1

Introduction

1.1. Uses of interferometry

Interference occurs when radiation follows more than one path from its source to the point of detection. It may be described as the local departures of the resultant intensity from the law of addition, for, as the point of detection is moved, the intensity oscillates about the sum of the separate intensities from each path. Light and dark bands are observed, called interference fringes. The phenomenon of interference is a striking illustration of the wave nature of light and it has had a considerable influence on the development of physics. Young's observation and explanation of the interference of the beams through two holes provided the basis for Fresnel's wave theory of light and the same experiment has been used as the foundation of modern coherence theory. Einstein's special theory of relativity is supported by the negative result of the Michelson–Morley experiment [Shankland, 1973].

Derived from interference is the technique of interferometry, now one of the important methods of experimental physics, with applications extending into other branches of science. The father of visible-light interferometry was Michelson [1902, 1927], who was awarded in 1907 the Nobel prize in physics for 'his optical instruments of precision and the spectroscopic and metrological investigations he has executed with them'. Applications to other spectral regions are more recent: the first use of interferometry in radio astronomy was reported in 1947, and infrared interference spectroscopy is even more modern.

A list of the fields of application of interferometry is given in Table 1.1. These applications range through the electromagnetic spectrum from X-rays to radio waves and apply also to acoustical waves [Magome *et al.*, 1981], electrons [Endo, Matsuda & Tonomura, 1979], and neutrons [Bonse & Rausch, 1979]. Techniques are furthest advanced, however, for visible light. The table follows from the theory given in Chapter 7, which provides a general description of two-beam interferometers. This theory is the unifying theme for this study of interferometry, while convenient boundaries to the subject are provided by those that traditionally separate interference from the other main branches of physical optics: diffraction and polarization. In some respects this boundary is artificial: a diffraction grating is probably more logically treated as a multiple-beam interferometer, as is the equivalent system in radio astronomy. Further, it is often customary to treat certain examples of diffraction, such as the holograms of Gabor [1949], as due to the interference between the *direct* and the *diffracted* radiation from an object. All such phenomena will not be classed here as interference; phase-contrast microscopy, for example, is not included. Traditionally, the effects of diffraction caused by apertures within the interferometer are ignored in interference theory, but they must be taken into account when the wavelength is large or when very great precision is required.

Table 1.1. *Fields of interferometry*

Measurement		Applications
Direct	Derived	
(1) Fringe position	(*a*) Mean phase difference	(i) Length standard and wavelengths (ii) Length comparisons and machine control (iii) Refractometry (iv) Velocity of light
	(*b*) Phase variations	(i) Interference microscopy (ii) Microtopography (iii) Optical testing (iv) Hologram interference
(2) Fringe visibility	(*a*) Spectrum of source	Profiles of symmetrical spectral lines
	(*b*) Spatial distribution at source	Stellar diameters
(3) Full intensity distribution (position and visibility)	(*a*) Spectrum of source	(i) Direct interference spectroscopy (ii) Fourier spectroscopy
	(*b*) Spatial distribution at source	(i) Optical transfer function (ii) Radio astronomy

In Table 1.1, the spectral and spatial distributions are those of intensity and apply to a source outside the interferometer. The measurements of phase apply to a sample inside it and, in fact, the amplitude is also given in this case. An alternative classification of the applications of interferometry is therefore possible: for an external sample it measures the spatial and spectral distributions of the intensity; for a sample inside it measures the spatial distribution of the complex amplitude transmission factor, provided the radiation used is sufficiently monochromatic.

General introductions to interferometry have been given by Williams [1930] and Tolansky [1955] and more details of the instruments by Candler [1951]. More recent treatments are given by Françon [1956, 1966], and Dyson [1970].

1.2. Interference and coherence

Interference and coherence are the experimental and theoretical aspects of the same phenomenon. While radiation from two separate sources produces no interference (except over short time intervals), that from the same source travelling by several different paths may do so. Initially the words 'coherent' and 'incoherent' were used to describe the addition of radiation in these two cases. When two beams came from the same source, they were coherent (provided the source was sufficiently small and of a sufficiently narrow bandwidth) and would interfere when added together. If from different sources, they were incoherent and no interference was produced; their intensities added directly.

Later the idea of partial coherence was introduced and coherence was given a scale of values, derived from the amount of interference produced. In recent years, coherence theory has developed considerably beyond the field of simple interferometry, but the earlier results are of direct application. It is on this theory that most of this study of interferometers is based.

Recently, however, the development of lasers has made available a light source that produces pairs of beams that are highly coherent with each other for almost all interferometer arrangements. Their interference can be treated by a simpler theory, expressed in terms of trains of waves. This is the historical treatment of interference, which was very much an idealization before lasers.

1.3. Classifications of interferometers

There are two traditional methods of classifying interferometers: by the number of interfering beams and by the method used to separate these beams. Modern advances in interferometry have introduced new instruments and new applications that give rise to further classifications.

1.3.1. Laser or thermal source

One of these is in terms of the source of radiation that is used. Of the applications listed in Table 1.1, those listed under measurements of fringe position are measurements that can be made with any suitable light source. For these a laser is being increasingly used. But for the other applications the source cannot be chosen at will, since these are measurements of the properties of the source itself.

1.3.2. Number of beams

Interferometers are classed as *two beam* or *multiple beam* according to the number of beams that interfere. As the typical multiple-beam interferometer usually has many interfering beams, there remains a group of interferometers that are not directly included in these classes: those with three or four interfering beams. These may be considered as variants of the two-beam interferometer, to which they are more closely allied.

Two-beam interferometers produce interference fringes with a sinusoidal variation of intensity. In a multiple-beam interferometer, each pair of beams contributes a Fourier component to the fringe pattern. The fringe pattern is still periodic and, in principle, any periodic profile should be possible. However, most interferometers have profiles that approximate to a series of narrow spikes, the Dirac comb.

1.3.3. Separation of beams

Another traditional basis for classifying interferometers is by the method used to divide the light into separate beams. If the radiation from the source may pass through one of several apertures in the same plane, it is said to be separated into beams by *division of wavefront*. These beams are made up of radiation that has left the source in different directions. If the beams consist of radiation that has left the source in the same direction but is then separated by a beam splitter, there is said to be *division of amplitude*.

Interferometers with division of amplitude can be further subdivided according to the type of beam splitter used or the number of passes made through it. A simple *partially reflecting* beam splitter consists of a thin film, either metal or dielectric, usually on a transparent support: the classical part-silvered mirror is an example. One beam is the reflected light, the other the transmitted. Although such films affect somewhat the polarization of the beams, this effect is relatively unimportant.

But if a stack of layers is used with each surface at the Brewster angle, the two beams leave with orthogonal linear polarizations. Some of the modern variants of the Nicol prism [Thompson, 1905] will produce the same result, provided they are made to pass both the transmitted and reflected beams. A Rochon or Wollaston prism transmits the two beams, but they leave in different directions. Any of these can be used as a *polarizing beam splitter*. The two beams are then labelled by their states of polarization and will be affected differently by further polarizing components. Thus, a second beam splitter can bring the two beams together without the further splitting that would occur at a partial reflector. In certain interferometers, a birefringent material such as calcite is used, not only for the beam splitter, but also to provide the different paths for the two beams, one of which acts as an ordinary ray, the other as an extraordinary ray. This is then a *polarization interferometer*.

The third beam splitter is the *diffracting beam splitter* which has either a random or a periodic variation of (complex) transmission across its surface; its use is reviewed by Lohmann [1962*a*]. The incident light is then divided into a direct beam and one or more diffracted beams. When the transmission of the beam splitter is periodic, the fringes obtained with an interferometer consisting of two beam splitters in series have the special name of *moiré fringes*, and a new branch of engineering metrology has been built around their use [Guild, 1960; Takasaki, 1979].

Any inteferometer with division of amplitude can appear in three very different guises, depending on which of the three beam splitters is used. An example is shown in fig. 1. Each is a *lateral-shearing interferometer* which, from each ray from the source, produces two rays leaving some point in different directions. The first is the form due to Bates [1947]. It is completely adjustable, and both the angle between the rays and the position of their intersection can be varied. The polarization form is a Wollaston prism which, when placed between two polarizers oriented at $\pi/4$ to it, will give two interfering beams at a fixed shear. The last form is the Ronchi grating with one direct and several diffracted beams, any pair of which represents a shearing interferometer with a fixed shear. Although the last two forms are not adjustable, they can be made adjustable if two are used in series. In some circumstances, however, lack of adjustment is an advantage. Usually interferometers based on these last beam splitters are more compact and more stable than those based on the first type.

The change of shear with wavelength differs for each form. For the form with mirrors and partial reflectors, the shear is independent of wavelength. The Wollaston prism has a shear that increases as the wavelength decreases while the grating has a shear that is proportional to wavelength. The fringe spacing for this last type of interferometer is independent of wavelength

[Leith & Swanson, 1980] and the fringes appear as images of the rulings of the grating: moiré fringes are black and white, not coloured.

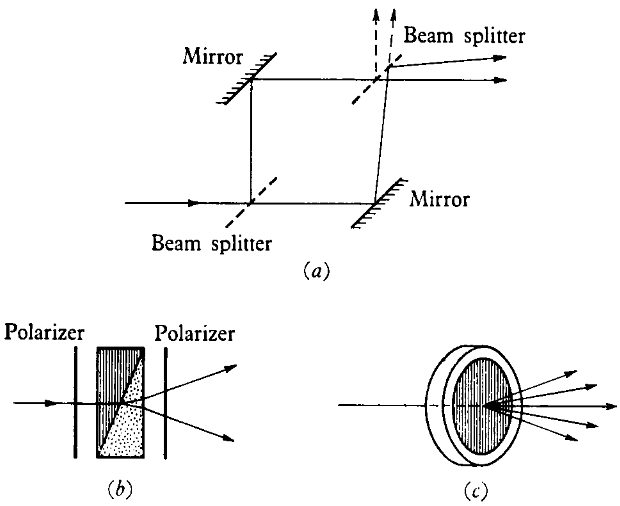
1.3.4. Number of passes

Each of these lateral-shearing interferometers may be described as a *single-pass* or *straight-through* interferometer. It will be seen later that there are often advantages in returning the radiation back through the same system to give a *reflex* system. If a sample being measured is inside such an interferometer, the radiation goes through it twice and the sensitivity is doubled by such a *double-pass* measurement. At the same time the second passage can be used to cancel out effects, such as shears, that would otherwise reduce or even destroy the visibility of the interference fringes.

1.3.5. Order of correlation

It will be shown later that a simple interferometer measures second-order correlations of the radiation field. Hanbury Brown & Twiss [1954, 1956] have developed a new class of interferometers, *intensity interferometers* or *correlation interferometers*, that measure fourth-order correlations. In principle, higher-order correlations can also be measured, but these have more limited application.

Fig. 1 Three forms of a lateral-shearing interferometer (*a*) form due to Bates [1947] with partially reflecting beam splitter; (*b*) birefringent form – a Wollaston prism; (*c*) diffraction form – a Ronchi grating.



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1.3.6. Hologram interference

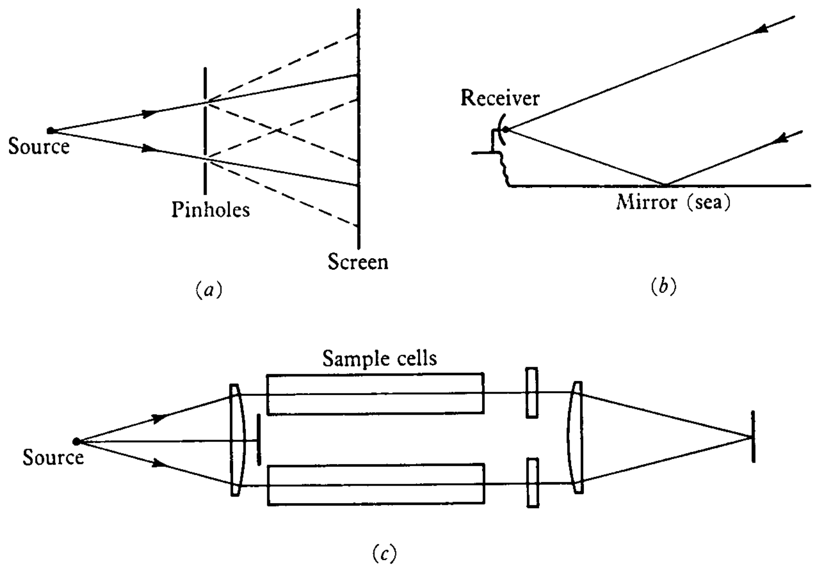
The new field of hologram interferometry has introduced a new class of interferometers and a new parameter, the time at which a wave was produced. Holograms can store waves so that they can be reconstructed later to interfere with either another stored wave or a wave produced directly. These two types of hologram interferometry are known, respectively, as *frozen-fringe* and *live-fringe* interferometry. A third method, *time-averaged* interferometry, is used to study vibrating specimens.

1.4. Basic interferometers

Some of the more important interferometers are introduced in figs. 2 to 5. Those in fig. 2 are two-beam interferometers with division of wavefront. The first is the classical experiment of Young where light from a source passes through two pinholes in a screen and the interference is observed on a second screen placed beyond the first. The second example is Lloyd's mirror where the interfering beams come from the source and from its image in the mirror. This is the first interferometer used in radio astronomy, the mirror there being the sea. The third example is the Rayleigh interferometer used for refractometry.

The more important two-beam interferometers with division of amplitude are shown in fig. 3. The first is the Mach–Zehnder interferometer,

Fig. 2 Two-beam interferometers with division of wavefront: (*a*) Young's experiment; (*b*) Lloyd's mirror; (*c*) Rayleigh interferometer.

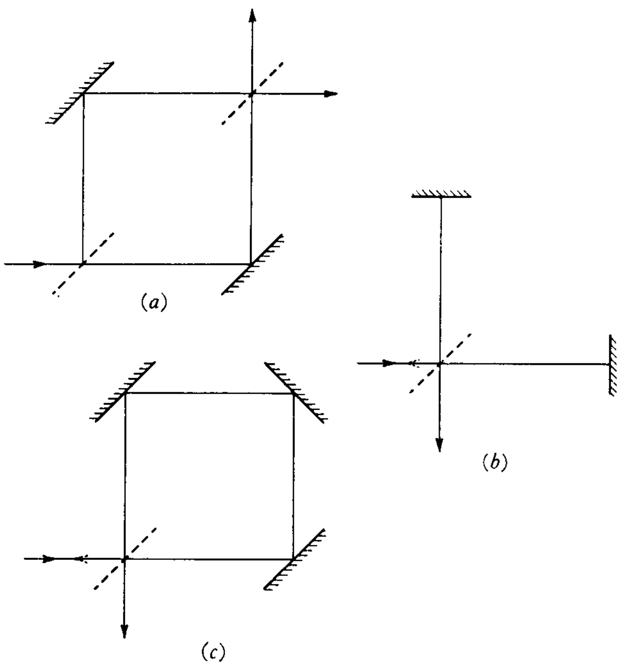


where the differences between the two beams are fairly generally adjustable. The beams are separated by one beam splitter and recombine at another. Fewer adjustments are possible with the Michelson interferometer, in which only one beam splitter is used, the two beams being reflected back to recombine where they separated. In the final interferometer they also come back to the same beam splitter, but on the other side, having each traced a loop. This is the cyclic interferometer, usually named after Sagnac, although it also was used earlier by Michelson [Hariharan, 1975*b*].

Two modifications of these interferometers are shown in fig. 4. The first is a Mach–Zehnder interferometer, in which the two mirrors have been replaced by mirror pairs [Hariharan, 1969]. This makes it possible to vary the path difference between the two beams, an adjustment that is not readily made to the simpler form. The second instrument is a Michelson interferometer, in which the mirrors have been replaced by cube corners.

Two multiple-beam interferometers are shown in fig. 5. The first is the Fabry–Perot interferometer with division of amplitude, first used by Boulouch [1893]. The second is the Christiansen cross [Christiansen *et al.*, 1961].

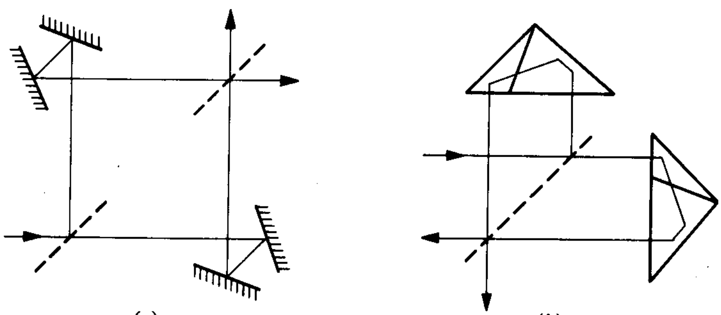
Fig. 3 Two-beam interferometers with division of amplitude: (*a*) Mach–Zehnder; (*b*) Michelson; (*c*) cyclic or Sagnac.



1.5. Description of an interferometer: complementary fringes

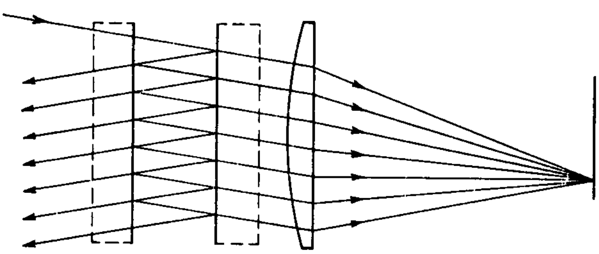
The Michelson interferometer of fig. 3(*b*) is probably the most widely used instrument in interferometry and it provides a suitable example for a general description of the properties of an interferometer and also for the theory given later. Let us consider it illuminated by a single spectral line from a small source that is effectively at infinity, that is, at the focus of a suitable collimating lens (fig. 6). Provided the two arms have about the same length, an observer looking into the interferometer and focusing on the

Fig. 4 Modified forms of two-beam interferometers with division of amplitude: (*a*) Mach–Zehnder with mirror pairs [Hariharan, 1969]; (*b*) Michelson with retroreflectors.

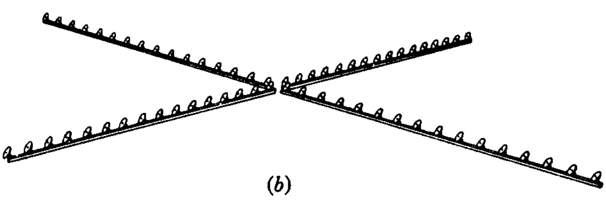


(*a*) (*b*)

Fig. 5 Multiple-beam interferometers: (*a*) Fabry–Perot interferometer; (*b*) Christiansen cross.



(*a*)



(*b*)

mirrors at the ends of the arms will see straight fringes there. These are contours of the wedge between one mirror and the image of the other reflected in the beam splitter, and are called *fringes of equal thickness* or *Fizeau fringes*. If one mirror is moved back parallel to itself to introduce a difference in the optical paths in the two arms, the fringes lose contrast. The narrower the bandwidth of the light, the further the mirror can be moved while still retaining visible fringes. If either mirror is tilted to remove the wedge, the fringes *spread out* to give a field of uniform intensity.

A second *complementary* set of fringes is produced by the other pair of beams that leave the beam splitter. In interferometers in which the beams are reflected back to recombine at the place where they separated, such as the Michelson, the second interferogram goes back to the source and another beam splitter is needed to see these fringes. But in other interferometers they are as accessible as the first set.

1.5.1. Alternative fringes

With a path difference present, not too large to reduce the fringe visibility to zero, an independent set of fringes may be seen. These are located at the image of the source, that is, infinity. They are only visible if the first set has

Fig. 6 The Michelson interferometer with collimated light, showing the two alternative sets of fringes.