# Nd3+:ethylene glycol amplifier and its stimulated emission cross section

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# $Nd^{3+}$:ethylene glycol amplifier and its stimulated emission cross section

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We demonstrate that $Nd^{3+}$:ethylene glycol can be used as an amplifier gain medium for a $Nd^{3+}$:YLF laser. It has been known that $Nd^{3+}$:liquid is hard to use as a gain medium due to fluorescence quenching. However, we could use $Nd^{3+}$:ethylene glycol as a gain medium by using a new amplification system, and we also measured the stimulated emission cross section of $Nd^{3+}$:ethylene glycol. A maximum gain of ~2 was obtained in our experimental setup, and the stimulated emission cross section of $Nd^{3+}$:ethylene glycol was measured to be $1.5(\pm 0.5) \times 10^{-19}$ $cm^2$. © *1995 American Institute of Physics.*

The production of high peak power optical pulses has greatly progressed. When we amplify a short pulse, the efficiency of energy extraction in a gain medium is very low. Thus, many researchers have proposed multipass and regenerative amplifiers that have high efficiency for energy extraction.[1–7] In these amplifiers, it is very important to avoid optically induced damage in the gain medium. Such a problem makes us have an interest in $Nd^{3+}$:liquid as a gain medium. $Nd^{3+}$:liquids have received considerable attention as gain media for high power lasers since they can have a high concentration of active ions and immunity to optical damage.[8–13] The absorption and emission spectra of the $Nd^{3+}$ ion in glass and in liquid show only minor differences.[12] However, except for inorganic liquids that are strongly corrosive, most liquids cannot be used as laser media because of fluorescence quenching. In most liquids the quantum yield of fluorescence is less than $10^{-3}$, whereas in most glasses it is ~0.3.[12] Thus, it is difficult to measure the gain bandwidth of a $Nd^{3+}$:liquid. The low quantum yield in a liquid is believed to be caused by the transfer of the electronic energy of the $Nd^{3+}$ ion to the most energetic vibration of the solvent molecules.[12] We thick that it is possible to use liquids as hosts of gain media when the interval between pumping and amplifying is shorter than or comparable to the lifetime reduced by fluorescence quenching. In this letter, we demonstrate that $Nd^{3+}$:ethylene glycol can be used as a gain medium by using a new amplification system. We also measured the stimulated emission cross section of $Nd^{3+}$:ethylene glycol. Ethylene glycol (EG) was chosen as a solvent because it readily dissolves $NdCl_3$ salt. $Nd^{3+}$:EG strongly absorbs the second harmonic ($\lambda = 527$ nm) of a $Nd^{3+}$:YLF laser. The absorption coefficient at this wavelength was 1.3 $cm^{-1}$ for a 10% $Nd^{3+}$ ion concentration. We used the second harmonic of the *Q*-switched and mode-locked (QSML) pulse train of a $Nd^{3+}$:YLF laser as a pumping source for a $Nd^{3+}$:EG amplifier.

We set up the new amplifier using a $Nd^{3+}$:EG cell as shown in Fig. 1. The $Nd^{3+}$:YLF laser was operated with an acousto-optic *Q* switch and a mode locker. The full width at half-maximum of the *Q*-switched pulse of $Nd^{3+}$:YLF was 300 ns, and the mode-locked pulse width and pulse-to-pulse interval were 500 ps and 10 ns. The polarization of the laser beam was oriented to satisfy the phase matching condition (type I) for second harmonic generation in a 1 cm KTP crystal. If we orient the polarization of one pulse in the QSML pulse train to be perpendicular to that of the original by using a Pockels cell, this single pulse is not converted to the second harmonic because of phase mismatching. We used this single pulse as the probe pulse. To increase the second harmonic conversion efficiency, the QSML pulses were amplified by a $Nd^{3+}$:glass preamplifier, PA in Fig. 1. The average efficiency for converting the QSML pulse train into a second harmonic train was ~15%.

To increase the second harmonic conversion efficiency, we reduced the laser beam cross section with a positive lens, L1 (focal length=50 cm), and a negative lens, L2 (focal length=−6 cm). The beam diameter at the entrance of the $Nd^{3+}$:EG amplifier was 0.35 mm.

A Glan–Thompson polarizer was set so that the second harmonic pulses could pass through it, and then these green waves were absorbed in the $Nd^{3+}$:EG amplifier as the pumping light. The original waves that were not converted to a second harmonic could not pass through the polarizer because the polarization of the original pulse and the second harmonic pulse were perpendicular to each other. However, the probe pulse could pass through the polarizer because the polarization of the pulse had been rotated by the Pockels cell. Figure 2 shows the case for the fifth pulse, after the highest peak was selected as the probe pulse.

The gain of the $Nd^{3+}$:EG amplifier depends on the position of the probe pulse in the QSML pulse train. Figure 3 shows the amplified probe pulse energy $E_{out}$, versus the po-

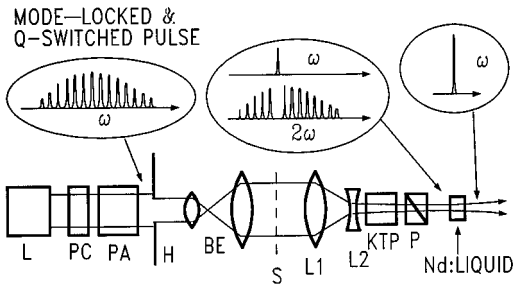


FIG. 1. Experimental setup. L is $Nd^{3+}$:YLF laser; PC, Pockels cell; PA, $Nd^{3+}$:glass preamplifier; H, hard aperture; BE, beam expander; P, polarizer; S, image plane of hard aperture.

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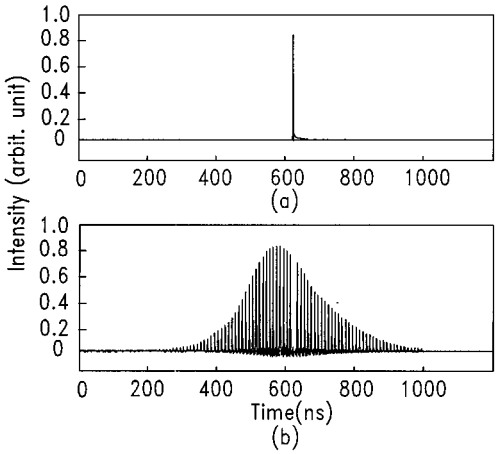


FIG. 2. Temporal profiles of (a) the probe pulse and (b) the second harmonic pulses.

sition of the selected probe pulse. The +5th pulse has the largest energy. This result means that the interval between pumping and amplifying is comparable to the lifetime reduced by fluorescence quenching. In Fig. 3, the negative and the positive numbers indicate the pulse position before and after the highest peak of the QSML pulses. To estimate the stimulated emission cross section $\sigma$ of $Nd^{3+}$:EG, we measured the gain of the +5th pulse by increasing the power of the original wave with the preamplifier PA. The result of the measurement is shown in Fig. 4. The maximum gain was ~2. We could determine the stimulated emission cross section $\sigma$ of $Nd^{3+}$:EG from the measured gain $G$. We fitted the gain curve to the experimental data by varing $\sigma$ and the stored energy $E_{\text{store}}$. The saturated gain equation is given by

$$G=\frac{h\nu A}{2\sigma E_p}\ln\left\{\exp\left(\frac{2\sigma E_{\text{store}}}{h\nu A}\right)\left[\exp\left(\frac{2\sigma E_p}{h\nu A}\right)-1\right]+1\right\}, \tag{1}$$

where $A$ is the cross section of the laser beam, $h\nu$ the photon

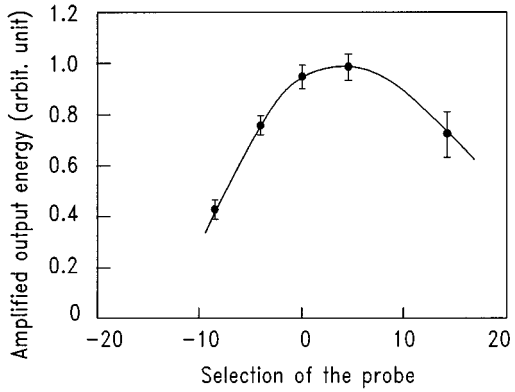


FIG. 3. Output energy vs the order of the selected pulses. The negative and positive numbers indicate the pulse position before and after the highest peak of the QSML pulses.

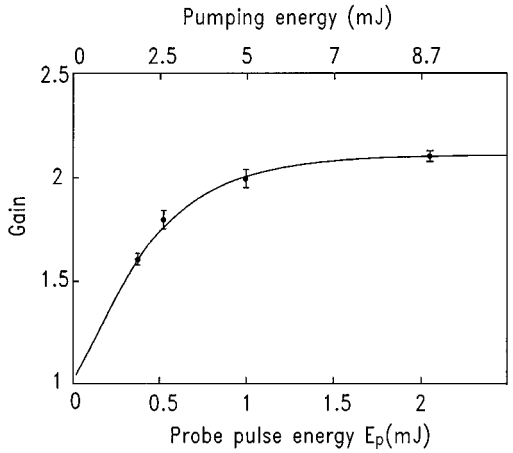


FIG. 4. The gain obtained in the $Nd^{3+}$:ethylene glycol amplifier.

energy of the probe pulse, $E_p$ the probe pulse energy, and $E_{\text{store}}$ the total energy stored in the liquid cell on the laser beam path.[14] From such a fit, we found that the stimulated emission cross section of the ${}^4F_{3/2}\rightarrow{}^4I_{11/12}$ transition is $1.5(\pm0.5)\times10^{-19}$ cm$^2$. This value is slightly larger than the stimulated emission cross section of the inorganic liquids, $Nd^{3+}$:$POCl_3$ and $Nd^{3+}$:$SeOCl_2$.[15,16]

In conclusion, we introduced $Nd^{3+}$:ethylene glycol as a gain medium. We demonstrated that an organic liquid can be used as a host of a gain medium by using a new amplifier scheme which can perform pumping and amplification within a $Q$-switching pulse duration. We also measured the stimulated emission cross section of $Nd^{3+}$:ethylene glycol to be $1.5(\pm0.5)\times10^{-19}$ cm$^2$ for a 10% $Nd^{3+}$ ion concentration.


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