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Acousto-optically induced unidirectional operation of a ring laser: a feedback mechanism

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A second mechanism for acousto-optically induced unidirectional operation of a ring laser has been identified and demonstrated experimentally. The mechanism involves feeding back the diffracted wave, thus restoring it to its original frequency and direction via a second diffraction from the travelling-wave acousto-optic modulator. Since the feedback resonance condition is different for the two counter-propagating waves of the ring laser, they experience a loss difference which results in unidirectional operation. Via this method a very large loss difference can be achieved with negligible insertion loss.

1. Introduction

Following the initial demonstrations of acousto-optically induced unidirectional operation of ring lasers [1–3], the technique was successfully applied to diode-pumped miniature Nd:YAG [4,5] and Nd:YLF [6] ring lasers, where it proved to be a particularly simple and effective means for achieving single frequency cw or Q-switched operation. The exact mechanism (or mechanisms) were not identified at first. Under some conditions it was found that displacement of a resonator mirror could reverse the oscillation direction, and another observation [5] was that by deliberately blocking the diffracted beams by means of an aperture so that they could not re-enter the resonator, one could prevent the reversal of oscillation direction via mirror displacement. This behaviour suggested that at least two mechanisms existed, one of which involved the diffracted beams, whereas the other mechanism did not. The latter mechanism has recently been identified and experimental results were found to agree well with a straightforward quantitative description of the mechanism [7,8]. The basis of this mechanism is that with a travelling-wave acousto-optic modulator the Bragg condition, i.e. the condition for maximum diffraction loss, is satisfied for slightly different angles of incidence at the sound wave for the two counter-propagating light waves. This difference in the Bragg conditions implies that in general there will be different diffraction losses for the counter-propagating beams. The loss difference changes sign as the angle of incidence is changed, passing through zero at an angle of incidence midway between the two Bragg conditions. To exploit this technique for unidirectional operation the A-O modulator is tilted slightly away from the Bragg condition, to enhance the loss difference [7,8]. We have also noted that another condition needs to be met for reliable exploitation of this mechanism, namely to ensure that the diffracted waves do not re-enter the resonator. This can be achieved simply by means of an aperture which blocks the diffracted waves [5,6] or by using a long enough resonator [7,8]. The basis for this precaution is that one is actually suppressing a second mechanism for unidirectional operation which can, under appropriate conditions, give a larger loss difference than the first mechanism. We have identified this mechanism and have carried out experimental measurements on an arrangement which deliberately enhances its effect whilst suppressing the first mechanism by virtue of operating at the nominal Bragg condition, (i.e. midway between the Bragg incidence angles for counter-propagating beams) where the intrinsic loss difference for the A-O Q-switch is zero. Calculations suggest that very large values for loss difference (approaching 100%) can be achieved with negligible insertion loss.

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2. Theory

The basic principle of the mechanism is illustrated schematically in fig. 1a. The light wave, frequency ν, incident from the left on a travelling-wave A-O Q-switch is partially transmitted (at the same frequency ν) and partially diffracted at frequency $\nu - \nu_s$ where ν_s is the frequency of the acoustic wave. The diffracted wave is then returned to the A-O modulator via a ring path involving three mirrors (a standing-wave two-mirror arrangement can also be used). The returning light wave is partially diffracted by the acoustic wave and frequency up-shifted so that the original frequency ν is restored and, if the feedback mirrors are correctly aligned, the original direction is also restored. The effective transmission of the incoming light wave at the A-O modulator then depends on the round-trip phase shift of the diffracted beam. The behaviour of the counter-propagating wave is shown in fig. 1b. Here the diffracted wave is up-shifted in frequency to $\nu + \nu_s$ and is then restored back to its original frequency ν and direction on the second diffraction. It is clear therefore, that since the diffracted waves corresponding to the counter-propagation directions, shown in figs. 1a and b, have different frequencies $\nu - \nu_s$ and $\nu + \nu_s$ respectively as they circulate around the feedback path, they must therefore experience different phase shifts. As a consequence the counter-propagating beams in the main laser cavity are generally attenuated by different amounts at the A-O modulator. We can consider this transmission loss as the effective diffraction loss, which under appropriate conditions can differ considerably from the diffraction loss in the absence of a feedback cavity. It can be shown, using a simple Fabry–Pérot analysis, that the effective diffraction losses $L^{+}_{\rm eff}$ and $L^{-}_{\rm eff}$ for laser beams of frequency ν propagating in the (+) and (−) counter-propagation directions respectively are related to the single pass diffraction loss L_d (in the absence of feedback) and to the round-trip loss L_r for the feedback cavity (excluding diffraction), in the limit where $L_d \ll 1$ and $L_r \ll 1$, by the approximate expression

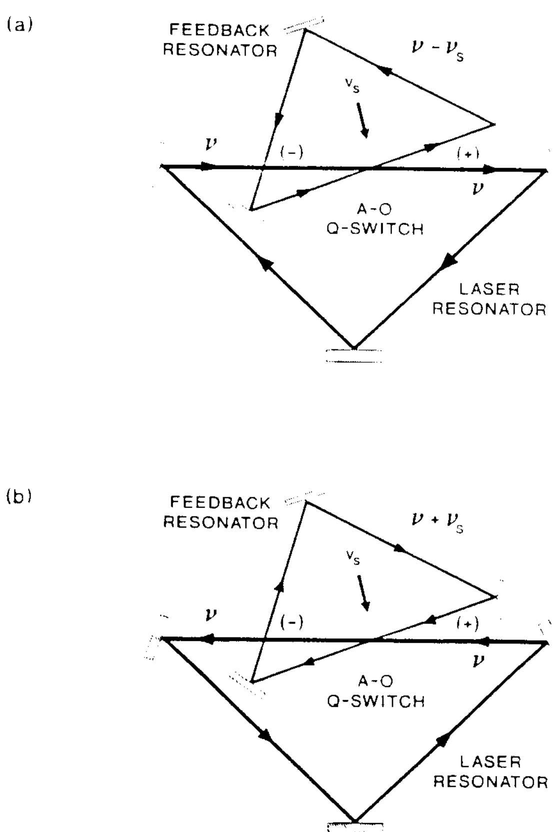

Fig. 1. (a), (b) Feedback technique for enforcing unidirectional operation of a ring laser using a travelling-wave A-O modulator.

$$L^{\pm}_{\rm eff} \approx \frac{4L_d L_r}{(L_d+L_r)^2+16\sin^2(\delta^{\pm}/2)}, \qquad (1)$$

where $\delta^{\pm}$ is the round-trip phase shift for the diffracted beams produced from the two counter-propagating beams. This is related to the optical path length l_r for the feedback cavity by

$$\delta^{\pm} = 2\pi l_r(\nu \pm \nu_s)/c\,. \qquad (2)$$

From eq. (1) it can be seen that the effective diffraction loss is a maximum when $\delta^{\pm} = 2q\pi$, where q is an integer, and is given by

$$L_{\max} \approx 4L_d L_r/(L_d+L_r)^2\,. \qquad (3)$$

The effective loss is a minimum when $\delta^{\pm} = (2q+1)\pi$ and is approximately given by

$$L_{\min} \approx L_d L_r/4\,. \qquad (4)$$

From eq. (3) it can be seen that the maximum loss achievable can be much larger than L_d and approaches 100% when the diffraction loss is matched to the feedback cavity loss (i.e. $L_d = L_r$), whereas, if

$L_r \ll 1$ the minimum effective loss L_{min} given by eq. (4) is much less than L_d. Clearly, the precise value of effective loss for a particular axial mode propagating in the (+) or (−) directions will depend on the phase shift $\delta^{\pm}$. In the ideal case one would like all axial modes propagating in one direction, say the (+) direction, to have phase shifts of $\delta^+ = 2q\pi$ and all counter-propagating modes to have phase shifts of $\delta^- = (2q+1)\pi$. In this way the net loss is much higher for all modes propagating in the (+) direction by an amount $L_{max} - L_{min}$, which we refer to as the loss difference. Then unidirectional lasing would occur preferentially in the lower loss (−) direction, and the effective insertion loss for the unidirectional device (disregarding loss of the undiffracted laser light due to imperfect antireflection coatings on the A-O modulator) is equal to L_{min}.

Similar considerations apply if a standing-wave two-mirror cavity is used to feed back the diffracted beams. This situation, however, is complicated by the fact that for each round-trip of the feedback cavity the beam passes twice through the A-O modulator in opposite directions. As a result, and in contrast to the ring feedback technique, light is now also partially diffracted into the counter-propagation direction of the main cavity. This light however is frequency shifted by twice the acoustic frequency with respect to the original laser frequency and therefore would usually be lost, since it would not in general be resonant with the main ring laser cavity. It can be shown that, for a standing-wave feedback cavity, the expression (1) for the effective diffraction loss must be modified by replacing L_r by $L_r + L_d$. The major consequence of this is that the minimum insertion loss has increased by an additional loss $L_d^2/4$. If $L_{d,r} \ll 1$ as is usually the case, then the insertion loss is still negligibly small compared to other resonator losses.

One point to note, using either feedback configuration (ring or standing-wave), is that the lasing direction is very sensitive to relative changes in length of the laser and feedback cavities, with a reversal in the lasing direction occurring for length changes of approximately half a wavelength. A typical situation is shown in figs. 2a and 2b, where the calculated loss difference for a ring feedback cavity is plotted as a function of feedback cavity length. It can be seen that loss difference is large only close to the resonance

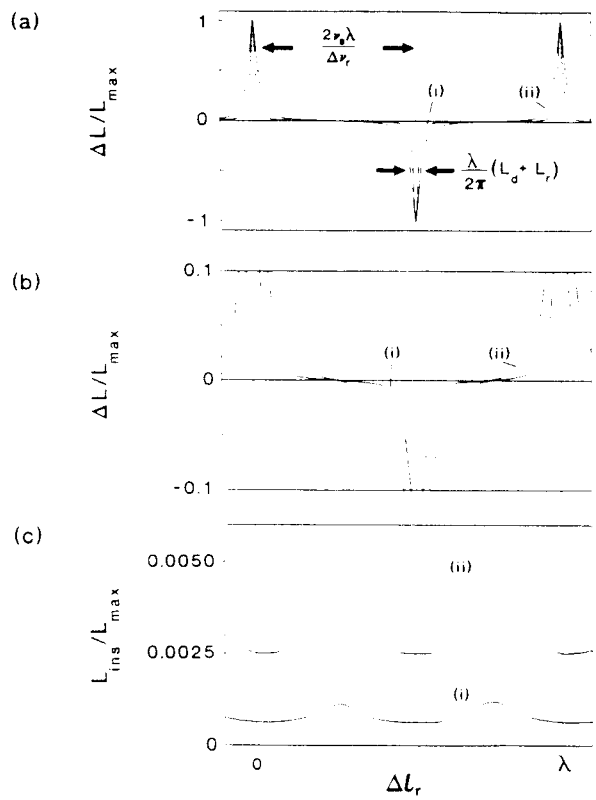

Fig. 2. (a), (b) Predicted curves for loss difference as a function of relative change in the feedback and laser path lengths. (c) Predicted curve for insertion loss L_{ins} ((i) $L_d + L_r = 0.1$, (ii) $L_d + L_r = 0.2$).

condition. At first sight this might lead one to believe that unidirectional operation is also only possible close to resonance. However, since the loss difference required for unidirectional operation is usually very small for example (~0.01%) [9], it can be seen from fig. 2b that it should be possible to maintain unidirectional lasing far from resonance. In fig. 2c the insertion loss, which is defined as the effective diffraction loss for the lower loss and therefore preferred lasing direction, is plotted as a function of change in feedback cavity length. It can be seen that the insertion loss is generally very small and reaches a maximum value when the loss difference is zero. The asymmetric nature of the insertion loss versus length change curve is a consequence of the frequency difference for counter-propagating diffracted beams (i.e. $2\nu_s$) not being exactly equal to half the free spectral range $\Delta\nu_r$, of the feedback resonator. (In the example illustrated $2\nu_s = 0.53\ \Delta\nu_r$, which was deliberately chosen to match the experimental conditions described in the next section.)

3. Experiment

To provide experimental verification of the proposed mechanism use was made of the experimental set-up shown in fig. 3. This consists of a Nd:YAG ring laser of triangular configuration pumped by two polarisation-coupled one-watt diode lasers, with a lead molybdate travelling-wave A-O Q-switch positioned approximately at the mid-point of the longest arm of the ring cavity. The Nd:YAG rod was positioned close to the beam waist, and the pump light delivered at a small angle to the laser beam as shown. The output coupler provided access to both counter-propagating laser beams. Pumped in this way the laser had a threshold of ~600 mW incident pump power and a maximum output power of ≈400 mW for 1.8 W of incident pump power. The Q-switch, designed to operate at 80 MHz, produced a diffracted beam inclined at twice the Bragg angle with respect to the laser beam. This small angle (≈2.6° in air), necessitated the use of a ring resonator of long perimeter (≈1 m) in order to access the diffracted beams (diffracted vertically, i.e. out of the plane of fig. 3) without clipping the main laser beam. This was achieved as shown in fig. 3 using a prism and a high reflecting 50 cm curved mirror placed, respectively, just above and just below the main beam. The feedback cavity was completed with a high reflecting plane mirror mounted on a piezo stage, so that the two resonators are inclined at twice the Bragg angle. The design of the feedback resonator closely resembled that of the laser resonator and the perimeter length was made approximately equal to that of the laser resonator. (A standing-wave feedback resonator configuration could also be selected, by simply changing the orientation of the feedback mirrors). In order to eliminate any contribution to the loss difference, and hence non-reciprocal behaviour, due to the other mechanism [7,8] for unidirectional operation, it was necessary to operate the A-O Q-switch at the nominal Bragg angle for which the single pass diffraction loss is the same for both counter-propagating beams. In practice this was achieved by operating the ring laser with the feedback path blocked, and then simply adjusting the angle of tilt of the A-O Q-switch near the Bragg angle until bidirectional lasing was observed. When the feedback path was restored and the appropriate adjustment made to feedback path length using the piezo, unidirectional lasing was observed. This was confirmed to be single frequency with the aid of a scanning confocal Fabry–Pérot interferometer with a free spectral range of 7.5 GHz. The minimum r.f. power required for unidirectional operation was found to be less than ~0.005 W, which for this modulator corresponds to a single pass diffraction loss of less than ~0.5%. From a comparison of the laser thresholds with and without the r.f. present and a knowledge of the laser round-trip loss (≈6.7% excluding diffraction), it was estimated that the effective insertion loss for the unidirectional device (excluding imperfect antireflection coatings) is <0.1%. This can be considered negligible compared to other resonator losses. For relatively low values of diffraction loss (<10%), the insertion loss was found to increase linearly with diffraction loss as expected, but its value (~$0.1L_d$) was significantly larger than the value $0.002L_d$ predicted by eq. (4) and based on a known value for the round-trip loss of the feedback cavity of 0.8%. This discrepancy was thought to be due to a combination of poor mode matching, and the fact that a significant fraction of the light was also

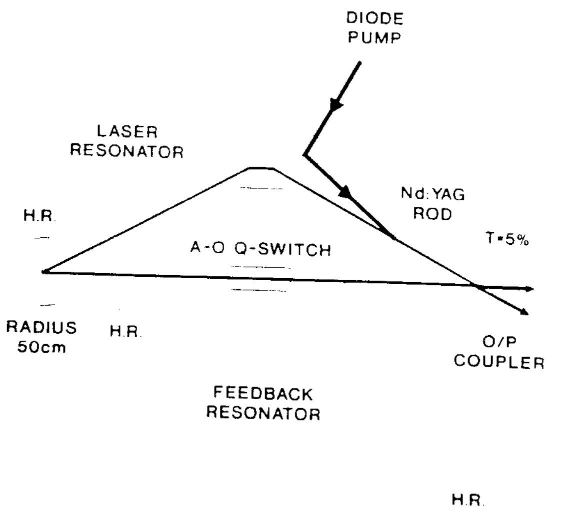

Fig. 3. Diode-pumped Nd:YAG ring laser using the feedback technique for unidirectional operation.

diffracted into other orders which were not resonated in the feedback cavity.

A direct measurement of the loss difference predicted by equation (1) has not been made. Measurement techniques based on transient laser behaviour as described in refs. [7] and [8] would be complicated by the fact that for a high finesse feedback cavity it takes many round-trips for the loss difference to buildup. Instead, to gauge some idea of the magnitude for the loss difference, we have scanned the feedback cavity length over several microns using the piezo length adjustment whilst monitoring the laser outputs for both lasing directions. A typical oscilloscope trace (fig. 4) shows the situation where $L_d \sim 1\%$. It can be seen that the lasing direction reverses as the feedback length is changed, as expected. In addition one also sees that unidirectional lasing is maintained over a range of feedback path lengths far from the resonance condition and that the change in lasing direction occurs rapidly over a very small cavity length change of $\sim\lambda/30$. This is consistent with our expectations from eq. (1) and figs. 2a and 2b, and suggests that more than sufficient values of loss difference to provide robust unidirectional operation are indeed attainable via this technique.

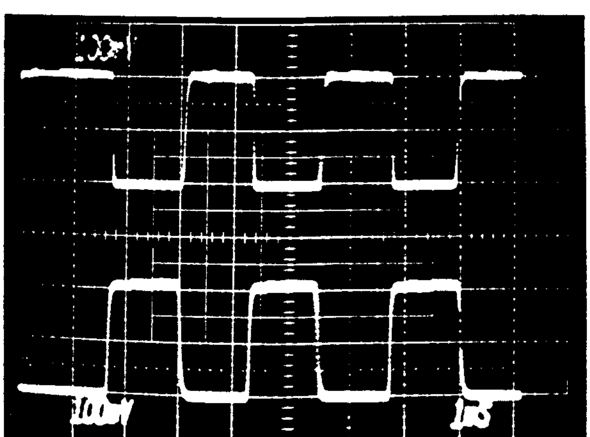

Fig. 4. Oscilloscope traces for opposite lasing directions as the feedback path length is scanned over several microns. The lasing direction reverses for each incremental change in feedback path length of $\lambda/2$.

4. Discussion

It should be stressed that the experimental situation that we have described is something of an idealization and is not intended to represent the most practical resonator design. For example: it is not always necessary to match the laser resonator and feedback resonator cavity lengths. Thus, if the laser resonator has a large enough axial mode spacing, so that the gain difference between adjacent modes exceeds the minimum loss difference required for unidirectional operation, then one only needs to resonate, in the feedback cavity, the highest gain axial mode for one of the two lasing directions. This obviously allows for much more flexibility in cavity design. One apparent disadvantage of this feedback technique for unidirectional operation is the sensitivity of the direction of oscillation to relative changes in the laser resonator and feedback resonator lengths. One way to overcome the problem is to use the laser resonator itself as the feedback resonator. This can be achieved rather easily in miniature ring lasers, where through the appropriate choice of resonator design, the sensitivity of lasing direction to cavity length can be reduced to such an extent that a resonator length change of several hundred microns is required for a relative change in the laser and feedback path lengths of $\sim\lambda/2$, and hence a change in the lasing direction. This will be discussed in more detail in a future publication. We believe that it is this effect which was responsible for the observation of a change in lasing direction with resonator length for the miniature ring lasers described in refs. [4–6], when the precaution was not taken of using an aperture to eliminate the diffracted beams.

5. Conclusions

We have described an alternative technique for enforcing unidirectional operation of a ring laser by feeding back the diffracted beams from a travelling-wave A-O modulator. The technique offers the advantages of very low insertion loss and, potentially, very large loss differences, and through the use of coupled laser and feedback cavity configurations should be particularly suitable for enforcing unidirectional and hence single frequency operation of miniature diode-pumped solid-state ring lasers.

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