Double heterodyne interferometry for high precision distance measurements

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Abstract

We present a double-heterodyne interferometer for absolute distance measurements at rough surfaces up to 100 metres. The two wavelengths are generated by frequency shifting the light of a monomode laser diode using a 500 MHz acoustooptic modulator. The synthetic wavelength obtained is Λ = 60 cm. In order to yield unambiguity up to 100 meter distance two measurements have to be taken using slightly different frequency shifts of 500 resp. 501.5 MHz. Measurements showing a resolution of 0.1 mm are presented.

1. Introduction

The absolute distance measurement techniques used so far seem to reach a resolution limitation. Incoherent phase measurement technique reaches resolutions in the submillimeter region when using a long integration time. It can hardly be improved significantly because of the bandwidth limitation of the photodetectors. With coherent interferometric techniques resolutions well below 1 micron are achievable. Using two wavelengths in principle the range of absolute distance measurement (i.e. the unambiguity range) and the desired resolution can be chosen suitably. In contrary to one wavelength interferometry measurements at rough surfaces are possible, because the speckle fields generated by the two wavelengths are highly correlated.

The technical problem is to achieve the desired ratio between resolution and the unambiguity range even if the system is designed to be cascaded by several subsystems where the ranges and resolutions are chosen appropriately. The present set-up yields a resolution of 0.1 mm with an unambiguity range of 100 metres (corresponding to a relative resolution of 10^{-6}). Such a system can easily be extended to 3-D-measurements with applications in robotics, profiling, tracing, low frequency vibration measurements (at buildings e.g.). An interesting feature of this system is that velocity or vibration amplitude and frequency of the object can be directly monitored evaluating the heterodyne signal of one wavelength. The technique allows to perform measurements at rough objects rotating or moving in or out of plane.

2. Set-Up

Fig.1 shows a principal sketch of the set-up. Light of a 30 mW monomode Laserdiode is focussed into a 500 MHz acoustooptic modulator, which provides the two wavelengths λ_1, λ_2 corresponding to the two light frequencies ν_1 and $\nu_2=\nu_1+\Delta\nu$, where $\Delta\nu$ is the frequency shift, which is imposed on the first diffraction order. The resulting synthetic wavelength is given given by

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

Thus with a frequency shift of 500 MHz a synthetic wavelength of roughly 60 cm is obtained. Light of this two wavelengths is passed to the object path, while the light in the reference path is frequency shifted by means of two additional AOM´s. The AOM´s are driven with f_1 = 80 and f_2 = 80.1 MHz in order to provide detection at the superheterodyne frequency of 100 kHz /1/. The AC-component of the intensity at the detector plane is then given by

$$I_{AC} \propto \cos(2\pi(\tfrac{f_1+f_2}{2} \cdot t + \tfrac{\nu_1+\nu_2}{c} z)) \cos(2\pi(\tfrac{\Delta f}{2} t + \tfrac{z}{\Lambda})) \quad (2)$$

where ν_1, ν_2 are the light frequencies corresponding to the two wavelengths used, $\Delta f = |f_1 - f_2|$ is the superheterodyne frequency and z is the distance to be measured. Dropping the dc-component the signal after demodulation is given by

$$i_{\det} = |i_{\det}| \cdot \cos\left(2\pi \cdot \left(\Delta f \cdot t + \tfrac{2z}{\Lambda}\right)\right) \quad (3)$$

The unambiguity range of the measurement is given half the synthetic wavelength $\Lambda/2$=30cm. The distance is evaluated from a measurement of the phase of the demodulated heterodyne signals of a measuring and a control interferometer with fixed paths (which is not depicted in fig.1). If the phase measurement provides a resolution of better than 0.12 degree, a distance resolution of 0.1 mm can be obtained. Instead of cascading this stage of high resolution with a system of 200 metres synthetic wavelength, the extended unambiguity range of 100 metres is obtained by computing the results of two measurements with slightly different synthetical wavelengths Λ = 60 cm and Λ = 59.8 cm corresponding to a frequency shift of the AOM of 500 resp. 501.5 MHz. In order to maintain the phase resolution of $2\pi/3600$ after more than 300 cycles of the unambiguity range, the relative stability of the synthetic wavelength has to be better than 10^{-6}. It can be seen from Eq.1 that in the stability of the phase is depending only on the frequency stability of the 500 MHz AOM and not on the frequency stability of the laser diode. The advantage of this approach is that a relative stability of an electronic oscillator of better than10^{-6} is relatively easy to maintain. In contrary if the two wavelengths are to be provided by coupling two laser sources the effort regarding their spectral purity and stability is considerable and increases with increasing synthetic wavelength.

In contrary to one wavelength interferometry measurements at rough surfaces can be performed, because the speckle patterns formed by the two wavelengths are highly correlated. The residual statistical phase error /3/ turns out to restrict the distance resolution to the roughness of the object /2/. However additional decorrelation of the speckle patterns will occur if the object light of the two wavelengths is not perfectly aligned. Therefore the light of the object path (ν_1, ν_2) and the light of the reference path (ν_1+f_1, ν_2+f_2) is launched into two monomode fibers. This ensures optimum correlation coefficient of the two speckle patterns.

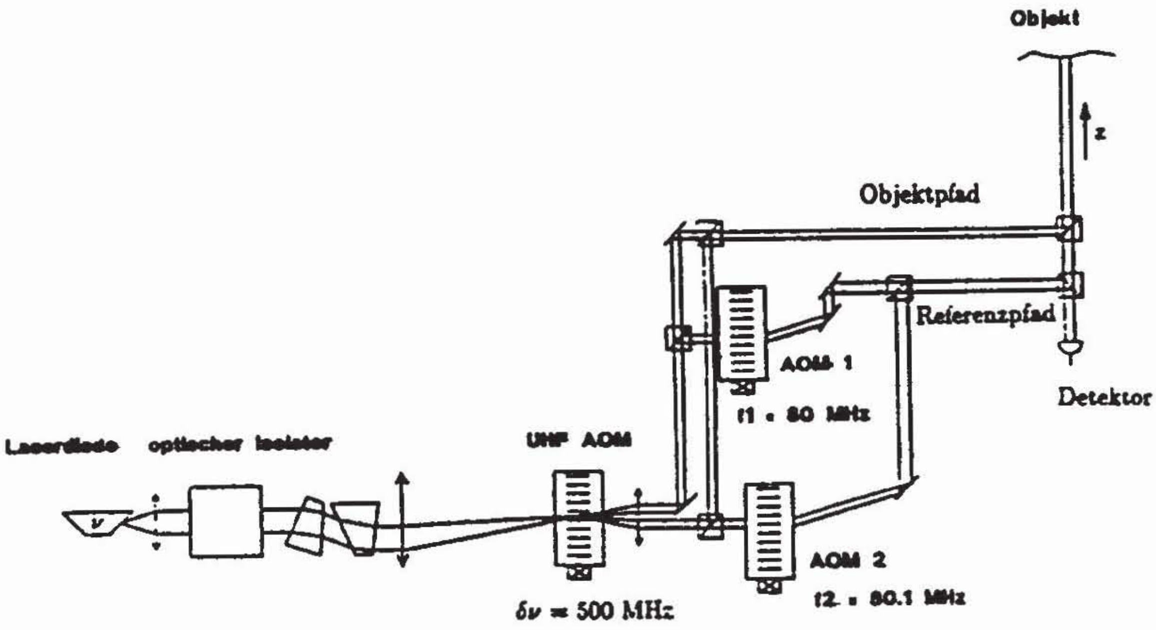
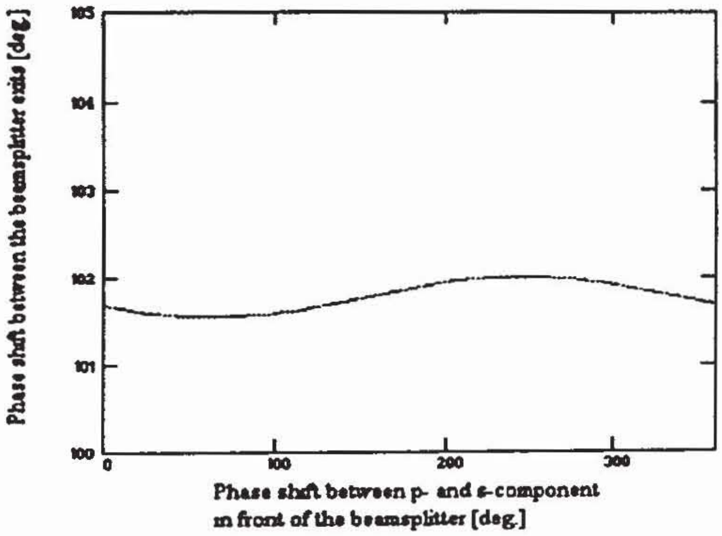


Fig.1: Principle sketch of a double heterodyne interferometer using a 500 MHz AOM.

In order to achieve a phase resolution of $2\pi/3600$ care has to be taken that phase changes which may occur in the interferometric set-up are transmitted equally to the measuring and the control interferometer. Since several birefringent optical elements are used phase changes will be different in the p- and s-component of the light. This phase changes are due to fluctuations of the laser frequency. The halfwidth of the spectrum of the diode used was about 30 MHz, but the fluctuations of the center frequency due to the thermal control loop of the diode is approximately 200 MHz. Fig.2 shows the differential phase between the reflecting and the transmitting output of a silver beam splitter and a polarizing one depending on the phaseshift between p-and s-component of the incoming ray. The phase between the two outputs of the beamsplitter were computed under the assumption that the incoming ray is linearly polarized with an extinction ratio of 10^{-5} in order to minimize the phase fluctuations. In the case of the silver beam splitter the phase of the outputs is analysed with a polarizer under 45°. In the case of the polarizing beam splitter the assumption was made that the splitting ratio is adjusted to be 1:100, which is realistic for the object path light since losses can exceed 60 dB easily when measuring at rough surfaces. In addition internal reflections from the fiber endfaces build a parasitic etalon /4/. Fluctuations of the center frequency of the laser diode then give rise to amplitude and phase changes.



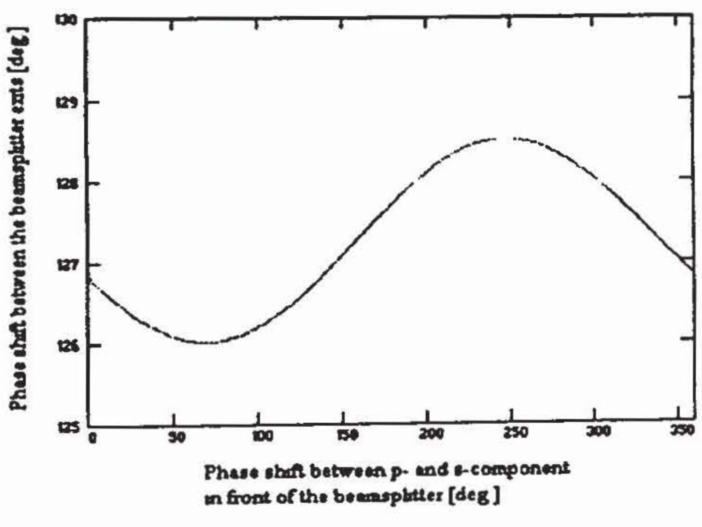
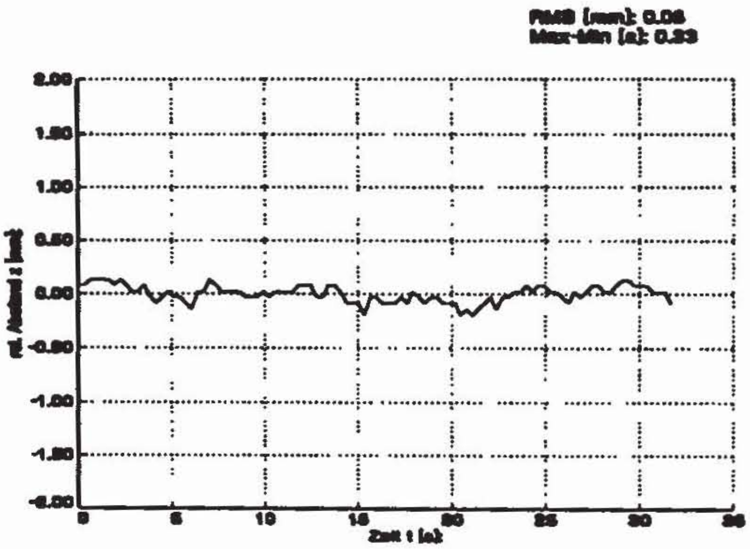


Fig.2: Effect of phase changes between p- and s-component of the input ray on the phase difference of the two outputs of a a) silver beam splitter and b) a polarizing beamsplitter.

3. Results

Fig. 2 shows a 30 s stability measurement at a rough surface at 20 m distance. The resolution is 0.08 mm. By now systematic errors reduce the accuracy to about 1 mm. Fig. 3 shows a measurement at 100 metres distance at a retroreflector with an rms-phase-deviation of 0.2 mm. The full width half maximum of the laser diode spectrum has been measured to be 22 MHz using a Fabry-Perot interferometer. This corresponds to a coherence length of about 5 metres. It shows, that a stable phase measurement is obtained at a distance the optical path length of which exceeds the coherence length of the laser considerably.



ig.3: Stability measurement at a rough target at 5 metres distance. Δz_{rms}=0.08 mm

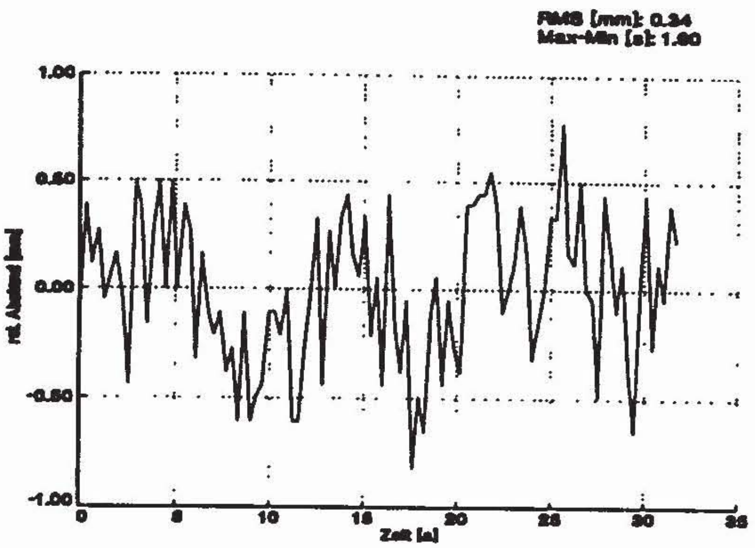


Fig.4: Stability measurement at a cornercube at 100 metres distance. $\Delta z_{rms} = 0.34$ mm.

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