Increasing laser brightness by transverse mode selection–1

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Transverse mode selection increases the brightness of solid-state lasers-useful in plasma generation, microcircuit machining, drilling and non-linear optics. This article enumerates advantages of transverse mode selection and gives the background to modes and resonators. Using mode selection solid-state lasers may become reliable with good repeatability of performance, removing their most serious drawbacks. Part 2 explains the basis of mode selection using the plano-concave resonator as an example and discusses a wide variety of resonators. Unstable resonators show particular promise for mode selection.

APPLICATION OF TRANSVERSE mode selection techniques to solid-state lasers has been described in a number of papers (Daneu et al., 1966, Soncini & Svelto, 1967). Despite the advantages of these simple techniques transverse mode selection is still not widely used with solid-state lasers. Axial mode selection however is widely used and was reviewed by Magyar (1969).

ADVANTAGES OF TRANSVERSE MODE SELECTION IN LASER APPLICATIONS

Transverse mode selection generally restricts the area of the laser cross section over which oscillation occurs, without altering the power emitted per unit area thus decreasing the total output power.

It reduces the beam divergence producing a diffraction-limited beam. Thus the overall effect of mode selection is generally an increase in the brightness of the laser (power/unit area/solid angle) although total power is decreased.

In many applications it is brightness rather than total emitted power that is needed. Rempel (1963) has compared in some detail the usefulness of spatially coherent sources with spatially incoherent sources for a number of applications. The same arguments may be applied to compare a transverse-mode-selected laser with an unselected laser and some of the conclusions are briefly presented here in terms of the brightness. This quantity is useful because it is an invariant in the sense that the brightness of the image formed by any optical system is the same as the brightness of the object (or light source), apart from losses due to absorption and reflection (Born & Wolf, 1965).

The maximum power per unit area that can be produced in the focal plane of an optical system (with no restrictions on focal spot size) is proportional to the brightness of the light source. Such a requirement can arise in plasma generation applications. A more common requirement of a laser is that it should be capable of producing as much power as possible in a spot whose size approaches the diffraction limit. Rempel (1963) has shown that the maximum power per unit area that can be produced within a diffraction limited spot is proportional to the brightness of the light source. Such a spot is necessary for microcircuit machining and trimming, and for drilling applications where controlled removal of extremely small areas of material is desired. The value of a single-mode laser in these microelectronic applications has been demonstrated by Cohen et al. (1968).

Another requirement commonly demanded is that the laser should be capable of producing a certain power density in the region of the focus of a lens, and that the beam spread should be small enough for this power density to be maintained over a reasonable distance. Again, brightness rather than total power determines the ability of the laser to fulfill this need. This requirement is common in non-linear optics where high power densities over paths of the order of a centimetre are necessary for efficient phase-matched second harmonic generation or parametric oscillation.

A similar requirement applies to the longitudinal laser pumping of a dye laser. Recent work by Soffer &

Evtuhov (1969) shows admirably how the high brightness of a TEM_{00}-mode ruby laser, despite modest total power (20kW), was capable of high efficiency s.h.g. ($>10\%$) and the resulting high brightness beam of second harmonic radiation was capable of producing laser oscillation in an organic dye. Similar experiments with non-mode-selected ruby lasers have used tens of megawatts of ruby power.

For holographic applications both spatial and temporal coherence are desired. Early difficulties with transverse mode selection in solid lasers meant that considerable effort was put into developing techniques for producing holograms without the need to satisfy stringent coherence requirements (Brooks et al., 1966). Jacobson & McClung, (1965) had improved coherence by mode selection of a ruby laser and had produced good holograms. At that time the small output power (as a result of transverse mode-selection) was a serious limitation. More recently, with similar laser power, La Macchia & Bjorkhom, (1968) have shown that excellent holograms can be produced with their mode-selected ruby laser. Further, with the more sensitive photographic plates that have recently become available, the present generation of mode-selected ruby lasers can be used to advantage in holography.

One further advantage of transverse mode selection is the extremely good repeatability of power and intensity distribution (e.g. Daneu et al., 1966, Bjorkholm & Stolen 1968, Ananev et al. 1969, Arnold & Hanna 1969). Thus it is possible to operate at powers close to the damage threshold of optical components such as mirrors without the risk of damage resulting from a randomly occurring pulse of excessively high power. Also carefully controlled experiments at extremely high power densities can be performed quickly and easily. This greatly strengthens the role of the solid-state laser as a scientific tool.

MODES AND RESONATORS—BACKGROUND*

Until recently it has been an almost universal practice with solid-state lasers to use a resonator consisting of two plane mirrors. An analysis of the modes of such a resonator was first carried out by Fox & Li (1961). In a companion paper Boyd & Gordon (1961) gave an analytical treatment of the modes of a special spherical mirror resonator, the confocal resonator. These analyses indicated that diffraction losses were orders of magnitude less in spherical mirror resonators compared with plane mirror resonators and the spherical mirror resonator was quickly adopted for the rather low gain gas lasers then available.

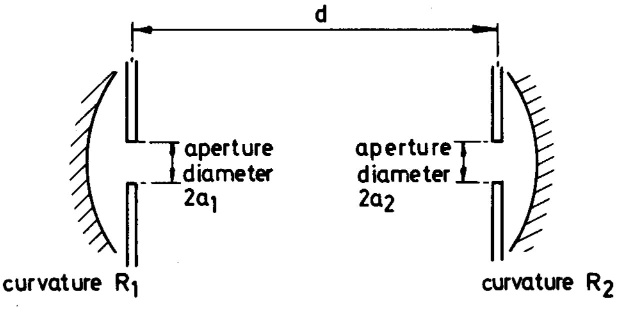
Use of plane mirrors with solid-state lasers was continued because these had gains large compared to the diffraction loss and alignment tolerances were not so severe. Two reasons have been put forward for this insensitivity to misalignment. First, the optical quality of the solid-state laser crystals was poor compared with gas lasers. Second, the thermal distortions produce a lens effect in the laser rod and this makes a nominally plane parallel resonator behave like some equivalent spherical mirror resonator with a corresponding relaxation of alignment tolerance. The evidence for the latter is now substantial (e.g. Evtuhov & Neeland, 1965, Stickley, 1966). The mode behaviour of plane-parallel solid-state laser resonators is therefore best analysed in terms of the modes of spherical mirror resonators.

Of the possible spherical mirror resonators the confocal resonator is of particular importance. It is the resonator with the greatest mode selection and secondly the properties of its modes can be expressed in a simple analytical form to a very good approximation (Boyd & Gordon, 1961). Thus the modes all have Hermite-Gaussian field distributions with spherically curved wavefronts. The lowest order mode, TEM_{00}, has a simple Gaussian field distribution.

These simple analytical properties of the modes allow an easy extension of the analysis to non-confocal spherical mirror resonators (Boyd & Gordon, 1961). Also a simple calculus was derived for these modes, based on the ray transfer matrices of paraxial geometrical optics (Kogelnik and Li, 1966). Using this calculus it is straightforward to calculate mode frequency, spot size and wave-front curvature. This can be done even for quite complicated resonators, for example resonators containing thick lenses such as thermally distorted laser rods (Stickley 1966). It also allows a simple calculation of the propagation behaviour of these beams outside the resonator as they pass through space or through various optical components. The ability to perform these calculations is invaluable to both the laser designer and user.

The diffraction loss of the modes is also of importance in the design of a single mode laser, because selection of transverse modes is made through this mechanism. The TEM_{00} mode is generally desired since it has the smallest beam divergence, and hence the highest brightness, and lowest diffraction loss. Selection of the TEM_{00} mode can therefore be achieved by arranging that the losses of higher order modes to be too great to allow oscillation whereas TEM_{00} oscillation is alowed. The laser designer must know the diffraction loss of the TEM_{00} mode and of the next lossy mode in a variety of resonator configurations.

The paper by Li (1965) is particularly useful and contains the results of calculations of diffraction



Fresnel number $N = a_1 a_2 / d\lambda$

$G_1 = [1 - d/R_1]\, a_1/a_2$

$G_2 = [1 - d/R_2]\, a_2/a_1$

Fig. 1 For two resonators having the same N, G_1 and G_2 the diffraction losses are the same for the same mode.

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* For a useful working knowledge of this field, and in particular of the elegant and useful calculus of ray transfer matrices, the reader is referred to the excellent review article by Kogelnik & Li (1966).

losses for a wide variety of spherical mirror resonators, having circular apertures, and for small enough Fresnel numbers. Although Li's results do not cover all possible spherical mirror configurations, the range can be extended with the help of certain equivalence relations (Gordon & Kogelnik, 1964). These relations show that if two resonators have the same value of N, G_1, G_2 (see Fig. 1) then they have the same diffraction losses for the same mode. These equivalence relations have also been expressed in a more general form in terms of ray transfer matrices (Baues, 1969). This allows Li's results to be extended to cover more complicated resonators such as resonators containing lenses. In practice the mode selectivity obtainable from the range of resonators directly treated by Li is sufficient for typical solid-state lasers.

PLANO-CONCAVE RESONATOR

Li has calculated the diffraction losses for the TEM_{00} and TEM_{10} modes in the symmetric resonator shown in Fig 2a for values of N down to 0.1 and for values of |g| from zero to one. We now consider the plano-concave resonator of Fig. 2b with a single aperture adjacent to the curved mirror. Provided the plane mirror is significantly larger than the lateral dimensions of the mode, any diffraction loss due to the aperturing effect of the plane mirror perimeter will be negligible. Then the double-pass diffraction loss for the plano-concave resonator of Fig. 2b is exactly the same as the single pass diffraction loss in the symmetric resonator of Fig. 2a.

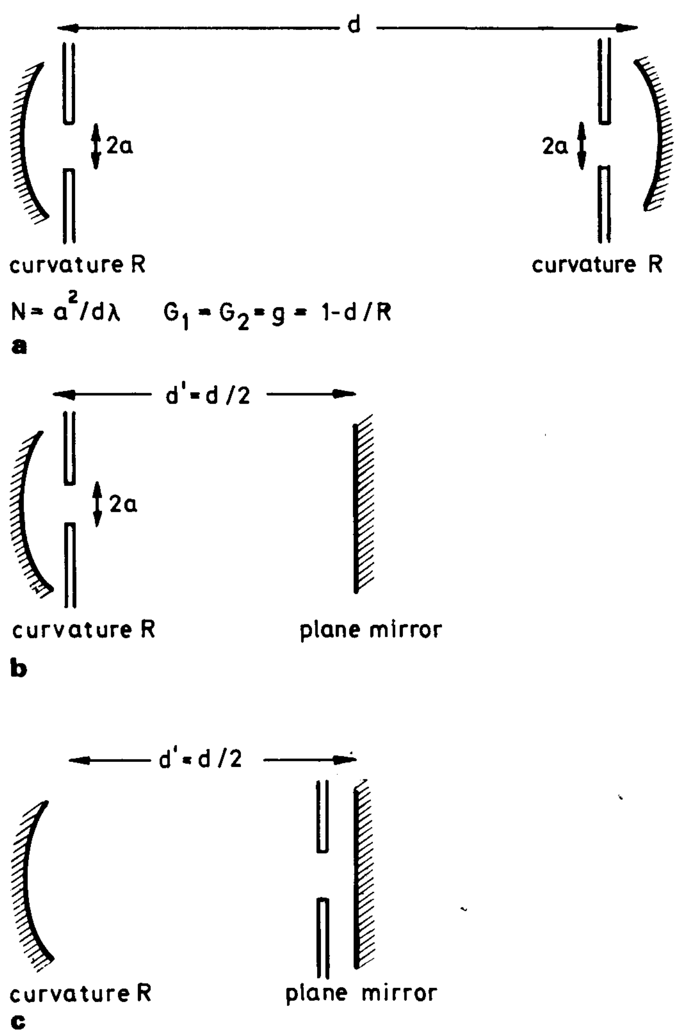

Fig. 2a Symmetric resonator. Fig. 2b Plano-concave resonator has half the diffraction loss of 2a. Fig. 2c Plano-concave resonator with single aperture adjacent to plane mirror has same mode selectivity as Fig. 2b.

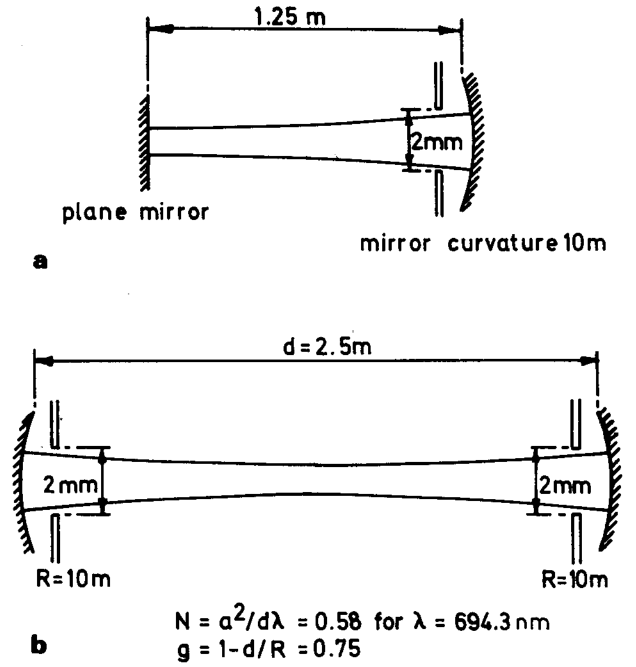

Fig. 3a Resonator used by Davis (1968) to produce TEM_{00} mode from ruby laser. Fig. 3b Related resonator—diffraction loss may be calculated from Li (1965).

The case of a plano-concave resonator with a single aperture adjacent to the plane mirror (Fig. 2c) can be treated in a similar way with the help of the equivalence relations mentioned above. The mode selectivity is exactly the same as for the resonator of Fig. 2b, i.e. for a given TEM_{00} diffraction loss, the diffraction loss of the TEM_{10} mode is the same in both configurations. To achieve the same TEM_{00} diffraction loss would involve the use of a smaller aperture in the configuration of Fig. 2c since the waist of the mode is formed at the plane mirror.

To make some of these ideas clear an example is given of a resonator configuration which has been used by L. W. Davis (1968) to produce TEM_{00} mode output from a ruby laser (Fig. 3a). The double-pass diffraction loss of this resonator is the same as the single-pass diffraction loss of the resonator shown in Fig. 3b for which the relevant parameters are $N = 0.58$ and $g = 0.75$. Knowing N and g it can be predicted from the calculations of Li (1965) that for resonator 3b the single-pass diffraction loss is ~20% for the TEM_{00} mode and ~50% for the TEM_{10} mode.

The ratio of the TEM_{10} loss to the TEM_{00} loss is generally taken as the measure of mode selectivity (e.g. Li, 1963). However it is more instructive for a Q-switched solid-state laser, in which the pulse builds up in a small number of passes, to calculate the relative intensities of the modes in the way that Sooy (1965) first discussed in connection with axial mode selection. Suppose the laser in Fig. 3a is Q-switched and 100ns elapse between the opening of the Q-switch and the peak of the giant pulse. This time corresponds to twelve round trips and following Sooy's analysis the ratio of the TEM_{00} to TEM_{10} intensities at the peak of the pulse is therefore

$$\left(\frac{100-20}{100-50}\right)^{12} \sim 300.$$

This figure arrived at in this way is a rough estimate since a number of simplifying assumptions have been made. The calculation ignores mode distortion effects which must arise as a result of a non-uniform gain distribution in the laser rod.

Mode distortion produced in this way may be regarded as a coupling of power from the TEM_{00} mode into higher order modes. Even if the gain is initially uniform the gain will eventually be depleted at the centre of the mode more than in the wings since the TEM_{00} mode has an intensity maximum at its centre. Imperfections such as bubbles and inclusions can have a drastic effect on diffraction loss if the imperfection falls within the area occupied by the mode and they ultimately limit the maximum mode size that can be achieved. In the next section it is seen that a mode diameter of ~1 mm can be readily achieved with typical laser material. Measurements of the diffraction loss of a TEM_{00} mode of ~1 mm diameter in a Nd : $CaWO_4$ laser have shown good agreement with Li's calculations (Arnold & Hanna, 1969).

To be concluded

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