OPTICAL METHODS FOR SURFACE MEASUREMENTS: STATE OF THE ART

H. J. Tiziani

University of Stuttgart, Institute of Applied Optics,

Pfaffenwaldring 9, 70563 Stuttgart

Zusammenfassung

Die Einsatzgebiete der optischen Meßtechnik haben sich durch die Einführung entsprechender Bildverarbeitung ausgeweitet. Neben der Triangulation und den Moiré-Verfahren bieten sich interferometrische Verfahren für die hochgenaue Messung an; ein großes Potential, das noch nicht voll ausgenutzt wird. Ansätze zur Reduzierung der Störanfälligkeit, aber auch der Auflösung werden diskutiert.

1. Introduction

Different techniques can be used for optical 3-D-micro- and macrostructure measurements. They are summarized in table 1. Time of flight and phase measurement techniques are well known and applied for distance measurements, the principle of triangulation as well as its extension to light sectioning and projected fringe methods can be applied succesfully for close range measurements. (1,2) Image plane locating systems interferometric methods as well as confocal principles can be used for optical topometry.

Moiré techniques or projected fringe techniques are becoming useful tools for topography measurements. They can be applied to determine surface shape or deviation of the shape or vibration amplitudes.

Image plane locating systems have reached a very high technical standard. They can be used to measure the topography of surfaces. Furthermore, confocal principles were introduced for biological objects mainly. They can be applied for the measurement of the surface geometry of technical objects as well.

Today, laser interferometry is probably one of the most commonly used technique for high resolution measurements in metrology. A stabilized He-Ne-laser is frequently used as light source with an absolute stability of better than 10^{-7}. The accuracy for length measurements is limited by the atmospheric conditions (humidity, temperature, pressure) rather than by the laser stability. Furthermore, single mode diode laser are used in metrology eventhough frequency stability is still a problem especially in interferometry.

Interferometry and Moiré techniques as well as image plane locating systems will be applied more frequently, when used with image processing. They are becoming useful tools for precision measurements in research and for industrial applications. Computer analysis is increasingly important for fringe analysis. The use of solid-state detector arrays, image memory boards together with microprocessors and computers for the extraction of the information from the interferograms and high-resolution graphic boards find important application in optical metrology. Much more information can be extracted from the sensor data, leading to higher sensitivities and accuracies. (3)

The phase shifting technique is very appropriate for digital processing and TV techniques. Two-beam-interferometry together with video electronic processing lead to a sensitivity of 1/100 of a fringe at any point of the fringe pattern in the TV image. In heterodyne methods the relative phase increases linearly in time and the reference phase is measured electronically at the beat frequency of the reconstructed wavefields. Heterodyne interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe. It requires, however, sophisticated electronic equipment and mechanical scanning of the fringe pattern.

2. Triangulation

Active and passive triangulation techniques are powerful tools for contactless measurements. Passive triangulation is used in photogrammetry to obtain the topography. For active triangulation a laser spot is projected on to the object. Its image position is recorded on a position sensitive detector or on a CCD-chip (line or array camera). The lateral displacement of the spot image is directly related to the depth in the object (fig.1). The resolution of the triangulation techniques is given by

$$dz = \frac{\Delta W . z_0^2}{B} \qquad 1)$$

where z_0 is the working distance, B is the base, ΔW is the angular resolution of the detecting system.

Triangulation based 3-D-sensors are appropriate tools for inspection and measurement in industrial environment. Especially synchronized single-spot-scanners fulfil the high requirements upon range, resolution and robustness. In fig. 1 the principle of a scanning triangulation system is shown schematically. The galvano scanner mirrors are controlled by computer to select the x - y coordinates. Angular resolutions of 5 µrad can be obtained. The z coordinate is given by the triangulation principle discussed before. Furthermore a synchronisation of the observation beam with the illumination beam of the scanner may be realized in a optomechanical way, typically by leading the observation beam by a mirror, which is rigidly connected to the scanning mirror of the illumination beam. (Fig. 2) Due to this rigid coupling of the mirrors there exists one fixed shape, which is imaged onto the scanning position on the detectors. To overcome the lack in synchronisation a computer controlled synchronisation is realized. For this purpose a galvanometer scanner driven mirror is located in the observation beam in front of the imaging lenses. This mirror deflects the observation beam depending on the angle for all points which lie on the selected reference contour.

The main advantage of the chip synchronization is the possibility to generate an arbitrary reference contour by altering the dependence between the detection on the projecting scanner. This dependence can be found by a teach-in process, where the shape of a masterpiece is measured, in order to act as a reference for the measurements of the following working parts. It is also desirable to get the reference contour from construction data by an analytical expression for instance.(4)

3. Projected fringe techniques for industrial inspection and micro shape analysis

Light sectioning and projected fringes are an extension of the triangulation for out of plane - and topography - measurements. Projected fringe patterns can be formed by different methods. Projecting either a grating like structure or an interference pattern, height variations or deformations lead to a deformation of the projected fringes, which in turn are compared with the original or synthetic grating like structure. Typical contour-line separations can vary between micrometer and millimeter.
In Moiré techniques a deformed grating structure is superimposed onto the original grating to lead to Moiré fringes. The grating structures do not need to be resolved by the image forming detecting system. Topography, deformations and vibration amplitudes can be analysed.

A number of techniques has been developed for micro - and macrotopography measurements. The choice of an appropriate technique depends on the sensitivity required, which in turn can be adjusted. Furthermore, grating like structures to be projected onto the object can be generated by means of liquid crystal cells. Moiré and projected fringe techniques are not as sensitive as interferometric and holographic techniques but are also less sensitive to environmental disturbances. An arrangement for microscopic topography measurement with projected fringes is shown schematically. The fringe projection occurs at an angle $ß_1$, the observation at an angle $ß_2$.
3 D-shape analysis by fringe projection can become an important method for micro structure analysis. A fringe projecting microscope, is shown schematically in Fig.3 , where the projection of the grating as well as its image forming on the CCD camera occurs with the same objective, L_4. High lateral and vertical resolution of the order of 1 µm and 0,1 µm respectively can be obtained.

In fig. 3 the binary line grating (Ronchi grating) is projected obliquely onto the object. The spectrum is therefore shifted off-axis (laterally), so that the principal rays corresponding to the zero-order of the spectrum of the projected grating form an angle $ß_1$ with the optical axis of the microscope objective.

The grating projection microscope (GPM) extends the range of applications. It will especially be applied where interference techniques cannot be applied such as for rough surfaces (mean roughness > 0,2 µm). The most demanding objects are objects with rough surfaces like sheet-metal, ground and turned metal surfaces, plastics, ceramics, even biological surfaces can be analysed.

A symmetrical configuration with $ß_2 = |ß_1|$ according to Fig. 3, was found to be the most suitable. The amount of the off-axis shift is matched to the pupil diameter in a way, that the outer first order of the grating spectrum can pass the entrance pupil and sufficient clearance is given for lateral displacement or dispersion of the spectrum of the back-travelling light reflected from inclined or rough surface elements.

For a telecentric GPM-arrangement both the entrance pupil of the imaging system and the exit pupil of the grating projection system lie at infinity in order to compensate variations in height sensitivity.

The grating can be illuminated by a tungsten halogenide lamp L as shown in fig. 3 via Lenses L_1 and L_2 or can be generated interferometrically. The grating structured image distorted by the object topography is formed onto the CCD interline transfer camera with 756 x 581 picture elements by the objective L_4 and the lens L_5. The conversion of the height variation Δh due to a local fringe displacement Δx in x-direction is for a grating projecting angle ß and an observing angle - ß:

$$\Delta h = \frac{\Delta x}{2 \sin ß} \qquad 2)$$

4. Interferometry for precision measurements

The introduction of the laser in 1960 and the progress made recently in automatic fringe analysis are mostly responsible for the widespread application of interferometry in industry today. Fringe analysis is not only important in interferometry, but also in holography, speckle applications and Moiré techniques.

Automatic quantitative evaluation of interferograms requires accurate interference phase measurements, independent of fringe position and intensity variations superposed onto the interferograms. For the fringe analysis static and dynamic techniques are used. Whereas in dynamic techniques an active phase shifting in the interference arrangement is required, it is not necessary in static methods. In many interferometric arrangements, however phase shifting or heterodyne techniques have been introduced for automatic fringe analysis.

In the phase shifting technique or quasi-heterodyne technique the relative phase is changed continuously or stepwise, using at least three phase shifts of 90° or 120°, for instance. The phase of the interference patterns can then be computed from the different stored intensity values. Very frequently 5 interferograms are analysed with 4 phase shifts between. The phase shifting technique is very appropriate for digital processing and TV techniques. Two-beam-interferometry together with video electronic processing lead to a sensitivity of 1/100 of a fringe at any point of the fringe pattern in the TV image. In heterodyne methods the relative phase increases linearly in time and the reference phase is measured electronically at the beat frequency of the reconstructed wave-fields. Heterodyne interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe. It requires, however, sophisticated electronic equipment and mechanical scanning of the fringe pattern. Alternatively, phase locked techniques can be very attractive for some applications as will be discussed.

Digital interferometry is very useful for getting the interferometric data into a computer for the analysis. An experimental arrangement with oblique incidence is shown in Fig. 4. For the automatic analysis of closed fringes a phase-shift technique is appropriate. Phase shifts can be introduced by tilting a plane-parallel plate, moving a mirror by means of piezo-elements or by polarization techniques. In Fig. 4 phase shifting occurs by means of a piezo driven mirror in the reference path.

Interferometry in a microscope arrangement with fringe analysis can be used for microstructure analysis. Linnik Type 2 beam interference or differential interferometry or Normarski interference contrast can be used with depth resolution of a few Angstroms.

5. Interferometry at oblique incidence

Interferometry is a powerful tool for high resolution measurement of the topography of polished surfaces. It can however not be applied to study and measure the topography and microstructure of optical rough surfaces. Height variations Δz of the object will change the phase ϕ of the reflected object beam. This phase variation detected by an interferometer, for instance can be measured as a function of position x on the surface. A problem occurs when the surface has step height variations greater than $\lambda/2$ in reflection. A discontinuous height variation Δz introduces a phase jump $\Delta\phi$ given by $\Delta\phi = (4\pi/\lambda)\Delta z$. However, the interferometer can only determine the phase ϕ modulo 2π . A reduction in sensitivity is obtained by an oblique incidence of the wavefront onto the test object. The optical path difference in air is $W = 2n\Delta z\cos\theta$, where Δz the distance between the reference surface and the object in a Fizeau arrangement and θ the angle of incidence onto the object. The optical sensitivity is therefore reduced by $\cos\theta$. For $\theta = 81^{\circ}$ the effective or synthetic wavelengh is 4 µm from a HeNe laser source with $\lambda =$ 633 nm. In Fig. 4 the incident beam is separated by the prism surface into the reference and object beam with oblique incidence. The reference wave is phase shifted by the piezo driven reference mirror MR before the reference and object beam are combined. The fringe pattern is projected onto the CCD chip. The special arrangement avoids multiple reflections and image distortions.

6. Heterodyne Interferometry

In interferometry, phase differences of optical fields are transformed into detectable intensity variations. In heterodyne interferometry the time-dependent phase variation is analysed in the frequency space. If two light coherent fields with a frequency difference f are superimposed a resulting intensity I is obtained

$$I = I_r + I_s + 2\sqrt{I_r I_s}\cos(2\pi f t + \phi) \qquad 3)$$

where Ir, Is are intensities of reference and signal beams respectively. The time-varying phase ϕ (x, y, t) can be detected. The Doppler shift frequency is

$$\delta f = \frac{\phi(x,y,t)}{2\pi t} = \frac{2dz}{\lambda dt} \qquad 4)$$

where z is the displacement projected parallel to the line of sight

$$z = \frac{\lambda}{2}\int_{t_1}^{t_2} \delta f dt \qquad 5)$$

In Fig. 5 a typical heterodyne arrangement for displacement and vibration analysis is shown schematically. The arrangement can also be used for micro structure analysis with depth resolution in subnanometer by a lateral resolution of better than 1 µm (9).

Heterodyne interferometry will lead to very useful future applications in precision measurements. For vibration analysis at given points, heterodyne interferometry gives not only the amplitude component of the vibration parallel to the line of sight, but also the frequency. In addition, it can be very useful for fringe analysis in holographic and speckle interferometry.

7. Two Wavelength Interferometry

Surface profiling is a useful application of interferometry where the object beam is focussed on an object that is scanned perpendicularly to the beam. The application of interferometry could be drastically increased, when the technique is extended to optically rough surfaces. In addition, with interferometry, phase measurement can only be determined with modulo 2π. An increase of the laser wavelength would be useful for the metrology of technical surfaces. Laser sources and the appropriate detectors are frequently not or not yet available. In addition, the high lateral resolution is lost by IR-laser wavelength.
In two-wavelength interferometry where the laser emits light with two slightly different wavelengths λ_1 and λ_2, the interferometer detects two separate interference patterns.
By an appropriate processing of the two individual interference patterns a new interference term of the form $\cos(4\pi z/\Lambda)$ is created where Λ is an equivalent or beat wavelength given by
$\Lambda = \lambda_1\lambda_2/|\lambda_1-\lambda_2|$
Since the wavelength difference $|\lambda_1-\lambda_2|$ is usually small, the equivalent wavelength is much larger than the original wavelength used. Since laser diodes can be easily tuned they are capable of generating a wide range of equivalent wavelengths.
The two-wavelengths used can either by time multiplexed or can be present continuously. Furthermore the two-wavelength techniques can be applied in interferometry as well as in holography and speckle-interferometry.

Two-Wavelength Heterodyne Interferometry

In a heterodyne interferometric set-up two waves are superposed to lead to a frequency shifted interference phenomenon.
The detected heterodyne signal is arranged to be shot noise limited. There are different techniques to introduce the frequency shift such as using an acousto optical modulator (AOM) or a rotating grating or by using the Zeeman splitting in a laser cavity.
In the DHI (double heterodyne interferometry) two heterodyne interference systems are superposed to lead to a beat frequency of the two wavelengths responsible for the distance measurement.
The heterodyne signals $I_h(t)$ are

$$I_h(t) = 2\sqrt{I_{r_1} I_{s_1}}\cos(2\pi f_1 t + \phi_1) + 2\sqrt{I_{r_2} I_{s_2}}\cos(2\pi f_2 t + \phi_2) \quad 6)$$

I_{r1}, I_{s1}, I_{r2}, I_{s2} are the intensities of the interfering reference and signal beams for the two wavelengths λ_1 and λ_2, f_1 and f_2 are the heterodyne frequencies

$$\begin{aligned} \phi_1 &= \frac{4\pi}{\lambda_1} z - 2\pi\left[\frac{\nu_1 + f_1}{c}\right] L \\ \phi_2 &= \frac{4\pi}{\lambda_2} z - 2\pi\left[\frac{\nu_2 + f_2}{c}\right] L \end{aligned} \quad 7)$$

z is the object distance to be measured and c the velocity of the light; ν_1, ν_2 are the frequencies of the corresponding wavelengths λ_1 and λ_2 , L is the reference path. The heterodyne signal after the mixer is $I_{sh}(t)$ (superheterodyne signal)

$$I_{sh}(t) = 4\sqrt{I_{r_1} I_{s_1} I_{r_2} I_{s_2}} \cos\left[2\pi(f_1-f_2)t + \frac{4\pi}{\Lambda}z - \frac{2\pi}{c}(\nu_1+f_1-\nu_2-f_2)L\right] \quad 8)$$

where $\Lambda = \lambda_1\lambda_2/|\lambda_1-\lambda_2|$

In double heterodyne interferometry two laser wavelengths and two heterodyne frequencies are used simultaneously. A low frequency detection signal with a phase shift that corresponds to the effective wavelength is generated. A two-wavelength double heterodyne interferometer (DHI) setup consists basically of two independent heterodyne interferometers working at different wavelengths λ_1 and λ_2 and different heterodyne frequencies f_1 and f_2. The phase of the beat frequency $f_1 - f_2$ depends on the effective wavelength and can therefore be examined for distance evaluation as has been shown in (8,10).

The DHI is very appropriate for high precision absolute measurements. There are different possibilities for the realization of a DHI. At first two diode lasers giving λ_1 and λ_2 look very promising. An interesting way to obtain various wavelengths is to use a single laser diode in combination with a Bragg cell and two acousto optic modulators (AOM's).

The high frequency AOM driven by 500 MHz and 501,5 MHz leads to wavelengths of 60 cm and 200 m (for 1,5 MHz). An experimental setup is shown in Fig. 6. The two AOM's driven at 80 and 80,1 MHz lead to the frequency difference of $f_1 - f_2 = 100$ kHz. Fluctuations of the AOM frequencies f_1 and f_2 will affect the beat detection frequency $f_1 - f_2$ but do not disturb the phase measurement if the reference signal for the phasemeter is interferometrically generated. (10)

A set up realized in our laboratory is shown in Fig. 7. Light of monomode laser diode with wavelength λ_1 is frequency-shifted by a frequency of 500 MHz by an acousto-optic modulator (AOM), leading to a second wavelength λ_2. This corresponds to a synthetic wavelength of 60 cm. Light of the wavelength λ_1, λ_2 is used as reference light, while the object light is shifted by means of two additional AOM with f1 = 80 resp. f2 = 80. 1 MHz in order to provide double heterodyne reception. The object and reference light are superimposed on a photodetector.

Heterodyne interferometry is a powerful tool for high precision distance measurements and vibration analysis. Two wavelength heterodyne techniques become very interesting for absolute distance measurement. A synthetic wavelength can be generated by two shorter ones, leading to techniques for absolute measurements and measuring on optically rough surfaces. The theory is based on the assumption that the optical path difference is to be compared with the synthetic wavelength.

8. Phase-locked technique for subsurface material analysis

Phase-locked technique can be very useful for subsurface material analysis. For non-destructive material analysis, photo-acoustic and photothermal methods can be applied (12). In photothermal interferometry the thermal expansion of the specimen is measured rather than the thermal wave itself.

In phase locked techniques the intensity variation slope due to the optical path difference is analysed. In two-beam arrangements phase difference of $\lambda/100$ can be detected and may be used for measuring surface topography and subsurface defects. The interferometer incorporates, as part of a servo-system, a piezoelectrically driven mirror that is capable of applying a known optical phase offset and a periodic optical modulation. The ac. signal is processed to generate an error signal for the servo-system.

A two-beam interferometer using a He-Ne laser is shown in Fig. 8 for the analysis of subsurface defects by measuring the small surface deformation caused by a chopped, focussed argon laser beam with wavelength λ (λ= 488 nm). The interferometer arrangement is not very sensitive to vibration occurring due to scanning the object for instance. It is a two-beam arrangement where the reference beam, a focussed spot, is placed close to the measuring laser spot (at 20 µm for instance). The phase shifting of the reference relative to the measuring object surface, for the phase locked techniques, occurs with the electrooptical modulator by introducing a computer controlled voltage, which changes the refractive index of the crystal. Low frequency chopping applications were used for the analysis of the quality of weldings, high frequency to detect impurities and their concentration in materials used for microelectronics.

Conclusion

Different optical methods can be used for distance and topography measurement. The range and sensitivity need to be selected. The methods are contactless and fast. Interferometric methods are sometimes, however too sensitive with respect to environmental disturbances and roughness of technical objects. Furthermore surface roughness leads to unwanted speckles to be taken care of by the analysis and information processing. Methods will be developed to measure topography of optically rough surfaces. Oblique incidence and 2λ interferometry are possibilities to overcome some of the limitations.

References

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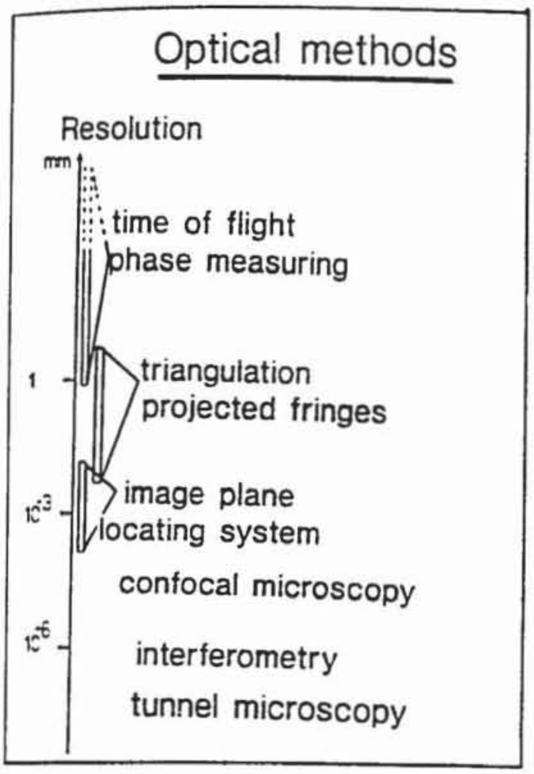

Table 1:
Resolution of optical 3-D-measuring principles

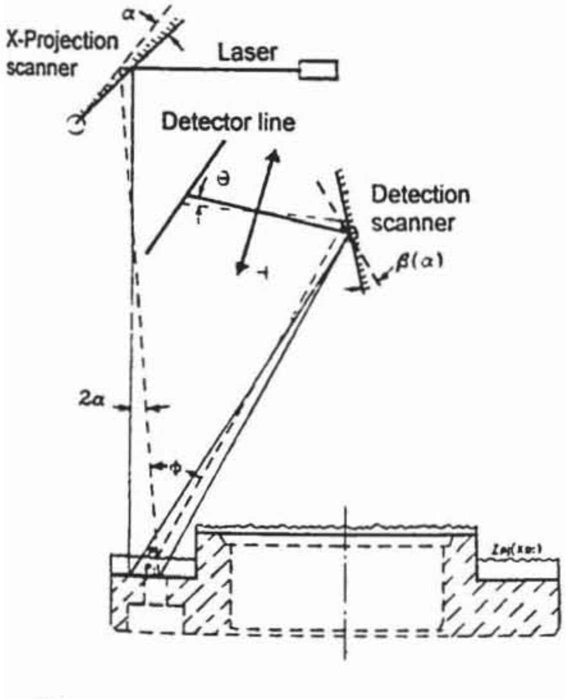

Figure2:
Dynamic triangulation with computer controlled mirror in the imaging path.

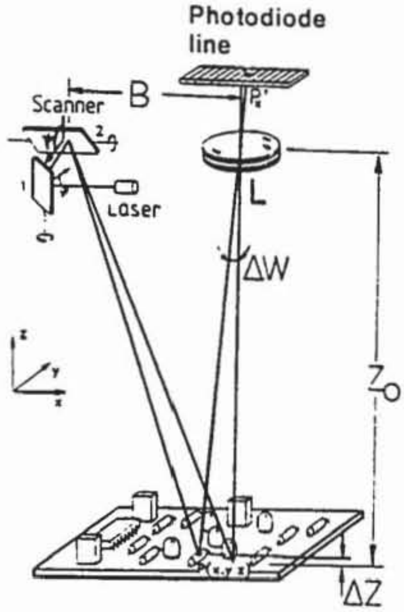

Figure 1:
Principle of dynamic triangulation

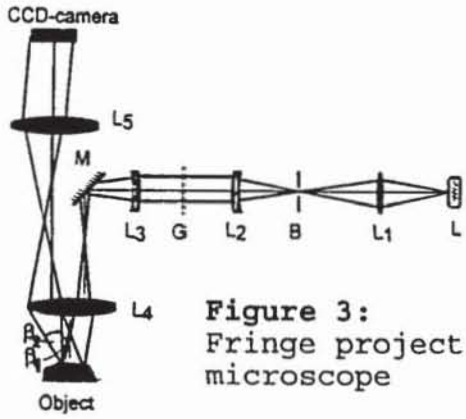

Figure 3:
Fringe projecting microscope

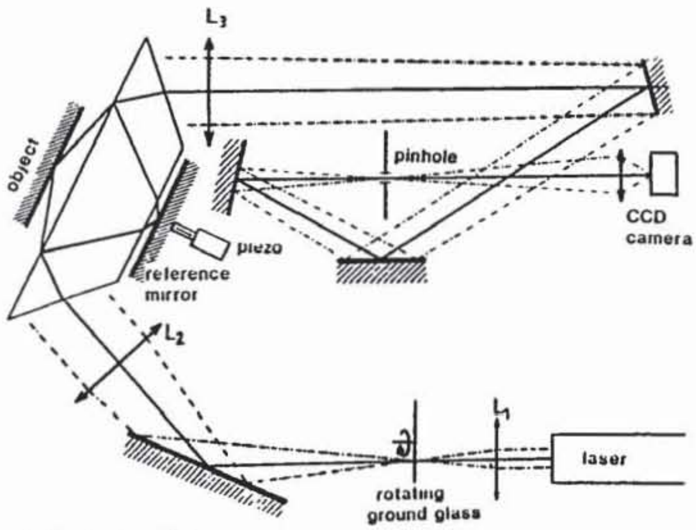

Figure 4:
Arrangement for interferometry with oblique incidence

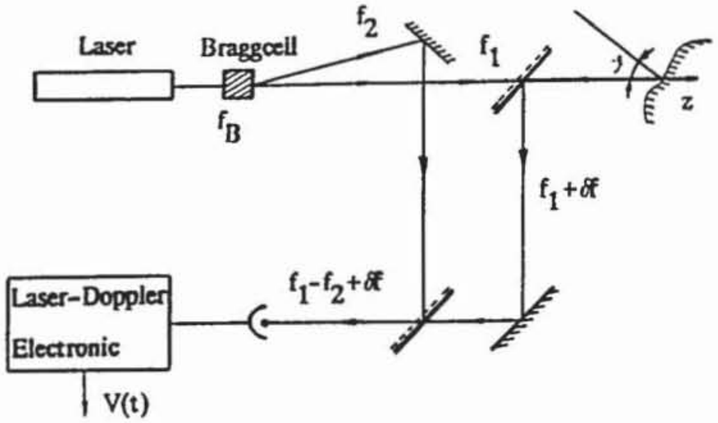

Figure 5:
Arrangement for two beam interferometry with a Bragg cell used for the constant frequency shift $f_2 - f_1$

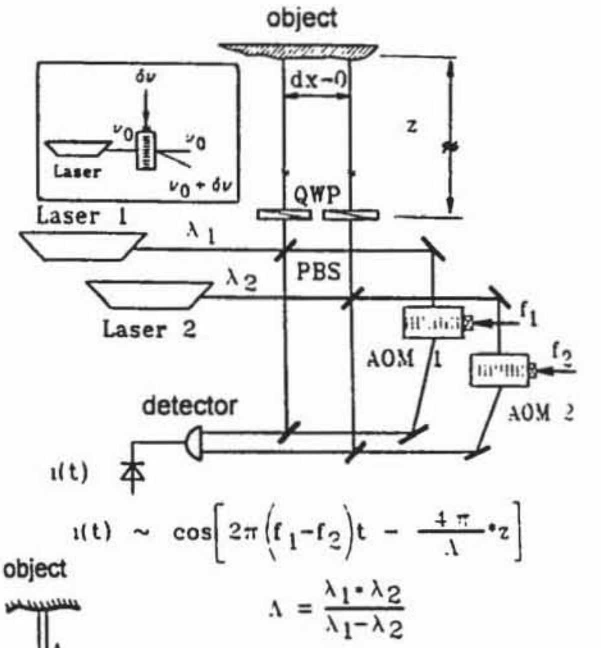

Figure 6:
Principle of two-wavelength heterodyne in interferometry

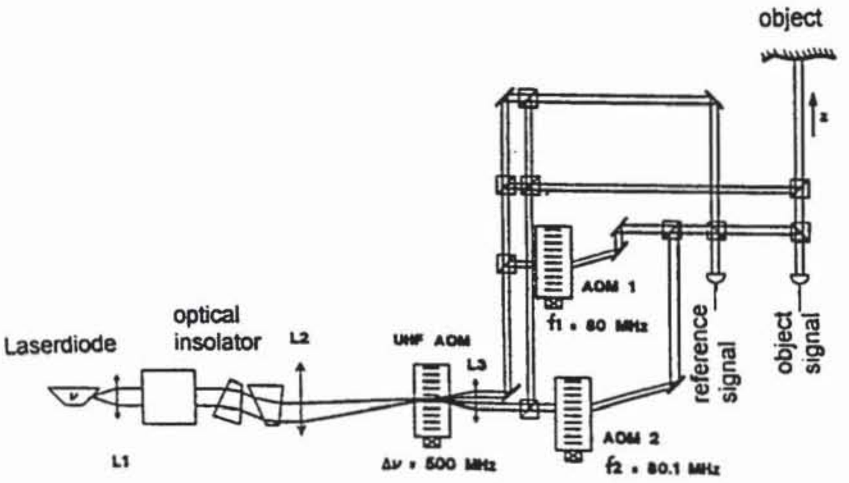

Figure 7:
Practical realization of a particular two wavelength heterodyne interferometer arrangement

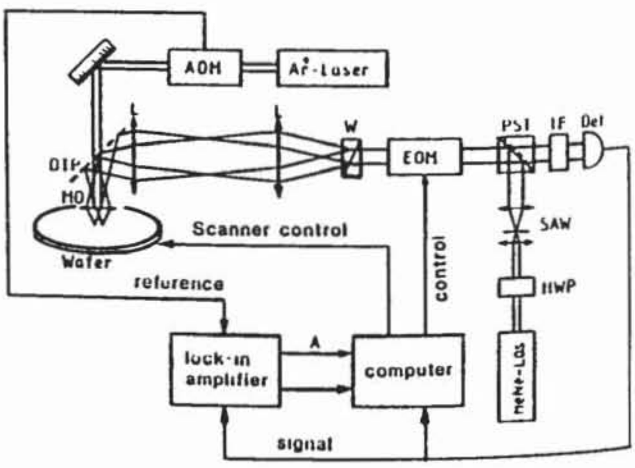

Figure 8:
Experimental arrangement for subsurface defect analysis