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APPLICATIONS NEWS FOR USERS OF PHOTOELASTIC MODULATORS

FALL 2001

MAGNETO-OPTIC KERR EFFECT

Magnetism in a New Light

by Professor Ron Atkinson, Queen's University, Belfast, UK

ABOUT THE AUTHOR

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Professor Ron Atkinson is Head of the Condensed Matter Physics and Materials Science Division in the Physics Department at the Queen's University of Belfast. He is also a Fellow of the Institute of Physics, a senior member of IEEE, and Honorary Visiting Professor in the Department of Physics at the University of Salford. Professor Atkinson took up a lectureship in the School of Maths and Physics at Queen's Belfast in 1973 and is leader of the Thin Film Magneto-Optics and Magnetics group and QUB-Director of the Northern Ireland Centre for Advanced Materials. He has 28 years experimental and theoretical experience in thin film optics, magneto-optics and magnetics of multilayered nanostructures.

You may also learn more about Professor Atkinson and the magneto-optic Kerr effect by visiting his website at *http://wwwparent.qub.ac.uk/mp/con/magnetics_group/magnetoptics.html*.

Introduction

In 1845 Michael Faraday carried out a series of experiments to determine whether linearly polarised light, when passed through a transparent insulator, was influenced by strong electric fields. Despite Faraday's renowned experimental skills, he failed to observe any effects. Frustrated, he turned his attention to magnetic fields. Eventually, using quality optical glass that he had made himself some twenty years previously, he was able to detect a small magneto-optical change that became known as the *Faraday effect*[1]. Amazingly, 30 years later in 1875, the Rev. John Kerr, a close collaborator of William Thompson (later Lord Kelvin), repeated Faraday's quest to demonstrate that electric fields can influence the polarisation state of optical radiation as it passes though a transparent material. It is a tribute to the keen experimental skills of Kerr that, where Faraday had failed, he was successful. Using a variety of materials, including glass and later a number of liquids, he demonstrated the electro-optic effect. In the following year on the 26th August 1876, at the annual meeting of the British Association for the Advancement of Science held in Glasgow, the Rev. John Kerr announced a further discovery of an effect that has since become known as the *Kerr magneto-optic effect*[2]. Using linearly polarised light from a narrow paraffin flame, Kerr showed that a change in polarisation state occurred on reflection from a polished, soft iron pole-piece of a strong electromagnet (Figure 1). *(continued on page 2)*

Excicor® Wins the 2001 R&D 100 Award

June 29, 2001, Hinds Instruments was notified that Exicor had been selected as one of the 100 most technologically significant products of the year. Through the combined effort and talented contributions of many Hinds employees, Exicor won the prized R&D 100 Award for the development of the technological innovation used in our birefringence measurement systems.

Now in its 39th year, the R&D 100 Award program is international in scope. Entries from the most prestigious companies, national laboratories, research organizations and universities are received then nominated in open competition. The news media refers to *(continued on page 4)*

Figure 1: Kerr's original elctromagnet Courtesy of the Hunterian Museum, Glasgow.

Magnetism in a New Light...

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Given that the changes produced by this effect are usually very small (< 0.1deg) and are difficult to observe, even with modern laser sources, the achievement of Kerr was spectacular. It is sobering to realise that the effects discovered over 125 years ago by Kerr now form the basis of a substantial magneto-optic recording industry.

Within the Physics Department at the Queen's University of Belfast the work of Kerr continues, where linear first-order magneto-optical effects are being used to study the magnetic properties of single and multiple layer materials. To make observations of Kerr magneto-optical effects on bulk samples is difficult enough. To do so at the atomic level, without modern light sources and optical modulation techniques, would be virtually impossible. However, it is the particular technological advantages, robustness and convenience of the Photoelastic Modulator (PEM) system that makes it possible to detect magneto-optical signals produced by sub-atomic magnetic layers relatively easily.

Operational Principles

The polar Kerr effect is illustrated phenomenologically in Figure 2, where linearly polarised light is incident normally (or obliquely) on a sample that may be magnetised (**M**) in a direction perpendicular to the surface. After reflection, in addition to the usual Fresnel amplitude component ***r***, a small orthogonal Kerr component ***k*** appears that, in combination with ***r***, leads to elliptically polarised light with a complex Kerr rotation θ_k and ellipticity ε_k given by $\theta_k + i\varepsilon_k \approx k/r << 1$. A full description of the effect, therefore, requires measurements of both rotation and ellipticity and it must be remembered that each angle may be very small. There are numerous photometric and ellipsometric techniques available for making measurements of polarisation states of optical radiation. However, the simplest are often slow in operation and precision is restricted by source instabilities and imperfections in the optical components, such as non-zero extinction coefficients of polarising prisms. In most situations, even when considering shot-noise limited cases and imperfect components, modulating the optical beam usually increases precision. Modulation may, for example, be accomplished using a simple chopper, a Faraday magneto-optical modulator, or polarisation modulator such as the PEM. The usefulness of the chopper is restricted and precision is usually not great. The Faraday modulator is excellent and allows one to approach theoretical shot-noise limits of precision. However, such modulators are often heavy, cumbersome and limited in spectral range. More importantly, it is not possible to measure both Kerr rotation and ellipticity simultaneously. In contrast, the PEM is lightweight, has a wide spectral range and operates at high frequency (***f*** = 50 kHz) enabling fast measurements to be made. In addition, since the PEM modulates the polarisation state of the light passing though it, it is possible to make measurements of both rotation and ellipticity at the same time and with a precision matching that of the Faraday modulator.

One of the arrangements for the detection of the polar Kerr effect, using the PEM, is also illustrated in Figure 2.

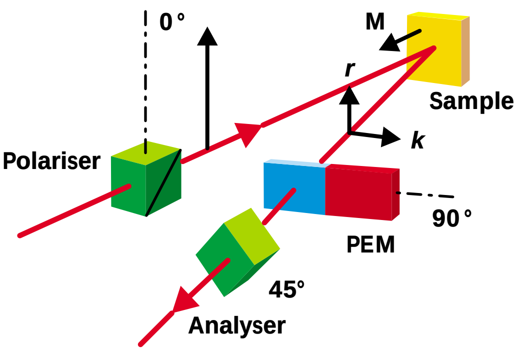

Figure 2: Arrangement for the detection of the polar Kerr effect.

After the sample, the radiation passes through the modulator and analyser (set at 45 degrees to the principal planes) and then falls onto a detector. The detected intensity may be written

$$I = I_0(1+2(\theta_k \cos\delta - \varepsilon_k \sin\delta)) \qquad (1)$$

where I_0 is related to the source intensity and reflectivity of the sample and δ is the phase introduced by the PEM and is given by

$$\delta = \delta_0 \sin \omega t \quad (\omega = 2\pi f). \qquad (2)$$

Normalising the detector output to the dc component I_0 one has to first– order in θ_k and ε_k

$$\frac{I}{I_0} = (1+4J_2\theta_k \sin 2\omega t - 4J_1\varepsilon_k \sin \omega t + \dots), \qquad (3)$$

where J_n is the n^th Bessel function. The beauty of the photoelastic modulation technique is that fundamental (ω) and second harmonic (2ω) signals are generated that are directly proportional to the Kerr ellipticity and rotation, respectively. Furthermore, the normalisation of these signals with respect to the measured dc level serves to reduce the effects of fluctuations in source intensity. Using lock-in amplifiers tuned to each frequency, and following simple calibration procedures, the Kerr effect can be fully characterised dynamically in real-time and with considerable speed and sensitivity. In the case described below, the precision was typically of the order of 1 arc sec with an instrumental time constant of 100 ms. However, this was limited by the mechanical stability of the experimental system rather than shot-noise or laser instabilities.

In situ dynamic studies of film growth.

With this level of instrumental sensitivity, the team at Queen's has followed the growth dynamics of multiple layers of materials such as Co-Pt, Co-Pd, and Co-Au, etc., that have potential for next generation magneto-optic information storage. Both *in situ* ellipsometry and Kerr polarimetry have been used to monitor the evolution of the physical properties of various layers in real-time as films are grown, layer-by-layer, in a sputter deposition vacuum chamber (Figure 3). The results of such experiments give tremendous insight into both the way in which material properties develop, as well as fundamentally new phenomena. The data that is produced, if obtained comprehensively, may be used to optimise the geometrical structure of the media in order to bring out the maximum potential for applications in magneto-optic read-out.

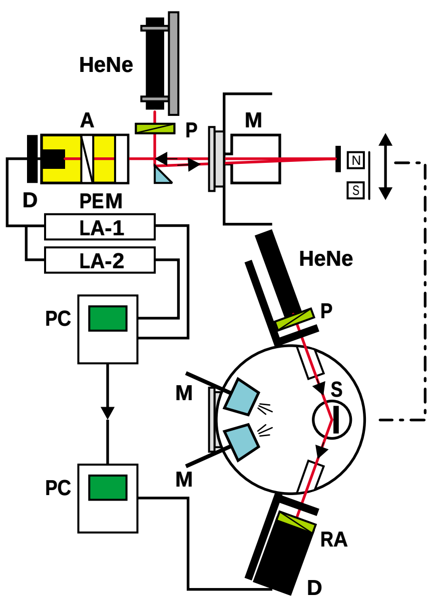

Figure. 3.
Schematic diagram of the deposition system.
HeNe: helium neon laser, A: analyser, P: polariser,
RA: rotating analyser, PEM: photoelastic modulator, M: magnetron,
PC: computer, S: substrate, D: detector, LA-1: lock-in amp (50kHz),
LA-2: lock-in amp (100kHz), F: field switch.

One of the more spectacular observations that has been made recently has been the oscillatory nature associated with the Kerr signal in Co-Au multilayers[3]. Figure 4 shows an example of the actual traces of the Kerr ellipticity signal monitored during the deposition of a ten period Co-Au multilayer on a 10 nm Au buffer layer. The rapid increase in the Kerr signal is seen on the deposition of the single monolayer of Co that, of course, is the only ferromagnetic component. During the deposition of the Au there are clear oscillations that are due to electronic transitions to thickness dependent quantumwell levels in the Au. Whether these are new magneto-optic transitions or not is a matter of debate. What is clear is that here, for the first time, they are observed reproducibly, repeatedly and with great clarity in multiple bi-layers and this is a tribute to the usefulness of the PEM technique. Another important feature of this trace is the behavior of the signal during the deposition of the Co layer.

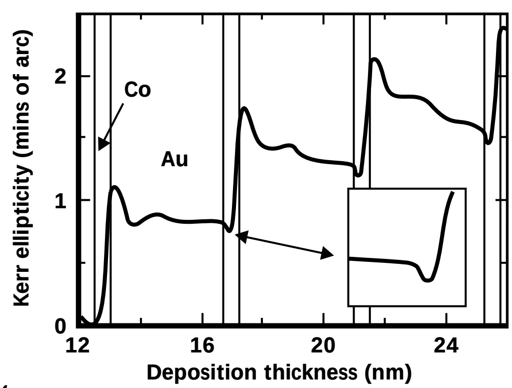

Figure 4.
Measured variation of the polar Kerr ellipticity during the deposition of the first three bi-layers of a glass/12.5Au/10(0.5Co/3.75nm), multilayer

Shown inset, it is clear that the magnetic properties of the Co layer do not switch on immediately. The first few atoms are deposited and, being optically absorbing, they reduce the Kerr signal until eventually they cluster together in sufficiently large numbers to collectively switch on their ferromagnetic behavior. When this occurs there is a rapid increase in the Kerr signal as the Co atoms form ordered perpendicularly orientated moments, as illustrated in figure 5. This occurs at an equivalent layer thickness of about 0.16 nm. *(continued on page 4)*

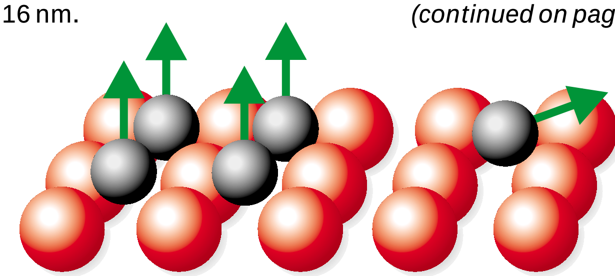

Figure. 5. Schematic showing perpendicular, ordered Co moments formed in clusters on a Au surface.

In the case of Co-Pd multilayers, observations of this type reveal vastly different behaviour[4]. Figure 6 shows real-time traces of Kerr rotation and ellipticity corresponding to the repeated deposition of Co and Pd onto a 10nm Pd buffer layer. In this case, the Kerr signal produced on the deposition of the Co is several times larger than one would expect on the basis of the magneto-optical activity of Co alone. The reason is simple. As the ferromagnetic properties of the Co switch on there is an immediate polarization of the Pd atoms in the underlying buffer layer and therefore the observed Kerr signal results from a combination of both the Co and the Pd. That the Pd is polarized is clearly demonstrated as further Pd is added on top of the Co. This too becomes polarized and

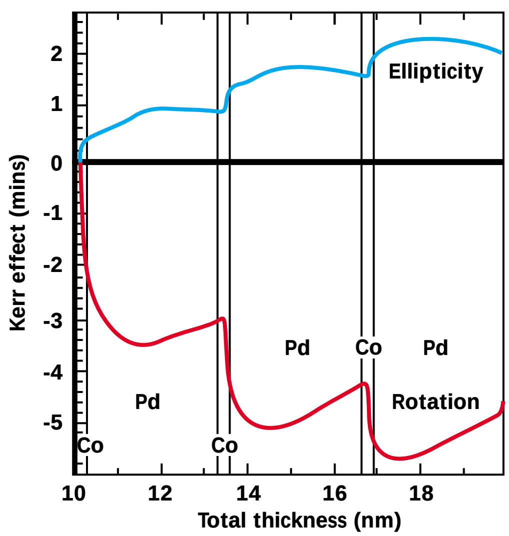

Figure 6. Measured and calculated complex polar Kerr effect during the continuous deposition of three Co-Pd bi-layers onto a Pd buffer layer.

there is a further increase in magneto-optic signal. Eventually this reaches a maximum and begins to fall back towards zero. If enough Pd were added, this would reduce the magneto-optical signal to zero owing to the effects of optical absorption. In addition to the clear evidence for the induced magnetic moment of Pd, it is also clear that this moment varies with distance from the interface. Optical and magneto-optical modeling using classical electrodynamic theory enables the Belfast team to determine the distribution of the moment of the Pd atoms (Figure 7) and also the fundamental optical and magneto-optical properties of the materials in their ultrathin film form. From such data it is possible to calculate the thicknesses required for the Co and Pd layers that will maximise the performance of the Co-Pd system for magneto-optic readout[5]. Interestingly, the Co-Pt system, that is assumed to have very similar properties to those of Co-Pd, forms in a completely different way. In the case of Co-Pd the perpendicular anisotropy is very strong and is effective immediately on the formation of the Co monolayer and remains throughout the deposition of the Pd. In contrast, the strong anisotropy in Co-Pt does not appear until the Pt is added when alloy formation at the interface is clearly indicated in the Kerr signal traces.

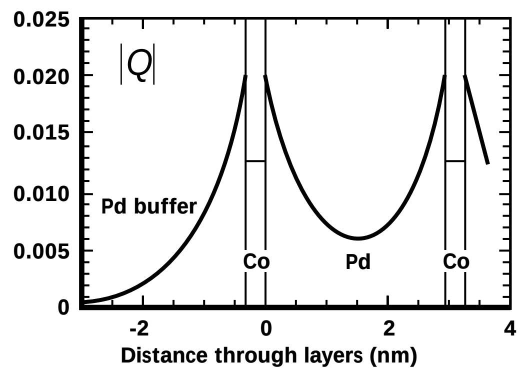

Figure 7. Spatial profile of the modulus of the magneto-optic Q-parameter, proportional to magnetic moment, as a function of distance through a Co-Pd system.

The information that is being revealed by these techniques is considerable and has given insight into the formation processes in multilayered systems as well as providing physical data from which optimised material performance can be determined. *(continued on page 6)*

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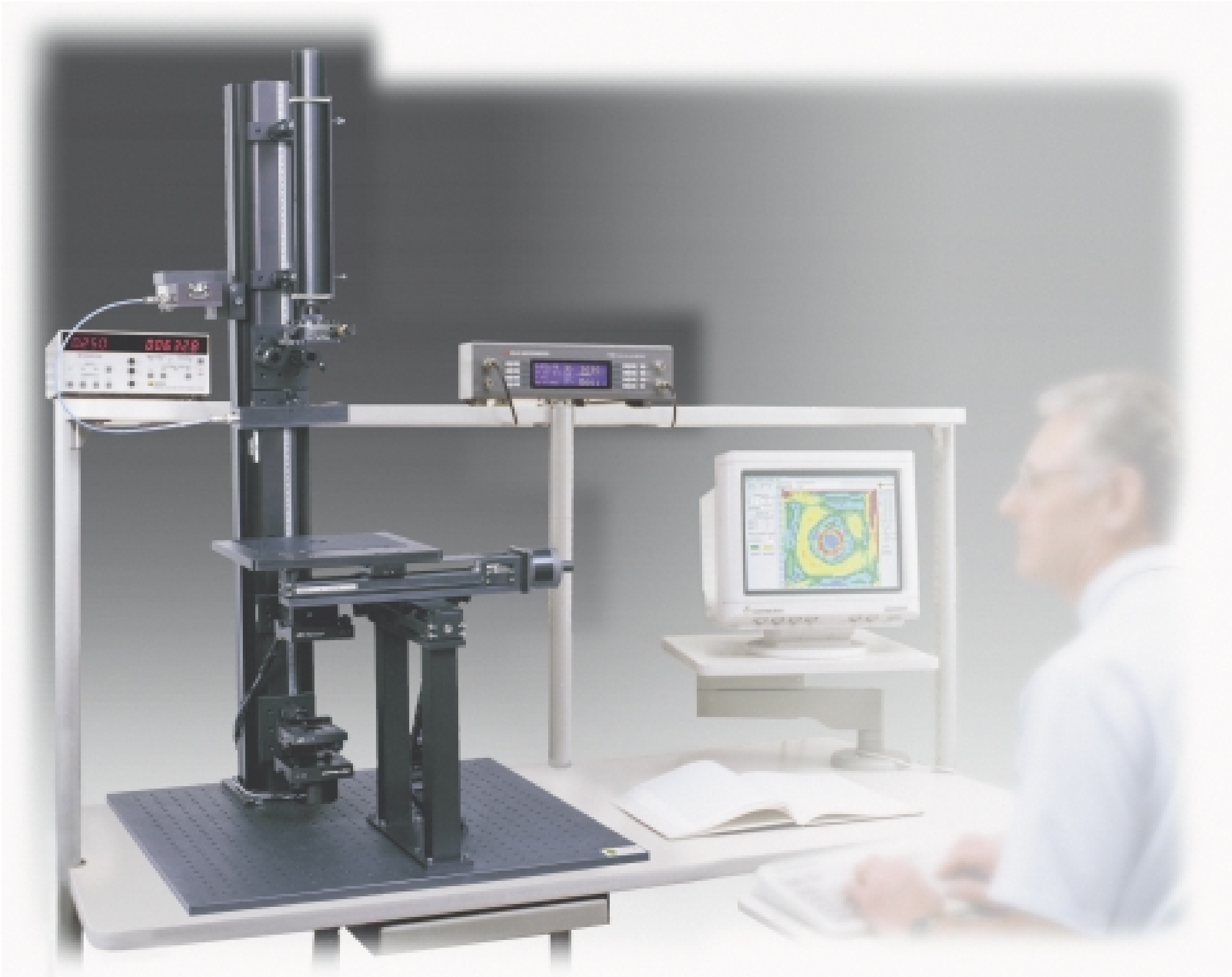
the R&D 100 Awards as "The Oscars of Invention" and the "Nobel prizes of applied research." Prior winning innovations include Polacolor film, the fax machine, the digital watch, the Automatic Teller Machine, and the Nicoderm® anti-smoking patch. Over seventy experts from a wide range of disciplines use a series of technical criteria to select 100 of the most important, unique, and innovative technologies from among thousands of nominations.

As noted in our communication with the R&D 100 Award committee, Exicor technology to date has been responsible for contributing to the solution of several significant technical challenges in the semiconductor optical lithography field. These successes signify major strategic advances for the semiconductor industry as well as those who rely on their product improvement stream.



Hinds Instruments Introduces the Exicor® R&D Series for Research and Commercial Metrology

The same award winning technology developed for the Exicor Birefringence Measurement Systems is now available in a modular, laboratory bench-top instrument for researchers and laboratory quality control professionals. Like the Exicor AT Series of industrial manufacturing systems, the Exicor R&D Series' cutting-edge sensitivity is the product of Hinds Instruments' PEMLabs℠ technology group which also pioneered the ultra-low birefringence photoelastic modulator (PEM). This research quality instrument was developed for any application requiring low-level birefringence analysis and characterization of a variety of materials. Birefringence characterization is increasingly important in optical materials used in many advanced applications. These include glass, crystal materials, plastic, polymers, silicon wafers, laser materials, thin films, and LCDs.

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Exicor birefringence measurement systems are currently used throughout the world by industry leaders in the development and manufacture of precision optical materials for complex, high resolution optical imaging systems. The Exicor R&D series now offers this unsurpassed technology in a variety of options which allows for adaptation to any application where high sensitivity, low-level birefringence measurements are critical.

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NEWS AND EVENTS

- Hinds Instruments has launched R&D projects to design and build systems for measurement of low-level birefringence at UV and IR wavelengths. Initial target wavelengths are 157 nm, 194 nm, and 1550 nm.
- During LASER 2001, in Munich, Germany, Dr. Baoliang (Bob) Wang presented his paper "A Near Infrared Linear Birefringence Measurement System Using a Photoelastic Modulator."
- As requested by International SEMATECH, Dr. Wang made a presentation titled, "157 nm Birefringence Measurement System Using PEM Technology," at the CaF2 Birefringence Workshop during SEMICON West on July 18, 2001 in San Francisco, California.

UPCOMING TRADE SHOWS

DATE/2002	EXHIBIT/CONFERENCE	LOCATION
Jan 22-24	Photonics West 2002	San Jose, CA
Mar 5-6	Microlithography 2002	Santa Clara, CA

Magnetism in a New Light

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There can be no doubt that the real-time dynamic *in situ* technique utilising the PEM provides a wealth of information that is lost to more conventional *ex situ* experiments where dynamic information, that may only last for a few seconds, is unavailable to the observer.

In addition to the exploitation of linear magneto-optics and, unimagined by the Rev. John Kerr, there are new developments in magneto-optics that are providing new opportunities for the application of optics to the study of magnetic media. The use of high intensity femtosecond lasers to generate second harmonic light, resulting from nonlinear interactions with magnetic media, is promising to provide additional information about magnetic surfaces and interfaces, particularly in centrosymmetric systems[6]. This new area is being pursued in several centres around the world, including Belfast, and it is anticipated that the new information will complement that which is already being produced by the application of *in situ* linear magneto-optics to the study of magnetic multilayered systems.

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