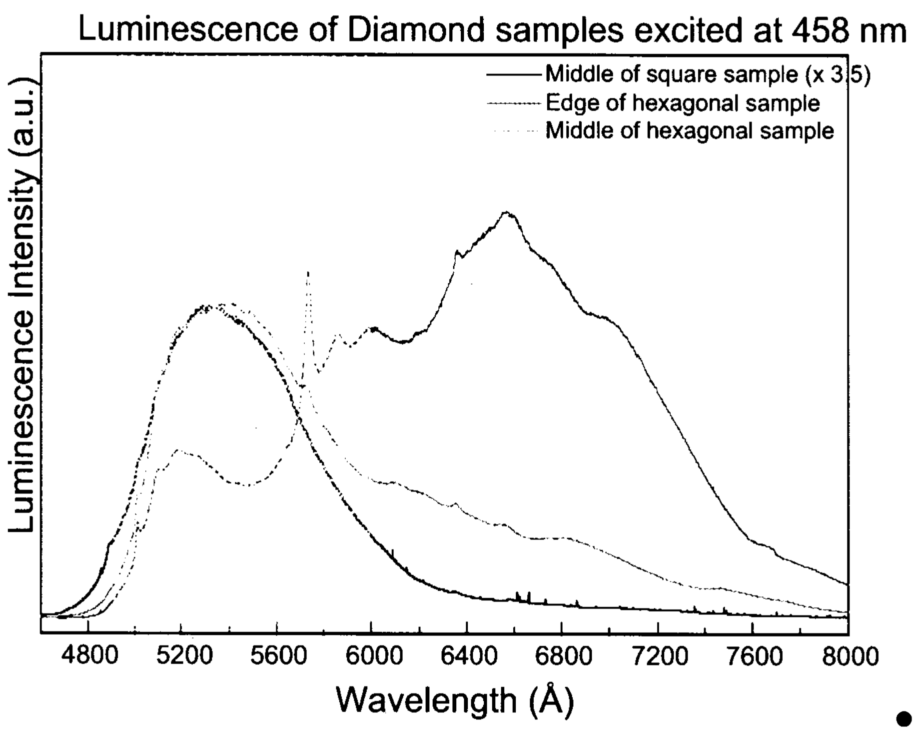
- 1985 - Rand and DeShazer report laser action in natural diamond sample pumped by pulsed coumarin dye laser
  - Feedback from Fresnel reflections from bare diamond surfaces
  - Measured 13.5% slope efficiency
- 1988 - Itami Research Laboratories generate laser action in natural diamond sample pumped by pulsed coumarin dye laser
  - HR and 97% mirrors used in two mirror external cavity
  - Lasing threshold observed at 3 MW/cm^2
- 1988 - Taylor at University of Strathclyde demonstrates CW lasing in cooled (77K) synthetic diamond samples
  - Demonstrated tuning from 505 nm - 575 nm
  - Very low slope efficiency (6.6×10^{-4} %)
- 2002 - Absorption cross section and number density in high-luminescence synthetic H3 samples measured (this work)
  - Prospects for lasing analyzed

Synthetic Diamond Samples



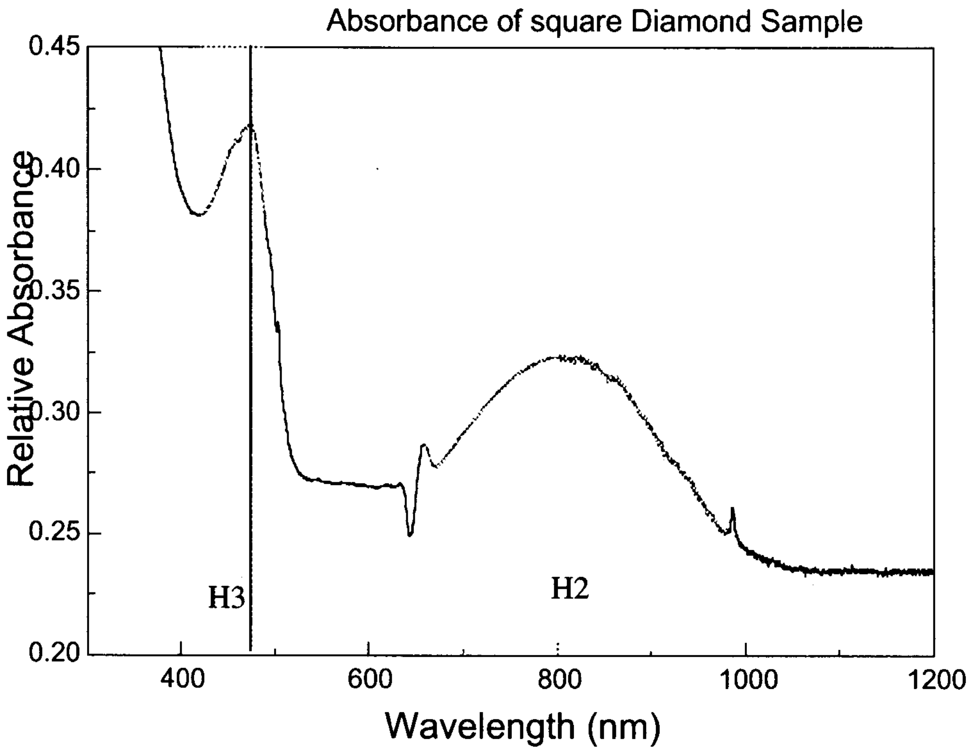
- Synthetic diamonds from Itami Research Laboratories
  - Produced to maximize formation of H3 color centers
  - Excellent optical clarity
- Regions with high concentrations of N-V color centers (purple)
- Regions with high concentrations of H3 color centers (yellow)
- Square sample exhibits strong birefringence

H3 Sample Emission Spectra



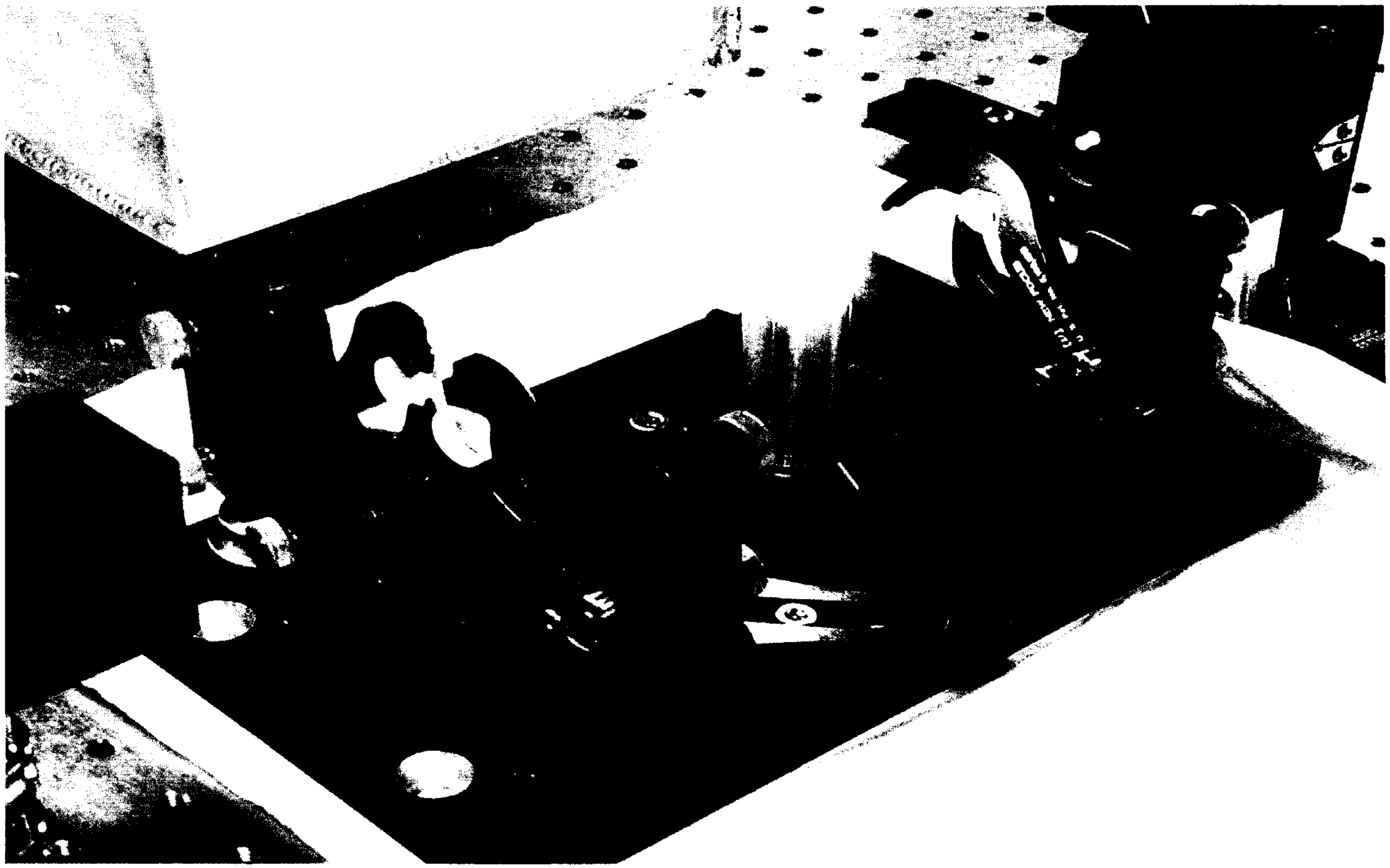
- Hexagonal diamond sample
  - Edge of sample reveals primarily N-V centers
    - Emission from 560- 760 nm
    - Absorption at 550 nm
  - Center shows primarily H3 centers
    - Primary emission at 530 nm
    - Residual emission from 610-760 nm (N-V centers)
- Square diamond sample
  - Strong emission over 500-600 nm
  - No emission in N-V center band

H3 Sample Absorption Spectrum



- H3 center absorption band ranges from 430-490 nm
- H3 absorption peak at 475 nm
- H3 zero-phonon line apparent at 503 nm
- H2 absorption from 650-980 nm
- H2 zero-phonon line at 980 nm

Bright H3 Fluorescence From Diamond Sample



Problem: Unknown Absorption Cross-Section

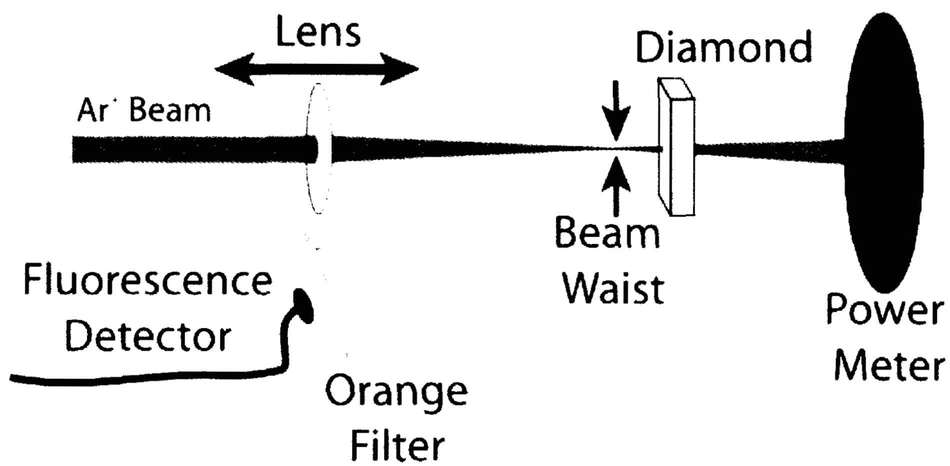
- To continue with design of a laser, the small signal gain g_0 must be known
- This requires knowledge of the color-center number density N
- Number density could be measured by quantitative absorption measurement IF the absorption cross-section σ were known

$$I = I_0 e^{-N\sigma l}$$

- Absorption saturation intensity is a function of absorption cross-section independent of number density

$$I_{sat} = \frac{hc}{\lambda_p \sigma \tau}$$

Measurement of Absorption Cross Section



- Color-center saturation should lead to
  - fluorescence reduction (observed by filtered detector) and

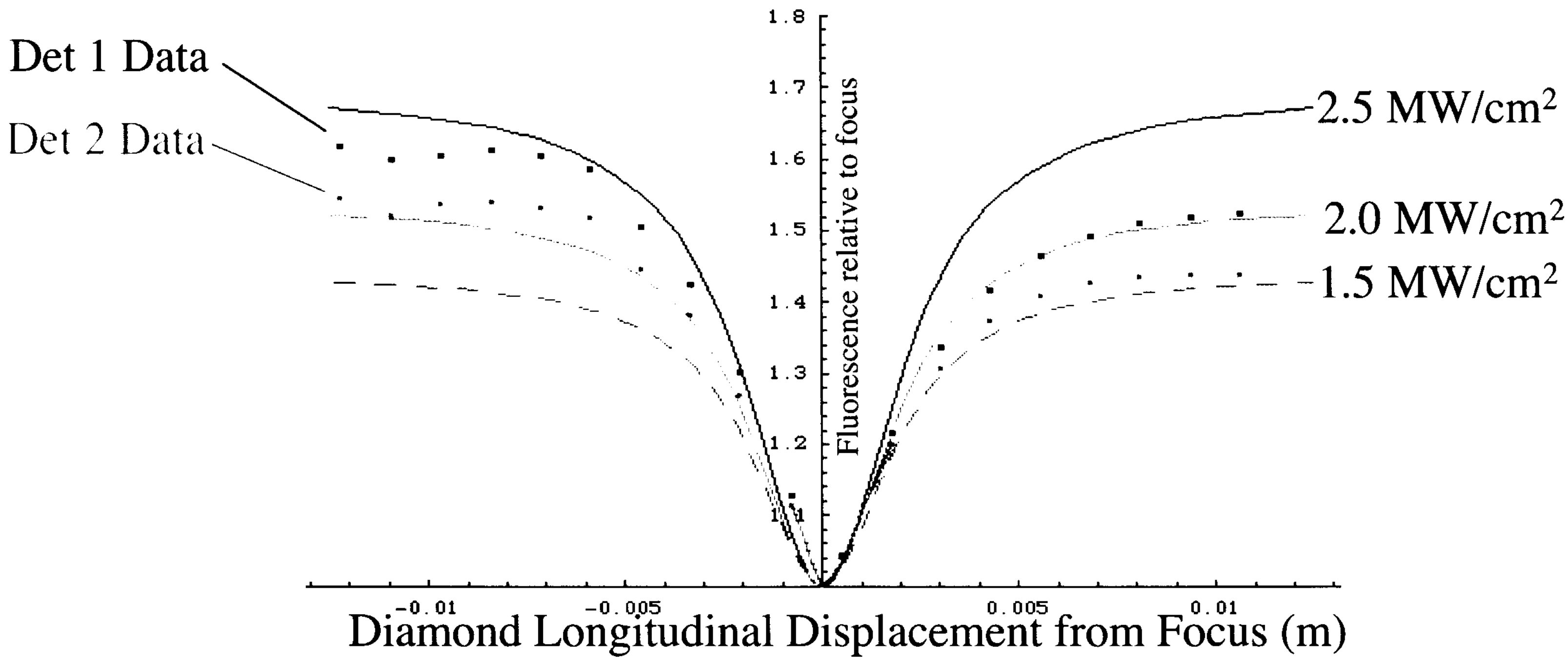
$$P_f \propto P_0 - A I_p \exp\left\{\frac{-\alpha_0 l}{1 + I_p / I_{sat}}\right\}$$

  - simultaneous transmission increase (observed on power meter)

$$P_{trans} \propto A I_p \exp\left\{\frac{-\alpha_0 l}{1 + I_p / I_{sat}}\right\}$$

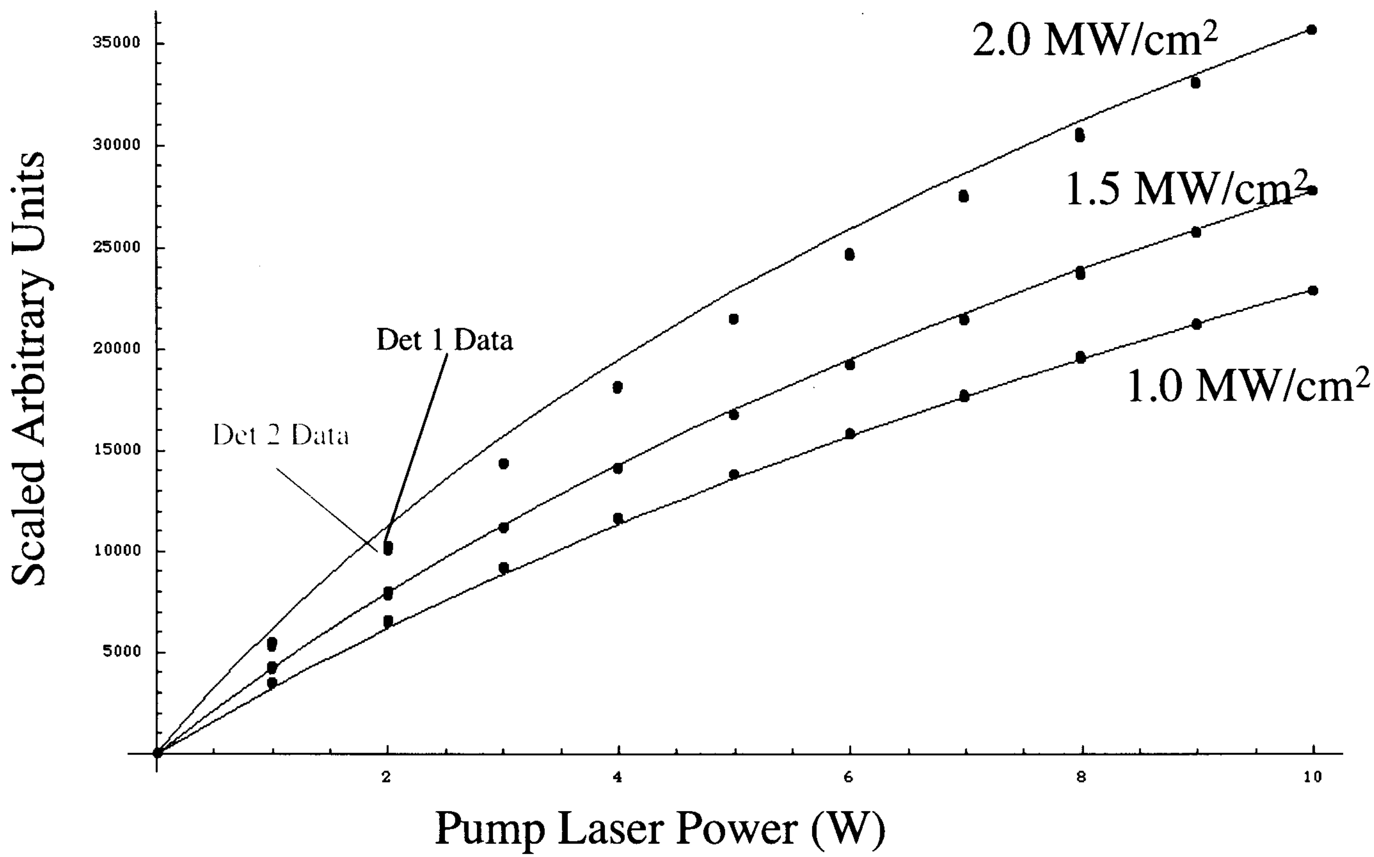
- Longitudinal motion of lens moves beam waist, changing intensity of pump beam in diamond

Absorption Saturation Analysis



- Independent fluorescence detectors measure same general curve
  - Offset and gain slightly different
  - Different blocking filter characteristics admit different portions of spectrum
- Different level of unsaturated fluorescence on each side of focus
  - Z-translation imparts slight transverse motion to beam
  - Probing area with slightly fewer color centers
- Theoretical fit indicates saturation intensity of about 2.0 MW/cm^2
- Absorption Cross-Section 1.3×10^{-17} cm^{-2}

Absorption Saturation Independent Confirmation



- Laser power increased with diamond fixed at beam waist
- Detector output at 10 W scaled to match value of theoretical curve (solid)
- Best fit with theoretical curve is for saturation intensity of 1.5 MW/cm^2
- Absorption cross-section of 1.7 x 10^{-17} cm^{-2}

Small-Signal Gain Calculation

- Known absorption cross section allows absorption measurements to place sample H3 density at 2.2 x 10^{17} cm^{-3}
- Stimulated emission cross-section σ_L calculated from known parameters to be 1.4 x 10^{-17} cm^{-2}
  - Reported elsewhere as 2 x 10^{-17} cm^{-2}
- Single pass pump rate (10 W) of 5.0 x 10^{24} cm^{-3} sec^{-1}
- By calculating the absorption saturation, we can determine that the pump rate for a second pass of pump radiation is 25% more at 6.3 x 10^{24} cm^{-3} sec^{-1}
- These values give a small-signal gain g_0 of
  - 1.1 cm^{-1} (single pass)
  - 1.4 cm^{-1} (double pass)

Summary of Square Sample Parameters

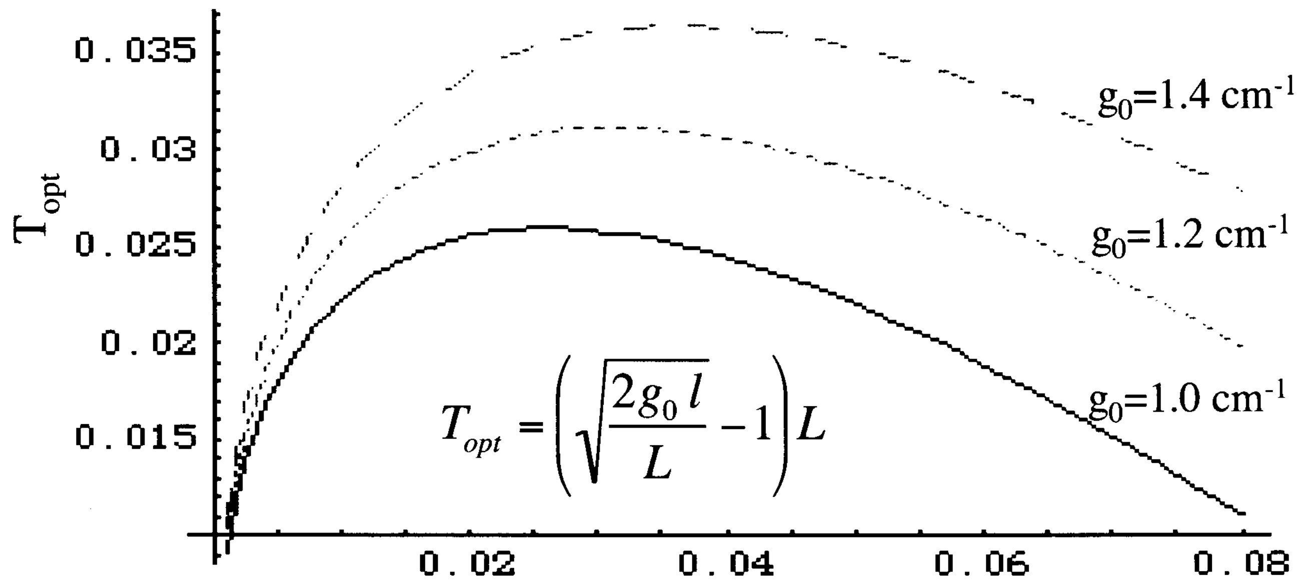
- Thickness t=0.052 cm
- H3 density $N = 2.2\ 10^{17}\ cm^{-3}$
- Small signal absorption α_0=3.35 cm^{-1}
- Small signal gain $g_0 = 1.1\ cm^{-1}$ (single pump pass)
  $= 1.4\ cm^{-1}$ (second pump pass)
- Polarization effects prevent Lyot-filter tuning
- Output potential (with 10W pump laser) 0.5 W

Guide Star Laser Development Plan

- Phase I: Demonstrate 1/2 Watt lasing with existing apparatus
    - Diamond coatings applied
    - System testing and analysis
- Phase II: Develop tunable guide star laser
    - Generate new H3 color center diamonds
    - Implement tunable cavity
    - Pump with high power (20 W polarization coupled) 488 nm Ar^+ ion laser

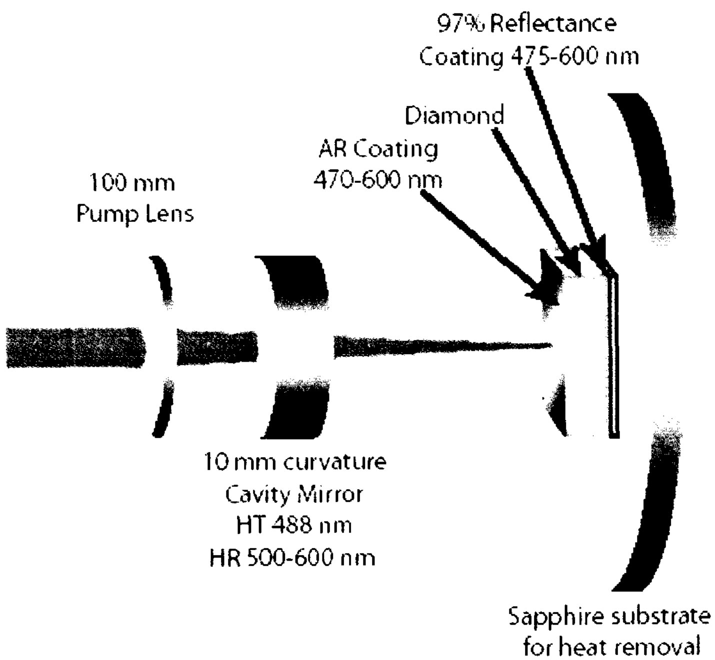
Phase I: Design with Square Crystal

Optimum Output Coupler Transmission



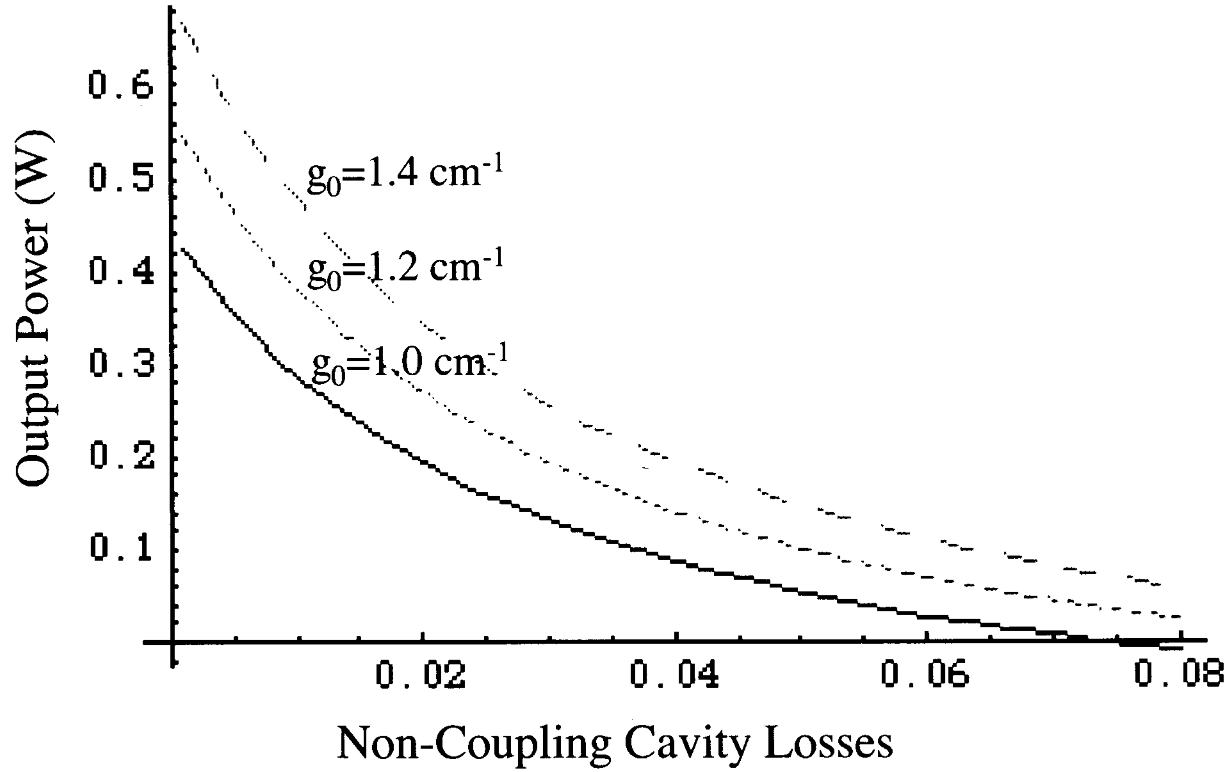
- Optimum CW lasing obtained with 97% reflectivity output coupler
  - Calculated small-signal gain of 1.1 cm^{-1} to1.4 cm^{-1}
  - Output coupling of roughly 2.5-3% is best for gain in the 1% loss range

Phase I: H3 Laser Design



- Demonstrate lasing using diamond at normal incidence
  - Stress birefringence in best sample prevents low loss at Brewster's angle
  - AR coating suppresses Fresnel reflections
  - High curvature end mirror
    - Minimum cavity mode for maximum efficiency
    - High transmission at pump wavelength for coincident pumping
  - 97% reflectance coating on back of diamond
    - Reflects most unabsorbed pump beam for second pass
    - Acts as laser output coupler
    - Separates pump light from lasing light
- Because of birefringence in laser crystal, this laser will not be tuned initially
  - Non-polarizing tuning methods may be attempted

Phase I: Expected Output Power



- Careful execution of the design of the laser should yield significant power
- For double pass (g_0=1.4 cm^{-1}) limiting the round-trip losses to 1% leads to 0.5 W output (at peak of 530 nm)

Phase II: Guide Star Laser Development

- Gain at 589 nm appears to be about 1/3 that at 530 nm
- Requires development of new color center diamonds
  - H3 density of $>10^{18}$ cm^{-3}
  - Depth of 2 mm
  - No birefringence
  - No N-V color centers
- Highest intensity pump source available
  - 20 W at 488 nm
  - Good beam quality ($M^2<1.5$)
- May be able to push small signal gain at 589 nm to 5 cm^{-1}
  - 90% absorption in double pass
  - 20 micron focus spot
  - Output power in excess of
    - 5 W (CW) for σ_L of 5 x 10^{-18} cm^2
    - 9 W (CW) for σ_L of 7 x 10^{-18} cm^2

Conclusions

- The H3 color center has excellent properties for production of an effective guide star laser
  - Broad absorption band for use with existing high power pump lasers (488 nm line of Ar^+)
  - CW operation directly at the 589 nm line of sodium
- The H3 color center has superior potential for scaling to high power operation
- We have measured the absorption cross section of the H3 center, allowing evaluation of laser capabilities
- We have developed designs for lasers providing
  - 0.5 Watts with existing pump lasers and diamonds
  - Multiple (5-9) Watts CW tuned to 589 nm with development of new color center diamonds