CHAPTER 1

INTRODUCTION

1.1 A brief overview of optical interferometry

Optical interferometers are instruments used for the production and observation of interference between two or more light beams to obtain a wide variety of information based on either the path traversed by the light beam or the nature of the light emitted by the source. The simplest form of interference occurs when light from a source is divided into two beams which, after traversing two different paths fall overlapped on an observing surface. The departure of the resultant intensity from the sum of the individual intensities from the two separate paths, giving rise to bright and dark bands of light are a manifestation of the interference phenomenon and this resultant variation in the intensity are called the interference fringes. Based on this, a wide variety of metrological measurements can be performed using the interferometers right from study of the surface quality of the optical components with an accuracy of few tenth of a nanometer ($1 \text{ nm} = 10^{-9} \text{ m}$) [1], to the measurement of separation of binary stars which are millions of miles apart, to the measurement of the refractive indices of materials to range finding and velocimetry [2], and so on. In spectroscopic applications, interferometers have practical advantage over the other methods in determining the spectra of sources and the hyperfine structure of spectral lines with a very high spectral resolution [3]. Large number of books and review articles are dedicated to the discussions on the general introduction to interferometry, details of different instruments, different applications and more recent developments [4-8]. The different classification of the interferometers, the quantities that are measured and some of the relevant applications are briefly summarized in the Table 1.1.

With the development of intense and coherent laser light sources, increasing use of computers for data processing and the availability of very low noise single-mode optical fibres, the optical interferometry has undergone a complete transformation with
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<th>Measurement</th>
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<td>Phase variations</td>
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<td><strong>Fringe visibility</strong></td>
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<td>Complete intensity distribution (position and visibility)</td>
<td>Spectrum of source</td>
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<td>Spatial distribution of source</td>
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**Table 1.1**

Fields of interferometry and their applications [5] t denotes the applications of the field of spectral interferometry developed and demonstrated in this thesis.
remarkably wide range of applications [8,9]. Some of the applications take advantage of the single frequency stabilized output from lasers for length and rotation measurements. Interference or Fourier transform spectroscopy with a Fabry-Perot or Michelson interferometer is used for the direct observation of spectrum at a high resolution. Digital interferometry for high precision tests of optical elements, fibre-optic interferometry for sophisticated detection techniques and nonlinear interferometry with very high light intensity from pulsed lasers are some of the other areas which are filled with the advantages of the interferometric measurements. Further, the holographic and speckle interferometers are very useful in the measurement of the deformation, vibrations and contour measurements of diffuse objects [10-12]. Even without much sophistication involved in some of the methods mentioned above, interferometers have been used to demonstrate the geometric phase [13] generated by a cyclic change in the polarization state of a beam of light.

1.2 Spectral interferometry

The advantages of the different interferometric techniques using monochromatic light source, mentioned in the last section however has its own limitations in some of the applications. For example, the interferometric surface profilers using monochromatic light suffers from the phase ambiguity problem which limits the test surface height measurement to not more than half the wavelength of the source [14]. The usual time domain interferometry has the difficulty that the interference signal recorded as a function of the time delay using a scanning Michelson interferometer oscillates very fast with the period of the mean wavelength of the source. Also, large number of points and large number of fringes must be scanned to obtain high spectral resolution. This limitation however, can be overcome by using Shannon principle. As most of the measurements are made from the fringe visibility, the vibration instability of the interferometer greatly affects the reliability of the data and an accurate knowledge of the optical path usually requires a reference laser beam through the interferometer.
Spectral interferometry with a broad bandwidth white light source is a potential technique to overcome most of the difficulties discussed above. First of all, the white light sources are cheap, efficient and can give an illumination which is free of speckle noise. White light interferometers have virtually unlimited unambiguous range. The phase storage and retrieval from optical systems based on achromatic interference effects [15,16] or the channeled spectrum [17] has potential application in the optical information processing. The main advantage of spectral interferometry is that the whole spectrogram can be recorded in a single shot using a dispersing element like a prism or a grating and a CCD array detector. Small vibrations do not invalidate the information that can be obtained from the spectrogram as most of the information is stored in the periodicity of the fringes and not in their contrast. Spectral interferometry has been applied to the measurement of the spectral phase introduced by optical fibers [18], differential refractive index of liquid samples [19], multimode reflectometers for ultra high spatial resolution [20], real time measurement of dispersion curves [21], polarization mode dispersion in optical fibers [22], group delay of dielectric laser mirrors [23], absolute distance [24], simultaneous measurement of the refractive index and thickness of transparent materials [25], high resolution profilometry [26] etc.

Since the prediction of coherence-induced spectral changes by Wolf [27], there has been increased interest in the theoretical studies and experimental demonstrations explaining the phenomenon of the spectral changes and the formation of spectral interference fringes in the framework of optical coherence theory [28]. The state of coherence can affect the spectrum of the interfering fields to the effect of shift in the peak to the observation of modulations in the spectrum depending on the bandwidth of the light source and the change in the degree of spectral coherence between the interfering fields. These spectral changes have been used to study the path difference between the interfering beams [29], estimate the field cross-correlation and hence the angular separation of sources [30], intensity distribution across the source [31], size of the source [32], etc.
1.3 Organization of the thesis

A complete theoretical background necessary to interpret the results obtained in the different experiments of spectral interferometry are discussed in detail in the chapter 2. All the relevant basic concepts and definitions necessary for describing the interference phenomenon in both the space-time and the space-frequency domains are given first. We have also presented a brief derivation and discussion of interference law and the second order correlation phenomenon in the time domain to emphasize the significance of the new treatment. Spectroscopy of partially coherent sources can be discussed more elegantly using the recently developed space-frequency description. Using the concept of second order correlation in this domain, the spectral interference law for the interference between two fluctuating optical fields is derived. The degree of spectral coherence which plays the central role in discussing the spectral interference phenomenon, has been derived for a statistically quasi-homogeneous source and is found to be identical with the far-zone form of the van Cittert-Zernike theorem. Two special types of fields produced by the planar, secondary, quasi-homogeneous sources and the limiting conditions under which they can be called spectrally impure beams and fully coherent light beams are also highlighted using the space-frequency description.

Interference phenomenon predicted in the complementary time and frequency domains, depending on the delay introduced between the interfering beams have been experimentally demonstrated using a home built broad band dye laser. The chapter 3 begins with a detailed description of the dye laser design and its performance with different cavity elements to decide on the suitable bandwidth for our experimental investigations. The coherence time ($\tau_c$) of the laser source, is a very important parameter in observing the transition of interference effects from one domain to the other. This is measured using the time delayed degenerate four wave mixing experiment. A simple demonstration of the interference phenomenon in the complementary domains is illustrated using a dispersion compensated Michelson interferometer along with the derivation of theoretical equations with the appropriate conditions necessary to understand the physical process involved. The interference
fringes in the spectral domain are then characterized by measuring the fringe modulations and the number of fringes over the entire source spectrum and the spectral intensity of the fringes at a particular wavelength as a function of the delay introduced between the two interfering beams of a Michelson interferometer.

The quantity that plays pivotal role in understanding the interference phenomenon in the space-frequency domain is the degree of spectral coherence. We have demonstrated two experimental schemes to measure the modulus and the real part of the complex degree of spectral coherence using the Michelson and Young's double slit interferometers respectively in the chapter 4. The degree of spectral coherence is found to change the spectrum radiated from a white light source drastically because of the field correlation effects. Theoretically derived equations are used to fit the experimental data to get a quantitative estimate of the effect of different experimental parameters like the path delay and the source size in the Michelson interferometer, slit widths of the spectrometer, width of the secondary source and the separation between the double slits in the Young's interference experiment, affecting the spectrum of the interfering light beams. The demonstration of the principle of space-frequency equivalence from the measurement of the degree of spectral coherence has found applications in the radio astronomy, aperture synthesis imaging, etc.

Chapter 5 deals with one of the applications of the interference phenomenon in the space-frequency domain. Spectral interferometry as it is called, has been used in the measurement of linear displacement from the periodicity of the spectral interference fringes. Use of the broad band dye laser constructed for the purpose of demonstrating the complementary nature of the interference phenomenon, was further extended to observing the effects of partial correlation between the interfering beams. We compare the absolute value of the displacement calculated from the theoretical fitting in our method [29] with the already established Fourier transform technique to substantiate the claim on the accuracy of our results. The Mach-Zehnder interferometer used for this purpose is prone to the effects of vibrations and other disturbances which spoil the modulation depth of the interference fringes and hence the quality of information that
can be obtained. We have tried different interferometer configurations to study the effect of various experimental parameters affecting the fringe contrast and to improve the stability of the interferometer against disturbances and hence getting spectral interference fringes with better fringe contrast.

In the process, we found out that more information can be obtained from spectral fringes obtained with an increased source bandwidth. Chapter 6 discusses a potential application of the spectrally resolved white light interferometry in determining simultaneously the refractive index over the entire visible region and the thickness of any transparent material placed in one of the arms of a Michelson interferometer [25]. Compared to other available techniques for the measurement of the refractive index and thickness, we have demonstrated the superiority of our method by measuring the optical constants of glass and polymer materials of different refractive index and thickness to a high accuracy of the order of $10^{-5}$. Single shot, real time, non-destructive measurement of the dispersion curve over the entire spectrum of the source is the highlight of the experiment. The versatility of the technique lies in its simplicity and the unlimited dynamic measurement range. Spectral phase and the appearance of stationary phase point are some of the other results discussed. The real and imaginary parts of the refractive index because of either a normal dispersive material or an absorbing sample can also be obtained from the frequency or amplitude modulated spectral fringes respectively.

The sinusoidally modulated spectral fringes with the flexibility over their periodicity obtained using a white light source and a Michelson interferometer can also be used to exactly quantify the optical characteristics of a dispersing spectrometer as demonstrated in the chapter 7. To exactly measure the line profiles of spectral sources, it is important to know the behavior of the instrument function of a spectrometer. The modulation transfer function (MTF) which is the Fourier transform of the instrument function, specifies the quality of the instrument and is experimentally measured for different slit widths of the spectrometer and at different resolution levels. The effect of these parameters of the spectrometer is found to affect the contrast or the MTF of the spectral fringes observed at the output. From their behavior, the instrument function
can be calculated by taking its inverse Fourier transform [33]. In the process, we have also measured the spectral slit width and hence the limit of the grating spectrometer under different experimental conditions.
References


