Some practical applications of the Faraday magneto-optic effect, the Kerr electro-optic effect, and the Pockels electro-optic effect in the early decades of the 20th century.  

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Research on very rapid processes

Let a beam of ordinary light pass through a polarizing Nicol prism and a glass vessel of several cm length containing nitrobenzene or CS$_2$ between capacitor plates (a Kerr cell, named after its 1875 inventor) tilted at 45° angle to the plane of polarization. If the beam then encounters a second Nicol prism set at right angles to the first one, no light is transmitted by this arrangement. When however a high voltage is applied to the plates, so that the fluid becomes doubly refracting to a significant extent, some of the light can pass through the second Nicol prism. The apparatus therefore constitutes a voltage-controlled light switch. Pauthenier (1920) and others showed that it could modulate light at frequencies up to at least a thousand times higher than mechanical devices (such as slotted metal plates or polygonal mirrors, rotated by electrical motors). These frequencies can even be increased to more than 1 GHz with suitable electronic circuitry. The Faraday effect is the rotation of the plane of polarization in any material when placed in a magnetic field. As an example, one may place a substance having a strong Faraday effect (such as CS$_2$, enclosed in a tube) between two crossed Nicol prisms. A light ray cannot pass through this setup until a magnetic field is switched on around the tube.

Fig. 1. Measurements by Crehore and Squier (1895) of the speed of cannon projectiles using the Faraday effect. To begin with, no light from a lamp at the far left passes through the analyzer prism $A$ which is set perpendicular to the polarizer $P$. When the projectile starts moving, it switches on a current in a coil around the tube $T$, causing a change in the light beam's direction of polarization. Some of the light then traverses $A$ and falls on a photographic plate at $W$. A motor $m$ rotates this plate at a known constant speed.
Before 1890 it was known that in the Faraday effect and the Kerr electric effect it took the molecules in material samples less than 0.1 millisecond to respond to externally applied fields. Abraham and Lemoine (1900) demonstrated that in the latter the time lag was only a small fraction of a microsecond. At the turn of the century, practical applications of these effects had also appeared. This was used e.g. in measuring the speed of artillery projectiles (Crehore and Squier 1895, Fig. 1) and in estimating the properties of oscillating currents (Pionchon 1895, Abraham and Buisson 1897, Federico and Baccei 1899). Tauern (1910) studied the double refraction in glass due to electric fields with great precision, as it was by then possible to detect changes in the phase angle of light to 1/2000th of a wavelength. He considered it possible that the Kerr effect might be employed in the measurement of high voltages. In fact, H. Becquerel had suggested in 1884 utilizing the Faraday effect in measuring currents. Similar ideas also cropped up later, but they have only been put into practice in some very specific cases.

Kerr cells were used up to 1940 or so in early research on very rapid processes and short-lived phenomena, including the duration of fluorescence in dissolved dyes (1-10 ns; Gottling 1923, Gaviola 1926, 1927, 1929, cf. Bruhat 1942, p. 738) and lifetimes of excited states in gas molecules (Hupfeld 1929, Griffiths 1934). Brown and Beams (1925, Fig. 2), Lawrence and Dunnington (1930), Hámos (1930) and others employed Kerr cells in studies on the formation of electrical sparks.

Fig. 2. Left: The setup by Brown and Beams (1925) to study the development of an electrical spark across the gap A. G is a mirror which can be moved farther away to delay the light that is analyzed by the spectrometer E. B and D are Nicol prisms, C is a Kerr cell. Right: Gutton’s (1911a) comparison of the speed of light in air (horizontally at the top) and as an electromagnetic wave along wires. O is an oscillator, P is a slider for changing the length of the wires. Z₁, Z₂ are Kerr cells and N₁, N₂ are Nicol prisms (Wien-Harms 1928).

The duration of continuous light pulses (i.e. without phase jumps) was a topic of interest in quantum theory, regarding the “length” of a photon. Thus, it was attempted to measure the time it took light to eject electrons from a metal surface (Lawrence and Beams 1927) but the results were probably not significant. E. Rupp (1928) investigated whether the spectrum of a monochromatic light beam which was chopped into short segments by a Kerr cell was altered in a particular way. This was in continuation of experiments that he had done in collaboration with A. Einstein to test certain aspects of quantum theory. Later however, it
has become evident that an account by Rupp in 1926 on the former experiments was mostly fiction (see the compilation by A.P. French in the journal Physics in Perspective 1, 1999), and so were papers published by him after 1930. Stauffer (1930) in fact pointed out deficiencies in Rupp’s (1928) procedures and improved on his experiments (Fig. 3) but did not obtain any unexpected results regarding the spectrum of the chopped beam.

**Fig. 3.** Stauffer (1930) investigated how the shape of the 546.1 nm green spectral line in a light beam from the mercury lamp on the left-hand side is changed when chopped into segments by the Kerr cell K. The spectrum is dispersed by the Lummer-Gehrcke plate L whose resolving power is increased by the Nicol prism N₃.

I. W. Beams and F. Allison (e.g., 1927) measured the time that it took the Faraday effect to become established in fluids upon the sudden application of a magnetic field. With his collaborators, Allison later developed from this a method of chemical analysis, which was also supposed to indicate what isotopes of each element were present in a fluid. One result announced by him around 1931 was that a heavy isotope of hydrogen existed. This prompted H.C. Urey to initiate an extensive research project to isolate this isotope and study its properties, see e.g. Urey (1934). The project yielded important results, for which Urey was awarded the Nobel prize in 1934. In that year it was also demonstrated (Phys. Rev. 47, 310-315 and 546-548, cf. a lecture by I. Langmuir reproduced in Physics Today, Oct. issue 1989, p. 36-48) that all the magneto-optical work of the Beams and Allison group was based on instrumental artifacts and its results were therefore totally meaningless!

The Faraday effect and Kerr cells in communications technology

A short paper by W. Lucas (1882) was among the first appearances in print where the possibility of transmitting pictures by wire was discussed. Like many later suggestions,
Lucas’ idea was based on the fact that the electrical conductivity of selenium metal depends on its illumination. He envisaged varying the light intensity with a pair of Nicol prisms, one rotating relative to the other.

Two years later a young man, P. Nipkow, was granted German patent no. 30105 on an “electrical telescope” to send a pattern of light dots in sequence between distant locations. A key element of his invention was a pair of rotating discs with a number of small perforations arranged in a spiral. The total transmission time had to be so short (0.1 second) that the dots appeared as a picture. The receiving apparatus contained Nicol prisms, and the light intensity passing through them was to be controlled by means of the Faraday effect, i.e. the rotation of the plane of polarization in heavy glass or CS₂ by a strong magnetic field. Sutton (1890) proposed a similar system as that of Nipkow, however employing the Kerr effect instead of the Faraday effect in his receiver.

These devices may not have been actually constructed at that time. Crehore and Squier (1897) tested a Faraday-effect telegraphic receiver, but their system was probably considered too complex to be practical. Stephan (1906) also describes equipment for transmitting images, his receiver employing the Faraday effect in heavy glass. The first system acknowledged to have been demonstrated with success was introduced by G. Rignoux (1914) in 1909. He sent pictures of four capital letters. At the receiving end the illumination was controlled in the same way as in Nipkow’s patent, i.e. through the use of the Faraday effect in CS₂. L.J. Leishman is also said (Isakson 1922) to have employed this effect in receivers for his commercial telegraphic and wireless transmission of photographs around 1920.

Nipkow put his Faraday-effect invention away until he retired in 1919. After he had improved his synchronized spiral-hole discs, his new patent on these (issued in 1924) was purchased by the firm Siemens & Halske in 1930. The German Biographic Encyclopedia states that A. Karolus had constructed a television receiver based on a modified Kerr cell in 1924, which indicates that it was superior to the Faraday-effect arrangement. F. Schröter asserts in Physikalische Blätter v. 24, 1968 that this convinced the technical community of the practicality of television. In the years to follow, Karolus patented several pieces of equipment containing Kerr cells, for use in communications and other fields.

In some of the first attempts at sending television pictures to be projected on large screens (by E.F.W. Alexanderson (Fig. 4) in 1930, J. L. Baird in 1931-32 and by Fernseh AG in 1933 or 1934), Kerr cells were also employed. Baird mentions this possibility in a patent application already in 1925. See Wright (1932), news items in The Times 6 Jan. 1931, and an account by R. Barthélemy in Revue Scientifique, 9 Dec. 1933. Scheduled transmissions began in Berlin in the Spring of 1935 and 15 screens were installed for public viewing (Fig. 4), but the transmitting station was destroyed in a fire in the late summer. Baird seems to have made use of Kerr cells for television displays until 1937, cf. a news item in The Times 7 Jan that year. However, cathode-ray tubes which were being developed rapidly in the 1930s, soon replaced both the Nipkow disks and the Kerr cells in television technology.
Around 1926, the above-mentioned A. Karolus and associates at the Siemens and the Telefunken companies had begun using his improved type of Kerr cell to make copies of documents that had been scanned with photocells in distant locations and transmitted by telephone or wireless. This was quite analogous to the more modern fax technology; however, it was not at all a new concept as other methods had been in use for that purpose since 1907 (cf. a paper by A. Korn in Die Naturwissenschaften in 1925). Following extensive tests, a commercial service was inaugurated at the end of 1927 to transmit photographs, bank documents, fingerprints of criminals, engineering drawings and the like between Vienna and Berlin. See Fig. 5. A news item on similar picture transmissions between Britain and the U.S. appeared in The Times 4 Feb. 1929, and E.V. Appleton (1929) described technical improvements in this service later that year. Incidentally, Appleton was at that time investigating how radio waves were propagated through the earth’s ionosphere or were reflected from it. He discovered among other things that the ionosphere acts on these waves as a doubly refracting substance, due to effects of the geomagnetic field. For his researches, Appleton was awarded the Nobel prize in physics in 1947. Kerr cells continued to be used in receivers for transmitted pictures at least until the mid-1930s (Küpfmüller 1936).

With the aid of Kerr cells, it is also a simple matter to use amplified sound oscillations to modulate a light wave. Tests of the application of this method to telephone communications were made around 1930 (e.g. West and Jones 1951) but it proved impractical as lasers and fiber optics had not yet arrived on that scene. The same technique was also tested in recording a sound track onto movie films (Zworykin et al. 1928, Gallahan 1931). Gibson (1929) considers U.S. talkie production still to be in its early stages, while according to him a company in Germany is already producing good-quality movies where a Kerr cell controls the sound. The method was in use into the 1930s according to Pauthenier (1932), Waetzmann (1932, Ch. 12) and Bruhat (1942, p. 518). Major firms (such as Westinghouse) on both sides of the Atlantic were taking out many related patents. However, the fluid most advantageous for Kerr cells is nitro-benzene which is both quite poisonous and sensitive to impurities which accumulate in it during use. Around 1950, attempts were initiated to employ the Pockels
effect (see below) in ammonium phosphate crystals, to make movie sound tracks (Carpenter 1953) and to replace Kerr cells in various other applications.

Fig. 5. Receiver outfit for transmission of single pictures or documents, from Grimsehl's Lehrbuch der Physik, 1931. The signal from the antenna (top left) is amplified and fed to the Kerr cell. This modulates the light coming from a carbon arc (bottom left) which falls on photographic paper wrapped around a synchronized rotating and moving drum. A typical test picture for transmitting (from an RCA publication, 1938) is on the right.

Kerr cells and the speed of light

The first suggestions to use the Kerr effect in light-speed measurements appeared in 1899, and Brunhes (1900) showed with the aid of a CS$_2$ Kerr cell that the speed of X-rays was of similar order of magnitude as that of light. Brace (1905a) proposed an experiment involving Kerr cells, to estimate the earth’s speed relative to the aether. Gutton (1911a, Fig. 2) compared the speed of light in air with that of electromagnetic waves propagating along wires, and found a difference of less than 1%. Gutton (1911b) also used Kerr cells to confirm certain theories regarding the so-called group velocity of light waves in dispersive media.

Around 1925, A. Karolus of the previous section, Gaviola (1926) and others discussed the possibility of measuring the speed of light directly with this technique. Results of such determinations (made indoors, for the first time) were published by Karolus and Mittelstaedt (1928) and by Mittelstaedt (1929). Here, a Kerr cell activated by high-frequency high-voltage oscillations (3-7 MHz, 6000 V) was in the role of a light gate, and a calibrated vacuum-tube oscillator served as a clock to measure the time it took a light beam to travel a known distance of some 330 m (i.e. four times back and forth between mirrors in the lower part of Fig. 6). Later, speed-of-light measurements were made with Kerr cells by Anderson (1937) and Hüttel (1940). In their work, Nicol prisms were employed, but in determinations published by Anderson in 1941 and by E. Bergstrand in 1950 (see West and Jones 1951, Jenkins and White 1957) the prisms were replaced by Polaroid polarizing sheets.

Due to certain problems with the Kerr cells which were not discovered until later, the light-speed determinations made with them in 1928-41 yielded values that were too high by 15 km/s or more. Measurements by A.A. Michelson in 1924-27 on a 35-km path in air with a
rotating-mirror octagon turned out to give better results, although this may have been due to chance (cf. Birge 1941). By 1948 the light speed in air was known so accurately that it was possible to measure distances in geodetic surveys by means of very stable high-frequency oscillators and Kerr cells. This technique was in use for a couple of decades (Rinner and Benz 1966). It may be added that A. Karolus returned to light-speed measurements around 1960, employing among other things laser light, a piezoelectric modulation technique, and Nicol prisms (Karolus and Helmberger 1967).

Fig. 6. Left: Measurement of the speed of light, made by Karolus and Mittelstaedt (1928). They employed the Kerr cells $K_1$ and $K_2$ whose voltages are governed by a stable MHz oscillator circuit, to measure the travel time to and from the mirror $S$ (about 41 m each way). This replaces the toothed wheel in the 1849 measurement by H. Fizeau. Anderson (1937) and Hüttel (1940) used a similar technique, with improvements such as a photocell detector and better frequency control. Right: A diagram (from Wikipedia) of one application of Pockels cells. Linearly polarized light enters from below and is converted into circularly polarized light. It can then be split into two linearly polarized rays going in different directions.

Pockels cells

The demand for polarizing prisms must have increased with the spread of laser devices after their invention around 1960 (cf. Nester and Schroeder 1967, Coetzee 1976). In a laser beam, considerable energy travels through a small cross-sectional area, and this can lead to rapid damage of Polaroid sheets or their successors due to the heat produced (e.g. Zirkl 1961). I have not looked much into the early history of the many applications of lasers, but one topic will be described briefly here.

Electrical fields have a certain effect on the refractive indices of crystals, which is named after F. Pockels (1891, and later). It occurs in those crystal classes which lack a center of symmetry (20 out of 32), i.e. the classes that exhibit piezoelectricity. This makes the effect
different from the Kerr electro-optical effect which only is found in liquids and gases. (Another difference between these two is that in the Pockels effect the change in refractive index is a linear function of the field strength, while the magnitude of the Kerr effect is proportional to its square). A transparent crystal fitted with two electrodes can then function as a controllable phase compensator (Fig. 6) for light in the same way as a Kerr cell. With a Nicol prism on each side of the crystal, we have a means of modulating the intensity of light beam, even shutting it off altogether.

Suggestions for technical applications of this effect in e.g. television sets had already appeared around 1930, cf. British patent no. 375856 and U.S. patent no. 1,879,138 (both granted in 1932) concerning the use of Rochelle salt (a hydrated tartrate) to control light. Among other suitable crystals is the compound NH$_3$H$_2$PO$_4$, i.e. ammonium dihydrogen phosphate (ADP). After WWII the Polaroid Corporation intended to base production of color television sets on the Pockels effect in this material (Land 1950), but very different approaches by competitors won that race. Before 1960, crystals of other compounds from the same symmetry class were being grown artificially for use in optics technology, including LiNbO$_3$ and KH$_2$PO$_4$ (KDP). However, the light beam needs to be quite monochromatic and parallel (see Goldstein 1986). These conditions could not be fully met until laser light became available in the 1960s.

In recent decades, people have mostly employed the so-called longitudinal Pockels effect, where the imposed electric field is parallel to the light beam. This variant of the effect primarily occurs in cubic or uniaxial piezoelectric crystals not having optical activity. It limits the choice to two crystal symmetry classes, KDP still being a popular candidate. Pockels cells do not require as high electric voltages as Kerr cells, have shorter response times (less than 1 ns), and are probably easier to handle. They are now found in many types of apparatus in the ultraviolet, visible and infrared ranges of the spectrum. Applications include fiber-optics communications, video recording, and laser distance meters. Non-linear Pockels effects have also become important in optical technology.

This account is condensed from Chapter 38 and Sections 30.2, 39.6 of "Iceland spar and its influence on the development of science and technology in the period 1780-1930" (Report JH-2015-02, updated to April 2017) at this website. The principles and early history of the Faraday, Kerr, and Pockels effects are dealt with in another short account on the website. Sources referred to here may be found in p. 341-470 of the Report.