DOUBLE-BEAM MACH-ZEHNDER INTERFEROMETER FOR THIN PIEZOELECTRIC FILMS MEASUREMENT

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Abstract: This paper describes a Mach-Zehnder double-beam interferometer for measurement of piezoelectric films thickness displacement. The measurement of the sample from both sides with probing beam leads to suppression of bending effect, which can otherwise strongly degrade the results acquired by other methods. The performances of the setup were tested on a reference PZT sample. The measured piezoelectric coefficient was in agreement with its theoretical value. The described setup utilizes minimal number of the optical components which are necessary for controlled phase drift compensation. Further techniques for performance enhancement are also proposed.

Keywords: Laser interferometry, Mach-Zehnder interferometer, double-beam, thin piezoelectric films.

1 INTRODUCTION

Measurement of electromechanical properties of thin piezoelectric layers has currently a considerable importance. Their major application includes various micro-electro-mechanical systems (MEMS). They are used as microsensors, micromotors, micropumps, microcantilevers, ultrasonic and RF arrays, etc. [2, 4, 5]. The advantage of piezoelectric films in MEMS systems is high force and low loss of electrical energy.

Development and modelling of such systems require accurate measurement of their electromechanical properties, especially the piezoelectric coefficients. There exist methods based on direct and converse piezoelectric effect [3]. The direct methods use measurement of electric charge induced by applied stress on the sample. However, this method is not suitable for thin piezoelectric films since it is difficult to achieve a homogenity of the applied stress [5]. Therefore, the converse methods are used, where the mechanical strain induced by electric field is measurement instead.

The most common converse methods for piezoelectric coefficients measurement are heterodyne laser vibrometer and single-beam interferometer (e.g. Michelson) since they achieve high accuracy and does not influence the measured sample. However, when the frequency of applied electric field increases, the mass centre of thin sample may oscillate and the sample bends, even if the holding is tight. The bending effect can significantly exceed the thickness changes even from several kHz [2].

This can be overcome by the double-beam Mach-Zehnder interferometer [1]. The sample movement is measured from both sides and the common mode displacement caused by bending is thus effectively subtracted. The interferometer described in this paper uses electro-optical phase shifter enabling simpler configuration in comparison to commonly used piezoelectric-driven mirror compensation [1, 2, 3] or modulation [4] method.

2 METHODS

2.1 LASER INTERFEROMETRY

The laser interferometry is based on adding the electric fields of a probing and a reference laser beam. If the beams are coherent and have a wavelength λ, the output power is

$$P_{\text{out}} = P_{\text{p}} + P_{\text{r}} + 2\sqrt{P_{\text{p}}P_{\text{r}}}\cos\left(4\pi\Delta d/\lambda\right), \tag{1}$$

where P_{p} and P_{r} are powers of the probing and the reference beam respectively, and Δd is their path difference. In case the beams do not interfere completely, the equation 1 can be rewritten as

$$P_{\text{out}} = \tfrac{1}{2}\left(P_{\text{max}} + P_{\text{min}}\right) + \tfrac{1}{2}\left(P_{\text{max}} - P_{\text{min}}\right)\cos\left(4\pi\Delta d/\lambda\right), \tag{2}$$

where P_{max} and P_{min} stand for the maximum and the minimum light power, which can be measured from interference curve easily. The interference curve of the interferometer is in fig. 1. The minimum power P_{min} then represents the residual power without interference. The contrast of the interference pattern is defined as a visibility $V = (P_{\text{max}} - P_{\text{min}})/(P_{\text{max}} + P_{\text{min}})$.

To achieve a maximal sensitivity of path change detection, the path difference Δd must be biased to $\Delta d_{\text{bias}} = \lambda(2n+1)/8$, so the difference is then

$$\Delta d = \Delta d_{\text{bias}} + \Delta d_{\text{piez}}, \tag{3}$$

where Δd_{piez} is a harmonic stretching of measured sample. Cosine response described by eq. 1 can be replaced by sine afterwards. If the displacement to wavelength ratio is $\Delta d_{\text{piez}}/\lambda < 0.04$, which is almost always satisfied, the eq. 1 can be further simplified to

$$P_{\text{out}} = P_{\text{p}} + P_{\text{r}} + 2\sqrt{P_{\text{p}}P_{\text{r}}}\left(4\pi\Delta d_{\text{piez}}/\lambda\right) \tag{4}$$

with error less than 1 %. The power on photodetector is converted to an electric current, which is then amplified and transferred to an output voltage, as can be seen in fig. 1. The amplitude Δd_0 of the harmonic displacement Δd_{piez} can be calculated as

$$d_0 = \frac{\lambda}{2\pi}\cdot\frac{U_{\text{out}}}{U_{\text{pp}}}, \tag{5}$$

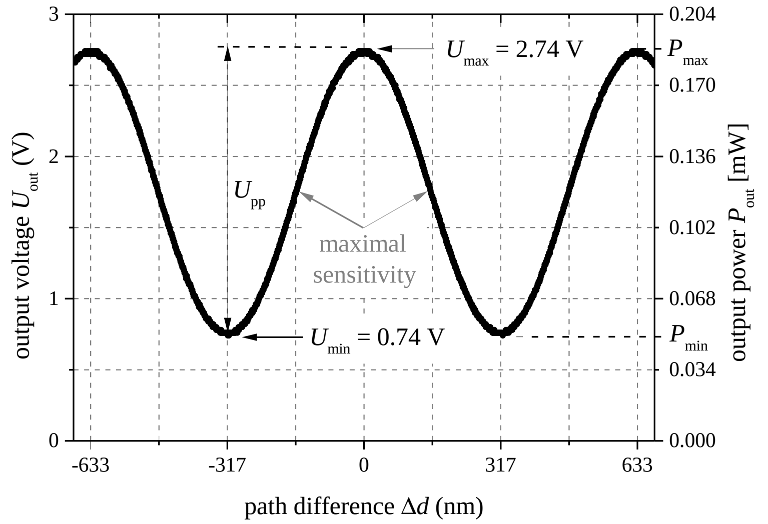

Figure 1: Output interference curve - Measured dependence of the output power P_{out} and the corresponding voltage U_{out} on the path difference Δd (centred to zero). Curve was acquired by sawtooth modulation of path difference with fall steps corresponding to 2π phase shift.

where U_{out} is the amplitude of the output voltage corresponding to the displacement Δd_0, and U_{pp} is a peak-to-peak voltage of the interference curve.

2.2 MEASUREMENT SETUP

The configuration of the double-beam interferometer consists of discrete optical elements. The whole setup is placed on a stable optical table with air damping to suppress the outer vibrations. The schematic of the double-beam interferometer is in fig. 2.

As a source, we use a frequency stabilized HeNe laser Thorlabs HRS015 producing vertically polarized light with wavelength $\lambda = 632.991$ nm and output power 1.2 mW. To ensure the interference of the reference and the probing beams, the divergence of the laser beam must be sufficiently low. By measuring the beam diameter in full width at half intensity maximum in 11 m distance from the laser we determined the divergence angle $\alpha = 1.16 \cdot 10^{-3}$ rad. The obtained value is better than the value stated by the manufacturer, which is $\alpha_{\mathrm{m}} = 1.25 \cdot 10^{-3}$ rad, and is sufficiently low for ensuring the interference.

The laser beam then must be split to the reference and the probing beam. The beam passes through the optical isolator which prevents reflected light coming back to the laser and also acts as a $\lambda/2$ plate turning the polarization by 45°. The polarized beam splitter PBS1 then divides the power equally to a vertically polarized reference beam travelling to a mirror M3, and a horizontally polarized probing beam going to a $\lambda/4$ plate, which changes the polarization to circular. After passing the lens L1 and reflection from the sample, the $\lambda/4$ plate changes the polarization to a vertical direction, which is then reflected by the PBS1 to a mirror M1. The vertically polarized probing beam is then reflected by a polarized beam splitter PBS2 towards the second $\lambda/4$, where the situation is similar. After passing the $\lambda/4$ plate twice, the polarization of the probing beam is horizontal again and it goes through the PBS2. Here the beam encounters with the reference beam, which travels between mirrors M3 and M4 to the PBS2 with no change of polarization state. After passing the PBS2 both beams have mutually orthogonal polarization, so they need to pas the polarizer to interfere. A Glan-Thomson polarizer with extinction ratio 100 000:1 is used to suppress undesired polarization components. Since the probing beam is more attenuated than the reference beam due to reflection from the sample, the polarization axis is not 45°, but is more close to the horizontal direction. Hence the equality of the probing and the reference beams powers is assured, and the visibility of the interference characteristic sensed by the detector is maximal. In this setup, the Si detector Thorlabs PDA36A-EC is used, which includes

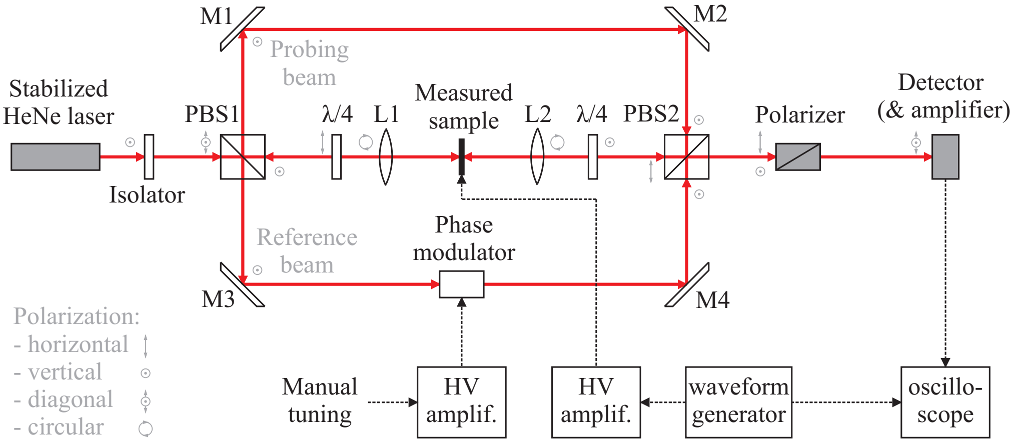

Figure 2: Schematic of the double-beam interferometer configuration.

a switchable amplifier in the case, which helps to suppress an additional noise in the output electric signal. The optical elements must be as close as possible to reduce diverging of the beams. In our setup, the distance between the laser and the detector is approximately 90 cm.

The measurement setup requires precise alignment of the arms sensing the sample. The amount of reflected power is also critical, the electrodes of the piezoelectric film must be therefore polished. A thin Au layer is then usually deposited on the surface for maximal reflectivity.

Further, to sense only the thickness changes and not the bending of the film, the opposite beams must be perfectly colinear and focused to single point in the same position from both sides. The focusing is ensured by condenser lenses L1 and L2 with focal lengths 90 mm to ensure high depth of view. By using the lenses, the slight tilt of the sample caused by its bending is suppressed.

To ensure the colinearity, a series of two or three pinholes placed between lenses instead of the sample is normally used. In this experiment we used a new method based on multiple recirculation of the laser beam through the polarized beam splitters and mirrors M1 and M2 instead. A $\lambda/2$ plate was placed between the $\lambda/4$ and the PBS2, and the lens L1 was moved towards the L2, so their focal points were coincident. The $\lambda/2$ was turned so that after every circulation, half of the beam was passed to the white plane placed behind the PBS2. Then the laser spots with exponentially decreasing power were observed at the white plate. The mirrors M1 and M2 were then tuned precisely to achieve coincidence of the spots.

After setting the probing arm of the interferometer, the reference arm must be adjusted so the both interfering beams were collinear. This can be done by fine movement of mirrors M3 and M4. If the interfering beams do not coincide, they will produce a fine interference fringe whose intensity is integrated through the PIN photodiode. The visibility of the interference then rapidly decreases.

To ensure an operation with maximal sensitivity, a phase modulator is placed between mirrors M3 and M4. The modulator is tuned manually via HV amplifier to introduce a stable phase shift. The sample is driven by harmonic signal from a waveform generator, which is then also amplified. The applied voltage and measured sample strain are displayed by an oscilloscope.

3 TEST MEASUREMENT

To verify the performances of the double-beam interferometer we performed a test measurement on the sample with known electromechanical properties. We used a PZT disc with 15 mm diameter and a thickness of 2 mm. The piezoelectric d_{33} coefficient of the sample was calculated between 380 and 400 pm/V. To perform the experiment the silver electrodes from both sides were polished to maximal reflectivity. Without depositing any further layers, we achieved reflectivity about 50 %, which already provided sufficient output signal. The disc was then clamped vertically to the focal points of the lenses and turned perpendicularly to the incident beams.

To achieve sensitive measurement of sample displacement, usually a lock-in amplifier is used to process the signal from the detector. To perform tests of general functionality of the interferometer, the oscilloscope was used instead. We applied a harmonic voltage with frequencies 10 Hz, 100 Hz, 1 kHz and 10 kHz, which were much lower than the resonance frequencies of the sample and ensured sufficient stability of the piezoelectric coefficient. A high voltage with amplitude of $U_0 = 40$ V was used to reduce a noise. The amplitude of corresponding displacement, determined from eq. 5, was $\Delta d_0 = 15.7$ nm by all frequencies. The piezoelectric coefficient for given frequency range can be then calculated as

$$d_{33} = \frac{\partial S_3}{\partial E_3} = \frac{\Delta d_0}{U_0} = \frac{15.7 \text{ nm}}{40 \text{ V}} \cong 393 \text{ pm/V}, \tag{6}$$

which is in close agreement with theoretical expectations.

4 CONCLUSION

In this paper, the design of a Mach-Zehnder double-beam interferometer for thin films' piezoelectric coefficients measurement was designed and tested. The functionality of the interferometer was proved by measurement of d_{33} coefficient of PZT test sample. The interferometer will be further used for measurement of thin films, where the bending effects needs to be suppressed. The double-beam interferometer can be easily transformed to a single-beam by placing a fixed mirror ahead of one of sample's surface. The results can be then compared and the influence of the bending effect determined. The experiment also proved strict demands on alignment of all optical components as well as sample reflectivity. Also the sensitivity on vibrations and refractive index fluctuations is substantial and outer disturbance must be avoided.

For more accurate measurement with low sample displacements, these condition changes must be suppressed. This will be solved by automatic compensation of phase drift by loopback control, which will be performed during further research. To detect small displacements with high resolution, a lock-in amplifier will be used, which enables great increasing of a signal-to-noise ratio. We are also working on a novel modulation technique, which could avoid the dependence on changes of the total power of the beam as well as the sample reflectivity. This method then could be used for scanning the vibrations along the surface by moving the sample.

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