

John Kerr and his effects found in 1877 and 1878

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(Received 1 October 2008; final version received 2 October 2008)

John Kerr's famous communications in the Philosophical Magazine in 1877 and 1878 are revisited, interpreted, and illustrated in terms of a present-day view of Kerr spectroscopy and applications thereof.

Keywords: magnetization; polarization

1. Introduction

*"I was led some time ago to think it very likely, that if a beam of plane-polarized light were reflected under proper conditions from the surface of intensely magnetized iron, it would have its plane of polarization turned through a sensible angle in the process of reflection."*¹

This is the very first sentence in the introduction of John Kerr's first article in the Philosophical Magazine from May 1877 [1], the abstract thereof simply stating: *On Rotation of the Plane of Polarization by Reflection from the Pole of a Magnet*. John Kerr, a Mathematical Lecturer from the Free Church Training College, Glasgow, probably did not envisage that, more than a hundred years later, we still speak of the polar Kerr effect, although horseshoe-shaped magnets are no longer used. Together with his second communication to the Philosophical Magazine [2] in March 1878, dealing with the *Reflection of Polarized Light from the Equatorial Surface of a Magnet*, these two publications gave rise not only to one of the most frequently applied experimental tools in magnetism, namely, Kerr spectroscopy, but also became immensely important in the technology of quality control of magnetic recording media. Even the expression magneto-optics, which was used deliberately in Kerr's second paper, became a standard term in physics textbooks.

One has to recall that at the time of John Kerr, optics was already a well established and amply formalized field of research, while magnetism virtually remained an enigma. The verb 'mesmerize'², which is still occasionally used in present-day colloquial English, is a reminder of how much the miraculous phenomenon magnetism raised scientific interests in the past (and still does) and of all the superstitions still connected with the 'magic power' of magnets. Clearly enough, in 1877 John Kerr could only give an account of the optical set-up in his experiments. In fact, he does not even attempt to give an explanation of the newly found property of magnetic matter, although Maxwell's theory of electromagnetism [3] has already been around for a few years.

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2. Kerr's first discovery

Kerr's experimental set-up consisted of a magnet (“*an upright horseshoe electromagnet*”) with polar surfaces perpendicular to the axes of the core of electromagnet (“*they had to be smoothed and brightened by polishing, a process I found troublesome and excessively tedious . . .*”), a light source (“*a paraffin-flame, narrow and very bright . . .*”) and two Nicols³, one of which was placed between the light source and the magnet, the other one between the magnet and the observer. Since he put an iron wedge very close to the top of the magnet, he only had to observe the slit between the two magnetic systems. Before switching on the electromagnet, he first organized the two Nicols so that the light beam shining on only one pole of the electromagnet was completely extinguished. Then, when the circuit was closed, the streak of light immediately reappeared. This experiment was repeated many times, varying the angle of incidence (direction of the incoming beam relative to the surface normal of the pole) between 60° and 80°. After having found that the interaction of light with the magnetic system obviously changed the character of the light, he tried to classify this new phenomenon by varying the set-up of his experiment, namely, by changing the orientation of the first and the second Nicol and by investigating the influence of the orientation of the pole (north pole or south pole) by alternating the direction of the current.

In varying the orientation of the first Nicol he found out, for example, that complete extinction was not necessary to enhance a reappearance of light whenever the electric circuit was switched on. Leaving the first Nicol untouched it turned out that the north pole restored light while the south pole did so only, “*weakly or not at all.*” Or, to use Kerr's words:

“The chief cause for my perplexity was what I may truly call the exquisite delicacy of the magnetic mirror as a test for fixing the positions of the plane of polarization of the incident light.”

These findings led him to arrange his observations into two groups, namely, the pairs (R, N) and (L, S), where R and L refer to right- and left-handed light – as he claims – produced by very small rotations of the first Nicol to the right (R) and to the left (L), and N and S correspond to the north and south poles of the electromagnet. Even more important than this clear scientific approach using classical optics, was the additional observation that

“the beam reflected by the mirror of magnetized iron is certainly not plane-polarized, as is the incident beam (and the reflected beam also before magnetization); for when the light is restored by magnetic force from pure extinction . . . it cannot be extinguished by any rotation of the second Nicol in either direction; nor (as far as I can judge of these faint effects and with the present means) is the light sensibly weakened by any such rotation.”

In short, John Kerr, in his very first attempts to characterize the interaction of light with a magnetic system, found that the polarization state of the reflected beam was changed when a plane-polarized incident beam shone on the surface of a horseshoe magnet.

3. Kerr's first set of experiments: the ‘polar geometry’

In Figure 1 the experimental situation, as described by John Kerr, is reproduced. Since Nicols are hardly in use nowadays, the essential features of such a prism are recalled in Figure 2. By choosing (as indicated in Figure 3, in the absence of a magnetic field) the extraordinary beam (plane-polarized parallel to the optical axis) generated by the first

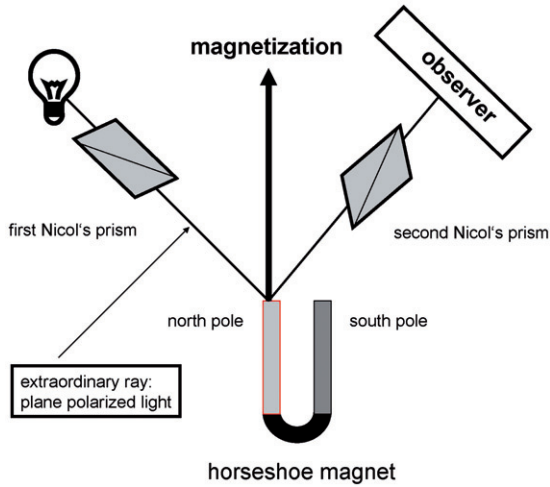


Figure 1. Experimental set-up used by John Kerr as described in [1]. According to his descriptions, the angle between the incident beam and the surface normal (magnetization) is between 60 and 80° .

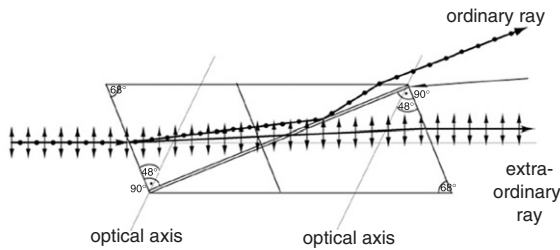


Figure 2. A ‘Nicol’ (Nicol’s prism) produces two rays: the ordinary ray is perpendicularly polarized to the optical axis, the extraordinary one parallel to it.

Nicol, by turning the second Nicol by a sufficient amount is totally extinguished. On switching on the magnetic field in the state of complete extinction, the beam passing through the second Nicol is only weakened and cannot be brought to complete extinction. “*The effect is very faint at best,*” as John Kerr notes. Clearly enough this effect can be reproduced an indefinite number of times by switching on and off the magnetic field.

His second observation is a bit more involved, since now he manipulates the first Nicol, “*ever so little*” as he stresses. Surely what happens is a variation of the angle of incidence, see Figure 4 . This is about all that can be said using only classical optics. As John Kerr realized, it seemed to be important whether the incident beam falls on the north or the south pole of the magnet. Depending on which one he chooses, a restoration of light may or may not be observed. At this stage we are a little bit left in the dark to judge what actually happens, since considering only sketches such as Figures 3 and 4 does not help in this case. His careful distinction between the north and right pair (rotating the first Nicol) and the south and left, see above, does not really help us to understand his observations and the discussion that follows. However, one has to realize that in 1877 this was most

Operating the second Nicol

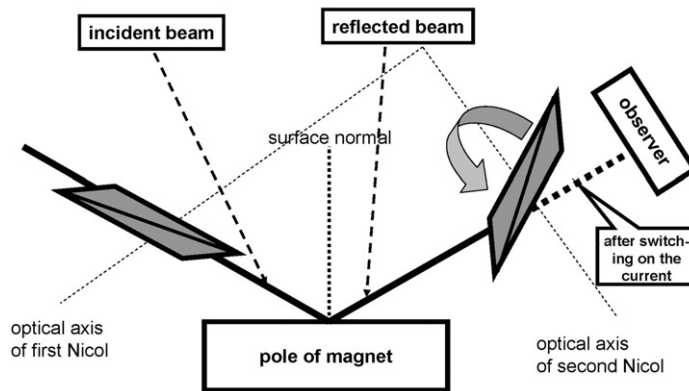


Figure 3. Stage 1: the second Nicol remains untouched and the magnetic field is switched off. The reflected beam can be clearly observed. Stage 2: the Nicol is rotated so that, in the absence of a magnetic field, complete extinction is observed. In the presence of the magnetic field ‘a streak of light’ appears.

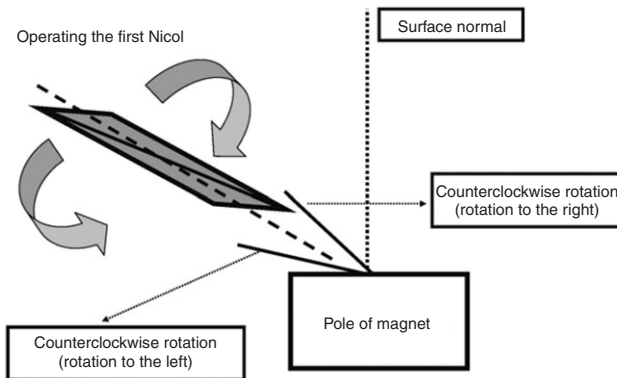


Figure 4. Operating the first Nicol. Very small rotations simply change the angle of incidence slightly.

likely the best characterization of the results he had obtained that could be given. Interestingly enough, in the formal discussion of his experimental data he already mentions the possibility of an elliptic polarization of the reflected light beam.

4. Kerr’s second set of experiments: the equatorial geometry

In his second contribution to the *Philosophical Magazine* [2], John Kerr extended his studies to a longitudinal arrangement of the magnetization; see Figure 5 showing the set-up for the ‘longitudinal’ magneto-optical Kerr effect.

“In trying to carry forward the magneto-optic inquiry which formed the subject of my last communication to this Magazine, I proceeded to examine a lateral face of an intensely

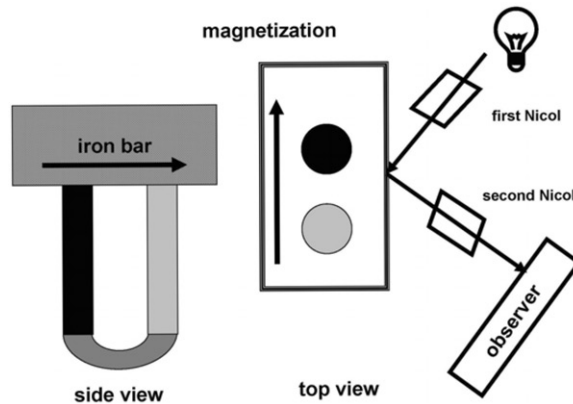


Figure 5. John Kerr's second set of experiments, now usually termed longitudinal magneto-optical Kerr effect (L-MOKE).

magnetized iron bar as a reflector, and had the pleasure of obtaining good effects in the first trial."

One of the main outcomes of his second communication was the observation that the angle of incidence played a crucial role.

"The intensity of these optical effects (complete extinction or not; note added by PW) of magnetization varies very noticeably with the angle of incidence. About incidence 85° the effects are very faint, but perfectly regular and much better than merely sensible; about incidence 75° they are more distinct, and very sensibly stronger; about incidences 65° and 60° they are comparatively clear and strong, a good deal stronger than at 75° ; about incidence 45° they are still pretty strong, but very sensibly fainter than at 60° ; about incidence 30° they are again very faint, much the same as at 85° ."

John Kerr carefully tried to vary all major pieces in his set-up: the two Nicols, the angle of incidence, and the direction of the current, needed to feed his electromagnet. He even tried to use different 'mirrors' to reflect the light beam: an iron bar, a polished steel knife, etc. In the end he had to summarize his discoveries as follows:

"The first facts of magneto-optics discovered long ago by Faraday, their more immediate consequences discovered afterwards by Verdet and others – these and the additional facts now published by myself must be all included ultimately under one physical theory." (Signed Glasgow, 21 January 1878.)

5. A present day view of the Kerr effect

All the variations in the set-up of his experiments that John Kerr described so carefully in every detail, already give a first impression of the complexity of magneto-optical phenomena. It seems that even today John Kerr's demand for an ultimate physical theory of his discovery is still partially wishful thinking. The reason for this regrettable fact is that in principle two types of physical levels have to be considered and combined, namely the quantum mechanical response of a magnetic material to an external electromagnetic field ('incoming beam of light') and the propagation of the reflected beam in terms of classical optics (Figure 6), the link between these two steps being an appropriate mapping of the

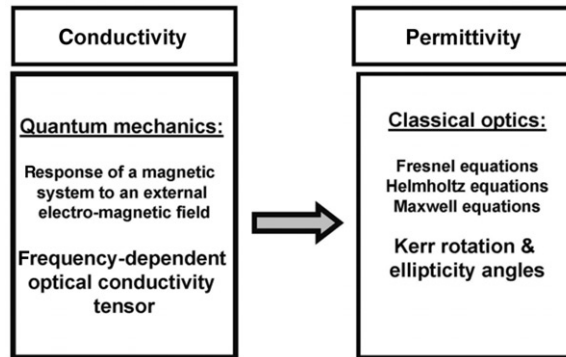


Figure 6. Mapping of the quantum mechanical information onto quantities defined in classical optics.

(microscopic) frequency-dependent optical conductivity $\sigma(\omega)$ onto the (macroscopic) permittivity $\epsilon(\omega)$:

$$f: \sigma(\omega) \rightarrow \epsilon(\omega).$$

As can be guessed in each step, in the quantum mechanical as well as in the classical optical description, special requirements have to be met. Furthermore, in most experimental or technological studies, only Kerr signals are recorded, in quite a few cases not even stating the actual geometry used. Experimental studies of (absolute) Kerr rotation and ellipticity angles are very rare indeed.

5.1. The quantum mechanical part

Since the frequency of the light source is, in the optical regime, a classical treatment of the electric field ('light') in the electric dipole, approximation can safely be used. Below, only the necessary requirements for the quantum mechanical part are listed without discussing the corresponding details. These can be picked up, for example, in Refs. [4–6] and from the references cited therein.

- The solid magnetic system has to be treated as a semi-infinite system, since the magnetic properties in near-surface regions are usually quite different from those deep inside the system. This applies particularly when describing magnetic overlayers on non-magnetic substrates. In many cases, it will turn out that Kerr spectroscopy is very surface sensitive!
- Since the orientation of the magnetization can be in-plane or perpendicular to the planes of atoms, an approach has to be used that includes, in an appropriate manner, spin-orbit interactions.
- The applied approach to evaluate the optical conductivity tensor has to include all contributions to the optical conductivity.

The above three requirements imply, for example, that bulk-like descriptions (three-dimensional periodicity) have to be avoided just as well as approaches in which an empirical Drude term has to be added.

5.2. The classical optics part

Of course, right from the beginning the actual geometry of the Kerr, set-up has to be taken into account, namely the angles of the incident beam with the surface normal and the magnetization. In principle the optical characterization has to start deep enough in the semi-infinite system under investigation in order to guarantee that, by adding even deeper atomic layers, the permittivity no longer changes; i.e. becomes 'intrinsic'. Then, by a subsequent use of the Fresnel, Helmholtz, and Maxwell equations (see also Figure 6), atomic-layer dependent (complex) refraction indices, electric- and magnetic-field amplitudes have to be determined. From these in turn, iteratively the so-called surface reflectivity matrix,

$$R_{\text{surf}} = \begin{pmatrix} r_{xx} & r_{xy} \\ -r_{xy} & r_{xx} \end{pmatrix}, \quad (1)$$

can be calculated, finally yielding the Kerr rotation and ellipticity angles. For an excellent introduction, in particular to the mentioned optical aspects, see Ref. [7].

5.2.1. Polar magneto-optical Kerr effect

Expressed in spherical coordinates, one immediately obtains the complex reflectivity of the right- (+) and left-handed (-) circularly polarized light as

$$r_{\pm} = r_{xx} \mp ir_{xy} = \frac{E_{\pm}^{(r)}}{E^{(i)}} = |r_{\pm}| e^{i\Delta_{\pm}},$$

where $E_{\pm}^{(r)}$ is the complex amplitude of the reflected right- and left-handed circularly polarized light, and $E^{(i)}$ that of the incident light. The Kerr rotation θ_K and ellipticity ϵ_K angles are then given by

$$\theta_K = -\frac{1}{2}(\Delta_+ - \Delta_-),$$

$$\epsilon_K = -\frac{|r_+| - |r_-|}{|r_+| + |r_-|},$$

or, expressed as a complex Kerr angle, as

$$\Phi_K = \theta_K + i\epsilon_K.$$

For an illustration of the definition of the Kerr rotation angle in the case of the polar Kerr effect and normal emission, see Figure 7.

5.3. The two-media approximation

In viewing a layered system that consists of only two optically homogeneous media, namely vacuum and the rest (Figure 8), an approximate formulation of the complex Kerr angle (polar geometry) is occasionally still in use, in which elements of the optical conductivity tensor (microscopic quantity) are directly related to the complex Kerr angle

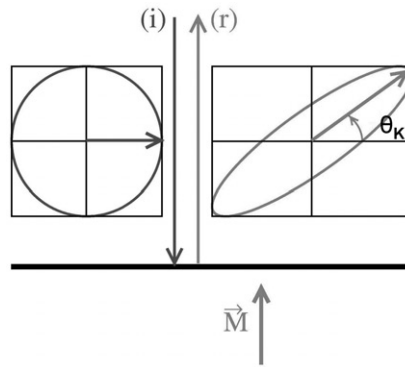


Figure 7. Definition of the (polar) Kerr rotation angle in the case of normal emission. Left: polarization of the incoming light beam, right: polarization of the reflected light beam.

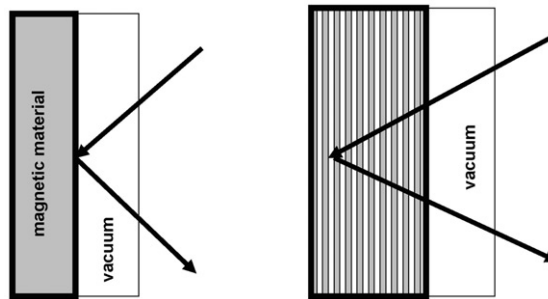


Figure 8. Left: The so-called ‘two-media’ model, right: an optical model that takes into account all interferences and reflections of the reflected beam.

(macroscopic quantity):

$$\Phi_K = \frac{\sigma_{xy}(\omega)}{\sigma_{xx}(\omega)} \left(1 - \frac{4\pi i}{\omega} \sigma_{xx}(\omega) \right)^{-1/2}.$$

It should be noted that in the case of the ‘two-media’ model, the penetration depth of the incident beam is zero!

6. An example for the use of different geometries

Perfect examples to illustrate both papers by Kerr, the polar as well as the longitudinal Kerr effect, are so-called (spin) reorientation transitions. It is well known by now that a noble metal serving as a substrate and covered by an increasing number of (epitaxially grown) monolayers of a magnetic 3D element, most likely shows a change in the orientation of the magnetization from perpendicular, to the surface, to an in-plane arrangement. A thin film of Fe on Au(100) is such an example. Clearly, as long as the orientation of the magnetization is parallel to the surface normal, the polar Kerr effect

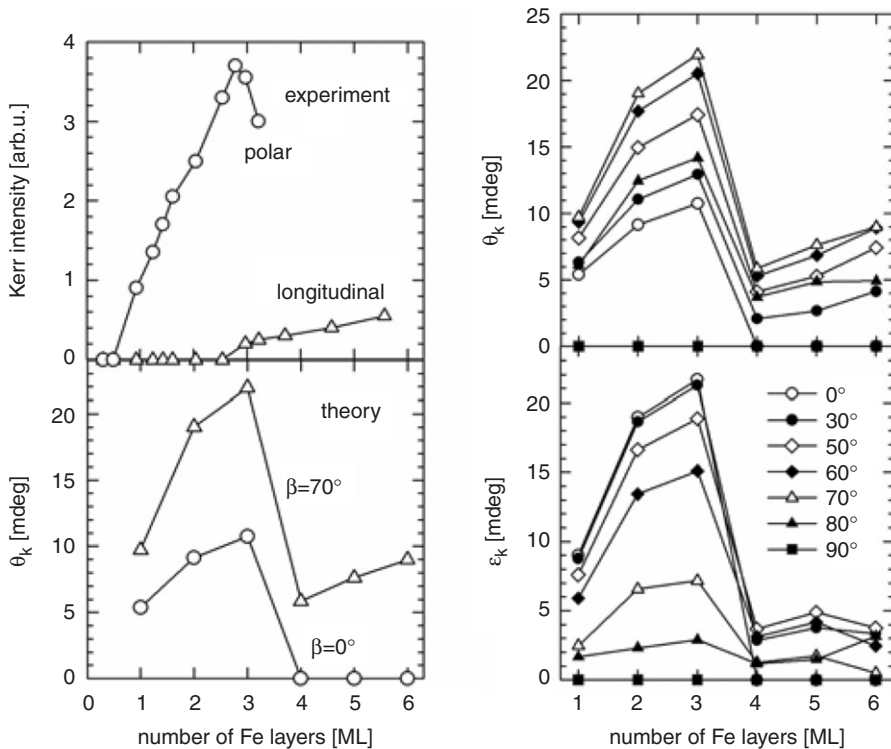


Figure 9. Left: Top: Surface magneto-optical Kerr experiments by Liu and Bader [8]. Circles denote the measured data for the polar, triangles for the longitudinal Kerr set-up. Bottom: calculated values of the Kerr rotation angle θ_K in the case of p -polarized incident light and for the magnetic ground state of $\text{Fe}_n/\text{Au}(100)$. Circles mark the theoretical results for a normal incidence ($\beta=0^\circ$) and triangles for an incidence of $\beta=70^\circ$. Right: Calculated Kerr rotation angle (upper part) and ellipticity angle (lower part) for different angles of incidence for the corresponding magnetic ground state of $\text{Fe}_n/\text{Au}(100)$. See also Figure 10. From Ref. [9].

will yield a distinct signal, which vanishes at a critical thickness of the magnetic film, while in a longitudinal geometry a vanishing Kerr intensity is observed. Increasing the thickness of the magnetic film beyond this critical thickness, the orientation of the magnetization being now in-plane, just the opposite finding occurs: a finite intensity in the longitudinal geometry is found and no signal in a polar arrangement. Exactly this kind of behavior is shown in the left half of Figure 9, in which available experimental data are compared with *ab-initio* theoretical calculations of the Kerr rotation angle. The right half of this figure is devoted to Kerr's observation that, particularly in a longitudinal arrangement, the angle of incidence (see in particular Figure 10) becomes important for the actual value of the Kerr rotation angle. As can be read from this figure, the changes in the Kerr rotation (ellipticity) angle with increasing angle of incidence are by no means straightforward: they jump in value. This illustrates nicely the experience made by John Kerr in 1878 when dealing with a longitudinal arrangement (see the quotation above).

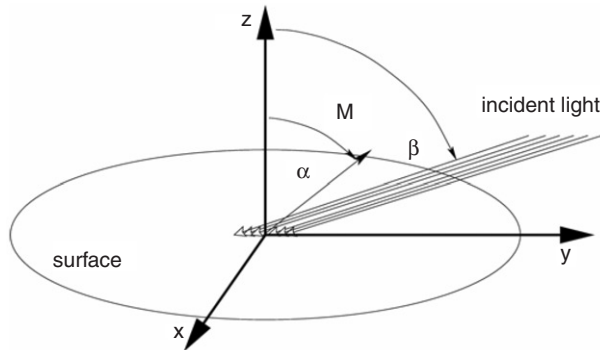


Figure 10. Kerr set-up in the case of p -polarized incident light. Here α and β specify the orientation of the magnetization M and the direction of the incident light, respectively. Both are specified with respect to the surface normal. Note that the magnetization always lies in the plane of incidence. From Ref. [9].

7. Summary and conclusions

The main point in John Kerr's first paper, namely the discovery that the polarization state of plane-polarized light is changed when reflected from a magnetic surface, turned out to be of crucial importance for a wide field of applications a century later. In his second communication, he addressed the question of reflections from a magnetic 'mirror' with the orientation of the magnetization lying in the plane of the 'mirror'. The observation made again gave rise to many applications, in particular in the quality control of magnetic storage media. Clearly, a paraffin flame is no longer used as a light source, but as a suitable laser. It is a well-known fact by now that the search for perpendicularly oriented magnetic materials, and for the most adequate laser frequency, led to a dramatic improvement in the efficiency of magneto-optical media.

This, however, is by no means the end of developments in Kerr spectroscopy. From so-called pump-probe experiments with magnetic materials, namely by using two lasers (the second one retarded only a few femtoseconds from the first one), it became clear that Kerr signals could be recorded even on the time scale of femtoseconds. It seems that what started with John Kerr's discoveries in 1877 and 1878, will eventually lead in the future to a completely new physics of magnetic phenomena, perhaps even to technological devices with access times of femtoseconds.

Notes

1. All quotations from Kerr's publications are in italics.
2. F.A. Mesmer (1734–1815) discovered what he called *magnétisme animal* (animal magnetism) and others often called mesmerism. In 1779 Mesmer wrote an 88-page book *Mémoire sur la Découverte du Magnétisme Animal*, for further details see http://en.wikipedia.org/wiki/Franz_Mesmer
3. William Nicol, 1770–1851. A 'Nicol' consists of two properly cut pieces of Iceland spar (rhombohedral calcite crystal), see also Figure 2, glued together with a special adhesive (Canada balsam, refraction index 1.54). The ordinary and the extraordinary ray have different refraction indices, namely, 1.66 and 1.49, respectively. The ordinary beam is reflected totally at the interface between the two crystal pieces, while the extraordinary one can pass through. Very

often the side of the reflected ordinary beam is blackened in order to achieve complete absorption of this particular beam. The plane-polarization of the ordinary beam is perpendicular to the optical axis, that of the extraordinary beam is parallel to it. See also: http://en.wikipedia.org/wiki/Nicol_prism

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