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Diode-pumped, Q-switched, 1.321 μm Nd:YLF laser and its frequency doubling

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Abstract

We describe the operation of a 1.321 μm electro-optically Q-switched Nd:YLF laser which is end-pumped by a 72 mJ, 180 W, quasi-cw three-bar stack laser diode. Near TEM_{00} Q-switched pulses of $\simeq$ 2.2 mJ energy and $\simeq$ 76 ns duration have been obtained. Long pulse operation at 1.313 μm enabled measurement of the relative gain of these two transitions, showing them to be equally strong. A comparison of the frequency doubling of this laser in LBO and KTP is reported. Optimum doubling performance of up to 40% conversion efficiency was achieved in LBO. The use of this frequency doubled output to pump a gain-switched Cr:LiSAF laser is also briefly reported.

1. Introduction

Transitions in the 1.3 μm spectral region have importance for the fibre-optic industry. There have been investigations of the 1.3 μm laser transitions in Nd:YLF and Nd:YAG under flashlamp pumping [1,2]. More recently the compactness, reliability and efficiency offered by laser diode pump sources has become apparent [3–5]. Although these advantages have been utilised in numerous solid-state lasers, there have been few reports relating to 1.3 μm Nd:YLF lasers, but in particular see Ref. [6]. If frequency doubled, lasers in this region can also be used to access the absorption bands of a new class of tunable vibronic solid-state laser materials including Cr:$LiSrAlF_6$ (Cr:LiSAF). Although rapid progress in red diode laser technology is being made, use of these sources to directly pump Cr:LiSAF is severely limited by their low brightness. As a high brightness alternative we therefore constructed and frequency doubled a diode-pumped 1.3 μm Nd:YLF laser. In this paper we report for the first time on a quasi-cw diode pumped, electro-optically Q-switched, 1.3 μm Nd:YLF laser and its frequency doubling in both LBO and KTP. This complements the previous report of a cw diode-pumped, high-repetition-rate acousto-optically Q-switched Nd:YLF system for 1.3 μm [6]. The advantages of our electro-optic Q-switch system is the substantially higher pulse energies/peak powers obtained, particularly important in the context of nonlinear optics. The Cr:LiSAF laser which this laser was used to pump is briefly described and will be considered more fully in a later article.

2. Experimental

To achieve short Q-switch pulses, an end pumped geometry was chosen. This facilitates good overlap of the pump volume and laser mode in a region of small

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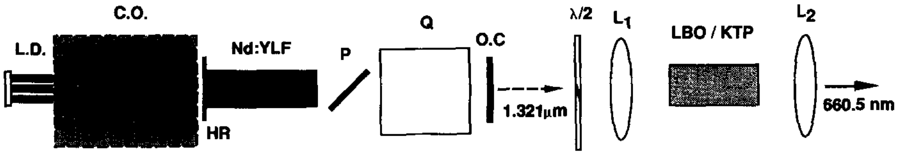

Fig. 1. Schematic of the cavity layout of the Q-switched 1.3 μm Nd:YLF laser as well as the frequency doubling arrangement. L.D. is the laser diode, C.O. the coupling optics, P the polariser, Q the Q-switch and O.C. the output coupler. L_1 and L_2 are the focusing and collimating lenses for the doubling.

cross-sectional area, enabling the high gain necessary for efficient Q-switch energy extraction. Short cavities are also possible with end-pumping, further contributing to rapid pulse extraction. Furthermore, with a small gain region located at one end of the cavity, spatial hole burning problems are reduced [7]. The simple linear resonator is illustrated in Fig. 1. The output from a three-bar-stack diode-laser [SDL-3231-A3] operating at 797 nm was coupled into the Nd:YLF rod using the coupling optic system described by Verdún and Chuang [8]. This led to an effective 85% transmission of the pump light into an elliptical spot, approximately 2.3 × 1.6 mm diameter, just inside the Nd:YLF rod. The Nd:YLF rod was 8 mm long and 3.3 mm in diameter. The cavity was formed by a high reflectivity coating, ($R \geq 99.3\%$ at 1.321 μm), on the plane rear surface of the Nd:YLF rod and a concave, (ROC= 10 m), partially reflecting output coupler, ($R \simeq 94\%$ at 1.321 μm), separated by a physical distance of 15 cm. This gave a laser mode radius of 0.75 mm, thus nearly matching the vertical dimmension of the pump mode. The coating on the rear surface of the rod was also chosen to be highly transmitting at the pump wavelength, ($T > 90\%$ at 800 nm). The a-axis rod was oriented such that the coupled in diode light was polarised parallel to the c-axis, thus accessing the higher absorption along this axis. The Neodymium dopant was nominally 1.1% at. wt. giving a peak absorption of > 7 cm^{-1}. Selection of either the π-polarised line at 1.321 μm or σ-polarised line at 1.313 μm was achieved by means of a high quality glass plate (flatness < $\lambda/50$ @ 633 nm) placed at Brewster's angle in the cavity.

A lithium niobate electro-optic crystal was used to implement Q-switched operation of the laser. The uncoated plate used for polarisation selection of one of the two 1.3 μm lines also provided the essential loss mechanism for Q-switching the cavity. The method employed was to apply a reverse bias of $\simeq$ 1.65 kV during the pump pulse and then to switch the cavity to a high Q by applying a forward bias pulse to the other terminal. The applied dc reverse bias voltage introduced the necessary change in the field polarisation so that the loss through the polariser was just sufficient to achieve holdoff of laser action. The switching voltage applied to the other terminal could then be adjusted such that maximum output coupling was achieved by overcoming any deleterious piezo-optic relaxation effects [9,10]. These effects could not be entirely overcome. The reasons for this will be described in detail in the next section. The laser rod was water cooled so that operation of the system at up to 100 Hz was possible.

The output in the form of single Q-switched pulses from this laser was then frequency doubled. The frequency doubling in both LBO, with type II temperature tuned noncritical phase matching (NCPM), and KTP, with type II critical phase matching (CPM), was investigated.

3. Results and Discussion

There have been few reports on the stimulated emission cross-sections of the two 1.3 μm lines of Nd:YLF in the literature, with some confusion regarding the relative strength of the transitions [1,2,6]. We, therefore, attempted to experimentally determine the ratio of the stimulated emission cross-section of the two transitions. In order to do this, we made a series of slope efficiency measurements at both transitions for a range of flat output couplers. The cavity parameters in each case were left unchanged with only the reorientation of the polariser plate required to select for the appropriate transition. The Q-switch crystal was removed for these measurements. The slope efficiency measurements were obtained for a number of output coupler reflectivities ranging from 2% to 15%. This

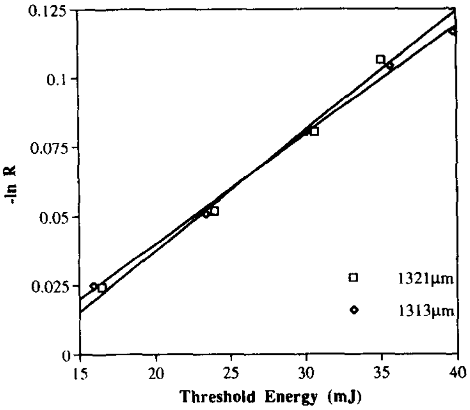

Fig. 2. Results of a Findlay-Clay measurement at 1.321 μm and at 1.313 μm, illustrating the close relationship of their slopes from which a near unity ratio of the two emission cross-sections may be inferred.

enabled a Findlay-Clay analysis [11] to be performed by plotting the pump threshold versus the negative logarithm of the output coupler reflectivity. The results are plotted in Fig. 2 from which it can be seen that they have very similar slopes. In each case the slope, $2K'$, where

$$K' = \eta' \sigma_e \lambda_p / Ahc \quad (1)$$

provides information about the gain [12]. By taking the ratio of the slope at each wavelength, the ratio of the cross-sections could be obtained,

$$\frac{K_1'}{K_2'} = \frac{\eta_1' \sigma_1 A_2}{\eta_2' \sigma_2 A_1}, \quad (2)$$

here η represents all of the efficiency terms [12], A is the beam area and σ is the stimulated emission cross-section. We assume that the efficiency term is the same in each case, since only the polariser was reoriented to discriminate between the two transitions. By scanning pinhole measurements it was also found that the beam areas were much the same in each case for a given output coupler. On the basis of Fig. 2 we therefore conclude that the cross-sections for the 1.321 μm and 1.313 μm transitions are the same within 10%.

We note that we have observed the behaviour reported by Cerullo et al. [13] and Frei and Balmer [14] in which one of the two laser transitions (π-polarised or σ-polarised) can be selected for without any intracavity selective elements. In our plane/plane cavity we observed that by tilting the output coupler

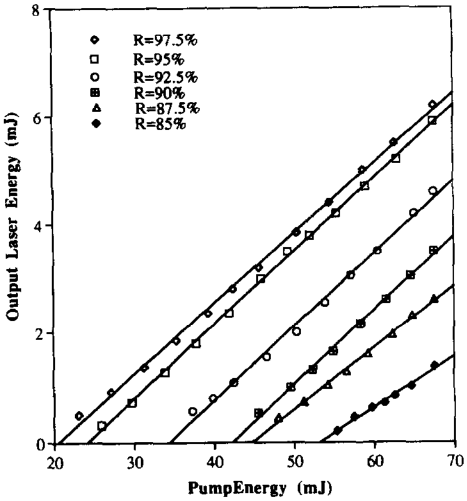

Fig. 3. Slope efficiency measurements of the laser at 1.321 μm line under long pulse operation for a range of output couplers. The maximum slope efficiency of near 14% is obtained for the 5%, 7.5% and 10% output couplers.

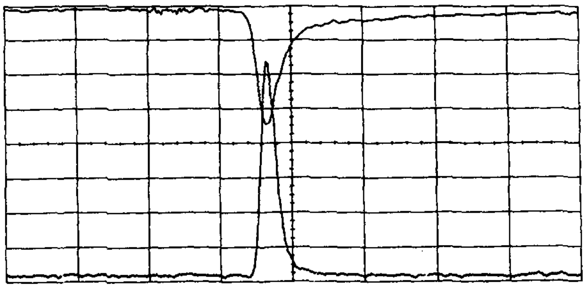

Fig. 4. The top curve is the single pulse Q-switched output of the 1.321 μm laser illustrating the long tail. The bottom trace is the corresponding frequency doubled pulse.

away from the optimum output energy location, either the 1.313 μm or the 1.321 μm line could be selected. Since in the 1.3 μm laser the two transitions are equally strong, the cavity alignment yielding maximum output is such that the laser operates on both transitions simultaneously. The explanation is that the two transitions see different thermal lensing powers [14]. Therefore tilting the output coupler results in the cavity becoming unstable for one of the transitions while for the other it is still stable.

We present in Fig. 3 a graph of slope efficiency measurements for our laser operating at 1.321 μm in long pulse mode with a series of output couplers. The highest slope efficiency of 14% was measured with an output coupling of 10%. The reduction in the slope efficiency with increased output coupling is explained by the fact that for higher output coupling the laser is nearer threshold and is therefore not solely on the linear portion of the efficiency curve [15]. Once again the threshold energy versus the negative logarithm of the output coupler reflectivity graph was plotted, enabling the round trip gain to be determined from the slope, yielding a value $2g_0l \simeq 0.231$. The internal round-trip parasitic losses in the cavity were estimated to be $L \simeq 3\%$. Following the analysis of Degnan et al. [16] for Q-switched lasers, the gain factor $z = 2g_0l/L \simeq 7.7$ was used to determine the optimum reflectivity. This was found to be $R_{opt} \simeq 93.7\%$. With a concave output coupler (ROC= 10 m), of reflectivity $R = 93\%$ we Q-switched the laser. Although energies of close to the predicted 4.2 mJ were extracted, this was achieved only under conditions of double pulse operation. This can be understood as a postlasing phenomenon caused by piezooptic effects in the $LiNbO_3$ Q-switch crystal. Whilst in 1 μm systems there is usually enough gain to extract the pulses in under 20 ns, the lower gain in the 1.3 μm system results in much slower pulse extraction. Undesirably these longer pulses fall prey to the changing polarisation characteristics (and hence cavity Q) due to the piezooptic "ringing" inherent in $LiNbO_3$. This means that the cavity is closed early while the population inversion is still above threshold for the highest Q-state of the cavity. When the cavity returned to a high-Q state a postlasing pulse was observed containing the remainder of the energy. This was overcome by increasing the switching voltage applied to the crystal so that the cavity stayed open long enough for all the energy remaining after the first pulse to decay away before the cavity returned to the high-Q state. This decay of energy can be seen as the tail of the Q-switched pulse depicted in Fig. 4. This is an example of the single Q-switched pulse which was then frequency doubled and used to pump a gain-switched Cr:LiSAF laser.

A scanning pinhole setup was used to measure the beam characteristics. A 25 μm pinhole was used to scan across beams of the order of 1 mm diameter. The pinhole could be scanned both horizontally and vertically. Both the near-field and far-field beam profiles were measured. The far field measurement was made in the image plane of a 20 cm focal length lens. In this way we could determine the departure of the beam from its diffraction limit. The mode was found to be elliptical in both long pulse and Q-switch modes of operation. The Q-switched beam quality was better than that under long pulse operation and seems to be much closer to TEM_{00} in nature, although it has poor divergence in the horizontal plane. Under Q-switch operation, the laser mode was determined to have radii in the horizontal and vertical planes of 0.88 mm and 0.59 mm with associated M^2 values of 2.7 and 1.3, respectively. The near field horizontal and vertical pinhole scans for a Q-switched pulse appear in Fig. 5. The horizontal scan clearly illustrates a ridged structure which explains the high departure from diffraction limited divergence. This is ascribed to a poor horizontal mode in our pump laser diode.

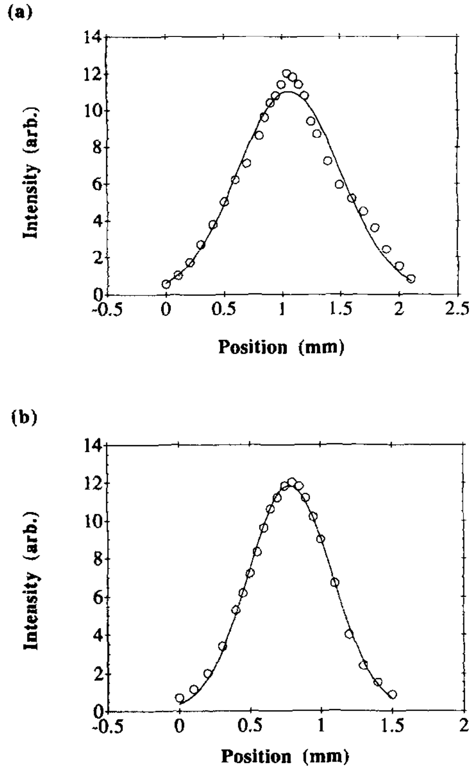

Fig. 5. Near field horizontal (a) and vertical (b) pinhole scans of the Q-switched laser beam mode. The ridge-like feature in the horizontal scan is responsible for the large departure from diffraction limited divergence in this plane.

The two well established nonlinear optical (NLO) materials, KTP and LBO, are suitable for frequency doubling in the 1.3 μm region. Although KTP had been identified as a possible doubling crystal for 1.3 μm radiation as early as 1985 [17], not many quantitative studies have appeared in the literature [18–21]. It soon became apparent that a type II phase matching geometry would be the most suitable due to the larger NLO coefficient and increased acceptance angle [19]. The major problem with using KTP was that it was found to have a rather large walkoff angle of about 2.5° for SHG at 1.3 μm [21–23]. Nevertheless, a high brightness beam should be efficiently doubled. The more recently discovered NLO material, LBO [24], has also been identified as an excellent candidate for SHG of 1.3 μm radiation [25–27]. The interesting phase-matching retracing behaviour exhibited for SHG in LBO facilitates noncritical phase matched (NCPM) SHG over a broad region near 1.3 μm under temperature tuning [27,28]. Although there have been a few reports of frequency doubled, 1.3 μm laser systems using this material [25,26,29,30], they have all employed a type I phase matching geometry. To achieve NCPM SHG of 1.3 μm radiation using this geometry necessitates elaborate schemes to prevent moisture condensation on the crystal surfaces as a result of the low temperatures required [25,26,29]. However, LBO also offers a type II NCPM geometry for SHG not yet utilised for 1.32 μm radiation, with operating temperatures around 40–50°C [27,28]. This property together with its high temperature- and angular acceptance bandwidth makes this configuration ideal for our purposes.The NCPM capability of LBO compared with the large walkoff angles in KTP is highly advantageous in this case, given the divergence characteristics of our 1.321 μm Nd:YLF laser.

The KTP crystal was 10 mm long and cut normal to $\theta = 60°$, $\phi = 0°$ for type II critical phase matched (CPM) doubling of 1.3 μm radiation. The high walkoff in the critical plane (⊥ Y-axis) together with the poor divergence in the horizontal plane of the 1.321 μm laser beam, meant that optimum doubling performance was achieved with cylindrical focusing of the horizontal plane of the pump beam in the noncritical direction. This resulted in a maximum conversion efficiency of 20% into the red at 660 nm. If the cylindrical focusing was effected on the vertical plane of the pump beam also in the noncritical plane, then a maximum conversion efficiency of 16% was achieved into the red.

A 16 mm long LBO crystal, cut for type II NCPM ($\theta = 0, \phi = 0$) was used. Optimum focusing yielded a beam waist of 40–55 μm in the LBO crystal, close to predictions of a computer model based on the work of Eimerl [31], the Sellmeier equations of Mao et al. [32] and the temperature dependence model of Velsko et al. [33]. We observed SH conversion efficiencies of up to 40%, delivering up to 0.85 mJ of 660 nm light in pulses of 60 ns. This compares to a predicted SH conversion efficiency of around 56%. In the model, the spatial beam profiles were represented by top-hat distributions and hence resulted in a higher than observed doubling efficiency. Also the temporal tail of the Q-switch pulse is not efficiently doubled (see Fig. 4), further lowering the observed conversion efficiency. The temperature was varied whilst the SH energy was observed in order that the optimum temperature for doubling the 1.321 μm radiation could be ascertained. The results are depicted in Fig. 6 from which the temperature acceptance bandwidth was found to be 8.3°C cm. This compares favourably with the 9°C cm predicted by our computer model, and it lies between the measured and predicted values of 6.7°C cm and 9.9°C cm respectively of Lin et al. [28]. The phase matching temperature for SHG of 1.321 μm radiation was found to be about 50°C. It should be noted, however, that the crystal was slightly tilted to avoid feedback into the Nd:YLF cavity. The output produced by the SHG process was of much improved spatial quality compared to the fundamental beam, with a near diffraction limited beam being obtained. This was attributed to the nonlinear nature of the gain in the SHG process.

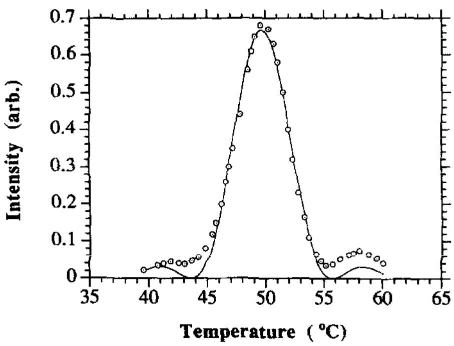

Fig. 6. The experimentally determined phase matching curve with respect to temperature in LBO for Type II NCPM frequency doubling of 1.321 μm as well as a fitted sinc function.

Finally we note that we have used this source to pump a tunable, gain-switched Cr:LiSAF laser. Thus far a threshold of 0.18 mJ has been obtained and it has been tuned over the range 797–887 nm. The full details of this laser will be presented in a later publication.

4. Summary

In summary, we have demonstrated what we believe to be the first all-solid-state, electro-optically Q-switched 1.3 μm Nd:YLF laser. This laser was able to deliver up to 2.2 mJ in single Q-switched pulses of 76 ns duration. A postlasing phenomenon caused by the piezooptic ringing in the $LiNbO_3$ Q-switch crystal prevented the extraction of the predicted 4 mJ in single Q-switched pulses. Furthermore, we have frequency-doubled the output from this laser in both KTP and LBO. The SHG process was optimised by using a type II NCPM geometry in LBO under temperature tuning. This process was 40% efficient and yielded frequency doubled pulses of up to 0.85 mJ in 64 ns. This compares favourably with a computer model of the SHG process in NCPM LBO.

Acknowledgements

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