Chapter 4

Fields

Michael Faraday is widely regarded as the greatest experimental scientist ever. He not only showed great skill and ingenuity in the laboratory, he also brought deep insight to bear on the problems he studied. He was able, far more than most, to see what issues were worth studying and to persevere with them even when he met with persistent failure.

From 1820 to 1831, working at the Royal Institution in London, Faraday established the laws of electromagnetic induction: the relationship between magnetism and electricity which produced the electric motor, the dynamo and the transformer. He then took up the subject of electrochemistry in which he established some fundamental relationships between electricity and matter. From all this he came to believe that all physical forces and phenomena must be related, even interchangeable—he would have had great sympathy with modern attempts to find a 'grand unified theory of everything'. In 1845 he wrote:

> I have long held an opinion, almost amounting to conviction. . . that the various forms under which the forces of matter are made manifest have one common origin; or in other words, are so directly related and mutually dependent. . . this strong persuasion extended to the powers of light. . . and (I) have at last succeeded in *magnetizing and electrifying a ray of light*. . . . (his own italics)

After exhaustive tests over a long period with completely negative results, on 13 September 1845 he tested some samples of glass that he had made some years earlier under a contract from the Royal Society. He found that when light was passed through a piece of very dense

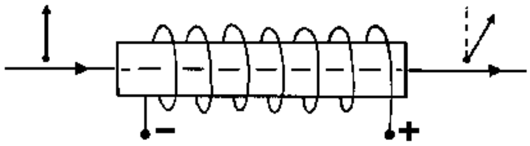

Figure 4.1. Faraday magneto-optical rotation. A rod of very dense glass is placed along the axis of a magnetic field, here represented by the coil of an electromagnet. Polarised light passing along the rod is rotated as indicated by the vector arrows.

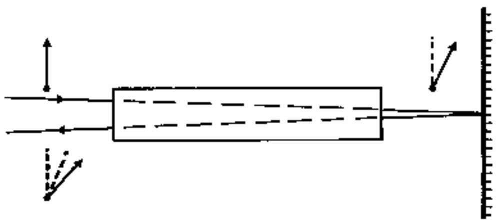

Figure 4.2. If the rotated beam of polarised light in figure 4.1 is reflected back down the glass rod, it is rotated further before emerging beside the source. This shows that it is the light itself that is influenced, not the material of the glass.

lead silico-borate glass along the direction of a magnetic field, then the direction of polarisation was rotated (figure 4.1). This effect is now universally known as Faraday magneto-optic rotation or simply the Faraday effect (although he discovered many other effects too).

He soon showed that the same effect was present, although to a lesser degree, in other materials, both solids and liquids. Its properties were that the rotation depended on the material used (a characteristic now known as the Verdet constant of the material), on the length of the material within the field and on the strength of the magnetic field itself. But the big surprise was that if the rotated beam was reflected back towards the source, the rotation was not reversed on the return trip and thus cancelled out, but occurred again so that the rotation was doubled (figure 4.2). This may seem paradoxical because light passing the opposite way in the same field is, of course, then being rotated the opposite way. But clockwise as seen from one direction is anticlockwise when seen from the other direction. So a ray whose polarisation has been rotated clockwise (say from 12 to 1 o'clock as seen from behind), and then reflected back by a mirror is now passing the other way and sets off vibrating at 11 o'clock as seen from behind; during the second passage through the glass it will be rotated anticlockwise, thus increasing the earlier rotation to end at 10 o'clock.

Michael Faraday had originally assumed that the magnetic field would somehow stress the atoms within the glass, in which case one would expect any effect on light to depend on its direction of travel and to be 'unwound' again on the way back. But the actual situation suggested that light itself must have some directional property across its line of travel. Faraday said it is as if the glass itself is somehow rotating in the magnetic field and carrying the light round with it. One must remember that the very nature of light was not at all well understood at the time but this discovery was clearly important in giving a new angle on it. Twenty years later, in 1865, James Clerk Maxwell of King's College, London published the now famous Maxwell equations, for which he acknowledged the influence of Faraday and specifically the magnetic rotation of polarised light. The new theory described light as an electromagnetic wave and predicted a much larger class of such waves of other wavelengths. We now know of electromagnetic waves extending from radio, with some wavelengths of over a thousand kilometres, through microwaves, infrared, the visible light spectrum at less than 1 micrometre (μm), ultraviolet, x-rays and, finally, gamma-rays less than 10^{-14} m: a continuous range of over 20 orders of magnitude. All can be described as the same interaction of a magnetic and an electric field, and all propagate at 'the speed of light'.

Faraday rotation is easy to demonstrate although the very dense glass that gives a large effect is extremely expensive. Figure 4.3 shows a homemade device using a 'borrowed' rod of density 6.63 g ml $^{-1}$ (most glasses have a density of around 2.5 g ml^{-1}). It is 1 cm in diameter and 5 cm long and is held in a plastic bobbin wound with thick wire, giving a resistance of half an ohm. A polaroid is fixed across one end and a rotatable polaroid cap on the other end is crossed with the first to give extinction of the light. Passing current from a 12 V lead–acid battery through a heavy-duty push button then allows light to shine through brightly. For demonstration to an audience, the device is put over a hole in a cardboard mask on the patten of an overhead projector. A very similar device, though not using polaroids of course, that was made by Michael Faraday himself is on display in the Faraday Museum at the Royal Institution in London.

In one of his papers, Faraday said that fused lead borate gave an

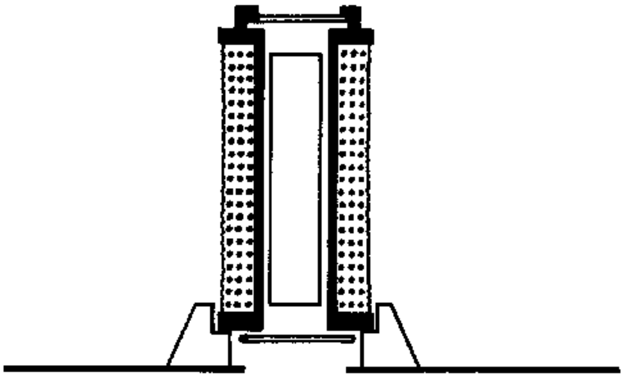

Figure 4.3. A Faraday rotation device for demonstration on an overhead projector. As it draws about 25 A from a 12 V accumulator, the power can only be maintained briefly, so a push button is used instead of a switch. When 'fired' it allows a bright beam to pass through crossed polaroids, thus demonstrating an extremely important historical phenomenon. The effect is made more clearly visible if the device stands over a hole in a cardboard mask.

effect that was equal to the best heavy glasses he tried. Two of my colleagues kindly helped me to try this. John Cowley, a glassblower, made a rod of fused lead borate with materials and a mould supplied by Isaac Abrahams. This rod is 55 mm long and has a density of about 6.25 g ml^{-1}. It is now mounted in its own coil (as in figure 4.3), using 500 g of enamelled copper wire 1.35 mm in diameter. It gives excellent results for direct viewing or for demonstration on an overhead projector, although the rod is coloured greenish rather than being clear.

The principle of the Faraday effect can be used to make a true one-way system for light—an optical isolator, invented by Rayleigh in 1885. The principle of this is shown in figure 4.4. Linearly polarised light is rotated by 45° by a magnetic field so that it passes through a second polariser orientated obliquely at the appropriate angle. But light passing in the opposite direction and starting with polarisation at 45° is then rotated further so that its exit polariser then appears crossed and extinction occurs.

Faraday rotation is not just a laboratory effect for it is used in astronomy to measure the strength of magnetic fields in the space between stars. Where it is possible to infer the original polarisation of

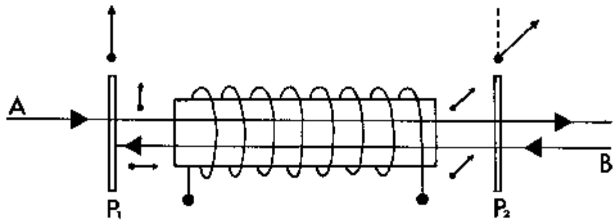

Figure 4.4. The principle of a one-way optical isolator. The left polariser P_1 is here set vertical; the light passing through it from A is then rotated clockwise by 45° by a Faraday rotator cell and passes freely through the right polariser P_2, set obliquely at 45°. But the lower beam of light entering from B is first polarised at 45° and then rotated to become horizontal so that it is blocked by the left polariser. The device is therefore transparent in one direction and opaque in the opposite direction. Large vector arrows show the setting of the polarisers, small ones show the polarisation of each light beam.

a light source (say when it is produced by scattering—see chapter 6), then any change in the direction of vibration during its journey to earth indicates the magnetic fields in the intervening space. In this way it has been shown that the interstellar magnetic field within our galaxy is about one-millionth of the strength of our own terrestrial magnetic field and is aligned along the spiral galactic arms.

Michael Faraday also tried to influence light with electric fields but he never succeeded. In the previous quotation, his use of the word ‘electrifying’ clearly refers to electric currents through the electromagnets used in some of his experiments, and not to a direct effect of electricity on light. It was not until 1875, 10 years after Maxwell’s theory and 3 years after Faraday died, that this was achieved by John Kerr. A Kerr cell (figure 4.5) consists of two sets of small plate electrodes immersed in nitrobenzene. They are set diagonally between crossed polaroids. An electrical pulse of several thousand volts then twists the direction of vibration so that the light can pass the second polaroid. Such a device, which is then sometimes called a Karolus cell, is used as the shutter for very high speed cameras because its action is extremely rapid. With a suitably short pulse of high voltage, the cell can be opened for as little as 1 ns (10^{-9} s), or one-thousandth of a millionth of a second. The light pulse that passes will then be only about 30 cm long—less than 1 foot! It may help to visualise such a short duration by saying that,

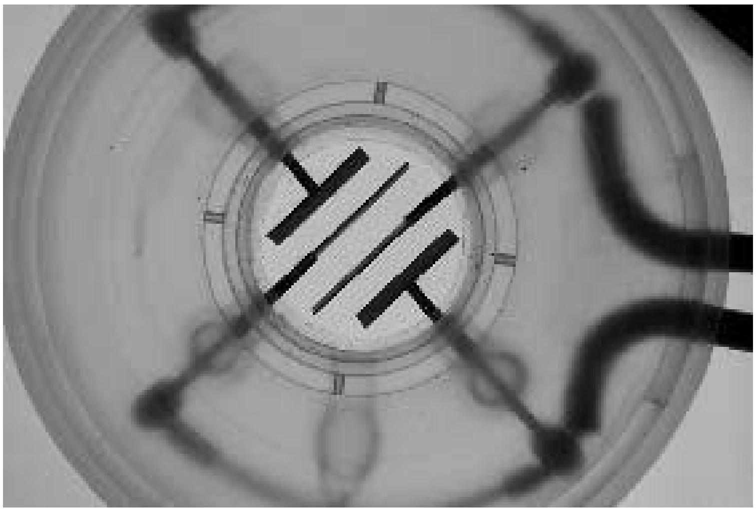

Figure 4.5. A Kerr cell showing the electrodes that are connected together alternately in pairs and immersed in nitrobenzene. The electrodes are set at 45° to the vibration directions of two crossed polaroids. A momentary application of several kilovolts rotates the direction of polarisation so that the combination becomes transparent. It can be simply demonstrated on an overhead projector, using a piezo-electric gas-lighter as the high voltage source.

going the other way, 10^9 s is nearly 32 years. Such very short exposure times allow sharp pictures to be taken of extremely fast events such as the course of development of explosions.

In 1877 John Kerr also showed that when polarised light is reflected from the surface of iron or certain other metals, alloys and even some oxides, the direction of polarisation is rotated by the application of a magnetising field. This effect is therefore called the magnetic Kerr effect.

Both Faraday cells and Kerr cells can be used to modulate the intensity of light for communication through light fibres. The currently fashionable form is a Pockel cell which is like a solid state version of the Kerr cell that works in a crystal, often potassium dihydrogen phosphate, instead of in liquid nitrobenzene. The physical basis of this device is somewhat different in detail but the effect is virtually the same. It can vary the light entering the optical fibre so rapidly that up to 100 000 telephone calls or 100 television channels can be transmitted simultaneously down a single tiny fibre.

So Michael Faraday's experiments in this area alone led to profound insights into the very nature of light, to a method for exploring features of the galaxy, to the fastest camera shutters and to the latest techniques for high-speed communications. There really is no way of knowing where a discovery may lead, no matter how 'rarified' it or the work leading to it may seem at the time.