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Stabilized detection scheme of surface acoustic waves by Michelson interferometer

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A new detection scheme of surface acoustic waves by Michelson interferometer has been proposed. A substantial advantage of this scheme lies in its being stabilized against vibration and independent sensitivity of the width of an optical beam. These effects were achieved by creating an interference field on the surface of a photodetector. The measurement scheme proposed was analyzed by means of a numerical modeling method. Experiments confirming the fact of the sensitivity of the proposed detection scheme being independent of vibration and width of optical beam have also been made.

Keywords: surface acoustic wave, Michelson interferometer, noncontact detection.

1. Introduction

Surface acoustic waves (SAW) are used for determining the space distribution of the elastic properties of coated materials, composite structures, materials that have sustained surface modifications. These materials are important for the aircraft industry, medicine and other applications. Laser ultrasound methods have been used for the excitation and detection of SAW in recent years. These methods are successful because they are noncontact and have a high space and time resolution. We consider the problem of detection of SAW using Michelson interferometer. This is a detection method of a sample surface displacement due to the acoustic wave [1–3]. It is quite easy to use and allows high sensitivity to be obtained. The sensitivity of Michelson interferometer is equal to zero when the optical path difference equals $0.5\lambda N$, where λ is the optical wavelength and N is an integer. Temperature drifts and vibrations can result in the change of optical path difference of several micrometers, thus seriously complicating an interferometer operation. Therefore, there is a problem of stabilization of Michelson interferometer against vibration. This problem is typical of other interferometers, too. The active and passive methods are used for stabilization of interferometers. The changing path length is stabilized by displacement of an interferometer mirror or electro-optic cell [1, 4]. The feedback signal is used in these methods. Another method is based on the quadrature dual interferometer. In this method, two interference signals with a $\pi/2$ shift phase are detected by two photodetectors [1]. However, all these require an essential complication of construction. We proposed a new stabilization scheme for detecting SAW by Michelson interferometer. A distinctive feature of this setup is that the interference pattern is formed on the surface of a photodetector in the form of space periodic fringes.

The sensitivity of the Michelson interferometer depends on the optical beam size [5]. When the optical beam size is proportional to the wavelength of SAW the sensitivity is small because different parts of the optical beam have a different optical path. In this case, the intensity of one part of interference field is increased and the intensity of another part of interference field is decreased, therefore the full signal has been compensated. The measurement scheme which we proposed is free from that defect. The sensitivity of this scheme is independent of the optical beam size, when the optical beam size is larger than certain value. This effect is possible due to the existing interference fringes with the width corresponding to the SAW length. This conclusion is confirmed by a numerical simulation and experiment.

2. Detection scheme of surface acoustic waves

A general scheme of the measurement setup is presented in Fig. 1. This setup differs a little from the classical setup of Michelson interferometer. Optical beams reflected from the sample and from the interferometer mirror interact and an interference pattern is formed. The intensity of interference field is registered by a photodetector. The displacement of the sample surface changes the optical path difference and correspondingly changes the intensity of interference field. A distinctive feature of the measurement setup proposed is that there is a certain angle between interfering beams. This angle appears as a result of the inclination of interferometer mirror (Fig. 1). The presence of an angle between interfering beams results in appearance of the spatial periodically modulated interference pattern. Thus, the interference field on the surface of the sensitive area of the photodetector is formed as a result of action of two factors: the angle between interference beams and modulation of phase shift between these beams due to propagation of SAW through a sample.

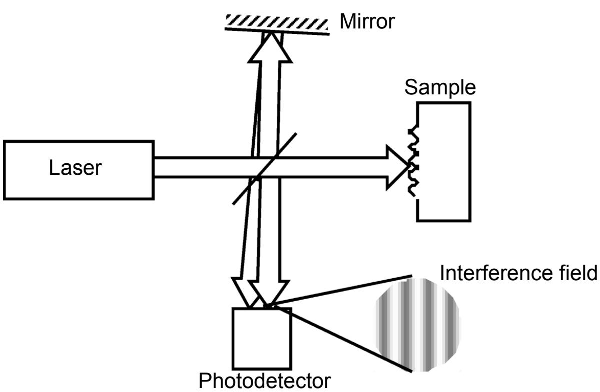

Fig. 1. A scheme illustrating detection of SAW by Michelson interferometer.

Both these factors result in forming a spatially-periodic interference pattern. The first factor made a static interference field, the second factor forms a dynamic interference field. However, the interference pattern created due to SAW is not visible because the shift of the sample surface caused by the acoustic wave is of the order of a few nanometers. The photodetector registers an integral change of intensity which is defined by both contributions in the interference pattern. The sensitivity of this scheme is independent of the change of path difference. On the other hand, sensitivity of the measurement scheme depend on the length of SAW Λ and the width of fringes L. The condition when sensitivity is maximum is defined by numerical simulation.

3. Numerical model of Michelson interferometer

In this paper, we consider the case where magnitude of SAW wavelength is about millimeter or few nanometers. These conditions correspond to conditions of using SAW in nondestructive testing.

For analysing the performance of Michelson interferometer the approach of geometrical optics has been used. The one-dimensional case is considered. The surface of the sample is taken as a mirror surface. The interference of optical waves with the same polarization and intensity is considered. In such a case the intensity of interference field is expressed by [6, 7]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \tag{1}$$

where I_1 and I_2 are the intensities of beams reflected from the mirror and from the sample, respectively, and δ is the phase difference between them.

It has been taken into account that optical beams have Gaussian distribution of intensity which is given by:

$$I_{1,2} = \frac{1}{\sqrt{2\pi}\,a} I_0 \exp\left(-\frac{x^2}{2a^2}\right) \tag{2}$$

Axis x is the axis on the plane of the photodetector, $(1/\sqrt{2\pi}\,a)\,I_0$ is the maximal intensity in the centre of the optical beam, a is the parameter of distribution. Expression (2) is normalized. The magnitude of full power of optical beam is independent of parameter a, which is convenient for numerical simulation.

The phase difference δ appears for a variety of reasons and, in general, it is different at various points of the interference field. First of all, δ is defined as the difference d of distance to the mirror and the sample. Correspondingly, it is possible to write:

$$\delta_1 = \frac{2\pi}{\lambda} 2d \tag{3}$$

In the case where one beam is parallel to the axis of the interferometer and the other one is inclined under a small angle β to this axis, the phase change between them is described by the expression [6]:

$$\delta_2 = \frac{2\pi}{\lambda} x \sin\beta \tag{4}$$

Thus, the periodic interference fringes are formed having a width $L = \lambda/\sin\beta$.

A particular feature of using Michelson interferometer for detection of the SAW is that the surface of the sample through which a wave propagates is displaced under the action of SAW. We considered the case where the frequency range of SAW is from a few MHz to tens of MHz (the wavelength ranges from less than a millimeter to a few millimeters) and its amplitude has value of a few nanometers. The minimal wavelength of SAW is 0.2 mm in the area considered. Since the magnitude of SAW amplitude is accepted as 1 nm, then the inclination of the surface is less than 2×10^{-5} radian. This magnitude is small and it can be assumed that the angle spectrum of the reflected optical wave is equal to the angle spectrum of the falling optical wave. The front of the reflected wave changes by a double value of surface displacement under the action of SAW. The space distribution of change of the front reflected wave corresponds to the space distribution displacement of the sample surfaces.

The phase shift between optical waves, caused by the SAW, will take the form:

$$\delta_3 = \frac{2\pi}{\lambda} 2h \sin\left(\omega t + \frac{2\pi}{\Lambda} x\right) \tag{5}$$

where ω is the frequency of SAW and Λ is the length of SAW, h is the amplitude of SAW.

Taking into account Eqs. (1)–(5) the distribution of intensity in plane of interference pattern can be written as follows:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left\{\frac{2\pi}{\lambda}\left[2d + x\sin\beta + 2h\sin\left(\omega t + \frac{2\pi}{\Lambda}x\right)\right]\right\} \tag{6}$$

For recording a signal the photodetector is placed in the interference field (Fig. 1). Photocurrent is proportional to the total intensity of incident light on the photodetector

$$i = g\iint_s I \,\mathrm{d}x \tag{7}$$

s is the area of interference field on photodetector, which was determined through the diaphragm size, g is the coefficient of proportionality.

When describing the measurement setup for registration of SAW the parameter V, *i.e.*, which is sensitivity, is used:

$$V = \frac{\Delta i}{hg \iint_s I \, \mathrm{d}x} \tag{8}$$

where Δi is the AC amplitude of the photodetector current.

A change in the magnitude of length difference produces modulation of the photocurrent. The depth modulation is:

$$G = \frac{\Delta i_{\max} - \Delta i_{\min}}{\Delta i_{\max} + \Delta i_{\min}} \tag{9}$$

$\Delta i_{\max}$ and $\Delta i_{\min}$ are maximum and minimum AC amplitudes of the photodetector current determined when the optical path difference is changed by the value $\lambda/2$.

The distribution of intensity in the interference field is determined by the numerical calculation. The interference field is in the plane of photodiode. The plane of photodiode is divided into small elements and we accept that the optical intensity is constant in each respective element. The intensity in one element is calculated by Eq. (6). The total intensity is calculated as the sum of the intensities in all elements. The photocurrent is proportional to the total intensity. The photocurrent is calculated for the different moments of time during the period of SAW. The amplitude of photocurrent is determined this way and correspondingly its dependence on the different parameters is calculated.

4. Numerical experiment

Equations (6)–(9) allow us to analyze the sensitivity of Michelson interferometer and to optimize parameters of the detecting scheme. The dependence of sensitivity V versus optical beam size r and width L of interference fringes is considered.

For numerical modeling the following values of parameters were taken: $a = 1.5$ mm, $\omega = 6.28 \times 10^6$ Hz, $\lambda = 0.6$ μm. A displacement h of the surface of the sample under the action of the SAW was taken sufficiently smaller than the optical wavelength and was equal to 1 nm, and this magnitude of displacement corresponds to the power of a few mW/cm [8].

A change of a few millimeters in length difference of the interferometer arms was considered in calculations. The wavelength of SAW is 1 mm.

The results of the numerical simulation are presented in Figs. 2–4. The sensitivity dependence of the optical beam width is shown in Fig. 2. This figure presents the case where the width of the interference fringes is infinity. The sensitivity is maximum

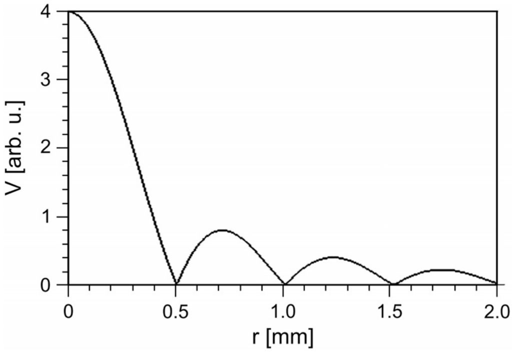

Fig. 2. Sensitivity versus width of optical beam.

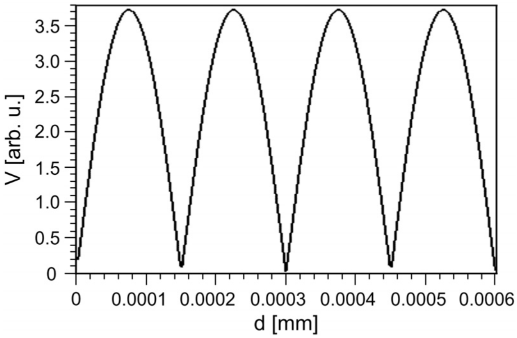

Fig. 3. Sensitivity versus distance difference, $r = 0.1$ mm.

under condition of the width of the optical beam being small. This principle is well known and therefore small width of the optical beam is used in this scheme of the detection of SAW. The change of sensitivity due to the path difference of optical beams is shown in Fig. 3. The Michelson interferometer sensitivity is minimal when the distance difference is $2d = N\lambda/2$. This dependence illustrates the need for stabilization of the path difference.

The sensitivity dependence of the optical beam width and the change of path difference is shown in Fig. 4. The difference distance d is presented as a sum of the constant part d_0 and variable part Δd. The cases when $d_0 = 0.1$ mm (see Figs. 4**a**–4**c**) and $d_0 = 2$ mm (see Figs. 4**d**–4**f**) are presented. As can be seen from the graphs there exists a strong dependence of sensitivity on magnitude Δd. The sensitivity changes in accordance with sinusoidal law from maximal value to zero. When the optical beam width increases the dependence sensitivity of the change in path difference decreases for all the cases presented in Fig. 4. Under condition of $\Lambda = L$ (Figs. 4**b** and 4**e**) the sensitivity approximates a constant magnitude but for $\Lambda > L$ (see Figs. 4**a**, 4**d**) and $\Lambda < L$ (see Figs. 4**c**, 4**f**) the sensitivity decreases to zero. The results of numerical simulation show that sensitivity is independent of the optical beam width when the latter is great.

The obtained results of numerical simulation agree with the known experimental data and show new possibilities for detection of SAW. In the traditional scheme of Michelson interferometer the optical beam width is much less than the wavelength

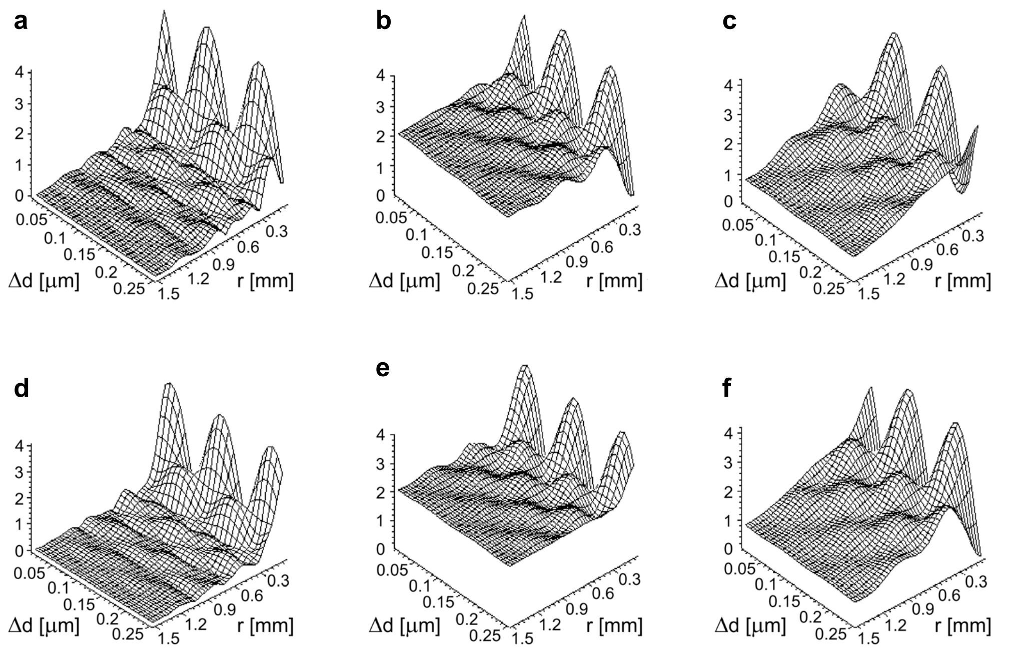

Fig. 4. Simulated sensitivity versus width of beam r and change of distance difference Δd. L = 0.4 mm, d_0 = 0.1 mm (**a**), L = 1 mm, d_0 = 0.1 mm (**b**), L = 1.4 mm, d_0 = 0.1 mm (**c**), L = 0.4 mm, d_0 = 2 mm (**d**); L = 1 mm, d_0 = 2 mm (**e**); L = 1.4 mm, d_0 = 2 mm (**f**); Λ = 1 mm.

of SAW. This case is shown in the area graphs where value r is small. The sensitivity is greatly dependent on path difference. Instability of the path difference magnitude of 0.1 μm can considerably change the sensitivity. Therefore, it is necessary to stabilize the interferometer against vibration. On the other hand, the numerical simulation shows that sensitivity is independent of the change of the path difference in the case of great optical beam width and it is maximum under condition of $\Lambda = L$ (Figs. 4**b**, 4**e**). Exactly such geometry is used in the proposed scheme of detection of SAW, which is independent of the change of path difference and is stabilized against vibration.

5. Experimental research

For verification of the results of numerical modeling a setup has been constructed in which the proposed scheme of detection of SAW is realized. The sensitivity depending on the size of the optical beam is investigated.

A schematic layout of the setup is shown in Fig. 5. The geometry in which the interfering beams are forming some angle between themselves due to inclination of a mirror is used. On the surface of the sample the SAW with frequency of 2.5 MHz generated by prismatic piezoelectric transducer is propagated. The acoustic pulse has duration of 50–100 μs. A He-Ne laser with output radiation wavelength of 632.8 nm is used. The interferometer mirror has been fixed on a piezoelectric washer to which

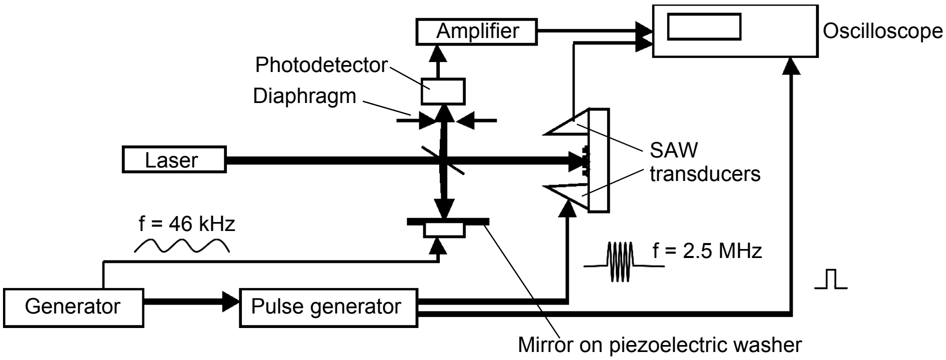

Fig. 5. Scheme of the experimental setup.

a sinusoidal signal with frequency of 46 kHz is supplied. It is the resonance frequency of the piezoelectric washer. Under the action of this signal the mirror oscillates, which causes a change of distance difference *d*. An oscillation of mirror simulates vibrations and allows us to study experimentally their influence on the sensitivity of the measurement setup. The oscillation swing of the mirror is a few hundred nanometers. A signal which is supplied to the interferometer mirror and a pulse of the SAW are synchronized with each other. An interference pattern is registered by the photodetector and the signal is observed on the oscilloscope. The signal is amplified by the band-pass amplifier. The setup also uses a diaphragm which allows changing of the width of the beam which falls onto the photodetector. The whole interfering field falls at the photodiode.

A glass plate is used as a specimen. The measured velocity of SAW is 3300 m/s and the wavelength is 1.32 mm. The result of the experiment is presented in Fig. 6. The sensitivity is maximum and changes very little with an increase in the size of optic

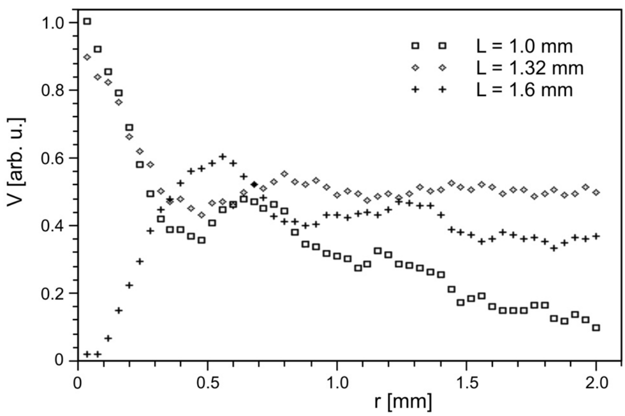

Fig. 6. Sensitivity versus width of optical beam. The wavelength of SAW is 1.32 mm. The starting optical path is different for L = 1.0 mm, L = 1.32 mm and L = 1.6 mm.

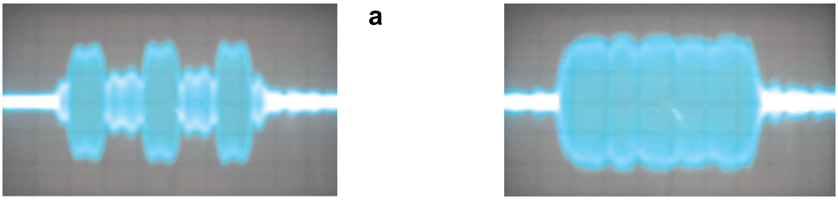

Fig. 7. Photocurrent at vibration of the interferometer mirror. Amplitude of the vibration larger than $\lambda/4$, $r = 0.1$ mm (**a**), $r = 1$ mm (**b**).

beam r beginning from $r \approx 0.5$ mm under condition of $L = \Lambda$. Otherwise, the sensitivity decreases when the optic beam size is increased. These results of the experiment agree with the results of the numerical calculation (Fig. 4).

The proposed scheme of measurement is stabilized against the change in path difference, too. The oscillograms of signals received at the registration of pulses of SAW at vibrations of the interferometer mirror are shown in Fig. 7. In this case, the scheme for which $L = \Lambda$ is used. The shape of the signal shows that the swing of the mirror vibration is greater than $\lambda/4$ (see Fig. 7**a**). The depth modulation decreases when the optical beam size increases. The amplitudes of the mirror vibration in both cases are equal. The shape of the signal (see Fig. 7**b**) shows that the sensitivity is less dependent on the change of path difference. The depth of modulation decreases to 0.07 when the width of optical beam increases to 1 millimeter. This result tells us that the proposed scheme of detection of SAW is stabilized against vibration.

6. Conclusions

A scheme for detecting SAW using Michelson interferometer in which the sensitivity does not depend on the change of length difference of interferometer arms has been proposed. The sensitivity is also independent of the change of optical beam size. The numerical simulation and experimental investigation of this scheme have been made. The proposed scheme of SAW may be used under conditions of vibration and temperature drifts.

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