Direct Upper-State Pumping of the 2.8 \text{	extmu}m
Er$^{3+}$ : YLF Laser

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Abstract—Direct resonant pumping of the $^4I_{11/2}$ upper state of the 2.8 \text{	extmu}m Er$^{3+}$ : YLF laser at 0.97 \text{	extmu}m is shown to be more efficient than other pumping schemes which have been used for this transition. Upper-state pumping avoids nonradiative losses arising from phonon and self-quenching decays inherent in other pumping schemes. Efficient performance of the 2.8 \text{	extmu}m laser is maintained on condition that extremely shallow pump absorption is avoided. Reduced efficiency for shallow pump absorption is attributed to upconversion loss arising from high pumping rates.

I. INTRODUCTION

The trivalent erbium $^4I_{11/2} \rightarrow ^4I_{13/2}$ laser transition, operating in the 2.7 to 2.9 \text{	extmu}m spectral region in various crystalline hosts (e.g. CaF$_2$ [1], YAG [2], and YAlO$_3$ [3]), is useful for medical applications owing to the strong absorption by liquid water of these wavelengths [4]. Both broad-band (flashlamp) and resonant (laser) pumping have been used for this transition. Continuous wave (CW) operation for this transition has been obtained for resonant laser pumping at 0.51 and 0.80 \text{	extmu}m in YLiF$_3$ (YLF) [5]–[7], 0.65 \text{	extmu}m in YSGG [8], and 1.51 \text{	extmu}m in CaF$_2$ [9]. Here we consider direct pumping of the $^4I_{11/2}$ upper laser state at 0.97 \text{	extmu}m in Er$^{3+}$ : YLF.

Direct upper-state pumping has several advantages over other resonant pumping schemes. Losses from nonradiative phonon decay, and bypass of the upper laser state via self-quenching decay, are avoided in the direct pumping scheme. These factors result in higher efficiency for the 2.8 \text{	extmu}m Er$^{3+}$ : YLF laser with 0.97 \text{	extmu}m pumping.

The investigation of the 2.8 \text{	extmu}m Er$^{3+}$ laser presented here utilizes a Ti : sapphire laser pumped at the 0.97 \text{	extmu}m $^4I_{11/2} \rightarrow ^4I_{13/2}$ absorption band. The pump wavelengths in this band are well within the range of the recently developed strained-layer InGaAs diode lasers [10], [11]. The narrow linewidth of the Ti : sapphire laser (= 0.1 nm) is particularly useful here as it allows a detailed investigation of the dependence of the 2.8 \text{	extmu}m laser performance on pump wavelength.

II. DIRECT VERSUS INDIRECT PUMPING SCHEMES

The direct upper-state pumping scheme is shown in Fig. 1. The theoretical maximum slope efficiency for the 2.8 \text{	extmu}m laser pumped at 0.97 \text{	extmu}m is $\eta_p/\lambda_i = 35\%$, where $\eta_p$ = 0.97 \text{	extmu}m is the pump wavelength and $\lambda_i = 2.8$ \text{	extmu}m is the laser wavelength. Alternative pumping schemes introduce nonradiative losses which lower the laser efficiency. For example, the Er$^{3+}$ $^4I_{13/2}$ state can be pumped at 0.80 \text{	extmu}m, as shown in Fig. 2. The upper laser state is populated indirectly through the $^4I_{11/2} \rightarrow ^4I_{13/2}$ phonon decay process. With 0.80 \text{	extmu}m pumping the theoretical maximum slope efficiency for the 2.8 \text{	extmu}m laser is $\eta_p/\lambda_i = 28\%$. Other pumping schemes are even less direct, and therefore less efficient owing to additional nonradiative loss.

Another nonradiative loss which is avoided in the direct upper-state pumping scheme is decay from the $^4I_{13/2}$ state through the self-quenching process $^4I_{13/2} \rightarrow ^4I_{13/2}$ shown in Fig. 2. This process bypasses the $^4I_{11/2}$ upper laser state when the $^4I_{13/2}$ state is pumped at 0.80 \text{	extmu}m. The self-quenching results from the dipole–dipole interaction between nearby Er$^{3+}$ ions in the YLF crystal lattice. The self-quenching rate is higher for larger Er$^{3+}$ concentrations, owing to the stronger dipole–dipole interaction for smaller interionic separations. The $^4I_{11/2}$ lifetime is therefore shorter for higher Er$^{3+}$ concentrations.

The lifetime of the $^4I_{13/2}$ state is determined for several Er$^{3+}$ concentrations in YLF by observing the fluorescence at 0.83 \text{	extmu}m from this state following excitation at 0.80 \text{	extmu}m. The excitation is provided by a dye laser with pulse duration (= 10 ns) significantly shorter than the $^4I_{11/2}$ lifetime. The results are shown in Fig. 3 for two Er$^{3+}$ conc-
The upper-state pumping efficiency is negligible in the limit of low Er\(^{3+}\) concentration, implying that \(\eta_{\text{p}} = 1/\tau(0)\). The upper-state pumping efficiency is therefore \(\eta_{\text{p}} = \tau(N)/\tau(0)\).

For the \(4I_{9/2}\) lifetimes quoted above, \(\tau(4\%)\) is not significantly longer than \(\tau(8\%)\), and therefore \(\tau(0) = \tau(4\%)\). Therefore, from the measured \(4I_{9/2}\) lifetimes, the upper-state pumping efficiencies are \(\eta_{\text{p}} = 100\%\) for 4% Er\(^{3+}\), \(\eta_{\text{p}} = 99\%\) for 8% Er\(^{3+}\), \(\eta_{\text{p}} = 94\%\) for 16% Er\(^{3+}\), and \(\eta_{\text{p}} = 78\%\) for 30% Er\(^{3+}\). The laser results presented here are obtained with a YLF crystal containing 30% Er\(^{3+}\).

The theoretical maximum slope efficiency for the 2.8 \(\mu\text{m}\) laser pumped at 0.80 \(\mu\text{m}\) is \(\eta_{\text{p}}(\lambda_{\text{p}}/\lambda_{\text{i}})\). For 30% Er\(^{3+}\): YLF the theoretical maximum slope efficiency is 22% (the 28% theoretical maximum quoted earlier assumed a low Er\(^{3+}\) concentration, i.e., the self-quenching bypass loss was ignored). Therefore the 0.97 \(\mu\text{m}\) pumping scheme is potentially 50% more efficient than the 0.80 \(\mu\text{m}\) pumping scheme for 30% Er\(^{3+}\): YLF.

It could be argued that the pumping efficiency for the 0.80 \(\mu\text{m}\) pumping scheme would be improved by using an Er\(^{3+}\) concentration lower than 30\%, thereby avoiding the self-quenching loss. This relatively high concentration is employed, however, in order to enhance the CW operation of the 2.8 \(\mu\text{m}\) transition [6]. This transition is potentially self-terminating owing to the long \(4I_{11/2}\) lower-state lifetime (13.2 ms) relative to the \(4I_{11/2}\) upper-state lifetime (4.2 ms) [12]. The lower-state lifetime can be effectively reduced, however, by taking advantage of the up-conversion process \(4I_{11/2} \rightarrow 4I_{15/2}\) (the inverse of the self-quenching process shown in Fig. 2) which partially depletes the \(4I_{15/2}\) lower laser state [12]–[15]. Before examining the effect of this process on the 2.8 \(\mu\text{m}\) laser, however, we will consider a simple model of the effect of lower-state self-termination on the laser threshold for a low-loss resonator.

The threshold condition for the 2.8 \(\mu\text{m}\) laser transition is

\[\Delta N = f_2 N_2 - f_1 N_1 > 0\]  \hspace{1cm} (1)

where \(\Delta N\) is the laser inversion density, \(N_1\) and \(N_2\) are the populations in the \(4I_{11/2}\) and \(4I_{13/2}\) states, respectively, \(f_1\) is the fraction of the \(4I_{11/2}\) population residing in the crystal-field component serving as the lower laser level, and \(f_2\) is the upper-laser-level crystal-field component. The population fractions \(f_1\) and \(f_2\) are given by the Boltzmann distribution.

The \(4I_{13/2}\) population satisfies the rate equation

\[\frac{dN_1}{dt} = \frac{b_{21}}{\tau_2} N_2 - \frac{1}{\tau_1} N_1 = 0\]  \hspace{1cm} (2)

in the steady state, where \(\tau_1\) and \(\tau_2\) are the lifetimes of the \(4I_{13/2}\) and \(4I_{11/2}\) states, respectively, and \(b_{21}\) is the branching ratio for decay from the \(4I_{11/2}\) state to the \(4I_{13/2}\) state. Equation (2) assumes a low-loss resonator, for which nonlinear processes such as upconversion can be neg-
neglected. The threshold condition for CW operation of the 2.8 μm laser can therefore be written

\[ \frac{f_1}{f_2} < \frac{\tau_2}{b_2 \tau_1}. \quad (3) \]

For the 2.8 μm Er\(^{3+}\) : YLF transition, \(f_1 = 0.11\), \(f_2 = 0.20\), and \(b_2 = 0.5\) [12], [16]. Therefore the Boltzmann ratio is \(f_1/f_2 = 0.55\), and the right-hand side of (3) is \(\tau_2/b_2 \tau_1 = 0.64\). The CW threshold condition is satisfied, although the margin by which self-termination is avoided is not large [the left-hand side of (3) is only 14% smaller than the RHS]. As mentioned above, however, this margin can be improved by utilizing higher concentrations of Er\(^{3+}\), for which the upconversion process \(^4I_{13/2} \rightarrow ^4I_{15/2} \rightarrow ^4I_{9/2} + ^4I_{11/2}\) effectively reduces the lower state lifetime \(\tau_1\). This effect has been demonstrated in Er\(^{3+}\) : YLF, for which a lower threshold is observed for 30% Er\(^{3+}\) compared to lower concentrations [6]. Therefore a fundamental tradeoff exists between improved CW operation (owing to upconversion depletion of the lower laser state) and reduced upper-state pumping efficiency (owing to self-quenching loss) for higher Er\(^{3+}\) concentrations. This tradeoff does not arise with direct upper-state pumping, but cannot be avoided with the 0.80 μm pumping scheme.

Another advantage inherent in the direct pumping scheme is the favorable pump absorption for Er\(^{3+}\) in the 0.97 μm region. The polarized \(^4J_{15/2} \rightarrow ^4J_{11/2}\) absorption spectrum for 30% Er\(^{3+}\) : YLF is shown in Fig. 4. The absorption is strong over a broad range of wavelengths for both the c- and a-axis polarizations, facilitating polarization-coupled pumping in this spectral region. In contrast, the \(^4J_{15/2} \rightarrow ^4J_{9/2}\) absorption spectrum for 30% Er\(^{3+}\) : YLF shown in Fig. 5, is strongly polarized, with very weak absorption along the a axis. The region of strong absorption for the 0.97 μm band is significantly broader than for the 0.80 μm band, facilitating more effective pumping in the 0.97 μm region by high power diode lasers, which typically have linewidths of ~3 nm.

The strained-layer InGaAs diode lasers which have been developed recently operate efficiently within the spectral region of strong Er\(^{3+}\) : YLF absorption shown in Fig. 4. These lasers have been shown to have smaller threshold current densities and less susceptibility to damage than AlGaAs diode lasers [10], [11]. The laser results presented here are obtained with a Ti:sapphire laser pump in order to examine the details of the dependence on pump wavelength which would be masked by the relatively broad linewidth of diode lasers.

III. LASER RESULTS

The direct upper-state pumping scheme is investigated with a monolithic laser cavity. The Er\(^{3+}\) : YLF crystal is 2 mm long, with a flat front surface and a concave (viewed from inside the crystal) 1 cm radius rear surface. The front surface has a dichroic dielectric coating, AR at 0.97 μm and HR at 2.8 μm, and the rear surface is the output coupler, with \(R = 99.7\%\) at 2.8 μm. The Ti:sapphire pump laser is focused longitudinally into the front surface with a 2.5 cm focal length lens.

In Fig. 6 the room temperature laser output at 2.8 μm is plotted versus the incident pump power for two pump wavelengths \(\lambda_p\). The pump laser is polarized parallel to the YLF c axis. The slope efficiency \(\eta\) is significantly reduced for the pump wavelength \(\lambda_p = 0.9720\) μm (triangles) compared to \(\lambda_p = 0.9733\) μm (circles).

The observed laser thresholds and slope efficiencies for several pump wavelengths at room temperature are given, for c-axis polarization in Table I, and for a-axis polarization in Table II. The results are generally uniform, with the exception of significantly reduced slope efficiencies and increased thresholds at \(\lambda_p = 0.9697\) μm and 0.9720 μm for c-axis polarization, and slightly reduced slope efficiency at \(\lambda_p = 0.9727\) μm for a-axis polarization. In all cases the laser wavelength is \(\lambda_l = 2.809\) μm, and is polarized along the YLF c axis.

A comparison of the laser results of Tables I and II with the absorption spectrum of Fig. 4 shows that the reduced slope efficiencies and increased thresholds occur at the strongest pump absorption peaks. This result contrasts
conversion loss arising from the elevated upper-state pumping rate on the strong absorption peak.

The pump laser is polarized parallel to the YLF c axis. The reduced slope efficiency \( \eta \) for \( \lambda_p = 0.9720 \, \text{\mu m} \) is due to increased upper-state upconversion loss arising from the elevated upper-state pumping rate on the strong absorption peak.

### Table I

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<th>( \lambda_c (\text{\mu m}) )</th>
<th>( P_{th} (\text{mW}) )</th>
<th>( \eta ) (percent)</th>
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with the usual expectation of improved performance for longitudinally-pumped lasers with higher pump absorption owing to better matching of the pump and laser modes. In the case of the 2.8 \( \mu \text{m} \) Er\(^{3+} \) laser, however, the diminished laser performance at the strongest pump absorption peaks can be attributed to loss arising from a second upconversion process [12], [15], \( {^4}_I_{13/2} + {^4}_I_{11/2} \rightarrow {^4}_I_{11/2} + {^4}_I_{13/2} \). This non-linear upconversion process removes population from the \( {^4}_I_{11/2} \) upper laser state at a rate which increases with the pumping rate. For extremely high values of pump absorption, e.g., on the strong c-axis peaks at 0.9697 \( \mu \text{m} \) and 0.9720 \( \mu \text{m} \), the high pumping rate, particularly near the front surface of the laser crystal, leads to large upconversion loss.

For more moderate values of pump absorption coefficient the lower pumping rate results in diminished upconversion loss. The pump absorption cannot be made arbitrarily small, however, because efficient laser operation requires that a significant fraction of the pump radiation be absorbed in the available crystal length. For example, with a pump wavelength of 0.9720 \( \mu \text{m} \), the c-axis absorption depth of only 200 \( \mu \text{m} \) is much shorter than required for efficient mode matching. For \( \lambda_p = 0.9686 \, \text{\mu m} \), however, with a c-axis absorption coefficient of 9 cm\(^{-1} \) more than 80% of the pump power is absorbed in a crystal length of 2 mm, and the reduced pumping rate diminishes the impact of the upper-state upconversion loss.

In addition to the upconversion effect, the influence of thermal effects on the laser performance as a function of pump absorption depth must also be considered. For shallow pump absorption the induced temperature gradient may lead to distortion of the laser mode and contribute to the reduced slope efficiency and higher threshold observed at the strongest pump absorption peaks.

Tables I and II show that for both the c- and a-axis pump polarizations there are broad spectral regions over which the 2.8 \( \mu \text{m} \) laser efficiency is uniformly high. Within these regions the pump absorption coefficient is high enough to provide efficient absorption in the 2 mm crystal length, while moderate enough to limit the upconversion loss. For both pump polarizations these regions are broader than the typical linewidths of high power diode lasers. Diode pumping of the 2.8 \( \mu \text{m} \) Er\(^{3+} \) : YLF laser with the recently developed strained-layer InGaAs diode lasers is therefore an attractive option.

The 15% slope efficiency for the directly pumped 2.8 \( \mu \text{m} \) Er\(^{3+} \) : YLF laser described here is 50% higher than the highest slope efficiency which has been obtained with 0.80 \( \mu \text{m} \) pumping of this transition [6]. The improved performance for the direct pumping scheme is consistent with the theoretical advantage predicted by the model given above. The limitations of this simple model will now be considered.

The maximum theoretical slope efficiencies quoted earlier, 22% for 0.80 \( \mu \text{m} \) pumping of 30% Er\(^{3+} \), 28% for 0.80 \( \mu \text{m} \) pumping of low-concentration Er\(^{3+} \), and 35% for 0.97 \( \mu \text{m} \) pumping, are based on a simple model which ignores the effects of upconversion on the laser efficiency. In principle, the lower-state upconversion process \( {^4}_I_{13/2} + {^4}_I_{11/2} \rightarrow {^4}_I_{13/2} + {^4}_I_{13/2} \) can recycle population from the \( {^4}_I_{13/2} \) state back into the \( {^4}_I_{11/2} \) upper laser state (via the \( {^4}_I_{13/2} \) phonon decay), resulting in greater than unity quantum efficiencies, and therefore laser slope efficiencies higher than the theoretical maximum values quoted above. The highest slope efficiencies presented here, however, while larger than those obtained with 0.80 \( \mu \text{m} \) pumping, are still well below the theoretical maximum values predicted in the absence of upconversion. Therefore the simple model which ignores the recycling
effect can be expected to give a reasonable approximation for the theoretical maximum efficiency for direct upper state pumping relative to the indirect 0.80 μm pumping scheme.

A more comprehensive model of the 2.8 μm Er³⁺ laser is required to account for the details of the dependence on pump wavelength observed here. Such a model would need to account for upconversion from both the upper and lower laser states. The nonlinear nature of these processes requires that the spatial dependence of the upper and lower laser states be carefully considered. That is, the spatial dependence of the pump and laser beams must be explicitly included in the model [17]. For a low-loss resonator, however, the simple model emphasizing the essential advantages of the direct pumping scheme, i.e., the avoidance of phonon decay and self-quenching bypass of the upper laser state, appears to provide a reasonably approximate description.

IV. CONCLUSION

Direct pumping of the upper laser state has been shown to be more efficient than indirect pumping schemes for the resonantly pumped 2.8 μm Er³⁺:YLF laser. Upper-state pumping avoids two sources of nonradiative loss, phonon decay to the upper laser state and self-quenching bypass of the upper laser state, inherent in the less direct pumping schemes. The dependence of the laser performance on pump wavelength is attributed to the interaction between the upper-state upconversion process and the dependence of the upper-state pumping rate on the pump absorption coefficient. Broad spectral regions within the direct pump band are observed for which the laser performance is not impaired by this nonlinear upconversion effect. Direct upper-state pumping into these regions with the recently developed strained layer InGaAs diode lasers is therefore a promising option for the 2.8 μm Er³⁺ laser.

REFERENCES


