DUAL WAVELENGTH HETERODYNE INTERFEROMETRY USING A MATCHED GRATING SET-UP

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Abstract

Two-wavelength double heterodyne interferometry is applied for topographic measurements on rough target surfaces. A two-wavelength HeNe laser and a matched grating technique are used to improve system stability and to simplify heterodyne frequency generation. Results obtained with an experimental set-up will be presented. The results obtained show that a dual wavelength heterodyne interferometer is appropriate for high precision ranging. Progressing developments for large distances will be discussed.

1. Introduction

Within the scope of SFB 228, we investigate a heterodyning approach for high precision ranging. This subproject D4 started in 1990. As follows the results achieved by now will be delineated.

There are several coherent and incoherent optical techniques for non contact ranging. High resolution for close and medium range are anticipated. The Triangulation- and Moiré-technique both need a large base (distance between transmitting and receiving optics). Time of flight measurements based on the use of pulsed lasers are suitable for cm-accuracy; otherwise the electronic expense rises unproportionally (see /1,2,3,4/).

Incoherent phase measurement techniques based on the detection of an intensity modulated laser beam /5/ require a high modulation frequency for precision measurements and therefore also a considerable electronic expense.

High resolution is in general the domain of the coherent techniques. Classical interfero metry using laser light of one wavelength and keeping the intensity as a measure of the distance is for the purpose discussed here not appropriate, because of the required optical smoothness of the object surface and the lack of absolute ranging. In addition, the required stability means a severe restriction to the system /6/.

If the object to be measured shows a rough surface, the advantage of coherent techniques can be employed using a wavelength considerably longer than the roughness of the surface. This can be achieved using two light beams of slightly different wavelengths. This so-called two-wavelength interferometry leads to a reduced sensitivity which depends on the beat-frequency according to the following equation:

$$\Lambda = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|} \tag{1}$$

where λ_1, λ_2 are the two wavelengths used.

Several double wavelength interferometry techniques have been reported /8,9,10,11/, all of them are relying on intensity measurements. A remarkably high precision provide phase measurement techniques working independent of intensity and contrast as phase shift, phase locked, phase sampling and heterodyne interferometry. Single wavelength heterodyne interferometers used in high precision ranging reach a resolution in the nm range. They apply only on optically smooth surfaces and provide only relative resp. incremental measurements.

Combination of two wavelength interferometry and heterodyning /12/ offers the opportunity of absolute ranging on optically rough surfaces. First investigations on this topic have been reported /13,14,15/. In the following chapters the basic principles of double heterodyne interferometry and some selected problems arising in that context will be discussed.

2. Theory

Fig. 1 shows the principle layout of a double heterodyne interferometer. It is composed of two independent single-wavelength heterodyne interferometers working both at different wavelengths λ_1, λ_2 and different heterodyne frequencies f_1, f_2. The optical amplitudes at the detector plane (s. fig. 1) consist of 4 components.

$$a_1 = A_1 \cdot \exp\left\{ i\left(2\pi\nu_1 \cdot t - 4\pi \frac{\nu_1}{c} z \right) \right\} \tag{2}$$

$$a_2 = A_2 \cdot \exp\left\{ i\left(2\pi\nu_2 \cdot t - 4\pi \frac{\nu_2}{c} z \right) \right\} \tag{3}$$

$$a_3 = A_3 \cdot \exp\left\{ i\left(2\pi(\nu_1 + f_1) \cdot t - 4\pi \frac{\nu_1 + f_1}{c} L \right) \right\} \tag{4}$$

$$a_4 = A_4 \cdot \exp\left\{ i\left(2\pi(\nu_2 + f_2) \cdot t - 4\pi \frac{\nu_2 + f_2}{c} L \right) \right\} \tag{5}$$

where equation (2) and (3) describe the contribution of the object path and eq. (4) and (5) that of the reference path. Within the expressions of the complex amplitudes A_1..A_4

constant phases are dropped as far as they do not affect the following discussion. c is the velocity of light, ν_1, ν_2 the frequencies of the light used, f_1, f_2 the AOM driver frequencies and L, Z the optical path lengths of the reference resp. object beam. The intensity at the detector plane equals the sum of the absolute squares of the amplitudes.

$$
\begin{aligned}
I &= |a_1 + a_3|^2 + |a_2 + a_4|^2 \\
&= (a_1 + a_3) \cdot (a_1^* + a_3^*) + (a_2^* + a_4^*)
\end{aligned}
\tag{6}
$$

Substituting eq. (2)..(5) in (6) yields

$$
\begin{aligned}
I = I_0 &+ 2 \cdot |A_1| \cdot |A_3| \cdot \cos\left(2\pi f_1 \cdot t + 4\pi \frac{\nu_1}{c} z - 2\pi \frac{\nu_1 + f_1}{c} L\right) \\
&+ 2 \cdot |A_2| \cdot |A_4| \cdot \cos\left(2\pi f_2 \cdot t + 4\pi \frac{\nu_2}{c} z - 2\pi \frac{\nu_2 + f_2}{c} L\right)
\end{aligned}
\tag{7}
$$

The constant contribution I_0 yields a direct current at the photodetector, which is suppressed by means of a high pass filter (e.g. a capacitor). The alternating current is composed of two components of the different frequencies f_1, f_2. Thus the signals appear to be amplitude modulated with suppressed carrier (carrier frequency $(f_1+f_2)/2$). Amplitude detection followed by a band pass filter yields a signal with the superheterodyne frequency (f_1-f_2), whose phase corresponds to the distance to be measured. A suitable choice of the heterodyne frequencies f_1, f_2 poses the superheterodyne frequency in a band, which is appropriate for the application of commercially available phase meters, such as lock in amplifiers or zero crossing phase meters. After demodulation of the detector signal (7), the superheterodyne signal becomes

$$
i(t) = 4 i_0 \cdot \cos\left(2\pi (f_1 - f_2) \cdot t + 4\pi \frac{\nu_1 - \nu_2}{c} z - \frac{2\pi}{c} (\nu_1 + f_1 - \nu_2 - f_2) L\right) \tag{8}
$$

where the distance Z turns out to be the phase of the signal. Error analysis of the double-heterodyne signal shows a close relationship between the precision of the measurements and the stability of several parameters. In the first place high stability is required for the heterodyne frequencies f_1, f_2, the laser-frequencies ν_1, ν_2, long-term temperature deviations and different path lengths of the reference and object beams.

Phasemeters require a reference signal to handle the measuring data. This signal can be generated electronically or via a second DHI System. If the reference signal is provided by a reference interferometer, deviations due to interferometer-internal fluctuations are compensated.

In general a high resolution of the measuring system is supported by the choice of a small beat-wavelength. On the other hand, a small beat-wavelength yields a small unambiguity range. A possible way to use both features provided by double heterodyne interferometry is to combine two measurements at different beat-frequencies /16/.

3. Double heterodyne interferometry with diffraction grating technique.

A double heterodyne interferometer has been built to be used for preliminary measurements at technical surfaces. Fig. 2 shows the set-up used. A commercially available He-Ne-Laser was used, which could be tuned to emit at two wavelengths simultaneously (λ_1= 633 nm, λ_2= 640 nm). The synthetic wavelength obtained is Λ= 55.5 μm, the unambiguity range covers 27.8 μm.

The frequency shift imposed on the two reference beams is provided by an AOM (f_d= 40 MHz) combined with a proper matched diffraction grating. After passing the AOM the light of the first diffraction order shows the frequencies ω_1+f_d and ω_2+f_d. A necessary condition to be fulfilled if the measurement is to be based on evaluation of the superheterodyne signal is, that the beat-frequencies of the two heterodyne interferometers combined are different. For this reason a combination of a stationary and a rotating diffraction grating provides a subsequent frequency shift for the light of one wavelength only, if the grating periods are suitably chosen.

The light of the first diffraction order imposed by the AOM passes at first a grating of a constant p_1 ($1/p_1$=600 Lp/mm). Because of the high spatial frequency the light is chromatically separated. The separating angle $\Delta\alpha$ between the light of the frequencies λ_1, λ_2 obeys the following equation:

$$\Delta\alpha = \arcsin\left[\frac{\lambda_2}{p_1}\sqrt{1-\left(\frac{\lambda_1}{p_1}\right)^2} - \frac{\lambda_1}{p_1}\sqrt{1-\left(\frac{\lambda_2}{p_1}\right)^2}\right] \tag{9}$$

The first diffraction grating is followed by a second one, whose lattice constant p_2 is chosen such, that for the average wavelength $\lambda=(\lambda_1+\lambda_2)/2$ the diffraction angle between the zero and first order beam equals the separating angle $\Delta\alpha$ of the first grating. The required lattice constant of the second grating becomes

$$p_2 = \frac{\lambda}{\sin\Delta\alpha} = \frac{\lambda}{\frac{\lambda_2}{p_1}\sqrt{1-\left(\frac{\lambda_1}{p_1}\right)^2} - \frac{\lambda_1}{p_1}\sqrt{1-\left(\frac{\lambda_2}{p_1}\right)^2}} \tag{10}$$

As shown in fig. 1, four rays leave the grating combination, consisting of two parallel ray pairs. In each pair the two rays have different heterodyne frequencies. The rotating grating imposes a frequency shift of f_m:

$$|f_m| = k \cdot f_r \tag{11}$$

where k is the number of periods of the circular grating, f_m the number of revolutions.

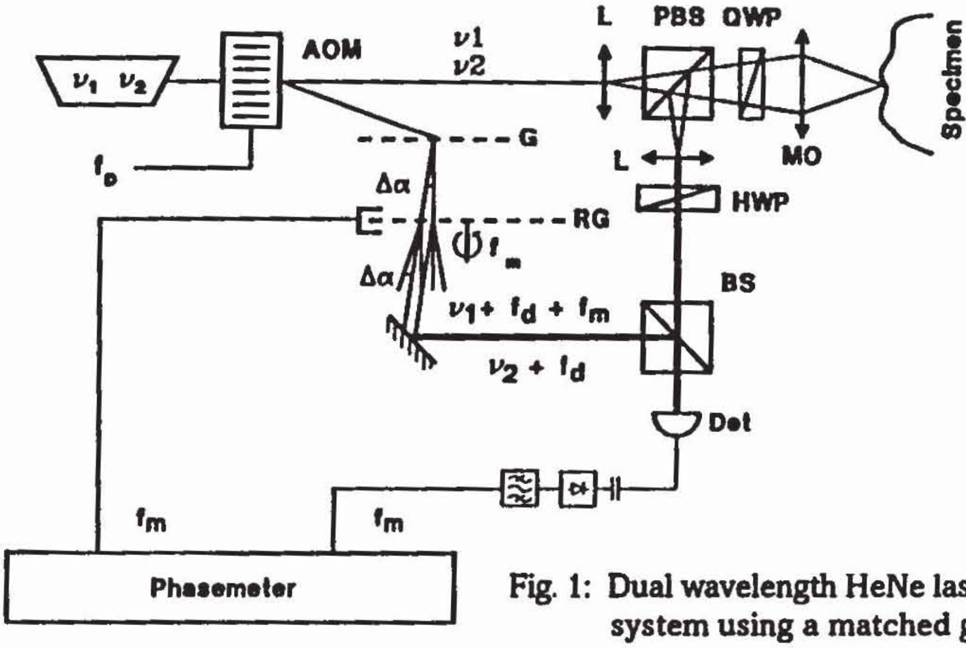

Fig. 1: Dual wavelength HeNe laser based DHI system using a matched grating set-up

The light of the object path interferes after passing the beamsplitter BS (see fig. 1). The amplitude-modulated signal received by the detector feeds after being demodulated a phase-meter, which obtains the reference signal from an angle encoder connected with the rotating grating. Fig. 2 shows two typical results of measurements obtained by the He-Ne-double heterodyne interferometer.

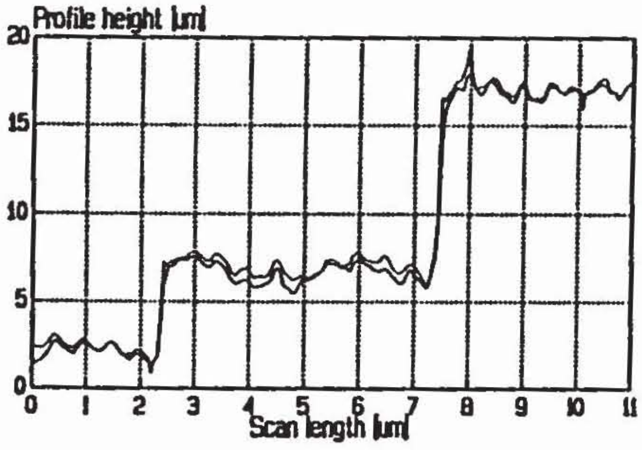

Fig. 2a: Repeated scan of a machined aluminium sample

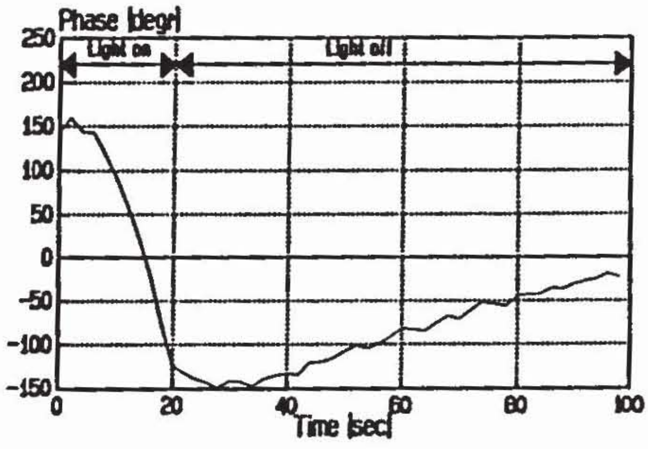

Fig. 2b: Expansion of a tungsten halogen lamp socket in dependence of time

Fig. 2a shows profile measurements of a milled aluminium surface with 5 µm and 10 µm steps. Two measurements spaced by a period of several minutes are plotted. The accuracy of the measurements is 0.5 µm. The slight difference between the two measurements are due to environmental influences (temperature fluctuations e.g.) on the one hand and system caused uncertainties (rotating grating etc.) on the other hand.

The result of measuring the expansion behaviour of a tungsten-halogen lamp socket in dependence of time is shown in Fig. 2b. After the lamp is switched off the socked cools down and therefore the sign of extension is inverted.

4. Near field double heterodyne interferometry

The aim of further developments carried out within the SFB 228 is to adapt the double heterodyne technique to measurements within the range of about 100 m. To enable high precision measurement in that range a capability of varying the synthetic wavelength is required. The attainable precision depends in the first place on the stability of the difference between the light frequencies used. There are several ways to change the synthetic wavelength. Tuning of gas-lasers is possible by thermal variation of the cavity length /17/. In the case of coupled laser diodes the synthetic wavelength can be tuned by the variation of the ratio of the automatic phase control system. The beforementioned techniques of the generation of the two wavelengths have some disadvantages, which make it hard to achieve high precision in the near field. If stabilized two-wavelength gas-lasers are used the change of the synthetic wavelength takes a considerable effort; in addition, the system will have a high response time. If coupled diode lasers are used, the strong dependence of the wavelengths on the injection current yields fluctuations of the synthetic wavelength.

If only one laser is used, emitting at one mode (current- and temperature stabilized laser diode), and an UHF-AOM generates the second wavelength, the difference frequency can be changed easily by varying the driver frequency. The stability of the synthetic wavelength is then determined by the frequency stability of the driver.

The phase of the superheterodyne signal obeys the following equation:

$$\phi = \frac{4\pi \Delta\nu}{c} z \qquad (12)$$

Partial derivation with respect to $\Delta\nu$ yields

$$d\Delta\nu = \frac{d\phi}{2\pi} \cdot \frac{c}{2z} = \frac{2 \cdot dz}{\Lambda} \cdot \frac{c}{2z} \qquad (13)$$

where $d\Phi/2\pi$ is the resolution of the phase-meter, dz the distance resolution. For dz = 0.1 mm and Λ = 0.6 m ($\Delta\nu$ = 500 MHz) one yield a required stability of the driver frequency of 1 ppm, which is achievable with commercially available AOM-Systems.

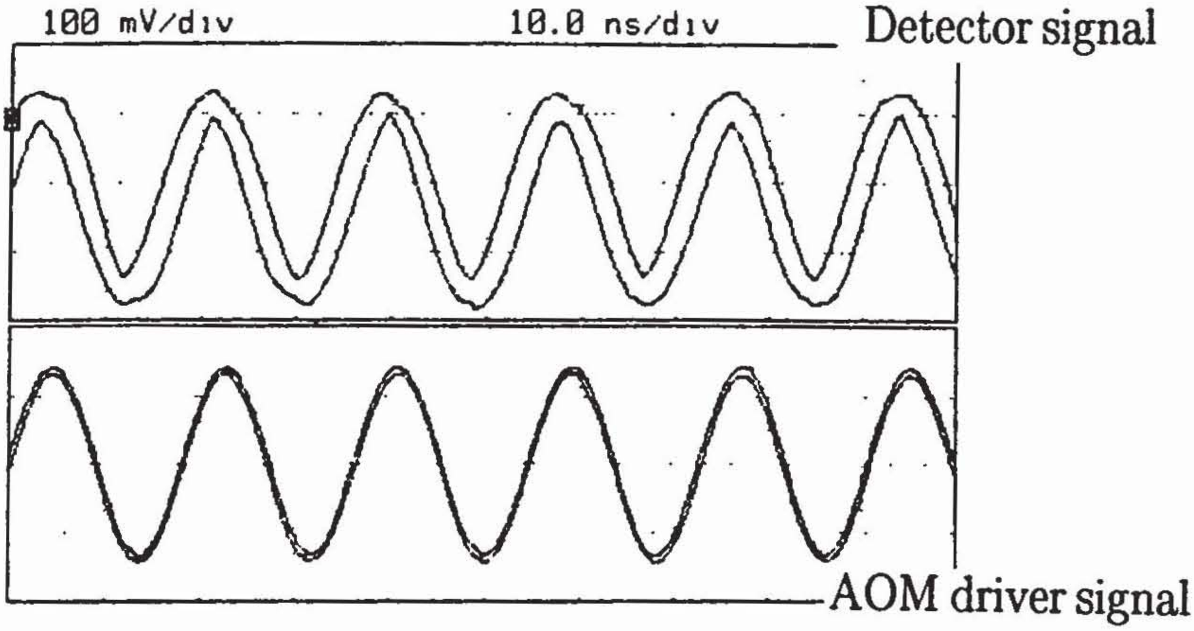

Fig. 3: Detector and oscillator signal envelopes of a heterodyne interferometer on which the light is frequency shifted by means of a high frequency AOM before entering the interferometer.

For a general proof of the principle a double heterodyne interferometer was built, which worked with the light of the first diffraction order of a 80 MHz AOM. Fig. 3 shows at the top the envelope of the heterodyne signal (integration time: 15 sec.). Below the driver signal of the AOM is depicted, which rendered the reference signal. The phase fluctuations are due to interferometric instabilities of the set-up. For the two single wavelength heterodyne interferometers of the double heterodyne system planned must use different paths, a reference interferometer has to be embedded.

Subsystems of the advanced interferometer are already tested. The laser used is a temperature- and current-stabilized laser diode with a maximum output power of 30 mW. The light passes a Faraday isolator with 45 dB isolation to avoid backscattering into the laser cavity, which would imply undesired mode hops. To achieve a diffraction efficiency of 50%, the light has to be focused into the acousto-optic crystal. A driver frequency of 500 MHz leads to an unambiguity range of about 30 cm. Two subsequent measurements using driver frequencies of 500 MHz resp. 501.5 MHz extend the unambiguity range up to 100 meter.

The frequencies of the AOM posed on the two reference beams are 80 resp. 80.1 MHz providing a superheterodyne frequency of 100 kHz. The 4 generated beams are coupled into glass-fibres to realize the system as compact as possible. Transmitting and receiving optics are intended to be well separated to prevent signal cross-talking.

5. Influence of speckling on the DHI-signal

The signal-to-noise-ratio (SNR) and the magnitude of the alternating component (AC) of the heterodyne signal depend on the ratio of the average speckle size and the detector aperture diameter. Since the phase in a fully developed speckle field is uniformly distributed /18/, the contributions of the speckle covered by the detector will obey different phases. Because of the integration over the detector area the resulting electric signal will be diminished. A measure for this effect is the mixing efficiency /19/ in analogy to the case of misalignment of a plane reference resp. object wave (e.g. measuring at optically smooth surfaces), where a fringe pattern appears in the detector plane and the fringes oscillate at different phases, therefore reducing the effective signal amplitude. The SNR depends on the square of the ratio between AC- and DC-component of the heterodyne signal and linearly on the average optical power received, which in turn is the product of the average intensity and the detector area.

$$SNR \propto \left[\frac{I_{AC}}{I_{DC}}\right]^2 \langle I_{ges} \rangle A_{Det} \qquad (14)$$

where I_{AC} is the AC-, I_{DC} the DC-component of the intensity at the detector plane, $<I_{ges}>$ the average intensity of the speckle field (i.e. of the object wave), A_{det} the detector area. To yield a good SNR the number of speckles covered by the detector has to be as small as possible and the average optical power received as large as possible. Provided an object wave consisting of some speckles formed by the receiving lens, a large detector diameter leads to a large average optical power, but in turn to a bad ratio between AC- and DC-component. Practically it is hard to achieve the condition, that only one speckle is formed by the receiving lens as is implied by the above considerations. A possible solution to circumvent the problem of phase perturbation is the use of a 4-quadrant-diode. In this case the four heterodyne signals are independently evaluated. Fig. 4 shows the magnitude of the alternating component of the signal received by 3 different detector ar-

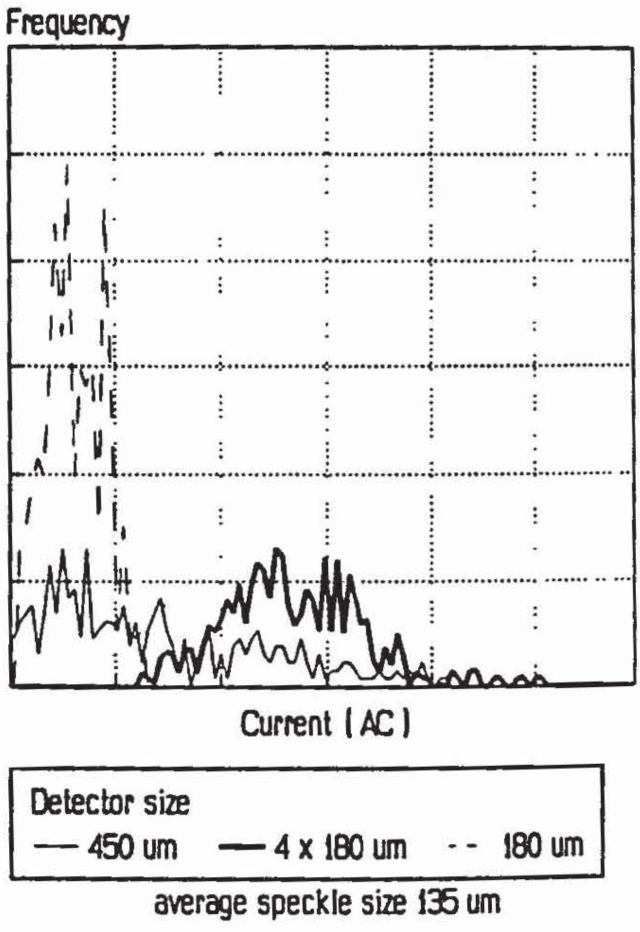

Fig. 4: Distribution of AC-component of heterodyne signal for several detector sizes and arrangements

rangements, evaluated by computer simulations on the data of a speckle field superimposed by a phase-shifted reference wave. It is clearly seen, that the detector of 450 µm size yields only a small advantage against the 90 µm-det., whereas the 4-quadrant detector gives a distinctly better signal while consisting of only 4 times 90 µm areas.

6. Intensity fluctuation caused by fibre optics

The use of a DHI interferometer system for ranging makes it necessary to increase the synthetic wavelength, as mentioned above, in the cm-region. For practical reasons (set-up compactness) no longer diffraction elements like gratings can be used to generate the two different heterodyne frequencies f_1 and f_2 as described in chapter 3. In such a case the use of independent frequency shifters in the reference arms of the two heterodyne interferometers (λ_1 and λ_2 resp.) is more suitable.

To avoid a decrease of the correlation coefficient between the speckle fields of λ_1 and λ_2 caused by displaced illumination spots at the target surface /20/ the beams of λ_1 and λ_2 are made ideal coaxial with the help of a mono-mode fiber. The use of fibers additionally reduces the size of the interferometer set-up, because beam rooting becomes more compact. When a cleaved mono-mode fiber is used time dependent output intensity fluctuation like in fig. 5 (thin solid line) can be observed.

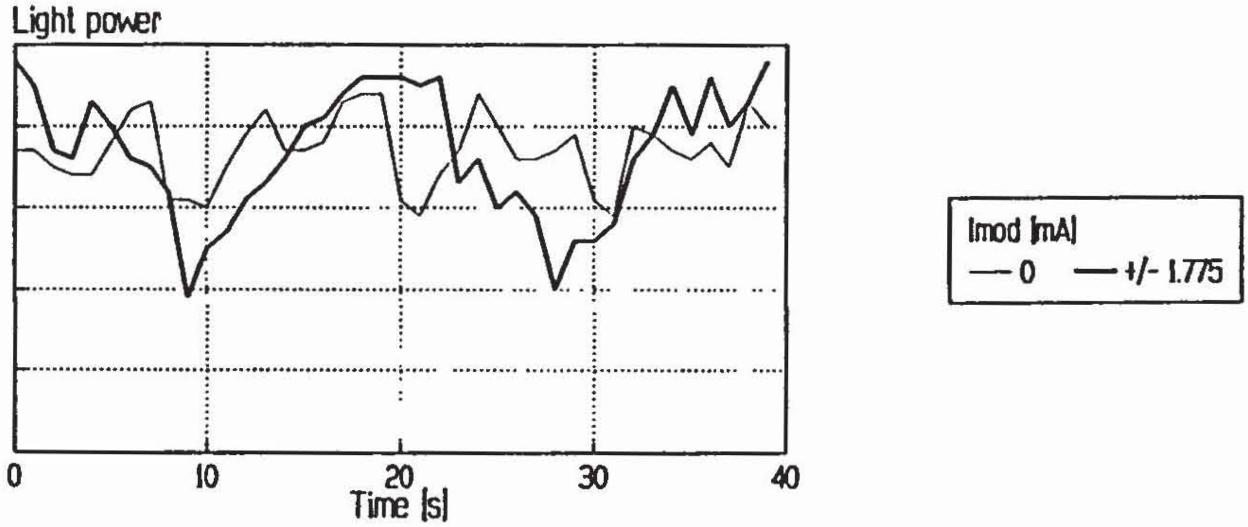

Fig. 5: Intensity fluctuation at the output of a monomode fiber in dependence of laser diode modulation.

This behaviour can be well explained by a fiber etalon and small laser frequency fluctuations. A small part of the light at the fiber endfaces is backreflected into the fiber so that direct light interferes for example with light which is reflected twice and has a time delay of 2L/c (c...speed of light, L...fiber length). If the intensity reflection coefficient is 4% and the laser frequency varies slowly an intensity modulation as observed in fig. 5 will occur. Cutting the fiber ends not perpendicular to the fiber axis which will reduce the backreflection caused effects is not a solution of the problem, because the fiber coupling efficiency depends very strong on good mode field matching. The highest efficiency is achieved if the optical axis is normal to the fiber endface and the endface itself perpendicular to the fiber axis.

Moderate modulation of the laser diode injection current at a sufficiently high frequency as shown in fig. 5 (thick solid line) allows to integrate a lot of modulation periods. The resulting signal level will then become constant.

7. Conclusions

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. The system behaves like a heterodyne interferometer with a light source emitting the effective wavelength Λ. Reduced sensitivity against environmental perturbations and vibrations, high resolution due to electronic phase measurement in real-time are further advantages.

Due to intensity fluctuations an automatic gain control should be foreseen especially when an avalanche photodetector is used. In our experiments intensity thresholding as mentioned in /20/ to achieve a sufficient high speckle pattern correlation was not necessary because of using an extended detector which provided some kind of integration.

Dual wavelength heterodyne interferometry will become an effective and highly dynamic measuring system for highly precise ranging with resolutions down to parts of microns.

Acknowledgement

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References:

/1/ Bickel, G. et al.: Triangulation with expanded range of depth. Optical Engineering 24, 975, (1985)

/2/ Rioux, M.: Laser range finder based on synchronized scanners. Applied Optics 23, 3837, (1984)

/3/ Häusler, G. et al.: Telecentric scanner for 3-D sensing. Optical Engineering 24, 978, (1985)

/4/ Seitz, G. et al.: 3-D-Koordinatenmessung durch optische Triangulation. Feinwerktechnik & Meßtechnik 94, 423, (1986)

/5/ Greve, A.; Harth, W.: Laser diode distance meter in a KERN DKM 3A theodolite. Applied Optics 23, 2982, (1984)

/6/ Tiziani,H.J.:Rechnerunterstützte Laser-Meßtechnik. Technisches Messen 54, 221, (1987)

/7/ Tiziani, H.J.: Optical methods for precision measurements. Optical and Quantum Electronics 21, 253, (1989)

/8/ Wyant, J.C.: Testing aspherics using two-wavelength holography. Applied Optics 10, 2113, (1971)

/9/ Polhenus, C.: Two-wavelength interferometry. Applied Optics 12, 2071, (1973)

/10/ Küchel, M.; Tiziani, H.J.: Real-time contour holography using BSO crystals. Optics Communications 38, 17, (1981)

/11/ Creath, K. et al.: Contouring aspheric surfaces using two-wavelength phase-shifting interferometry. Optica Acta 32, 1455, (1985)

/12/ Harnisch, B.; Truckenbrodt, H.: Optische Mikroprofilometrie: Meßprinzipien, Auflösungsvermögen und Meßwertverarbeitung. Optica Aplicata XXVIII, 295, (1988)

/13/ Fercher, A.F. et al.: Rough surface interferometry with a two-wavelength heterodyne speckle interferometer. Applied Optics 24, 2181, (1985)

/14/ Kikuta, H. et al.: Distance measurement by the wave length shift of laser diode light. Applied Optics 25, 2976, (1986)

/15/ Dändliker, R. et al.: "Two wavelength laser interferometry...". Proceedings of ICO 14 Congress, Quebec, Canada, paper B 1.2, (1987)

/16/ Hartl, P.: Fernwirktechnik der Raumfahrt. Springer Verlag Berlin, Heidelberg, 2. Auflage, (1988)

/17/ Seta, K.; O'ishi, T.: Distance meter utilizing the intermode beat of a He-Ne laser. Applied Optics 29, 354, (1990))

/18/ Goodman, J. W.: Statistical properties of laser speckle patterns. in J. C. Dainty (Ed.) "Laser Speckle and Related Phenomena". Springer, Heidelberg, Berlin, New York, 1979

/19/ Kingston R.: Detection of optical and infrared radiation. Springer, Heidelberg, Berlin, New York, 1978

/20/ Vry U. et al.: Higher order statistical properties of speckle fields and their application to rough surface interferometry. JOSA A 3, (1986), 988