Near-IR Dye Laser for Diode-Pumped Operation

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Abstract—A dye laser pumped by AlGaInP laser diodes produced efficient, low threshold operation at wavelengths between 740 and 800 nm. Rhodamine 700, oxazine 750, DOTCI and oxazine 1 dyes were demonstrated. Optical conversion efficiencies approaching 50% and output power as high as 361 mW were obtained when pumping with a DCM-based dye laser. Parametric variations of the pump power and wavelength were performed over the range of 615 nm to 690 nm to provide a more complete characterization of the dye laser.

I. INTRODUCTION

OVERALL electrical efficiency is an important consideration for lasers operating in an environment where primary power is limited. For laser-pumped lasers the overall electrical efficiency η_e is determined by the product of the electrical-to-optical conversion efficiency of the pump laser η_p , the efficiency of the relay optics used to transport the optical pump flux to the laser gain element η_r , and the optical conversion efficiency η_o . The optical conversion efficiency is the ratio of laser output power to pump power incident on the gain element. For cw dye lasers η_o can exceed [1] 30%, but the electrical efficiency of the pump laser is generally quite low. For ion lasers η_p is typically 0.05% exclusive of cooling. One method of producing higher η_p is to pump with a cw, laser diode-pumped, doubled Nd:YAG laser. However, the cost per Watt of a diode-pumped Nd:YAG laser is substantially higher than that of an ion laser. In addition, 532 nm is an ineffective wavelength for pumping near-IR emitting dyes.

For dyes that absorb near 670 nm, pumping directly with visible laser diodes can provide a significant improvement in electrical efficiency. Commercially available AlGaInP diodes produce up to 500 mW with an η_p greater than 20%. These diodes emit between 670 nm and 690 nm, although shorter wavelengths have been demonstrated [2] at output power levels of several hundred milliwatts. An important consideration is that the cost per Watt for AlGaInP pump lasers is lower than that for krypton ion lasers. In addition, the pump diodes do not require cooling for either wavelength control or thermal management. These devices can be powered by ordinary flashlight batteries, and diode-pumped dye lasers can readily be scaled to higher pump power by angular multiplexing individual pump diodes.

The first demonstration of a diode-pumped dye laser was reported [3] in 1974. A 50 ns pulsed AlGaAs laser diode operating at 820 nm was used to excite an IR 140 waveguide

dye laser. Subsequently, rhodamine 6G and coumarin 47 dye lasers were demonstrated [4] using a 25 ns pulsed, *e*-beam excited, CdS or ZnO semiconductor laser, respectively. While these investigations are of interest, neither technology can be efficiently scaled to higher power. More recently, a cw diode-pumped dye laser design [5] was proposed that is based on a commercial ion laser-pumped dye laser [6]. The high pump threshold associated with commercial dye lasers requires high power, gain-guided pump diodes, but the poor coherence across the diode emitting aperture limits the overall dye laser performance.

In the present work, a novel dye laser resonator is described that is designed specifically for efficient pumping by laser diodes. An earlier publication reported [7] preliminary results for this laser in which rhodamine 700 was demonstrated. Exceptionally high optical conversion and slope efficiencies were obtained. This work extends those results by more fully characterizing the performance of the dye laser and demonstrating low threshold, diode-pumped operation with the dyes oxazine 750, DOTCI and oxazine 1. These dyes are well-suited for diode pumping due to their strong absorption between 670 and 690 nm. The ability to scale to higher output power is demonstrated using a tunable DCM dye laser as the pump source, and the results of a parametric study of the longitudinally-pumped dye laser are presented.

II. EXPERIMENT

The pump laser diodes were single stripe, low power index-guided devices. The diodes were commercially packaged and emitted a collimated, plane-polarized output. Both 10-mW diodes operating at approximately 670 nm and 30-mW diodes operating at approximately 690 nm were used. A schematic of the pump optics is illustrated in Fig. 1. The pump geometry permits excitation of the dye jet by any combination of the three pump sources shown. This is accomplished with two polarization beam combiner cubes (PBC) and a half-wave plate. The polarization of the pump dye laser and one of the laser diodes (LD 1) are mutually orthogonal to allow combination by PBC 1. The orientation of the half-wave plate determines the fraction of laser diode and dye laser power from PBC 1 that is transmitted by PBC 2. In the absence of polarization rotation the dye laser power is completely reflected out of the pump path. LD 2 is polarized parallel to the dye laser output and is folded into the pump path by reflection from PBC 2. Due to losses in the pump relay optics, the maximum laser diode power incident on the 14.5-mm focusing lens was 13.5 mW when using two 10-mW diodes, and 44 mW with the two 30-mW diodes. The measured wavelengths of the

Manuscript received March 9, 1993; revised June 20, 1994. This work was supported in part by the Office of Naval Research.

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IEEE Log Number 9406895.

Fig. 1. Pump optics and laser resonator configuration. Polarization beam combiner cubes are labeled PBC.

Fig. 2. Dye laser configuration showing the nearly hemispherical resonator mode.

two "670-nm" diodes were 672 nm and 674 nm, respectively, while the two "690-nm" diodes operated at 689 nm and 690 nm, respectively.

Considering the level of laser diode pump power, low threshold operation of the dye laser was required. Initially, a low threshold concentric dye laser design was evaluated which had been reported [8] to operate efficiently with HeNe laser pumping. However, this dye laser proved to be both difficult to align and highly sensitive to vibrations caused by the dye jet pump. These problems are a consequence of operating the resonator near the stability limit, a necessary condition for achieving low-threshold operation. A significantly improved dye laser design was developed that is similar to those used for diode pumped Cr-doped solid state tunable lasers [9] [10] and is shown in Fig. 2. The laser resonator consists of a highly reflective (HR) flat and a 10-cm radius of curvature (ROC) output mirror in a nearly hemispherical configuration. The HR flat is a 2-mm thick plane parallel quartz plate which has a dichroic coating on one face that is HR from 720 nm to 850 nm and highly transmissive (HT) from 600 nm to 690 nm. The quartz plate was oriented so that the coated face was adjacent to the dye jet. The exterior face of the flat (the face closer to the lens) was uncoated. Several 10-cm ROC output couplers were used, each having a broadband coating that reflected both the pump and laser emission wavelengths. Coating reflectivities were determined both from spectrophotometric transmission and direct reflection measurements. These measurements agreed to within 0.03% R.

There are several benefits of using this laser resonator configuration when low threshold operation is important. For one, longitudinally pumping through the HR flat allows the

pump beam to be focussed with a short focal length lens, resulting in a small pump waist at the dye jet. Pumping the jet at an angle with respect to the resonator axis (similar to the orientation used in most commercial dye jet lasers) requires a longer focal length lens to avoid clipping the resonator mode. In addition, a nonnormal angle of incidence at the plane of the jet produces an elliptical pump spot and consequently reduced pump power density. Another benefit of longitudinal pumping is that a pump beam can be produced that approximately matches the resonator mode. Therefore unabsorbed pump radiation is reflected by the output mirror back to the jet where it undergoes a second pass. Double pass absorption permits high pump flux deposition at a lower dye concentration, reducing the distributed loss.

The plane of the dye jet is orthogonal to the laser resonator axis. This reduces the laser threshold power requirement compared to the more traditional Brewster orientation, as the decrease in resonator mode area increases the extraction efficiency [11]. Note also that the 3% Fresnel reflection of the resonator mode at each of the air-jet interfaces is approximately mode matched, does not significantly increase the passive loss. Minimizing the spacing between the dye jet and the HR flat provides the best mode matching for reflected radiation, and allows the use of a lens with the shortest possible focal length as well. The spacing between the jet and interior face of the flat was approximately 400 μm .

The concentration of each dye was optimized for pumping at the appropriate diode wavelength. For DOTCI this wavelength was 690 nm, while for the other three dyes the wavelength was 670 nm. Initial dye concentrations were prepared that were similar to those reported for krypton ion laser pumping at 647 nm. These concentrations were then increased to minimize the incident threshold power under laser diode pumping. For the optimum concentration it was found that the single pass absorption at the pump wavelength was approximately 70%. The solvent for oxazine 750 was a 20:1 mixture of ethylene glycol and propylene carbonate; the solvent for the three other dyes was ethylene glycol. The absorption spectra for the four dyes in their respective solvents are shown in Fig. 3. These spectra are similar to those in which ethanol is used as a solvent [1], although there is a small shift in both the wavelength and magnitude of the peak absorption.

III. RESULTS

In this section, the laser results obtained with each of the four dyes will be presented separately. All pump power levels discussed below refer to the power incident on the dye jet. The incident power is approximately 83% of the pump power incident on the focusing lens and is reduced due to surface reflections encountered at the lens and HR flat. Common synonyms for the dyes used in this work are LD 700 for rhodamine 700, oxazine 725 for oxazine 1, and DOTC or DOTC-iodide for DOTCI.

A. Rhodamine 700

Some of the results obtained for rhodamine 700 have been presented previously [7], [12] and will be briefly summarized

Fig. 3. Absorption spectra of the four dyes demonstrated in this work. (a) rhodamine 700 in ethylene glycol. (b) oxazine 750 in 20:1 ethylene glycol:propylene carbonate. (c) DOTCI in ethylene glycol. (d) oxazine 1 in ethylene glycol. The spectrometer resolution is 2 nm.

below. The optimum dye concentration for 670 nm pumping was 1.76×10^{-3} M. The dye solution was maintained at 12°C although temperature had little effect on threshold operation between 10°C and 20°C . A Findlay-Clay [13] analysis was performed by measuring the variation of 670-nm pump threshold power with output coupler reflectivity. The output mirrors ranged from HR to 96%R and the threshold data were fit by linear regression. The round-trip resonator loss is 5.4×10^{-3} and the round-trip small signal gain is 8.6×10^{-4} per mW of pump power. An alternative measure of the passive loss was obtained from the variation of the slope efficiency with output mirror reflectivity. The data are shown in Fig. 4 along with a linear regression fit to the expression

$$\frac{1}{\eta_s} = \frac{1}{\eta_o} \left[\frac{L}{T} + 1 \right], \quad (1)$$

where η_s is the slope efficiency, T is the transmission of the output coupler at the laser emission wavelength, L is the round-trip passive loss and η_o is the slope efficiency that would be obtained in the absence of resonator loss. The round-trip loss obtained from the fit to (1) is 4.0×10^{-3} .

Using an HR output mirror the lowest incident threshold power was 6.6 mW at 670 nm. The pump spot diameter at the dye jet was $36 \mu\text{m}$ and the absorbed pump power density at threshold was approximately 550 W/cm^2 . This is lower than that reported previously [8] for rhodamine 700. The laser emission band full width half maximum (FWHM) was 16 nm, centered at 758 nm. The diodes were powered by four AA batteries, and the maximum laser output power measured through the output coupler was $280 \mu\text{W}$. A DCM pump dye laser was used to determine the scalability of the resonator. With the pump wavelength set to 670 nm the maximum

Fig. 4. Plot and linear regression fit of the inverse slope efficiency ($1/\eta_s$) as a function of the inverse output mirror transmission ($1/T$) for rhodamine 700. The fit is based on (1) in the text, and the pump wavelength was 670 nm. The fit parameters give a slope of 7.93×10^{-3} , an intercept of 1.98, and a coefficient of determination of 0.9996. A sixth data point located at $1/T = 3.3 \times 10^3$ is not shown, but was included in the fit. For comparison, the fit to the five data points shown in the figure produces a slope, intercept and round-trip loss of 7.19×10^{-3} , 2.05 and 3.5×10^{-3} .

output power obtained from the laser was 237 mW using a 96.7% R output mirror. The pump power was 689 mW and the slope efficiency was 37%. The best performance for this dye concentration was obtained with a 98.5% R output mirror and a pump wavelength of 660 nm. The slope efficiency was 51%, the optical conversion efficiency was 49%, and 361 mW of output power was produced at 742 nm. The power data are shown in Fig. 5. The highest optical conversion efficiency previously reported [15] for rhodamine 700 was 33%.

Using the DCM pump laser the threshold power as a function of pump wavelength was determined and the data are shown in Fig. 6. The data were taken with a 96% R output mirror and show the beneficial effect of double pass absorption on the threshold operation of the laser. At wavelengths for which the dye transmission is below 30% the threshold power is constant at 25 mW. For the concentration of rhodamine 700 used in the jet, this covers the wavelength range of 640 nm to 670 nm. The optical conversion efficiency as a function of pump power for rhodamine 700 can be extracted from the data plotted in Fig. 5. This conversion efficiency is over 40% when the incident pump power is above 200 mW.

While no tuning elements were inserted into the cavity, the dye laser output wavelength is sensitive to the spectral dependence of the output coupler reflectivity. For the various output mirrors used in this work the central wavelength shifted over a range of 14 nm. This had been observed with other tunable lasers [9] and is a result of self-tuning to the wavelength which provides the highest net gain. The free running bandwidth also changes as the central wavelength shifts.

B. Oxazine 750

Oxazine 750 is a stable dye [16] that produces longer wavelength emission than rhodamine 700. The absorption

Fig. 5. Output power dependence on incident pump power for rhodamine 700. The line represents the fit to the data, and the slope efficiency is indicated.

peak for oxazine 750 in the solvent ethylene glycol/propylene carbonate 20:1 is 7.02×10^4 L/Mole-cm and occurs at 672 nm. The optimum dye concentration for diode pumping was 6.44×10^{-4} M. A Findlay-Clay analysis was performed and the data are shown in Fig. 7. The linear regression fit produced values of 3.17×10^{-3} and 3.07×10^{-4} mW⁻¹ for the round trip passive loss and small signal gain, respectively. An analysis of the data based on (1) indicate a round trip loss of 4.16×10^{-3} . The lowest incident threshold power was 10.0 mW at 10°C. The output spectrum under diode pumped operation is illustrated in Fig. 8 and shows a central wavelength of 772 nm. The structure in the output spectrum is due to etalon effects in the dye jet. The best output power was achieved with a 98% R mirror. With an incident pump power of 650 mW at 670 nm, 94 mW of output power was obtained. The slope efficiency was 18% and the optical conversion efficiency was 15%.

C. DOTCI

DOTCI has been used as a saturable absorber as well as a laser dye. Early laser results were obtained [17], [18] using krypton ion laser pumping and it was reported that this dye has a relatively short operating lifetime. Brackmann [1] indicates that performance comparable to DOTCI can be obtained using the more photochemically stable dye methyl-DOTCI. The peak absorption wavelength at 686 nm is substantially longer than that of the other three dyes. As higher power laser diodes are available at 690 nm, it was considered important to demonstrate a diode pumped DOTCI dye laser.

The peak absorption of DOTCI in ethylene glycol is 1.89×10^5 L/Mole-cm and the optimum concentration for 690 nm pumping is 3.55×10^{-4} M. A Findlay-Clay analysis of the threshold data produced values of 8.03×10^{-3} and 6.24×10^{-4} mW⁻¹ for the round-trip loss and gain, respectively. The dye temperature was 12°C. The lowest incident threshold power

Fig. 6. Spectral dependence of the incident threshold power and single-pass dye jet transmission for rhodamine 700. The filled circles represent the threshold data and are referenced to the ordinate on the left, while the open circles represent the dye transmission and are referenced to the ordinate on the right. The threshold power for pumping at 690 nm is 350 mW.

Fig. 7. Findlay-Clay data and linear regression fit for oxazine 750. Dots are data and straight line is a linear regression fit. The coefficient of determination for the fit is 0.9840. The pump wavelength was 670 nm and the dye temperature was 10°C.

was 10.0 mW and the two 690-nm laser diodes were easily capable of producing stable laser emission. The emission wavelength band was centered at 798 nm and the output spectrum is shown in Fig. 9. The etalon effects are clearly visible in the emission spectrum and indicate the jet thickness was 102 μm . The thickness changed in response to changes in

Fig. 8. Output spectrum of oxazine 750 under diode pumped operation. The output mirror contained a broad-band HR coating centered at 770 nm. The interference pattern results from etalon effects caused by reflections from the air-jet interfaces. The emission band is centered at 772 nm and the FWHM is 10 nm. The spectrum was recorded using an optical multichannel analyzer (OMA) with a resolution of 0.3 nm.

Fig. 9. Output spectrum of DOTCI recorded under diode-pumped operation. The emission band is centered near 798 nm and the FWHM is 14 nm. The spectrum was measured with an OMA.

the jet pressure and dye temperature, and both parameters were continuously adjusted to provide optimum laser performance. Using a 97% R output mirror, 93 mW of output power were achieved with 572 mW of incident power. The slope efficiency was 17% and the optical conversion efficiency was 16%.

D. Oxazine 1

Oxazine 1 is an efficient [18], [19] dye for which the fluorescence quantum efficiency is strongly dependent on temperature [20]. To produce laser emission when pumping with a HeNe laser, Thiel *et al.* [8] chilled the dye solution to temperatures as low as -35°C . A threshold power of 10 mW at 633 nm was obtained under these conditions. The lowest temperature used in this work was 8°C , which proved adequate for pumping with the 670-nm laser diodes. The peak absorption of oxazine 1 in ethylene glycol was measured to be 9.7×10^4 L/Mole-cm at 654 nm.

Fig. 10. Emission of the oxazine 1-dye laser under diode pumped operation. The FWHM is 16 nm and the dye temperature was 8°C. Two polarization-combined laser diodes are used to pump the dye and the diode emission lines can be seen near 670 nm. The intensity shown in the figure for the diode emission relative to the dye laser output is exaggerated by the substantially higher detector sensitivity at the diode wavelength.

The optimum dye concentration for 670 nm pumping was 1.81×10^{-3} M. The oxazine 1 dye laser threshold was low enough at this concentration to allow lasing when pumping with only one of the two laser diodes. The minimum incident pump threshold power was 5.4 mW and was obtained with the 674-nm laser diode. Under laser diode pumping the maximum output power transmitted through the HR output coupler was 334 μ W. The central wavelength was 760 nm and the broadband emission spectrum is illustrated in Fig. 10. Also shown in the figure are the laser diode emission lines at 672 nm and 674 nm. For longitudinal pumping the residual (unabsorbed) pump light propagates collinearly with the dye laser emission.

A Findlay-Clay analysis was performed and produced values of 6.6×10^{-3} and 4.4×10^{-4} mW^{-1} for the loss and gain, respectively. The data were taken at 12°C at a pump wavelength of 670 nm. An output power of 324 mW was obtained with a 98% R output mirror and a pump wavelength of 660 nm. The slope efficiency was 49.4% and the optical conversion efficiency was 46%. The power data are illustrated in Fig. 11. The spectral dependence of the optical conversion efficiency is shown in Fig. 12 and is a result of the variation of absorbed pump radiation with pump wavelength.

IV. DISCUSSION

The loss and gain values for each dye are listed in Table I and are consistent with the experimentally determined threshold power levels. The threshold power P_{th} is related to the round trip loss L and gain G by [21]

$$P_{th} = \frac{L - \ln R}{G} \quad (2)$$

where R is the reflectivity of the output coupler, $G = 2g_0l/P_{in}$, g_0 is the small signal gain, P_{in} is the pump power, and l is the thickness of the dye jet. Since the threshold powers given in Table I are for $R \approx 1$, the ratio L/G provides the threshold pump power in mW. These values are 6.3, 10.3,

Fig. 11. Output power dependence on incident pump power for oxazine 1. The line represents the fit to the data and the slope efficiency is indicated.

12.9, and 15.0 mW for rhodamine 700, oxazine 750, DOTCI and oxazine 1, respectively. The agreement for the first two dyes listed in the table is excellent, and is within experimental error for DOTCI. The discrepancy for oxazine 1 is due in part to the different dye temperatures for which the Findlay-Clay data (12°C) and the threshold power measurements (8°C) were taken. The threshold power for the 12°C dye mixture is 11.3 mW.

The laser output power P_{out} is related to the loss and gain by

$$P_{out} = T(\pi w_d^2) I_s \left(\frac{g_0 l}{\frac{L}{2} + T} - 1 \right) \quad (3)$$

where w_d is the laser mode waist and I_s is the pump-intensity dependent saturation intensity [15]. The slope efficiency is given by [22].

$$\eta_{slope} = \left(\frac{h\nu_d}{h\nu_p} \right) \left(\frac{\sigma_d - \sigma_{ESA}}{\sigma_d} \right) \left(\frac{T}{T + L} \right) f_a \eta_{pump} \quad (4)$$

where $h\nu_d$ and $h\nu_p$ are the dye laser emission and pump laser photon energies, respectively, σ_d is the stimulated emission cross section, σ_{ESA} is the excited state absorption (ESA) cross section at the laser emission wavelength, f_a is the fraction of incident pump power absorbed by the dye jet, and η_{pump} is the fraction of absorbed pump photons that populate the upper laser level.

The saturation intensity can be calculated for each dye from (3) using a ratio of pump waist to resonator mode waist [23], [24] of 2. For rhodamine 700 the absorbed pump power of 657 mW produces 361 mW of output, and (3) gives $I_s = 6.3 \times 10^5$ W/cm^2 . The saturation intensity can be calculated for oxazine 750, DOTCI and oxazine 1 and is 0.86

TABLE I
SUMMARY OF DYE LASER RESULTS

Dye	Concentration (M)	Incident Threshold Power (mW)	Loss ^a $\times 10^3$ L	Gain ^a $\times 10^4$ (mW ⁻¹) G	Slope Efficiency ^b (%)	Optical Conversion Efficiency ^b (%)
Rhodamine 700	1.76×10^{-3}	6.6	5.4	8.6	51	49
Oxazine 750	6.44×10^{-4}	10.0	3.2	3.1	18	15
DOTCI	3.55×10^{-4}	10.0	8.0	6.2	17	16
Oxazine 1	1.81×10^{-3}	5.4	6.6	4.4	49	46

^a Round-trip

^b Maximum values obtained

MW/cm², 0.32 MW/cm² and 1.3 MW/cm², respectively. The ESA cross section can be calculated using (4). The product $(h\nu_d/h\nu_p)(T/T + L)$ is 0.65 for rhodamine 700, and the value of $f_a\eta_{\text{pump}}(\sigma_d - \sigma_{\text{ESA}}/\sigma_d)$ must be 0.78 to match the measured slope of 0.51. If $f_a \approx 0.9$ and $\eta_{\text{pump}} \approx 1$, σ_{ESA} must be $0.13\sigma_d$. For rhodamine 6G the ESA cross section at the laser wavelength is [25] $0.17\sigma_d$.

The use of the linear regression fit parameters from the Findlay-Clay analysis to generate gain and loss values for each dye laser brings up the issue of whether the dye laser is a four-level laser. The four-level laser is one for which [13] $n_3 > n_2$, where n_2 and n_3 are the number densities of the population in the terminal and upper laser levels, respectively. For dye lasers these levels are vibronic in nature and the inequality is generally valid. Population in the terminal laser level simply adds to the Findlay-Clay passive loss as had been discussed [26] for the quasi-three level Yb-doped fluorapatite laser. Terminal level absorption is assumed to be non-saturable and independent of the pump power near threshold.

The passive loss is primarily due to reflections at the jet-air interfaces. The loss measured for the four dyes is similar, which by itself is a strong indication that most of the loss is not related to factors specific to the individual dyes. The distributed passive loss can be estimated. Using oxazine 1 as an example, the single pass loss from Table I is 3.3×10^{-3} . If all of this loss were distributed, the dye absorbance at the laser wavelength (ϵ_λ) would have to be $-\log(0.9967)/1.81 \times 10^{-5} = 79$ L/Mole-cm. It can be seen from Fig. 3(d) that ϵ_λ at 760 nm is approximately 0, but an upper limit of 10 L/Mole-cm can be assigned to ϵ_λ from the spectrophotometer accuracy. In this case the contribution to L due to dye absorption at 760 nm is 8.3×10^{-4} , which corresponds to a linear loss of $4\% \text{ cm}^{-1}$. The residual, non-distributed loss for oxazine 1 is 5.8×10^{-3} . The residual loss can be calculated for the other dyes and is 4.6×10^{-3} , 2.9×10^{-3} , and 7.8×10^{-3} for rhodamine 700, oxazine 750 and DOTCI, respectively. The variation in residual loss among the dyes is due to small variations in the resonator alignment, particularly the jet-to-HR flat spacing, as well as to the accuracy of the Findlay-Clay loss determination.

It is interesting to compare the results obtained in the present work with those recently reported [27] for the design described

Fig. 12. Spectral dependence of the optical conversion efficiency for oxazine 1. A 98% R output mirror was used.

in [5]. Two polarization-combined broad stripe 670-nm laser diodes were used to pump a 1.9×10^{-3} M rhodamine 700 dye solution in a Coherent 599 commercial dye laser. With 405 mW from the diodes the maximum output power obtained with an HR output mirror was 2.8 mW. Using a slightly lower reflectivity output mirror provided a slope efficiency of 2.2%. The low slope efficiency is a result of the approximately 180 times diffraction-limited pump spot measured at the dye jet. Laser diodes similar to those used in [27] had been used to pump several Cr³⁺-doped solid state lasers [2], [9], [10]. It was found that diodes with this architecture cannot produce the small spot size required for efficient pumping.

To produce a practical dye laser, both tuning and scaling issues must be addressed. An appropriately designed dye laser will have a region where the resonator mode is collimated to permit the insertion of a tuning prism or birefringent filter. This can be accomplished while retaining the end-pumped characteristics of the resonator by rotating the output coupler about the axis normal to the plane of Fig. 2 and adjusting the separation between the mirror and HR flat. A flat output mirror is used to complete the resonator and the design assumes some of the features of the dye laser resonator discussed [6] by Kogelnik *et al.* Note that the dye jet interference fringes prevent continuous wavelength tuning, although orienting the jet at Brewster's angle eliminates the etalon effects.

Scaling the dye laser to higher output power is straightforward. One can take advantage of the fact that the gain medium is essentially two-dimensional and utilize angular multiplexing of the pump diodes as illustrated in Fig. 13. Unlike longitudinally pumped solid state lasers [9] it is not necessary to match the pump and resonator modes over a significant pathlength in the gain element. Pump light incident on the jet at any angle will excite the dye only within the active region and therefore contribute equally to the emitted laser output power. When using angular multiplexing, double-pass absorption of the pump light will occur for angles contained within the solid angle determined by the resonator optical configuration. The optics required for an angularly multiplexed pump geometry can be relatively simple if the collimated output from each diode is reflected by one face of

Fig. 13. Pump configuration using five angularly multiplexed diode beams. The diode output is focused through the HR flat onto the dye jet at the angle shown. Each diode is aligned to illuminate the active region of the dye. This geometry can be modified to include fewer or a greater number of diodes. Refraction of the pump beams by the HR flat is omitted and the angles are exaggerated for clarity.

a multifaceted prism [28]. Upon reflection all pump beams are parallel and can be focused on the dye jet using a single lens. This geometry had been discussed in more detail in relation to an end-pumped alexandrite laser [29].

As an example of the design criteria for angular multiplexing, consider five 1-W pump beams, each originating from two polarization combined, collimated 500-mW laser diodes. As described in greater detail in [28], two side-by-side wedge prisms can produce a pump array of five parallel beams arranged in an "X" constellation when viewed in the plane of the focussing lens. The central, paraxial beam defines the intersection point of the X, while the four other beams identify the end points of the X. The separation of the beams is several mm at the focusing lens. With this type of pump beam configuration Fresnel losses at the HR flat and dye jet for the extreme rays are not substantially different than for the paraxial ray. Additional losses for the extreme rays due to the angular dependence of the transmission of the dichroic coating will also be small. As the five pump beams can be contained within a circle of ~6-mm diameter at the focusing lens, the optical flux transport efficiency for the extreme rays will be comparable to that for the paraxial ray. On the other hand, the pump spot size is sensitive to misalignment of each of the five beams. Finally, note that although some of the advantages of longitudinal pumping are not relevant to the extreme rays, these are most important when low threshold is the major factor determining the laser design. The angularly multiplexed pump configuration requires a higher threshold but allows high power, high efficiency diode pumped operation.

V. CONCLUSION

In summary, rhodamine 700, oxazine 750, DOTCI, and oxazine 1 have been evaluated under diode-pumped operation. A low threshold dye laser was established to demonstrate laser operation using two polarization combined low power visible laser diodes. Parametric variations were performed by pumping with a DCM-based dye laser. Over 360 mW were obtained with a slope efficiency of 51% for rhodamine 700, and comparable results were obtained for oxazine 1. Oxazine 750 and DOTCI did not perform as well.

Laser diode pumped dye lasers are of interest for a number of applications. Although the first diode pumped dye laser was reported in 1974, the current generation of visible laser diodes has made this technology a practical one. Since these diodes emit at wavelengths near the peak absorption of several near-IR emitting dyes, diode pumping can be an effective alternative to krypton ion laser pumping. With laser diode pumping, significant increases in the overall electrical efficiency and lifetime of near-IR dye lasers are possible. The overall electrical efficiency is given by

$$\eta_e = \eta_p \eta_t \eta_o. \quad (5)$$

As it is relatively simple to construct a low loss optical relay system for the pump beam, η_t can be set to 0.9. Using $\eta_p \approx 0.2$ and with η_o given in Table I, η_e for oxazine 1 and rhodamine 700 will be nearly 10%. Anticipated improvements in η_p will further increase η_e .

REFERENCES

- [1] U. Brackmann, *Lambdachrome Laser Dyes*, Göttingen, Lambda Physik GmbH, pp. III-117-III-175, 1986, and references therein.
- [2] R. Scheps, J. F. Myers, T. R. Glesne, and H. B. Serreze, "Monochromatic end-pumped operation of an alexandrite laser," *Opt. Commun.*, vol. 97, pp. 363-366, 1993.
- [3] G. Wang, "Infrared dye laser excited by a diode laser," *Opt. Commun.*, vol. 10, pp. 149-153, 1974.
- [4] O. V. Bogdankevich, M. M. Zverev, E. M. Krasavina, I. V. Kryukova, and V. F. Pevtsov, "Dye lasers pumped by radiation from high-power semiconductor lasers," *Sov. J. Quantum Electron.*, vol. 17, pp. 133-134, 1987.
- [5] D. P. Benfey, D. C. Brown, S. J. Davis, L. G. Piper, and R. F. Foutter, "Diode-pumped dye laser analysis and design," *Appl. Opt.*, vol. 31, pp. 7034-7041, 1992.
- [6] H. W. Kogelnik, E. P. Ippen, A. Dienes, and C. V. Shank, "Astigmatically compensated cavities for cw dye lasers," *IEEE J. Quantum Electron.*, vol. QE-8, pp. 373-379, 1972.
- [7] R. Scheps, "Low-threshold dye laser pumped by visible laser diodes," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1156-1158, 1993.
- [8] E. Thiel, C. Zander, and K. H. Drexhage, "Continuous wave dye laser pumped by a HeNe laser," *Opt. Commun.*, vol. 60 pp. 396-398, 1986.
- [9] R. Scheps, "Cr-doped solid state lasers pumped by visible laser diodes," *J. Opt. Materials*, vol. 1, pp. 1-9, 1992.
- [10] —, "Laser-diode-pumped Cr:LiSrGaF₆ laser," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 548-550, 1992.
- [11] J. T. Verdeyen, *Laser Electronics*. Englewood Cliffs, NJ: Prentice-Hall, 1981, pp. 159-170.
- [12] R. Scheps, "Low threshold, diode-pumped dye laser," in *Visible and UV Lasers*, R. Scheps, Ed., vol. 2115 of *Proc. SPIE*. Seattle, WA: Society of Photo-Optical Instrumentat. Eng., 1994, pp. 213-218.
- [13] D. Findlay and R. A. Clay, "The measurement of internal losses in 4-level lasers," *Phys. Lett.*, vol. 20, pp. 277-278, 1966.
- [14] J. A. Caird, S. A. Payne, P. R. Staver, A. J. Ramponi, L. L. Chase, and W. F. Krupke, "Quantum electronic properties of the Na₃Ga₂Li₃F₁₂:Cr³⁺ laser," *IEEE J. Quantum Electron.*, vol. 24, pp. 1077-1099, 1988.
- [15] T. F. Johnson, *Physical Science and Technology*, R. A. Myers, Ed. New York: Academic Press, 1987, pp. 96-141.

- [16] G. W. Fehrenback, K. J. Gruntz, and R. G. Ulbrich, "Subpicosecond light pulses from a synchronously mode-locked dye laser with composite gain and absorption medium," *Appl. Phys. Lett.*, vol. 33, pp. 159-160, 1978.
- [17] A. Donzel and C. Weisbuch, "CW dye laser emission in the range 7450-8880 Å," *Opt. Commun.*, vol. 17, pp. 153-54, 1976.
- [18] K. M. Romanek, O. Hildebrand, and E. Göbel, "High power cw dye laser emission in the near IR from 685 nm to 965 nm," *Opt. Commun.*, vol. 21, pp. 16-19, 1977.
- [19] K. H. Drexhage, *Dye Lasers*, F. P. Schäfer, Ed. Berlin: Springer-Verlag, 1977, pp. 172-175.
- [20] R. Sens and K. H. Drexhage, "Fluorescence quantum yield of oxazine and carbazine laser dyes," *J. Lumin.*, vol. 24/25, pp. 709-712, 1981.
- [21] W. Koechner, *Solid State Laser Engineering*. New York: Springer-Verlag, 1976, pp. 85-88.
- [22] S. A. Payne, L. L. Chase, H. W. Newkirk, L. K. Smith, and W. F. Krupke, "LiCaAlF₆:Cr³⁺: A promising new solid-state laser material," *IEEE J. Quantum Electron.*, vol. 24, pp. 2243-2252, 1988.
- [23] W. P. Risk, "Modelling of longitudinally pumped solid-state lasers exhibiting reabsorption losses," *J. Opt. Soc. Am. B.*, vol. 5, pp. 1412-1423, 1988.
- [24] B. B. Snavely, *Dye Lasers*, F. P. Schäfer, Ed. Berlin: Springer-Verlag, 1977, pp. 91-103.
- [25] L. W. Hillman, *Dye Laser Principles*, F. J. Duarte and L. W. Hillman, Eds. San Diego, CA: Academic Press, 1990, pp. 26-30.
- [26] R. Scheps, J. F. Myers, and S. A. Payne, "End-pumped Yb-doped fluorapatite laser," *IEEE Photon. Technol. Lett.*, vol. 5 pp. 1285-1287, 1993.
- [27] D. P. Benfey, R. E. Boyd, D. C. Brown, J. C. Watkins, W. J. Kessler, S. J. Davis, C. Otis, and L. Pedulla, "Continuous wave visible diode-pumped dye laser," in *Visible and UV Lasers*, R. Scheps, ed., vol. 2115 of *Proc. SPIE*. Seattle, WA: Soc. of Photo-Optical Instrumentat. Eng., 1994, pp. 204-212.
- [28] U.S. Patent 5 119 394, "Technique for longitudinal optical pumping of a laser," June 2, 1992.
- [29] R. Scheps, B. M. Gately, J. F. Myers, J. S. Krasinski, and D. F. Heller, "Alexandrite laser pumped by semiconductor lasers," *Appl. Phys. Lett.*, vol. 56, pp. 2288-2290, 1990.
- [30] R. S. Geels, D. F. Welch, D. P. Bour, D. W. Treat, and R. D. Bringans, "High-power visible semiconductor lasers," in *Visible and UV Lasers*, R. Scheps, Ed., vol. 2115 of *Proc. SPIE*. Seattle, WA: Soc. of Photo-Optical Instrumentat. Eng., 1994, pp. 250-261.

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