A 200 mJ UNSTABLE RESONATOR Nd:YAG OSCILLATOR

R.L. HERBST, H. KOMINE and R.L. BYER
Applied Physics Department, Edward L. Ginzton Laboratory, W.W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305, USA

Received 21 January 1977

We have designed and operated a positive branch 6.3 mm diameter rod Nd:YAG unstable resonator oscillator with a 12 nsec, 200 mJ Q-switched output at 10 Hz repetition rate. When followed by a single 9 mm diameter Nd:YAG amplifier output energies up to 750 mJ were obtained with a divergence less than 0.5 mrad.

Unstable resonators offer the advantage of obtaining diffraction limited output from a large volume, high gain laser medium. The design and theory of unstable resonators has been reviewed and extended since their introduction by Siegman [1]. However, to date experimental work has been primarily limited to CO_2 lasers [2,3] and to Nd:Glass laser–amplifier systems [4], although a negative branch Nd:YAG unstable oscillator has been investigated [5].

We report the design and operation characteristics of a positive branch Nd:YAG unstable resonator. The output energy and mode stability of the Nd:YAG unstable resonator oscillator is considerably improved over an equivalent stable resonator configuration. The Nd:YAG oscillator has been used in a series of nonlinear optical experiments to further illustrate the stability and quality of the output beam. We note that the high gain of Nd:YAG makes it an ideal medium for use in unstable resonators where optimum cavity design usually leads to high output coupling.

Fig. 1 shows a schematic of the Nd:YAG unstable resonator oscillator. In designing the confocal positive branch resonator we have included the thermal focussing effect of the Nd:YAG rod. Our measurements of Nd:YAG rod focal length f in meters versus average lamp input power P in kW is closely approximated by $f(\mathrm{m}) = 2.1/P(\mathrm{kW})$. This focal length expression applies to a 6.3 mm diameter 0.7% Nd doped rod pumped by a 7 mm diameter xenon flashlamp within a gold plated single ellipse cavity and is in agreement with previous results [6–8].

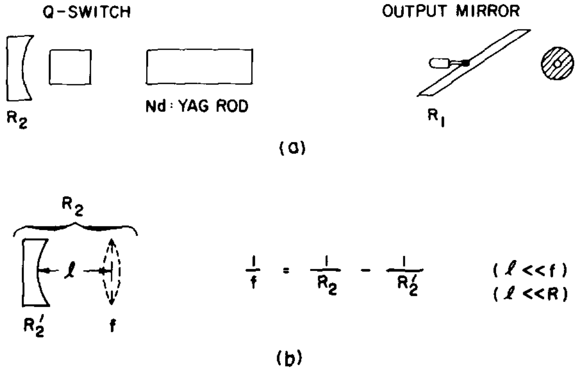

Fig. 1. (a) Schematic of the confocal unstable resonator cavity with a KD^*P electro-optic Q-switch, 6.3 mm diameter 50 mm long Nd:YAG laser rod and 1.8 mm diameter output mirror. For this cavity $R_2 = 300$ cm, $R_1 = -50$ cm and $M = 3.3$ giving an output coupling $\delta = 83\%$. (b) Effective mirror radius of curvature R_2 fir due to combination of geometrical curvature R_2' and Nd:YAG rod focal length f.

The design of the unstable resonator is complicated by interdependence of the cavity length, output coupling, rod diameter, and mirror radii of curvature. Since the cavity length and output coupling are conveniently varied, we chose we fix the Nd:YAG rod diameter and mirror radii of curvature at standard values.

The mirror radii of curvature for the positive branch confocal cavity are $R_1 = -2L/(M-1)$ and $R_2 = 2ML/(M-1)$ where L is the empty cavity length, R_1 and R_2 are the output and back cavity mirror curvatures and M is the magnification which is the ratio of the rod diameter to the output mirror diameter. The geometrical output coupling is $\delta = 1 - 1/M^2$. In practice diffraction effects reduce the output coupling to values slightly less than δ if the cavity is designed to operate at equivalent Fresnel numbers

$$N_{eq} = \frac{M-1}{2M^2}\frac{D^2}{4L\lambda}, \qquad (1)$$

with values of 0.5, 1.5, 2.5, ... [1].

In designing the cavity we chose to eliminate M from this equation using the above relation $M = 1 + 2L/|R_1|$ and to solve for the cavity length given by

$$L = -\tfrac{1}{2}|R_1| + \tfrac{1}{4}D\left(\frac{|R_1|}{\lambda N_{eq}}\right)^{1/2},$$

where D is the laser rod diameter. The geometrical value for R_2 is given by the above relation for a given value of M and L.

As a final step we introduce the effect of the Nd:YAG rod focal length f as shown schematically in fig. 1b. We choose an available mirror curvature R_2' and calculate the Nd:YAG rod focal length required to achieve an effective mirror curvature equal to R_2. If the mirror to rod distance l is less than the rod focal length, then $1/f = 1/R_2 - 1/R_2'$ holds to a good approximation. Of course R_2' is chosen such that f corresponds to the desired average input lamp power.

As an example, with $R_1 = -50$ cm (convex) radius and $N_{eq} = 1.5$ we find that $L = 64$ cm and $R_2 = +178$ cm (concave) at $M = 3.53$. The geometrical output coupling is 92% but the output coupling including diffraction effects is 84%. For the 6.3 mm rod diameter the magnification dictates a 1.8 mm diameter output mirror. Operating at an input lamp power of 500 W (50 J at 10 pps) gives a rod focal length near 437 cm which leads to a standard 300 cm (concave) back mirror curvature. Our measurements were made using a cavity of this design.

The output mirror was carefully ground to 1.80 mm diameter, coated for high reflectivity at 1.06 μm and then cemented to a 1 mm post which was held in a Brewster angle window. The cavity was aligned using a helium neon laser incident through mirror R_2. The alignment tolerance of the output mirror was measured to be 24 μrad for 10% output power variation. Off axis transverse modes occurred symmetrically at output mirror tilts of ±1.36 m rad so that the cavity exhibited good mode selection.

The output beam pattern is a 6.3 mm diameter spot with a 1.8 mm diameter hole. In the near field the Fresnel diffraction rings from the rod and output mirror apertures are evident; In the far field the beam converts to a modified Airy disk pattern with the fraction of energy in the central lobe equal to the fractional output coupling.

The Q-switched oscillator output energy versus input energy to the flashlamp is shown in fig. 2. We have operated the oscillator at up to 250 mJ output energy but normally operate between 150 to 200 mJ. For 200 mJ input energy without beam expansion into a 9 mm amplifier rod at 90 J lamp energy we have measured 750 mJ output energy. All measurements have been taken at our usual operating repetition rate of 10 pps.

The output 1.06 μm beam quality was investigated by a series of nonlinear interactions. The half angle beam divergence was determined to be 0.5 m rad by noting the acceptance angle for SHG in a 3 cm long Type II KD*P crystal. With the 3 cm long Type II

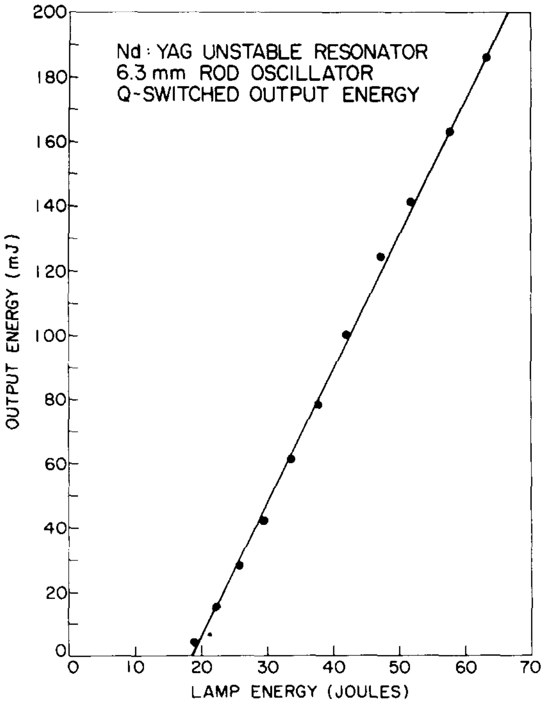

Fig. 2. Unstable resonator Q-switched output energy versus lamp input energy at 10 pps for a 6.3 mm diameter Nd:YAG oscillator.

KD*P crystal 30 mJ of 0.532 μm was generated using 150 mJ unfocussed input energy. The 0.532 μm was summed with 1.06 μm in a second KD*P crystal to generate 12 mJ at 0.3547 μm and doubled in ADP to give 10 mJ at 0.2660 μm. The angle phasematched harmonic processes are convenient to align and remain stable for hours of operation.

We have directly pumped a $LiNbO_3$ parametric oscillator at 1.06 μm with both the oscillator and oscillator/amplifier system [9,10]. The threshold energy with the unstable resonator was reduced compared to an equivalent gaussian beam pump. The parametric oscillator tunes over a 1.4 to 4.3 μm range and operates at the expected 20% energy conversion efficiency at three times above threshold [11].

Finally, in order to compare the unstable resonator performance to a stable resonator, we operated the 6.3 mm diameter Nd:YAG oscillator with a beam expansion telescope in order to fill the rod with the TEM_{00} mode. The equivalent two mirror cavity is a 400 m versus a flat so that rod focussing is critical. By carefully adjusting the lamp power and telescope we were able to obtain 50 mJ of output energy with close to TEM_{00} mode output. The cavity was significantly more stable with a 2 mm diameter aperture at an output energy of 20 mJ. This experiment clearly demonstrates the advantage of an unstable resonator for energy extraction from large mode volume high gain lasers and for Nd:YAG in particular.

In conclusion, we have operated two unstable resonator Nd:YAG lasers on a daily basis for over four months at near 200 mJ output energy at 10 Hz repetition rate. An oscillator/amplifier has operated for the same period with output energies near 750 mJ. The increased output energy at low beam divergence available from the positive branch confocal unstable resonator Nd:YAG system considerably enhances its usefulness as a laser source.

Acknowledgements

We wish to acknowledge the support of LASL and AFOSR in this work and helpful discussions with Professor A.E. Siegman.

References

[1] A.E. Siegman, Proc. IEEE, Vol. 53 (1965) p. 277; see also Laser Focus (May 1971) p. 42, Appl. Optics 13 (1974) 353; and IEEE J. Quant. Elec. QE-12 (1976) 35.

[2] W.F. Krupke and W.R. Sooy, IEEE J. Quant. Elec. QE-5 (1969) 575.

[3] P.E. Dyer and D.J. James, Appl. Phys. Letters 26 (1975) 331.

[4] Yu.A. Anan'ev, N.A. Sventsitskaya and V.E. Sherstobitov, Sov. Phys. JETP 28 (1969) 69;
Yu.A. Anan'ev, G.N. Vinokurov, L.V. Koval'chuk, N.A. Sventsitskaya and V.E. Sherstobitov, Sov. Phys. JETP 31 (1970) 420;
Yu.A. Anan'ev, N.I. Grishmanova, I.M. Petrova and N.A. Sventsitskaya, Sov. J. Quant. Electron. 4 (1974) 689.

[5] T.F. Ewanizky and J.M. Craig, Appl. Optics 15 (1976) 1465.

[6] J.D. Foster and L.M. Osterink, J. Appl. Phys. 41 (1970) 3656.

[7] T. Kimura and K. Otsuka, IEEE J. Quant. Elec. QE-7 (1971) 403.

[8] W. Koechner, Appl. Optics 9 (1970) 2548.

[9] R.L. Herbst, R.N. Fleming and R.L. Byer, Appl. Phys. Letters 25 (1974) 520.

[10] R.L. Byer, "Parametric Oscillators", published in Tunable Lasers and Applications, Eds. A. Mooradian, T. Jaeger and P. Stokseth (Springer-Verlag, Berlin, 1976) p. 70–80.

[11] R.L. Byer, R.L. Herbst and R.N. Fleming, "A Broadly Tunable IR Source", published in Laser Spectroscopy, Eds. S. Haroche, J.C. Pebay-Peyroula, T.W. Hansch and S.E. Harris (Springer-Verlag, Berlin, 1975) p. 207–225.