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ADAPTIVE PHOTODETECTORS FOR VIBRATION MONITORING

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Abstract: We report on simple high-sensitivity interferometric technique of detecting vibrations and present characteristics of laser vibrometer using GaAs and SnS_2 adaptive photodetectors based on the effect of the non-steady-state photoelectromotive force. It enables efficient direct conversion of high-frequency phase modulation of speckle-like optical wave reflected from the vibrating object into an output electrical signal with concomitant setting of optimal operation point of the interferometer and suppression of amplitude laser noise. The results of measurements of small vibration amplitudes of the mirror and diffusely scattering objects are presented. Preliminary studies at 1.06 mm showed that it is possible to detect ultrasonic vibrations with the amplitude of 0.2 Å with a signal power of 20 mW and a bandwidth of 15.5 MHz. This optical phase-to-electrical signal converter is not sensitive to ambient vibrations, thermal drift, amplitude laser noise and is therefore appropriated for industrial applications.

Keywords: homodyne laser interferometry, optical detection of ultrasound, photorefractive crystals

1 INTRODUCTION

Detection of low-amplitude acoustic vibrations of real (not model) objects, such as ultrasonic transducers, is an important scientific and technique problem. Homodyne laser vibrometers [1] are suitable for practical applications in this regard for their high sensitivity which is limited in principle only by shot-noise of the laser used. These vibrometers allow detection at a distance, with high spatial localization of the measurement region and wide frequency range.

However, their utilization is restrained now by some problems such as slow phase drifts in the interferometer arms due to environmental reasons, necessity of fine optical adjustment and suppression of laser amplitude noise connected with utilization of standard photodiodes for detection of the output optical signals. Conventional interferometric and heterodyne receivers are unable to compensate for workpiece vibrations and wavefront distortions, relative platform motion and local turbulence. Compensated interferometers employing phase conjugation [2] or wave-front matching [3] typically lack the speed-of-response to function in the factory, especially in the case of inspection of rapidly moving components on an assembly line or in case of raster scanning a workpiece.

The basic scheme of the interferometric devices includes two arms: the signal arm, where the phase modulation to be measured is performed, and the reference arm. A conventional beamsplitter is usually used to produce interference between the signal and the reference waves at the photodetector. The measured phase shift is converted here into amplitude modulation of the output light beams, and then to an electrical signal. Let us discuss in more details the mentioned above problems of operation of such interferometric devices. The first problem is the need for precise (with the accuracy of about $\lambda/10$) optical adjustment of the interfering wavefronts. The second problem is the necessity to keep constant the average phase shift between the interfering wavefronts. Indeed, the maximum possible sensitivity of the arrangement is reached in the linear regime of operation when this shift is equal to 90^0. In this case the sinusoidal phase modulation of the input signal beam with the frequency ω is converted into an output electrical signal of the same frequency. If the phase shift is equal to zero or $\pm 180^0$, the operating regime is a quadratic one and the sensitivity for the detection of low-amplitude, high-frequency phase modulation is minimal.

We present the new technique for vibration analysis - utilization of the laser vibrometer using GaAs and SnS_2 adaptive photodetectors based on the effect of the non-steady-state photoelectromotive force (photoEMF) [4-6]. In the first part of the paper we describe the physics of the effect, present typical parameters of the GaAs photodetectors used in the laser vibrometer. In the second part we describe experimental setup and give the results of vibration measurement at different wavelengths

(0.325 µm, 0.63 µm and 1.06 µm). We present the estimation of the vibrometer sensitivity at these wavelengths and discuss noise contributions to the output electrical signal.

2 NON-STEADY-STATE PHOTOEMF EFFECT

The effect of the non-steady-state photoelectromotive force consists of an alternating electric current arising in a short-circuited bulk sample of a photoconductor illuminated by a vibrating sinusoidal pattern. The mechanism responsible for the effect can be described as follows. Illumination of a photoconductive sample by an interference pattern I(x) formed by two coherent light beams produces a nonuniform excitation of free carriers. Diffusion of the photoexcited carriers towards the dark regions leads to a charge redistribution between traps. A space charge field grating $E_{sc}(x)$ arises; this grating is spatially shifted by 90^0 relative to the optical interference pattern and photoconductivity distribution. For the steady-state conditions the current $J = \int\sigma(x)E_{sc}(x) = 0$. Small vibrations of the light pattern along the grating vector excites an alternating current through the short-circuited crystal because of the time-dependent phase shift between oscillating spatially-periodic free carriers and fixed space charge field distributions.

For the standard model of the photocurrent generation (see, for example, [4]), i.e., small contrast of the interference pattern (m<<1), linear generation and recombination of photocarriers and small amplitudes of phase modulation, Δ^{ω}, the output electrical signal from the interferometer could be expressed by the following equation:

$$J^{w} = \frac{m^2}{2} s_0 \frac{K}{1+K^2 L_D^2} \frac{k_B T}{e} \Delta^{w} \frac{-iw/w_0}{1+iw/w_0} \qquad (1)$$

Here σ_0 is the average photoconductivity of the sample, L_D is the diffusion length of photocarriers, k_B is the Boltzman constant, T is the temperature, e is electron charge, and $\omega_0 = \tau_{sc}^{-1}$, where τ_{sc} is the characteristic time of the dynamic space-charge grating relaxation. As follows from equation (1) the output signal of the adaptive interferometer is suppressed at modulation frequencies lower than the characteristic cutoff frequency ω_0 , so the slow phase drifts due to, for example, low-frequency vibrations or temperature variation are efficiently compensated for in the adaptive interferometer [5, 6]. The output electrical signal peaks at spatial frequency equal to the inverse diffusion length of photocarriers L_D which is about 10 µm for GaAs crystals [5] and 1 - 3 µm for photorefractive sillenites $Bi_{12}SiO_{20}$ [6].

Typical frequency transfer function of the photocurrent in semi-insulating GaAs crystal is presented in Fig. 1.

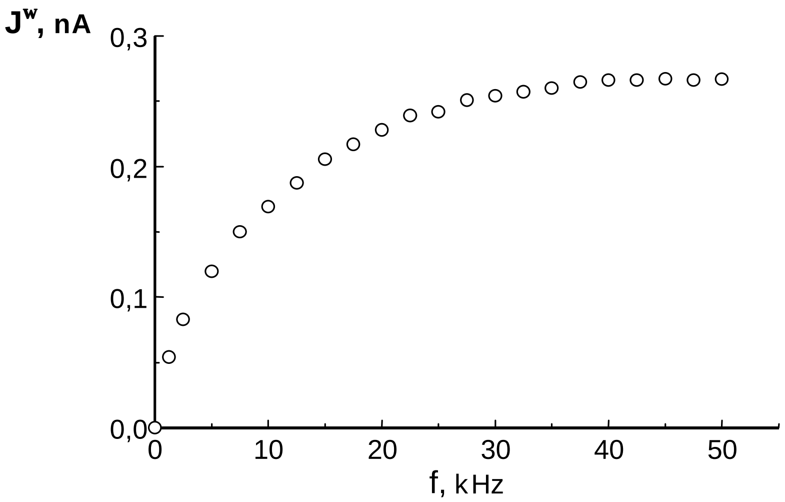

Figure 1. Frequency transfer function of the non-steady-state photocurrent in GaAs:Cr.

The experiment was performed at the wavelength of 0.63 µm, the power of the signal beam was adjusted in the range of 40 µW in order to simulate experimental conditions of the laser vibrometer operation: low power of the signal wave reflected from the diffusely scattering surface. The characteristic cut-off frequency for moderate light powers on photodetector of several mW are in the range form 1 kHz to 100 kHz which is compatible for most industrial applications.

It is important to point out that the photoEMF scheme combines the optical compensation and detection stages as well as electronic post-processing tracking systems into a single semiconductor element. Recall, that the above mentioned real-time holographic compensation schemes require three stages of processing: a spatial compensation element (Phase Conjugate Mirror, Two-Wave Mixing, Double-Pumped Phase Conjugate Mirror) to deal with wavefront distortions, a conventional photodetector to coherently detect the ultrasonic information, and an electronic post-processing tracker system to sense and compensate for global optical-phase noise due to low-frequency whole-body vibrations, temperature variations, etc.

3 EXPERIMENTAL SETUP

The scheme of laser vibrometer using GaAs adaptive photodetector is shown in Fig. 2. We have tested our vibrometer at two wavelengths - 0.63 µm and 1.06 µm. In the first case due to very high absorption coefficient (10^4-10^5 cm^{-1}) the photoEMF signal is excited in a thin layer about 1 micron. At the wavelength of 1.06 µm the crystal is transparent with the absorption coefficient of about 1.5 cm^{-1}.

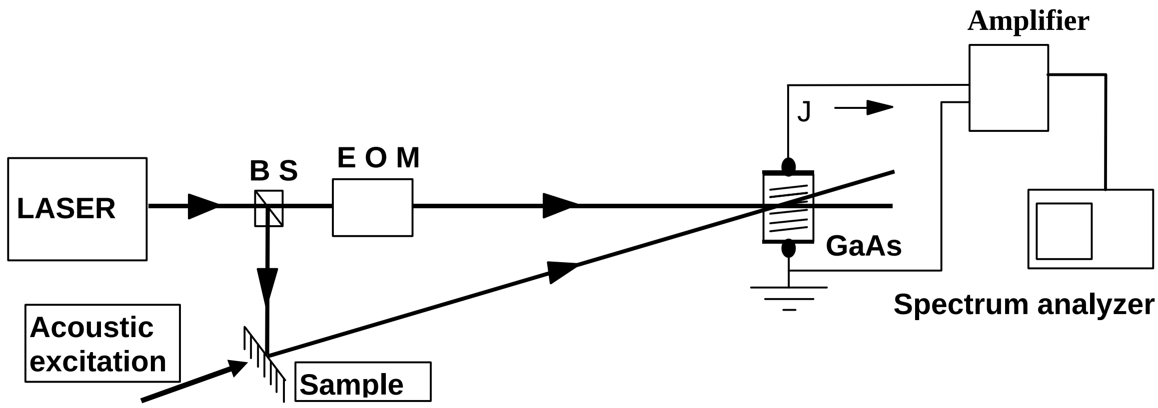

Figure 2. Experimental set-up for the vibration measurement.

The signal beam which is scattered by the rough surface and reference beam which is directly derived from the laser interfere inside the GaAs crystal. The size of an active area of the photodetector was about 1x2x2 mm^3 (5x5x5 mm^3), necessary electrodes were painted by a silver paste. The signal from the crystal was amplified and visualized on the screen of oscilloscope or spectrum analyzer. In the experiments at 0.63 µm the carrier spatial frequency was chosen higher than the inverse size of the speckle spots, so an interference pattern with the spatial frequency 30 lines/mm was formed on every speckle spot. This spatial frequency is an optimal one for observation of non-steady-state photoEMF in a semi-insulating GaAs (which corresponds to the inverse diffusion length of photocarriers). In order to simulate real experimental conditions we set the power of the signal speckle wave equal to 40 µW. The elecrtooptic phase modulator (EOM) in the reference arm was used for calibration of the vibrometers well as for simulation of the low-frequency phase shifts in the interferometer arms. Below we present the results of vibration measurements of piezoceramic plate (thickness 3 mm, diameter 65 mm) in the frequency range 10 Hz- 50 kHz. The experiments were carried out in a setup without any special vibroinsulation. Moreover, additional low-frequency phase modulation at 20 Hz with the amplitude of phase modulation of 2.4 rad (corresponding vibration amplitude of 0.12 µm) was introduced in the interferometer to simulate real experimental conditions (whole-body shifts of the tested object).

As it was shown in our earlier papers [5, 6], the suppression of high-frequency phase-modulated signal (as well as low-frequency jamming signal at Ω) is proportional to the ratio ω_0/ω (ω_0/Ω). It means that adaptive photodetectors based on the effect of the non-steady-state photoEMF allow efficient detection of high-frequency phase-modulated signal in the presence of low-frequency jamming signal with frequency $\Omega < \omega_0$ and amplitude ω_0/Ω rad. For the cut-off frequency ω_0 of 20 kHz of the photodector used the amplitudes of the jamming signal of 10 rad for Ω=2 kHz, 10^2 rad for Ω=200 Hz, and 10^3 rad for Ω = 20 Hz could be efficiently suppressed.

As an example of the practical application of the given laser vibrometer system at 0.63 µm we present the frequency response and of the vibration amplitude of a piezoceramic plate - the component used in piezoelectric actuators and transducers. The plate was in the shape of a disk of diameter 65 mm and thickness 3 mm with silver electrodes deposited on its opposite faces. The absolute amplitude of vibrations were estimated in our experiments in the following way. The output electrical signal J^{ω} is proportional to the product [5, 6]:

$$J^{\omega} \propto J_0(4\pi X/\lambda)J_1(4\pi X/\lambda) \qquad (2)$$

Here $J_n(\Delta)$ is the Bessel function of the order n, and X is the vibration amplitude. So, if the maximum amplitude of the signal can be reached in the experiment, corresponding vibration amplitude can be estimated rather easily: the first maximum of the output signal is observed for vibration amplitudes $X_M \approx \lambda/4\pi = 0.05$ µm.

Fig. 3 presents the dependence of the signal-to-noise ratio dependence on the excitation frequency of piezoceramic plate. The minimum detectable vibration level was approximately 0.1 Å for the signal beam power of 0.04 mW, registration bandwidth of 1 Hz.

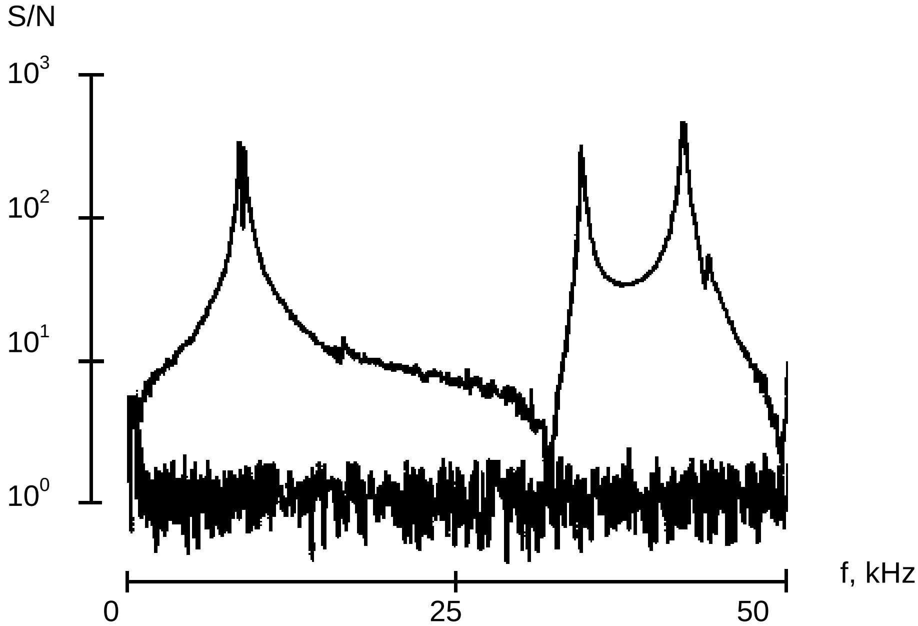

Figure 3. Frequency response of the piezoceramic plate.

Higher sensitivity of the vibrometer was observed at the wavelength of the 1.06 µm. Preliminary studies showed that it is possible to detect ultrasonic vibrations with the amplitude of 0.2 Å with a signal power of 20 mW and a bandwidth of 15.5 MHz. This value corresponds to the detection limit of 5.1 10^{-5} Å for the 1 Hz bandwidth and the signal power of 20 mW.

Theoretically, the signal-to-noise ratio for m <<1, K = L_D^{-1} and for the crystal resistance equal to the load resistance of the amplifier is:

$$\frac{S}{N}=\frac{1}{2\sqrt{2}}\frac{P_S}{\sqrt{P_P}}\sqrt{\frac{a\quad L}{hw\qquad\qquad \Delta f}}\frac{4p}{l}d \qquad (3)$$

here h is the Planck constant, Δf is the frequency bandwidth, δ is the transient surface displacement, P_S is the signal power, P_p is the pump power, L is the crystal length, λ is the laser wavelength. The sensitivity of the device calculated in accordance with (1) for P_S = 20 mW, α L = 1 and the bandwidth of detection Δf = 10 MHz was found to be 0.1 Å.

Recently we have investigated SnS_2 crystals grown by vapor transport method [7]. The size of the sample was 6 x 5 x 0.042 mm^3 . The silver paste electrodes were painted on the front surface 6 x 5 mm^2. We observed the pronounced photocurrent signal in SnS_2 crystal in the ultraviolet and red region of spectrum: the signal-to-noise ratio for the optimal spatial and temporal frequencies was about 50 dB. Here we present vibration measurements of piezoelectric transducer Physik Instumente Model P-840.10 at the wavelength 0.325 µm. The output electrical current was measured using the lock-in voltmeter EG&G Instruments Model 7260 (input resistance R_{in} = 10 MΩ, input capacitance (with cable 10 cm) C_{in} = 50 pF). The capacitance of the investigated PZT transducer was 1.8 µF. In order to ensure the linear response of the transducer up to 75 kHz the sinusoidal voltage from the signal generator was applied to the PZT using voltage divider (R_1 = 20 Ω, R_2 = 1.2 Ω). As the result the excitation voltage amplitude applied to PZT was about 0.14 V. Fig. 4 presents the frequency response of the photocurrent amplitude and vibration amplitude versus excitation frequency. We observed three resonance peaks on the frequency response at 25, 55 and 95 kHz. The transducer has linear response in the following frequency ranges: 570 ÷ 2200 Hz and 3700 ÷ 12000 Hz (non-linearity is less than 20%). The vibration amplitudes drops significantly for the excitation frequencies higher 55 kHz. This fact can be due to the decrease of the applied voltage (the characteristic frequency of the R_2 C_{PZT} circuit is equal to 74 kHz).

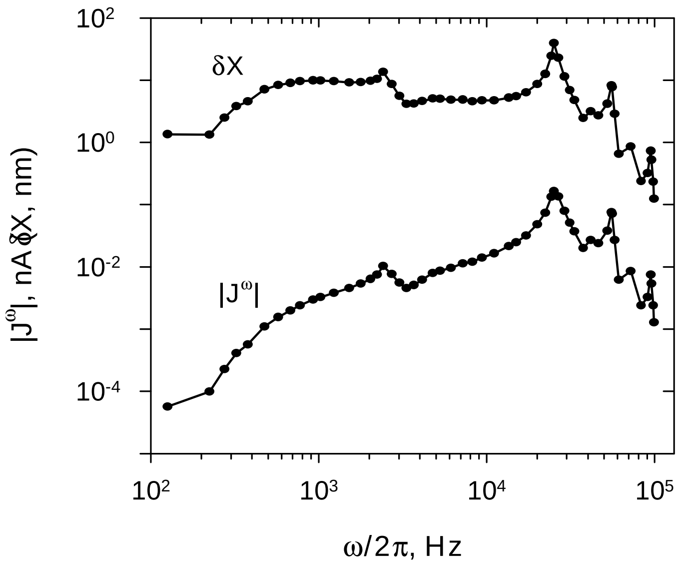

Figure 4. Frequency response of the piezoelectric transducer Physik Instrumente Model P-840.10.

Let us list some specific features of the interferometric receiver under discussion: (1) nearly shot-noise limited surface displacement sensitivity in the Å range with a processing bandwidth of at least 10 MHz at a received power level of ~ 1 mW, (2) the ability to process speckled beams from machined surfaces and (3) the ability to compensate for low-frequency wavefront disturbances resulting from turbulence, workpiece translation and mechanical noise.The use of semiconductors (GaAs, CdTe:V, etc.) in photoEMF-based interferometric systems allows to get very fast grating buildup time. In the case of GaAs, the grating buildup time is on the order of 0.1-10 μs. The fast buildup time allows for compensation of wavefront distortions at bandwidths exceeding 1 MHz. The upper limit on the ultrasonic signal processing bandwidth is determined by the average recombination time of photocarriers, which is about 30 MHz in conventional semi-insulating GaAs. This bandwidth can be extended toward 1 GHz by means of introducing defects to reduce the recombination time.

Further improvement in operation of the adaptive photodetectors under discussion can be achieved using the surface passivation in alcoholic solutions [8]. The sulfide treatment of GaAs in alcohol-based solutions leads to an essential decrease of surface recombination losses compare with the commonly used passivation in aqueous sulfide solutions. With the point of view of the degradation of the properties of sulfidized GaAs such treatment also more promising. We have obtained preliminary results proving that this technique can be directly used for GaAs adaptive photodetectors based on the effect of the non-steady-state photoelectromotive force. The passivation of GaAs surface prevents contacts and surface from degradation and as the result the time of operation of commercial laser-based ultrasonic systems is increased.

4 CONCLUSION

In conclusion, we have reported on simple high-sensitivity interferometric technique of detecting vibrations using GaAs adaptive photodetectors based on the effect of the non-steady-state photoelectromotive force. The technique enables efficient direct conversion of high-frequency phase modulation of speckle-like optical wave reflected from the vibrating object into an output electrical signal with concomitant setting of optimal operation point of the interferometer and suppression of amplitude laser noise. The results of measurements of small vibration amplitudes of the mirror and diffusely scattering objects are presented. Preliminary studies at 1.06 μm showed that it is possible to detect ultrasonic vibrations with the amplitude of 0.2 Å with a signal power of 20 mW and a bandwidth of 15.5 MHz. The sensitivity of GaAs adaptive photodetectors at 0.63 µm was found to be 0.1 Å for excitation frequency 1 kHz, registration bandwidth 1 Hz and average laser power on the photodetector 200 µW. This optical phase-to-electrical signal converter is not sensible to ambient vibrations, thermal drift, amplitude laser noise and is therefore appropriated for industrial applications.

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