Heterodyne Interferometry using two wavelengths for dimensional measurements

H. J. Tiziani

Stuttgart University, Institut of Applied Optics,
Pfaffenwaldring 9, D-7000 Stuttgart 80

1. INTRODUCTION

Optical methods become useful tools for dimensional measurements. Different techniques have been developed in the last few years. In addition to the well known time of flight and phase measuring principles other methods such as focussing and interferometric techniques are implemented.

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 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.

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 they lead to some additional requirements. 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. On the other hand their frequency can easily be tuned over tenth of GHz by changing the current and hunderts of GHz by controlling the temperature.

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 distance of at least to reference points is often needed. Furthermore, classical interferometry can only be applied when smooth surface (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, which can be 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 have to be employed. 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

 0-8194-0681-3/92/$4.00

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. However, since two wavelengths must be optically seperated (prism, grating) before detection, the technique can be used only for relatively large wavelength differences and thus small synthetic wavelength Λ (<1 mm). 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 for interferometric stability at the optical wavelengths λ_1 and λ_2.

2. 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 present on the surface of the object will change the phase ϕ of the reflected object beam. This phase variation is detected by an interferometer, and measured as a function of position x on the surface.

A problem, however, occurs if the surface has stepwise height variations greater than $\lambda/2$. A discontinuous height variation Δz introduces a phase jump $\Delta\phi$ given by $\Delta\phi = 4\pi/\lambda\, \Delta z$. The interferometer can only determine the phase ϕ modulo 2π.

Furthermore, it would be very useful to apply interferometry to measure 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 avalaible. 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 seperated interference patterns.

By an appropriate processing of the two individual interference patterns a new interference term of the form $\cos(4\pi/\lambda\, z)$ is created where Λ is an equivalent 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 wavelength, making them a good alternative to more expensive dye lasers or argon lasers.

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 holography[2] and Speckle-Interferometry. A typical example of two wavelength interferometry will be given in fig. 1 for λ_1 =618,6 nm and λ_2 =550 nm. The object to be tested was a computer generated reflection hologram with the depth of the grooves of about 1,6 μm (Fig. 2). Fig. 1 shows the setup for two beam interferometry with phase shifting and two wavelength.

An alternative setup for two-wavelength holography in quasi real time is shown in fig. 3a, where two holograms are stored in a BSO crystals at the same time. The two-wavelength λ_1 and λ_2 from an Argon laser are used. For the reconstruction one-wavelength is selected by fulfilling the Bragg condition for the BSO-crystal. The reconstructed holograms lead to contourlines. A typical result of the topographics of a metallic surface with contour-line seperation of 17 μm .

3. TWO-WAVELENGTH HETERODYNE INTERFEROMETRY

Two-wavelength heterodyne Interferometry can overcome some of the drawbacks of classical interferometry. A scanning two wavelength speckle interferometer using a Krypton laser was described by Fercher et al.[4].

In a heterodyne interferometric set-up two waves are superposed to lead to an interference phenomenon. One of the two beams is frequency shiftened 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 superimposed to lead to a beat frequency of the two wavelength responsable 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_{s2} , I_{s2} are the intensities of the interfering reference and signal beams for the two wavelengths, f_1 and f_2 are the heterodyne frequencies

$$\phi_1 = \frac{4\pi}{\lambda_1}z - 2\pi\left[\frac{\nu_1 + f_1}{c}\right]L$$

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

z is the object distance to be measured and c the velositiy of the light ν_1, ν_2 are the frequencies of the corresponding wavelength 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.[5,6]. Using two (highly stable) laser sources emitting different wavelengths, the heterodyne frequency shifts can easily be obtained by acoustooptical modulation (AOM) as shown in Fig. 4. 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.

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. 4. The quarterwave plate is passed twice and used to rotate the polarization by 90^o to achieve reflection at the polarizing beam splitter. To match the polariziations 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 reference signal for the phase detector is generated in an additional interference arrangement to compensate for phase fluctuations of the two highly stable laser sources.

In the case of a multiline laser, to be discussed here, 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. 4), but with a multiline laser instead of two lasers) the laser radiation would be first divided into target and reference beams.

The DHI is very appropriate for high precision absolute measurements. For the realization of a DHI there are different possibilities. At first two diode laser to give λ_1 and λ_2 look very promising. An interesting way to obtain the various wavelength is to use a single laser diode in combination with a Bragg cell and two acousto optic modulators (AOM's). The high frequency AOM to be driven by 500 MHz and 501,5 MHz leading to wavelengths of 60 cm and 200 m (for 1,5 MHz). An experimentel setup is shown in fig.5. 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 not disturb the phase measurement if the reference signal for the phasemeter is interferometrically generated. In fig.6 it should be indicated that the object can be scanned with the koaxial 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.

4. 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 wavelength was generated by a rotating grating for instance. After passing a lens L , a polarizing beam splitter PBS and a quarter wave plate (QWP) the object beams are focussed on to the specimen under test by a microscopic objective (MO).

In the set-up shown in fig. 6 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, strifted 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 ν_1 and ν_2 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 ν_1 $+f_d$ and ν_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 $\nu_2 + f_d$, become parallel as shown in fig. 6.

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. 6) 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 beam 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 and 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 $U(t) = U_0 \cos(2\pi f_m t - 4\pi/\Lambda z + \varphi)$. Results were otained with a 10x microscope objective and an avalanche diode as photodetector. 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 7 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.

Two successive measurements on a machined aluminium sample are shown in fig. 8. 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 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 wavelength itself were (632.8 nm and 640.1 nm).

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.

The matched grating principle was extended and modified and the moving grating was replaced.

5. DOUBLE HETERODYNE INTERFEROMETER WITH SOLID STATE MATCHED GRATINGS

Figure 9 shows a multiwavelength He-Ne laser ((Spindler & Hoyer) tuned to emit simultaneously and with equal intensity at 632,8 nm and 640.1 nm. This leads to an effective wavelength of 55.5 μm. As shown, only one AOM is required (compared to the setup shown in Fig.4). The AOM is operated in suppressed carrier mode, where a modulation signal fm is applied to the AOM driver, while the driver carrier amplitude is turned to zero. This results in a multiplication of the driver carrier frequency f_d with the modulation frequency f_m leading to two side bands $f_1=f_d+f_m$ and $f_2=f_d-f_m$ and suppressed carrier f_d. As a result, the AOM is operated at two frequencies, f_1 and f_2, simultaneously. Two individual phase gratings are established in the AOM crystal leading to two first-order beams that leave the AOM under slightly different angles α_1 and α_2 . The diffraction efficiency (the energy distribution between the zero-order and the two first-orders) is optimized (bragg angle) and adjusted with the driving power of the modulation signal f_m. In this way the frequencies of the two first-order diffracted beams are $\nu_1 +f_d-f_m$, $\nu_2 +f_d-f_m$ and $\nu_1 +f_d+f_m$, $\nu_2 +f_d+f_m$ respectively.

The small angle between the two first-order diffracted beams is approximately given by

$$\Delta\alpha = 2\frac{\lambda}{\nu}f_m$$

where $\lambda = \lambda_1$ or λ_2 one of the He-Ne laser wavelengths (the spatial frequency of the AOM phase grating is far too low to seperate the two laser wavelengths λ_1 and λ_2 . The term ν is the speed of sound in the AOM crystal.

In our new approach, we matched the angle $\Delta\alpha$ to the difference of the first-order diffraction angle (between λ_1 and λ_2) was matched by using a high spatial frequency grating (G).

$$\Delta\alpha = \lambda_2 g\sqrt{1-(\lambda_1 g)^2} - \lambda_1 g\sqrt{1-(\lambda_2 g)^2}$$

with the spatial frequency g of the grating. Matching two gratings accordingly, only beams with frequencies $\nu_1 +f_d-f_m$ and $\nu_2 +f_d+f_m$ become parallel. They are extracted to serve as reference for the interferometer as shown in Fig.9. In this setup there is no (or hardly any) reference pathlength difference introduced as compared to the setup shown in Fig.4. This makes the system almost insensitive to laser frequency variations. The shear of the reference beams shown in Fig.9 is negligible because of a very small divergence angle $\Delta\alpha$. The modulation frequency is generated by an oscillator and divided by two before being applied to the AOM driver. Because of the two sidebands generated, the beat frequency is twice that of the modulation frequency f_m. Further down-mixing of the signals is helpful, since highly accurate phase meters are easier to obtain that work at low frequencies.

6. CONCLUSION

Heterodyn interferometry is a powerful tool for high precision distance and vibration analysis. Two wavelength heterodyne techniques become very interesting for absolute distance measurement. It was shown, that a synthetic wavelength can be generated by two shorter ones. This leads also to the techniques to measure optically rougher surfaces because the optical path difference is to be compared with the synthetic wavelength. Further work will be reported.

7. ACKNOWLEDGEMENT

I thank for the contribution and discussion with Z.Sodnik, E.Fischer and Th.Ittner from the Institute of Applied Optics, S.Manhart and R.Maurer from Messerschmitt-Bölkow-Blohm, as well as P.Roussel from the European Space Research and Technology Center.

8. REFERENCES

1. J.C.Wyant, "Testing Aspherics Using Two Wavelength Holography," Appl. Opt. 10, 2113-18(1971)
2. F.M.Kuchel, and H.J.Tiziani, "Real-Time Contour Holography Using BSO Crystals, "Opt. Commun. 38, 17-00(1981).
3. 'C.Polhemus."Two-Wavelength Interferometry,"Appl.Opt.12,2071-2074(1973).
4. A.F.Fercher,H.Z.Hu.and U.Vry"Rough Surface Interferometry with a Two-Wavelength Heterodyne Speckle Interferometer,"Appl.Opt. 24,2181-2288(1985).
5. R.Dändliker,R.Thalmann, and D.Prongue, "Two Wavelength Laser Interferometry Using Super-Heterodyne Detection,"Proc.Soc.Photo-Opt. Instrum.Eng.813(1987).
6. Z.Sodnik, E.Fischer, I.Ittner, H.J.Tiziani, "Two wavelength double heterodyne Interferometry using a mathed grating technique, Appl.Opt.(in print).

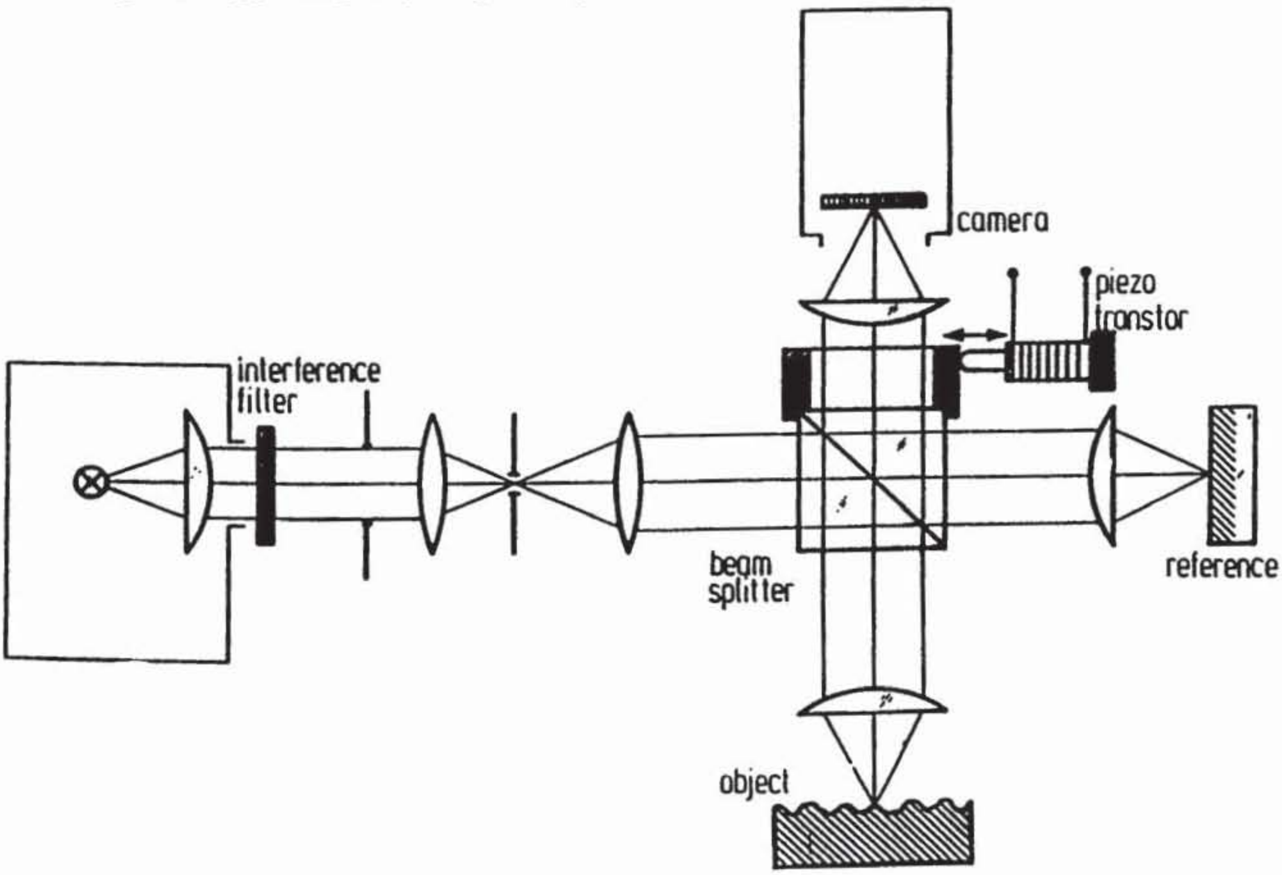

Figure 1. Linnik Interference microscope arrangement.

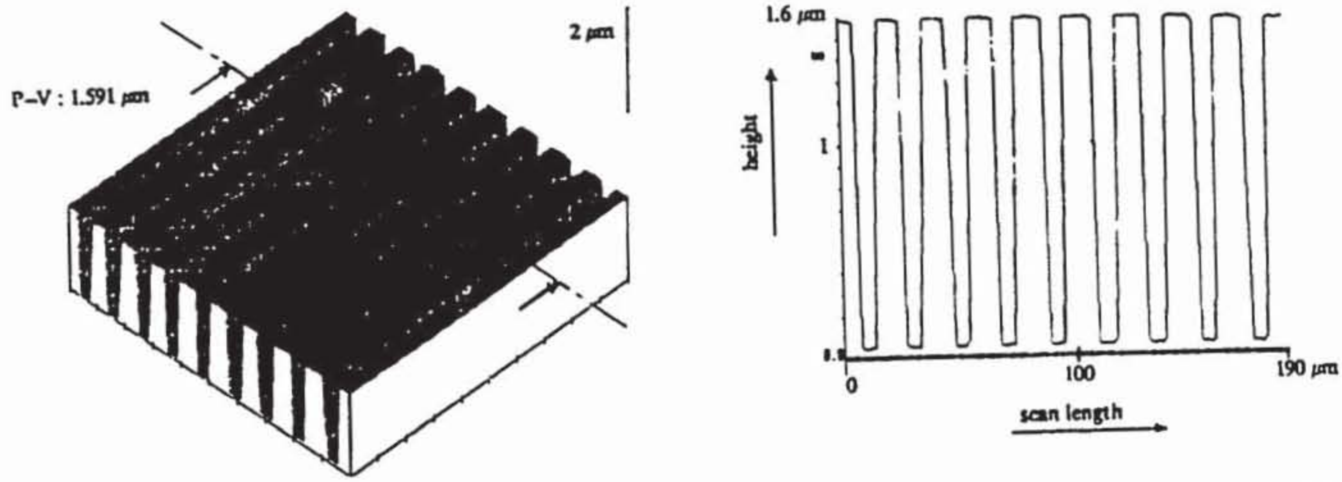

Figure 2. Topography of a reflection grating obtained by time multiplexed two-wavelength interferometry with

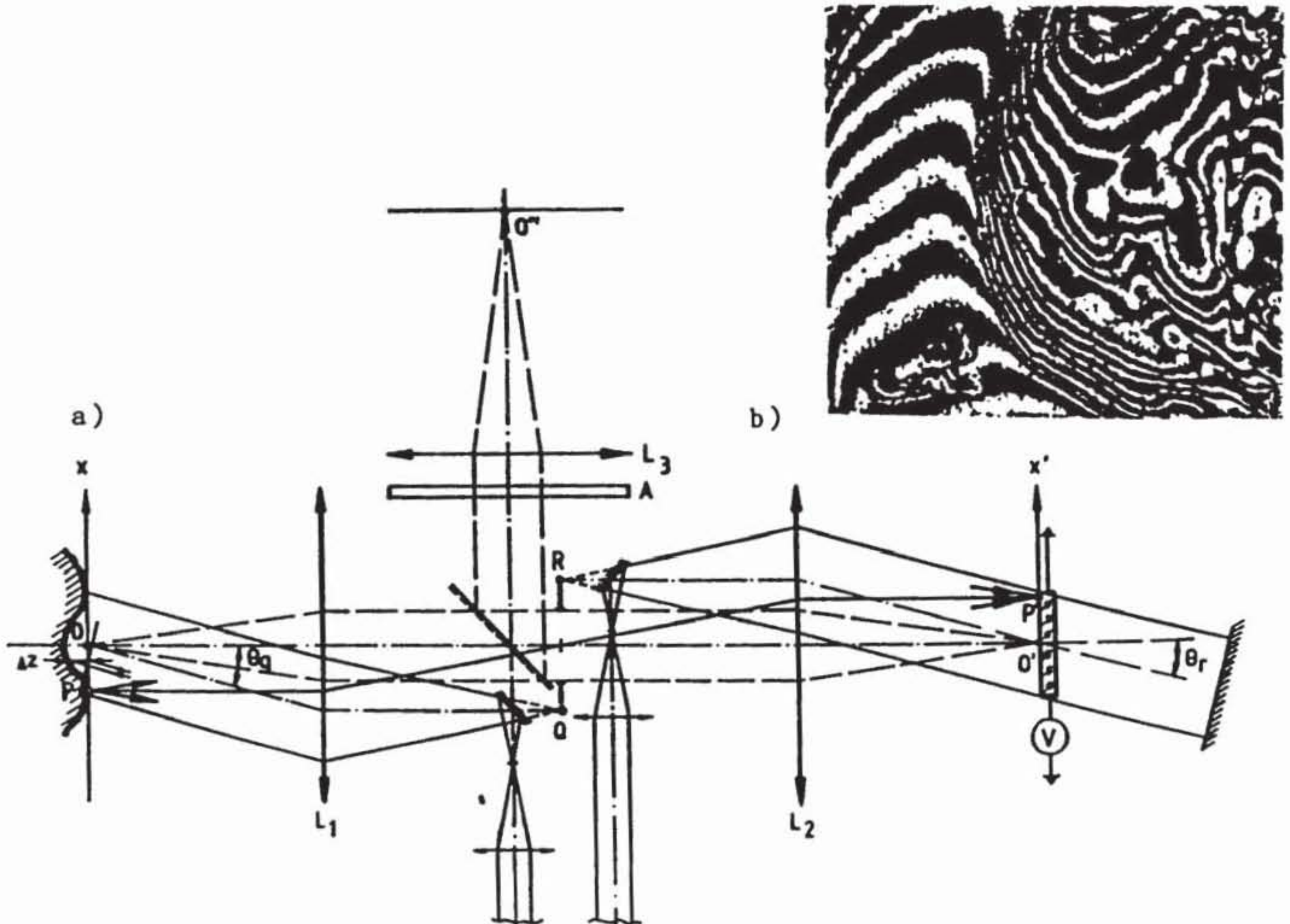

Figure 3. a) Setup for quasi real time two wavelength holography using a BSO crystal as storage material.
b) A reconstructed object, a metallic surface, with the contour-line separation of 17 μm

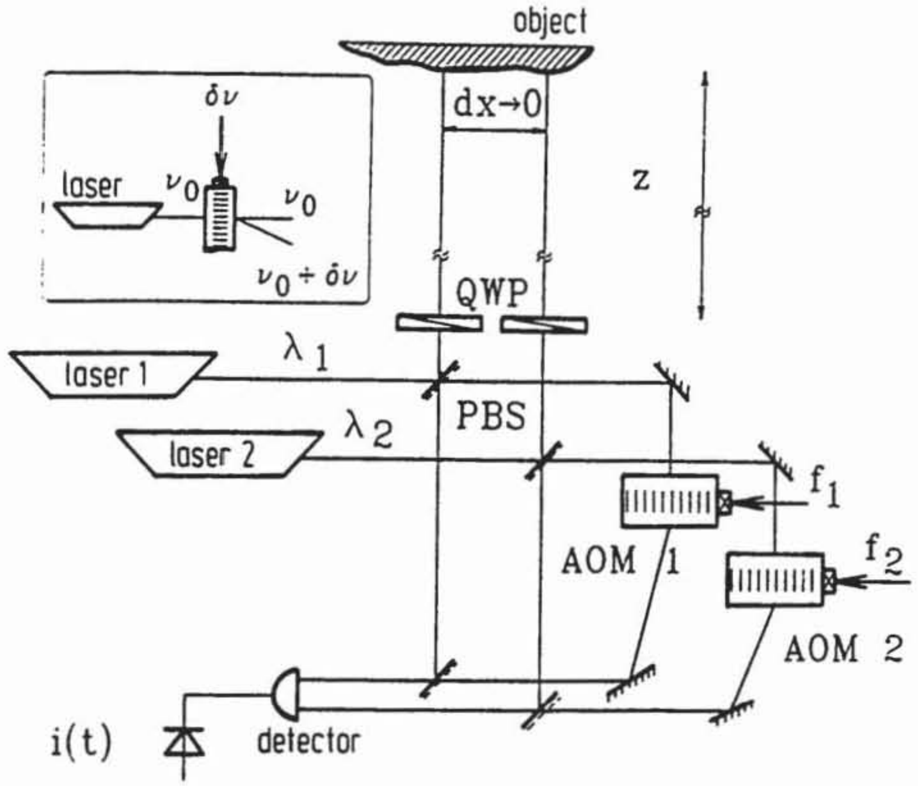

Figure 4. Principle of two-wavelength double heterodyne interferometry.

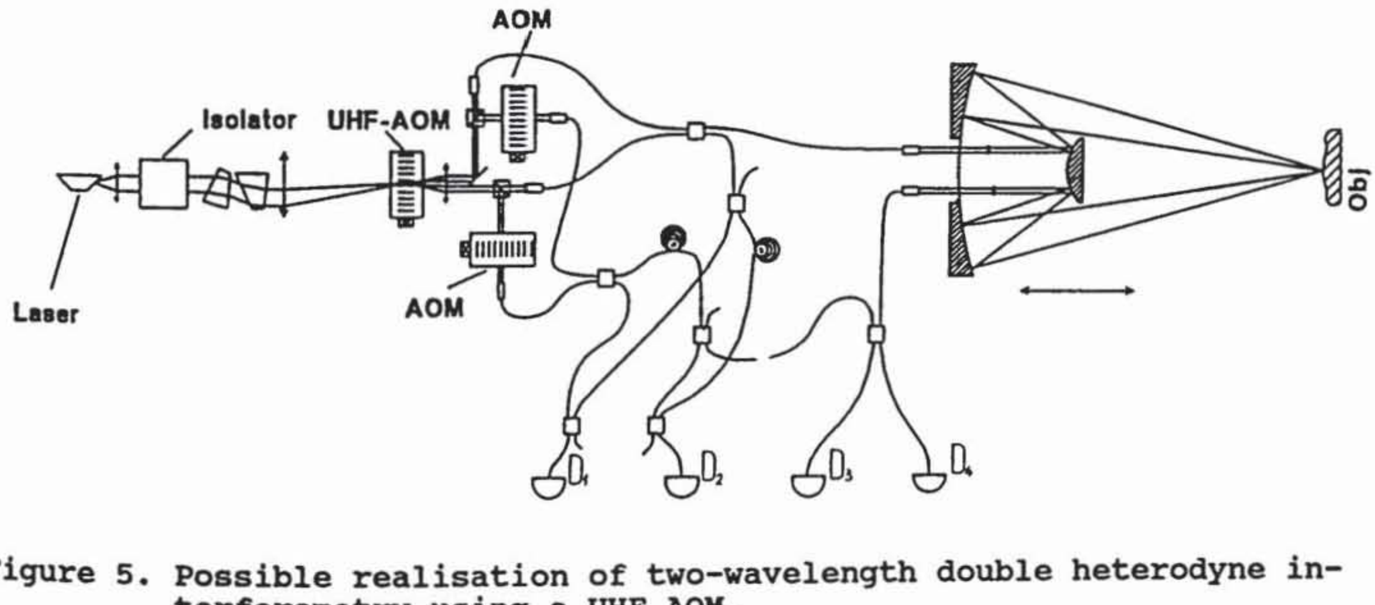

Figure 5. Possible realisation of two-wavelength double heterodyne interferometry using a UHF AOM.

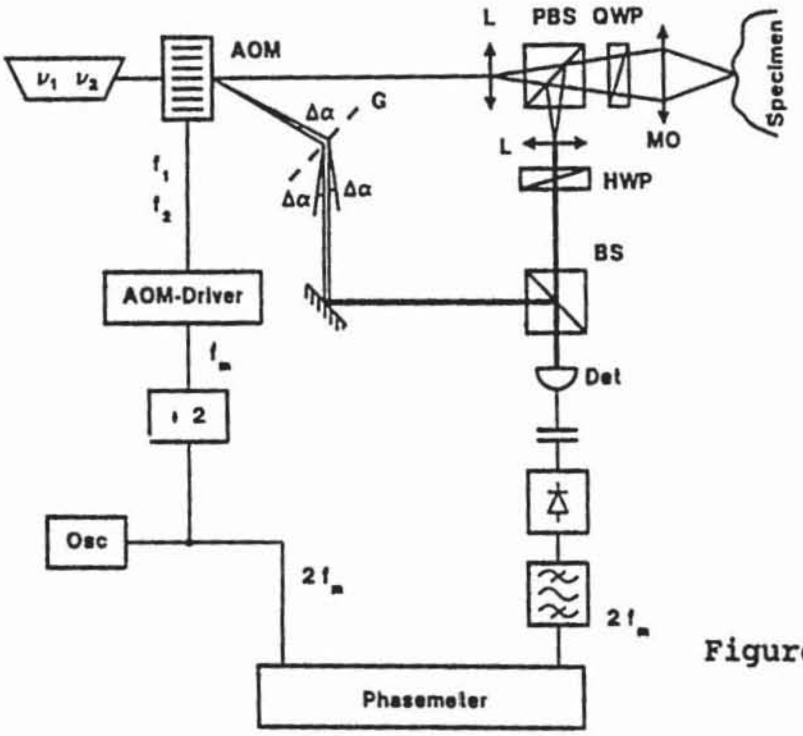

Figure 6. Principle of DHI with rotationed matched grating

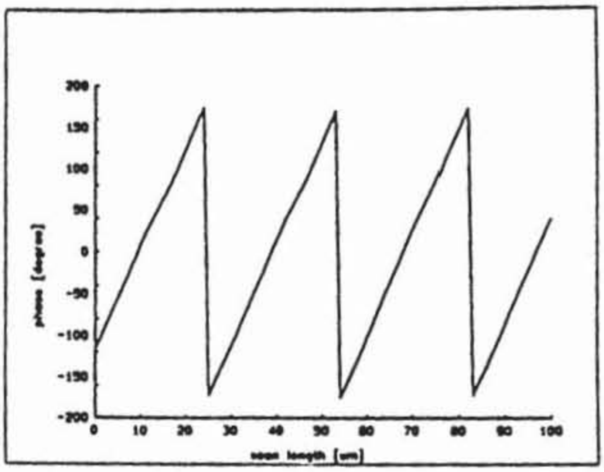

Figure 7. Phase response from a target distance variation of 100 μm

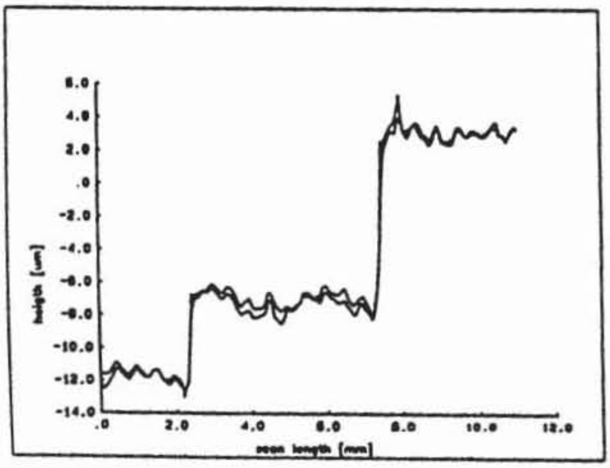

Figure 8. Result of two successive line focus on a milled aluminum sample with step heights of 5 μm and 10 μm

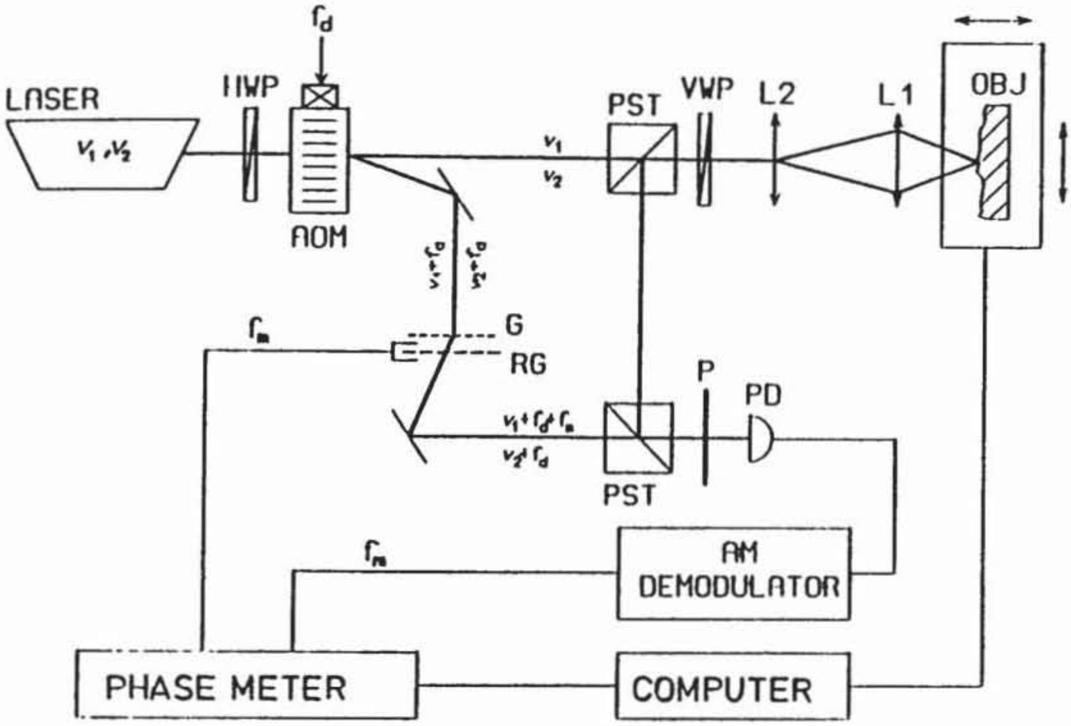

Figure 9. Principle of DHI solide state matched grating.