Acousto-optically induced unidirectional and single-frequency operation of a Nd:glass ring laser based on the acousto-optic effect in the laser medium

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Received August 17, 1994

A traveling-wave acousto-optic modulator fabricated from Nd-doped phosphate glass is used both as the laser gain medium and as the unidirectional element in a diode-pumped ring laser. Unidirectional operation can be maintained with applied rf powers as low as 6.7 mW and results in cw single-frequency output powers as high as 200 mW for a pump power of 1.2 W.

For homogeneously broadened laser transitions the use of a ring resonator configuration and the enforcement of unidirectional lasing is an attractive route to a single-frequency output. The main attraction of this technique that renders it particularly suitable for low-gain diode-pumped solid-state lasers is that usually only a very low loss discrimination (typically $\sim 0.01\%$; Ref. 1) between the two lasing directions is required, without any additional mode selection (e.g., intracavity étalons). This permits the design of compact and efficient single-mode lasers.

There are several different techniques for enforcing unidirectional operation. Many of these make use of the Faraday effect to generate different eigenpolarizations for counterpropagating lasing directions that are then discriminated between by a polarizer. More recently, increasing attention has been directed toward relatively new techniques based on the acousto-optic (A-O) effect. The particular advantage of the A-O techniques over the Faraday techniques is that they do not rely on polarization discrimination and hence are largely unaffected by the presence of birefringent components in the cavity. There are two A-O techniques for enforcing unidirectional operation. One of these makes use of an intrinsic property of all traveling-wave A-O modulators, which is that the Bragg angles are different for opposite directions of propagation, and, as a result, counterpropagating beams experience slightly different diffraction losses. The second technique, which we refer to as the feedback technique, exploits the fact that the frequency shifts given to the scattered waves by the modulator, although is both equal to the acoustic frequency, are of opposite sign for counterpropagating laser modes. The basic idea, which is described in Ref. 4, is to deliberately feed back the diffracted beams into the A-O modulator using an arrangement of mirrors known as the feedback resonator, so that they retrace their original paths. The effective diffraction losses for the counterpropagating incident beams are now modified from the value in the absence of feedback (i.e., the single-pass diffraction loss) according to the round-trip phase shifts (around the feedback optical path) for their respective diffracted beams. Thus a loss difference is established since the counterpropagating beams have different frequencies and therefore experience different phase shifts around the feedback optical path. This technique is of particular interest to low-gain lasers since relatively large loss differences can be achieved for only a very low insertion loss ($<0.1\%$). A further advantage of this technique is that the single-pass diffraction loss required for unidirectional operation need be only very small, suggesting that A-O materials with very low diffraction figures of merit (e.g., many solid-state laser materials) may also be suitable. This opens up the prospect of much more compact and lower-loss resonators with fewer components. There are, however, a number of practical problems with the feedback technique. In particular, the use of a separate feedback resonator adds extra complexity to the overall system, and because of the interferometric nature of the technique the lasing direction is rendered extremely sensitive to alignment; a relative change in the laser and feedback resonator optical path lengths by half a wavelength causes a flip in the lasing direction.

In this Letter we describe a diode-pumped single-frequency Nd:glass ring laser that uses an A-O modulator fabricated in the same piece of Nd-doped glass that also acts as the laser gain medium. To overcome some of the practical problems associated with the feedback technique, we adopt a modified approach that we refer to as the self-feedback technique. The principle of operation is essentially the same as for the feedback technique, but instead of using a separate feedback resonator we adopt a laser resonator design that permits the laser mirrors themselves to be used to feed back the diffracted beams. Apart
Fig. 1. (a) Top view and (b) side view of the diode-pumped Nd-glass ring laser, showing the lasing direction perpendicular to the pump and the path of the diffracted wave undergoing four mirror reflections before being diffracted back into the laser beam. H.R., high reflector.

Fig. 2. Top view of the Nd:glass A-O modulator.

from the obvious reduction in the number of components, this approach has the advantage that variations in resonator length are shared both by the laser resonator and the feedback resonator. This provides a high degree of stability to the lasing direction with respect to changes in resonator length or alignment. The ring resonator used, shown in Fig. 1, consists of only three optical components: a Nd:glass traveling-wave A-O modulator and two 20-mm radius-of-curvature curved mirrors. One mirror has high reflectivity (>99.8%) at the lasing wavelength of 1.053 μm and high transmission (>95%) at the pump wavelength of ~800 nm, and the other, serving as an output mirror, has a reflectivity of ~98.5% at 1.053 μm. The A-O modulator was constructed, as shown in Fig. 2, from a square-shaped prism of 4% Nd-doped phosphate laser glass (Schott LG760), with a lithium niobate transducer, designed to operate at a rf of 250 MHz bonded onto its top surface. This Nd:glass prism defines a figure-eight ring path of relatively low internal loss owing to the Brewster orientation of its four faces with respect to the incident light path. This particular shape of A-O modulator the physical length of the ring cavity is determined by the prism side length, which in this case is approximately 10 mm, resulting in a resonator length of 23.5 mm. To maximize the loss difference generated by the Nd:glass A-O modulator and hence minimize its effective insertion losses that due to diffraction, we positioned the electrodes so as to produce diffraction loss along only one of the two optical paths through the modulator. In this way, the loss difference generated as a result of diffraction along one optical path does not tend to be canceled by the opposite sign of loss difference generated along the other optical path through the A-O modulator. The feedback path for the diffracted beams is determined by the radii of curvature of the two mirrors. To maximize the loss difference, we must choose a feedback path that has a relatively low round-trip loss. Ideally we would like the feedback resonator loss to equal the laser resonator loss. In practice this is difficult to achieve with the self-feedback technique, since a self-reproducing path for the diffracted beams generally requires many round trips of the laser resonator. For this reason a confocal self-feedback resonator has been chosen since it requires only two round trips of the laser resonator.

We initially investigated the performance of the Nd:glass A-O modulator, before insertion into the cavity, by simply propagating a laser beam from a diode-pumped Nd:YAG laser at 1.06 μm into the modulator at the Bragg angle. By optimizing the alignment and position of the modulator we measured a diffraction loss of ~1% for an applied rf power of ~250 MHz of 1 W. This suggested that the diffraction figure of merit of Nd-doped phosphate glass is ~1.9 × 10⁻¹⁶ s² kg⁻¹, which is ~180 times smaller than that of tellurium dioxide. The Nd:glass A-O modulator was then inserted into the cavity and pumped by as many as two diode lasers (Spectra Diode Laboratories SDL-2362), each with a maximum output power of 1.2 W and each temperature tuned to the absorption peak in Nd:phosphate glass near 800 nm. The output from each diode was collected and focused into the Nd:glass modulator by use of a fairly standard arrangement consisting of a 6-mm focal-length collimating lens, a 3.5× expansion anamorphic prism pair, and two crossed cylindrical lenses of focal lengths 60 and 20 mm. This pumping arrangement permitted both optical paths within the Nd:glass modulator to be pumped independently, with the pump beams’ sizes matched approximately to the laser mode waist diameter (170 μm × 116 μm). This type of pumping configuration was chosen to optimize coupling of the two diodes both to maximize the pump transmission at the Brewster-angled faces of the modulator and to distribute the heat generated in the Nd:glass so as to increase the threshold for thermally induced damage.

The performance of the Nd:glass ring laser was initially investigated in the absence of a rf drive and by use of only one of the diode pump lasers. At threshold the incident pump power was measured to be 145 mW. Above threshold the laser operated bidirectionally on the TEM₀₃ mode, with a slope efficiency of ~21% for the combined output power, close to threshold. At higher pump powers the slope efficiency decreased [Fig. 3(a)] because of thermal effects, with the maximum laser output power limited to ~80 mW for a pump power of 700 mW. A pump powers greater than 700 mW the output remained approximately constant until thermally induced fracture of the Nd:glass occurred for incident pump powers of ~1 W. The decrease in slope efficiency with pump power at <700 mW was originall
thought to be the result of an increase in thermally induced birefringence. Measurements of the polarization state of the laser output showed that this was not the case, with the loss owing to birefringence not exceeding 0.1%. Further investigation revealed that the loss mechanism was due mainly to a thermally induced deformation and, in particular, to wedging of the Nd:glass surface. At low pump powers it was possible to compensate partially for this thermally induced wedge by a readjustment of the alignment of the output coupler. Alternatively, a more symmetrical pumping arrangement employing two diodes operating at the same output power can provide some degree of compensation. In this case significantly higher output powers as high as 200 mW were achieved for a combined incident pump power of 1.2 W, as shown in Fig. 3(b), and without the need for any realignment of the output coupler as pump power is increased. Even for this pumping scheme, thermal effects still caused a marked reduction in the lasing efficiency. We can see this by comparing the results for cw pumping and low-duty-cycle pulsed pumping (with a chopper), as shown in Fig. 3.

For cw pumping we can obtain unidirectional operation by simply applying a low-power rf signal (at 250 MHz) to the modulator, aligning it at the Bragg angle, and adjusting the cavity length slightly until unidirectional lasing is observed. Unfortunately, as a result of incorrect positioning of the transducer electrode close to the one of the prism vertices, it was impossible to operate the laser at its optimum efficiency while achieving the optimum diffraction efficiency because of the relatively high cavity loss caused by face curvature close to the vertex. For this reason it was necessary to operate with the laser path (as shown in Fig. 2) displaced from the acoustic column, with diffraction occurring only on the return path through the modulator as it crosses the acoustic column. In this case the single-pass diffraction loss achieved is much lower (~0.1% per watt of rf power). Nevertheless, reliable unidirectional operation can be achieved with applied rf power as low as 6.7 mW, corresponding to a single-pass diffraction loss of $8 \times 10^{-5}$%, with as much as 200 mW of maximum laser output power. This level of diffraction loss implies that the loss difference required for unidirectional operation is extremely small, i.e., $<4 \times 10^{-5}$%, which is comparable with the minimum loss difference reported for a monolithic Nd:glass ring laser when the Faraday effect was used. For unidirectional operation the laser output was verified to be single frequency with a plane-mirror scanning Fabry–Perot interferometer. Since the effective insertion loss (owing to diffraction) is very small there is no measurable reduction in lasing efficiency for single-frequency operation. For operation at the minimum loss difference required, reliable unidirectional operation can be maintained only for a cavity length change of approximately a few micrometers. As the rf power and hence the loss difference is increased, the sensitivity to cavity length changes is significantly decreased, and at rf powers of ~0.5 W (corresponding to a single-pass diffraction loss of approximately 0.06%), unidirectional operation can be maintained over a cavity length change of $>50 \mu m$ with no measurable degradation in lasing efficiency.

In conclusion, we have demonstrated reliable unidirectional and single-frequency operation of Nd:glass ring laser by means of the self-feedback of diffracted beams generated by an A-O modulator that also serves as the laser gain medium. In view of the very low diffraction loss required, it should be possible to extend this technique to other laser host materials (e.g., YAG, YLF). This might ultimately permit the construction of monolithic single-frequency lasers from a wide variety of laser materials operating over a wide range of wavelengths.

This study was funded by the Department of Trade and Industry and by the Science and Engineering Research Council under the LINK Optoelectronics scheme.

References