

HIGH PRECISION LASER SUPPORTED CLOSE RANGE DISTANCE MEASUREMENTS

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Abstract

Optical methods become useful tools for dimensional measurements. Methods based on triangulation, time of flight, phase measurements and interferometry are used and will be further developed. Multiple wavelength interferometry allows the reduction of the sensitivity by a range extension leading to robust measuring systems. Superheterodyne interferometric techniques based on two wavelength heterodyne interferometry will also be discussed and experimental results will be shown.

1. Introduction

Different techniques for dimensional measurements have been developed the last few years. In addition to the well known time of flight and phase measuring techniques other principles based on triangulation, structured light illumination, image focussing and interferometry are implemented.

In fig. 1 some methods for high precision measurements with some rough estimations of the depth resolution are indicated. The resolution for time of flight measurements is in the cm-region with expensive electronics for pulse shaping in the mm-region. Phase measurement can be applied for mm or even submillimetre resolution. For close range application "triangulation" and "image plane locating" principles can be used. However for high resolution, interferometric methods can be useful but for nearly polished surfaces only.

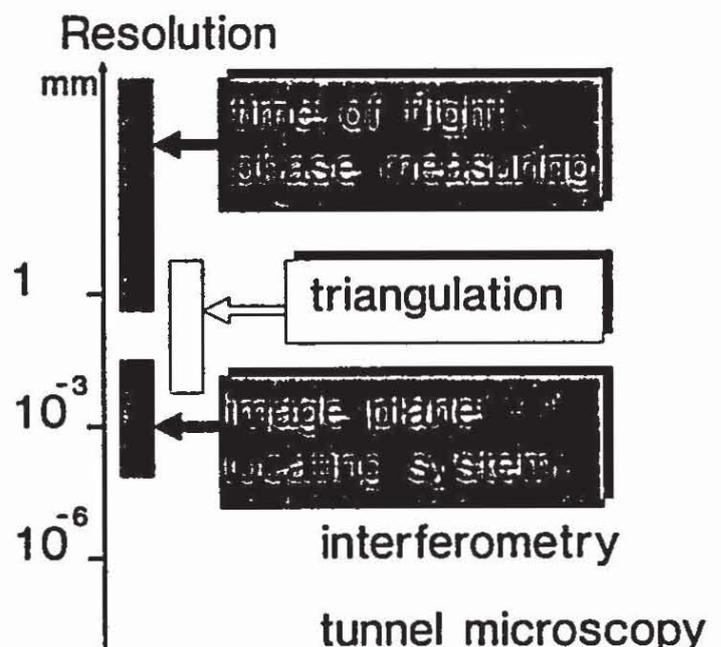


Fig. 1. Optical methods for precision measurements

Today, laser interferometry is probably one of the most commonly used interferometric methods in metrology. A stabilized He-Ne laser is frequently used as light source. The

accuracy for length measurements is limited by the atmospheric conditions (humidity, temperature, pressure) rather than by the laser system capability.

In some applications of interferometry single frequency diode laser begin to replace the traditional He-Ne laser. Diode lasers are small, cheap and easy to operate but some additional requirements need to be taken into account. Current and temperature stabilization is needed for single frequency operation without mode hops. The spectral emission is very sensitive to optical feed back (optical isolators are needed). An external reference is useful for absolute frequency stability.

To measure length with a laser interferometer the fringes are counted while displacing a mirror respectively a corner cube over the distance. Any change of the length results in fringe movement followed by forward-backward counting, as long as no fringes are lost. In this way however, no absolute distance information can be obtained. In optical profiling and optical ranging the absolute distances of reference points are often needed. Furthermore, classical interferometry can only be applied when smooth surfaces (optically polished) are to be measured.

Multiple wavelength interferometry allows to reduce the sensitivity and to extend the range of unambiguity for interferometric measurements^{1,2,3}. The use of multiple wavelengths permits to generate new synthetic wavelengths, much longer than the optical wavelengths used. For two wavelengths λ_1 and λ_2 , e.g., one obtains the synthetic wavelength Λ given by $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$

In order to obtain the desired synthetic wavelengths, single frequency lasers at appropriate wavelengths can be used. The He-Ne laser with its newly available lines in the visible is still a good candidate, but diode lasers have even better potential to cover a wide range of synthetic wavelengths. Absolute distance ranging can be performed by continuous wavelength tuning, another potential of diode lasers. The accuracy of multiple wavelength interferometry depends essentially on the coherence and stability properties of the laser sources.

Multiple wavelength interferometry offers great flexibility in sensitivity by an appropriate choice of the different wavelengths. Two-wavelength heterodyne interferometry was first reported by Fercher et al.⁴. By simultaneous phase measurement at both wavelengths, the interference phase at the synthetic wavelength can be directly determined. This method provides fast measurements and in addition works for rough surfaces.

Because of the availability of tunable diode lasers, multiple-wavelength interferometry with small wavelength differences is receiving increased practical interest. Two wavelength heterodyne interferometry, sometimes called two wavelength-superheterodyne interferometry provides a demodulated signal directly at the synthetic wavelength and permits therefore high-resolution measurements at arbitrary synthetic wavelengths without the need of interferometric stability at the optical wavelengths λ_1 and λ_2 .

2. Triangulation and structured light illumination

Triangulation is a very powerful tool for stereo vision. Our visual system as well as photogrammetric techniques are based on passive triangulation. In active triangulation a laser spot is imaged onto the object.

The lateral displacement of the spot imaged onto a position sensitive detector is a measure for the depth of the object point as indicated in fig. 2. The depth resolution Δz can be estimated according to

$$\Delta z = \frac{z_0^2 \Delta w}{B}$$

where B is the base and Δw the angular resolution of the detection system and z_0 the working distance. Resolutions better than one thousandth of z_0 can be obtained. Fig. 2 shows a dynamic triangulation system where the computer driven galvano mirror system deflects the laser spot in the x and y direction.

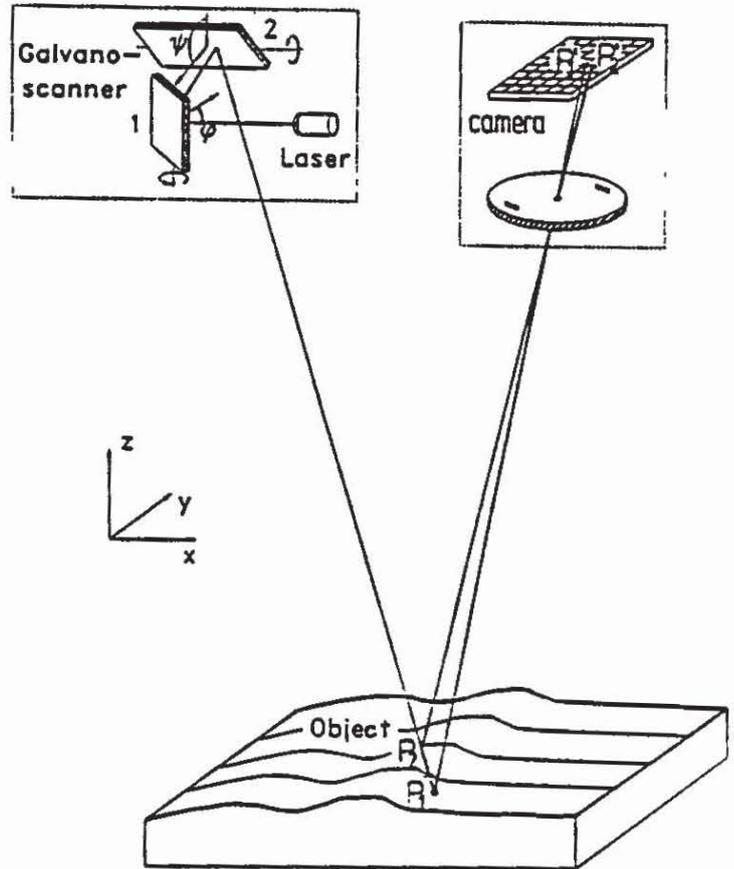


Fig. 2. Principle of a scanning triangulation method.

Extending the techniques by projecting a line instead of a point leads to the principle of light sectioning (Lichtschnitt according to Schmaltz). The object topography leads to a deformation of the line image which in turn is analysed using image processing methods to obtain the object topography. Extending the method by using a number of lines leads to the structured light technique where periodic grating like structures are projected onto the object. The deformed lines are compared with those of a reference periodic structure such as of a CCD array for instance. Different methods to generate the grating like structures can be used. If the spatial resolution is not the problem the gratings can be generated by LCD (liquid crystal).

Different structures such as binary, sinusoidal, triangular and trapezoidal structures were analysed. Trapezoidal structures were finally chosen for our gray-code projecting method. Furthermore it was found very important to use different structures at least two namely a fine structure for high accuracy measurement and a coarse one for absolute measurements especially when steps are present. In addition, the brightness of the code structures should be adapted to the local brightness of the object.

Patterns were generated by the mean of a pattern generator, a light emitting diode and a galvano scanner. Fig. 3 shows such a pattern where horizontally up to 3000 lines can be generated. The time varying patterns are indicated on the ordinate. Fig. 4 shows a typical result of a topography of a workpiece. The depth resolution is better than 1 mm for a working distance of 2 m.

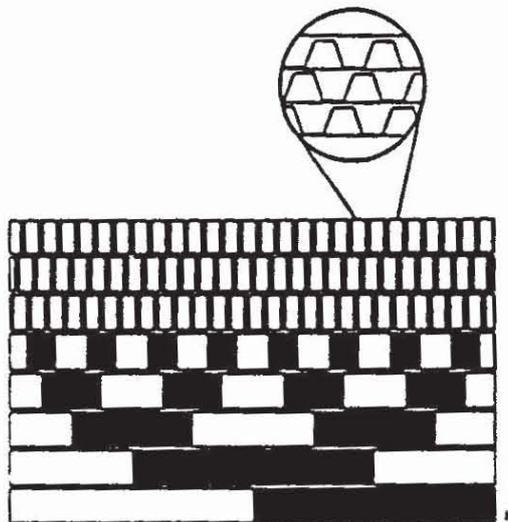


Fig. 3. Code for projected pattern

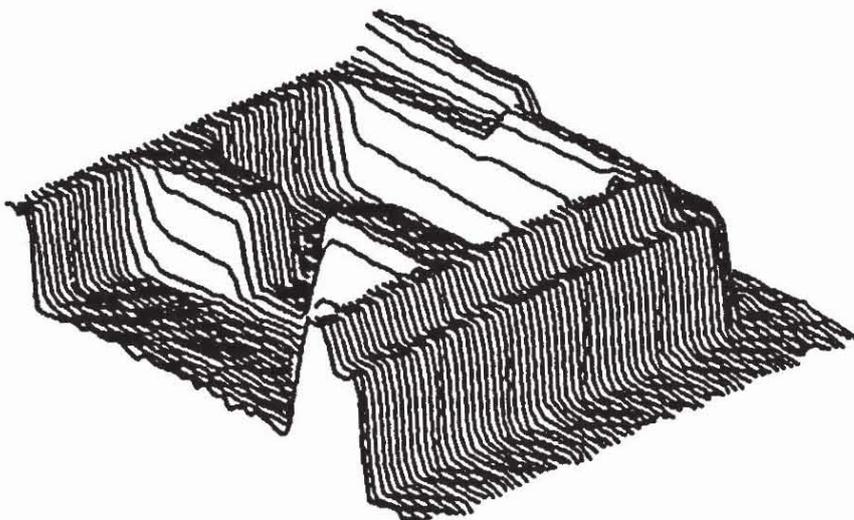


Fig. 4. Topography of a workpiece

3. Two wavelength interferometry

Surface profiling is a useful application of interferometry where the object beam is focused on an object that is scanned perpendicularly to the beam. 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 $\sum \Delta\phi = \sum (4\pi/\lambda) \Delta z$. However the interferometer can only determine the phase ϕ modulo 2π .

Furthermore, the application of interferometry could be drastically increased when the technique is extended to optically rough surfaces. 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.

In two-wavelength interferometry where the laser emits light with two slightly different wavelengths λ_1 and λ_2 , the interferometer detects two separated 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, making them a good alternative to more expensive dye lasers or multi-frequency gas lasers.

The two-wavelengths used can either be time multiplexed or can be present continuously. Furthermore the two-wavelength techniques can be applied in interferometry as well as in holography² and Speckle-Interferometry. A typical example of two-wavelength interferometry will be given in fig. 6 for $\lambda_1 = 618,6 \text{ nm}$ and $\lambda_2 = 550 \text{ nm}$. The object to be tested was a computer generated reflection hologram with the depth of the grooves of about $1,6 \mu\text{m}$ (Fig. 6). Fig. 5 shows the setup for two-beam interferometry with phase shifting and two wavelengths. Phase shifting with a piezoelement for automatic fringe analysis is indicated.

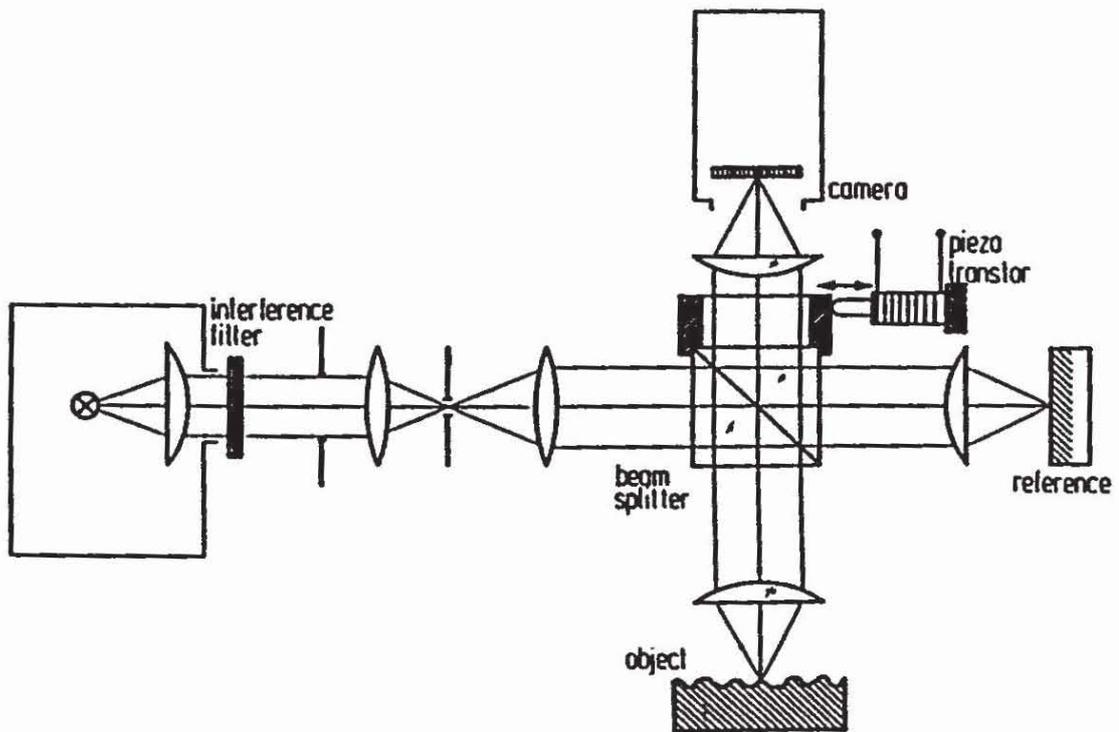


Fig. 5. Principle of two wavelength-interferometry in a microscopic arrangement with phase shifting for fringe analysis

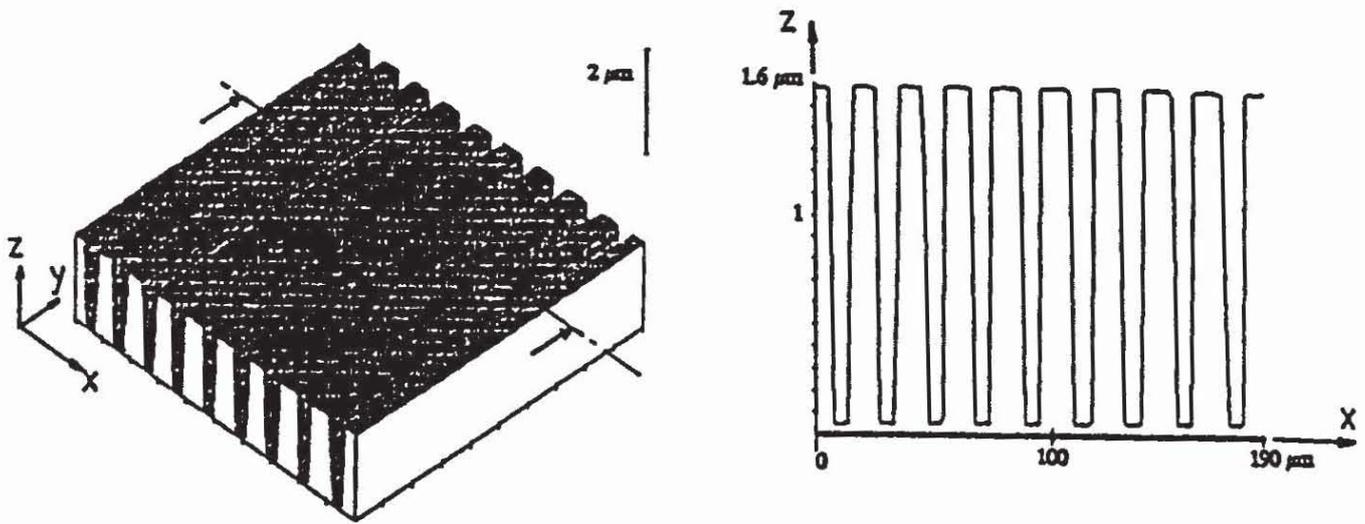


Fig. 6. Two wavelength interference pattern

4. Two-wavelength heterodyne interferometry

Two-wavelength heterodyne interferometry can overcome some of the drawbacks of classical interferometry.

In a heterodyne interferometric set-up two waves are superposed to lead to an interference phenomenon. One of the two beams is frequency shifted by f .

The optical heterodyne signal is

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

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

$$I_h(t) = 2\sqrt{I_{r1} I_{s1}} \cos(2\pi f_1 t + \phi_1) + 2\sqrt{I_{r2} I_{s2}} \cos(2\pi f_2 t + \phi_2)$$

$I_{r1}, I_{s1}, I_{r2}, I_{s2}$ 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

$$\phi_1 = \frac{4\pi}{\lambda_1} z - 2\pi \left(\frac{v_1 + f_1}{c} \right) L$$

$$\phi_2 = \frac{4\pi}{\lambda_2} z - 2\pi \left(\frac{\nu_2 + f_2}{c} \right) L$$

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)

$$I_{sh}(t) = 4 \sqrt{I_{r1} I_{s1} I_{r2} I_{s2}} \cos \left(2\pi (f_1 - f_2) t + \frac{4\pi}{\Lambda} z - \frac{2\pi}{c} (\nu_1 + f_1 - \nu_2 - f_2) L \right)$$

where

$$\Lambda = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|}$$

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 Λ and can therefore be examined for distance evaluation as shown by Dändliker et al.⁵. Using two (highly stable) laser sources emitting different wavelengths, the heterodyne frequency shifts can easily be obtained by acousto optical modulation (AOM) as shown in Fig. 7 and 8. The unshifted wavelengths are combined in a beam splitter (BS) and a monomode fiber (MMF) to generate an identical wavefront before being focused onto an optically rough specimen (Fig.8).

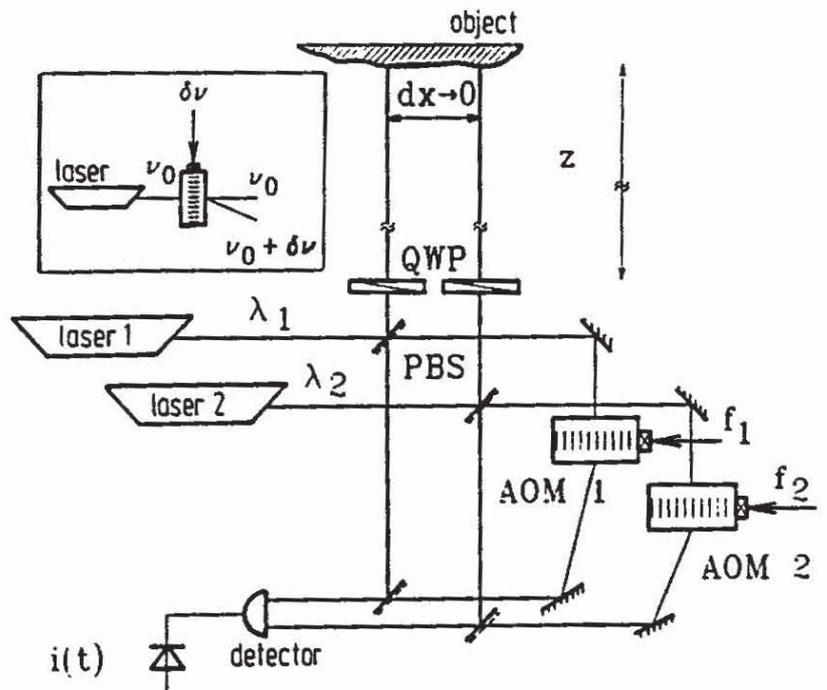


Fig. 7. Principle of two-wavelength double heterodyne interferometry

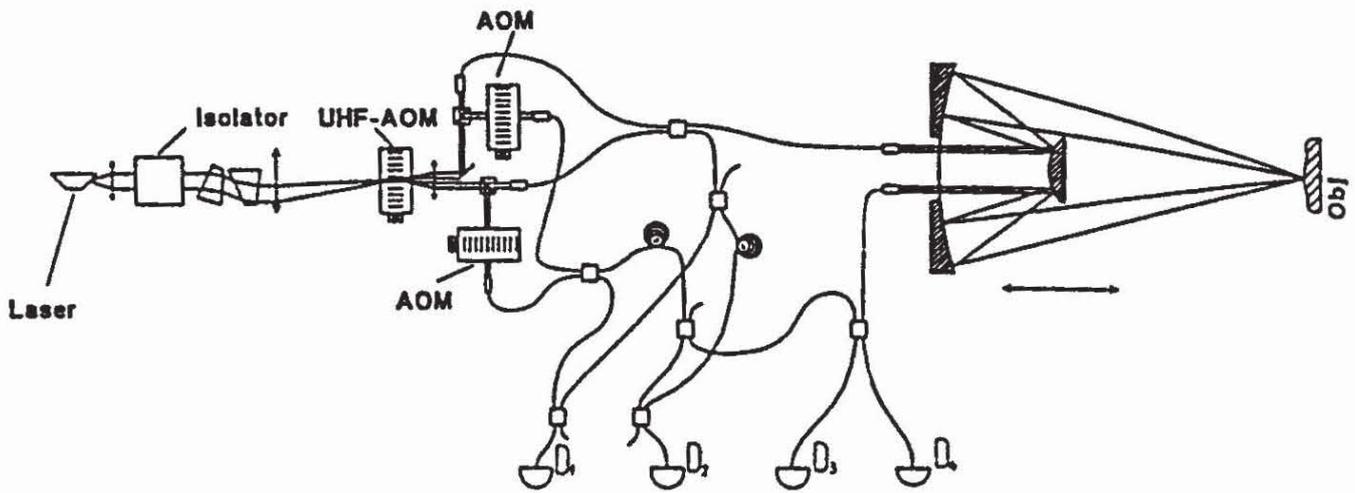


Fig. 8. Possible realisation of two-wavelength double heterodyne interferometry using a UHF AOM

Only identical wavefronts of λ_1 and λ_2 will generate identical speckles in the entrance pupil of the imaging system and onto the detector. After passing a lens (L), a polarizing beam splitter (PBS) and a quarterwave plate the light is focused onto the specimen by a microscope objective (MO) as shown in Fig. 9. The quarterwave plate is passed twice and used to rotate the polarization by 90° to achieve reflection at the polarizing beam splitter. To match the polarizations of the reference and the target beam the polarization in the target beam is then rotated back by a halfwave plate (HWP) and combined in a beam splitter with the heterodyne frequency shifted beams. The interference signal is observed by a photodetector (Det). The beat frequency is generated by squaring the signals with a Schottky diode and then fed to a phase detector.

The DHI is very appropriate for high precision absolute measurements. For the realization of a DHI there are however different possibilities. 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. 8. 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. In fig.8 it should be indicated that the object can be scanned with the coaxial focused beams with λ_1 and λ_2 produced by the high frequency AOM. For synthetic wavelengths of 200 m and 60 cm absolute measures up to 100 m with a resolution of 0,1 mm can be obtained. It should however be noted that almost focussed coaxial laser beams are needed. Furthermore only a few speckles should be accepted by the aperture respectively the detector.

In the case of a multiline laser, to be discussed, the wavelengths λ_1 and λ_2 are perfectly combined and have a good relative stability. In a conventional setup (similar to the one shown in Fig. 7, but with a multiline laser instead of two lasers) the laser radiation would be first divided into target and reference beam.

5. Double heterodyne interferometer with rotational matched grating

A two-wavelength heterodyne interferometry technique was developed for precision measurement. The heterodyne frequency difference for the two wavelengths was generated by a rotating grating for instance. After passing a lens L, a polarizing beam splitter PBS and a quarterwave plate (QWP) the object beams are focussed on to the specimen under test by a microscopic objective (MO) (fig.9).

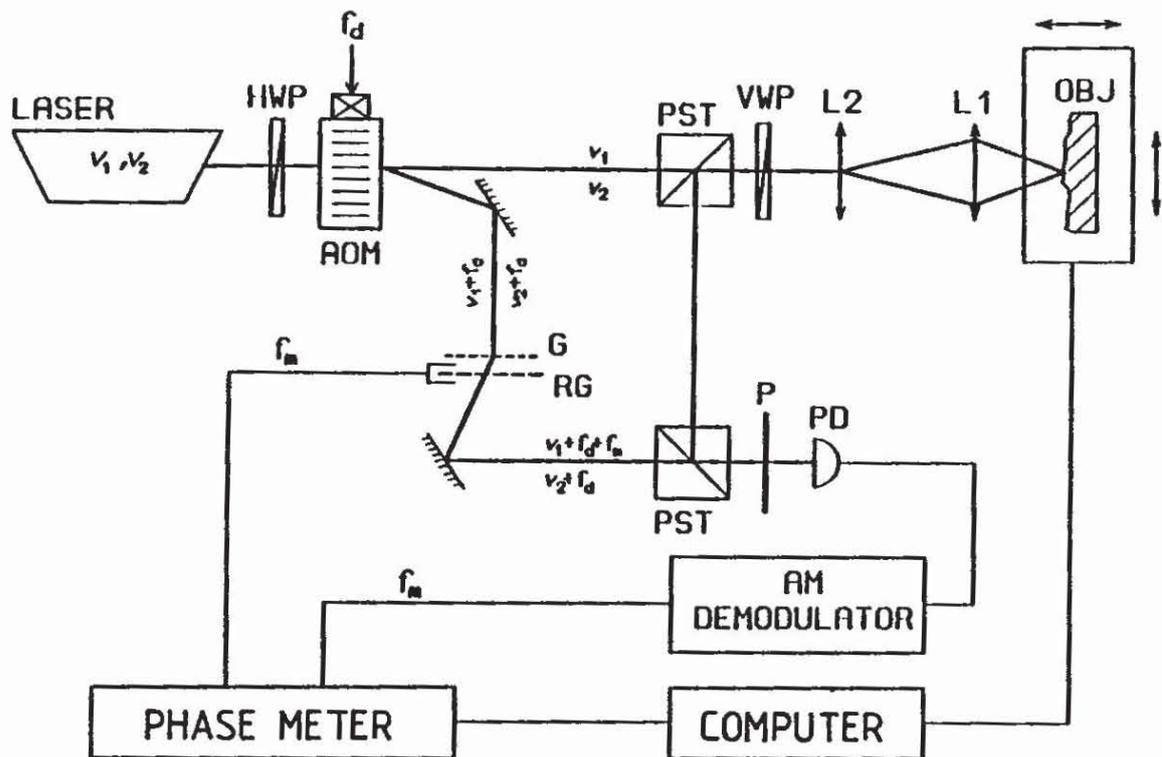


Fig. 9. Principle of DHI with matched rotating grating

In the set-up shown in fig. 9 the AOM is operated at driver frequency f_d leading to two frequencies in the first order diffracted beam for λ_1 of $\nu_1 + f_d$ and for λ_2 of $\nu_2 + f_d$. λ_1 and λ_2 are the wavelengths and ν_1 , ν_2 the frequencies of the two wavelengths, f_d is the shifted frequency, the shift was introduced by the AOM.

The beams pass two diffraction gratings. The diffraction at the first grating (G) with a high spatial frequency (600 lp/mm) splits the two HeNe frequencies $\nu_1 + f_d$ and $\nu_2 + f_d$ where the first diffraction orders occur at α_1 and α_2 . The grating was designed in such a way (and produced on photoresist) that the diffraction angle difference $\Delta\alpha$ between $\nu_1 + f_d$ and $\nu_2 + f_d$

is compensated at a second (low spatial frequency) grating. Therefore the first order diffraction of ν_1+f_d and the zero order of ν_2+f_d , as well as the zero order of ν_1+f_d and the minus first order of ν_2+f_d , become parallel as shown in fig. 9.

The second grating (RG) is a standard low cost angle encoder (Hewlett Packard) with a spatial frequency of about 7.2 lp/mm. It is continuously rotated by a motor. Due to a rotation of the grating, the first order diffracted light is frequency shifted by f_m while the zero order light passes the grating unaffected. Selecting one pair of parallel beams (as shown in fig. 9) the frequencies of the beams are written as ν_1+f_1 and ν_2+f_2 where $f_1=f_d+f_m$ and $f_2=f_d$. They serve as reference beams in the interferometer. The beat frequency $f_m=f_1-f_2$ is generated due to the rotation of the angle encoder. In the experiment the angle encoder wheel with 1000 lp/revolution was rotated with 1200 revolutions/minute, the heterodyne beat frequency of 20 KHz was found to be most appropriate. This frequency can be directly applied to a low frequency phase meter (e.g. two channel lock-in-amplifier LIA).

The reference for the lock-in-amplifier is directly taken from the angle encoder detector (square wave signal) output. Care must however be taken by the design of the encoder wheel when phase fluctuations in the reference path occur. The beat of the two heterodyne signals can be observed after demodulation and bandpass filtering, leading to

$$U(t) = U_0 \cos(2\pi f_m t - 4\pi z/\Lambda + \varphi)$$

Results were obtained with a 10x microscope objective and an avalanche diode as photo-detector. The diffraction limited target spot was in the order of 3 μm . The clear working distance to the target was 6.5 mm.

The target was moved with a computer controlled stepper motor. Figure 10 shows a measurement where the target distance was varied by 100 μm . The unambiguous distance range of 27.7 μm as well as the good linearity can be observed when a mirror like structure was displaced.

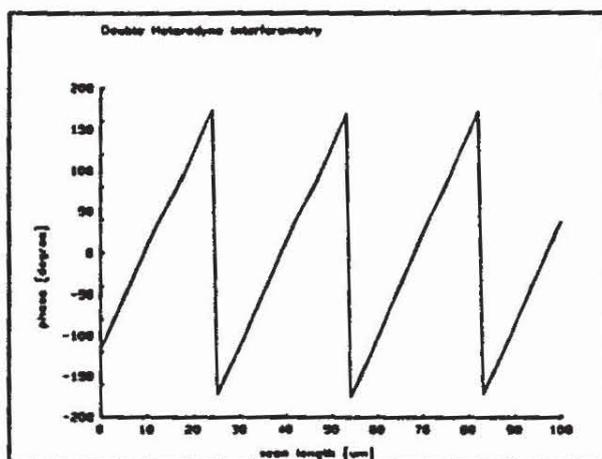


Fig. 10. Phase response from a target distance variation of 100 μm

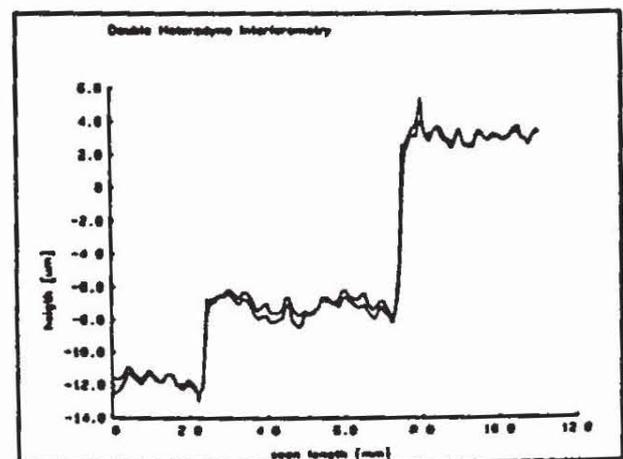


Fig. 11. Result of two successive line focus on a milled aluminium sample with step heights of 5 μm and 10 μm

Two successive measurements on a milled aluminium sample are shown in fig. 11. On the sample two steps of 5 μm and 10 μm were milled into the surface. In the experimental set-up a resolution in the order of 0.5 μm was obtained. It is expected to improve the resolution by the use of a solid state approach to be reported later.

Two wavelength double heterodyne interferometry has proven to be a powerful tool for accurate interferometric measurements on smooth as well as on optically rough surfaces. It is important especially for rough target surfaces to notice that the system behaves like a heterodyne interferometer with a synthetic wavelength $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$. In the special arrangement the effective wavelength was 55.5 μm . The laser wavelengths themselves were 632.8 nm and 640.1 nm. It should be noticed that the roughness of the surface should be slightly smaller than the depth resolution expected. Fig. 12 shows the results of the measurement of a parabolic metallic surface scanned in the x-direction.

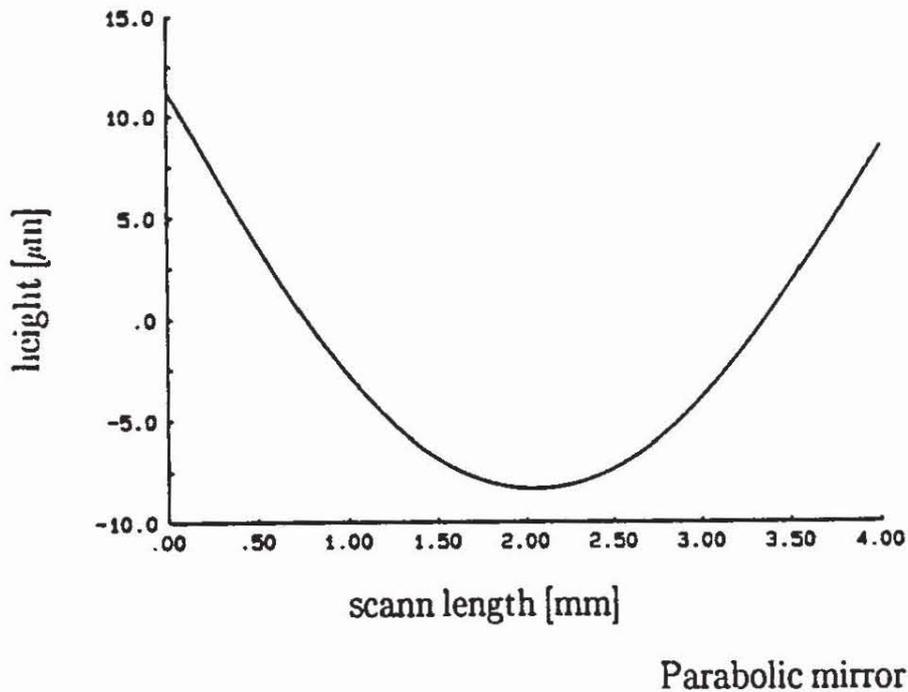


Fig. 12. Results of the measurements obtained by scanning a parabolic metallic surface

Due to intensity fluctuations an automatic gain control should be foreseen especially when an avalanche diode is used as photodetector. Intensity thresholding to reject distance data in case of low amplitudes was not required in our experiments.

6. Conclusion

Different optical methods can be used for distance and topography measurement. Some optical methods together with their limits were discussed.

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. It has been shown, that a synthetic wavelength can be generated by two shorter ones, leading to techniques for measuring optically rougher surfaces. The theory is based on the assumption that the optical path difference is to be compared with the synthetic wavelength.

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