# A STABLE YAG RESONATOR YIELDING A BEAM OF VERY LOW DIVERGENCE AND HIGH OUTPUT ENERGY

P.H. SARKIES
*J.K. Lasers,*
*23, Somers Road, Rugby, England*

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This paper describes a stable resonator configuration which yields 200 mJ of output energy from a $3 \times \frac{1}{4}$ YAG rod in a highly collimated beam, of divergence less than 1 mrad, (full angle 90% included energy), with a quasi gaussian amplitude profile and with the capability of working at any repetition rate up to 20 Hz without mirror realignment. This novel configuration is of a general applicability to other laser systems.

## 1. Introduction

A considerable amount of effort has been expended in the design of resonators which allow the extraction of all the stored energy from large active volumes in a beam of very low divergence. Until recently the only kind which fulfilled this requirement was the unstable resonator as discussed by Krupke [1], An-Ananev [2], and Siegman [3]. With the increasing demand for higher energies from YAG pump lasers the cost advantage of the high brightness beam furnished by the unstable YAG resonator is well recognised. However, although the output beam is a plane wave of sufficiently low divergence to allow high harmonic conversion in KD*P, (typically 90% included energy in 1 mrad or less), the hole in the middle does present problems when transversely pumping dye lasers, giving rise to multiple line focussing. Also the extremely short pulse length is not advantageous for pumping very narrow band dye lasers or OPO's. To some extent these objections may be overcome by side extraction but there still remains the very significant disadvantage of the unstable resonator that the output beam collimation is a very sensitive function of mean input power and hence repetition rate. It is thus not possible to maintain full output energy over a wide repetition rate without considerable realignment.

The purpose of this paper is to describe a resonator configuration in which all the stored energy can be extracted in a beam of very low divergence.

## 2. Resonator description

A schematic of the resonator is depicted in fig. 1. It is phase coupled and consists of two distinct portions, an output leg and a feedback leg. The output leg which is also the energy generating portion of the resonator is quite conventional and consists of a 100% plane mirror, a quarter wave plate, $3'' \times \frac{1}{4}''$ YAG rod and a dielectric plate polariser. Energy entering the output leg from the feedback leg is amplified by the YAG rod and after passing through the quarter wave plate returns to the YAG rod for further amplification before being coupled out by the dielectric polariser. The quarter wave plate is set such that 90% of the amplified beam is coupled out by the dielectric polariser and 10% returned to the feedback leg to sustain oscillation.

The feedback leg consists of a Pockels cell, a telescope of magnification $M$, an aperture $A$, and a 100% mirror of 5 metre radius separated from the aperture $A$ by a spacing $L$. The feedback leg acts as a transverse mode filter on the circulating energy before returning it to the energy generation leg for amplification and output.

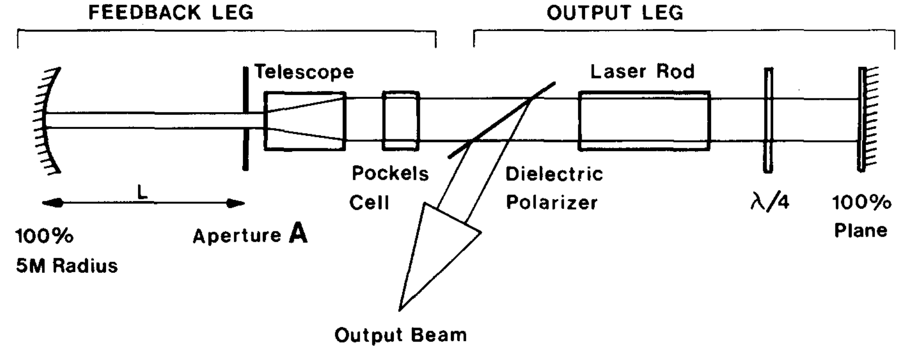


Fig. 1. Schematic layout of phase coupled resonator.

The telescope performs two distinctly separate functions. Firstly it reduces the size of the beam to increase the diffraction per unit length. Since the beam size on the input side is always the same as the rod diameter the diffraction is constant and dependent only on the telescope magnification. Aperture $A$ was set to be $D/M$ where $D$ is the rod diameter. Secondly the telescope is an element of variable focal length. It can therefore be adjusted to place the resonator anywhere on the stability diagram. Because the ratio of the diffraction losses of the higher order modes to the lower order modes increases as the modulus of the trace of the ray matrix approaches 1, (Kogelnik and Li [4]), the telescope can be adjusted to ensure that modes above a certain order do not reach threshold. Thus the mode selection process is controlled by two telescope parameters, the magnification $M$ and the focal length $f$. Clearly sufficient mode selection can be achieved by either parameter alone, but, on the one hand too high a magnification may result in a very high power density in the feed back beam which could exceed the damage threshold of the components. On the other hand too much bias introduced by the telescope could result in a laser threshold that is very high. Thus the correct balance must be established to ensure optimum operation.

The telescope also introduces the additional feature of making the rear mirror less sensitive to misalignment by a factor of $M$.

## 3. Experimental

A conventional phase coupled resonator was set up, that is a resonator without the telescope and aperture but otherwise the same as in fig. 1 and aligned for maximum output. A ×3 galilean telescope was set up for normal adjustment at 650 nm with an autocollimator. The focal length of the telescope versus deviation from normal adjustment was then determined with a series of mirrors of known radius of curvature. A correction was then made using refractive index data to convert the results to 1060 nm, and the telescope was then inserted to give a diffraction length of 50 cm corresponding to aperture $A$ seeing one Fresnel zone of itself in the rear mirror. Only the adjustments on the telescope were used to reoptimise the resonator.

Referring to table 1 it can be seen that for a constant input of 18 J the optimum output of 200 mJ occurred when the telescope had a focal length of 25 m. The focal length of the rod at this input due to thermal lensing was 7.7 m. From table 1 it can be seen that as the telescope focal length was adjusted

Table 1
Summary of experimental results for diffraction length $L$ = 50 cm

| Telescope focal length ($f_2$) [m] | Output for 18J input [mJ] | Energy contained within 1 mrad [%] | $T/2$ |
|---|---|---|---|
| −6.25 | 165 | 91 | 0.61 |
| −16.6 | 180 | 90 | 0.43 |
| 25.0 | 200 | 92 | 0.26 |
| 7.7 | 160 | 93 | 0.12 |
| no telescope | 210 | 17 | 0.33 |

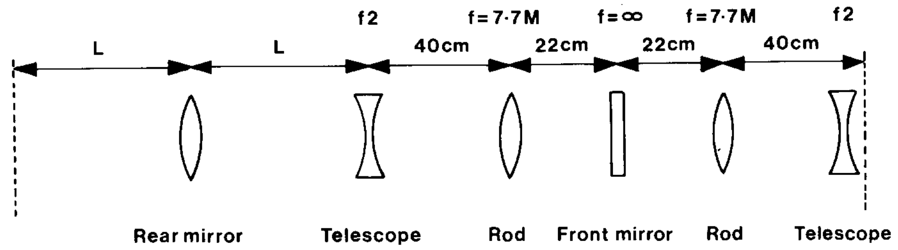


Fig. 2. Equivalent sequence of lenses for resonator shown in fig. 1. The telescope and laser rod have been approximated by lenses situated at the centre of the real elements. The values of $f_2$ and $L$ are given in tables 1 and 2.

from −6.25 m to +7.7 m the beam divergence remained essentially constant. The output energy dropped by 10–20% either side of optimum. Calculation of the ray matrix for the equivalent cavity depicted in fig. 2 shows that in all positions $-1 \leqslant T/2 \leqslant 1$ where $T$ is the trace of the matrix. The resonator is therefore always stable. The value of $T/2$ varies from 0.6 to 0.11 with the total excursion of the telescope with little change in beam divergence. With no telescope $T/2 = 0.33$, but the beam divergence is now 4 mrad. Thus with the 50 cm feedback leg the mode selection is predominantly due to diffraction and the position of the resonator within the stability region i.e. the value of $T/2$, has no significant effect.

Table 2 shows similar results with a 5 cm feedback leg. For this case the focal length of the telescope has a very marked effect on beam divergence. The lowest being obtained with the largest $T/2$. The largest beam divergence is 3.5 mrad and was obtained with the lowest $T/2$ of 0.42. This agrees well with the slightly larger beam divergence obtained with no telescope and a $T/2$ of 0.33. With this feedback leg mode selection is primarily due to the telescope focal length and the position of the resonator within the stability region determined the beam divergence of the output beam.

No gross variation of pulse length with telescope adjustment could be found. The difference in the pulse lengths obtained in each case was due solely to the difference in cavity length and was 15 ns for the 50 cm feedback leg and 11 ns (lower case) for the 5 cm one.

The reduction in output energy as the telescope is adjusted from its optimum position is probably partly due to the mirror curvature of the 100% plane mirror not being correct to extract all the stored energy. Ideally it should be convex to ensure that the incident and reflected beam both fill the rod.

Table 2
Summary of experimental results for diffraction length $L$ = 5 cm

| Telescope focal length ($f_2$) [m] | Output for 18J input [mJ] | Energy contained within 1 mrad [%] | $T/2$ |
|---|---|---|---|
| −6.25 | 185 | 85 | 0.78 |
| −16.6 | 190 | 57 | 0.66 |
| 25.0 | 190 | 25 | 0.53 |
| 7.7 | 200 | 20 | 0.42 |

Fig. 3 shows the amplitude profile of the output beam for the optimum position of the telescope with the 50 cm diffraction leg. Although not gaussian it is considerably smoother than from an unstable resonator and its precise shape is dependent on the diffraction leg length and telescope magnification $M$. It is however most strongly dependent upon the laser rod, the thermally-induced birefringence considerably distorting the phase front of the wave, and, in combination with the polariser the amplitude distribu-

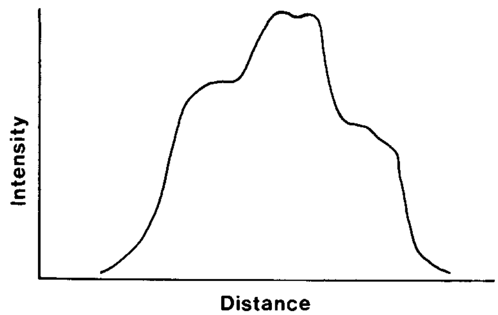


Fig. 3. Near field intensity profile of output beam.

tion as well. This birefringence ensures that it is not possible to obtain a full aperture uniphase gaussian beam from any YAG laser resonator. The output amplitude may be smooth but it is not possible for the phase front to be uniphase. Also this phase and amplitude distortion is considerably greater in the side exit resonator where the radiation executes a double pass of the rod before being coupled out. Fortunately however the mode selection concept is also applicable to in line configurations and these are being studied at the present time.

One very interesting feature of this type of resonator is that the irreducible beam divergence is tunable. The extent over which it may be varied is dependent on the ratio of diffraction to telescope adjustment being used to control the mode selection. This is extremely useful in experiments where the YAG output beam or its harmonics are mixed with the output from another laser, (as in the case of a co-linear CARS experiment for example) because not only can the beam waist at the focus of a lens be matched but also their "confocal parameters" thus ensuring overlap over a considerable distance rather than just in the immediate vicinity of the beam waists. This could greatly enhance the efficiency of these experiments.

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