Interferometry: From Hooke till Date

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Abstract Coloured fringes seen in white light when the two glass plates in near contact enclose a very small angle were first observed by Boyle and independently by Hooke in the later part of 17th century and the explanation given using wave theory of light could be taken as the starting point of optical interferometry. Wave theory used by Boyle and Hooke, and in much refined form as proposed by Huygens in 1690 remained unaccepted until Young in 1801 demonstrated the interference between two waves by a very simple but ingenious way. Fizeau (Acad Sci 66:429, 1862 [1]) carried out experiments with a pair of plates using Na light and showed that the fringe pattern disappears when a certain distance separates the plates, essentially sowing the seeds for interference spectroscopy. Michelson in 1891 carried out measurement of visibility of fringes as a function of path difference between the two beams derived from various sources and showed that except for cadmium, other spectral lines showed the variation in visibility. Fizeau is also accredited to have suggested in 1868 that interferometry may be used for measuring stellar dimensions: the idea being taken forward by Michelson by inventing stellar interferometer. The manuscript presents the chronology of development in interferometry. Some current applications may also be highlighted.

1 Introduction

Interferometry makes use of the phenomenon of interference. When two or more waves of the same wavelength are superposed, irradiance varies in the region of superposition. The waves could be longitudinal or transverse and could have any wavelengths. In other words, the phenomenon of interference is observed with

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sound waves and also with the light waves. The irradiance variation in the region of superposition shifts when the phase of one of the interfering waves changes. The variation repeats when the phase-shift is equal to 2π or a its multiples. In practice, this shift is introduced by the external variable that is being monitored.

2 Historical Perspective

Light, in times of Al Hazan and until the 17th century, was considered as stream of particles either emanating from the eye or the object. Newton provided explanation to the various kinds of colors that he observed. Somewhat different explanation of appearance of colors, particularly in thin air wedges, was provided by Robert Boyle (1664) and independently by Robert Hooke (1672) in the later half of the 17th century and their explanation based on somewhat akin to wave theory may be considered as the beginning of interferometry. Huygens in 1678 proposed the wave theory of light that could explain the known phenomena. However it was not accepted partly owing to the authority of Newton who was proponent of corpuscular theory of light and partly it could not explain rectilinear propagation of light. Young, while delivering the Bakerian Lecture in 1801, demonstrated the interference of light waves by a very simple but ingenious experiment, which has come to be known as Young's double-slit experiment. Since interference is a wave phenomenon, light was considered as a longitudinal wave motion. But Young did not attract support for the wave theory. His confidence in wave theory was further shaken when Malus in 1809 announced that the reflected light is polarized. During 1814–1818, Fresnel advanced the Huygens wave theory and wrote a brilliant memoir on diffraction in 1818 that contained the treatment of interference phenomenon. Fresnel also suggested arrangements to observe interference of light: these arrangements are known as Fresnel bi-mirror and Fresnel bi-prism. Lloyd described another way of observing interference by wavefront division in 1834, which is known as Lloyd's mirror arrangement. Complex phenomenon like appearance of a bright spot, Arago or Poisson spot, in the center of the shadows of circular objects could be explained using Fresnel theory of diffraction. Through careful experiments of reflection from good quality glass interfaces, Brewster in 1815 discovered what is today known as Brewster law. Further Arago and Fresnel conducted experiments with polarized light waves and showed that two orthogonally polarized waves do not interfere. These investigations led both Young and Fresnel to believe that light waves are transverse waves. In order for the transverse waves to propagate, Fresnel postulated the presence of an elastic medium pervading all matter—the *luminiferous aether*. He also showed that in a medium of refractive index μ moving with a velocity v, the aether should be carried along with a velocity $v(1 - 1/\mu^2)$.

2.1 Search for Aether

Hippolyte Fizeau in 1851 conducted an interference experiment in which one beam of light propagated along the flow of water and the other beam opposite the flow. He seemingly detected the *aether* drag effect but its magnitude was far smaller than expected. However, his result convinced the physicists to accept Fresnel's *aether* theory. Michelson and Morley in 1886, repeated Fizeau's experiment using a common path interferometer, which supported Fizeau result. Jamin and Hoek (1868) also repeated Fizeau's experiment. Fresnel's almost stationary theory of aether was accepted by almost all the 17th century physicists.

Maxwell in 1880 predicted that the earth motion through the aether should result in a change in the speed of light proportional to $(v/c)^2$, where v is the speed of the earth and c is the speed of light. He thought that the effect is too small to be measurable. However, Michelson in 1881 designed a two-crossed arms instrument and attempted to use it in Germany but with little success, as it could not support any of the existing aether drag theories. Later in 1887 he along with Morley set-up an interferometer with 11 m long arm that floated on mercury pool. Again they could not observe the expected shift of the fringe pattern. This failed experiment, known as Michelson-Morley experiment [2], rejected the Fresnel's stationary aether theory with partial dragging and confirmed the Stokes' hypothesis of complete aether dragging.

2.2 Variation of Fringe Visibility and Interference Spectroscopy

While experimenting with his interferometer using sodium lamp, Fizeau [1] found that the fringe pattern almost disappeared when the gap is increased such that 490 fringes passed and further increase in gap resulted in appearance of fringes reaching maximum contrast when 980 fringes passed. It suggested that the sodium light had two wavelengths—a doublet line. Michelson carried this work forward by plotting fringe visibility as a function of path difference for a number of sources using his interferometer in 1891. He found that the visibility exhibited maxima and minima for all the sources except the Cd red line, thereby showing that the radiation from these sources had multiple wavelength components. Ruben and Wood in 1911 extended this work to far infrared region (100–300 μm). However it was not until 1951 when Fellgett extracted the spectrum from the recorded interferogram as a function of path difference using Fourier transform theory and showed other advantages of the technique. Subsequent developments in Fourier Transform spectroscopy have made this technique preferable over the dispersive instruments in the whole optical region (IR-Vis-UV).

2.3 Physical Parameters Measurement

In 1846, Haidinger observed a fringe pattern at the focal plane of a lens when a plane parallel plate was illuminated normally by an extended source. The Haidinger fringes have been used to measure the wedge angle of thin plates. Jamin [3] invented a plates-based interferometer that was well suited to measure the refractive indices of gases and also to study the temperature dependence of refractive index of liquids and gases. The two waves were created by amplitude division and their paths were matched within the coherence length of the then available sources. This therefore required two identical thick plane parallel plates, which were illuminated by a collimated beam. The two beams generated by first plates were separated and recombined by the second plate.

In 1882 Michelson invented a new kind of refractometer, which came to be known as Michelson interferometer. The interferometer is used for the measurement of wavelength, wavelength difference and refractive indices of thin samples. The beams has to travel twice through the specimen, which results in an increase in sensitivity but at the same time may lead to erroneous results if the beam does not retrace its path. Mach [4] and Zehnder [5] independently described an interferometer, which came to be known as Mach-Zehnder interferometer in which the reference and test beams can be widely separated still retaining its almost equal path feature. This interferometer found many applications in aerodynamics and aerospace engineering. This had the feature to measure the refractive index of gases and also to study the temperature dependence of refractive index of liquids and gases. Rayleigh [6] developed an interferometer utilizing the Young's double slit geometry, which was earlier used by Fizeau and added some very convenient features for accurate measurement of fringe shifts. The interferometer was used to measure refractive indices of gases.

Sagnac [7] provided correct explanation of the fringe formation in a cyclic interferometer. This is a true common path interferometer and its variants have been used in optical testing. The interferometer is sensitive to the rate of rotation about an axis that passes through the interferometer loop. This interferometer finds application in gyros.

2.4 Optical Testing

Fizeau is accredited to have invented in 1862 what is now known as Fizeau interferometer, wherein the interference fringes are observed between a thin air-wedge illuminated by a broad source. This was a standard equipment in optical workshop for testing surfaces. Michelson interferometer was not suited for optical testing. Twyman and Green [8] modified the Michelson interferometer so that it could be used for testing optical components and it then became the workhorse of optical workshops. Linnik [9] modified the Michelson interferometer to examine surfaces under magnification thus expanding applications of interferometry to metallurgy. In the same year, he invented a simple interferometer for testing spherical wave. The point diffraction interferometer was revisited by Smartt and Strong [10], and Smartt and Steel [11]. Burch [12] provided the theory of scatter plate interferometer: another interferometer that could be used with low-coherence sources. Hariharan and Sen extended the Fizeau, and Rayleigh two-beam wavefront interferometer to three beams [13]. They described a cyclic interferometer for optical testing [14].

2.5 Optical Microscopy

Optical microscopy evolved to examine objects and surfaces under magnification. The microscopes were also equipped to make dimensional measurements. Microscopy had immense applications in medical examinations. However, the observation of transparent objects like the cells required staining. The theory of microscope imaging, known as Abbe's theory, was very well developed: imaging in a microscope was considered as two-step process involving diffraction at the object followed by diffraction at the objective. It was only around 1934 when Zernike devised a method to examine transparent/phase objects under microscope. The Zernike phase contrast was based on the simple fact that the directly transmitted and diffracted beams should be phase shifted by $\pi/2$ or odd integer multiple of $\pi/2$: the directly transmitted beam does then interfere with the diffracted beam resulting in positive or negative phase contrast. It also became necessary to incorporate an interferometer into a microscope objective or use Linnik like arrangement to examine surfaces under magnification. Dyson invented an interferometer microscope [15], which could be used to examine objects in transmission. Mirau objective [16] is a direct descendent of this arrangement. The microscope objectives could also be fitted with a tiny Michelson interferometer. Polarization based interferometer that forms part of a microscope was invented by Nomarskii [17]. This is known as Nomarskii microscope or Nomarskii differential interferential contrast (DIC) microscope.

3 Arrival of the Laser

Interferometry evolved as a technique for testing optical components and as a measurement tool. The interferometers were conceived and designed keeping the availability of sources and detectors. Arrival of lasers in 1960 relaxed several constraints on the interferometer design and new interferometers like Murty's plane parallel plate shear interferometer [18] came into existence. First one was the LUPI: the laser unequal path interferometer, allowing the testing of mirrors of long radii of curvatures.

With the availability of tabletop compute power and array detector, a new approach for interferogram evaluation was initiated in 1969. This approach has undergone continuous refinements and is a standard procedure for the evaluation of interferograms.

Initially the length measurement by counting the fringes electronically using Michelson type interferometer with mirrors replaced by corner cubes was carried out. Direction sensitivity was built-in by using two detectors in quadrature. Some interferometers used even four detectors to overcome the problem of irradiance variations. However, Hewlett-Packard came up with an AC fringe counting interferometer based on heterodyne in 1972 that revolutionized the dimensional measurements in the workshop environment. Barker and Hollenbach in 1965 used Michelson interferometer for impact studies and modified it in 1972 in which Doppler-shifted light was used for interferometry. This interferometer came to be known as VISAR: velocity interferometer system for any reflector. Currently it uses fiber-optics and has many good features. Holographic interferometry and speckle interferometry and its electronic version, ESPI, have found numerous applications. One of most exciting applications of interferometry is in the detection of gravitational waves.

4 Conclusion

The field of interferometry is an exciting field from both theory and applications. With the advent of lasers, and availability of tabletop compute power and array detectors, it has undergone immense changes in presentation of the final results and in the range of applications.

Acknowledgements To write the history of any subject is a very demanding task and it has not been easy to write the developments in the field of interferometry. I have used more space in the early part of the history and have very briefly gone over the developments after the advent of laser. I have drawn material from various sources, books [19–24], journals, magazines, Net etc. I would like to acknowledge all these media.

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