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MICHELSON INTERFEROMETER STABILIZED SCHEME FOR DETECTING SURFACE ACOUSTIC WAVES

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The operation of Michelson interferometer stabilized scheme for detecting acoustic surface waves (SAW) is analyzed. The case when interfering beams form a certain angle between them resulting in the formation of interferential field in the form of periodic fringes is examined. The analytical expression for the signal obtained in the SAW detection, using such a scheme is formulated and considered. The conclusion on the resistance of the suggested interferometer scheme to vibrations is proved.

Keywords: *Michelson interferometer, non contact detection, stabilized interferometer.*

СТАБІЛІЗОВАНА СХЕМА ІНТЕРФЕРОМЕТРА МАЙКЕЛЬСОНА ДЛЯ РЕЄСТРАЦІЇ ПОВЕРХНЕВИХ АКУСТИЧНИХ ХВИЛЬ

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Проаналізовано роботу та запропоновано схему інтерферометра Майкельсона, який стійкий до вібрацій за реєстрації ним поверхневих акустичних хвиль. Розглянуто схему, в якій промені утворюють певний кут між собою, внаслідок чого на поверхні фотоприймача виникає інтерференційна картина у вигляді паралельних смуг. Іншою особливістю вимірювальної схеми є те, що ширина зондувального променя більша за довжину поверхневої акустичної хвилі. Виконано числовий аналіз розподілу зміни фази променя, відбитого від поверхні зразка, збуреної поверхневою акустичною хвилею. Для розрахунку застосовано метод Кірхгофа. Прийнято гаусівський розподіл напруженості електричного поля лазерного випромінювання. Подано результати розрахованого просторового розподілу фази оптичного поля для різних довжин поверхневих акустичних хвиль. Показано, що після відбивання від поверхні зразка розподіл фази оптичного поля має періодичний характер, який визначається довжиною поверхневої акустичної хвилі. Також виявлено особливості фазової структури оптичного поля, які пов’язані з порушенням періодичності і залежать від співвідношення довжин оптичної і акустичної хвиль. Враховуючи періодичний розподіл зміни фази в зондувальному промені, отримали вираз для сигналу, який реєструють за допомогою запропонованої схеми інтерферометра Майкельсона. Аналітично отримано розв’язок, який визначає умови, коли чутливість інтерферометра не залежить від різниці ходу променів. Такою умовою є рівність довжини поверхневої акустичної хвилі та ширини інтерференційної смуги, а також достатня ширина зондувального оптичного променя, яка повинна бути більшою за довжину поверхневої акустичної хвилі.

Ключові слова: *інтерферометр Майкельсона, безконтактна реєстрація, стабілізований інтерферометр.*

The registration of ultrasonic waves in solid state with the help of laser interference methods has been intensively developing lately. Such methods have considerable advantages over contact detection methods, such as high time and space resolution and lack of contact. Detection of the SAW by Michelson interferometer belongs to such methods. One of the major problems complicating the application of this scheme is the negative impact of mechanical vibrations. The components of the interferometer affected by vibrations are displaced and the interferometer path difference changes. For the values of path difference equal to $N\lambda/2$, where N is an integer and λ – optical wavelength, its sensitivity is equal to zero. Various methods of eliminating this effect are used [1– 3]. A new method of stabilization which can be used for the detection of SAW was suggested and investigated experimentally in papers [4]. The main feature of the suggested measuring scheme consists in the creation of interference pattern in the form of periodic fringes on the photodetector surface. This pattern is formed as a result of the existence of some angle between the interfering beams. The scheme of the detection setup is shown in Fig. 1. The total interference field is registered by the photodetector. The width of interference fringes is commensurable with the SAW wavelength. The diameter of the interferometer optical beam is equal to the SAW wavelength or larger. With the help of such a scheme a few millimeters long SAW can be detected. We considered the case when the SAW frequency range is changing from a few MHz up to tens of MHz. The sensitivity of this scheme is stable under vibrations and is not critical to the diameter of the reference optical beam. The paper provides the analysis of the features of the SAW detection by this scheme.

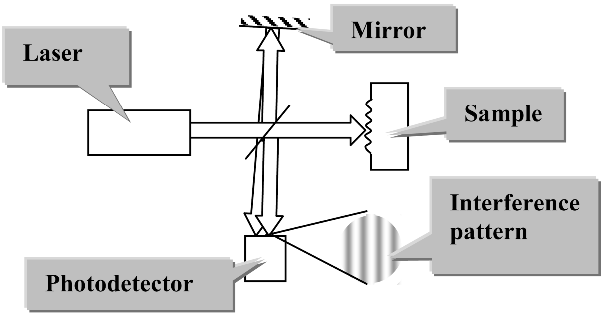

Fig. 1. Scheme detection of SAW by Michelson interferometer.

Mathematical scheme model. Sample mirror surface, where SAW propagates, is considered. In the analysis of the measuring scheme the SAW amplitude is assumed to be significantly smaller than the length of optical radiation. Fig. 2 shows a part of the interferometer scheme illustrating the operation of the scheme. The interference pattern is formed on the sensitive section of the photodetector. The sum of the wave reflected from the interferometer mirror and phase modulated wave reflected from the sample surface is considered. The reflected wave phase modulation arises as a result of the sample surface shift under the effect of SAW (see Fig. 2). The optical beam width is significantly greater than the SAW wavelength, but the photodetector diameter is smaller than the optical beam width registering only some portion of its radiation.

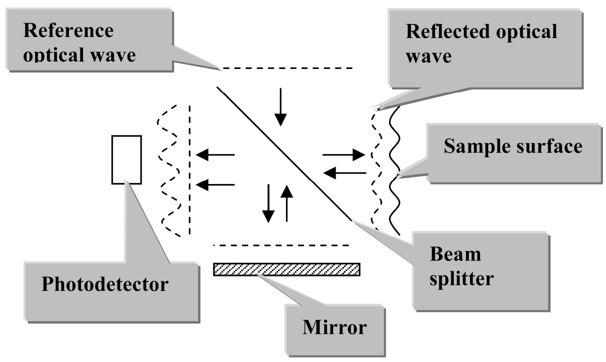

Fig. 2. Schematic of a Michelson interferometer.

Spatial distribution of the phase of the reflected optical wave near the sample surface has the same period as the SAW length. The same spatial period of the reflected wave phase modulation is assumed to exist near the surface of the photodetector as well. Let us consider the conditions for which this statement is true. The Talbot effect consisting in the reproduction of the image of the grate at some distance from it, when parallel beam of light passes through it, is well known. This distance is equal to the value $2\Delta^2/\lambda$, where λ is the optical wavelength, while Δ is a periodic structure period. The image is also created at a distance Δ^2/λ with the image phase-shifted by half period. It should also be noted that there appear a few images at different distances. This is a near-field diffraction effect. Its emergence is conditioned by $\lambda << \Delta$, as well as by a great number of grate periods. The emergence of the image is caused by the regeneration of the optical wave spatial phase field distribution. The width of the optical beam should be large enough since diffraction effects distorting the optical field structure arise when the beam is narrow.

For the wave reflected from the surface of the sample over which the SAW propagates the condition $\lambda << \Lambda$, where Λ is the acoustic wave length, is true. It gives us reasons to expect the spatial phase structure of the optical wave reflected from the surface over which the SAW propagates to be regenerated at some distance.

In order to make sure the numerical simulation for determining spatial phase distribution of the reflected optical wave was carried out. The simulation was performed with the help of Huygens–Fresnel's principle, Gauss distribution of the amplitude of electromagnetic wave electric field on the sample surface

$$E(x_1) = \frac{1}{b\sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2b^2}} , \qquad (1)$$

where x_0 is optical beam centre coordinate, b is distribution parameter.

The shift of the sample surface under the SAW effect at a certain period of time was preset by the expression:

$$y = h \sin\left(\frac{2\pi}{\Lambda} x\right), \qquad (2)$$

where y is a coordinate perpendicular to the sample surface; h is the SAW amplitude; Λ is the SAW wavelength.

For determining the phase of the optical wave reflected from the sample surface the following expression was used [5]:

$$E(x_i, y_i) = \frac{k}{2\pi i} \int_{-a}^{a} E(x_j, y_j) \frac{z e^{ikr}}{r^2} dx_j \ , \qquad (3)$$

where $E(x_i)$ is electric field stress of electromagnetic wave on the surface in the spot with coordinate x_i; k is wavenumber; z is distance from the sample surface to the surface on which the electromagnetic wave amplitude is calculated; r is distance from the area of the sample surface to the surface area on which the electromagnetic wave amplitude is calculated; $2a$ is size of the sample surface over which the integration is carried out. With the help of expression (3) spatial distribution of the change of the optical wave phase, owing to the shift of the sample surface, is found. That is, spatial distribution of β value is calculated

$$\beta = \beta_{saw} - \beta_0 \ , \qquad (4)$$

where β_{saw} is the phase of the optical wave reflected from the sample surface at the presence of the acoustic surface wave; β_0 is phase of the optical wave reflected from the sample surface in the absence of the acoustic surface wave.

In the calculations the SAW amplitude was taken to be equal to 1 nm, optical wave length – 0.5 μm, distribution parameter in expression (1) b = 0.7 mm. Spatial distribution of the change of phase δ, obtained from numeric calculations is shown in Fig. 3. The diagrams for different SAW wavelengths are given. From the diagrams obtained one can see that the change of the wave phase due to surface deformation will be restored in the phase of the reflected wave at some distance from the sample surface. A distinct periodic structure of the optical field phase change is observed at a distance Λ^2/λ, which corresponds to the same distance for the Talbot effect. Numeric calculations show that phase change distribution at distance Λ^2/λ and distance $2\Lambda^2/\lambda$ are shifted by a half-period that also corresponds to the same quality of the Talbot effect.

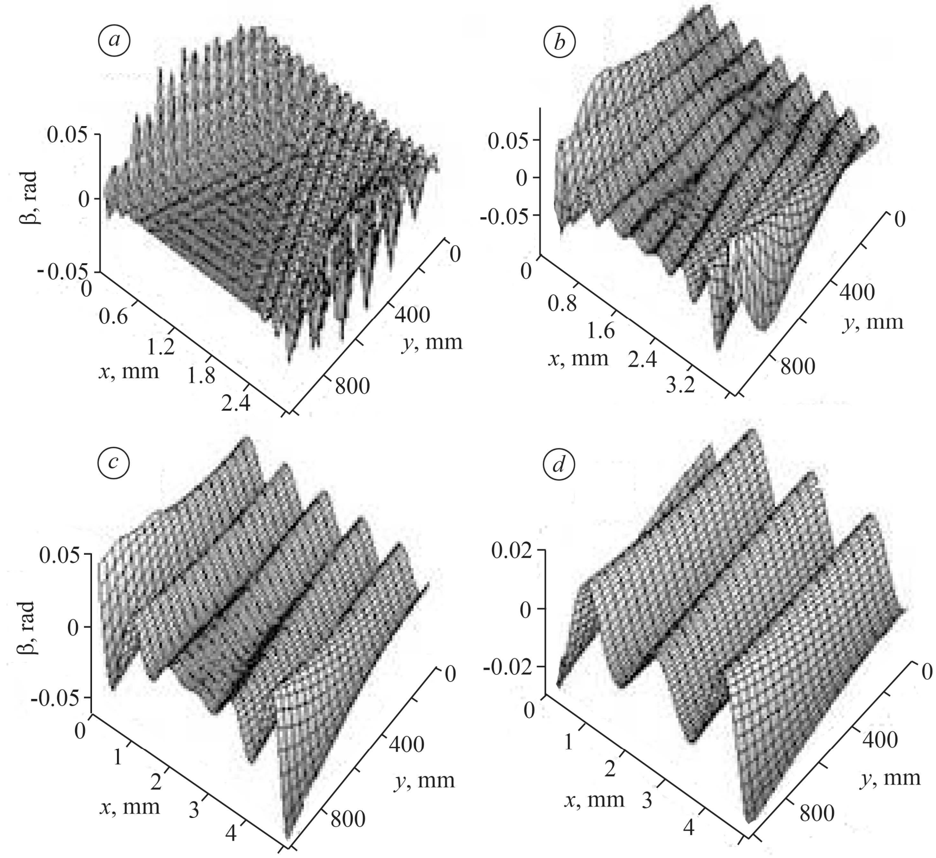

Fig. 3. Space distribution of the reflected wave shift phase:
a – Λ = 0.2 mm; *b* – Λ = 0.5 mm; *c* – Λ = 1.0 mm; *d* – Λ = 1.5 mm.

Numeric calculations show that for each SAW length there exists some distance beginning from which the phase change has no spatial periodic structure. With SAW wavelength equal to 0.2 mm periodic phase change will be observed at a distance not greater than 300 mm from the sample surface (Fig. 3*a*). This distance increases with increasing SAW wavelength, and periodic dependence of phase change will be observed at a much greater distance (Fig. 3*b*–*d*). When the SAW wavelength decreases the value of Λ^2/λ becomes small; the area, where periodic structure of optical wave phase change is observed, becomes smaller as well. That is why we can assume that periodic structure of the reflected optical wave corresponding to the shift of the sample surface can be obtained for the SAW wavelengths over 0.1 mm.

Thus, on the basis of numeric calculations it can be concluded that at some distances from the surface spatial periodic structure of the optical field phase change with the period equal to the SAW length, is observed. This fact is used in the stabilized scheme of SAW registration and correspondingly the analysis of this scheme is based on it.

Analytical analysis of the SAW detecting scheme. We assume that SAW is a plane wave. As we have already mentioned we assume that spatial phase distribution in the photodetector plane corresponds to the sample surface shift. We also assume that optical beam width is greater than several SAW wavelengths that corresponds to the given numeric analysis.

Light intensity in interference is determined by expression [6]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \ , \tag{5}$$

where I_1 and I_2 are interfering beam intensity; δ is phase difference between these beams. Expression (5) describes spatial distribution of the interference pattern intensity in the case when phase shift and intensities I_1 and I_2 in its each area are preset. We assume that the intensity of interfering beams is constant at each spot of the interfering pattern.

Phase difference in the Michelson interferometer is formed due to several mechanisms: path difference *d*, the angle between rays that form a periodic interference pattern, shift of the sample surface under the effect of SAW by amplitude *h*, frequency ω and wavelength Λ. Thus, expression (5) describing the intensity of the interference pattern at each spot can be written as [3]:

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

Let us expand expression (6) into Taylor series and reject summands with a degree higher than one by *h* because of their being very small since the value of *h* is much smaller than λ:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\left\{\cos\left(\frac{4\pi d}{\lambda} + \frac{2\pi x}{L}\right) + \frac{4\pi h}{\lambda}\sin\left(\frac{4\pi d}{\lambda} + \frac{2\pi x}{L}\right)\sin\left(\frac{2\pi x}{\Lambda} + \omega t\right)\right\}. \tag{7}$$

The intensity of the interference pattern consists of two parts, one of which being unchanged with time while the other changes with time. Later on we will consider only the part of this expression $I_{\approx}$ that changes with time, since it is this part that determines the signal which is the informative signal during the SAW registration.

$$I_{\approx} = 8\sqrt{I_1 I_2}\,\frac{\pi h}{\lambda}\sin\left(\frac{4\pi d}{\lambda} + \frac{2\pi x}{L}\right)\sin\left(\frac{2\pi x}{\Lambda} + \omega t\right). \tag{8}$$

Photocurrent is proportional to the total intensity of the light obtained on the sensitive area of the photodetector. Let's assume the width of the optical beam be considerably larger than the width of the sensitive area of the photodetector *r*. For the changing part of the photocurrent we can write down:

$$i_{\approx} = \frac{g}{r}\int_{-r/2}^{r/2} I_{\approx}\,dx\,, \tag{9}$$

where $i_{\approx}$ is changing constituent of photocurrent; *g* is proportionality factor; *r* is width of the sensitive part of the photodetector. With the *r* increase the total capacity on the photodetector increases and, correspondingly, the signal from the photodetector grows as well. Therefore it is necessary to introduce multiplier *l*/*r* for sensitivity rating. Even spatial distribution of light intensity over the beam section is adopted.

After integration we get the expression:

$$\begin{aligned} i_{\approx} = {} & 4\frac{g}{r}\sqrt{I_1 I_2}\,\frac{hL\Lambda}{\lambda(\Lambda - L)}\sin\left(r\left(\frac{\pi}{L} - \frac{\pi}{\Lambda}\right)\right)\cos\left(\frac{4\pi d}{\lambda} - \omega t\right) - \\ & -4\frac{g}{r}\sqrt{I_1 I_2}\,\frac{hL\Lambda}{\lambda(L + \Lambda)}\sin\left(r\left(\frac{\pi}{L} + \frac{\pi}{\Lambda}\right)\right)\cos\left(\frac{4\pi d}{\lambda} + \omega t\right). \end{aligned} \tag{10}$$

Expression (10) shows the dependence of photocurrent on the relation of optical scheme parameters, optical wavelength λ and the SAW wavelength Λ. The major importance for our case is the dependence of the value of photocurrent on the value of path difference *d* and photodetector width *r*.

First of all, the characteristic of the traditional scheme of the SAW detection is worth examining [1]. Geometry is used in it when the width of the interference fringe is very large, while the width of the sensitive area of the photodetector is considerably smaller than the SAW wavelength. Having assumed that the width of the interference fringe is equal to infinity, expression (10) can be reduced to the following form:

$$i_{\approx} = 8\frac{g}{r}\sqrt{I_1 I_2}\,\frac{h\Lambda}{\lambda}\sin\left(\frac{r\pi}{\Lambda}\right)\sin\left(\frac{4\pi d}{\lambda}\right)\sin\left(\omega t\right). \tag{11}$$

It is seen from the equation that the current will be equal to zero when the path difference is equal to $d = \lambda N/4$. Then the phase difference between the interferometer rays will be equal to πN. This causes some difficulties with the acoustic waves detection using Michelson interferometer, since slight vibrations can lead to the change of the path difference sufficient for the scheme sensitivity to become equal to zero. In order to eliminate this effect we suggest a stabilized scheme with the angle between the interfering beams [4].

It can be concluded from expression (11) that there is some effect of the width r on the scheme sensitivity. With the substitution $r\pi/\Lambda = v$ this expression can be written as follows:

$$i_{\approx} = 8g\pi\sqrt{I_1 I_2}\,\frac{h}{\lambda}\frac{\sin(v)}{v}\sin\left(\frac{4\pi d}{\lambda}\right)\sin(\omega t)\ . \tag{12}$$

Multiplier $\sin(v)/v$ will determine the dependence of sensitivity on the width of the part of optical beam getting on the photodetector. Thus, maximum sensitivity will be for small values of r. It also proceeds from (12) that photocurrent will be equal to zero for the values of r determined from the condition:

$$\sin\frac{r\pi}{\Lambda} = 0\ . \tag{13}$$

The width of the optical beam in this case has to be commensurable with the SAW wavelength. On the other hand, it results from expression (12) that SAW can be registered with the help of beams wider than Λ, but the signal from the photodetector will be much smaller than in the case of beams with low values of r.

Let us consider a more common case when the interference pattern is a periodic system of interference fringe, caused by the existence of the angle between the interfering beams. The case when the interference fringe width is commensurable with the SAW length is of special interest. To analyze such a situation it is necessary to come back to the analysis of expression (10). This expression allows us to find conditions under which the sensitivity will not depend on the change of path difference d and thus the detection scheme will be stabilized. From the way expression (10) looks one can conclude that d will not affect sensitivity in case one of the summands is equal to zero. In this case the other summand will determine the value of the signal from the photodetetor. The change of the path difference will result only in the change of the signal phase leaving the signal amplitude of the signal unchanged. Thus, we can name two sets of r values with which the scheme will be stabilized in regard to vibrations. These values are preset by the expressions:

$$\begin{gathered}\sin\left(r\left(\frac{\pi}{L}-\frac{\pi}{\Lambda}\right)\right)=0,\\ \sin\left(r\left(\frac{\pi}{L}+\frac{\pi}{\Lambda}\right)\right)=0\ .\end{gathered} \tag{14}$$

Besides, one more condition of the detecting scheme to be stable to vibrations resulting from the condition when one summand is much greater than the other, can be named. The first summand of expression (10) has multiplier:

$$\frac{L\Lambda}{r(\Lambda - L)}\sin\left(r\left(\frac{\pi}{L}-\frac{\pi}{\Lambda}\right)\right)=\frac{\sin\left(r\pi\left(\frac{\Lambda - L}{L\Lambda}\right)\right)}{\frac{r(\Lambda - L)}{L\Lambda}}. \quad (15)$$

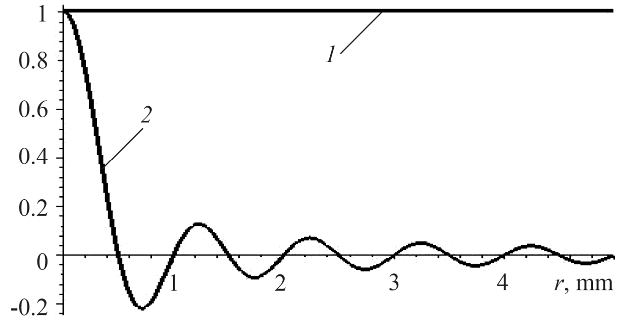

Fig. 4. The amplitudes of two summands of expression (10) versus the width of the photodetector *r* ($L = \Lambda = 1$ mm): *1* – angent; *2* – addend.

Expression (15) adopts maximum value when $L = \Lambda$, while r can adopt any values. Thus, when $L = \Lambda$ the value of the expression does not depend on *r*. On the other hand, the second summand of expression (10) has multiplier *l*/*r* and decreases with the increase of *r*. Fig. 4 shows the dependence of the amplitudes values of these two summands on *r*. In the calculations we assume that $L = \Lambda = 1$ mm. It is clear that as *r* increases the value of the second summand considerably decreases in regard to the first one. The contribution of the second summand is insignificant at rather high values of *r* allowing us to state that the scheme is stable to vibrations.

CONCLUSION

The scheme of the SAW detection built on the basis of Michelson interferometer has been examined. The characteristic feature of the scheme is the existence of some angle between the interfering beams as well as the fact that the size of the beam is larger than the SAW wave length. Conditions under which this scheme will be stable to vibrations have been found with the help of numeric simulation and analytical examination. The stabilization is possible in two cases. The first one corresponds to certain width of the optical beam determined by the SAW wavelength and the interference fringe width. The other case is observed under the condition of equal value of the SAW wavelength and interference beam width under the condition the width of the optical beam is larger than the SAW wavelength.

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