Aust. J. Phys., 1993, **46**, 103–19

Optical Interferometry: The Post-Michelson Era*

P. Hariharan

Division of Applied Physics, CSIRO,
P.O. Box 218, Lindfield, N.S.W. 2070, Australia.

Abstract

Michelson's contributions to optical interferometry, over the half century from 1880 to 1930, won him the Nobel Prize and dominated the field to such an extent that, at the end of this period, optical interferometry seemed to be an area in which there was little left to be done. In retrospect, it is now apparent that this pessimistic view was totally unjustified. Significant advances were, in fact, made over the next two decades, but these were merely a prelude to the explosion of activity that was triggered by the development of the laser and progress in related fields such as fibre optics and nonlinear optics. Some of these advances will be reviewed, and some future possibilities will be discussed.

1. Introduction

Just over a century ago, Michelson and Morley (1887) performed an experiment to measure the speed at which the earth was moving through the luminiferous ether—the medium that was supposed to support light waves. This celebrated experiment ruled out the existence of any such medium and provided a firm experimental basis for the special theory of relativity.

Over the years, Michelson continued to work at improving his interferometer and adapting it to novel uses. Some of the applications that he found for interferometric measurements, apart from the one that 'disproved' the existence of a luminiferous ether, included determinations of the thickness of soap films, indices of refraction, coefficients of expansion, the gravitational constant, the wavelengths of spectral lines, the fine structure of spectral lines, the diameters of stars and the measurement of the metre bar in wavelengths. It was quite proper that the citation to his Nobel Prize in 1907 referred to 'his precision optical instruments and the spectroscopic and metrological investigations conducted therewith'.

Michelson's contributions to interferometry during the half century from 1880 to 1930, which were summarised in his two books *Light Waves and Their Uses* (Michelson 1903) and *Studies in Optics* (Michelson 1927), dominated the field to such an extent that they created the impression that there was little of any importance left for his successors. However, it is now quite obvious that this pessimistic view was totally unjustified. Significant advances were, in fact, made

* Paper presented on the occasion of the award of the Thomas Young and Walter Boas Medals to the author, Tenth AIP Congress, University of Melbourne, 12 February 1992.

0004-9506/93/010103$05.00

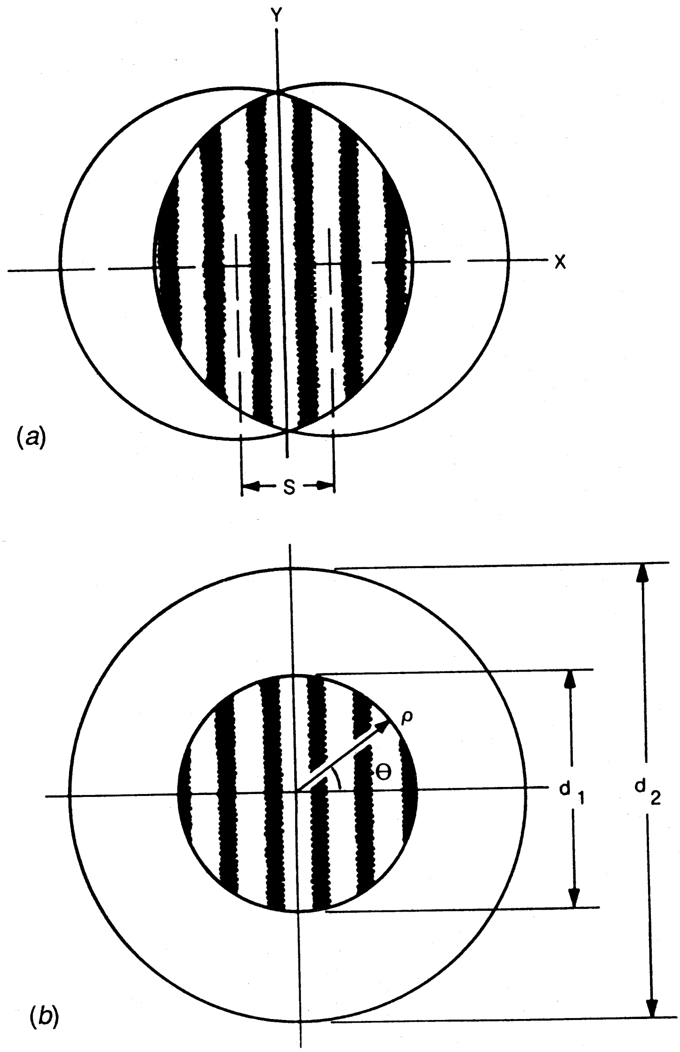

Fig. 1. Images of the test field in (a) a lateral shearing interferometer and (b) a radial shearing interferometer.

over the next two decades, but these were merely a prelude to the explosion of activity that was triggered in the last twenty years by the development of the laser and progress in related fields, such as fibre optics and nonlinear optics.

This paper reviews some of these developments and discusses some future possibilities.

2. The Pre-laser Era

One of the first major advances in the pre-laser era was in interferometers for testing optical components and optical systems. For many years, the only interferometers used for this purpose were the Fizeau and a modified form of Michelson's interferometer known as the Twyman–Green interferometer (Twyman 1918), both of which required a high quality reference surface of similar dimensions to the test piece.

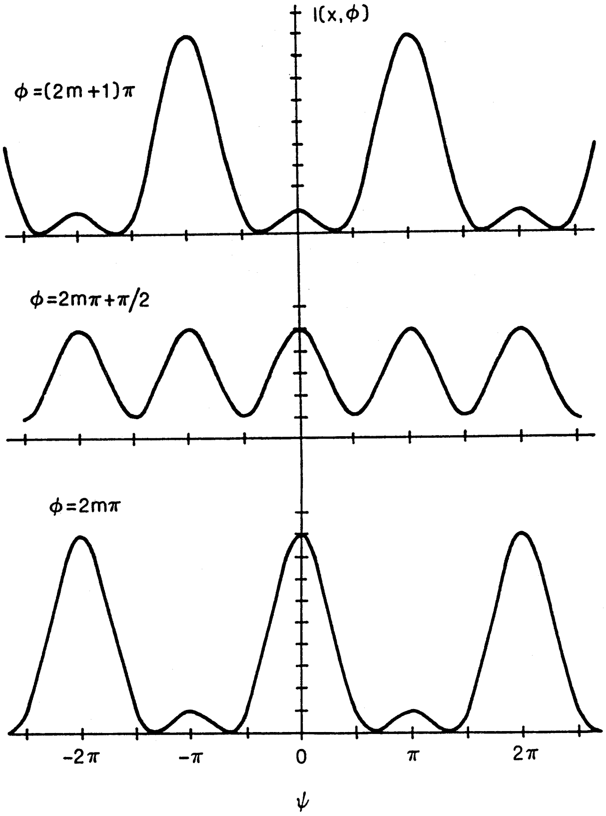

Fig. 2. Intensity distribution in the fringes in a three-beam interferometer for different values of the phase of the third beam (Hariharan *et al.* 1959).

This bottleneck was broken by the development of shearing interferometers in which interference takes place between two images of the test wavefront, thereby eliminating the need for a reference surface (Bryngdahl 1965). The two most commonly used types are lateral shearing interferometers and radial shearing interferometers. In a lateral shearing interferometer, as shown in Fig. 1*a*, these images are of the same size but are laterally displaced with respect to each other by a distance s, conventionally expressed as a fraction of the diameter of the test pupil (Bates 1947). In a radial shearing interferometer, as shown in Fig. 1*b*, the two images are concentric but have different diameters, d_1 and d_2 (Hariharan and Sen 1961*a*). Shearing interferometers are now widely used in optical testing.

Another significant advance during this period was Zernike's (1950) three-beam interferometer. With two-beam interference, it is difficult to estimate the position of a fringe visually to better than 1/20 of the inter-fringe spacing. In Zernike's three-beam interferometer the third beam modulates the interference pattern produced by two reference beams. As shown in Fig. 2, the intensities of adjacent maxima are unequal except when the phase difference ϕ at the centre of the field between the third beam and the reference beams is equal to an odd multiple of $\pi/2$. This setting can be made visually to $\lambda/200$ and, with a photoelectric detector, to better than $\lambda/2000$ (Hariharan *et al.* 1959).

Similar fringes can also be obtained by double-passing a two-beam interferometer, in other words, by reflecting the beams emerging from the interferometer back through it. In this case, displacements of one of the mirrors of $\lambda/1000$ can be detected visually (Hariharan and Sen 1960).

Finally, there was the development of the double-passed Fabry–Perot interferometer (Hariharan and Sen 1961*b*) and the confocal Fabry–Perot interferometer (Connes 1956, 1958). The increase in contrast obtained with the former made it possible to observe faint satellites near a strong spectral line and opened up the field of Brillouin spectroscopy (Sandercock 1970), while the increase in throughput obtained with the latter was utilised effectively in the construction of high-resolution scanning interferometers and, ultimately, in confocal resonators for lasers.

3. The Laser as a Light Source

The development of lasers made available intense sources of light with a very high degree of coherence, and removed most of the limitations imposed on interferometric techniques by conventional light sources. In addition, the unique properties of lasers opened up many new techniques in interferometry (Hariharan 1987).

In the first instance, the high degree of monochromaticity of laser light makes it possible to observe beats between two laser beams with slightly different frequencies (Javan *et al.* 1962). This phenomenon is used in heterodyne interferometers, in which interference takes place between two beams derived from the same laser, one of which has its frequency shifted by a known amount (Eberhardt and Andrews 1970). The output from a photodetector is then at the beat frequency, and its phase corresponds to the difference in the phases of the interfering beams (Crane 1969).

Another interesting possibility opened up by laser sources is frequency modulation. A change in the injection current of a diode laser produces, in addition to a change in the output power, a shift in the output frequency. This frequency shift is due to two causes. One is the change in the refractive index of the active region induced by the change in the number of the charge carriers. The other is the thermally induced change in the length and refractive index of the laser cavity (Dandridge and Goldberg 1982; Kobayashi *et al.* 1985). Frequency modulation has been used effectively in several types of interferometers (Hariharan 1990).

4. Length Measurements

Michelson's imaginative proposal to use the wavelength of a spectral line as a standard of length was finally adopted in 1960, when the metre was defined in terms of the wavelength of the orange line from a discharge lamp filled with an isotope of krypton (Baird and Howlett 1963). However, this standard soon became outdated with the availability of frequency-stabilised lasers, since their wavelengths were much more precisely reproducible than the wavelength of the krypton standard.

The metre was therefore redefined in 1983 in terms of the second and the best available value for the speed of light (Petley 1983). Practical methods for realising the metre now involve interferometric measurements with lasers whose frequencies have been compared with the cesium standard.

While Michelson had to go through a laborious series of comparisons to measure the number of wavelengths of a spectral line in the standard metre, the great coherence length of laser radiation has made possible measurements of very large distances in a single step. Lasers have also made electronic fringe counting a practical technique for length interferometry. Typically, an interferometer is used that provides two interference fields, in one of which an additional phase difference of $\pi/2$ has been introduced. Two detectors viewing these fields yield signals in quadrature to drive a bidirectional counter (Gilliland *et al.* 1966).

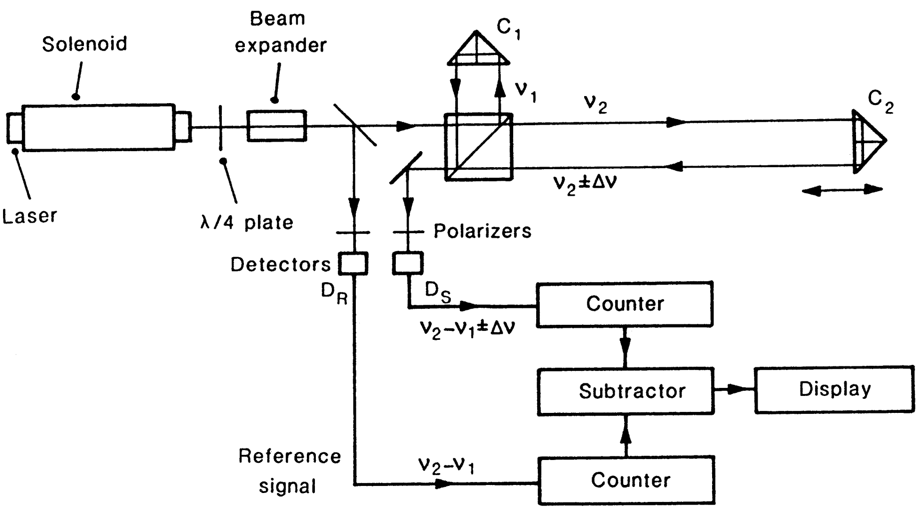

Fig. 3. Heterodyne interferometer for length measurements using a two-frequency laser (reproduced with permission from Dukes and Gordon 1970).

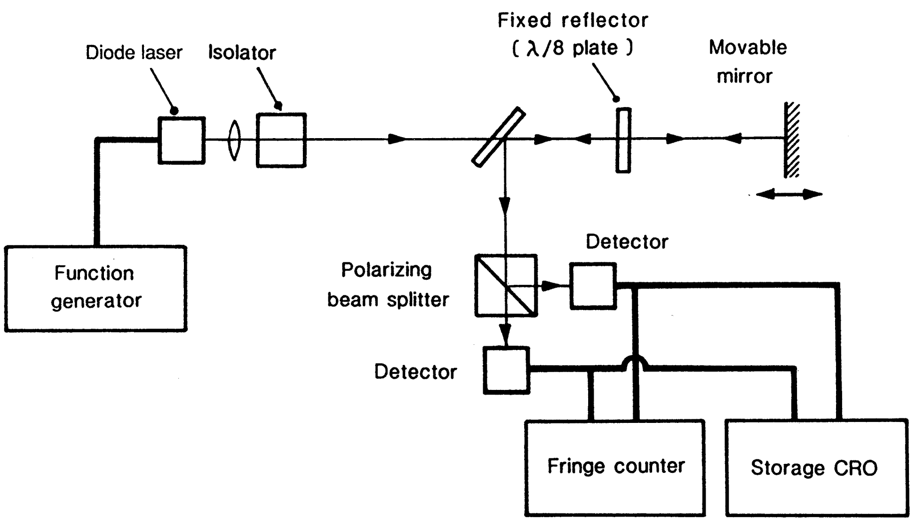

Fig. 4. Laser interferometer using a linear frequency sweep (Kubota *et al.* 1987).

As mentioned earlier, the very narrow spectral line widths of lasers make it possible to observe beats between two laser frequencies. This has led to the development of systems for length measurements based on heterodyne techniques. One of these, shown in Fig. 3, uses Zeeman splitting of the levels in a He–Ne laser to produce two frequencies separated by about 2 MHz (Dukes and Gordon 1970). Normally, the frequencies of the outputs from the two detectors in this interferometer are the same and no net count accumulates. If one of the reflectors is moved, the net count gives the change in the optical path in wavelengths.

Small changes in length can also be measured very accurately by heterodyne techniques (Jacobs and Shough 1981). The two mirrors of a Fabry–Perot interferometer are attached to the two points between which measurements are to be made, and the wavelength of a laser is locked to a transmission peak of the interferometer. A displacement of one of the mirrors results in a change in the wavelength of the laser and a corresponding change in its frequency. This frequency change is measured by mixing the beam from the laser with the beam from a reference laser and measuring the beat frequency.

New techniques for distance measurements are also possible with diode lasers which can be tuned electrically over a range of wavelengths. In the interferometer shown in Fig. 4, the frequency of the laser is swept linearly with time (Kubota *et al.* 1987). If the optical path difference between the two beams in the interferometer is p, they reach the detector with a mutual time delay p/c, where c is the speed of light, and interfere to yield a beat signal with a frequency

$$f = (p/c)(d\nu/dt)\,, \tag{1}$$

where $d\nu/dt$ is the rate at which the laser frequency varies with time.

5. Optical Testing

Lasers have led to the development of several new types of interferometers for optical testing, as well as new techniques for directly measuring wavefront errors with very high precision. Heterodyne interferometers use two beams with slightly different frequencies. The intensity in the interference pattern then varies at the

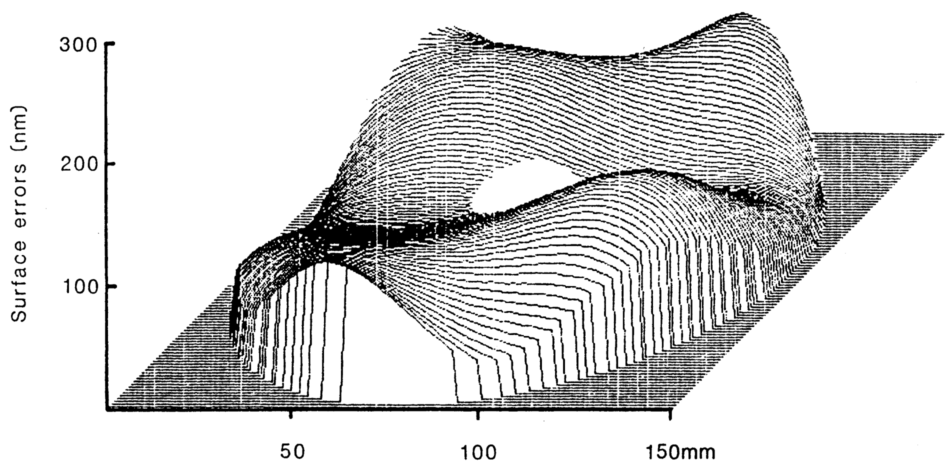

Fig. 5. Three-dimensional plot of the errors of a concave spherical surface produced by a digital phase-shifting interferometer.

difference frequency, and the phase difference at any point can be determined by comparing the phase of the output from a movable detector with that from a fixed reference detector (Crane 1969).

Alternatively, the phase difference between the interfering beams is varied with time, either continuously or step wise, and the values of the intensity at each data point in the interference pattern are measured for a set of equally spaced values of this additional phase difference. The values of the intensity at each point can then be represented by a Fourier series whose coefficients can be evaluated to obtain the original phase difference between the interfering wavefronts (Bruning *et al.* 1974; Creath 1988).

The simplest way to generate the phase shifts or phase steps is by mounting the reference mirror in the interferometer on a piezoelectric transducer to which appropriate voltages are applied. Another way is to use, as the source, a diode laser whose output wavelength can be changed by varying the injection current (Ishii *et al.* 1987). If an optical path difference p exists between the two arms of the interferometer, the additional phase difference $\Delta\phi$ introduced between the beams by a wavelength change $\Delta\lambda$ is given by the relation

$$\Delta\phi = 2\pi(p/c)\Delta\nu/\nu\,, \tag{2}$$

where c is the speed of light. Since measurements can be made rapidly and the data can be stored, the effects of vibrations and air currents can be minimised by averaging a number of readings. Errors due to the interferometer optics can be subtracted from the readings and the results can be presented as a three-dimensional plot as shown in Fig. 5.

Laser interferometers with digital phase measurement systems are now used extensively in the production of high-precision optical components. Another application has been in studies of surface structure and surface roughness, where heterodyne and polarimetric techniques have been used to measure rms deviations as small as 0·01 nm (Huang 1984; Downs *et al.* 1985).

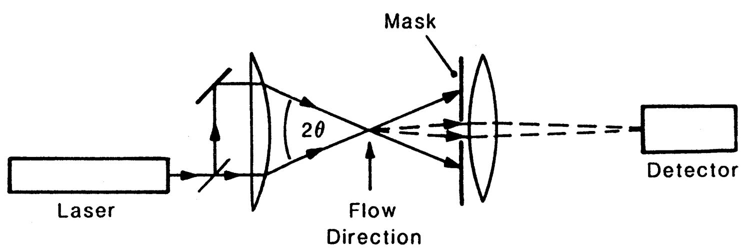

Fig. 6. Typical optical system used for laser-Doppler interferometry.

6. Laser-Doppler Interferometry

Light scattered from a moving particle undergoes a frequency shift. This frequency shift can be measured using the beats produced by interference between the scattered light and a reference beam (Yeh and Cummins 1964), or by the scattered light from two illuminating beams incident at different angles (Durst and Whitelaw 1971).

A typical optical system using two intersecting laser beams making equal, but opposite, angles $\pm\theta$ with the direction of observation is shown in Fig. 6. With such an optical system, the frequency of the beat signal is given by the relation

$$f = \frac{2v \sin\theta}{\lambda}, \tag{3}$$

where v is the component of the velocity of the particle in the plane of the beams at right angles to the direction of observation.

Laser-Doppler interferometry is now used widely to map flow velocities. With turbulent flows, the sign of the velocity component can be identified by introducing an initial frequency difference between the beams. Where required, simultaneous measurements of the velocity components along two orthogonal directions can be made with an arrangement using two pairs of illuminating beams, with different wavelengths, in orthogonal planes (Durst *et al.* 1976).

Laser-Doppler techniques can also be used to study vibrating objects. Typically, one of the beams is reflected from a point on the vibrating surface, while the other is reflected from a fixed mirror. If the frequency of one beam is offset by a known amount, the output from a detector consists of a component at the offset frequency (the carrier) and two sidebands. The amplitude of the vibration can be determined by a comparison of the amplitudes of the carrier and the sidebands, while the phase of the vibration can be obtained by comparison of the phase of the carrier with a reference signal (Puschert 1974). Vibration amplitudes down to a few thousandths of a nanometre can be measured by such techniques.

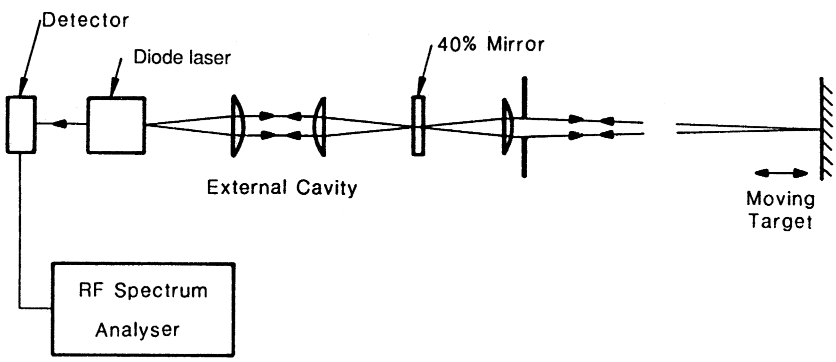

Fig. 7. Laser-feedback interferometer used for velocimetry (de Groot and Gallatin 1989).

7. Laser-feedback Interferometers

If a fraction of the output from a laser is reflected back into the laser cavity by an external mirror, the output of the laser is found to vary cyclically with the position of this mirror, one cycle of modulation corresponding to a displacement of the mirror by half a wavelength. This effect is used in laser-feedback interferometers (Ashby and Jephcott 1963).

A very compact laser-feedback interferometer can be set up with a single-mode diode laser. Small displacements of the external mirror can be detected by holding the laser current constant and measuring the changes in the laser output.

Measurements can be made over a larger range by mounting either the laser or the external mirror on a piezoelectric translator, and using an active feedback loop to stabilise the length of the optical path between them (Yoshino *et al.* 1987).

Laser-feedback interferometers can also be used for velocimetry. In the system shown in Fig. 7, a diode laser is operated near threshold in an external cavity. The light reflected from the moving object is mixed with the original oscillating wave inside the laser cavity, and the beat signal is detected in the beam leaving the other end of the laser. This arrangement yields very high sensitivity, as well as a single-mode output with a coherence length that is great enough to allow measurements to be made over ranges up to 50 metres (de Groot and Gallatin 1989).

8. Fibre Interferometers

Advances in fibre optics have made it possible to build analogues of conventional interferometers using single-mode fibres. Optical fibres permit very long paths in a small space. In addition, because of the low noise levels possible with proper design, sophisticated detection techniques can be used with fibre interferometers.

One of the first applications of fibre interferometers was in rotation sensing. The possibility of using an interferometer to detect rotation in an inertial frame was first demonstrated by Sagnac (1913) and, independently, by Michelson and Gale (1925) in experiments with an interferometer in which the two beams traveled around the same closed circuit in opposite directions. However, much higher sensitivity can be obtained if the optical path consists of a closed multi-turn loop made of a single fibre (Vali and Shorthill 1976).

Fibre-optic rotation sensors are attractive because of their small overall size and low cost. Performance close to the limit set by shot noise is possible if precautions are taken to minimise the effects of local temperature variations, vibration and external magnetic fields (Bergh *et al.* 1984).

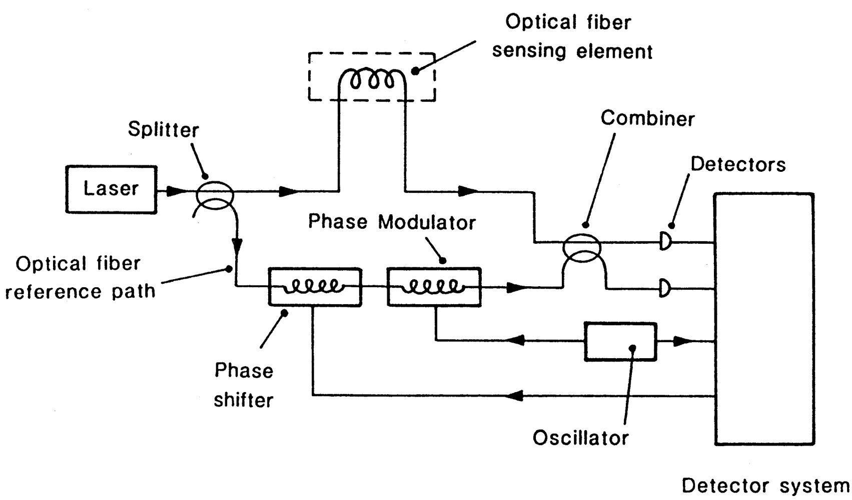

Fig. 8. Schematic of a typical fibre-interferometer sensor (Giallorenzi *et al.* 1982).

Since the optical path in a fibre changes when the fibre is stretched, and is also affected by the ambient temperature and pressure, fibre interferometers can be used as sensors for these quantities. They can also be used to measure magnetic or electric fields by bonding the fibre sensor to a magnetostrictive or piezoelectric element (Culshaw 1984). Fig. 8 is a schematic of a typical fibre-interferometer sensor using a layout analogous to a Mach–Zehnder interferometer, with optical fibre couplers replacing beam splitters. Optical phase shifts as small as a microradian can be detected (Giallorenzi *et al.* 1982).

Fibre-interferometer sensors have the advantage that they can be multiplexed to measure different parameters at different locations with a single light source and detector and the same set of transmission lines. Techniques developed for this purpose include frequency-division multiplexing, time-division multiplexing and coherence multiplexing. These techniques can be combined to handle a large number of sensors (Farahi *et al.* 1988*a*, 1988*b*).

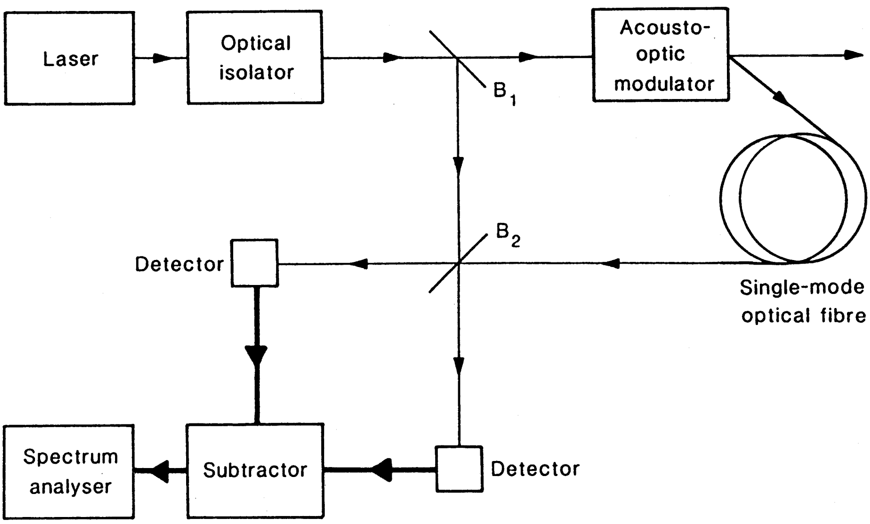

Fig. 9. Heterodyne interferometer used for measurements of laser linewidth (Abitbol *et al.* 1984).

9. High-resolution Spectroscopy

Michelson (1891, 1892) was the first person to derive the structure of spectral lines from observations of the visibility of the fringes in his interferometer as a function of the optical path difference. His work laid the foundation for the technique of Fourier transform spectroscopy which is widely used now for studies on faint sources as well as to obtain very high resolving power (Jacquinot 1960).

A completely different method which has been used to obtain very high resolution is based on laser heterodyne techniques. One application of this technique has been to measure the extremely narrow width of laser lines. In this case, as shown in Fig. 9, light from the laser is mixed at a detector with a frequency-shifted reference beam derived from the same laser. An optical fibre is used to introduce a delay τ between the two beams which is much larger than $1/\Delta\nu$, where $\Delta\nu$ is the width of the laser line. The spectral width of the beat signal is then twice the width of the laser line (Abitbol *et al.* 1984).

10. Stellar Interferometry

Since a star can be regarded as a small incoherent light source, its angular diameter can be calculated from observations of the visibility of the fringes in an interferometer that uses light from the star incident on the surface of the earth at points separated by a suitable distance. Michelson's stellar interferometer (Michelson and Pease 1921) used a pair of mirrors mounted at the ends of a 6 m long support on the 2·5 m telescope at Mt Wilson. However, attempts to

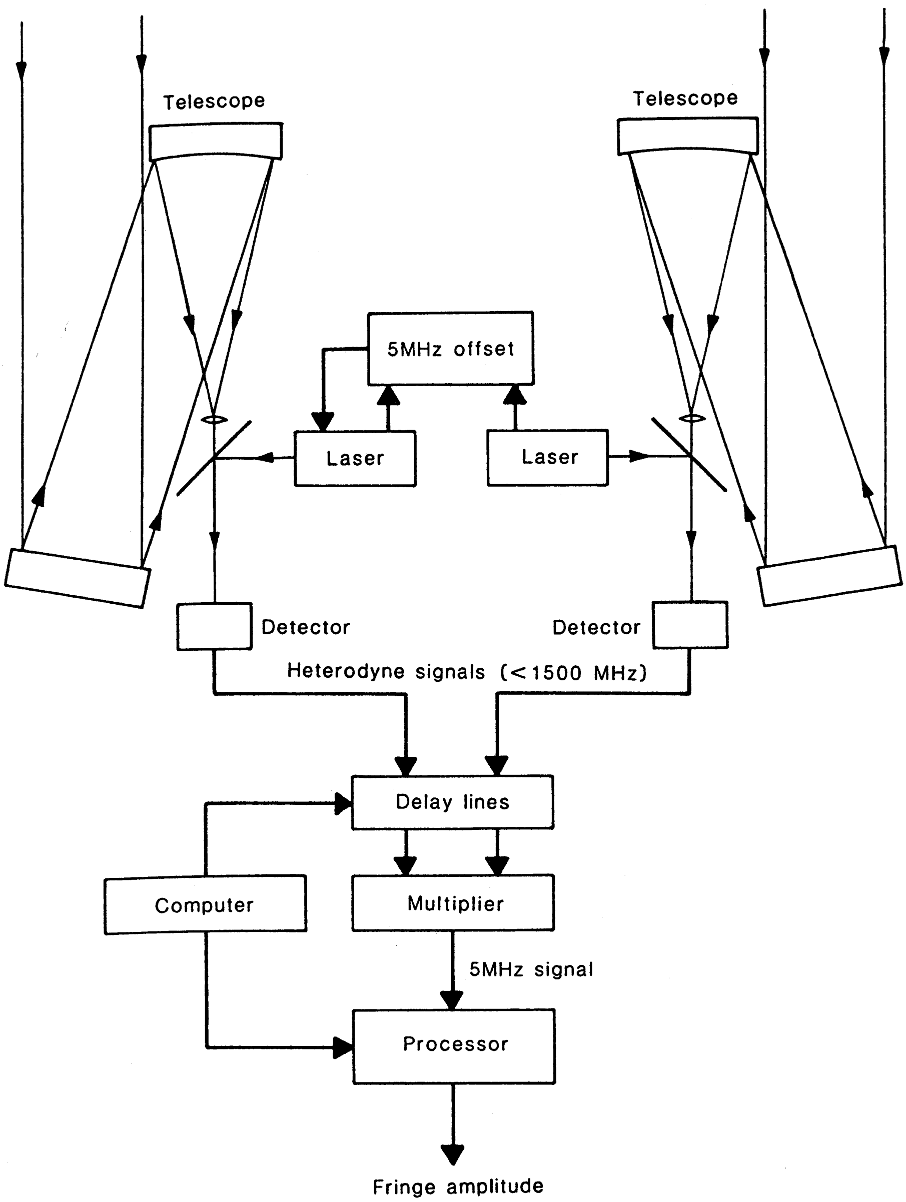

Fig. 10. Schematic of an infrared heterodyne stellar interferometer (Johnson *et al.* 1974).

increase the baseline to 15 m failed because of problems with mechanical stability and atmospheric turbulence.

A remarkably successful solution of these problems was based on measurements of the degree of correlation between the outputs of two photodetectors at the ends of a baseline (Hanbury Brown 1974). The 'intensity interferometer' has the advantage that atmospheric turbulence only affects the phase of the incident wave and has no effect on the measured correlation. In addition, because of the narrow bandwidth of the electronics, it is sufficient to equalise the paths to within a few centimetres. A resolution of less than a thousandth of a second of arc has been obtained with a baseline of 188 m.

Unfortunately, the low sensitivity of the intensity interferometer limits measurements to a few bright stars. As a result, a new version of Michelson's stellar interferometer using modern detection, control and data-handling techniques is under construction (Davis and Tango 1986). This instrument is expected to make measurements on a very large number of stars by using baselines of up to 1000 m.

Yet another approach, made possible by the development of lasers, is based on heterodyne techniques (Johnson *et al.* 1974; Townes 1984). In this case, as shown in Fig. 10, the light from the star is mixed with light from a laser at two photodetectors, and the resulting heterodyne signals are multiplied in a correlator. The output signal from the correlator is a measure of the degree of coherence of the wave fields at the two photodetectors. As with the intensity interferometer, the two optical paths need be equalised only to within a few centimetres, but the sensitivity is much higher than with direct detection, because the output is proportional to the product of the intensities of the laser and the star.

11. Relativity and Gravitational Waves

Laser heterodyne techniques have also been used to verify the null result of the Michelson–Morley experiment to a very high degree of accuracy (Brillet and Hall 1979). In this experiment, the output frequency of a He–Ne laser was locked to a resonance of a Fabry–Perot cavity mounted along with it on a rotating horizontal granite slab. Any changes in the length of the cavity could be detected by comparing the frequency of this laser with that of a stabilised reference laser.

A phenomenon predicted by the general theory of relativity is gravitational radiation from binary systems of neutron stars or from black holes and supernovas. However, early attempts to detect gravitational waves using short resonant detectors were unsuccessful. An alternative which appears to offer advantages is a wide-band antenna consisting, as shown schematically in Fig. 11, of a Michelson interferometer in which the beam splitter and the end reflectors are attached to separate, freely suspended masses (Forward 1978). Because of the transverse, quadrupole nature of gravitational waves, the arm lying along the direction of propagation does not experience a strain, whereas the strain produced by the gravitational wave acts on the other arm. With a gravitational wave propagating at right angles to the plane of the interferometer, the changes in length of the two arms have opposite signs.

Theoretical estimates of the intensity of bursts of gravitational radiation suggest that a sensitivity to strains of the order of a few parts in 10^{21} is needed. This is beyond present capabilities, and a number of ways to obtain higher sensitivity are being explored. One promising arrangement uses two identical

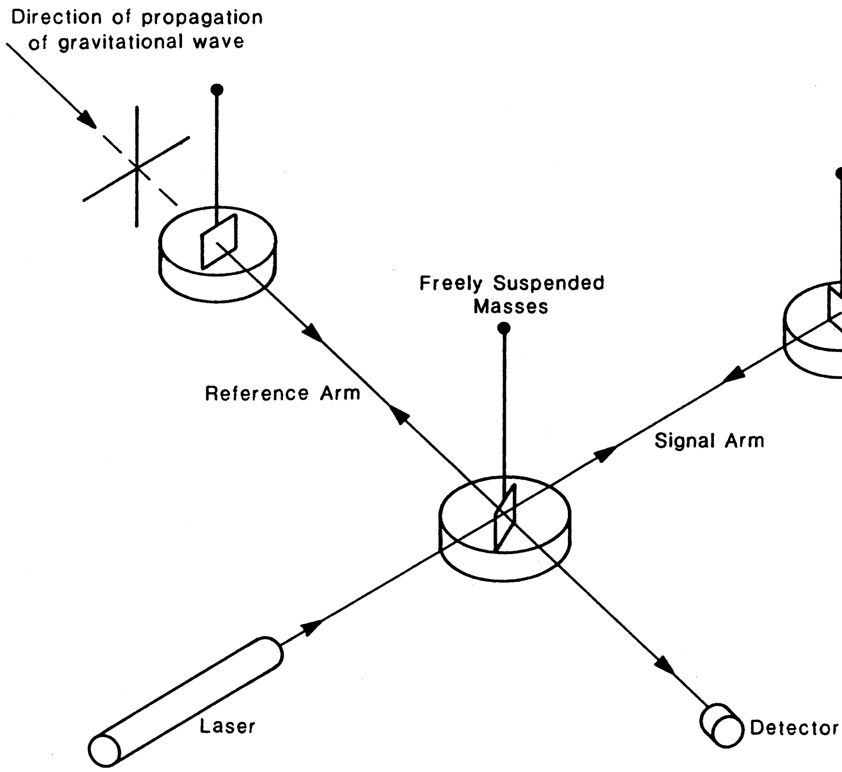

Fig. 11. Interferometric detector for gravitational waves.

Fabry–Perot interferometers at right angles whose mirrors are mounted on freely suspended masses. The frequency of a laser is locked to a transmission peak of one interferometer while the separation of the mirrors in the other is continually adjusted so that its peak transmittance is at this frequency. The corrections applied to the second interferometer are used to monitor changes in the relative lengths of the two interferometers. Even higher sensitivity can be obtained by reflecting back, with the appropriate phase, the light leaving the unused port of the interferometer (Drever 1983).

12. Phase-conjugate Interferometers

The availability of lasers capable of producing light of extremely high intensity has led to the development of new types of interferometers using nonlinear optical elements. Perhaps the most important of these are phase-conjugate interferometers.

In a phase-conjugate interferometer, the wavefront under study is made to interfere with its complex conjugate (Hopf 1980). As a result, no reference wavefront is necessary, and the sensitivity is doubled. A very simple phase-conjugate interferometer is an analogue of the Fizeau interferometer (Gauthier *et al.* 1989). In this interferometer, the input beam is incident on a partially reflecting mirror placed in front of a crystal of barium titanate, which functions as an internally self-pumped phase-conjugating mirror.

It is also possible, as shown in Fig. 12, to replace both the mirrors in a conventional interferometer with a phase-conjugating mirror. The interference pattern obtained in such an interferometer is unaffected by misalignment of the mirrors, and the field of view is normally completely dark. However, because of the delay in the response of the phase conjugator, any sudden local change in the optical path difference results in a bright spot which slowly fades away (Anderson *et al.* 1987).

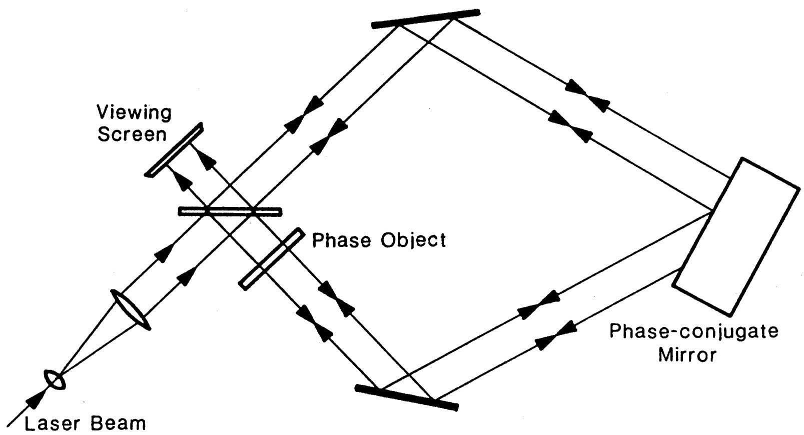

Fig. 12. Phase-conjugate interferometer (Anderson *et al.* 1987).

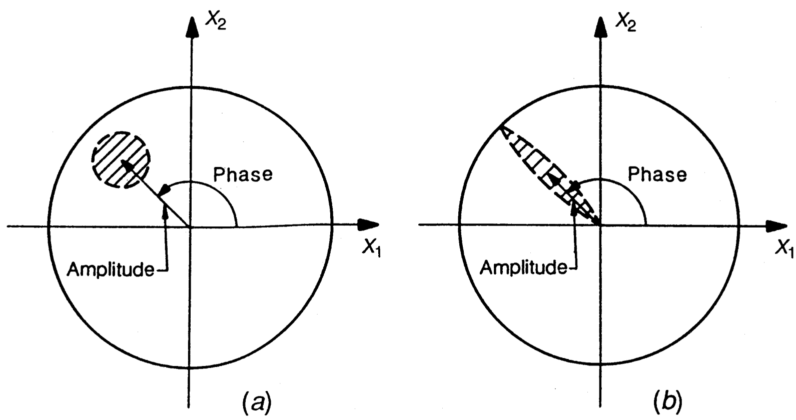

Fig. 13. Variances of phase and amplitude in (*a*) normal coherent light and (*b*) phase-squeezed light.

13. Squeezed States of Light

As shown in Fig. 13, we can represent the electric field of a light wave in the form

$$E = E_0[X_1 \cos \omega t + X_2 \sin \omega t]\,, \tag{4}$$

where X_1 and X_2 are field quadrature operators whose variances obey an uncertainty relationship. For normal coherent light the variances are equal, but for a squeezed state the variances can be different, though their product remains the same. Typically, phase fluctuations can be reduced at the expense of a corresponding increase in the amplitude fluctuations (Walls 1983).

Squeezed light can be generated by several nonlinear processes including four-wave mixing (Slusher *et al.* 1985) as well as directly, by stabilising the drive current in a diode laser (Machida *et al.* 1987). The use of squeezed light could lead to major improvements in the performance of high precision interferometers, such as those under construction for the detection of gravitational waves. The fractional error of such measurements is limited by shot noise and is equal to $1/\sqrt{N}$, where N is the number of photons detected. With squeezed light, the measurement uncertainty could be reduced, in principle, to $1/N$ (Caves 1980, 1981).

14. Future Directions

This review shows that the post-Michelson era has seen major advances in interferometry. It is an interesting, though risky, exercise to speculate on future directions in this field.

Some trends are, of course, obvious. With the rapid progress that is being made in the development of solid-state lasers, we can expect them to be used to an ever-increasing extent. The wider use of photodetectors and digital signal processing should result in further increases in the scope, speed and accuracy of measurements. We can also expect new devices to be built incorporating fibre interferometers, while improved nonlinear materials should lead to new applications for self-referencing instruments using phase-conjugate interferometers. Finally, the successful detection of gravitational waves, besides helping to decide between competing theories of gravity, would open up a completely new field in observational astronomy.

All these possibilities suggest that the post-Michelson era is likely to yield more interesting developments and point to an exciting future for optical interferometry.

References

Abitbol, C., Gallion, P., Nakajima, H., and Chabran, C. (1984). *J. Optics (Paris)* **15**, 411.

Anderson, D. Z., Lininger, D. M., and Feinberg, J. (1987). *Opt. Lett.* **12**, 123.

Ashby, D. E. T. F., and Jephcott, D. F. (1963). *Appl. Phys. Lett.* **3**, 13.

Baird, K. M., and Howlett, L. E. (1963). *Appl. Opt.* **2**, 455.

Bates, W. J. (1947). *Proc. Phys. Soc. London* **59**, 940.

Bergh, R. A., Lefevre, H. C., and Shaw, H. J. (1984). *IEEE J. Lightwave Technol.* **LT-2**, 91.

Brillet, A., and Hall, J. L. (1979). *Phys. Rev. Lett.* **42**, 549.

Bruning, J. H., Herriott, D. R., Gallagher, J. E., Rosenfeld, D. P., White, A. D., and Brangaccio, D. J. (1974). *Appl. Opt.* **13**, 2693.

Bryngdahl, O. (1965). *In* 'Progress in Optics' (Ed. E. Wolf), Vol. IV, p. 37 (North Holland: Amsterdam).

Caves, C. M. (1980). *Phys. Rev. Lett.* **45**, 75.

Caves, C. M. (1981). *Phys. Rev.* D **23**, 1693.

Connes, P. (1956). *Rev. Opt.* **35**, 37.

Connes, P. (1958). *J. Phys. Radium* **19**, 262.

Crane, R. (1969). *Appl. Opt.* **8**, 538.

Creath, K. (1988). *In* 'Progress in Optics' (Ed. E. Wolf), Vol. XXVI, p. 349 (Elsevier: Amsterdam).

Culshaw, B. (1984) 'Optical Fibre Sensing and Signal Processing' (Peregrinus: London).
Dandridge, A., and Goldberg, L. (1982). *Electron. Lett.* **18**, 302.
Davis, J., and Tango, W. J. (1986). *Nature* **323**, 234.
de Groot, P. J., and Gallatin, G. M. (1989). *Opt. Lett.* **14**, 165.
Downs, M. J., McGivern, W. H., and Ferguson, H. J. (1985). *Precis. Eng.* **7**, 211.
Drever, R. W. P. (1983). *In* 'Gravitational Radiation' (Eds N. Deruelle and T. Piran), p. 321 (North Holland: Amsterdam).
Dukes, J. N., and Gordon, G. S. (1970). *Hewlett-Packard J.* **21** (No. 12), 2.
Durst, F., and Whitelaw, J. H. (1971). *J. Phys. E: Sci. Instrum.* **4**, 804.
Durst, F., Melling, A., and Whitelaw, J. H. (1976). 'Principles and Practice of Laser Anemometry' (Academic Press: London).
Eberhardt, F. J., and Andrews, F. A. (1970). *J. Acoust. Soc. Am.* **48**, 603.
Farahi, F., Jones, J. D. C., and Jackson, D. A. (1988*a*). *Electron. Lett.* **24**, 409.
Farahi, F., Newson, T. P., Jones, J. D. C., and Jackson, D. A. (1988*b*). *Opt. Commun.* **65**, 319.
Forward, R. L. (1978). *Phys. Rev.* D. **17**, 379.
Gauthier, D. J., Boyd, R. W., Jungquist, R. K., Lisson, J. B., and Voci, L. L. (1989). *Opt. Lett.* **14**, 323.
Giallorenzi, T. G., Bucaro, J. A., Dandridge, A., Sigel, G. H., Jr, Cole, J. H., Rashleigh, S. C., and Priest, R. G. (1982). *IEEE J. Quantum Electron.* **QE-18**, 626.
Gilliland, K. E., Cook, H. D., Mielenz, K. D., and Stephens, R. B. (1966). *Metrologia* **2**, 95.
Hanbury Brown, R. (1974). 'The Intensity Interferometer' (Taylor and Francis: London).
Hariharan, P. (1987). *In* 'Progress in Optics' (Ed. E. Wolf), Vol. XXIV, p. 103 (North Holland: Amsterdam).
Hariharan, P. (1990). *Proc. SPIE* **1400**, 2.
Hariharan, P., and Sen, D. (1960). *J. Opt. Soc. Am.* **50**, 357.
Hariharan, P., and Sen, D. (1961*a*). *J. Sci. Instrum.* **38**, 428.
Hariharan, P., and Sen, D. (1961*b*). *J. Opt. Soc. Am.* **51**, 398.
Hariharan, P., Sen. D., and Bhalla, M. S. (1959). *J. Sci. Instrum.* **36**, 72.
Hopf, F. A. (1980). *J. Opt. Soc. Am.* **70**, 1320.
Huang, C.-C., (1984). *Opt. Eng.* **23**, 365.
Ishii, Y., Chen, J., and Murata, K. (1987). *Opt. Lett.* **12**, 233.
Jacobs, S. F., and Shough, D. (1981). *Appl. Opt.* **20**, 3461.
Jacquinot, P. (1960). *Reports Progr. Phys.* **23**, 267.
Javan, A., Ballik, E. A., and Bond, W. L. (1962). *J. Opt. Soc. Am.* **52**, 96.
Johnson, M. A., Betz, A. L., and Townes, C. H. (1974). *Phys. Rev. Lett.* **33**, 1617.
Kobayashi, S., Yamamoto, Y., Ito, M., and Kimura, T. (1985). *IEEE J. Quant. Electron.* **QE-18**, 582.
Kubota, T., Nara, M., and Yoshino, T. (1987). *Opt. Lett.* **22**, 310.
Machida, S., Yamamoto, Y., and Itaya, Y. (1987). *Phys. Rev. Lett.* **58**, 1000.
Michelson, A. A. (1891). *Phil. Mag.* **31**, 338.
Michelson, A. A. (1892). *Phil. Mag.* **34**, 280.
Michelson, A. A. (1903). 'Light Waves and their Uses' (University of Chicago Press: Chicago).
Michelson, A. A. (1927). 'Studies in Optics' (University of Chicago Press: Chicago).
Michelson, A. A., and Gale, H. G. (1925). *Nature* **115**, 526.
Michelson, A. A., and Morley, E. W. (1887). *Am. J. Sci.* **34**, 333.
Michelson, A. A., and Pease, F. G. (1921). *Astrophys. J.* **53**, 249.
Petley, B. W. (1983). *Nature* **303**, 373.
Puschert, W. (1974). *Opt. Commun.* **10**, 357.
Sagnac, G. (1913). *Comptes Rendus* **157**, 708.
Sandercock, J. R. (1970). *Opt. Commun.* **2**, 73.
Slusher, R. E., Hollberg, L. W., Yurke, B., Mertz, J. C., and Valley, J. F. (1985). *Phys. Rev. Lett.* **55**, 2409.
Townes, C. H. (1984). *J. Astrophys. Astron.* **5**, 111.
Twyman, F. (1918). *Phil. Mag.* **35**, 49.
Vali, V., and Shorthill, R. W. (1976). *Appl. Opt.* **15**, 1099.
Walls, D. F. (1983). *Nature* **306**, 141.

Yeh, Y., and Cummins, H. Z. (1964). *Appl. Phys. Lett.* **4**, 176.
Yoshino, T., Nara, M., Mnatzakanian, S., Lee, B. S., and Strand, T. C. (1987). *Appl. Opt.* **26**, 892.
Zernike, F. (1950). *J. Opt. Soc. Am.* **40**, 326.

Manuscript received 10 March, accepted 7 May 1992