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Single frequency CW and Q-switched operation of a diode-pumped Nd:YAG 1.3 μm ring laser.

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Abstract

The use of an acousto-optic modulator in a ring laser to enforce unidirectional and hence single-frequency operation has been extended to the 1.3 μm lines in Nd:YAG. We have also been able to obtain stable simultaneous operation on a single frequency in each of the 1.319 μm and 1.338 μm transitions either CW or Q-switched. The mechanism behind this behaviour is described and implications for other laser systems are discussed. When operated single frequency, up to 155 mW of CW output is produced, and 30 μJ, 40 nsec Q-switched pulses have been obtained.

In recent papers we have reported stable, single frequency operation at wavelengths around 1 μm for Nd:YAG and Nd:YLF ring lasers incorporating a rhomb-shaped acousto-optic (A-O) Q-switch [1,2]. Following observations that A-O modulators could be used to enforce unidirectional operation in a variety of ring laser systems [3,4,5,6] we have now identified and given a quantitative description of two distinct mechanisms by which the A-O effect can be used to induce unidirectional operation [7,8]. Armed with these simple quantitative models it is now possible to predict performance for a variety of conditions, e.g. different laser media, different wavelengths, different resonator configurations, etc.

In this paper we report the application of the technique to a diode-pumped Nd:YAG laser at around 1.3 μm. Single frequency sources at this wavelength are of interest in a number of communications applications. The strongest of the 1.3 μm ($^4F_{3/2}$ - $^4I_{13/2}$) transitions is a much lower gain transition than the strongest of the 1 μm ($^4F_{3/2}$ - $^4I_{11/2}$) transitions, however the very low insertion loss of the A-O rhomb used has allowed efficient single frequency operation at 1.3 μm, both CW and Q-switched. A further interesting observation is that the laser can also operate simultaneously and stably, either CW or Q-switched on two transitions of nearly equal gain (1.319 μm and 1.338 μm), with a single frequency oscillating on each transition. This stable two frequency operation is potentially of interest for a number of applications. While simultaneous oscillation on these two lines has been previously observed (e.g Ref 9 & 10), in this paper we describe, for the first time, the mechanism responsible for this behaviour. This mechanism suggests that extension of the two-frequency operation to a wide range of lasers should be possible.

The experimental arrangement is similar to that described in references [1] and [2], and is shown in Figure 1. The laser cavity consists of only three elements; a Nd:YAG rod, a lead molybdate A-O Q-switch and an output coupler. The Nd:YAG rod was coated at its input face to be highly reflecting (>99.8%) at 1.3 μm and highly transmitting (>95%) at the pump wavelength (~0.8 μm), with its other face antireflection coated at 1.3 μm. The resonator itself is easy to align, as it is first aligned as a standing wave laser without the rhomb, with the pump beam at the appropriate incident angle. The rhomb is then inserted and rotated until lasing is observed. The rhomb-shaped lead molybdate A-O Q-switch defines the ring path in the resonator, acts as a polarizer, and is used to enforce unidirectional operation. The output coupler had a radius of curvature of 50 mm, and reflectivity of 96% at the lasing wavelength. Output couplers with transmissions ranging from 0.7% to 10% were tested, with the 4% output coupler giving the maximum output power. Comparing laser threshold for each of these output couplers allowed the loss in the cavity (excluding the output coupling) to be determined as 1.4%. The short cavity length (physical length of 35 mm) is advantageous, since it increases the discrimination between adjacent axial modes, thus facilitating single frequency operation, and also leads to shorter Q-switched pulses. The ring laser was pumped by two 0.5 Watt laser diodes (SDL-2430), each collimated and compensated for astigmatism using anamorphic prisms and then polarization coupled and focused into one arm of the ring cavity with spot sizes matched to the lasing mode size. When combined, these diodes, temperature tuned to the peak of the Nd:YAG absorption, gave a maximum incident pump power of 850 mW.

Unidirectional operation of the ring laser can be achieved using either the "intrinsic" or "feedback" mechanisms described in references 7 & 8 respectively. The intrinsic method is implemented by placing an aperture in the cavity to prevent the diffracted beams from being fed back into the cavity, and then tilting the Q-switch to bias it slightly to one side of the Bragg condition, as explained in reference 7. Alternatively, without the aperture, the diffracted beam can be fed back, via a second A-O diffraction, into the main resonator as described in reference 8, thus introducing a large loss difference between the counterpropagating waves and thereby favouring one direction of propagation. The intrinsic method required more r.f. power to the A-O modulator than the feedback method for unidirectional operation, leading to an increase in loss in the cavity of ~2% under the conditions of this experiment. By comparison, the feedback mechanism only required sufficient r.f. power to produce ~0.025% diffraction loss, resulting in only a marginal increase in laser threshold and no observed change in maximum output power.

Initially, when the laser was operated bi-directionally (i.e. with no applied r.f. field), it was noted that two wavelengths were lasing, corresponding to the 1.319 μm and 1.338 μm transitions of Nd:YAG. When the laser was made to operate unidirectionally by applying r.f. power to the A-O modulator, it continued to lase at these two wavelengths. Using a scanning Fabry-Perot plane-plane interferometer with a free spectral range of 37.5 GHz, it was confirmed that for both of these lines lasing occurred on a single axial mode, i.e. just two lasing modes were being supported [Fig 2]. It was observed that by applying a higher r.f. power, the 1.319 μm line could be suppressed completely. This is consistent with the fact that the diffraction loss is inversely proportional to the square of the optical wavelength, thus an increase of r.f. power leads to a greater increase (by ~3%) in loss for the 1.319 μm transition compared to the 1.338 μm transition. It was also noted that the 1.319 μm transition had the lowest lasing threshold of the two transitions for all the output couplers tried. Thus if the losses in the cavity were to be increased uniformly for both wavelengths, eventually only the 1.319 μm transition would lase, as indeed observed by Trutna [9].

The CW performance of the laser, as shown if Figure 3, was as follows. With a 4% output coupler the threshold incident pump power was 285 mW, and a slope efficiency of 28% (for the sum of the output at the two frequencies) was achieved, with 155 mW output for 850 mW incident power. The output power at both frequencies was approximately equal under these conditions and their relative intensities (as well as the total output) remained very stable.

If the laser is Q-switched by allowing build up from noise the output is observed to be multi-axial mode, as noted in ref 1, since there is then insufficient time to establish unidirectional operation, and Q-switch pulses are then produced in both directions. To ensure single frequency Q-switched operation, we operate the laser with a low level unidirectional single-frequency prelase. At low prelase powers, i.e. 1-2 mW output, operation on the 1.338 μm line alone was observed, whereas for higher prelase powers simultaneous Q-switched pulses at both 1.319 μm and 1.338 μm were produced with single frequency operation on both of these lines. This is consistent with the earlier observation that the diffraction loss is higher at 1.319 μm and hence with the higher r.f. power required to maintain a low prelase level, this transition can be suppressed. A scanning Fabry-Perot interferometer was used to confirm that the Q-switched pulses which build up from the prelase were single frequency. When the laser was operated Q-switched with only the 1.338 μm transition operating single frequency, pulse energies of 30μJ were obtained at a 500 Hz repetition rate, with pulse widths of 40 nsec (Fig 4), corresponding to a peak power of 630W.

The stable simultaneous operation on two lines is at first sight surprising, since the two transitions share the same upper laser level ($^4F_{3/2}$) and hence compete for the same excited population. Single frequency operation is achieved in most systems with adjacent mode frequencies of slightly lower gain suppressed once spatial hole burning is eliminated. On the same basis the expectation would be that one or other 1.3 μm transition would dominate since gain on the two transitions would be unlikely to be equalised to such a degree as to allow stable simultaneous operation. In fact the mechanism that we propose here relies on the fact that spatial hole burning is not completely eliminated, there being a small degree of spatial hole burning at the high reflector of the laser rod, where there is an overlap between the incident and reflected beam. Thus, when the laser operates on a single frequency there is some gain available at the nodes of the standing wave pattern in the overlap region, as shown schematically in figure 5. For another frequency to access this gain it must be sufficiently well spaced from the oscillating frequency that its standing-wave pattern gets out of step with that of the oscillating frequency, within the overlap region, i.e. its antinodes fall on the nodes of the first frequency. Further, the gain of the second frequency must be close enough to that of the first frequency so that the extra gain it can access in the overlap region will allow it to reach threshold and oscillate simultaneously with the first. These requirements are both met under the conditions of our experiment for the 1.319 μm and 1.338 μm lines in Nd:YAG. Stable operation occurs because competition between the two frequencies is removed where the nodes of one standing-wave pattern overlap the antinodes of the other. All other frequencies are suppressed since near-neighbouring axial modes have antinodes closely coincident over the overlap region with antinodes at the already oscillating frequencies and thus find insufficient extra gain available to them. Stable, simultaneous two-mode operation is thereby achieved on these transitions.

The observation that a small degree of spatial hole burning can produce stable oscillation on more than one isolated frequency (i.e. with no neighbouring modes oscillating) has implications for many unidirectional ring laser systems [11]. Complete elimination of spatial hole burning would require the gain medium to be moved away from the high reflector. Attention may also have to be paid to residual reflections from antireflection coatings. Conversely the mechanism can be exploited for deliberate two (or more) frequency operation, and in this case control over the degree of spatial hole burning can be achieved by controlling the distance by which the high reflector is displaced from the gain medium, and by changing, for example, the mode size and beam angles in the gain medium.

The measured losses in our cavity (1.4%) proved to be higher than expected, based on typical figures for 1 μm lasers. The cause of this is not certain, however with an improved cavity design (i.e. lower resonator loss) we would expect to see a marked improvement over the powers reported here. A CW output of in excess of 200 mW and Q-switched pulses of 40μJ should be readily realizable for 1 Watt of pump power.

In conclusion, we have reported here a reliable technique for single frequency operation on the 1.319 μm and 1.338 μm lines of Nd:YAG, operating either CW or Q-switched. With appropriate mirror reflectivities it would be easy to discriminate between the two lines and hence ensure operation on only one of the two lines. On the other hand the stable two mode operation that we have described is also of interest and may have a number of applications, including the generation of short wavelength microwave radiation, and the generation of high frequency phonons. The same principle can be extended to other lasers by deliberately equalising the (net) gain of two transitions, or inserting a Fabry-Perot etalon so as to give two equal (net) gain peaks within a single laser transition.

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Figure Captions

Figure 1

Resonator design for 1.3 μm rhomb-ring laser.

Figure 2

Spectrum analyzer traces showing frequency spectra of the 1.3 μm laser when operating unidirectionally. The two peaks show that both wavelengths are operating on a single longitudinal mode.

Figure 3

CW single frequency output of 1.3 μm ring laser. The outputs at 1.319 μm and 1.338 μm have been summed.

Figure 4

Oscilloscope trace showing Q-switched pulse at 1.338 μm.

Figure 5

Overlap of incident and reflected beams results in standing wave pattern in the gain medium.