OPTO-ELECTRONICS 3 (1971) 163–169

A Two-Step Q-Switching Technique for Producing High Power in a Single Longitudinal Mode

D. C. HANNA, B. LUTHER-DAVIES, H. N. RUTT, R. C. SMITH
Department of Electronics, The University of Southampton, Southampton, UK

Received 8 October 1971

An electro-optic Q-switch has been opened in two steps to allow slow pulse build-up giving, in conjunction with a resonant reflector, a high degree of mode selection in a way analogous to the use of saturable absorbers. Using this technique, a flash pumped Nd:$CaWO_4$ laser has produced reliable operation in a single longitudinal and transverse mode with an output power of 250 kW.

1. Introduction

The production of high power pulses of single frequency radiation is a prerequisite for many laser applications in holography and non-linear optics. In low power, low gain lasers it is found that relatively simple procedures, such as introducing an etalon (often uncoated) into the cavity [1-4], are effective in restricting oscillation to a single longitudinal mode. In conventional actively Q-switched high power lasers the net gain after switching is so large that typically only a few tens of cavity transits are needed for the build-up from noise to the peak output power. To obtain single longitudinal mode output from such a laser would require mode selecting devices with a frequency selectivity which is extremely difficult to realise in practice.

By deliberately lengthening the build-up time to allow more transits through the mode selector, simple devices such as resonant reflectors can offer sufficient selection to provide single mode output. With ruby lasers considerable success has been obtained in this way using saturable absorber Q-switches such as the phthalocyanine and polymethine dyes [5-8]. Sooy has shown theoretically [9] and Daneu *et al* [7] have confirmed experimentally that these dyes give build-up times of several hundred cavity transits, and thus lead quite readily to single frequency output. For neodymium doped lasers however, the choice of saturable absorbers is more restricted and those available suffer from chemical degradation which becomes a serious problem even at modest repetition rates. For ruby lasers the use of saturable absorbers at these repetition rates is rather unsatisfactory since heating of the dye solution leads to considerable turbulence. A logical step is therefore to use an active Q-switch but to switch it in a way that ensures a large build-up time. McMahon [10] has gone some way towards this by using a slowly opening Faraday rotation Q-switch with a ruby laser and did indeed find a narrowed spectral output (in good agreement with Sooy's theory) although it was far from being single mode. A Pockels cell Q-switch is much more convenient and it lends itself to a much more rapid, and therefore more easily controlled, switching behaviour. In this paper we report the use of such a Q-switch with Nd:$CaWO_4$ and Nd:YAG lasers. Switching is in two stages; firstly to a level just above threshold where it is held until a single mode is established; in the second stage the switch is completely opened to allow this mode to build up to maximum power. With a two-plate resonant reflector this technique has led to a single frequency TEM_{00} power of 250 kW.

2. Design Considerations

Sooy has shown that in an actively Q-switched laser, after N cavity round trips (provided the total laser power is still below the level at which the gain begins to saturate), the ratio of the powers in any two modes is G^N where G is the ratio of the loop gains. Since a number of modes may be above threshold, we have adopted as our definition of "single mode operation" the situation where one mode is at least ten times greater in intensity than any other. Thus for our technique a frequency selective element is required and a two-step Q-switch permitting at least N round trips during pulse build-up such that $G^N > 10$ for all modes, where G is the ratio of the gain of the dominant mode to that of any other mode.

For high power solid-state lasers a resonant reflector (RR) is a frequency-selective element which can be simple, robust and damage resistant. Examination of the typical values of G that can be obtained from a practical RR leads to a value of N which must be achieved in order to satisfy the condition $G^N > 10$ for all modes. To illustrate the basic design principles a particular RR is considered (the one we have used in our experiments), and a particular laser (Nd:$CaWO_4$). With only slight changes the same figures can be applied to Nd:YAG or ruby lasers. There is considerable choice available for a number of parameters, e.g. number of plates in the RR, materials used in the RR, types of electro-optic Q-switch, etc., and the system we have used is not claimed to be an optimum one as far as these parameters are concerned. Indeed, in some respects, our laser has not been operated under the conditions indicated by these design considerations and the RR, which was obtained before the design study was made, is known to be less convenient to tune than a somewhat different design. However, the experimental results do show that by keeping roughly to the design principles outlined here it is possible to achieve high power in a single mode.

3. Resonant Reflector

Hercher [5] and Watts [11] have described RR's having plates which are much thinner than the spacer. The frequency selection properties of this type of RR can be seen from figs. 1 and 2. In fig. 1 the computed reflectivity at 1.06 μm is shown for the RR we used, a two-plate reflector having plate thickness 2.5 mm, both plates of Schott BK7 glass and of identical thickness, and a spacer also of BK7 glass having a thickness of 25 mm. The spacing of the fine-structure peaks is essentially determined by the spacer thickness (spacing $\sim 1/(2\,\mu l)\,\text{cm}^{-1}$ where μ is the refractive index of air, l is thickness in cm) and the envelope

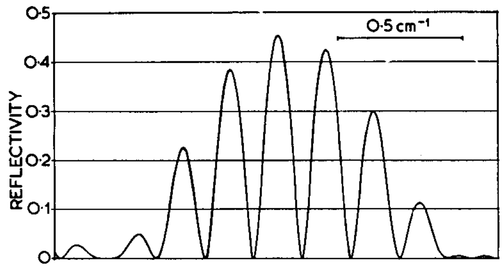

Figure 1 Theoretical reflectivity of two plate resonant reflector at 1.064 μm.

is essentially determined by the thickness of the plates (spacing of envelope peaks $\sim 1/(2\,nt)\,\text{cm}^{-1}$ where n is the refractive index of the plates and t their thickness in cm). Fig. 2 shows schematically the position of the resonant reflector peaks relative to the laser gain profile and in the expanded inset of fig. 2, the position of the "comb"

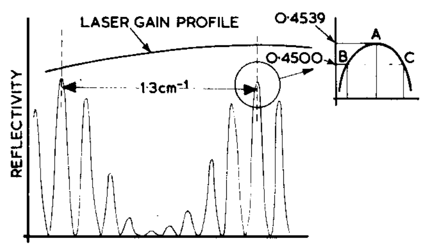

Figure 2 Ideal positioning of resonant reflector peaks relative to the laser gain profile and resonator axial modes.

of mode frequencies (for a 75 cm cavity) relative to the highest of the fine structure peaks of the RR. This type of RR is seen to be characterised by narrow fine structure peaks, close together but having widely differing reflectivities. Good frequency discrimination between fine structure peaks therefore exists. In addition the highest of the fine structure peaks are widely separated so that the laser gain profile can give good frequency discrimination between these (at least for Nd:YAG, Nd:$CaWO_4$ and ruby).

The ideal experimental situation is therefore where the following conditions are achieved:

(i) A coarse peak of the reflectivity envelope (see fig. 2) lies at the centre of the laser line.
(ii) The highest fine structure peak is at the centre of this envelope peak.
(iii) A longitudinal mode frequency is at the centre of this fine structure peak.

The last of these conditions is the most difficult to achieve since it requires that the laser resonator length be controlled to much better than $\lambda/4$. A change of resonator length by $\lambda/4$ will shift the axial mode frequencies by half the intermode spacing. This could lead to two modes being symmetrically disposed either side of the fine structure peak thus allowing oscillation on these two modes at equal powers. In our laser no attempt was made to control overall cavity length to avoid this situation, but in practice it was found that it only occurred rather infrequently.

Conditions (i) and (ii) can be controlled by variation of the temperature of the resonant reflector. The temperature change ΔT required to shift an envelope peak at wavelength λ by an amount equal to the spacing between envelope peaks is given by Peterson and Yariv [12] as

$$\Delta T = \frac{\lambda}{2nt\left(\frac{1}{t}\frac{dt}{dT} + \frac{1}{n}\frac{dn}{dT}\right)} \cdot \quad (1)$$

For $\lambda = 1.06$ µm, $t = 2.5$ mm, and using the glass manufacturers' data (20 to 40° C) of $(1/n)(dn/dT) = 0.86 \times 10^{-6}/°$ C, $(1/t)(dt/dT) = 7.1 \times 10^{-6}/°$ C, $n = 1.507$ (BK7), then $\Delta T = 17.7°$ C.

Similarly the temperature change required to shift a fine structure peak by an amount equal to the spacing between fine peaks is:

$$\Delta T = \frac{\lambda}{2\mu l\left(\frac{1}{l}\frac{dl}{dT} + \frac{1}{\mu}\frac{d\mu}{dT}\right)} \cdot \quad (2)$$

For a given temperature change the ratio of the frequency shift of a coarse peak to the frequency shift of a fine structure peak is thus:

$$\frac{\frac{1}{t}\frac{dt}{dT} + \frac{1}{n}\frac{dn}{dT}}{\frac{1}{l}\frac{dl}{dT} + \frac{1}{\mu}\frac{d\mu}{dT}} \cdot \quad (3)$$

From the expression 3 can be seen the disadvantage (from the point of view of achieving frequency tuning by temperature control), of having end plates and spacer made of the same material. Thus if $(1/t)(dt/dT) = (1/l)(dl/dT)$ and since $(1/n)(dn/dT)$ and $(1/\mu)(d\mu/dT)$ are typically much less than $(1/t)(dt/dT)$ it follows that the ratio in (3) is approximately unity. It is then more difficult to satisfy simultaneously conditions (i) and (ii) since the fine structure peaks and the envelope move at approximately the same rate. It may be necessary to tune in temperature over more than one spacing of the envelope peaks before the fine structure peaks have moved sufficiently relative to the envelope to be able to satisfy (ii). To this extent the RR we used was not ideal and a better design would have a spacer made of fused silica since $(1/l)(dl/dT) = 0.4 \times 10^{-6}/°$ C for this material. A RR using BK plates and a fused silica spacer of the same dimensions as our RR would then show a temperature tuning behaviour in which the envelope peaks moved ~8 times more quickly than the fine structure peaks. Conditions (i) and (ii) can then be satisfied by temperature tuning the envelope peak onto the fine structure nearest the laser line centre.

Schotland [13] has used such a resonant reflector with a passively Q-switched ruby laser. The temperature was varied to set the end plate optical thickness and then at a fixed temperature the air pressure was varied so as to change the air space optical thickness and thus tune the fine structure peaks. Pressure tuning is attractive since it can be adjusted much more rapidly than temperature, and this allows successive laser shots to be tuned rapidly to new frequencies and also makes continuous frequency tuning simpler since conditions (i) and (ii) can be met separately [14]. However, if the desired application of the RR is simply to produce single mode without control of absolute frequency then temperature tuning alone is quite sufficient. Some form of control is desirable to prevent drift away from single mode operation due to atmospheric pressure changes, although these are generally slow enough to be compensated for by temperature control, i.e., by shifting the envelope peak onto the new position of the fine structure peak.

When conditions (i) and (ii) have been met it can now be shown that the number of passes N during build-up to achieve $G^N > 10$ is determined essentially by the need to suppress modes adjacent to the dominant mode. This is because the frequency discrimination (due to the laser line shape) between adjacent envelope peaks and the frequency discrimination between adjacent fine structure peaks (due to their different reflectivities) are both much greater than the discrimination between adjacent modes. The inset of fig. 2 shows a mode (A) at the centre of the fine structure peak. By choosing N such that $G^N > 10$, where G is the ratio of the gains of mode A and mode B (see fig. 2) with mode A at the peak, it follows that even if mode A drifts away from the peak then at the worst two-mode operation will occur. Thus if mode C drifts towards the peak, mode C may oscillate as well as A, but the ratio of gains of A to B has then increased so that B does not oscillate. From fig. 2 it is seen that $G = 1.009$ when mode A is at the peak. To satisfy $G^N > 10$ then requires $N = 260$, or for our 75 cm cavity, a build-up time of 1.3 μs.

4. Control of Build-up Time

To obtain some specific, long build-up time requires that the cavity loss be switched to give a particular loop gain close to unity. One factor which limits the maximum length of build-up which can be attained with an electro-optic Q-switch is the appearance of piezoelectric effects. Hilberg and Hook [15] reported that such effects occur in KD*P immediately after switching the applied voltage but our experience has been similar to that of Christmas and Wildey [16] who observed a delay of ~2 μs before their onset. For this reason the first stage of Q-switching to a level just above threshold, has been limited in our laser to a maximum of 1 μs. Since the laser cavity length could not be shortened below 75 cm it has not been possible to achieve the required 260 round trips. A shorter cavity would also have been an advantage in providing a larger ratio G between adjacent mode gains. Another important factor limiting the build-up time is the fluctuation in gain in the laser rod from shot to shot, due to varying output from the flashlamp. Significant variation may still be present even if the total emission of the lamp is extremely repeatable since the intensity distribution of the discharge may vary in a random way.

5. Experimental

The laser resonator and the method used to analyse the frequency structure of the output are shown in fig. 3. A 76 × 6.4 mm A.R. coated Nd:$CaWO_4$ laser rod was used. Some preliminary results were obtained with a Nd:YAG rod and were similar to those for Nd:$CaWO_4$. However, for our particular application of pumping a proustite parametric oscillator [17] it was decided to use the Nd:$CaWO_4$ because of the longer pulses that could be produced. The rod was pumped at 2 pps by a 76 mm linear xenon-filled flash-tube giving an approximately rectangular pulse, 120 μs long, at an input energy of 90 J. The rod was cooled by a water solution of potassium dichromate to prevent solarisation, but no special precautions were taken to control its temperature.

Plane reflectors were used and a 2 m convex lens was added to the resonator to control the size of the TEM_{00} mode. Selection of the TEM_{00} mode was achieved by means of a circular aperture. Operation on the lowest order transverse mode was confirmed by scanning across the beam with a slit and a vacuum photodiode. The transverse field distribution was found to fit a Gaussian distribution very closely, both in the near field and far field. At the resonant reflector, the spot size (the radius of the $1/e$ electric field contour) was measured to be 0.59 mm. The calculated size was 0.65 mm, the difference being probably due to lenslike thermal distortion of the laser rod.

Q-switching was produced by a KD*P electro-optic shutter and a calcite block as polariser. The calcite block was 25 mm long, with the optic axis at 45° to the beam axis and polarisation selection accomplished by double refraction walk-off of the extraordinary beam. The z-cut KD*P crystal was a 25 mm cube with 9.5 mm aperture ring electrodes and was immersed in a fluorocarbon index matching liquid between A.R. coated windows. The RR was surrounded by a water tank whose temperature was controlled to within ± 0.025° C and the end plates were protected from draughts. Temperature changes were made very slowly (at < 0.2° c/min) to reduce thermal gradients within the RR.

The required two-step Q-switching waveform is shown in fig. 4a and the circuit which produced this waveform in fig. 5. The quarter-wave voltage

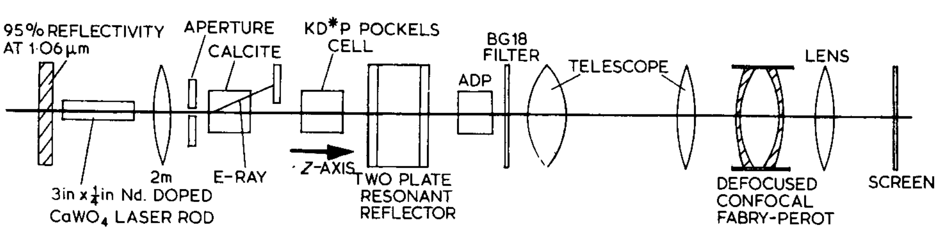

Figure 3 Arrangement of laser resonator and frequency analysis equipment.

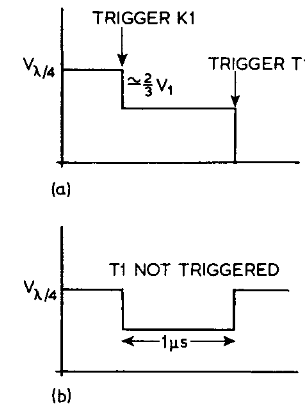

Figure 4(a) and (b) Q-switch waveforms.

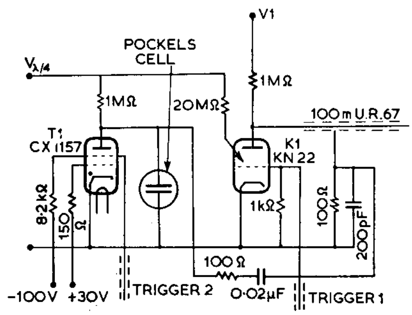

Figure 5 Circuit of double Q-switch drive.

$V_{\lambda/4}$ varied slightly across the aperture of the cell, being 3.4 kV (for 1.06 μm) at the centre of the aperture. Voltage V_1 (see fig. 5) could be varied from 800 V to 2.5 kV. Krytron K_1 (E.G. & G. Type KN22) was triggered 110 μs after initiation of the pump pulse (120 μs long) and the triggering of the thyratron T_1 (English Electric CX1157) could be delayed between 0 and 1 μs after the Krytron trigger. By triggering T_1 only, the circuit acted as a conventional fast Q-switch. By triggering K_1 only, the waveform shown in fig. 4b was produced and this mode of operation was found useful in our setting up procedure. The trigger pulses for K_1 and T_1 were derived from avalanche transistor Marx banks [18] which delivered 1 kV pulses with 2 ns rise-time. When T_1 was triggered the fall-time of the voltage across the cell was $\sim$5 ns, but the fall generated by K_1 was deliberately slowed by the capacitor C_1 to $\sim$40 ns to avoid any overshoot.

The time behaviour of the output was observed using an ITT F-4000 S1 bi-planar vacuum photodiode and a Tektronix 519 oscilloscope giving a combined risetime of $\sim$0.6 ns.

Two Fabry-Perot (F P) interferometers have been used to observe the spectral structure; for low resolution a Hilger and Watts plane parallel F P with aluminised flats, of free spectral range 0.71 cm^{-1} and finesse $\sim$15; for high resolution a defocused confocal F P with a free spectral range of 0.1 cm^{-1} and a finesse > 20 [19]. This latter instrument readily resolved the laser longitudinal modes which were separated by 0.007 cm^{-1}. To avoid using an image converter or I.R. film the second harmonic of the laser beam was used to illuminate the interferometers. Ample second harmonic for this purpose was generated by passing the unfocused laser beam through a 1.5 cm phase-matched ADP crystal. The green output was expanded or diverged as appropriate before entering the interferometer and the F P rings were recorded on Ilford Pan-F film.

Some care must be exercised in interpreting these second harmonic spectra when more than one mode oscillates. If q modes are oscillating there are 2q − 1 frequencies present after passing through the harmonic generator because all sum frequencies are phase-matched. Our main interest has been to distinguish between the cases of single mode and two mode oscillation. It can be shown that two modes at frequencies ω_1 and ω_2 with intensities in the ratio x:1 will produce sum frequencies $2\omega_1, \omega_1 + \omega_2, 2\omega_2$ with intensities in the ratio $x^2{:}4x{:}1$. This effect must be borne in mind when examining interferograms showing three equally spaced rings. Two adjacent rings much stronger than the third imply the presence of one strong mode and one weak mode whilst one strong ring with a weak ring either side imply the presence of two modes of roughly equal intensities.

A convenient setting-up procedure has been developed for adjusting the double Q-switch. With the laser conventionally Q-switched, (i.e. with T_1 triggered but not K_1), all normal alignment and optimisation procedures were carried out to obtain reliable high power operation of the TEM_{00} mode and the RR temperature was adjusted to give minimum bandwidth. The trigger to T_1 was then removed and the waveform of fig. 4b was applied. This led to a reduction of cavity loss for a period of 1 μs and the amount of this reduction was controlled by varying V_1. V_1 was adjusted so that a weak laser pulse always appeared during this 1 μs. In fact the timing of this weak laser pulse was then found to jitter between 800 ns and 1 μs. The trigger to T_1 was then reconnected and its timing adjusted to occur 800 ns after K_1 had triggered, that is just before the time at which a weak pulse could appear. This jitter of the weak pulse timing was due to random variations of the loop gain from pulse to pulse and has limited the length of build-up time that could be obtained. Knowing the power of this weak pulse it is estimated that the cavity round trip gain during the slow build-up varied by $\sim \pm 2\%$ from pulse to pulse.

6. Results

When conventionally Q-switched (T_1 only triggered), the delay between Q-switching and the peak of the output was $\sim$70 ns. A preliminary measurement with a multilayer dielectric reflector in place of the RR gave a bandwidth of 1 to 2 cm^{-1}, in agreement with the spectral narrowing implied by Sooy's analysis and indicating that oscillation on just one RR envelope peak should be possible under these fast Q-switched conditions. When the RR was retuned and its temperature set properly the bandwidth was reduced to typically 0.2 to 0.3 cm^{-1}, corresponding to oscillation on two adjacent fine structure peaks. Within these two bands the power appeared to be fairly evenly distributed amongst all the allowed longitudinal modes. Under these conditions the output was 8 mJ in 26 ns (FWHM), i.e. a peak power of 320 kW. This output power was stable to within $\pm 5\%$ over many hours and to within $\pm 2\%$ for short periods. The output pulse showed an irregular and highly variable modulation of 5 ns period (the cavity transit time) to a depth of 10 to 20%.

When the two-stage Q-switch was applied the bandwidth contracted to less than 0.05 cm^{-1} with at most three modes oscillating within this bandwidth. These modes were not necessarily adjacent ones and this behaviour is not entirely understood at present although it is felt that spatial hole-burning and cavity length scanning play some role. With fine adjustment of cavity alignment and RR temperature, oscillation was easily reduced to a single mode on 60 to 70% of shots with oscillation on two or occasionally three modes on the remaining shots. The two interferograms in fig. 6 show the immediate improvement obtained by applying the two-step Q-switch. In fig. 6a the RR temperature was optimised but only the single step (fast) Q-switch was used, whereas in fig. 6b the two-step Q-switch was used. Under the latter conditions the output power was found to be reduced by about 25% (to 240 kW) and amplitude jitter increased to $\pm 10\%$ from pulse to pulse. The amplitude modulation of the pulse envelope was much reduced and became more sinusoidal in nature. When only one mode could be detected on the interferometer this sinusoidal modulation had a depth of a few per cent. Under stable laboratory conditions (i.e. late at night), the performance was much improved and single mode oscillation could be maintained on all pulses for more than 1 h (at 2 pps). The amplitude jitter was then substantially less and the absolute frequency was stable to within better than one longitudinal mode interval.

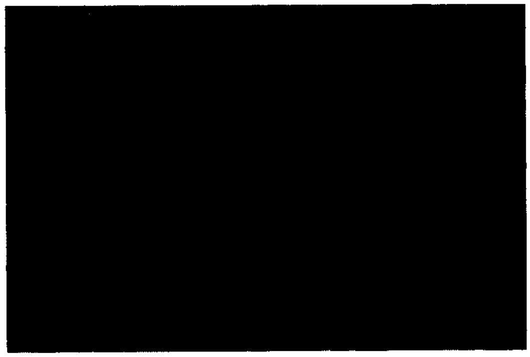

Figure 6(a) Multimode spectral output with fast Q-switch monitored by a plane FP with free spectral range 0.71 cm^{-1}.

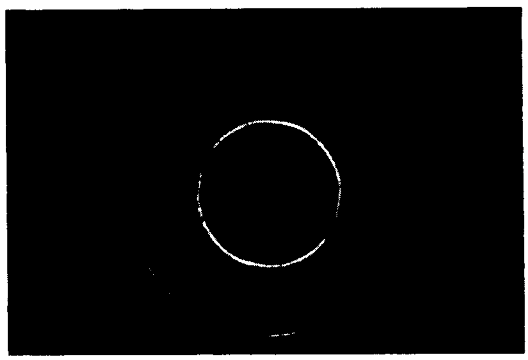

Figure 6(b) Single mode output with two-step Q-switch monitored by defocused confocal FP with free spectral range 0.1 cm^{-1}.

7. Conclusions

A two-step active Q-switching technique has been demonstrated which allows single longitudinal mode operation at powers which are essentially the same as those from conventional fast Q-switches. The technique has been studied in detail with a $Nd{:}CaWO_4$ laser but may readily be applied to Nd:YAG and ruby lasers.

The Nd:$CaWO_4$ laser system described above has been an important factor in obtaining reliable oscillation from a proustite optical parametric oscillator where damage considerations have made it necessary to limit oscillation to a few axial modes [17].

Acknowledgements

We wish to acknowledge the patient and expert work of Mr D. Wyatt on the mechanical aspects of this project. This research was supported by grants from the Science Research Council.

References

1. H. MANGER and H. ROTHE, *Phys. Lett.* **7** (1963) 330-331.
2. H. P. BARBER, *Appl. Optics* **7** (1968) 559-561.
3. M. HERCHER, *ibid* **8** (1969) 1103-1106.
4. H. G. DANIELMEYER, *IEEE J. Quantum Electr.* **QE-6** (1970) 101-104.
5. M. HERCHER, *Appl. Phys. Lett.* **7** (1965) 39-41.
6. F. T. MCCLUNG and D. WIENER, *IEEE J. Quantum Electr.* **QE-1** (1965) 94-99.
7. V. DANEU, C. A. SACCHI, and O. SVELTO, *ibid* **QE-2** (1966) 290-293.
8. J. E. BJORKHOLM and R. H. STOLEN, *J. Appl. Phys.* **39** (1968) 4043-4044.
9. W. R. SOOY, *Appl. Phys. Lett.* **7** (1965) 36-37.
10. J. M. MCMAHON, *IEEE J. Quantum Electr.* **QE-5** (1969) 489-495.
11. J. K. WATTS, *Appl. Optics* **7** (1968) 1621-1623.
12. D. G. PETERSON and A. YARIV, *ibid* **5** (1966) 985-991.
13. R. M. SCHOTLAND, *ibid* **9** (1970) 1211-1213.
14. T. A. WIGGINS, C. E. PROCIK, and J. PLIVA, *ibid* **10** (1971) 304-310.
15. R. P. HILBERG and W. R. HOOK, *ibid* **9** (1970) 1939-1940.
16. T. M. CHRISTMAS and C. G. WILDEY, *Electronics Lett.* **6** (1970) 152-153.
17. D. C. HANNA, B. LUTHER-DAVIES, H. N. RUTT, and R. C. SMITH *Appl. Phys. Lett.* (1 January 1972).
18. H. N. RUTT and N. G. VINTER, (unpublished).
19. D. J. BRADLEY and C. MITCHELL, *Phil. Trans. Roy. Soc.* **A.263** (1968) 209-223.

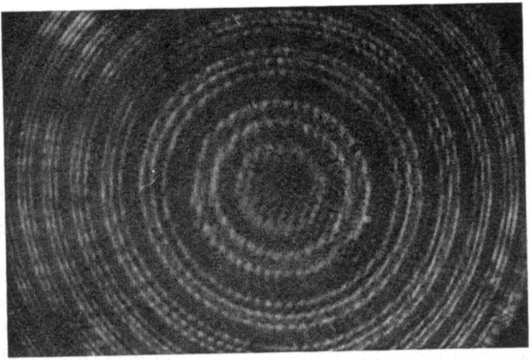

Figure 6(*a*) Multimode spectral output with fast Q-switch monitored by a plane FP with free spectral range 0.71 cm^{-1}.

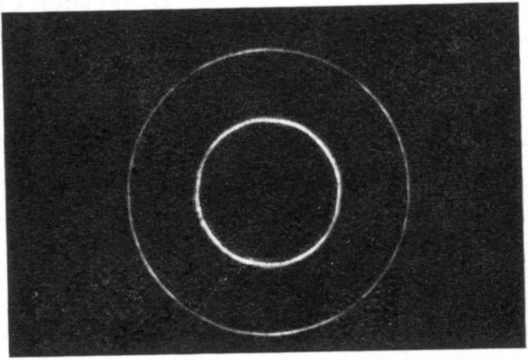

Figure 6(*b*) Single mode output with two-step Q-switch monitored by defocused confocal FP with free spectral range 0.1 cm^{-1}.