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A ground state depleted laser in neodymium doped yttrium orthosilicate

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ABSTRACT

A ground state depleted (GSD)^{1,2} laser has been demonstrated in the form of a Q-switched oscillator operating at 912 nm. Using Nd³⁺ as the active ion and Y₂SiO₅ as the host material, the laser transition is from the lowest lying Stark level of the Nd³⁺ ⁴F_{3/2} level to a Stark level 355 cm⁻¹ above the lowest lying one in the ⁴I_{9/2} manifold. The necessity of depleting the ground ⁴I_{9/2} manifold is evident for this level scheme as transparency requires a 10% inversion. To achieve the high excitation levels required for the efficient operation of this laser, bleach wave pumping using an alexandrite laser at 745 nm has been employed. The existence of a large absorption feature at 810 nm also allows for the possibility of AlGaAs laser diode pumping. Using KNbO₃, noncritical phase matching is possible at 140°C using d₃₂ and has been demonstrated. The results of Q-switched laser performance and harmonic generation in KNbO₃ will be presented.

Orthosilicate is a monoclinic biaxial crystal. An oriented spectroscopic evaluation consisting of a Judd-Ofelt analysis of oriented absorption spectra and the measurements of oriented emission spectra has been completed and will be presented. Results of modeling using these spectroscopically determined parameters will be compared with the actual laser performance. The performance of this laser at 911 nm which allows accessing Cs atomic resonance filters through harmonic doubling will also be discussed.

Orthosilicate can be grown in large boules of excellent optical quality using a Czochralski technique. Because of the relatively small 912 nm emission cross section of 2-3 x 10⁻²⁰ cm² (orientation dependent) fluences of 10-20 J/cm² must be circulated in the laser cavity for the efficient extraction of stored energy. This necessitates very aggressive laser damage thresholds. Results from the Reptile laser damage facility at Lawrence Livermore National Laboratory (LLNL) will be presented showing Y₂SiO₅ bulk and AR sol-gel coated surface damage thresholds of greater than 40 J/cm² for 10 nsec, 10 Hz, 1.06 μ pulses.

1. INTRODUCTION

Ground state depleted (GSD) lasers are characterized by a low laser ion doping density (5-10 x 10¹⁸ cm⁻³) and a large fractional excited state population inversion density (4-8 x 10¹⁸ cm⁻³). For efficiency, these lasers must be pumped by narrow band (< few nm), intense (> 10-50 kW/cm²) sources. The large fractional excited state population inversion allows efficient quasi-four level laser operation to a high lying Stark level in the ground state electronic manifold. In this manuscript we report on progress made in the experimental demonstration of a GSD laser using the Nd³⁺ ⁴F_{3/2} - ⁴I_{9/2} transition. This transition is of interest because it offers the possibility of constructing a laser operating at the wavelengths of 911 or 919 nm giving access to Cs atomic resonance filters through simple and efficient harmonic doubling.

The organization of this paper is to first present the orientationally resolved spectroscopic evaluation that we have performed on Nd³⁺:Y₂SiO₅ detailing those features that make it attractive as a 911 nm host

material. Additionally, we present data that will be of interest to experimenters wanting to laser pump this material. We then discuss techniques to suppress the competing $\text{Nd}^{3+} {}^4\text{F}_{3/2} - {}^4\text{I}_{11/2}$ laser transition without degrading the desired $\text{Nd}^{3+} {}^4\text{F}_{3/2} - {}^4\text{I}_{9/2}$ transition. The suppression of this unwanted gain is critical to the successful demonstration of our GSD laser. The peak ${}^4\text{F}_{3/2} - {}^4\text{I}_{11/2}$ emission cross section is 5 times larger than the desired ${}^4\text{F}_{3/2} - {}^4\text{I}_{9/2}$ emission cross section. Next, the laser demonstration and results of laser modeling are presented. Here experiments were designed to demonstrate 912 nm extraction efficiency, the feasibility of suppressing the unwanted $\text{Nd}^{3+} {}^4\text{F}_{3/2} - {}^4\text{I}_{11/2}$ gain, and to demonstrate closure with the predictions of our laser modeling codes. Finally, we give a brief discussion of the results we have achieved to date in harmonically doubling the GSD laser output using non-critically phase matched KNbO_3 .

2. $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ SPECTROSCOPY

The Judd-Ofelt^{3,4} model has become a standard tool for calculating the parity-forbidden electric-dipole radiative transition rates between the various levels of rare earth ions in both glass and crystalline hosts. This technique is based on an analysis of measured optical absorption line strengths^{5,6} and is easily applied to isotropic host materials. The same analysis can be applied to anisotropic crystals if proper account is taken of the fact that measured absorptions can vary with directions in these crystals. Such an analysis was first performed by Lomheim and DeShazer⁷ in their investigation of Nd^{3+} in the uniaxial crystal YVO_4 . The central point made in their analysis was that because the Judd-Ofelt theory uses line strengths summed over all directions and polarizations some suitable type of averaging would have to be performed on the measured line strengths to properly apply the Judd-Ofelt theory to anisotropic crystals. Here the results of a Judd-Ofelt analysis of Nd^{3+} in the biaxial crystal yttrium orthosilicate are presented.

Yttrium orthosilicate belongs to the monoclinic crystal class 2/m (space group C2/c).⁸ Tkachuk et al.⁹ report that Nd^{3+} ions occupy two distinct optical sites; they have also made resolved Stark level measurements on both sites as detailed in Table 1 which are in agreement with our own low temperature emission and absorption measurements. The same group has reported the results of a Judd-Ofelt analysis of integrated optical spectra averaged over the various orientations of the crystal. The values given in their paper for the Judd-Ofelt intensity parameters differ markedly from those extracted from our own very similar analysis of the data to be presented herein. As they do not include their measured line strength values and only state the results of their study, it is difficult to guess the reason for the large discrepancies between the two sets of values.

	Type 1 (cm^{-1})	Type 2 (cm^{-1})
${}^4\text{F}_{3/2}$	11500 11325	11500 11311
${}^4\text{I}_{11/2}$	2288 2190 2162 2051 1988 1949	2274 2176 2148 2055 2001 1951
${}^4\text{I}_{9/2}$	472 357 229 88 0	472 354 216 66 0

Table 1. Stark level structure of the ${}^4\text{F}_{3/2}$, ${}^4\text{I}_{11/2}$, and ${}^4\text{I}_{9/2}$ manifolds of Nd^{3+} in Y_2SiO_5

As a reasonable approximation to actually measuring absorption line strengths over all possible directions and polarizations, a rectangular sample was fabricated with each of its sides oriented perpendicular to one of the principal axes of the optical indicatrix. We denote these principal axes by X, Y, and Z for the fast, intermediate, and slow vibration directions, respectively. Using this sample then allowed the measurement of

absorption spectra along the three mutually perpendicular principal axes of the indicatrix. The orientation of the cube was accomplished by first identifying the $\langle 010 \rangle$ direction which is a two-fold symmetry axis of the crystal using an X-ray back reflection Laue camera. Symmetry requires that a principal axis of the optical indicatrix be parallel to the $\langle 010 \rangle$ direction.¹⁰ Fabricating a sample with faces normal to the $\langle 010 \rangle$ direction then allowed the remaining two principal axes to be found by identifying extinction directions with the sample viewed between crossed polarizers. Our particular sample was cut from a boule with a Nd concentration of $9.3 \times 10^{18} \text{ cm}^{-3}$ ($\pm 10\%$) as determined using an inductively-coupled plasma atomic emission spectrometer. The crystal was grown using a Czochralski technique with the crystal growth axis oriented approximately 20° off the $\langle 010 \rangle$ crystal symmetry axis.⁸

The principal indices of refraction were measured from the single crystal sample described above using a high accuracy Abbe refractometer. Critical angle methods were used to measure the three principal indices at several different wavelengths of light from 435.8 to 643.8 nm. The wavelength dependent refractive indices for each principal direction were then fit by the method of least squares to a Sellmeier dispersion equation of the form:

$$n^2 = A + \frac{B}{\lambda^2 + C} + D\lambda^2 \quad (1)$$

where λ is the wavelength in microns and n is the principal refractive index of interest. The coefficients for the best fit are given in Table 2 for each of the three principal directions and give calculated values within 0.00002 of the measured indices.

	A	B	C	D
n_x	3.0895	0.0334	0.0043	0.0199
n_y	3.1173	0.0283	-0.0133	0.00
n_z	3.1871	0.03022	-0.0138	0.00

Table 2. Sellmeier coefficients for the principal indices of refraction of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$

These results reveal $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ is biaxial positive with an optic axial angle of approximately 41° and with a principal birefringence of approximately 0.021. The $\langle 010 \rangle$ symmetry axis of the crystal has been determined to be coincident with the X axis of the optical indicatrix. In general, crystals belonging to the monoclinic class $2/m$ may demonstrate a rotation with wavelength of the privileged vibration directions that lie in the $\langle 010 \rangle$ plane. Evidence of significant dispersion for the Y and Z directions was not, however, observed in this crystal over the indicated range of wavelengths.

A Perkin-Elmer Lambda-9 spectrophotometer was used to acquire oriented absorption spectra. Spectra were recorded at room temperature from 400 to 950 nm for light polarized along each of the three principal axes of the optical indicatrix. Figure 1 depicts a spectrum with the crystal orientated such that Y is parallel to the electric field of the absorbed light. The spectroscopic band assignments made in Fig. 1 follow Krupke⁶ and will be used to calculate reduced matrix elements. Similar sets of absorption spectra were acquired with the absorbed light polarized along the X and Z axes of the indicatrix. Because of the interest in making a laser pumped laser using this material, Figs. 2 and 3 present the orientationally resolved absorption spectra of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ for ranges that are of interest for alexandrite laser pumping and AlGaAs laser diode pumping. Table 3 summarizes the peak absorption cross sections at 745 nm and 810 nm, the most likely candidates for alexandrite and AlGaAs pumping, respectively.

Figure 1. Absorption spectrum and band assignments of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ for light polarized parallel to the Y-axis of the optical indicatrix. The sample is doped with Nd at $9.3 \times 10^{18} \text{ cm}^{-3}$ ($\pm 10\%$) and the sample thickness is 0.795 cm.

Figure 2. Oriented absorption spectra in the vicinity of 745 nm. The labels X, Y, and Z refer to the axis of the optical indicatrix that was parallel to the vibration direction of the electric field.

Figure 3. Oriented absorption spectra in the vicinity of 810 nm. The labels X, Y, and Z refer to the axis of the optical indicatrix that was parallel to the vibration direction of the electric field.

	$\sigma_{abs}^{745\text{ nm}} (\text{cm}^2)$	$\sigma_{abs}^{810\text{ nm}} (\text{cm}^2)$
X-axis (X is parallel to (010))	4.9×10^{-20}	9.9×10^{-20}
Y-axis	2.7×10^{-20}	1.6×10^{-20}
Z-axis	3.3×10^{-20}	6.6×10^{-20}

Table 3. Peak oriented absorption cross sections near 745 and 810 nm

Rather than give a comprehensive review of the Judd-Ofelt theory as it applies to our problem, the reader is referred to the already excellent treatments available in the literature.^{5,7,11} Here we present only a brief outline giving the equations used in our analysis. Measured line strengths are extracted from recorded absorption spectra using the relation,¹¹

$$S_{\text{meas}}(J \rightarrow J') = \frac{3ch}{8\pi^3} \frac{1}{e^2} \frac{2J+1}{n_{\text{Nd}}} \frac{9n}{(n^2+2)^2} \frac{\ell n 10}{\lambda \ell} \int_{J \rightarrow J'} \text{OD}(\lambda) d\lambda \quad (2)$$

where $J(J')$ is the angular momentum quantum number of the initial (final) state, n is the refractive index of the sample, n_{Nd} is the Nd number density, and ℓ is the sample length. This relation is applied to each of the bands detailed in Fig. 1, giving a total of 8 measured line strengths. Additionally, since we are dealing with an oriented sample, the procedure was repeated for measurements made with light polarized parallel to the X, Y, and Z axes of the optical indicatrix. Data reduction of absorption spectra for line strengths was performed by computer and is summarized in Table 4 where we have listed the measured line strengths as well as the mean absorption wavelengths for each of the eight bands we could resolve and each of the three crystal orientations investigated. For these calculations, the value of the refractive index was taken to be 1.782 the average of the three principal values at 911 nm. Polarization averaged line strengths were then calculated by averaging each of the three orientations with equal weight. These data are summarized in Table 5 along with the polarization averaged mean absorption wavelength for each of the eight resolved bands. Using the measured line strengths as detailed in Table 2, the three Judd-Ofelt intensity parameters, Ω_{λ} , can be found by solving the overdetermined set of equations

$$S_{\text{meas}}(J \rightarrow J') = \sum_{t=2,4,6} \Omega_t |\langle \psi J || U^{(t)} || \psi' J' \rangle|^2 \quad (3)$$

where the matrix elements $\langle \psi J || U^{(t)} || \psi' J' \rangle$ are the doubly reduced unit-tensor operators of rank t calculated in the intermediate-coupling approximation. Values of these reduced matrix elements for the spectroscopic band assignments detailed in Fig. 1 are listed in Table 5 and were compiled using values for these matrix elements calculated by W. T. Carnall et al.¹² Solving the set of equations in (3) for the Judd-Ofelt parameters that give the best least-square fit to the measured line strengths gives^{5,11}

$$\begin{aligned} \Omega_2 &= 3.34 \times 10^{-20} \text{ cm}^2 \\ \Omega_4 &= 4.35 \times 10^{-20} \text{ cm}^2 \\ \Omega_6 &= 5.60 \times 10^{-20} \text{ cm}^2 \end{aligned} \quad (4)$$

Transition ($^4I_{\nu_2} \rightarrow$)	x-axis		y-axis		z-axis	
	λ (nm)	$S(10^{-20} \text{ cm}^2)$	λ (nm)	$S(10^{-20} \text{ cm}^2)$	λ (nm)	$S(10^{-20} \text{ cm}^2)$
$^1P_{1/2} + ^1D_{3/2}$	434.1	0.157	432.9	0.105	433.8	0.092
$^1G_{11/2} + ^1G_{9/2} + ^1D_{3/2} + ^1K_{13/2}$	470.0	0.538	472.6	0.338	469.8	0.435
$^1G_{7/2} + ^1G_{9/2} + ^1K_{13/2}$	526.5	2.301	525.6	1.688	526.0	1.904
$^1G_{3/2} + ^1G_{7/2} + ^1H_{11/2}$	588.3	6.925	586.6	7.140	586.1	4.520
$^1F_{9/2}$	681.5	0.298	686.7	0.159	689.7	0.295
$^1F_{7/2} + ^1S_{3/2}$	751.7	4.920	750.5	2.386	752.6	4.015
$^1F_{3/2} + ^1H_{9/2}$	808.9	5.615	810.5	2.684	808.6	4.152
$^1F_{3/2}$	882.2	1.437	892.6	1.011	886.7	0.957

Table 4. Oriented absorption transition intensities in $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$

Table 5. Polarization averaged absorption transition intensities in $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$

Transition ($^4I_{\nu_2} \rightarrow$)				Polarization Averaged		
	$ \langle U^x \rangle ^2$	$ \langle U^y \rangle ^2$	$ \langle U^z \rangle ^2$	λ (nm)	$S_{\text{meas}}(10^{-20} \text{ cm}^2)$	$S_{\text{calc}}(10^{-20} \text{ cm}^2)$
$^1P_{1/2} + ^1D_{3/2}$	0	0.0398	0.0017	433.6	0.118	0.183
$^1G_{11/2} + ^1G_{9/2} + ^1D_{3/2} + ^1K_{13/2}$	0	0.0306	0.0229	470.8	0.437	0.261
$^1G_{7/2} + ^1G_{9/2} + ^1K_{13/2}$	0.0711	0.2295	0.1279	526.0	1.965	1.953
$^1G_{3/2} + ^1G_{7/2} + ^1H_{11/2}$	0.9682	0.5873	0.0724	587.0	6.195	6.197
$^1F_{9/2}$	0.0009	0.0092	0.0406	686.0	0.251	0.270
$^1F_{7/2} + ^1S_{3/2}$	0.0011	0.0431	0.6619	751.6	3.774	3.896
$^1F_{3/2} + ^1H_{9/2}$	0.0101	0.2419	0.5178	809.3	4.151	3.985
$^1F_{3/2}$	0	0.2283	0.0554	887.2	1.134	1.304

The values of the Judd-Ofelt parameters and Eq. (3) can now be used to calculate the transition line strengths between any two levels of Nd^{3+} in Y_2SiO_5 . In particular, if we use these Judd-Ofelt parameters to go back and calculate the line strengths of the eight absorption bands used in our analysis, we can get an idea of the validity of our polarization averaging approximation. The theory predicted or calculated line strengths are displayed along with the measured line strengths in Table 5. Defining ΔS to be the difference between the measured and calculated line strength values and defining RMS ΔS by

$$\text{RMS } \Delta S = \sqrt{\frac{\sum (\Delta S)^2}{(\text{number of transitions}) - 3}} \quad (5)$$

the RMS ΔS value for the line strength set listed in Table 5 is $0.146 \times 10^{-20} \text{ cm}^2$. A measure of the relative error of the fit is given by $(\text{RMS } \Delta S)/(\text{RMS } S) = 0.048$, giving one a high degree of confidence in the validity of our original polarization averaging approximation. Although the self consistency of the Judd-Ofelt parameter values is very good, our absolute values are limited to $\pm 10\%$, the accuracy to which we know the Nd concentration of the crystal.

Using the determined Judd-Ofelt parameters, line strengths corresponding to transitions from the $^4F_{3/2}$ to the $^4I_{11/2}$, $^4I_{13/2}$, and $^4I_{15/2}$ manifolds can now be calculated. The calculated line strengths for these transitions as

well as the measured ${}^4F_{3/2}$ to ${}^4I_{9/2}$ line strength are listed in Table 6. From these line strengths radiative transition rates can be calculated using the relation

$$A(J \rightarrow J') = \frac{64\pi^4 e^2}{3h(2J+1)\lambda^3} \frac{n(n^2+2)^2}{9} S(J \rightarrow J') \quad (6)$$

Transition	λ (nm)	Polarization Averaged	
		S_{calc} (10^{-20} cm^2)	A (s^{-1})
${}^4F_{3/2} - {}^4I_{13/2}$	1830	0.157	24.4
${}^4F_{3/2} - {}^4I_{11/2}$	1330	1.17	474
${}^4F_{3/2} - {}^4I_{9/2}$	1050	2.90	2390
${}^4F_{3/2} - {}^4I_{8/2}^*$	894	1.13	1550

Table 6. Calculated transition rates in $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$

*Measured not calculated

These rates recorded in Table 6 predict a total radiative rate out of the ${}^4F_{3/2}$ level equal to 4438 s^{-1} or a radiative lifetime for the meta-stable ${}^4F_{3/2}$ state of $225 \mu\text{sec}$.

Figure 4 shows measured fluorescence decays from two crystal samples having different Nd concentrations. Fitting the "effective lifetime"¹³ defined by

$$\tau_{\text{eff}} = \frac{1}{I_0} \int_0^\infty I(t) dt \quad (7)$$

to the expression for the Nd self-quenched lifetime,

$$\tau = \frac{\tau_0}{1 + \left(\frac{n_{\text{Nd}}}{n_{1/2}}\right)^2} \quad (8)$$

yields a value of $214 \mu\text{sec}$ for τ_0 , the zero Nd concentration ${}^4F_{3/2}$ fluorescence lifetime, and a value of $5.7 \times 10^{20} \text{ cm}^{-3}$ for $n_{1/2}$, the Nd concentration that halves the zero Nd concentration fluorescence lifetime. Comparing the measured $214 \mu\text{sec}$ zero concentration $\text{Nd}^{3+} {}^4F_{3/2}$ lifetime with the Judd-Ofelt predicted value of $225 \mu\text{sec}$ implies a radiative quantum efficiency of 0.95.

Knowing the radiative transition rates of the ${}^4F_{3/2}$ level down to the various 4I levels, it is possible to calculate absolute emission cross sections from calibrated emission spectra using the relation,

$$\sigma_{J \rightarrow J'}(\lambda) = A(J \rightarrow J') \frac{\lambda^4}{8\pi c n^2} g(\lambda) \quad (9)$$

(a) Decay signal from a sample doped at $2.1 \times 10^{19} \text{ cm}^{-3}$.

(b) Decay signal from a sample doped at $2.66 \times 10^{20} \text{ cm}^{-3}$.

Figure 4. Measured fluorescence decays from samples of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$. τ_1 , τ_2 , and τ_3 represent the measured lifetimes during the first three e-folding times, respectively. τ_{EFF} represents the "effective lifetime" as defined by Eq. (7).

where $g(\lambda)$ is the normalized line shape function. Using our oriented sample, three calibrated emission spectra were acquired in the interval from 850 to 1100 nm covering both the $\text{Nd}^{3+} \ ^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ and $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ transitions. As in the case of absorption spectra, the three emission spectra were acquired for light polarized along each of the three principal axes of the optical indicatrix. The excitation source used in acquiring these emission spectra was an AlGaAs laser diode operating at 810 nm. Experimentally, emission spectra were acquired for two orientations by keeping the sample and pump beam fixed while a Glan-Thompson polarizer located at the input slit of our spectrometer was rotated. The sample was then rotated 90° and the process repeated giving another set of emission spectra consisting of two more orientations with one of the orientations being common to both sets of data. Because of the change in the way the pump excitation beam coupled into the Y_2SiO_5 sample when it was rotated by 90° and possible minor changes in the collection efficiency of the emitted light, the two sets of data are not absolutely calibrated to each other. The one orientation that is common to both sets of data can, however, be used to remedy this situation by scaling the two common spectra to each other. This technique allows the acquisition of calibrated emission spectra over all three orientations that were studied. Having oriented calibrated emission spectra then allows us to calculate the relative values of the orientation dependent line strengths for both the $^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ and $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ transitions. Using these relative line strength values to weight the polarization averaged measured line strength for the $^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ transition allows the $^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ stimulated emission cross section to be calculated for each of the three orientations being studied. The same procedure was followed for calculating the $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ stimulated emission cross section except the Judd-Ofelt predicted line strength was used rather than a measured value. The results of these calculations are presented in Fig. 5 where we have plotted the $^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ and $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ stimulated emission cross sections for the three orientations under consideration.

Figure 5. Orientationally resolved stimulated emission cross sections of the $\text{Nd}^{3+} 4\text{F}_{3/2} - 4\text{I}_{9/2}$ and $4\text{F}_{3/2} - 4\text{I}_{11/2}$ transitions. The labels X, Y, and Z refer to the axes of the optical indicatrix that were parallel to the emitted light

Of particular interest to programs involving laser communication systems based on the Cs atomic resonance filter is the peak in the $4\text{F}_{3/2} - 4\text{I}_{9/2}$ emission cross section at 911.06 nm, twice the acceptance wavelength of the filter.¹⁴ Figure 6 shows the same cross sections of Fig. 5 in the vicinity of 911.06 nm with the three different orientations investigated overlaid on each other. As seen, the emission cross section at 911.06 nm is only 12% down from the peak emission cross section at 912 nm for each orientation providing the possibility for laser operation at 911.06 nm.

Figure 6. The same $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5 4\text{F}_{3/2} - 4\text{I}_{9/2}$ stimulated emission cross sections shown in Fig. 5 are overlaid here and shown on an expanded scale in the vicinity of 911 nm.

3. $\text{Nd}^{3+} \text{ } ^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ GAIN SUPPRESSION

An important design consideration in Nd-based GSD lasers is the ability to hold off the gain of the stronger emission feature near 1.07μ corresponding to the $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ transition. In the case of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$, Fig. 5 shows the peak cross section of the $^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ manifold at $1 \times 10^{-19} \text{ cm}^2$ is a factor of 5 times larger than the peak cross section of the $^4\text{F}_{3/2} - ^4\text{I}_{9/2}$ manifold at $2.0 \times 10^{-20} \text{ cm}^2$. In laser designs where the gain of the 0.912μ line is so large as to make it impossible to hold off the larger 1.07μ gain using intracavity dispersive optics and dichronically coated mirrors alone, one possible suppression technique is the use of a co-doped ion that selectively absorbs at 1.07μ but not at 0.912μ . One possible scheme relies on using Sm ions as the co-dopant. The Sm absorption spectrum shown in Fig. 7a is on the same scale as the Nd emission spectrum shown in Fig. 7b, and as can be seen good overlap exists between the Sm absorption and the $\text{Nd}^{3+} \text{ } ^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ emission features. Additionally, Sm shows no absorption at the desired laser emission wavelength of 0.912μ . Comparing the peak 1.07μ Nd emission cross section of $9 \times 10^{-20} \text{ cm}^2$ with the corresponding Sm absorption cross section of $1 \times 10^{-20} \text{ cm}^2$ indicates the required Sm doping density needed will be an order of magnitude larger than the Nd doping density.

Figure 7(a). Sm absorption spectrum taken from a sample of $\text{Sm}^{3+}:\text{Y}_2\text{SiO}_5$. The peak absorption feature at 1070 nm corresponds to an absorption cross section of $1.3 \times 10^{-20} \text{ cm}^2$.

Figure 7(b). Plot $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ emission cross section shows the same wavelength scale as the Sm absorption spectrum in 7(a).

To determine the detrimental effects, if any, of co-doping Sm with Nd in Y_2SiO_5 , a series of $\text{Sm}^{3+}:\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ powder samples were prepared having a range of Sm concentrations. For each of these powder samples, fluorescence lifetimes of the Nd $^4\text{F}_{3/2}$ level were measured. These results presented in Table 7 indicate the Nd is strongly quenched by the Sm, reducing the energy storage time in a co-doped laser. The results of these quenching measurements drive any laser design in which it is desired to use Sm absorption to suppress the $\text{Nd}^{3+} \text{ } ^4\text{F}_{3/2} - ^4\text{I}_{11/2}$ transition to a segmented design in which heavily doped samples of $\text{Sm}^{3+}:\text{Y}_2\text{SiO}_5$ or Sm^{3+} in some other host are interlaced between samples of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$, which may still be co-doped with Sm but not to a level high enough to significantly quench the $\text{Nd}^{3+} \text{ } ^4\text{F}_{3/2}$ state.

n_{Nd} ($10^{20}/cm^3$)	n_{Sm} ($10^{20}/cm^3$)	t_{eff} (μsec)
1.37	0	219
0.304	0.182	142
0.266	0.91	59
0.144	1.07	54

Table 7. Measured effective fluorescence lifetimes of the $Nd^{3+}:Y_2SiO_5$ $^4F_{3/2}$ state from powder samples having various Sm concentrations

As an example of Sm^{3+} in a host other than Y_2SiO_5 , our current laser design uses samarium scandium gallium garnet (SSGG) samples inserted in the cavity at Brewster's angle. Figure 8 presents the absorption spectrum of this stoichiometric crystal which exhibits strong features near 1074 nm but is completely transparent near 912 nm.

Figure 8. Absorption spectrum from the stoichiometric crystal samarium scandium gallium garnet.

4. 912 NM LASER DEMONSTRATION AND MODELING

Q-switched oscillator experiments have been performed to demonstrate the principles of GSD laser operation. In particular, these experiments were designed to demonstrate 912 nm extraction efficiency, the feasibility of using SSGG in the laser cavity to suppress the undesired gain of the $Nd^{3+} ^4F_{3/2} - ^4I_{11/2}$ transition, and finally to demonstrate closure with our laser performance computer modeling codes.

A schematic drawing of our Q-switched oscillator is shown in Fig. 9. The oscillator cavity was 100 cm long. the $Nd^{3+}:Y_2SiO_5$ laser sample was 7.1 cm long and doped with Nd^{3+} at $0.9 \times 10^{19} cm^{-3}$. The SSGG sample was 0.5 mm thick and had an insertion loss of approximately 4% at the 912 nm laser wavelength. The SSGG sample served the dual purpose of providing a polarization selective loss in the cavity for Q-switching and also suppressing the $Nd^{3+} ^4F_{3/2} - ^4I_{11/2}$ gain. The flat high reflector had a greater than 99% reflectance at 912 nm and a transmission of ~70% at 745 nm to allow the 745 nm pump beam to enter the cavity and longitudinally

pump the laser sample. Two different output couplers were available with reflectances at 912 nm of either 70 or 80%.

Figure 9. Schematic drawing of the Q-switched oscillator used in our laser demonstration experiments.

The boules from which our laser samples of $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ were cut were grown with their boule axis 20° off the $\langle 010 \rangle$ direction, as shown in Fig. 10. Laser samples were then cut with their faces normal to the boule axis. In terms of the optical indicatrix, this means the axis of the laser samples used in our experiments were 20° away from the X-axis and tipped toward the Y-axis. With no polarization selective components in the cavity, 912 nm free lasing was always observed to occur with the electric field parallel to the Z-axis. For our particular orientation of the crystal, this is what one would expect based on the oriented emission cross section data of Fig. 5.

Figure 10. This sketch shows the orientation of our laser samples relative to the optical indicatrix of Y_2SiO_5 . Laser samples were cut with their faces normal to the boule growth axis.

To model the excitation of the laser sample during the application of the bleach wave pump pulse, the following equations were used in generating our bleach-wave pump-pulse propagation code,

$$\begin{aligned} \frac{\partial n_{F3/2}(x, t)}{\partial t} &= \frac{\sigma_P}{h\nu_P} I_P(x, t) [n_{Nd} - n_{F3/2}(x, t)] - \frac{1}{\tau_F} n_{F3/2}(x, t) - \Gamma_{Auger} n_{F3/2}^2(x, t) \\ \frac{1}{c} \frac{\partial I_P(x, t)}{\partial t} + \frac{\partial I_P(x, t)}{\partial x} &= -\sigma_P I_P(x, t) [n_{Nd} - n_{F3/2}(x, t)] \end{aligned} \quad (10)$$

where:

n_{Nd} is the Nd^{3+} number density

$n_{4F_{3/2}}(x, t)$ is the local Nd^{3+} excited state number density

σ_p is the absorption cross section seen by the pump wave

$h\nu_p$ is the energy of a pump photon

$I_p(x, t)$ is the local pump wave intensity

τ_F is the $Nd^{3+} 4F_{3/2}$ fluorescence lifetime

Γ_{Auger} is the Auger decay rate and included because of the high excitation levels required for laser operation

Figure 11 shows predictions made by our pump pulse propagation code along with the results of experimental measurements. Figure 11a shows the time resolved excited state fraction that our code predicts will result from the application of the displayed 745 nm excitation pulse. Overlaid with this prediction is the experimentally measured $4F_{3/2}$ fluorescence decay signature that was measured by monitoring $4F_{3/2} - 4I_{11/2}$ fluorescence at 1074 nm during and after a shot of the exciting alexandrite laser. The excellent agreement between the shapes of the predicted excited state fraction and the measured $4F_{3/2}$ fluorescence signature which should follow the excited state fraction are a strong indication that our code is correctly modeling the physics of the excitation process. As a further check of the code's validity, Fig. 11b displays the predicted time resolved excited state fraction and a plot of the natural log of the experimentally measured small signal gain at 912 nm. The small signal 912 nm gain was measured during and after an alexandrite shot using a cw 912 nm probe beam generated by a Ti-sapphire laser. The natural log of this small signal gain should follow the transient excited state fraction. Again, the excellent agreement between measurement and code prediction gives us confidence in the code's validity.

Figure 11(a). Computer predicted excited state fraction is overlaid with the measured $Nd^{3+} 4F_{3/2}$ time resolved fluorescence signature.

Figure 11(b). Computer predicted excited state fraction is overlaid with the natural log of the measured 912 nm small signal gain.

A series of computer codes have also been written to model the 912 nm energy extraction of the laser after the sample has been excited. The starting point for generating these laser performance codes is the laser rate equations. In this analysis we assume that intra-manifold relaxation occurs on a time scale much shorter than any inter-manifold processes. This means the various manifolds involved in the lasing process will remain in thermal equilibrium throughout the generation of an output pulse. Of particular importance to our rate equation analysis will be the fractional thermal population of the $4F_{3/2}$ and $4I_{9/2}$ manifolds that lie in the laser initial and final crystal field states. Figure 12 shows detailed Stark splittings of the $Nd^{3+}:Y_2SiO_5$ $4F_{3/2}$ and $4I_{9/2}$ manifolds for both types of cationic sites that Nd can occupy as reported by Tkachuk, et al.⁹ In this

diagram, level a and b refer to the terminal and initial crystal field state of our laser, respectively. The fractional thermal population of the ${}^4F_{3/2}$ manifold located in crystal field level b is given by the Boltzmann occupation factor as

$$f_b = \frac{e^{-E_b/KT}}{\sum_i e^{-E_i/KT}} \quad (11)$$

(All crystal levels in the ${}^4F_{3/2}$ manifold)

where we have neglected the degeneracies of the various crystal field states as they are all doubly degenerate. Using the splittings in Fig. 12, the value of f_b is calculated to be 0.70. A similar calculation for f_a gives 0.078. The rate equations appropriate for our laser now take the form

$$\begin{aligned} \frac{d\phi}{dt} &= \phi \left[c\sigma \frac{\ell}{\ell'} (n_b - n_a) - \frac{\delta}{t_n} \right] \\ \frac{dn_b}{dt} &= -f_b (n_b - n_a) c\sigma \phi \\ \frac{dn_a}{dt} &= f_a (n_b - n_a) c\sigma \phi \end{aligned} \quad (12)$$

where ϕ is the cavity photon density, n_a and n_b are the final and initial crystal field level population densities, respectively, ℓ is the sample length, ℓ' is the cavity length, δ is the fractional round trip cavity loss given by $-\ln(T^2 R_{OC})$, t_n is the round trip cavity time and given by $2\ell'/c$, and σ is the actual spectroscopic cross section of the laser transition. This last distinction is an important one as the emission cross sections derived from our previous Judd-Ofelt analysis were effective cross sections and $\sigma_{eff} = f_b \sigma$.

Figure 12. Detailed Stark splittings of the ${}^4F_{3/2}$ and ${}^4I_{9/2}$ manifolds of Nd^{3+} in Y_2SiO_5 for both types of sites as reported in Ref. 9.

We now present a short derivation of the GSD external extraction efficiency based on the rate Eq. (12). To begin, we write down the internal extraction efficiency,

$$\eta_{internal} = \frac{n_b(0) - n_b(\infty)}{n_b(0)} \quad (13)$$

Assuming we know $n_b(0)$, the extraction efficiency could be calculated if we also knew $n_b(\infty)$. To find $n_b(\infty)$, we resort to the rate equations and begin by defining a new variable, $\Delta n(t)$, the difference between the population in the laser initial crystal state and final crystal state,

$$\Delta n(t) = n_b(t) - n_a(t) \quad (14)$$

Calling Δn_{th} the threshold value of Δn ,

$$\Delta n_{th} = \frac{\delta}{2\sigma\ell} \quad (15)$$

the rate equations (12) can be rewritten in the simpler form

$$\begin{aligned} \frac{d\phi}{dt} &= \frac{\ell}{\ell'} [\Delta n - \Delta n_{th}] \phi \\ \frac{d\Delta n}{dt} &= -(f_a + f_b) \sigma \Delta n \phi \end{aligned} \quad (16a, b)$$

Dividing Eqs. (16a) and (16b) and integrating gives a transcendental equation for $\Delta n(t)$,

$$\phi(t) - \phi(0) = \frac{\ell}{\ell'} \frac{1}{(f_a + f_b)} \left[\Delta n_{th} \ln \left(\frac{\Delta n(t)}{\Delta n(0)} \right) - (\Delta n(t) - \Delta n(\infty)) \right] \quad (17)$$

Letting $t = \infty$ in Eq. (17) and noting that $\phi(0) = \phi(\infty)$, both being nearly 0, a slight rearrangement gives

$$\frac{\Delta n(\infty)}{\exp \left(\frac{\Delta n(\infty)}{\Delta n_{th}} \right)} = \frac{\Delta n(0)}{\exp \left(\frac{\Delta n(0)}{\Delta n_{th}} \right)} \quad (18)$$

which can be solved for $\Delta n(\infty)$ since we know $\Delta n(0)$. The solution to Eq. (18) was programmed on a computer to find $\Delta n(\infty)$. Since we have assumed all the population is located in either the Nd $^4F_{3/2}$ or the $^4I_{9/2}$ manifold,

$$\frac{1}{f_a} n_a(t) + \frac{1}{f_b} n_b(t) = n_{Nd} \quad (19)$$

and a simple relationship between $\Delta n(\infty)$ and $n_b(\infty)$ exists,

$$n_b(\infty) = \frac{\Delta n(\infty) + f_a n_{Nd}}{1 + f_a/f_b} \quad (20)$$

Finally, the external extraction efficiency is approximately given by

$$\eta_{\text{external}} = \eta_{\text{internal}} \frac{1 - R_{oc}}{1 - T^2 R_{oc}} \quad (21)$$

As a check on the validity of the preceding analysis and the laser performance codes we have written based on the rate equations (12), a comparison of code predictions and experimentally measured laser performance has been made.

The laser cavity shown in Fig. 9 was pumped by an alexandrite laser at 745 nm. The effective absorption cross section seen by the pump laser was $3.2 \times 10^{-20} \text{ cm}^2$ (see Fig. 2). To optimize the 912 nm performance of the

laser, an analysis was made to determine what spot size the pump should have at the sample for a given fixed amount of pump energy to maximize the 912 nm Q-switched output energy. The tradeoff here is between the pump induced excited state fraction in the sample at the time the Q-switch is opened and the total volume of sample excited by the pump. The results of this analysis are shown in the map of Fig. 13 in which sample length and the diameter of the pump excited region at the sample are varied and for each possible combination the output 912 nm energy of the laser is calculated. For the particular map shown in Fig. 13, the output coupler was assumed to be 70% reflective at 912 nm, the one-way cavity transmission was fixed at 0.9, and the pump was assumed to be capable of delivering 4.5 Joules at the input side of the laser sample. The output energy represented by the contours increases going toward the top center of the plot, and for our particular sample length of 7.1 cm the optimum pump geometry occurs when the pump fluence is adjusted to be 25 J/cm² and is not very sensitive in the range between 20 and 30 J/cm². Taking the pump sat fluences as $h\nu_P/\sigma_P = 8.4$ J/cm² means the optimum pump configuration corresponds to pumping between 2.5 and 3.5 sat fluences.

Figure 13. Optimization map in which contours of constant 912 nm Q-switched output energy are plotted against sample length and the diameter of the pump excited region at the sample. For this particular map it was assumed the output coupler was 70% reflective, the one-way cavity transmission was .9, and the pump laser was capable of delivering 4.5 J of 745 nm energy to the input side of the sample.

Laser performance measurements were made using a pump fluence of 21.2 J/cm². Figure 14 shows the measured temporal profile of the alexandrite laser used in our experiments together with the calculated excited state fraction induced by the pump excitation pulse. The Q-switch was opened at the time the excited state fraction was at its maximum value – the time of peak inversion. As a measure of the efficiency with which energy was extracted from the sample during the Q-switched pulse, the population in the ⁴F_{3/2} level was tracked by monitoring the ⁴F_{3/2} - ⁴I_{11/2} fluorescence at 1074 nm. A scope trace of this fluorescence signal is shown in Fig. 15a and demonstrates the operation of the laser at an internal extraction efficiency of 70%. For this particular measurement, the output coupler reflectivity was 0.8 at 912 nm and the cavity transmission was estimated at 0.86 using a 912 nm probe beam. Figure 15b shows the internal extraction efficiency predicted by our laser modeling code as a function of cavity transmission and parameterized by the excited state fraction just prior to opening the Q-switch. At our estimated cavity transmission of 0.86 and excited state fraction of 0.63 (see Fig. 14), the projected internal extraction efficiency of the laser is 0.7, in excellent agreement with the results of our measurements.

In addition to validating the operating principles of the GSD laser and demonstrating the effectiveness of using SSGG in the cavity to standoff the 1074 nm gain, the foregoing measurements demonstrate the efficiencies that can be reasonably obtained with such lasers. The limiting factor in the operation of our present laser is scatter losses at the sample interface due to a degradation in the AR coatings on the Nd³⁺:Y₂SiO₅ sample with laser operation. This problem has been successfully addressed at the crystal growth stage using the Reptile laser damage facility at LLNL to assess crystal quality. At present, selected samples of Nd³⁺:Y₂SiO₅ have bulk and AR sol-gel (AlOOH) coated surface damage thresholds of 40 J/cm² for 10 nsec,

10 Hz, 1.06 μm test pulses. This damage threshold is adequate for the foreseen operational envelope of the present GSD laser as the sat fluence at 912 nm is $\sim 9 \text{ J}/\text{cm}^2$.

Figure 14. Temporal profile of the 745 nm alexandrite laser excitation pulse used in our experiments. The solid line shows the calculated excited state fraction induced by the excitation pulse in the laser sample for an assumed input pump fluence of $21.2 \text{ J}/\text{cm}^2$ ($2.5 \times \Gamma_{\text{sat}}$).

Figure 15(a). 1074 nm fluorescence trace showing the operation of the GSD laser at an internal extraction efficiency of 70%.

Figure 15(b). The predictions of our laser performance code for the internal extraction efficiency of the GSD laser as a function of the one-way cavity transmission and parameterized by the excited state fraction just prior to the opening of the Q-switch. The operating point of the laser for the measurement in (a) is as indicated. The constant excited state fraction contours start at 1 and decrement by .1 going left to right.

Because of the modest values of cavity transmission achieved in our present laser, we have found we can increase the output energy per pulse by using a higher transmission output coupler. Figure 16a shows the time resolved Q-switched output pulse as measured by a fast photodetector for an output coupler reflectivity of 0.7 at 912 nm. At this operating point, the output energy per pulse was measured to be 375 mJ and the sample was lased over an area having a diameter of 0.42 cm (area = .14 cm²). The sample was being excited by the same 21.2 J/cm² alexandrite pulse depicted in Fig. 14 and so the excited state fraction as predicted by the pump pulse propagation code is 0.63. Knowing the laser cavity transmission is 0.86, a self-consistent check of the laser operation was made to experimentally determine the excited state fraction present in the sample just prior to the opening of the Q-switch. By measuring the initial risetime of the laser pulse when plotted on a semi-log scale, the initial excited state fraction can be determined. This is easiest to see by making a slight rearrangement in Eq. (16a)

$$\text{slope} = \frac{\frac{d\phi}{dt}}{\phi} = c\sigma \frac{\ell}{\ell'}(n_b - n_a) - \frac{\delta}{t_n} \quad (22)$$

This method relies on measuring the slope before the building laser pulse has had a chance to significantly deplete the ⁴F_{3/2} excited state. Figure 16b takes the same pulse displayed in Fig. 16a and plots it in a semi-log scale. Fitting a line to the initial rising part of the pulse gives a slope of 0.049/nsec, which together with Eq. (22) leads to an excited state fraction of 0.60. Again this value is in good agreement with the pump pulse propagation code prediction of 0.63.

Figure 16(a). Time resolved 912 nm Q-switched output pulse from the GSD laser. The output coupler used had a 912 nm reflectivity of 0.7 and the measured output energy was 375 mJ/pulse.

Figure 16(b). The same experimentally measured pulse of (a) but plotted on a semi-log scale. Fitting a straight line to the initial rise of the pulse leads to a slope of 0.049/nsec.

Figure 17 plots our laser performance code prediction for the external extraction efficiency as a function of output coupler reflectivity and parameterized by the excited state fraction just prior to Q-switching. The cavity transmission was set at 0.86 in this calculation, leading to a predicted external extraction efficiency of 0.30 for a 70% reflective output coupler and an initial excited state fraction of 0.60. For our 7.1 cm long sample doped with Nd^{3+} at $0.9 \times 10^{19} \text{ cm}^{-3}$ and lased over an area of $.14 \text{ cm}^2$, the stored 912 energy in the active laser volume just prior to Q-switching is 1.18 Joules. The performance code prediction of 0.3 for the external extraction efficiency then implies the output energy should be 353 mJ, which is in good agreement with our measured value of 375 mJ.

Figure 17. Our laser performance code prediction for the external extraction efficiency of the GSD laser as a function of the output reflectivity and parameterized by the excited state fraction just prior to the opening of the Q-switch. The operating point of the laser for the operating point depicted in Figure 16 is as indicated. The constant excited state fraction contours start at 1 and decrement by .1 going from left to right.

5. HARMONIC GENERATION

Doubling of the 912 nm output of the laser has been accomplished using an A-cut crystal of KNbO_3 . For this orientation of crystal, efficient non-critically phase matched harmonic generation can be accomplished using fundamental light polarized parallel to the KNbO_3 B-axis with the crystal held at approximately 135°C . Figure 18 shows a map of doubling efficiency (taken from Ref. 15) as a function of the input beams dephasing parameter and drive,

$$\begin{aligned} \eta_0 &= C^2 I L^2 \text{ (drive)} \\ \delta &= \frac{1}{2} \Delta k l \text{ (dephasing)} \end{aligned} \quad (23)$$

where

$$C = 5.46 d_{\text{eff}} \left(\frac{\text{pm}}{\text{v}} \right) \frac{1}{\lambda_1 (n_1 n_2 n_3)^{\frac{1}{2}}}$$

Because of the large nonlinear optical coefficient of KNbO_3 used for this doubling geometry [$d_{32} = 19.7 \text{ (pm/v)}$],¹⁶ modest values of input laser intensity give sufficiently large drives to achieve good doubling efficiencies even with high order multi-transverse mode beams. To date the best doubling efficiencies we have observed has been in a KNbO_3 crystal supplied by Virgo Optics and having an input aperture of $5 \text{ mm} \times 5 \text{ mm}$ and a length of 15 mm. Using an input 912 nm pulse with an average intensity of 7 MW/cm^2 and a beam divergence of 9 mrad (FW), making it 5 times diffraction limited, we have achieved conversion efficiencies of 25%. We estimate the drive of this beam to be 18 and the dephasing parameter to be approximately 0.9, putting us in the fringe area of the secondary lobe on the doubling efficiency map of Fig. 18. From the map it is clear that we can increase our

doubling efficiency to values of 50-60% without any improvement in beam quality by either increasing the drive from its present value of 18 to 24 or by decreasing it to 3. This work is currently in progress.

Figure 18. Contour plot of the conversion efficiency η as a function of the (dimensionless) drive C^2I^2 and the dephasing $(1/2) \Delta kl$. The line of zeros between the first and second lobes follows the approximate curve $\delta = 8\eta_0^{1/2} \exp(-\eta_0^{1/2})$. Conversion using the first lobe becomes increasingly sensitive to detuning at higher drive. Taken from Ref. 15.

6. CONCLUSION

A spectroscopic evaluation of Nd^{3+} in the biaxial crystal yttrium orthosilicate has been performed. Using the Judd-Ofelt theory to analyze optical line strengths measured in absorption, we have extracted radiative rates for transitions from the $\text{Nd}^{3+} {}^4F_{3/2}$ manifold to the various 4I manifolds and emission cross sections for the ${}^4F_{3/2} - {}^4I_{9/2}$ and ${}^4F_{3/2} - {}^4I_{11/2}$ transitions. The ${}^4F_{3/2} - {}^4I_{9/2}$ transition is of particular interest to laser communication programs using receivers based on the Cs atomic resonance filter because of the fortuitous Stark structure of Nd^{3+} in Y_2SiO_5 giving rise to a peak in the emission spectrum near twice one of the filter's acceptance wavelengths. In connection with this we have also measured optical absorption spectra that will be of interest to experimenters wanting to laser pump this material. We have also demonstrated for $\text{Nd}^{3+}:\text{Y}_2\text{SiO}_5$ that instead of the polarization and direction averaging strictly required for the application of the Judd-Ofelt technique, it suffices to average over the three principal directions of the optical indicatrix as evidenced by the good agreement (4.8%) between measured and calculated line strengths used in the fitting procedure. The advantage of being able to do this lies largely in the experimental simplicity that ensues from being able to use a single oriented rectangular sample for all measurements.

GSD laser operation has been demonstrated on the $\text{Nd}^{3+} {}^4F_{3/2} - {}^4I_{9/2}$ transition at the lasing wavelength of 912 nm. The physics of the bleach wave excitation process and the 912 nm Q-switched energy extraction process have been modeled in a series of computer codes that accurately predict the performance of the actual laser. SSCG has been demonstrated as an effective gain suppressor of the unwanted and competing $\text{Nd}^{3+} {}^4F_{3/2} - {}^4I_{11/2}$ transition at 1074 nm which has a cross section 5 times larger than the lased 912 nm transition. Additionally, the level of efficiency that one can reasonably expect from GSD lasers has been demonstrated in our energy extraction measurements that have documented internal extraction efficiencies as high as 70%. Finally, doubling efficiencies of 25% have been demonstrated using KNbO_3 in a non-critically phase matched geometry. Because of the large nonlinear optical coefficient of KNbO_3 and the non-critical phase matched geometry used, the doubling is forgiving of beam quality and allows efficiencies of 50-60% for our present 5 times diffraction limited laser at modest laser intensity levels.

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