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Single frequency Q-switched operation of a diode-pumped Nd:YLF ring laser

W.A. Clarkson and D.C. Hanna

Optoelectronics Research Centre, University of Southampton, Southampton SO9 5NH, UK

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A diode-pumped Nd:YLF ring laser is described which incorporates an acousto-optic rhomb to enforce unidirectional single frequency operation and Q-switching. Since unidirectional operation does not depend on polarization discrimination it can easily be applied to birefringent laser materials such as YLF. Q-switched pulses of 70 μJ and 10 ns duration are achieved.

1. Introduction

In a recent paper we described a low-loss, easy-to-align ring laser design based around a rhomb-shaped electro-optic Q-switch [1]. In that first device unidirectional, and hence single frequency operation was achieved via the non-reciprocal polarization rotation provided by the Faraday effect in the Nd:YAG laser material. More recently, [2], we have described another version of the ring laser in which the rhomb device was an acousto-optic Q-switch. This made use of the phenomenon, reported by [3,4], and subsequently applied to a diode-pumped Nd:YAG laser [5], that the travelling acoustic wave in such a Q-switch material can provide a loss-difference between the counter-propagating laser beams, and thus lead to unidirectional operation. While the detailed mechanism or mechanisms responsible for this non-reciprocal behaviour have not been identified, it was shown in refs. [2–5] that it provided a simple and reliable means for achieving single frequency operation, either cw or Q-switched. In ref. [2] it was further pointed out that since the mechanism does not rely on polarization discrimination, as in conventional schemes for unidirectional operation, using the Faraday effect, then it should be more widely applicable, for example to laser media which do not show a significant Faraday effect or which exhibit birefringence. To confirm this point we have investigated the application of the technique to a Nd:YLF laser. Nd:YLF is particularly attractive for Q-switching, having a significantly longer fluorescence lifetime than Nd:YAG for example, and hence better energy storage, but which, unlike Nd:YAG, exhibits birefringence. Our results confirm that single frequency Q-switched operation works well for Nd:YLF using the rhomb acousto-optic Q-switch, and we have obtained peak Q-switched powers of 6.2 kW (70 μJ, 10 ns) at 1.053 μm and 4.4 kW (48 μJ, 10 ns) at 1.047 μm. In addition, using a constant drive to the acousto-optic device simply to induce cw unidirectional operation, the laser has been operated single frequency up to the maximum power available, 340 mW at 1.047 μm and 285 mW at 1.053 μm.

2. Experiment

The resonator layout is the same as that described in ref. [2], with the Nd:YAG laser rod now replaced by a plane-plane Nd:YLF rod, 5 mm in length, with one face coated for high reflectivity (>99.8%) for wavelengths in the range 1.04 μm to 1.06 μm and high transmission (>95%) at the pump wavelength (≈0.8 μm), and antireflection coated at 1.06 μm on the other face. The concave output mirror, 75 mm radius of curvature, had a transmission of 10% at the lasing wavelength. To increase the pump power we have used two diode lasers to pump the Nd:YLF, their focused beams being arranged to meet at the

Nd:YLF reflector, with an angle of ≈26°, corresponding to an internal angle in the Nd:YLF of ≈17.5°, allowing both sections of the ring path in the Nd:YLF to be pumped (see fig. 1). This type of pumping configuration was used in preference to polarization coupling of the two diodes since the absorption length for the pump in Nd:YLF is polarization dependent. The use of this scheme allows both of the pump polarizations to be adjusted, via appropriate orientation of half-wave plates, to maximize pump absorption and hence gain. The diode lasers, provided by STC, were of the single broad stripe type, both having a rated output power of 0.5 W, one having a stripe width of 75 μm, the other a stripe width of 40 μm. These diode lasers, particularly the latter, had a significantly higher brightness than a number of other commercially available diode lasers, and allowed tighter focusing and higher gain to be achieved in the Nd:YLF. Relevant performance statistics for the laser are: a threshold pump power incident on the Nd:YLF of 255 mW for operation at 1.053 μm, or 180 mW for operation at 1.047 μm, and a maximum (pump-limited) single frequency cw output of 285 mW at 1.053 μm, or 340 mW at 1.047 μm, in either case with 1 W of pump power incident on the Nd:YLF rod. Slope efficiencies, with respect to incident pump power were 40% at 1.053 μm and 41% at 1.047 μm. To obtain laser operation at either of the two wavelengths, the Nd:YLF rod was merely rotated about its cylindrical axis until either the *c*-axis is parallel (for 1.047 μm) or perpendicular (for 1.053 μm) to the plane of incidence for the light path at the rhomb.

The acousto-optic rhomb *Q*-switch, described in ref. [2], was fabricated from lead molybdate with a side length of 10 mm, and an angle between its faces of 72.5°. This component has a very low insertion loss of around 0.5%, due to the Brewster orientation of its our faces, and resulted in a total physical length for the resonator of approximately only 35 mm. The use of such a short resonator allows short *Q*-switched pulses and hence high peak powers to be achieved. It is also advantageous, in that the axial mode spacing is relatively large (≈3 GHz) and hence may aid single mode selection. In this work, with the higher gain achieved from the Nd:YLF, a higher power radio-frequency (RF) driver has been used with the rhomb to increase the diffraction loss and hence the ability to "hold off" oscillation. The diffraction loss at 1.06 μm for a round-trip through the rhomb is 34% at a 80 MHz RF drive power of 2 W.

To obtain unidirectional operation under cw (non-*Q*-switched) conditions it was found that as little as 0.01 W of RF power was required. The correspondingly very small diffraction loss had a negligible effect on laser output power. One interesting feature of the unidirectional behaviour described in ref. [2], and also observed for this laser, was that the direction of operation reversed for incremental changes in the resonator length by ≈0.3 mm. This length dependence of the direction of operation is connected with multiple reflections of the diffracted beams between the cavity end-mirrors. When an aperture was inserted to prevent such reflections, then the direction of operation was independent of cavity length. Under these circumstances it was observed that for

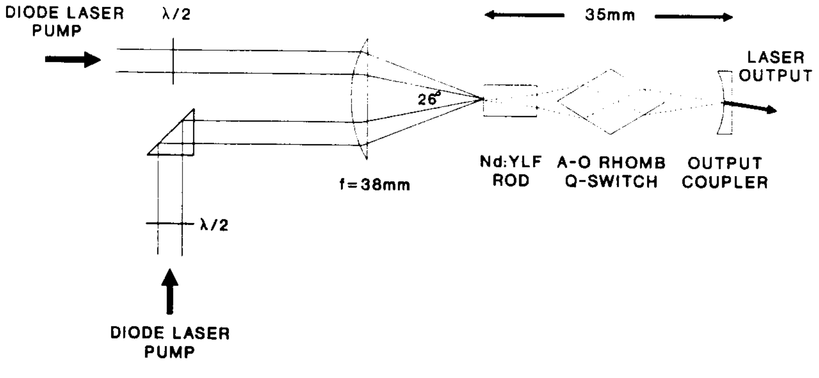

Fig. 1. Pumping scheme for Nd:YLF ring laser. The collimated outputs from two diode lasers are focused into the Nd:YLF with a single plano-convex lens.

reliable unidirectional operation the rhomb had to be tilted by a small angle (of the order $\approx 0.05^\circ$) from the orientation at which the maximum diffraction loss occurred (i.e. where the Bragg condition was satisfied). Furthermore, it was noticed that the actual direction of operation depended on the sense in which the rhomb was tilted. When the rhomb was tilted off the Bragg condition in the opposite sense the direction of operation reversed. The mechanism for this behaviour is unclear at present, and the compact nature of our resonator design makes a detailed investigation into the unidirectional behaviour difficult. We are therefore, currently carrying out a more detailed experimental investigation of the effect in a much longer resonator. So far we have established that the loss-differences achievable can in some circumstances be within an order of magnitude of the diffraction loss itself. A more detailed discussion of our findings will follow in a future publication.

Observation of the spectrum of the laser output with a scanning Fabry-Perot interferometer showed that in the absence of an RF drive, the laser output was bidirectional and multi-frequency. However, when sufficient RF power was supplied to the rhomb to enforce unidirectional lasing, our results confirmed that the output was always in a single longitudinal mode, even up to the maximum output power achievable with the available pump diodes.

To achieve single frequency *Q*-switched operation the laser was operated with a prelase [6], i.e. the *Q*-switch did not completely prevent oscillation, so that single frequency unidirectional operation at a low-power level (ideally less than a few milliwatts) was present prior to the opening of the *Q*-switch. This ensured that the *Q*-switched pulse itself was also single frequency. The pulse energies achieved in this way were 48 μJ in 10 ns at 1.047 μm and 70 μJ in 10 ns at 1.053 μm, the latter corresponding to a peak power in excess of 6 kW. The better performance on the lower gain 1.053 μm line reflects the fact that there was insufficient diffraction loss available to adequately hold off oscillation on the higher gain transition at 1.047 μm, for which hold off could only be achieved up to a total pump power of approximately 700 mW. This suggests that, for a better optimized *Q*-switch which could hold off oscillation up to a pump power of 1 W, pulse energies in excess of 70 μJ at 1.047 μm could also be obtained. For pulse repetition rates up to 500 Hz, the laser provided an extremely stable single frequency output, with pulse to pulse amplitude fluctuations less than 1%. At higher repetition rates however, single frequency operation became less reliable, the probable cause being that insufficient time was then allowed between pulses for the establishment of a unidirectional single frequency prelase. The bandwidth of the *Q*-switched pulse was determined using a scanning confocal Fabry-Perot interferometer, with a free spectral range of 300 MHz and a resolution limit of 1.5 MHz. This was found, as expected, to be transform-limited at approximately 42 MHz.

3. Conclusions

We have confirmed that the use of the acousto-optic effect to enforce unidirectional oscillation allows convenient, reliable and efficient single frequency operation of a Nd:YLF ring laser, either cw or *Q*-switched. The rhomb geometry is particularly effective and very simple to align. Significant further improvement in performance of the present laser should be possible, since the antireflection dielectric coatings on the Nd:YLF rod were not optimal, having a reflectivity of $\approx 1\%$. Furthermore the acousto-optic rhomb design could be modified to give higher diffraction loss. In its present form the rhomb is not able to hold off the maximum gain available with the existing diode laser pumps. So, with increased diffraction loss from the rhomb, higher *Q*-switched pulse energies and shorter pulses should be achievable.

The basic ring resonator design incorporating the rhomb device appears to offer a versatile scheme for single frequency laser oscillation. Considerable scope exists for further development and extension of the design. For example we have recently demonstrated that it is possible to add a frequency doubling crystal to the resonator and thus produce single frequency operation in the visible. Results on this intracavity frequency doubling will be reported in a further publication.

Acknowledgements

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