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On the measurement of surface oscillations using a femtosecond laser

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***Abstract*. The results of experimental measurements of small surface oscillations using a femtosecond laser are presented. It is shown that an increase in the number of spectral components in the radiation leads to a decrease in the minimum detectable amplitude of surface oscillations.**

Keywords: *femtosecond laser, precision measurements, small surface displacements.*

Many applied problems and precision physical experiments employ optical methods that allow detection of small phase variations of optical signals caused by a change in the optical path length due to various reasons. The sensitivity of measurements of small mechanical displacements of the resonator mirror in a stable single-frequency laser was found to be 6×10^{-14} cm on a base of 5 m [1]. The possibilities of measuring small surface displacements induced by a femtosecond laser were analysed in [2] where it was shown that the signal-to-noise ratio could be increased. In this paper study, we present the experimental results confirming this fact.

Let us first explain the principle of measuring surface oscillations using the laser technique. Optical radiation of frequency ω reflected from a surface has three frequency components:

$$E(t) = E\cos\omega t + kaE\sin(\omega - \Omega)t + kaE\sin(\omega + \Omega)t, \quad (1)$$

where Ω and a are the frequency and amplitude surface oscillations; E is the amplitude of the incident wave; $k = \omega/c$; $ka \ll 1$. The spectrum contains two side frequencies $\omega \pm \Omega$ whose amplitudes are proportional to the amplitude of surface oscillations. It can be easily shown that there is no beat signal at frequency Ω in the case of the square-law detection (1). However, in the experiment described here, a voltage at this frequency is induced on the photodetector, which is apparently due to the difference in the phases and amplitudes of the side components (1) appearing during passage of radiation through dispersive and absorbing elements. It is convenient to write the voltage at frequency Ω as the real part of the expression

$$U(t) = U_{\text{sign}}\exp(-\text{i}\Omega t) + U_{\text{noise}}\exp(-\text{i}\Omega t + \text{i}\varphi). \quad (2)$$

Here, U_{sign} is the signal voltage proportional to the amplitude of surface oscillations; U_{noise} is the noise amplitude at the frequency Ω; and φ is the slowly varying random phase. In the experiments, the quantity $P = \langle U(t) \times U^*(t)\rangle$ is detected, where the averaging is performed over the random phase. Since $\langle\exp(\text{i}\varphi)\rangle = 0$, we can write

$$P = U_{\text{sign}}^2 + U_{\text{noise}}^2. \quad (3)$$

Suppose that femtosecond laser radiation consisting of N spectral components is incident on a reflecting surface. The signal at a frequency Ω for each of the N components of the reflected wave is detected by the same photodetector. In this case, the induced voltage at frequency Ω is the sum of the signal components from expression (2):

$$U(t) = \exp(-\text{i}\Omega t)\sum_{n=1}^{N}[U_{\text{sign}} + U_{\text{noise}}\exp(\text{i}\varphi_n)]. \quad (4)$$

We assume that U_{sign} and U_{noise} are independent of N and the phases φ_n are uncorrelated, i.e., $\exp[\text{i}(\varphi_n - \varphi_{n'})] = \delta_{nn'}$. In this case,

$$P = N^2U_{\text{sign}}^2 + NU_{\text{noise}}^2. \quad (5)$$

It follows from this that upon an increase in the number of spectral components, the signal-to-noise ratio increases by a factor of N. In fact, we are dealing with the intensity interferometry whose efficiency in astronomical studies was demonstrated by Brown and Twiss for $N = 2$ [3].

To verify this conclusion, we performed the following experiment. One of the mirrors of a femtosecond laser was glued to a piezoelectric-ceramic plate to which a sinusoidal voltage of frequency Ω was applied. The weakest detectable signal of beats at a frequency Ω was measured as a function of the number N of the spectral components of laser radiation. The radiation power incident on a photodetector was maintained constant so that the signal being detected depended only on N. The amplitude of mechanical vibrations of the mirror was determined from the sensitivity of the piezoelectric ceramic ($\sim 10^{-2}$ μm V^{-1}).

We used a 870-nm, 500-mW femtosecond Ti : sapphire laser emitting 40-fs pulses with a pulse repetition rate of 100 MHz. The laser line full width at half-maximum was

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25 nm ($N \approx 10^5$). The signal at the frequency $\Omega/2\pi =$ 10 kHz was recorded with a Rohde&Schwarz FSP spectrum analyser. The number N could be decreased by using an interference filter. The radiation power incident on the photodetector was maintained constant by means of a neutral optical filter, and the operation regime of the laser, photodetector and spectrum analyser remained the same in this case. To determine the minimum detectable amplitude of mechanical vibrations, the voltage applied to the piezoelectric ceramic was lowered to a value at which the signal could still be detected against the noise background.

For a maximum number N of the spectral components, the minimum signal was detected at a voltage ~ 1 V across the piezoelectric ceramic, corresponding to the amplitude $\sim 10^{-6}$ cm of the mirror oscillations. As the number N was decreased by a factor of 2.5, the voltage across the piezoelectric ceramic was 3 V, while the amplitude of oscillations was $\sim 3 \times 10^{-6}$ cm. Thus, an increase in the number of spectral components by a factor of 2.5 led to a threefold decrease in the minimum detectable amplitude of oscillations, in accordance with the above analysis.

A simple stabilisation of radiation parameters allowed detection of the oscillation amplitude $\sim 10^{-7}$ cm. We did not intend in our experiments to measure small surface displacements with the precision achieved by using stable single-frequency lasers. However, such experiments are planned in the future. Note that the accuracy of measurements can be improved by using femtosecond lasers because the number of spectral components in their radiation can be as high as 10^6 and more. It can also be expected that the use of special optical fibres to broaden the spectrum will increase the number of spectral components by more than an order of magnitude. This will open up wide prospects for increasing the sensitivity of precise measurements of various quantities.

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