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J. W. Beams

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A REVIEW OF THE USE OF KERR CELLS FOR THE MEASUREMENT OF TIME INTERVALS AND THE PRODUCTION OF FLASHES OF LIGHT

By J. W. Beams

[Rouss Physical Laboratory, University of Virginia, University, Va.]

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The measurement of very minute intervals of time and the production of short flashes of light are often essential both in industry and in pure research. The Kerr Cell is particularly well suited for both these purposes, since it can be made to operate as a quick-acting light shutter which responds almost instantaneously to electrical control. The phenomenon which makes possible the operation of Kerr Cells was discovered by Kerr[1] in 1875 and is usually known as the "Kerr electro-optic effect." He observed that when an electric field was established in some isotropic substances they became doubly refracting with their "optic axes" in a direction parallel to the lines of force. The effect can best be observed by an arrangement similar to that schematically sketched in Fig. 1.

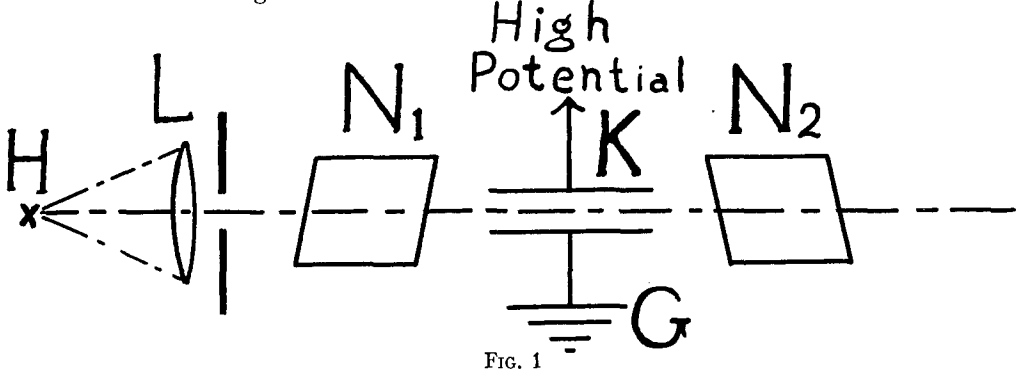

Fig. 1

Light from a source H made parallel by a lens L, plane polarized by a Nicol prism N_1, passes between two metal plates immersed in a liquid such as CS_2 (usually called a Kerr Cell) and to a second Nicol prism N_2 crossed with respect to N_1. For the maximum effect, the Nicol N_1 is so oriented that the plane of vibration of the light entering K makes an angle of 45° with the lines of force. With zero potential across K no light passes N_2 since the liquid is isotropic. The liquid becomes doubly refracting, however, as soon as the field is established, *i.e.*, the component of the light vibrating parallel to the lines of force travels

with a different velocity from that vibrating perpendicularly to the lines of force.[2] The light therefore emerges from K elliptically polarized and a part of it can pass N_2. If μ_1 and μ_2 are the refractive indices for the two rays, then their phase difference after passing through the Kerr Cell is

$$D = \frac{2\pi l(\mu_1 - \mu_2)}{\lambda} = 2\pi BlE^2 \tag{1}$$

where λ is the wave length of the light and l is the length of the light path through the electric field whose magnitude is E. B is usually called the Kerr constant, but has been found to vary with different substances, temperatures, and wave lengths. In general the intensity of light passing N_2 is[3]

$$I = I_0\left[\cos^2(\alpha - \beta) - \sin 2\alpha \sin 2\beta \sin^2\frac{D}{2}\right] \tag{2}$$

where I_0 is a constant, α and β are the angles that the planes of vibration of the transmitted light of N_2 and N_1 make with the lines of force, respectively. In the case where N_2 is crossed with respect to N_1 and the plane of transmission of N makes an angle of 45° with the lines of force

$$I = I_0 \sin^2\frac{D}{2} = I_0 \sin^2 \pi BlE^2 \tag{3}$$

Table 1 gives the value of B for a number of liquids while Table 2 gives the variation of B with wave length for CS_2 and for nitro-benzol. If the electric field is measured in esu, l in cms., and the value of B taken directly from the table, πBlE^2 will then be expressed in radians.

Kerr, in his original experiments found that, in the case of some solid substances such as glass, several seconds were required for the double refraction to reach full value or to disappear after the electric field was applied or removed respectively. However, in the case of liquids he could find no such time lag. Later Blondlot[8] showed that any existing lag of the Kerr effect in the liquids that he studied was less than 2.5×10^{-5} sec Abraham and Lemoine[9] in 1899, by means of a very ingenious experiment, came to the conclusion that in CS_2 the Kerr effect did not persist as long as 10^{-8} sec after the electric field was removed. On the other hand experiments[10] since that time have been interpreted as indicating time lags in CS_2 and in nitrobenzol of over 10^{-8} sec. However, Professor Lawrence and the writer[11] have recently concluded that there is, at least, no experimental evidence for the exist-

TABLE 1. *Kerr constants.*

Substance	Kerr constant B 5600A	Temp.	Dielectric constant	Total absorption begins
Amyl chloride	3.47×10^{-7}	23°C	6. (11°C)	—
Benzol	.60	23.7°	2.28(20°)	2750A
Brom-benzol	9.9	24.9°	5.4 (20°)	3400
Carbondisulphide	3.36	22.5°	2.9 (0°)	3720
Chlorbenzol	10.2	24°	5.9 (20°)	—
Chloroform	−3.53	23°	5. (20°)	2550
Diethylaniline	10.4	25.2°	— —	3460
Dimethylaniline	10.3	25°	4.4 (20°)	3460
Ethylene chloride	4.86	18.5°	10.4 (20°)	3400
Nitrobenzol	346.0 (5460A)	20°	36. (20°)	4200
Nitrotoluol	122.	24°	23–25(20°)	4250
α-monobromnaphtalene	9.5	21.5°	5. (22.7°)	3450

Note: The above values were taken from a paper of McComb[4] with the exception of nitrobenzol which was taken from Moller.[6] Values for other substances as well as those for the above at various wave lengths of the light and different temperatures can be found in the literature.[5] The values for the dielectric constants were taken from the International Critical Tables.

TABLE 2. *Dispersion in the Kerr effect.*

Wave length A.U.	Carbondisulphide (McComb 22.5°C)	Nitrobenzol Handbuch der Physik Bd. 21. p. 777, 1929
4400	4.82×10^{-7}	
4600	4.53	
4800	4.28	
5000	3.92	503×10^{-7}
5200	3.69	
5270		466.
5400	3.51	
5600	3.36	427.
5800	3.17	
5860		401.
6000	3.00	
6170		376.
6300	2.88	
6450		357.
6600	2.64	

Note: In the case of nitrobenzol Hehlgans[7] has recently found that the effective Kerr constant and dielectric constant depend upon the purity of the sample.

ence of time lags in the Kerr effect for liquids having comparatively light molecules and low viscosity. In the case of viscous liquids there have been observed considerable time lags.[12] It is the absence of long time lags in liquids that makes the Kerr cell useful in the measurement of short time phenomena or as light shutters.

It perhaps would be worth while briefly to recall the arrangement used by Abraham and Lemoine[9] shown in Fig. 2. First, with the mirror M_1 removed, light from the spark E was polarized by N_1 in a plane 45° to the lines of force in the Kerr cell K. K was then removed from the optical path and the double image prism B, oriented until only one

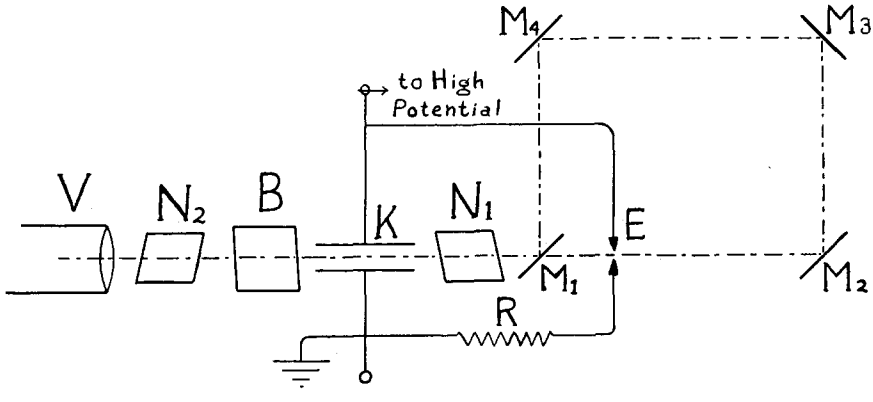

FIG. 2

image of the spark gap E could be seen in the telescope V. The Nicol prism N_2 next was placed in the line of sight and turned to the position of extinction of this image of E. K was then returned to its original position in the optical path and hence one of the images was restored because of the double refraction produced by the electric field in K. By turning N_2 either clockwise or counterclockwise through a small angle the other image appeared. The angle A, through which N_2 was turned in order to bring the two images to the same intensity in the field of view of V gave a measure of the double refraction produced in K. When the mirror M_1 was returned to its position, thus causing the light to traverse the path $EM_2M_3M_4M_1N_1$ before entering K, the angle A was reduced. It varied, in their experiments, from 17.3° to zero when the light path was increased 400 cm. The plates of K were 18 cm × 3 cm and were spaced 3 mm apart. The experiment therefore gives the rate at which the double refraction decays in K under a given set of electrical conditions. The method has since been used by Lord Rayleigh[13] for com-

paring the velocity of light in CS_2 and in air; by Wood[14] and by Gottling[15] for measuring the average time between excitation and emission in fluorescence. Also it has been used by a number of other investigators[16] for the study of phenomena that occur in a very short interval of time. The precision of the arrangement is indeed very high but the dispersion in the electric double refraction (see Table 2) and the fact that all the spectrum lines in the spark do not appear simultaneously may introduce large errors unless extreme care is taken to investigate or eliminate them.

A modified form of the above method has been used to investigate the order of appearance of spectrum lines in sparks and condensed discharges[17,18]. The double image prism was removed from the above arrangement and the time of discharge of the Kerr cell reduced to such a value that it could be used directly as a light shutter. Since the instant of optical cut off of the shutter could easily be changed by known amounts, the variation of the time at which the shutter closed was used to determine intervals between the occurrence of phenomena rather than the change of ellipticity produced by the relatively slow rate of discharge in the manner of the cell of Abraham and Lemoine discussed above. Since there has been some difference of opinion[19] concerning the essentials of the method, and especially because of its large number of possible applications in the study of short time phenomena, it will be described somewhat in detail.

In Fig. 3, a high potential is applied across the variable condenser C_1. (.005 to .0005 microfarads) and the spark gap A by means of a transformer and kenotron until the spark occurs. The light of the spark travels over the variable light path $AL_1M_1L_2M_2K$ while the fall of potential travels along the symmetrical and equal lead wires ATK. If the light arrives at K before the electric field in K is relaxed, it will pass N_2, but if the fall of potential arrives before the light long enough to discharge K no light passes N_2. It was found that if K were only a few cm capacity and if the capacity and inductance of the circuit were as small and uniformly distributed as possible no light intense enough to be seen by the eye passes N_2 when the light path and wire path were roughly equal in length. However, when the light path was decreased the spectrum lines in the spark appeared in a definite sequence and the time between their appearance could be measured directly in terms of the velocity of light.

The lead wires from A to K were either symmetrical and equal in length, as shown in Fig. 3, or else one side each of A and K was grounded

by short leads to independent high capacity grounds. The resistances $R_2 = \sqrt{L/C} = 450$ ohms, where L and C are roughly equal to the inductance and capacity per unit length of the circuit, were placed across the open ends of the wires to prevent possible reflections. The variable condenser C_1 and variable resistance R_1 were used to change the conditions in the spark. The latter circuit was in a plane at right angles to

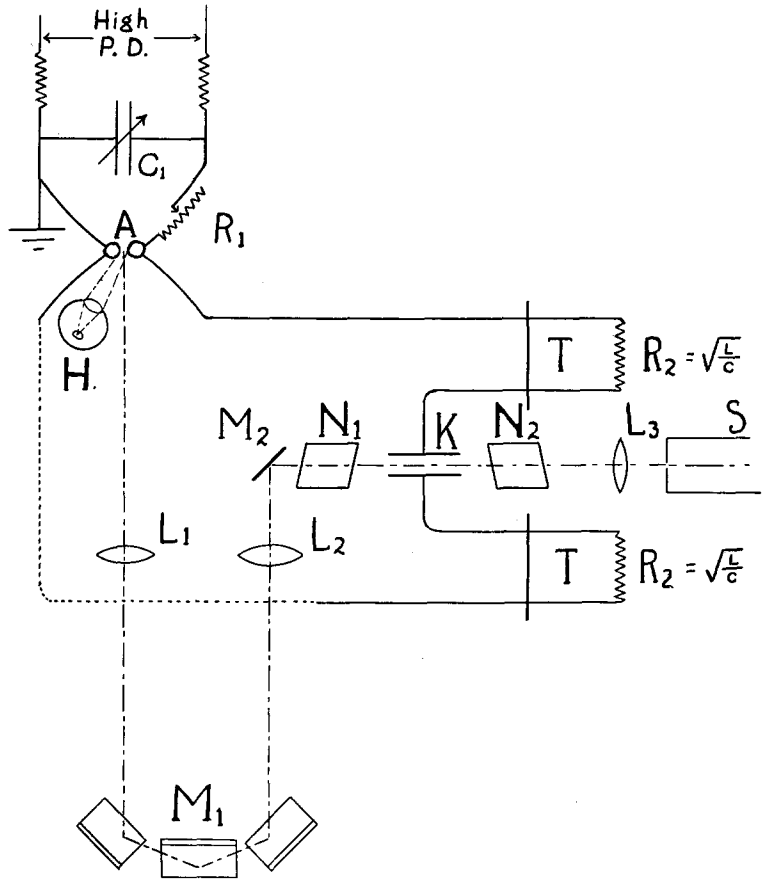

FIG. 3

the Kerr cell circuit to prevent unnecessary inductive coupling when the resistance R was made small and hence the circuit oscillatory. When the spark at A was oscillatory the period of oscillation was always small enough to prevent the complete deionization in the gap between vibrations, so that, after the initial fall, the potential across it would not again reach a value that would reopen the cell. A source of ultraviolet

light H, placed vertically over A in a direction at right angles to the direction in which A was observed, was used to irradiate the spark gap so that the time lag of the spark is reduced,[20] thereby causing the spark to jump when the potential reached approximately the same value each time. The movable mirror system M_1 was designed by Professor Hoxton to return a beam of light in a parallel but displaced path. The mirrors, $7'' \times 11''$ and silvered on the front face, were obtained from Bausch and Lomb. They were mounted with their faces mutually perpendicular in a steel frame that moved on a wooden track 23 meters in length. The arrangement was ideal for a variable light path because the light always returned practically to the same place regardless of the considerable unsteadiness of the mirror system on its track. The polarizing prisms N_1 and N_2 were crossed with the plane of transmission of N_1 oriented 45° with the lines of force in K. They were of the Glan Thomson type to prevent displacing of the ray by crossing. The spectrographs had low dispersion but large light gathering power. The Kerr cell K was made by mounting in a pyrex glass tube two brass plates carefully rounded on their edges and ends to prevent high local electric fields. The plates were supported by nickel rods screwed into them and welded to 50 mil. tungsten wires which, in turn, were sealed through the pyrex tube. It was sometimes important to design the cell to give a maximum field and at the same time have a minimum capacity at a sacrifice of uniformity of field. This makes it necessary to have the light pass through the cell roughly parallel or so focused as to give equal transmission to all parts of the source A, with the field on in K. The ends of K were thin strain-free cover glasses and were cemented to the tube with water glass. Gelatine, covered on the outside with shellac, was sometimes substituted for water glass. CS_2 was used here because of its transparency in the visible regions, good insulating properties, high dielectric strength, and comparatively low dielectric constant. The dielectric strength of CS_2 can be increased very much by careful dehydration distillation and filtration. It should also be noted here that impulsive fields of 10^6 volts per cm. can be established in CS_2 for over 10^{-7} sec without dielectric breakdown.[21]

In most of the experiments it was found unnecessary to work with a Kerr cell and applied voltage that would give a relative retardation D of the elliptically polarized light greater than from 8° to 18° because of the very great intensity of the light at A, in the initial stages of the spark. Under these conditions the intensity of light passing N_2 as can be seen from equation (3), varies approximately as the fourth power

of the field strength in the cell. If the exact rate of fall of potential across A were definitely known, it would then be possible with the known constants of K to compute the time of optical cut off after the fall of potential reached the cell. The fall of potential across a spark probably depends upon several different factors but, in a case similar to that used here, the potential has been found to fall to half value in roughly 5×10^{-9} sec.[22] Now, since it was possible to use a Kerr cell of only about 4 cm capacity, the rate of fall of potential across K was not very much slower than the rate of fall of potential across A but at a definite time later equal to the length of lead wire divided by the velocity of the electromagnetic wave. Since any lag in the Kerr effect is small enough to be neglected, equation (3) shows that the intensity of light passing N_2 falls to $1/e$ of its value when the potential across K falls to only 77 percent of its original magnitude so that the cell is effectively closed optically when the potential falls to half value. This property of the Kerr cell of optically closing by the time that the potential across it reaches half value makes it possible not only for the cell to close very quickly but for it to fail to reopen due to any electrical oscillations in the Kerr cell with amplitude smaller than one half the initial potential.* Therefore it is only necessary to make sure that the magnitude of the potential across the cell after the initial discharge never rises much above half value. For a small cell (4 cm capacity). and lead wires not longer than about 10 meters no additional resistance in the copper lead wires is necessary because of the resistance of the initial stages of the spark, high frequency resistance of the wires, etc. However, when longer lead wires are used or a larger capacity Kerr cell, enough resistance must be inserted in the circuit to prevent the cell from optically reopening. It is usually best, as pointed out by Lawrence and Dunnington[23] to distribute when possible, the resistance over the whole lead wire rather than place it all in one position. Small wires of pure metals can be used to advantage as resistances for Kerr cells of sufficient capacity provided that the time between sparks is long enough to allow the wire to cool. The resistance of the wire is multiplied several times when it

* The meaning of oscillations as used in this paper includes the reversals of potential at the Kerr cell due to the reflected electromagnetic waves or transients. As the inductance and capacity of the circuit are distributed, the well known theory of transients (for example see Bush Operational Circuit Analysis Wiley 1929) must be used to determine the electrical behavior of the Kerr cell. The failure of the potential of the cell to reverse enough optically to reopen it because of the reflection of the initial potential wave at the cell, when lead wires less than 10 meters are used, probably results in part at least from the finite rate of fall of resistance in the spark gap or the finite length of the transient potential wave.

reaches incandescence. As a result it lets the first rush of current through with an effectively low resistance but damps the oscillations after the wire is heated. It is important to emphasize that this type of resistance is definitely limited to Kerr cells of large capacity and comparatively slow rate of discharge because of the skin effect of the small wires at the very high frequencies. This same principle has been used at R to produce a bright spark in the initial stages without later oscillations. In the above work the dispersion in the electric double refraction gave no serious trouble since the time of closing of the cell was of the same order of magnitude as the precision of the method. This was borne out experimentally in numerous cases by the appearance of spectrum lines of longer wave length first. However, if the time of

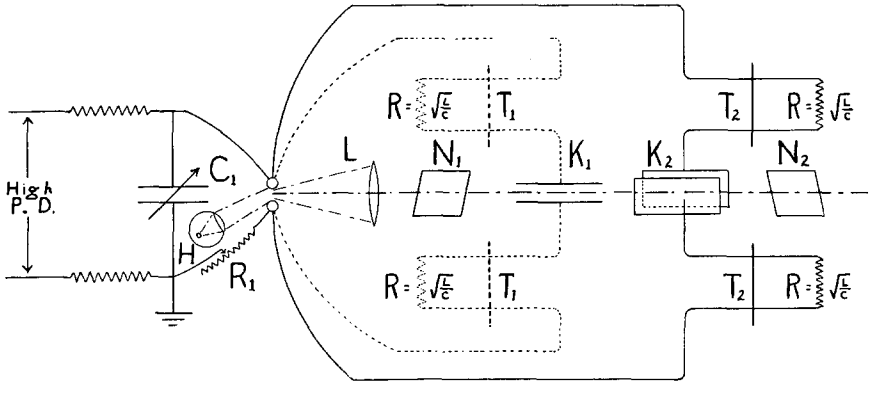

FIG. 4

discharge of the Kerr cell is increased sufficiently, the dispersion in the electric double refraction becomes important and should be allowed for.

For work in the ultraviolet region CS_2 must be discarded because strong absorption begins about 3800 A. The writer has used chloroform with good results down to about 2580 A. It has a Kerr constant of about the same magnitude as CS_2 (Table 1) and high dielectric strength. Its dielectric constant, however, is about twice that of CS_2. It should be carefully purified by repeated distillations, the final one being directly into the Kerr cell. The polarizing prisms were of the Foucault type where an air film replaces the Canada balsam for, absorption in the latter begins quite appreciably at about 3650A. If the Foucault prisms are not available the Canada balsam film can be replaced by a thin film of purified glycerine. Although not practical at present it may be possible in the future to use Kerr cells filled with gases under high pressure, for although the Kerr constants of gases

under high pressure are small, the dielectric strength is high. There exists a great need for a liquid with a large Kerr constant, high dielectric strength, good insulating properties, low dielectric constant and high transparency, both in the visible and ultraviolet. Nitrobenzol has the large Kerr constant but is lacking in most of the other essentials. However, considerable progress has recently been made, as will be referred to later, in purifying nitrobenzol until it will withstand large static fields without becoming sufficiently conducting to heat the liquid in a manner that distorts the field of view.

It is sometimes desirable to view phenomena for a very short time, at a definite stage without the masking effects of the preceding and succeeding parts, or to produce flashes of light of short duration. The arrangement previously described can easily be modified[24,11] to accomplish this as shown schematically in Fig. 4.

Two Kerr cells K_1 and K_2, as nearly identical as possible, are used with the planes of their plates at right angles. Before the discharge of the spark the two cells are at the same potential and the double refraction produced in K_1 is compensated by that in K_2. The light, therefore, emerges from K_2 plane polarized in the plane of transmission of N_1 and is extinguished by the crossed Nicol N_2. Upon discharge of the spark the fall of potential travels along the lead wires and, at a time approximately equal to the length of lead wires divided by the velocity of the electromagnetic waves, starts discharging the Kerr cells. If then the length of the equal and symmetrical lead wires to K_1 are shorter than those to K_2 (plus the distance between K_1 and K_2) K_1 will start discharging before K_2. During the period when the fields in the two cells are unequal the light emerges from K_2 elliptically polarized and hence part of it passes N_2. The intensity of light passing N_2 is

$$I = I_0 \sin^2 \pi Bl(E_1^2 - E_2^2) = A(E_1^2 - E_2^2)^2 \text{ approximately}$$

where I_0 is the proportionality constant, E_1 is the electric field strength in K_1 at a given time and E_2 is the electric field strength in K_2 at a previous time equal to the distance between the cells divided by the velocity of light. The theory for the case of an exponential discharge of Kerr cells has been worked out in detail[11] but will not be repeated here. The operation of each of the Kerr cells is essentially the same as that of a single cell described previously except that care must be taken to prevent inductive coupling between the two Kerr cell circuits. The circuit to K_1 (dotted in the figure) is usually placed, when possible, in a plane at right angles to the circuit of K_2. If desired one of the sym-

metrical lead wires to each cell may be dispensed with, as in the case of the single Kerr cell, and the other side of each of the two Kerr cells attached to independent grounds.[18] It is important to test for oscillations. This can be done by several different methods, the easiest of which is to view the spark A through the two cells. It is well known[25,18] that the spectrum lines of air appear first in the spark and that the luminous metallic vapor appears on the electrodes as points and moves toward the center of the gap. If this process can be traced by gradually lengthening the lead wires to K_1 and K_2, respectively, the Kerr cells are not oscillating. Another test that has been used for comparatively long period oscillations, which might possibly be expected to occur, is to view the light emerging from N_2 in a mirror rotating about 3000 rps. In some unpublished experiments the writer has used the latter method and found that with Kerr cells of about 4 cm capacity and lead wires under 12 meters in length that the light appeared as a single sharp image. With longer lead wires other faint images appeared but were easily eliminated by adding resistance in a manner similar to that in the case of the single cell discribed above. A third method,[18] making use of the fact that the size of a Lichtenberg figure is roughly proportional to the magnitude of the applied potential,[26] has been used successfully for getting the order of magnitude of the oscillations but is not to be recommended if either of the above methods can be used.

The Kerr cell operated by a high frequency continuously oscillating circuit has found application in many different fields.[27] In a recent paper in this Journal Kingsbury[3] has presented the theory for the amount of light passing a light shutter of this type so that it is unnecessary to repeat it here. With frequencies from 10^6 to 10^8 sec^- it is somewhat difficult to apply high voltage to Kerr cells. Therefore, nitrobenzol has been almost exclusively used as a medium because of its very large Kerr constant. As mentioned earlier nitrobenzol, at best, is not transparent and unless carefully purified is electrically conducting. The heating effect of a current through the medium may be large enough to distort the field of view and render the shutter useless. It is the usual procedure in working with nitrobenzol to apply a steady dc field across the liquid continuously as this keeps its resistance high. Besides increasing the resistance this dc potential offers another advantage by making it possible for the Kerr cell to be actuated by a smaller ac potential than would otherwise be necessary. Usually the applied dc potential is of such a magnitude as to produce a relative retardation

D (Eq.2) of an integral number of half wave lengths. It can easily be seen by differentiating Eq. (3).

$$\frac{dI}{dE} = 2I_0\pi BlE \sin 2\pi BlE^2 \tag{4}$$

that the rate of change of intensity of the light varies with the absolute field strength in a way to allow a smaller ac potential when superimposed upon a dc potential to operate the Kerr cell.

Considerable progress has been made by a number of investigators[7,28] in the purification of nitrobenzol. An especially notable advance in the technique has recently been made by Professor Lawrence[29] and his students. They first carefully distilled the nitrobenzol in vacuo, in an apparatus including the Kerr cell, that had previously been baked out under high vacuum conditions. During the operation of the cell the usual steady dc potential was applied and the nitrobenzol continuously circulated between the plates of the cell and through cooling coils. Under these conditions the field of view remained remarkably clear. By this procedure they[30] were able to obtain a relative retardation of as much as sixteen wave lengths between the two components of the polarized light during each electrical vibration of the Kerr cell which was continuously oscillating. The frequency was 2×10^7 sec.$^{-1}$. As can be seen from equation (3) this obviously gives them a method of obtaining a large number of light flashes per sec.

The type of electrical circuit used to generate the alternating potential applied to the Kerr cell depends upon the number of times that it is necessary to interrupt the light beam. For the case where it is desired to interrupt the light beam from 10^3 to 10^9 times per second the continuously oscillating vacuum tube circuits have been most extensively used. By this method Karolus,[31] in 1925, produced light flashes 15 meters in length and later[32] developed an arrangement for measuring the velocity of light. Some other uses of this type of arrangement include the modulation of light,[34,30,33] the decay time of fluorescence,[35] television, and in general cases where light flashes are to be generated by rapid electric oscillations.[36]

The damped oscillatory circuit has also been used by several investigators[38,37] to operate Kerr cells but not so extensively in recent years due to the development of the vacuum tube methods of generating undamped oscillations.

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