LASER TECHNIQUES SERIES–1

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Increasing laser brightness by transverse mode selection–2

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The first part of this article gave the background to modes and resonators and the advantages of transverse mode selection. Part 2 gives a review of methods of mode-selection and discusses a wide variety of resonators with emphasis on the experimental results obtained from them. Unstable resonators show particular promise for mode selection of solid state lasers.

REVIEW OF MODE-SELECTION EXPERIMENTS

A LARGE NUMBER of early investigations were made into the transverse mode behaviour of pulsed ruby lasers (Evtuhov & Neeland 1964) and some success in mode selection was achieved (Skinner & Geusic 1964, Evtuhov & Neeland 1965). An important development came when Daneu et al. (1966) reported their elegant results obtained by much simpler techniques. They showed that it was possible by using a spherical mirror resonator to obtain ~1MW of power in the TEM_{00} mode from a Q-switched ruby laser even using a laser crystal of modest length (7.5cm) and of quite poor optical quality (~ 10 fringes across the rod). With essentially the same technique but using 24-cm length of ruby in the oscillator, Korneev & Pavlov (1968) have obtained as much as 40MW in the TEM_{00} mode. Many of the results discussed in this section have been obtained using spherical mirrors to help mode selection. It is an experimental point worth noting that a concave spherical mirror of curvature R may be simulated using a plane mirror (which may be a resonant reflector) with an adjacent converging lens of focal length R.

The laser used by Daneu et al. was Q-switched by a saturable absorber, they found that the use of a mode-selecting aperture, although helpful, was not essential for single mode operation. This may be due to the fact that the saturable absorber itself can act as an aperture when the laser beam bleaches a hole through it (Stein 1967). The laser rod was pumped by a helical flash lamp and any lens-like distortion of the rod due to pumping would therefore have cylindrical symmetry. The use of a helical flashlamp is not essential as transverse mode selection has been achieved in lasers using elliptical cylinder pumping arrangements (Mikaelyan et al. 1967, Korneev, 1968, Davis, 1968, Arnold & Hanna, 1969) which produce more complicated thermal distortions. On the other hand the systems which have so far produced the largest TEM_{00} spot sizes, and which are discussed below, have used either helical flash lamps (Bjorkholm & Stolen, 1968, Soncini & Svelto, 1967, Stickley, 1966) or several linear flash lamps in a close-wrapped configuration (Hagen 1968).

The laser used by Bjorkholm had two plane mirrors, a plane-ended 10cm long ruby of high optical quality and a 2mm diameter aperture. When Q-switched by a saturable absorber the laser produced 2MW of TEM_{00} output in a beam of ~2mm diameter and of accurately Gaussian profile. The extreme temporal and spatial coherence of the output were demonstrated by its use in a holographic application (La Macchia & Bjorkholm 1968) and in a parametric oscillator experiment (Bjorkholm 1968). The same laser was also operated with curved mirrors and as the mode spot size was then smaller it was found that single mode operation could be achieved over more regions (i.e. more transverse positions) of the rod but at reduced power.

Instead of using two plane mirrors Stickley (1966) has described an experiment involving one plane and one convex mirror. The ruby, of good optical quality, was pumped by a helical flash lamp, so allowing an accurate measurement to be made of the focal length of the lens-like thermal distortion in the rod. The convex mirror was chosen to compensate this positive lens action and increase the mode size by making the cavity more nearly equivalent to a perfect plane mirror cavity. The mode diameter obtained was 1.5mm, mode selection being produced by the aperture effect of the rod perimeter. The laser brightness was increased by a factor of one hundred over the uncompensated laser (i.e. with two plane mirrors).

Soncini & Svelto (1967, 1968) and Cubeddu et al. (1969) have obtained mode selection in a special resonator which uses two total internal reflection (t.i.r.) prisms instead of plane mirrors (see Fig. 4). The prisms have plane faces, the resonator is therefore equivalent to a plane mirror resonator, apart from the thermal lens effect in the laser rod. It was proved that the TEM_{00} spot size was determined solely by the strength of this thermal lens. The special feature of this resonator is that the two identical t.i.r. prisms have a roof angle of less than 90°. This allows the mode to be reflected well clear of the knife edge thus avoiding the roof edge diffraction loss (see Fig. 4). The most striking effect of this resonator is that reliable TEM_{00} operation with a large spot size (~1.2mm diameter) was obtained even from poor quality laser rods. These rods normally produced oscillation in small filaments when placed between two ordinary plane mirrors.

Soncini & Svelto therefore conclude (and have shown with a Twyman-Green interferogram) that the effect of the prisms is to reduce the apparent inhomogeneities of the laser rod because of the unusual path

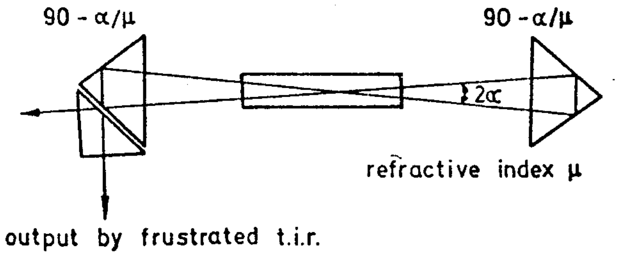

Fig. 4 Total internal reflection prism resonator, equivalent to a plane mirror resonator.

of the laser beam through the rod. This laser has been Q-switched (Soncini & Svelto, 1968) and mode-locked (Cubeddu et al. 1969) with excellent repeatability. Their technique seems to present the hitherto unfortunate owners of poor quality laser crystals with a solution to their problems. The extent to which this laser is well behaved may also be judged from the fact that when Q-switched by a saturable absorber (Asvazadurian et al. 1968) the output power and pulse duration were in good agreement with the theoretical calculations of Szabo & Stein (1965) and Wagner & Lengyel (1963). An objection to this laser is the need to obtain output by frustrated internal reflection, giving rise to two beams.

Hagen (1968) has reported the largest TEM$_{00}$ spot size so far, using a system consisting of a Nd glass oscillator and two Nd glass amplifiers. These laser rods had extremely good optical homogeneity, and this was maintained, even when pumped, by careful choice of rod doping and surface finish, and by using a pumping arrangement of four linear flash lamps in a close-wrapped configuration. Magnifying optics were used to transform the 3-mm diameter TEM$_{00}$ beam from the oscillator into a final output beam of 30-mm diameter. Transverse mode selection in the oscillator was achieved by means of a resonator of the general sort shown in Fig. 5a. This resonator uses two apertures, one of which is a pinhole placed at the common focus of the afocal lens-mirror combination.

If laser material of good optical homogeneity is available which can support a large mode volume, then this type of resonator is preferable to the long radius plano-concave system. This is because the Fresnel number of the latter will be large (and mode selection therefore slight) unless an impracticably long resonator is used. A number of different afocal resonators have been considered (Burch, 1962, 1964). The 'cat's-eye' resonator shown in Fig. 5b has been used to obtain good mode selection for large mode size in a He-Ne laser. The mode selectivity is the same as for a confocal resonator having an effective Fresnel number given by $N_{eff} = a_1 a_2/d\lambda$ as can be shown by using the equivalence relations. By making a_2 much less than a_1 the mode size to the left of this lens is made large (and the laser medium is placed here) while the effective Fresnel number is small and hence mode selection is good.

Damage to the small mirror would immediately become a problem with solid-state lasers. It is more usual to use resonators of the type shown in Fig. 5a since the pinhole which now provides the mode selection can withstand high powers and the power density on the mirror is acceptable. This type of resonator is closely related to the concentric resonator of Fig. 5c for which Li (1963) has calculated the diffraction losses. The calculations have been made for square apertures in this case but the conclusions, that mode selectivity can approach that of the confocal resonator, are also expected to hold for circular apertures. At high powers a diamond pinhole is necessary to withstand damage and it may be necessary to reduce the power to avoid air breakdown at the focus (Hagen, 1968). A disadvantage of all pinhole mode selection techniques is that the pinhole must be positioned to an extremely high degree of accuracy.

MODE-SELECTION IN ROTATING MIRROR LASERS

Single transverse mode oscillation in rotating mirror Q-switched lasers has been reported for low-gain systems such as continuously pumped Nd:YAG (Smith & Galvin, 1967) and continuously pumped ruby (Evtuhov & Neeland, 1969). Both lasers operated predominately in the TEM$_{00}$ mode without any special mode-selection being provided, although Smith & Galvin did note that the output became a cleaner TEM$_{00}$ mode when a circular aperture was inserted. The mode purity in these lasers is probably due to the fact that gain was low, hence mode discrimination need only be small. This required degree of selection could be obtained from the small diameter aperture formed by the laser rod which was only about 2-mm diameter.

In pulse-pumped laser systems, which have a higher gain and typically use larger diameter laser rods,

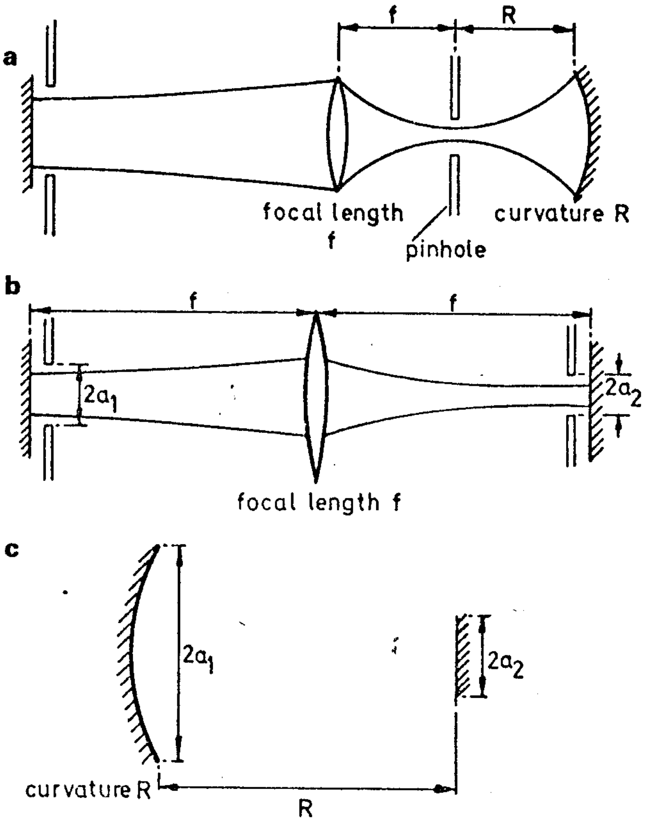

Fig. 5 (a) A focal system with pinhole mode selection. (b) Cat's eye resonator for selection of large mode size. (c) Concentric resonator—diffraction losses calculated by Li (1963).

the laser operation is generally found to be multimode and even multipulse when a rotating mirror is used to Q-switch. Mode selection of such a system has been recently reported (Arnold & Hanna, 1969). A plano-concave resonator was used and instead of a fixed circular aperture, a slit aperture and an edge were used, since the laser mode sweeps out a plane through the laser rod as the mirror rotates (Fig. 6).

This technique was used to obtain TEM_{00} operation in a Nd: $CaWO_4$ laser, a Nd: YAG laser and a CO_2 laser. In each case the laser output was found to be repeatable from shot to shot and multiple pulsing was suppressed. As in the work of Asvazadurian et al. (1968) it was found that for the Nd: $CaWO_4$ laser the output power agreed well with predictions of the Q-switching theory of Wagner & Lengyel (1963). It is therefore anticipated that this technique should be even more readily applicable to ruby and Nd glass lasers since these materials have smaller gains, longer build-up times and hence a longer time for mode-selection to become established.

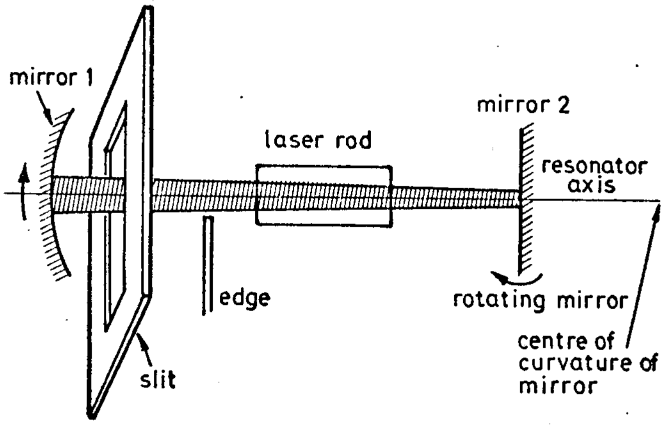

Fig. 6 Mode selection of rotating mirror laser. Mode is centred on the axis which passes through the centre of curvature of mirror perpendicular to mirror 2.

UNSTABLE RESONATORS

If the plano-concave resonator of Fig. 2b (Part 1) is used with a large Fresnel number ($N > 1$ say), it is found that the diffraction loss shows a very rapid increase when the mirror separation is increased from just less than R to just greater than R. The cavity is therefore said to be unstable when $d' > R$. In a low gain gas laser this would manifest itself as an inability to oscillate for $d' > R$. For small Fresnel numbers the diffraction losses are large even for the stable resonator ($d' < R$) and the transition from stable to unstable does not show such dramatic change.

A great variety of possible unstable resonators exist. In an unstable resonator rays bouncing between the mirrors become progressively defocused whereas in a stable resonator the rays are periodically refocused. This 'walk-off' in an unstable resonator produces the high loss.

Siegman (1965, 1967) considered in some detail the suitability of unstable resonators for laser applications, indicating that they possessed certain attractive features for mode selection of solid state lasers. Since these lasers generally have a high gain, adequate mode selection involves a high loss even for the wanted mode and the usual objection to unstable resonators, viz. their high loss, is therefore no longer valid. On the credit side, unstable resonators offer the possibility of large mode volume, diffraction coupled output and a high degree of mode selection. These points will be discussed with reference to a particular unstable resonator which Siegman named the 'Cassegrainian' unstable resonator (Fig. 7).

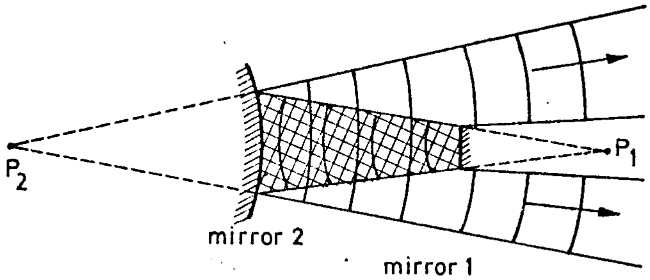

Fig. 7 Cassegrainain unstable resonator (after Seigman).

Siegman (1965) made a theoretical study of the properties of unstable resonators using a geometrical optics approximation. Thus in the resonator of Fig. 7 the lowest order mode is assumed to be a spherical wave of uniform intensity completely filling the surface of mirror 1. This wave which appears to diverge from some point P_1, impinges on mirror 2 and is reflected back as a spherical wave appearing to diverge from some point P_2. If mirror 2 is sufficiently large there is no loss due to walk-off around mirror 2, however the wave which returns to mirror 1 is now larger than mirror 1 and light escapes around the edge of the mirror as a uniformly illuminated annulus having a spherically curved wavefront.

The reflected portion from mirror 1 is again a uniform-intensity spherical wave filling mirror 1; it is always possible to find some position for P_1 such that this reflected wave also appears to diverge from P_1, i.e. the field pattern has the self-consistency criterion for a cavity mode. The loss due to escape round the edge of mirror 1 may be readily calculated (Siegman, 1965). By increasing the size of mirror 1 the mode volume (occupying the hatched area) may be increased, but Siegman showed that this does not change the loss of the resonator. The general result was that (within the geometrical optics approximation) the round trip losses of an unstable resonator are independent of mirror sizes and depend only on mirror curvatures and separations.

Both mirrors may be 100% reflecting and the light escaping around the edge of mirror 1 can be taken as output. This 'diffraction coupling' was suggested by La Tourette et al. (1964) for use in stable resonators where a low Fresnel number and hence high diffraction loss is necessary to mode select a high gain laser. The advantage of the scheme is that the high diffraction loss is taken as useful output whereas the use of an aperture in an opaque screen means that the diffracted radiation intercepted by the screen is wasted. Apart from the results reported by La Tourette et al. (1934) and Treacy (1969) this scheme appears to have been little used with stable resonators. One difficulty for visible lasers is the fabrication of a small mirror. In an unstable resonator the mirror can be much larger whilst still providing adequate mode selection and the technique comes into its own.

Experimental results on diffraction-coupled outputs from unstable lasers have been reported by Siegman (1965, 1967), Sinclair & Cottrell (1967) and Anan'ev et al. (1968, 1969). Sinclair & Cottrell demonstrated that the output coupling could be usefully varied by varying the mirror separation and hence the walk-off losses. Anan'ev's results are promising as he has shown a sixfold increase in ruby laser brightness by using the Cassegrainian system described above. The repeatability was found to be excellent and the resonator was remarkably insensitive to misalignment.

So far the experimental and theoretical work on unstable resonators is of a preliminary nature, indicating the feasibility of the techniques. Much more work is needed before a fair comparison can be made between stable and unstable resonators.

CONCLUSION

All the mode-selection schemes described depend ultimately on using a resonator with diffraction losses which are larger for the unwanted modes than for the wanted mode. In continuously operating lasers, where the gain per resonator transit is usually rather low, only a small diffraction loss is required to suppress unwanted modes. In pulsed solid-state lasers, especially Q-switched lasers, the gain is generally much higher and the number of transits during which mode-selection can operate is quite small. This means that large diffraction losses must be introduced.

Two approaches to this problem are possible, using a stable resonator with a small Fresnel number, or using an unstable resonator. Since the latter arrangement is experimentally relatively untried and the theoretical investigations have been rather limited, only a brief discussion was given in this article. The rewards of large mode volume and efficient diffraction coupling suggest that more work in this area might be profitable.

A number of different stable resonator configurations have been reviewed. The choice of which configuration to use must depend largely on the quality of the laser rod and hence the size of mode that it can accommodate clear of imperfections. In general the plano-concave resonator produces the smallest mode size and is therefore appropriate to laser rods of average quality. Since this resonator is amenable to analysis it has been treated in the text more fully than the other resonators in order to illustrate the basis of any mode-selection technique.

For better quality laser rods it is possible to use plane mirrors and rely on the lens-like thermal distortion of the rod to determine the Gaussian spot size. The optimum size of mode-selecting aperture must be determined by experiment unless the focal length of the rod is known. A special type of plane mirror resonator was described which can be used even with average quality rods. The spot size can be increased further, if the rod quality will permit, by compensation of the thermal distortion by the appropriate lens or mirror. The largest spot size has been obtained in Nd-glass of very good optical homogeneity with a very uniform pump distribution. For such large spot sizes it becomes necessary to use a pinhole mode selector to obtain sufficient selectivity.

In discussing the advantages of mode-selection the dramatic improvement in repeatability of performance was mentioned. One of the most serious drawbacks to high-power solid-state lasers has been the lack of reliability and repeatability with a consequent psychological effect on the unfortunate user which further prejudices the success of the experiment. Perhaps as transverse mode selection becomes more widely practised, the bad old days of solid-state lasers will have finally been left behind.

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