Beam distortion detection technique for picosecond ultrasonics

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Abstract. Beam distortion detection (BDD) technique was successfully used for the detection of picosecond longitudinal and shear acoustic pulses in micrometric metallic layers. It is optimised for the measurement of the displacement pulse shape. In this communication the application of BDD for the evaluation of displacement acoustic echoes in 250 nm tungsten film is presented. The reflectivity term has been removed from photoacoustic signal by the introduction of reference channel in the differential photodetection. The result of test experiment with W film has shown promising ability of BDD technique for the surface displacement detection without interferometry and deflectometry.

1. Introduction
Picosecond ultrasonics is a rather popular technique for numerous tasks of solid state physics and microelectronics. Low-energy laser pulses available from commercial femtosecond systems produce very small deformation of the surfaces. For this reason the elaboration of a sensitive non-contact method for the detection of short acoustic pulses is an important task for picosecond ultrasonics. Different methods have been developed for this purpose since pioneering works in this area [1,2,3]. These methods are applied in the frame of well known pump-probe experimental set-up. In this set-up the pump pulse excites local deformation on the surface of the sample. Afterwards an optically delayed probe pulse reflects from the area of the deformation to provide the information about displacement or strain. The methods of reflectivity detection [3], interferometry [4] and deflectometry [1,2] are usually used for optical detection. Meanwhile, all these methods are not desirable in several tasks of picosecond ultrasonics related to sharp focusing of the beams into the spots ~1 μm. Sharp focusing is demanded when the diffraction of picosecond acoustic pulse in micrometric metallic layers is expected [5]. For this reason, BDD technique was proposed for the goals of picosecond ultrasonics [6]. The technique relies on the detection of a change of the beam wavefront due to acoustically induced curvature of the surface. This technique is sensitive, simple and stable. It does not demand any stabilization system to detect surface displacement. It works very well when photoelastic coefficients of the material are low enough to prevent the superposition of terms related to BDD and reflectivity. This superposition was observed in the materials with short wavelength of photoinduced acoustic pulse [6]. In this communication the optimization of BDD technique allowing to obtain displacement acoustic echoes in the materials such as tungsten is proposed.
2. Method of sound detection

For the description of BDD method, gaussian curvature of the surface of the sample induced by absorption of pump radiation is assumed. Pump and probe beams pass through the same objective to be focused on the surface of the sample with spots of radius $a_{p0}$ and $a_0$, respectively. Reflected beam of the probe passes back through the same objective and it falls on an iris diaphragm of variable radius $a_d$ (Fig.1).

The beam after the diaphragm is focused on the surface of a photodiode by a lens. The local curvature of the surface changes the angle of divergence of the reflected probe beam, and its radius $a$ after the objective. The probe beam power after the diaphragm varies according to this change of radius $a$.

Basic relations describing the variation of probe beam radius in the frame of paraxial approximation of diffraction [7] are obtained in [6]. Resulting formula for relative reflectivity change for the case of small enough radius of the diaphragm is:

$$\frac{\Delta R_d}{R} = \Delta R_{i} + \frac{\Delta R_{r}}{R},$$

where $\Delta R_{i} = \text{Re}(\Delta R_{0}/R)$, $\Delta R_{r} = \text{Im}(\Delta R_{0}/R)$ and $\Delta R_{d} = 4k_0\gamma_0\chi U_0$. The last expression is related to the displacement of surface at the epicentre of the deformation ($U_0$), wavevector modulus of probe beam ($k_0$), position of the sample surface ($z_0$), the diffraction length ($z_d$), $\gamma_0 = z_0/z_d$, $\chi = (a_0/a_{p0})^3$. Expressions $\Delta R_{r}/R$ and $\Delta R_{i}/R$ are related to the relative reflectivity change $\Delta R_{0}/R$ without the diaphragm. It should be mentioned that $\Delta R/R$ is observable by interferometric technique only. The real part of (1) corresponds to the signal provided by reflectivity measurements with a diaphragm. The term $\Delta R_{i}/R$ is related to strain [4]. To be sensitive only to the displacement of the surface it is necessary to satisfy the relation $\Delta R_{d} >> \Delta R_{r}$. It is easy to achieve this condition when the typical wavelength of sound $\Lambda$ is significantly larger than the probe light penetration depth $\xi$. In case signal $\Delta R_{i}/R$ is negligibly small due to the boundary condition for the strain $\eta$ at free surface. Otherwise, the superposition of terms due to strain and displacement appears. The ratio of BDD to the signal of reflectivity change is:

$$\frac{\Delta R}{\Delta R_{0}} = \frac{\partial \kappa_m}{\partial \eta}^{-1},$$

where $\partial \kappa_m/\partial \eta$ stands for the maximum value of the photo-elastic coefficients. The superposition has been observed in tungsten [6]. Following parameters of tungsten have been used for the estimation: $\xi \approx 20$ nm, velocity of sound $c_s \approx 5200$ m/s, pulse duration $\tau \approx 10$ ps [8] and $\partial \kappa_m/\partial \eta \approx 5.1$ [9]. They provided typical wavelength of acoustic pulse as $\Lambda \approx 50$ nm which is of the same order as light penetration depth $\xi$. Taking $\gamma_0 \approx 0.25$ and $\chi \approx 1$ for the estimation we obtain $\Delta R_{d}/\Delta R_{r} \approx 1$ from (2). The last result shows that...
BDD and reflectivity signals are of the same order in tungsten. For this reason, the superposition of terms of displacement and strain is important in tungsten.

3. Experimental set-up

In this section the modification of BDD technique for the drastic reduction of signals superposition in BDD method is described. The radiation of a Ti:Sapphire femtosecond laser was split into the beams of pump and probe (Fig. 2). The pump beam passed through an acousto-optical modulator (~300kHz) to provide the reference signal for Lock-In amplification. To reduce the beam waist in the focus, the pump radiation was doubled in a BBO crystal. Radiation of probe at 795 nm passed through an optical delay line operating in the range 0-6ns. Parallel beams of pump and probe were axially coincident on the input of a 100x microscope objective focusing them normally to the surface of the sample. Ultra-short acoustic pulses were generated and detected in ~250 nm tungsten film on Si substrate. The RMS roughness of the film has been measured by an AFM technique at ~1nm.

Mentioned improvement concerns the photo-detection part of the set-up (Fig. 2, dashed square). The probe beam was divided by a beamsplitter into two parts of approximately the same power to be detected by two-channel differential photodetector. Iris diaphragm (aperture in the range 0.2-16mm) was introduced in one way (Channel 1) to be sensitive to BDD signal. The power of second part (Channel 2) was reduced by a variable optical attenuator to have zero DC output of photodetector. This output was fed to a Lock-In amplifier.

4. Experimental results

Using the experimental set-up, described in the previous paragraph, test experiments with 250 nm thick tungsten film have been performed. First, the beam in the channel 1 was closed to obtain signal of reflectivity variation (Fig. 3 (1)). Corresponding shape of acoustic pulse is typical for tungsten probed by a light at 795 nm [8].
Second, the signal was detected by channel 1 with closed channel 2 to measure BDD signal without reference. It is clear from Fig. 3 (2) that the shape and of this pulse is different from reflectivity signal. Third, the signal was detected with open channel 1 and 2 to have DC output of photodetector about zero Fig. 3 (3). The shape of the pulse detected in third case is practically unipolar with typical duration ~10 ps. Same shape of signal was obtained in this sample of tungsten by interferometric technique [6]. So, the displacement wavefront has been measured in tungsten using BDD technique with differential photodetection.

5. Conclusion
In this communication, the capability of the BDD technique in the detection of displacement has been demonstrated on the materials with short acoustic pulses and large photoelastic coefficients. It allows the application of this technique instead of interferometry in several tasks of picosecond ultrasonics. It could be interesting when long-time scans of picosecond acoustic fields are detected in micrometric metallic layers. Another application of our technique could be the detection of displacement acoustic pulses in objects of micrometric size such as spheres and fibres. The probe beam reflected from curved surfaces of these micro-objects would be distorted. For this reason, the stabilization of interferometric system would be complicated. Meanwhile, the application of BDD technique is possible in case of curved and even irregular surfaces.

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