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Heterodyne standing-wave interferometer

Heterodynes Stehende-Welle-Interferometer

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Abstract: This manuscript describes a novel standing-wave arrangement with two laser sources of different wavelengths, emitting towards each other. The resulting standing wave has a continuously moving intensity profile, a thin, transparent photo sensor is inserted into. When the sensor is moved along the optical axis a frequency shift, proportional to the velocity, occurs. This frequency shift can be evaluated for the purpose of interferometric length measurements.

Keywords: Standing wave, heterodyne, interferometer, photo sensor.

Zusammenfassung: Dieser Artikel beschreibt einen neuartigen Stehende-Welle-Aufbau, bei dem zwei Laserstrahlen unterschiedlicher Wellenlänge in entgegengesetzter Richtung interferieren, wodurch eine heterodyne stehende Welle entsteht. In deren kontinuierlich bewegtes Intensitätsprofil wird ein dünner, transparenter Photosensor eingefügt. Bei einer Verschiebung des Sensors entlang der optischen Achse erfährt das Sensorsignal eine geschwindigkeitsproportionale Frequenzverschiebung, welche für interferometrische Längenmessung ausgewertet werden kann.

Schlüsselwörter: Stehende Welle, heterodyn, Interferometer, Photosensor.

1 Introduction

Interferometers are the measuring instrument of choice in industrial applications, for calibrations, semiconductor processes and other precision length measurements. In contrast to their simple basic principle, however, their actual optical structure is very complex and consists of numerous optical precision components. For this reason, interferom-

eters are usually made in single piece manufacturing and are therefore price-intensive. Furthermore, there are narrow limits to their miniaturization. The reason for this are the minimum dimensions of the optical components used in the assembly, combined with the basic optical design with a right angle between the measuring and reference beam of the widespread Michelson interferometer.

The interferometer set-up described in this manuscript traces back to the homodyne standing-wave interferometer described by Büchner [2]. To overcome some issues involved in the original principle, the new approach utilises the optical interference of two counter-propagating laser beams with different wavelengths. The two laser beams form an optical standing wave, which is detected by an ultra-thin transparent photo sensor. The interferometer based on this approach therefore has a very simple linear structure, consisting of only two laser sources facing each other and one single photo sensor. The developed heterodyne standing-wave interferometers can hence be significantly smaller than the common Michelson interferometer. Furthermore, the transparent sensors can be manufactured using established semiconductor technologies.

The sum of these properties results in an enormous potential for cost savings and extreme miniaturisation of laser interferometric measuring arrangements.

2 The optical standing-wave

2.1 Homodyne standing-wave

The existence of optical standing waves was already proofed by Wiener [8] in 1890. They arise when electromagnetic waves, e.g. after perpendicular reflection at a mirror, collinearly propagate in opposite directions. In this case, interference occurs between incident wave E_{in} and reflected wave E_{re} , even if they have different directions of propagation.

The field strength E_{sw} of the resulting standing wave can be calculated by the superposition of the partial field strengths (eq. 1).

$$E_{\text{sw}} = E_{\text{in}} + E_{\text{re}} . \quad (1)$$

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During the reflection on the mirror surface, the reflected wave undergoes a phase jump of π in relation to the incident wave. Therefore, the field strength of the standing wave and hence the intensity I_{sw} on the mirror surface is zero at any time. For this reason, the phase jump of π entails a fixed coupling of I_{sw} to the mirror surface which in turn means that the minima and maxima of the intensity profile are located in well-defined positions in front of the mirror. The intensity of the standing wave is thus a function of the wavelength λ , the intensity I_0 of the incident wave, and the distance z from the mirror surface:

$$I_{\text{sw}} = 2I_0 \left(1 - \cos \left(\frac{4\pi}{\lambda} z \right) \right) \quad (2)$$

Equation 2 shows that the intensity I_{sw} varies between 0 (destructive interference) and $4I_0$ (constructive interference) and the minima respectively the maxima have a distance of $\lambda/2$ to each other.

The intensity profile I_{sw} can be scanned by a photo sensor (fig. 1). In order that the sensor can detect the intensity profile, it must be sufficiently transparent, flat and significantly thinner than the optical wavelength [2, 4]. When the standing-wave sensor and the measuring mirror are moved relative to each other in z -direction, the intensity profile will shift through the sensor and a sine-shaped sensor signal will occur.

Fig. 1: Optical standing wave: incident and reflected wave interfere in opposite directions and form the static intensity profile I_{sw} of the standing wave. The intensity profile can be detected by a thin, transparent photo sensor, and thus can be used for length measurements.

A disadvantage of the set-up shown above is that a second standing-wave sensor is required for distinct determination of the moving direction. The second sensor has to be arranged with a phase shift of 90° with respect to the first one to obtain quadrature signals and allow forward-backward counting.

2.2 Heterodyne standing-wave

The second standing-wave sensor in the homodyne set-up means an additional influence of the standing wave, furthermore it has to be arranged long-term stable with a

distance of $\lambda/8$ to the first standing-wave sensor. In order to avoid the second standing-wave sensor, two opposite directed laser sources of different frequencies f_1 , emitting in $+z$ -direction and f_2 , emitting in $-z$ -direction and with $f_1 > f_2$ are used in this work. In this case, the intensity profile of the resulting standing wave is no longer stationary in space, but is moving with a velocity of

$$v_{\text{sw}} = c_0 \cdot \frac{f_1 - f_2}{f_1 + f_2} \quad (3)$$

through the standing-wave sensor, where c_0 is the speed of light. The moving intensity profile results in a periodic photo signal of a frequency f_{photo} which equals the difference frequency of the two laser sources $f_1 - f_2$, also called the beat frequency f_{beat} . When the standing-wave sensor is moved along the z -axis, due to the Doppler-effect a frequency shift $f_{\text{photo}} = f_{\text{beat}} + \Delta f$ will occur. Based on the detected frequency shift the moving direction and velocity can be deduced. The value of Δf represents the velocity while the sign represents the moving direction.

Fig. 2: Arising of a heterodyne standing wave between two laser sources of different wavelengths λ_1 and λ_2 . The heterodyne standing wave is moving along the optical axis and passes through the sensor with a velocity v_{sw} .

In this arrangement, the interferometer itself consists only of a single, transparent photo sensor and does not require any further parts. An interferometer based on the described principle possesses a considerable potential for miniaturisation. Because of the simple linear structure the required assembly space for the measuring head is only slightly larger than the diameter of the laser beam.

3 State of the art

All previous applications of standing waves for length measurements exclusively use homodyne standing waves which occur after the reflection of a laser beam at a reflective element, in general a mirror. The possibility of using standing waves for length measurements was first described by Büchner [2]. There, the fundamental arrangement of a standing-wave interferometer with laser source, measuring mirror and two serially arranged, 90° phase shifted sensors is described.

Sasaki describes a transparent photo sensor made of silicon deposited on a quartz plate [6]. In this photo sensor, the two photo diodes for forward-backward counting are

arranged side-by-side. The optical path lengths of the partial beams differ by $\pi/2$, which is achieved by local etching of the carrier material in the area of one photo diode.

Bunte [1] and Mandryka [3] developed a photo sensor which is made by vapour deposition of amorphous silicon on a glass carrier. Several appropriate doped sensor layers are successively deposited on the carrier, resulting in two stratified p-i-n photo diodes. The 90° phase shift between the sensors as well as an anti-reflection coating are achieved by an adequate choice of the individual layer thicknesses.

4 The transparent photo sensor

4.1 Mechanical requirements

The fundamental property of the standing-wave sensor is the thickness d of the active, photosensitive layer. The standing wave is pervading the whole sensor, thus the intensity profile I_{sw} is integrated over the complete sensor volume. The ideal thickness of the active sensor layer is a compromise between the amplitude of the sensor signal and the signal contrast (ratio between signal amplitude and signal offset). For an ideal signal contrast (minimal signal offset), the thickness of the photo active layer has to approach zero, $d \rightarrow 0$. However, in this case the signal amplitude also approaches zero $s \rightarrow 0$ because of the vanishing photo-active volume. As the thickness d increases, the amplitude of the photo signal also increases. Though, at the same time the sensor integrates over a growing phase range of I_{sw} , resulting in a growing offset in the photo signal derogating the signal contrast. Reaching a thickness of $d = \lambda/2$, the sensor integrates over a whole period of I_{sw} . At this point, the AC component of the photo signal vanishes completely resulting in a photo signal being a pure, constant offset. In both cases, $d \rightarrow 0$ and $d = \lambda/2$, the sensor is not applicable for length measuring in a standing wave. The ideal active layer thickness lies between these two extrema and is $d \approx \lambda/4$. For a photo active layer made of silicon and a wavelength $\lambda = 633 \text{ nm}$ of the laser source, the resulting thickness of the active layer is $d \approx 40 \text{ nm}$ which is the particular challenge for this interferometer principle.

Similar considerations apply for the flatness of the sensor. If the photo active layer is curved, the intensity profile I_{sw} will be integrated over a larger phase range. This likewise results in a derogated signal amplitude and thus a smaller signal contrast. To keep the signal distortions to a minimum the sensor flatness should not exceed $\lambda/4$.

4.2 Optical requirements

The photo sensors for detection of the intensity profile I_{sw} is placed right inside the optical path and thus directly influences the standing wave.

An ideal standing wave arises when incident and reflected beam are of the same intensity I_0 . Otherwise, the intensity in the minima of I_{sw} will not fall to zero resulting in a growing signal offset and thus lower signal contrast. To ensure similar intensities of incident and reflected beam the standing wave sensor should affect the optical path as little as possible. This results in the demands for low absorption and low reflection.

4.3 Fabrication

The standing-wave sensors are based on the Silicon-on-Insulator-Technology (SOI) which enables the described sensor properties. Commercially available SOI-wafer are the starting point for the sensor fabrication. A striped p-i-n profile is doped in the upper silicon layer, forming a lateral p-i-n photo diode (fig. 3).

Fig. 3: Front view of the standing-wave sensor. The transparent, photo-active area has a size of $1 \text{ mm} \times 1 \text{ mm}$. The p- and n-doped stripes are connected with aluminium conductors for further connection.

As a next step the base silicon on the rear side of the wafer is locally etched in the area of the p-i-n photo diode to achieve a thin, transparent standing-wave sensor. The sensor has a cross section of appr. $1 \text{ mm} \times 1 \text{ mm}$ while being only 600 nm thick including the actual photo active layer and surrounding layers. In that respect the standing-wave sensor is an ultra-thin membrane and hence has to be stabilised by a glass plate to fulfil the demands for the flatness of the photo active layer. Furthermore, two anti-reflection (AR) layers are deposited on the front and the rear side of the wafer to reduce the reflection coefficient of the whole layer system (fig.4).

Fig. 4: Cross section of the standing-wave sensor. The photo active layer is electrically isolated by surrounding SiO_2 -layers. For transparency, the base silicon is etched in the region of the p-i-n diode. Additionally, the front and rear side of the sensor is anti-reflection (AR) coated. The glass plate stabilises the ultra-thin membrane (thickness ≈ 600 nm).

The final step of the fabrication is the separation of the standing-wave sensors by scribing and breaking of the SOI-wafer. For convenient handling the sensors are pasted on a PCB and electrically connected by wire bonding.

The SOI technology enables the fabrication of the standing-wave sensors with cost-efficient standard semiconductor materials and series production capable procedures. The resulting lower manufacturing costs compared to classical interferometers open up completely new fields of application for interferometric measurement methods.

5 Measurements

The basic functional capability of the standing-wave sensors was already proofed in past studies. Among other things the measurements therein showed the typical electrical diode behaviour of the standing wave sensors and a sufficient photo sensitivity. Furthermore, the ability of length measurements in a homodyne standing wave could be proofed [5].

5.1 Frequency response

For the application of the standing-wave sensors in a heterodyne standing wave there are particular requirements concerning the cut-off frequency. As shown in eq. 3 the heterodyne standing wave is moving with a velocity of v_{sw} in z direction. When a sensor is inserted into the standing wave, an alternating photo signal with the frequency difference of the laser sources f_{beat} will occur. A limit for the displacement velocity v_{sen} of the moving sensor and hence the maximal possible measuring velocity arises when the sensor is moving in the same direction as the standing wave itself. When the sensor reaches the velocity of the standing

wave ($v_{\text{sen}} = v_{\text{sw}}$) the Doppler-shift will be $\Delta f = -f_{\text{beat}}$ which leads to $f_{\text{photo}} = 0$. Given that at even higher velocities $v_{\text{sen}} > v_{\text{sw}}$ an alternating photo signal $f_{\text{photo}} \neq 0$ will recur, $v_{\text{sen}} = v_{\text{sw}}$ represents the limit of the unambiguous velocity range. This limitation of the unambiguous velocity range does not exist for the inverse moving direction (contrary to the standing wave). Nevertheless the sensor velocity should be limited to $-v_{\text{sw}} \leq v_{\text{sen}} \leq v_{\text{sw}}$ for practical application of the standing-wave interferometer which results in $-f_{\text{beat}} \leq \Delta f \leq f_{\text{beat}}$. The standing-wave sensors therefore have to cover a frequency range of $f_{\text{photo}} = 0 \dots 2f_{\text{beat}}$.

In the set-up for determining the cut-off frequency, the standing-wave sensors were illuminated by a modulated diode laser instead of two He-Ne lasers. This method saves the need for moving the sensors with high velocities. The modulation frequency was started at 10 Hz and then increased until the signal amplitude of the sensors dropped below the -3 dB limit. This frequency represents the cut-off frequency f_c . In this measurements, a partial beam was split off the main beam and directed to a reference photo diode to compensate the frequency response of the diode laser (fig. 5).

Fig. 5: Set-up for measuring the cut-off frequency f_c of the standing-wave sensors. The diode laser is modulated between 10 Hz and 100 MHz. To compensate the frequency response of the diode laser, the output is monitored by a reference diode ($f_c = 500$ MHz).

The measured cut-off frequencies are in the range of up to 70 MHz (fig. 6) thus the standing-wave sensors are capable for measuring speeds up to $\pm 10 \text{ ms}^{-1}$ for a wavelength of $\lambda = 633 \text{ nm}$. This can be considered sufficient for most measurement applications.

Fig. 6: Exemplary frequency response of a standing-wave sensor. The relative amplitude of the sensor signal drops below 0.7 at 74 MHz.

The measurements carried out until now show that the standing-wave sensors are suitable for the application in a heterodyne standing wave due to their optical and electrical properties. The following sections describe the investigations of the sensors inside the standing wave.

5.2 Laser source

The laser source for the interferometric measurements is a pair of He-Ne lasers which are frequency-coupled by means of a phase locked loop (PLL) [7]. The master laser is a two mode laser, stabilised to itself by two-mode stabilisation. In this technique, the resonator length of the laser (glass tube) is thermally adjusted with a wire heating. The set-point is the resonator length at which the two laser modes are of the same intensity. As long as the ratio of intensity of the two laser modes remains constant, the absolute frequency f_1 is constant as well.

The frequency f_2 of the slave laser is tuned relative to the master laser to a fixed frequency difference (beat frequency f_{beat}). For that purpose, the actual beat frequency is continuously measured and regulated by a PLL to match an external reference frequency (fig. 7). As with the master laser, the setting of f_2 is done by thermal change of the resonator length. With the described principle, the beat frequency does only depend on the reference frequency of the PLL and hence can be adjusted arbitrarily. During the measurements carried out, the beat frequency was set to $f_{\text{beat}} = 4 \text{ MHz}$.

Fig. 7: Working principle of the heterodyne laser source. The master laser is a classical stabilised He-Ne laser, the slave laser is controlled by a phase locked loop (PLL) to accomplish a stable frequency offset between master (f_1) and slave (f_2).

The main beams of master and slave laser are coupled into polarisation maintaining mono-mode fibres leading to the actual interferometer. This way, the laser tube as a substantial source of heat can be kept off sensitive measurement set-ups.

5.3 Standing-wave sensor at rest

First of all, a measurement according to fig. 2 was carried out with the standing-wave sensor at rest. For that purpose, the two laser beams were adjusted exactly coaxial to each other. The counter-propagating beams interfere with each other and form a heterodyne standing wave with plane wave fronts which are perpendicular to the optical axis and moving in positive z -direction with a velocity v_{sw} according to eq. 3.

After the adjustment of the laser beams, the standing-wave sensor is inserted into the beam path and adjusted perpendicular to the optical axis. The moving standing wave is now streaming through the sensor and a periodical alternating photo signal occurs. As the standing-wave sensor is not moving relatively to the laser sources, there is no additional frequency shift due to the Doppler-effect. Thus, the photo signal corresponds to the difference frequency of the two laser sources $f_1 - f_2$ (fig. 8).

Fig. 8: Signal of the standing-wave sensor at rest. The photo current is in accordance with the beat frequency $f_{\text{beat}} = 4 \text{ MHz}$.

The sensor signal was AC-coupled during the measurements, so the existing offset in the signal could be suppressed. That is one of the advantages of the heterodyne standing-wave technique: even when the sensor is at rest, the signal offset can be eliminated by AC-coupling, having no longer any influence on the subsequent signal evaluation electronics.

5.4 Moving standing-wave sensor

After the previous measurement showed the ability of the standing-wave sensors to detect the heterodyne standing wave, measurements with a moving sensor were carried out. For that purpose, the standing-wave sensor was mounted onto a linear axis (DC motor driven spindle) and moved in a repetitive motion between the two laser sources. The maximum velocity between the reversal points amounts to appr. 100 mm s^{-1} . In a phase of constant velocity, the

sensor signal was recorded with a digital storage oscilloscope and evaluated. Now, in contrast to the sensor at rest, the photo signal does not correspond to the pure beat frequency f_{beat} . Due to the relative movement between the standing-wave sensor and the laser sources, there is an additional Doppler frequency shift. This leads to an increasing or decreasing frequency of the sensor signal, depending on the direction of movement ($+z$ - or $-z$ -direction). Fig. 9 shows the resulting frequency spectrum for a sensor moving contrary to the standing wave, resulting in an increased sensor signal frequency (Doppler-shift $\Delta f > 0$).

Fig. 9: Spectrum of the photo current for the standing-wave sensor moving at a constant speed contrary to the standing wave, in $-z$ -direction. The frequency shift $\Delta f = f_{\text{photo}} - f_{\text{beat}} = +300 \text{ kHz}$ corresponds to the sensor velocity $v_{\text{sen}} = -100 \text{ mm s}^{-1}$.

6 Conclusion and outlook

In this manuscript, ultra-thin, transparent photo sensors were proposed which are suitable for interferometric length measurements in a heterodyne standing wave. Heterodyne standing waves arise when two laser beams of different frequencies propagate in opposite directions, interfusing each other and at the same time interfere. The resulting intensity profile with minima and maxima is moving along the optical axis with a constant velocity. The sensors for detecting this intensity profile are fabricated based on the SOI-technique and feature a thickness of the active, photo sensitive layer of only 40 nm. The standing-wave sensors are sufficiently transparent not to interfere with the standing wave. Their cut-off frequency is beyond two times the used beat frequency (4 MHz) which makes the whole measurement arrangement suitable for length measurements with a measuring velocity of 1.25 m s^{-1} . The ability for detection of the standing wave was proofed for a sensor at rest as well as a moving sensor with a velocity of up to 100 mm s^{-1} . The detected frequency shift of the sensor signal due to the Doppler-effect corresponds to the moving velocity and direction of the standing-wave sensor.

In future works, a reference photo diode will be added in the optical path to compensate the phase noise arising from mechanical influences on the optical fibres. The reference photo diode will be permanently fixed, providing a stable signal, the signal of the moving sensor can be compared to. With the reference and measuring signal it will be possible to set-up an evaluation electronic determining the phase difference between the two signals and thus allow length measurements based on the described principle.

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