Reprinted from *Electronics Letters*, Vol. 5, No. 16, 7th August 1969

TRANSVERSE-MODE SELECTION OF ROTATING-MIRROR *Q*SWITCHED LASERS

The TEM_{00} mode has been selected in a rotating-mirror *Q*switched Nd^{+3} : $CaWO_4$ laser by insertion of a slit and an edge into the resonator. Shot-to-shot repeatability was enhanced, and multiple pulsing was suppressed. The same technique has been successfully applied to a CO_2 laser.

Methods of selecting TEM_{00}-mode operation in lasers with fixed mirrors are now well established. The most common technique is to use a spherical-mirror resonator with a small circular aperture placed within the resonator and centred on the resonator axis.[1] The aperture size is chosen to introduce a large diffraction loss for all modes except the TEM_{00} mode.

If, however, one of the resonator mirrors is being rotated to provide *Q*switching, the axis of the resonator is also being swept, and a fixed circular aperture is therefore not appropriate. We have used a slit instead to provide mode selection in one dimension. The slit was parallel to the *x*axis (see Fig. 1) and was bisected by the *x–z*plane, i.e. the plane swept out by the rotation of the resonator axis. The slit width was variable in the *y*direction and was chosen to be approximately equal to the calculated[2] spot diameter of the TEM_{00} mode. By means of this slit, only modes of the form TEM_{m0} were allowed to oscillate, where *m* refers to the number of modes in the *x*direction. The usual Porro-prism rotating reflector was avoided, since the lossy roof edge discriminates against TEM_{m0} modes and favours TEM_{m1} modes which have zero intensity on the roof edge.

A further mode-selection mechanism is also present in any rotating-mirror laser, tending to favour the TEM_{00} mode over higher-order TEM_{m0} modes. All modes are centred on the instantaneous position of the resonator axis, and as a result suffer heavy losses until the axis has been swept clear of the edge of the laser rod and into the active medium. The TEM_{00} mode has the smallest extent in the *x*direction and starts to build up before higher-order modes which have not yet cleared the edge. It therefore reaches a higher initial intensity than these modes, and this initial advantage is maintained as the axis is swept further into the active medium when all TEM_{m0} modes have the same net gain. In conjunction with the use of the slit, this introduces sufficient mode selection in practice to give predominantly TEM_{00} output.

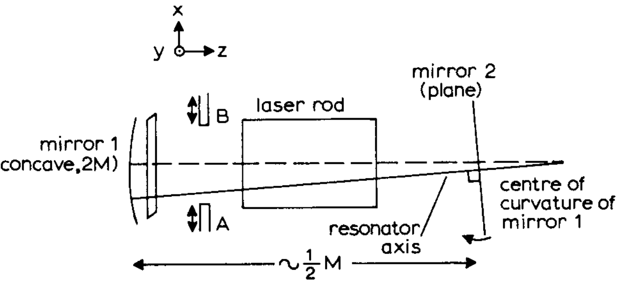

Fig. 1 *Arrangement of mode-selecting elements in rotating-mirror resonator*

Optimisation of TEM_{00} power can then be achieved in the usual way by varying mirror speed or pump energy (and hence gain). However, a consideration of the dynamics of mode buildup shows that a laterally adjustable edge placed at A (Fig. 1) achieves the same effect and is, in fact, a much simpler adjustment to make. Thus once the TEM_{00} mode has cleared the edge, the mode intensity grows as it is swept through the amplifying medium until it reaches an intensity sufficient to deplete the gain. The intensity then passes through a maximum and decays. If this occurs before the axis has been swept halfway across the medium, the whole process of pulse buildup can repeat, resulting in multiple pulsing. If, however, the mode is constrained to reach its maximum intensity in the region of maximum gain, not only is the output maximised but also the multiple pulsing is greatly suppressed, since any second pulse sees little gain available. This constraint amounts to an adjustment of the total gain available between the time when the axis clears the edge and when the axis reaches the region of maximum gain. This can be achieved by an adjustable edge, by varying mirror speed, by varying the resonator length, or by varying pump energy. In practice, with large-diameter laser rods or tubes, the latter three adjustments can imply an inconveniently high mirror speed, an inconvenient length of resonator, or limitation of gain and hence of output power to a much lower level than can be produced by the full available pump energy.

Using the slit and adjustable edge, we have found that, when the output power is maximised, the shot-to-shot repeatability is extremely good (Fig. 2), and multiple pulsing is greatly reduced. Any residual multiple pulsing is conveniently removed by another edge at B (Fig. 1). Near-field intensity distribution of the laser output has been investigated using a photodiode behind a slit which could be scanned vertically or horizontally. The measured distribution is very close to Gaussian, and the spot size agrees with calculated TEM_{00} spot sizes to within 10%. A small degree of broadening of the spot occurs in the *x–z*plane, since the mode is being swept in this place. The extent of broadening was found to agree with the distance swept by the resonator axis during the laser pulse. An additional check on beam quality was made by generating the second harmonic of the 1·06μm output under optimum focusing conditions[3] in a 36mm-long crystal of ADP. A conversion efficiency of 15% was obtained for a 1·06μm power of 14kW, which is within a factor two of the predicted efficiency.

From a 50mm × 6mm $CaWO_4$ rod, a maximum 1·06μm output of 70kW was obtained, this being limited by mirror damage. Up to this power level, we found that peak output power was predictable within experimental error by Wagner and Lengyel's theory,[4] and an extrapolation for a system with optimised mirror transmission and damage resistance indicates that 1MW of TEM_{00} power should be possible with this technique. The applicability of Wagner and Lengyel's fast *Q*switching theory to what is traditionally regarded as a slow switch may, at first sight, appears surprising. However, the theory shows that the peak output power depends only on cavity losses, oscillating volume, population inversion and stimulated-emission cross-section, and is quite insensitive to the switching time. All these quantities were known in our laser from previous measurements.[5] In particular, it should be noted that the measurements of loss and population inversion were made using the technique of Findlay and Clay.[6] As a result, these quantities were known only for the region of maximum gain, but this was precisely the region in which the pulse was constrained to reach its peak power. Further details of the power calculations and the second-harmonic generation will appear in a fuller publication.

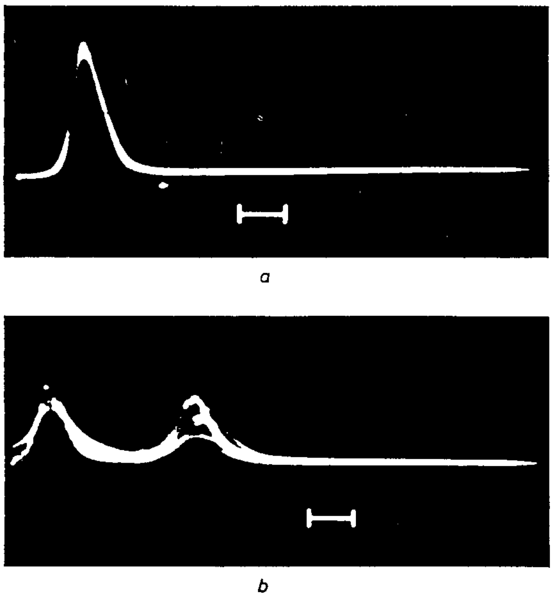

Fig. 2 *Oscilloscope trace (with 100ns scale indicated) showing laser output on ten consecutive shots*

(i) With edge A positioned for maximum power output, 14kW
(ii) With edge A removed, ~4kW

This technique of mode selection is applicable to any laser using a rotating-mirror Qswitch. We have tested it also on a Qswitched CO_2 laser and have observed a considerable improvement in conversion efficiency and repeatability when the 10·6 μm output was frequency-doubled in a crystal of tellurium.

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2nd July 1969

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References

1 LI, T.: 'Diffraction loss and selection of modes maser resonators with circular mirrors', *Bell Syst. Tech. J.*, 1965, **44**, pp. 917–932
2 KOGELNIK, H., and LI. T.: 'Laser beams and resonators', *Appl. Optics*, 1966, **5**, pp. 1550–1567
3 BJORKOLHM, J. E.: 'Optical second harmonic generation using a focussed Gaussian beam', *Phys. Rev.*, 1966, **142**, pp. 126–136
4 WAGNER, W. G., and LENGYEL, B. A.: 'Evolution of the giant pulse in a laser', *J. Appl. Phys.*, 1963, **34**, pp. 2040–2046
5 ARNOLD, D. H., and HANNA, D. C.: 'Measurement of the stimulated emission cross section of Nd^{3+} in $CaWO_4$', *Brit. J. Appl. Phys.* (to be published)
6 FINDLAY, D., and CLAY, R. A.: 'The measurement of internal losses in 4-level lasers', *Phys. Lett.*, 1966, **20**, pp. 277–278