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A FARADAY Q-SWITCH

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A FARADAY Q-SWITCH

by

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ABSTRACT

Electro- and magneto-optic Q-switches suitable for use with narrow line-width ruby lasers are briefly reviewed. Experiments on $\pi/2$ and $\pi/4$ Faraday-rotation Q-switches are described, and the operational convenience and merit of these switches is assessed.

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CONTENTS

1. INTRODUCTION

Many experiments require a high power laser pulse which can be synchronized to other events with a high degree of reproducibility. To achieve this, either an electro-optical or magneto-optical shutter may be used to Q-switch the laser. The most commonly used shutter is the (electro-optical) Kerr Cell containing an organic liquid such as nitro-benzene, but this liquid exhibits a strong stimulated Raman effect[1,2] and the line width of the ruby laser is then too broad (or its coherence length too short) for several high resolution scattering, interferometric, and holographic applications.

This report briefly discusses electro- and magneto-optic shutters which do not exhibit this defect (in particular, the Pockels Cells and the Faraday Q-switch). Ruby laser experiments with two types of Faraday Q-switch are then described. (The main purpose of these experiments was to compare the operational convenience of a typical magneto-optical shutter with the more usual Kerr Cell). Finally, the practical advantages of the various types of Q-switch are summarised.

Electro-optic Crystals

All materials exhibit some change in refractive index when placed in an electric field; isotropic substances become birefringent and uniaxial crystals become biaxial. The exact nature and magnitude of the effect depends on the symmetry of the medium. Thus, all crystals possessing a centre of symmetry, and all other non-crystalline media, exhibit a birefringence which varies as the square of the applied electric field (the Kerr Effect), but acentric crystals have additionally a birefringence which varies linearly[3] with the applied field (the Pockels effect).

Biaxial crystals are usually avoided when constructing electro-optic light modulators because the directions of their optic axes are colour and temperature-sensitive; uniaxial crystals are normally aligned with their optic axis along the light beam. When aligned in this way, birefringence can be induced by an electric field oriented along the light path to give a longitudinal Pockels effect, or perpendicular to the light path to give a transverse effect; inspection of the non-zero components of the tensor describing the linear electro-optic effect[3] indicates that tetragonal crystals in the classes $\bar{4}$ and $\bar{4}2m$ can then exhibit a longitudinal effect, crystals in classes 3, 32, 3m, $\bar{6}$ and $\bar{6}\,m2$ can exhibit a transverse effect, and cubic crystals of the classes 23 and $\bar{4}3m$ can exhibit both effects[4]. Several of these crystal classes have a symmetry which also allows optical activity, but when light travels along the optic axis the polarization axes are rotated only in crystals of the classes 3, 32, and 23[4]. The remaining classes are therefore more commonly used in light shutters. The most familiar of these are ZnS, hexamethylene tetramine and other isomorphs of the $\bar{4}3m$ class, and ammonium and potassium dihydrogen phosphate ("ADP" and "KDP" respectively) of the $\bar{4}2m$ class. Commercial Pockels Cells usually use crystals of ADP or KDP, and they are now frequently employed as Q-switches in ruby lasers when a narrow line width is required. Some difficulties exist in the construction of Pockels Cells:

(1) The crystals are rather difficult to polish and are often hygroscopic, so that they must be encapsulated in a suitable liquid. Even when the liquid is indexed-matched there are four interfaces in the cell, so that the laser's optical cavity is rather complicated.

(2) The Pockels effect is strongest when the electric field vector and the direction of light propagation are both parallel to the Z axis of the crystal. It is therefore necessary to produce a uniform electric field along the length of the crystal, but at high light intensities it is undesirable to use a gridded electrode and so the usual procedure is to use ring electrodes. Such an arrangement may typically produce a variation of 20% between the half wave voltage on the axis and at the edge of the electrode and this therefore affects the minimum transmission attainable when the Pockels Cell is crossed with an external polarizer. Because of the natural birefringence of the crystal, the divergence of the light beam is another factor which can affect the extinction efficiency.

The Magneto-optic Effect

All materials exhibit the (diamagnetic) Faraday effect, i.e. they rotate the plane of polarisation of plane polarised light by an amount

$$\theta = V \ell H \qquad \ldots (1)$$

where θ is the clockwise rotation in minutes of arc viewed along the lines of force, ℓ is the length of the light path in the sample (cms), H is the magnetic field component (Oe) in the direction of transmission, and V, the Verdet constant, is +ve and insensitive to temperature. If the direction of light propagation is perpendicular to the magnetic field, there is a very weak magneto-optic effect (the Cotton-Mouton effect) which causes isotropic media to become birefringent. The magnitude of this effect varies as the square of the applied field and it therefore resembles the Kerr effect, but it is normally too weak to be of any practical importance. The Verdet constants of several glasses are listed in Appendix 1, together with typical figures for the absorbance, which is also a critical parameter when evaluating the merit of any material for use as a Faraday rotator[5]. Transition metal ions are a contaminant which can frequently cause a variation of the absorbance from sample-to-sample unless the manufacturing process is closely controlled. The very high quality lead silicate optical glasses are good examples of diamagnetic Faraday rotators which are cheap and commercially available. (For example, a 10 cm × 2 cm diameter cylindrical rod of Schott SFS 09 costs £13, whereas the cost of polishing the ends is approximately £30).

There is a far stronger effect associated with para and ferro-magnetic materials. For example, glasses heavily doped with paramagnetic rare-earth ions have a (negative) Verdet constant which is inversely proportional to temperature. At a temperature of 196^{o}K they can have a Verdet constant which is an order of magnitude higher than that of the lead glasses[6] and a damage threshold greater than 200 MW/cm^2[7], but they have not yet been produced in bulk and so their optical quality is not quite so good as that of conventional glasses. Rods of experimental grade terbium glass[7], 10 cm long × 1 cm diameter, cost £2000 at the time of writing and it seems likely that these glasses will continue to be expensive because they are made from very high purity oxides, in order to avoid unwanted absorption bands from other rare-earth contaminants. They are normally made by induction melting in a platinum container and precautions must be taken to avoid minute inclusions of platinum in the glass[6].

In conclusion, it is an important characteristic of the magnetic-optic shutter that the active element can consist solely of high quality optical glasses, so that the Q-switch can be, in principle, a very simple component of the complete laser. For this reason the authors have not investigated magneto-optic crystals, which appear to offer no a priori advantages over the Pockels Cell. It may be noted in passing that a Faraday rotator activated by a permanent magnet can constitute an optical isolator consuming no power, and this fact may prove to be a more important incentive for the development of highly active Faraday glasses than the rather specialised application of the present report. The use of such isolators in optical radar systems and laser amplifiers is discussed, for example, in references 8 and 9 respectively.

2. THE FARADAY Q-SWITCH

$\pi/2$ Rotator

A Faraday rotator sandwiched between crossed polarizers constitutes a shutter which can be used to Q switch a laser cavity. Normally the cavity will have a sufficiently low Q that lasing is inhibited whilst the ruby is pumped above threshold; if a suitably pulsed magnetic field is then used to rotate the plane of polarization by 90°, the shutter is opened to initiate the build up of the giant pulse (Fig.1). Helfrich[10] and McMahon and Bricks[11] have used this method with heavy flint glass and fused silica respectively. Fused silica appears to be the most damage-resistant material for use in lasers operating at intensities above 100 MW/cm²[11] but rather high fields are required for the Faraday Q switch if excessive lengths are to be avoided (e.g. McMahon and Bricks used a field of 150 kG rising to 2.5 μsec to switch a 5 cm length of fused silica).

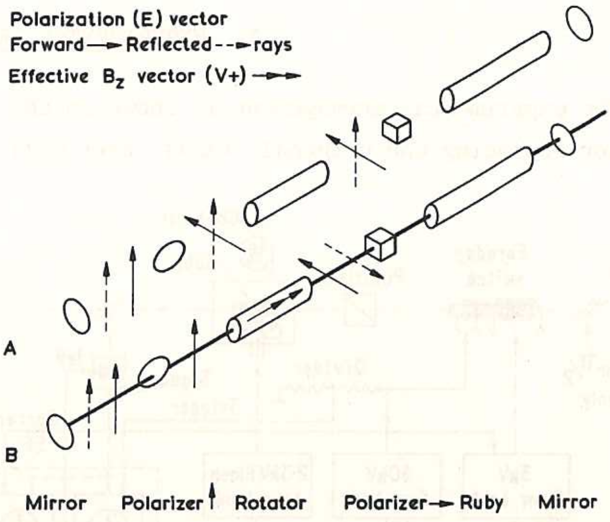

Fig.1 (CLM-R73)

$\pi/2$ Faraday Rotator (a) When the field is zero there is a high reflection loss at the stacked-plate polariser and free-lasing is thus prevented. (b) When the plane of polarisation of the light from the ruby is rotated through 90° by the pulsed rotator there is no reflection loss at the end of the cavity and a giant pulse is produced.

$\pi/4$ Rotator

A system of greater (optical) simplicity has also been described[12]. A quasi-static magnetic field rotates plane-polarised light by 45°; the light is then reflected from a mirror and rotated by a further 45° before it again reaches a polarizer (with which it is now crossed), and lasing is thus prevented (Fig.2). A fast magnetic pulse equal and opposite to the initial

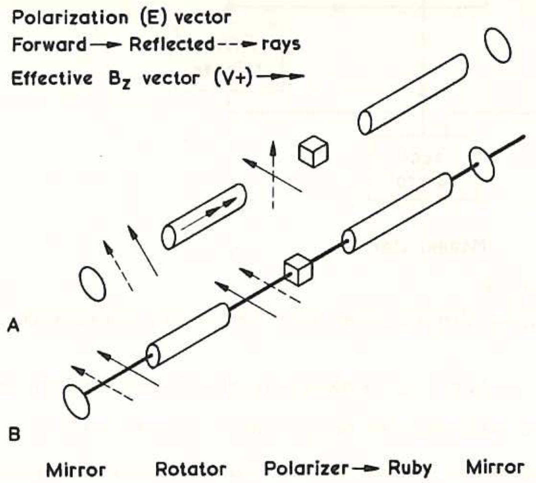

Fig.2 (CLM-R73)

$\pi/4$ Faraday Rotator (a) The quasi-static magnetic field rotates the ruby light by two successive 45° steps, and free-lasing is then prevented by the polariser. (b) The fast pulsed field cancels the Faraday rotation so that the light returning from the end mirror through the rotator is no longer crossed with the polariser and a giant pulse ensues.

quasi-static magnetic field subsequently removes the Faraday rotation and so initiates laser action. In addition to its optical simplicity this system uses a pulsed field which is only half as strong as in a comparable $\pi/2$ rotator, and this can be a considerable advantage when a very fast Q-switch (and hence a high voltage, low inductance, energy source) is required.

The systems described above both constitute light 'shutters' which, in principle, are perfect Q-switches. In practice, it is sometimes possible to dispense with the second polarizer, since a ruby crystal cut with its optic axis at 60^{o} or 90^{o} to the rod axis has its own preferred plane of polarisation[13].

3. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in the block diagram of Fig.3 with the Faraday rotator replacing the original ($\lambda/4$) Kerr Cell of a commercial 30 MW ruby laser. This laser (Barr & Stroud type LU3) used a linear flash tube FX47 (E.G & G) operating at 2.5 kV, 7.5 kJ, to pump an air-cooled anti-reflection coated, Linde S1Q 60^{o} ruby of length 6" and diameter ½". The preferred plane or polarisation of the latter was further defined by a Glan Thomson prism. For the $\pi/2$ Faraday rotator on additional polariser of larger aperture was required and a National Photocolour Corporation "Quint Stack" was used for this purpose. This stacked-plate polariser is an assembly of five 8 μ thick NPC uncoated pellicles (η = 1.49) spaced 1/16" apart with an I D of 3". Selected pellicles showing high transmission and low scatter are used in the stack which therefore withstands high power laser intensities. It is difficult to calculate the degree of polarisation afforded by such 'stacked plate' systems because of the effect of multiple reflections. However, it is estimated from Weinberg's tables[14] that unpolarised light traversing the Quint-stack twice should have a polarisation (at the Brewster angle) of between 65% and 93%. In principle multiply reflected rays, which 'walk off' on one pass to 'walk back' on the return, can be intercepted by a stop between the back mirror and the polariser; such a precaution was not taken in the present experiments to avoid any possibility of laser damage to the stop (and hence the pellicle). The end surfaces of the

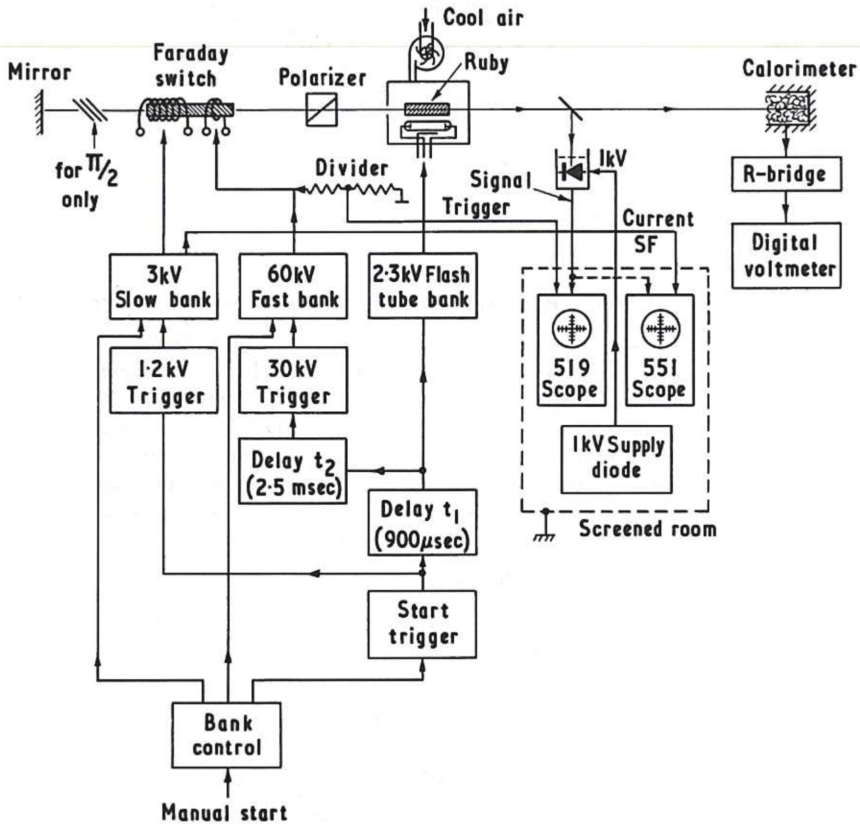

Fig.3 (CLM-R73)
Block diagram for $\pi/2$ and $\pi/4$ Faraday Q-switches.

Faraday rotator were polished to a flatness of $\lambda/10$ and a parallelism of 3 seconds of arc. As these surfaces were uncoated it was necessary to align their normals at least 20 minutes off axis to inhibit an unspoiled mode reflected at the surface adjacent to the ruby.

Circuitry for $\pi/2$ Rotator

A cylindrical rod (10 cm long × 2 cm diameter) of Schott SFS09 glass was used as the Faraday rotator, so that a field of approximately 8 kG was required to give a 90^o rotation. A pulse rise time of 65 nsec (to 63% peak field) and a pulse length of 300 nsec was achieved by discharging coaxial cables through a single low inductance pressurised (Mk.II) spark gap[15], into a copper bronze 4½ turn spiral-wound coil having an inside clearance of 2 cm and a length of 12 cm. The circuit utilized readily available 60 kV components and the details are given in Appendix 2 and Fig.4.

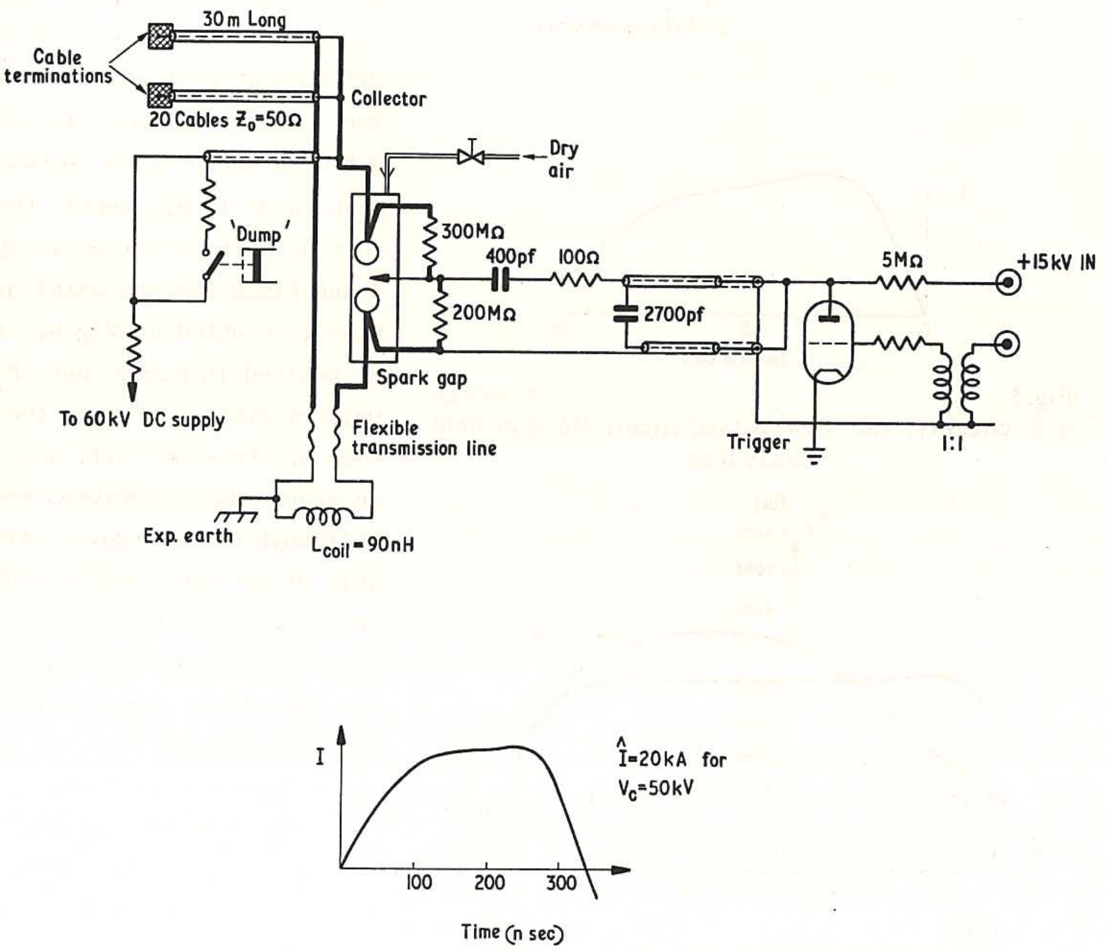

Fig.4 (CLM-R73)
$\pi/2$-circuitry. (a) 'fast' pulse circuit (b) fast field pulse.

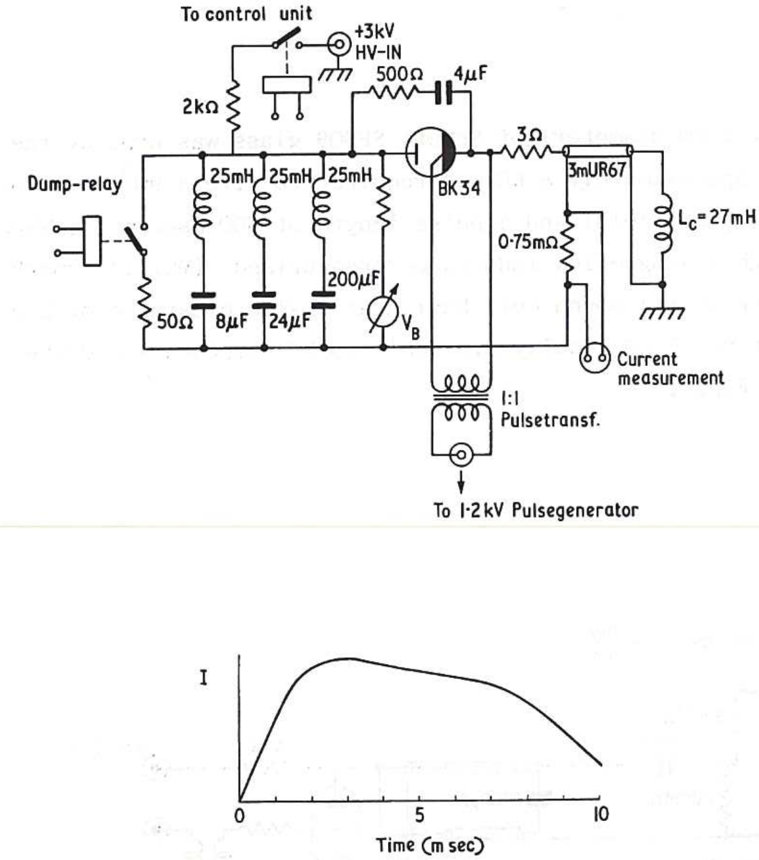

Fig.5 (CLM-R73)
$\pi/4$-circuitry. (a) 'slow' pulsed circuit (b) slow field versus time

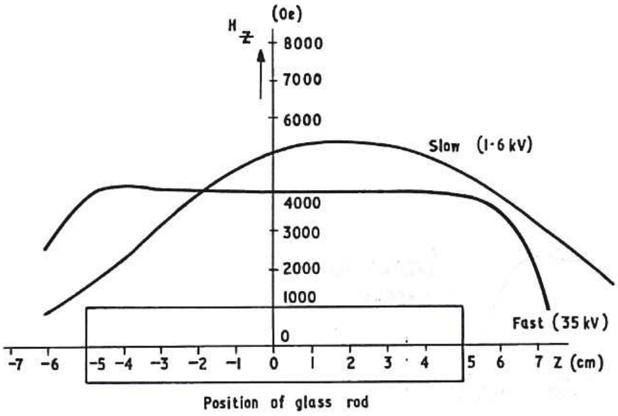

Fig.6 (CLM-R73)
Axial variation of peak fast and slow fields.

Circuitry for $\pi/4$ Rotator

In this system a rapidly rising field of 4 kG was supplied by the fast bank described above, and an additional quasi-static field of 4 kG was generated by a 1000 turn solenoid wound symmetrically around the 'fast' coil. A 2 mm thick stainless steel cylinder was used to isolate the multi-turn solenoid from high voltages which would otherwise be induced by the fast coil. The slow coil (of length 12 cm and I/D 4.6 cm) was energised by a 3 section C-type network working at a potential of 3 kV and switched by a standard ignitron. The 4 kG field had a rise time of 0.8 msec and decayed to 63% of the peak value in 8.2 msec; the circuit details are given in Appendix 3 and Fig.5 and the axial distribution is plotted in Fig.6. It will be noticed in Fig.6 that B_z is uniform within 10% over the central 6 cm of the slow coil, but there is an appreciable variation over 10 cm. (Although both circuits were capable of giving a rotation of $\pi/4$ in a 6 cm length of glass, the present experiments were made with the same 10 cm sample used in the $\pi/2$ experiment).

4. EXPERIMENTAL RESULTS

The main characteristics of the laser system when switched by the Kerr Cell, and alternatively by the $\pi/2$ or $\pi/4$ Faraday rotator, are given in Table 1:

TABLE I

	$\pi/4$ Kerr Cell	Faraday Q-switch	
		$\pi/2$	$\pi/4$
Peak output power(1) (MW)	60	30	34
Laser Pulse Half-width (nsec)	20	40	40
Q-switch giant pulse delay	-	-	150 ± 10
Laser Beam Divergence(2)	5.8 m rad. horiz. 8.2 m rad. vert.	-	3 m rad. horiz. 4 m rad. vert.
Laser Line Width	$\sim 0.5A^{o}$(3)	-	0.08(4)
Trigger HT (kV)	11.6 (shorted)(5)	50 ±4(6)	35 ± 2(6)
Slow Bank HT (kV)	-	-	1.6 ± 0.1(7)

(1) Flash lamp energy of 6.2 kJ; power measured with rat's nest calorimeter and ITT photodiode. All other measurements were made at this same pumping level.

(2) Width at 1/e of the peak power, measured by Winer's technique[16] (In the horizontal direction there was a similarly narrow peak of lower intensity displaced by 10 milliradians; this was probably due to an internal cavity mode). (See Fig.7)

(3) The Stokes and anti-Stokes lines at ± 0.5 cm^{-1} were resolved by the etalon.

(4) i.e. Two lines separated by $0.06A^{o}$ with an overall width of $0.08A^{o}$.

(5) $\pi/4$ Kerr Cell operates by shorting the HT supply

(6) This variation represents the range over which the output power was not noticeably affected.

(7) This variation represents the limits over which free lasing was inhibited.

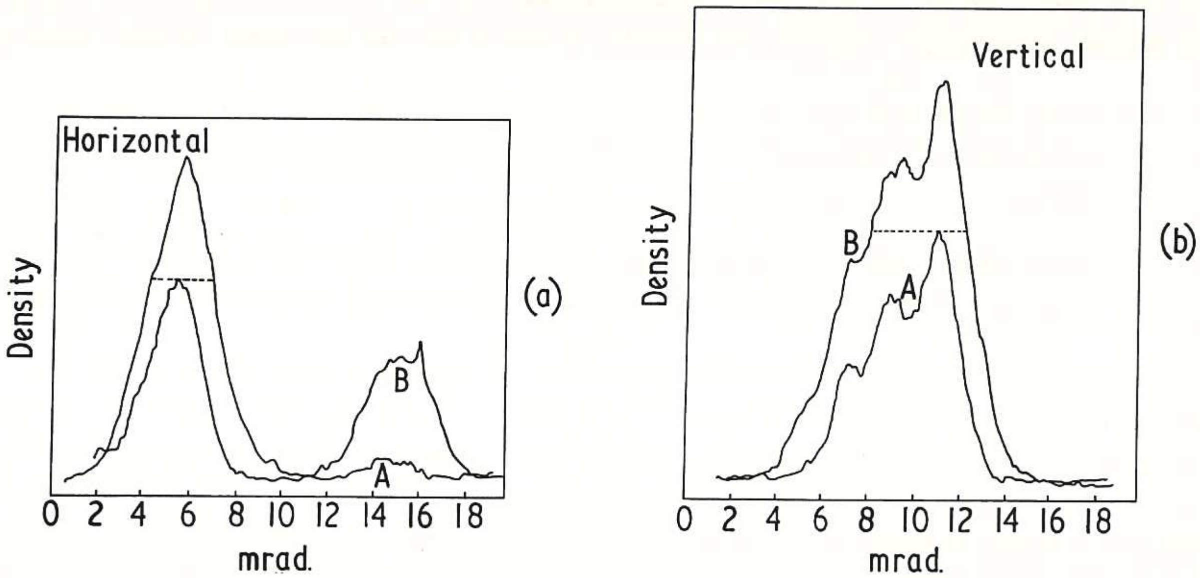

Fig.7 (CLM-R73)
Micro densitometer traces of focussed 34 MW laser beam A/B exposure ratio e^{-1}.
($\pi/4$ Faraday Q-switch)
(a) Horizontal (1/e) beam divergence.
(b) Vertical (1/e) beam divergence.

It should be noted that:

(1) The $\pi/4$ Faraday rotator gave a line width of less than 0.08A^{0} at 35 MW without the use of auxiliary mode selectors (such as a sapphire resonator)

(2) Over five consecutive shots there was an optical delay of some 150 nsec, with a jitter of less than 10 nsec, between operating the Q-switch and the appearance of the giant pulse. There is an additional electronic delay of 350 nsec (with a measured jitter of 5 nsec) between a 200V trigger pulse and the operation of the Mk II spark gap. (About 330 nsec of the electronic delay is associated with the thyratron used to trigger the spark gap). Thus, the overall jitter in firing the laser is of the order of 15 nsec.

(3) The overall reproducibility of the system was determined by the temperature of the ruby, rather than by any variation in circuit performance.

(4) The lower power and longer pulse duration of the Faraday Q-switched system is probably due to the lack of anti-reflection coatings on the Schott SFS09 glass rod. A subsidiary experiment was performed in which the glass and Kerr Cell were inserted simultaneously into the optical cavity. The laser power and pulse duration were then 30 MW and 40 nsec respectively, irrespective of whether the Kerr Cell or the glass rod were switched.

(5) The sample of Schott SFS09 glass used in these experiments showed some evidence of damage after several hundred shots. Fine bubbles extended linearly along the axis of the rod. The measured beam divergence showed that the laser output was not spatially uniform and it may be concluded that the power density in the Faraday Q-switch certainly exceeded 100 MW/cm^2 locally.

5. DISCUSSION

A Faraday Q-switch of best optical-quality glass has the dual advantages of homogeneity and optical simplicity. However, the Faraday Q-switch has the following disadvantages:

(1) It is fundamentally more difficult to switch high currents very rapidly than to switch a voltage pulse of some 20 kV into the 10 pF capacitance of a Pockels Cell.

(2) There is the practical disadvantage that a fairly large spark gap and flexible, high-voltage low-inductance transmission line must be connected to the Q-switch.

If existing commerical glasses (in particular the Schott SF glasses, which at the moment have the highest figure of merit[5]) do not withstand high power laser pulses sufficiently well, it should be possible to construct a liquid cell having high quality fused silica windows which will do so, but then the advantage of optical simplicity is lost. However, a liquid rotator has the additional advantage that it is self-heating to laser damage and is inherently more homogeneous than a Pockel's Cell, which is subject to electro convection[17] in the matching liquid and to parametric effects in the crystal itself. (It should be noted, for example, that the tensor describing the Pockels effect has identical symmetry to the third-rank tensors governing the piezo-electric and frequency-doubling effects, i.e. the same crystal symmetry is required to exhibit any of these three effects[13]. Although transparent ferro-magnetic crystals such as Eu_2SiO_4[18] have recently been developed which have a high Verdet constant (of the order -1 min Oe^{-1} cm^{-1}) at room temperature, it is not apparent that crystalline magneto-active materials offer any significant advantage as a laser Q-switch over the electro-optic shutters discussed in section 1.

The fast circuit described in this report could be modified by using a Blumlein voltage doubling circuit, Mk.I spark gap and a slightly smaller coil to give a magnetic pulse rising a factor of 2-3 faster than in the present Q-switch. (The rise time of the Faraday rotator is then sufficiently short to provide a 'fast'[2] Q-switch for any laser having a build-up time greater than about 50 nsec). A glass (or a liquid) having a higher Verdet constant than Schott SFS09 would permit a still faster switch, or a simpler high voltage circuit.

6. CONCLUSIONS

The Faraday rotator is most likely to be of use as a triggered Q-switch in narrow line-width ruby lasers required for high resolution scattering, interferometric, and holographic applications, where an exceedingly fast (nano-second) Q-switch is not required. Other uses for Faraday-active glasses exist and it is therefore probable that damage-resistance para-magnetic glasses having high Verdet constants will become available commercially, so that the additional electrical complexity of the slow bank circuit appears to out-weigh the other advantages of the $\pi/4$ Faraday Q-switch.

The total cost of the present $\pi/2$ Q-switch is comparable to that of commercial electro-optic laser Q-switches and at the time of writing the decisive factor between them would appear to be their respective damage-resistance. Reliable information concerning this is not yet available.

7. ACKNOWLEDGEMENTS

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