Single-frequency Q-switched operation of a diode-laser-pumped Nd:YAG ring laser using an acousto-optic modulator

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Received June 28, 1990; accepted January 4, 1991

Single-frequency Q-switched operation of a diode-laser-pumped Nd:YAG ring laser has been achieved by using an acousto-optic modulator both to enforce unidirectional operation and to provide Q switching. Pulses with energies of 13 μJ and 36-ns duration have been obtained, corresponding to a peak power of 400 W, at a repetition rate of 1 kHz.

Unidirectional or traveling-wave operation in a ring cavity is a well-established technique for achieving stable single-longitudinal-mode (SLM) output from lasers.[1] The most common method of enforcing unidirectional operation involves the use of a Faraday rotator. A particularly elegant implementation was demonstrated[2] in a monolithic Nd:YAG ring laser in which the laser crystal provided the Faraday effect medium and the out-of-plane resonator geometry provided the required reciprocal polarization rotation. A limitation of monolithic designs, though, is that Q switching is precluded. Recently a Q-switched miniature Nd:YAG ring laser was reported[3] in which a rhomb-shaped electro-optic Q switch was used, with unidirectional operation enforced by Faraday rotation in the Nd:YAG medium.

The Faraday effect is not the only means of enforcing unidirectional operation, and in fact two papers[4,5] have recently described the successful application of an acousto-optic modulator (AOM) for that purpose to a cw dye laser and a cw Ti:sapphire laser. Since the technique offered potential for a miniature diode-laser-pumped Nd:YAG laser, we decided to investigate its applicability in this context. The experimental performance reported here has certainly confirmed its value. In particular we have used the one AOM both to enforce unidirectional (and hence SLM) operation and also to Q switch, so that high-peak-power SLM operation is achieved.

For the first demonstration of this unidirectional acousto-optic Q-switched operation we chose a simple triangular ring resonator (Fig. 1), since this allowed us to use available components. The AOM (Isle Optics QS080) was a standard antireflection-coated Q switch made of lead molybdate, driven by a traveling acoustic wave at 80 MHz. The design of the resonator of Fig. 1 has not been optimized but was chosen simply to have the following features: (1) small dimensions, so that the large frequency spacing between modes would help ensure single-frequency operation, and (2) the use of a prism, with near-Brewster-angle incidence, to provide polarization selection and avoid the need for a special mirror with high reflectivity at large angles of incidence. In addition, the prism provided some compensation for the astigmatism caused by the off-axis reflection from the curved mirrors.[6] One should note in passing that the prism could in principle also serve as the AOM. The prism apex angle dictated the angle of incidence (10.5°) on the mirrors, and their curvature (100 mm) and spacing (70 mm) were chosen to give an acceptable compromise among astigmatism, cavity dimension, and a spot size in the Nd:YAG rod commensurate with the spot size from the diode-laser pump. The Nd:YAG rod, of 5-mm length, unwedged and antireflection coated for 1.064 μm, was placed close to the prism where the calculated laser spot size was $w = 160$ μm. The pump laser was a 500-mW laser diode array (SDL 2432), temperature tuned to the Nd:YAG absorption peak at 808 nm. The output beam from the laser diode array was first collimated, using a 6.5-mm focal-length compound lens, and then circularized by expanding the beam in the plane parallel to the diode array, using a 3.6× magnification anamorphic prism pair. The beam was then focused by a 40-mm focal-length lens to give a pump spot size of 180 μm in the Nd:YAG rod. It is well known that reflecting the light propagating in one direction back into a ring laser can cause bidirectional operation, and care was taken (by slightly misaligning these optical components from normal incidence) to ensure that there

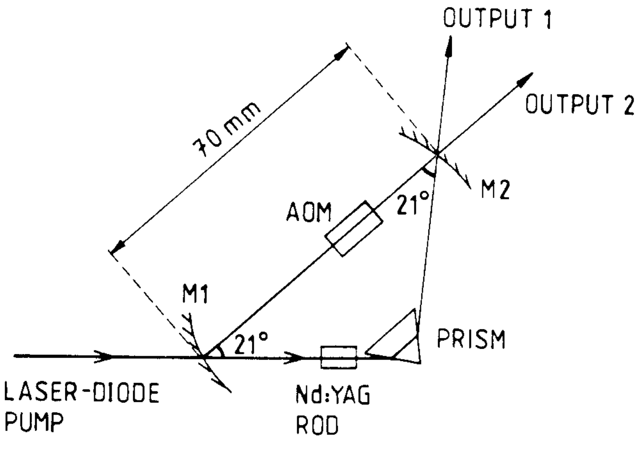

Fig. 1. Schematic diagram of the ring resonator (not to scale).

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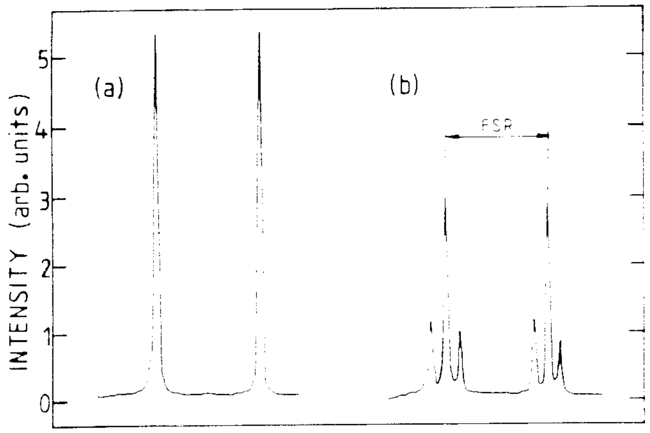

Fig. 2. Frequency spectra of the ring laser when running (a) unidirectionally (rf on) and (b) bidirectionally (rf off). The distance between the main peaks corresponds to one FSR (25 GHz).

was no feedback of this type from the Nd:YAG rod, the AOM, or the diode-pumping optics.

With no radio-frequency (rf) power applied to the AOM, the laser operated bidirectionally. However, with only 250 mW of rf power applied, and with careful adjustment of the AOM such that the intracavity beam propagated through it at close to the Bragg angle, stable unidirectional operation was achieved. With mirrors M1 and M2 having reflectivities at normal incidence of 99.9% and 95%, respectively, at 1.064 μm, it was found that the threshold for unidirectional operation was 193 mW of diode pump power incident upon the Nd:YAG rod. For the maximum available incident pump power of 410 mW, a ring-laser output power of 54 mW was measured, corresponding to a slope efficiency of 25%. Resonator losses were estimated from measurements of both slope efficiency and relaxation oscillation frequency[7] and indicated a round-trip loss, not including the output coupling, of 5.5%. Of this some 3% was due to the insertion loss of the AOM. Beam profiles measured with a scanning photodiode array confirmed TEM_{00} mode operation with no observable departure from circularity.

SLM operation of the unidirectional cw output was confirmed from observation of the frequency spectrum with a scanning plane–plane Fabry–Perot interferometer that has a free spectral range (FSR) of 25 GHz. Figures 2(a) and 2(b) are typical traces and show SLM unidirectional operation (rf on) and multiaxial-mode bidirectional operation (rf off), respectively. Measurement of the frequency spectrum with a higher-finesse scanning confocal interferometer, with a FSR of 300 MHz, gave an instrument-limited SLM linewidth of 3 MHz over the 5-ms time taken to scan between two Fabry–Perot transmission peaks. The intensity ratio of the counterpropagating beams when they were oscillating SLM was found to be 2000:1, indicating a high degree of unidirectionality.

The underlying cause of unidirectional operation with use of an AOM has not yet been unambiguously identified. As in Ref. 4, we have noted that longitudinal movement of the curved mirrors (by approximately 0.4 mm) caused the unidirectional operation to switch to the opposite direction. Progressive longitudinal displacement of the mirror caused this switch to occur every 0.4 mm of movement. Changing the rf power and varying the angle of tilt of the AOM also caused reversal of the oscillation direction. Despite these various parameters that led to reversal of the oscillation direction, we have found that, provided that these parameters are left unchanged, the oscillation continues to maintain unidirectional operation in the same sense indefinitely, without any need for deliberate stabilization to be introduced.

To achieve Q-switched operation we oriented the AOM so that the laser beam passing through it was closer to the Bragg angle. Sufficient diffraction loss was available to prevent lasing completely when the AOM was set to the Bragg angle. However, we deliberately tilted the AOM away from this setting by 0.4° so that it operated under conditions in which lasing was not completely prevented. In this way, a low-level, unidirectional, and therefore SLM prelase was produced.[5] To Q switch we switched the rf power off, and to prevent postlasing we switched the rf power back on after 350 ns. Typically the prelase level corresponded to 20-μW output power. A repetition rate of as much as 1 kHz has been used, producing Q-switched pulse energies of 13 μJ and 36-ns duration (FWHM), corresponding to a peak power of 400 W. These pulses showed excellent amplitude stability. The measured contrast ratio between counterpropagating directions was measured to be typically 100:1 under these Q-switched conditions. Single-frequency operation was again confirmed with the 300-MHz FSR Fabry–Perot interferometer, giving a linewidth measurement of 28 MHz. This is somewhat greater (2.3×) than the bandwidth-limited value for Gaussian pulses, probably because the measurement took place over many shots and so includes an average of frequency jitter. Higher-repetition-rate operation, at greater than 1 kHz, revealed a tendency to lower contrast ratio between the counterpropagating beams and unreliable SLM operation. This is probably due to the reduction in prelase duration, with a consequent reduction in the time available for unidirectional operation to be established. An understanding of the mechanism responsible for unidirectional operation would clearly be desirable since this would enable the effect to be maximized, and this in turn could permit operation of the laser at higher repetition rates.

We have demonstrated the use of an acousto-optic modulator to produce both unidirectional (and hence single-longitudinal-mode) operation and Q switching of a miniature laser-diode-pumped Nd:YAG laser. The 13-μJ, 36-ns pulses (of 400-W peak power) were obtained from an unoptimized resonator, and the expectation is for pulses of 1 kW or greater for an optimized resonator. Despite the fact that the cause of the unidirectional operation is not clear, in practice such operation has proved extremely reliable and simple. A particular benefit of this scheme is that it does not exploit polarization-dependent loss discrimination, as in the more conventional Faraday rotator schemes, and therefore should be readily applicable to resonators containing highly birefringent laser media or nonlinear crystals.

This study has been supported by the Ministry of Defence, UK.

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