Measuring vibration amplitudes in the picometer range using moving light gratings in photoconductive GaAs:Cr

S. I. Stepanov, I. A. Sokolov, and G. S. Trofimov

A. F. Ioffe Physico-Technical Institute, Leningrad 194021, USSR

V. I. Vlad, D. Popa, and I. Apostol

Institute of Atomic Physics, Bucharest R-76900, Romania

Received December 27, 1989; accepted June 27, 1990; manuscript in hand July 27, 1990

We report the measurements of picometer vibration amplitudes produced by a piezo mirror in an interferometric setup, using a GaAs:Cr photoconductive device. The moving light fringes (gratings) induce in this new detector periodic photocurrents characterized by efficient suppression of the low-frequency drifts of the working point and low sensitivity to the amplitude laser noise. The optimum operation conditions of this system are also shown.

Dynamic holographic recording in semi-insulating GaAs:Cr has recently been reported.[1,2] Efficient phase conjugation in four-wave mixing geometries employing this photorefractive crystal, using the moving-grating technique or application of alternating electric fields, was observed.[3,4] Formation of dynamic space-charge gratings in GaAs:Cr was also investigated by means of a non-steady-state photoelectric current.[5] This new effect consists in generation of an alternating electric current through a short-circuited sample of the crystal illuminated by a vibrating interference pattern.[6,7] Recently[8,9] we investigated the high-pass frequency-transfer function of GaAs:Cr in this geometry and its use for measuring mechanical vibrations.

In this Letter we report the measurements of vibrations in the picometer range made with a similar GaAs:Cr device. Working only in conditions of holographic mechanical isolation, we developed an efficient and simple technique for measuring vibration amplitudes in a range that usually demands sophisticated optomechanical equipment.[10–16]

The experimental setup is shown in Fig. 1. The vibrating interference light pattern was produced by two beams derived from a cw He–Ne laser ($P_0 = 5$ mW, $\lambda = 633$ nm, polarization orthogonal to the plane of incidence), one of them after a reflection from piezo mirror M2. The average light intensity on the sample was $\sim I_0 = 1$ mW/mm^2. The grating spacing, Λ, was controlled by the angle of incidence, θ [$\Lambda = \lambda/2\sin(\theta/2)$].

The crystal (4 mm × 4 mm × 1 mm in size) was cut perpendicularly to the [100] crystallographic axis and polished to optical quality. A pair of stripe electrodes parallel to the [010] crystallographic axis was deposited upon its front surface with an interelectrode separation $d = 1.5$ mm. The interference fringes were imaged onto the detector nearly parallel to the electrodes. A sinusoidal voltage with an amplitude U_g and a frequency f was applied to the piezo mirror. The first harmonic of the electrical signal with frequency f from load resistor R_L was selectively amplified and measured.

The frequency response of this system (Fig. 2) shows a high-pass characteristic with the maximum output at $\Lambda^{-1} = \Lambda_{0M}{}^{-1} = 15$ mm^{-1}. These experimental results are in good agreement with theory.[6,7] Indeed, for small vibration amplitudes, $A \ll \lambda/2\pi$ and $\Lambda \ll d$, the output amplitude varies as

$$U_{SO} \propto I_0 A m^2 \frac{f/f_0}{(1 + f^2/f_0{}^2)^{1/2}}, \quad (1)$$

where I_0 is the laser power density, m is the fringe contrast, and f_0 is the cutoff frequency, given by

$$f_0 = [2\pi\tau_M(1 + 4\pi^2 L_D{}^2/\Lambda^2)]^{-1} = [2\pi\tau_M(1 + \Lambda_{0M}{}^2/\Lambda^2)]^{-1}, \quad (2)$$

where τ_M is the Maxwell relaxation time determined by the average photoconductivity of the crystal and L_D is the diffusion length of photocarriers.

Equation (2) provides a reasonable fit to the experimental data for $\tau_M = 80$ μsec and the diffusion length $L_D = \Lambda_{0M}/2\pi = 10.6$ μm. This confirms the experimental results obtained earlier for τ_M and L_D.[1,4]

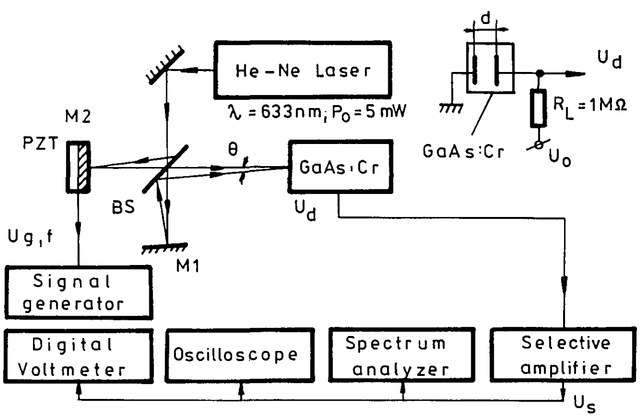

Fig. 1. Interferometric geometry of a GaAs:Cr photodetector: M1, M2, mirrors; BS, beam splitter; PZT, piezoceramic transducer; R_L, load resistor.

0146-9592/90/211239-03$2.00/0

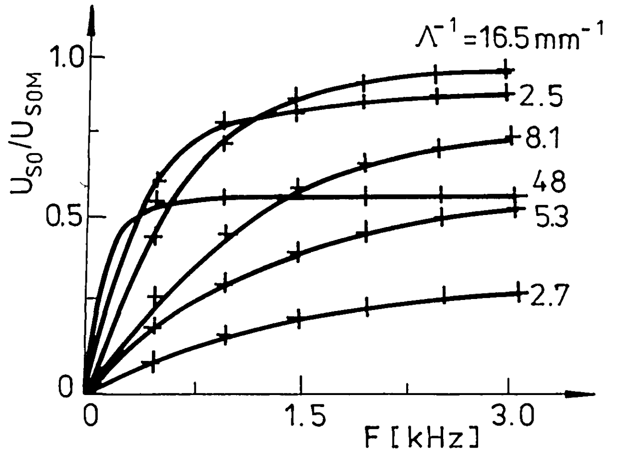

Fig. 2. Normalized signal amplitude (first harmonic) as a function of the vibration frequency f for different fringe spacings Λ. U_{SOM}, maximum value of the signal U_{SO}, obtained for optimal working conditions. The solid curves show the theoretical calculations (λ = 633 nm, U_g = 70 V, U_0 = 0 V, τ_M = 80 μsec, L_D = 10.6 μm, $\mu\tau = 4.6 \times 10^{-5}$ mm^2/V, T = 300 K).

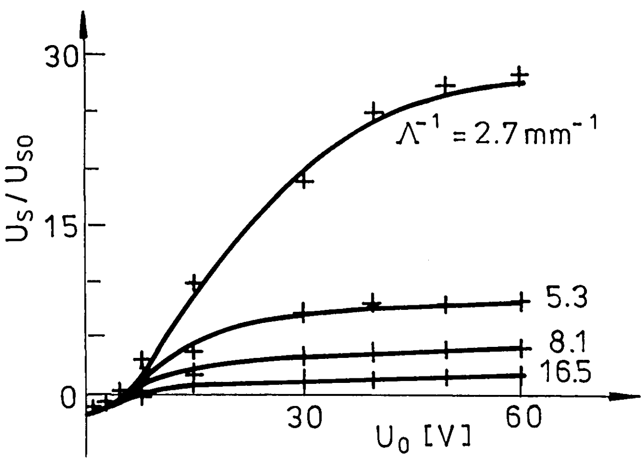

Fig. 3. Dependence of the amplification ratio U_S/U_{SO} on the external voltage U_0. U_S is the signal in the presence of the external field, and U_{SO} is the signal in the absence of the field. The solid curves show theoretical calculations (λ = 633 nm, f = 1 kHz, U_g = 10 V, L_D = 10.6 μm, $\mu\tau = 4.6 \times 10^{-5}$ cm^2/V, T = 300 K).

When an external dc voltage, U_0, is applied to the crystal, theory[7] also predicts a remarkable increase of the first harmonic of the output signal and the appearance of the second harmonic (at a frequency $2f$) with a comparable amplitude. The experimental dependence of the first-harmonic amplitude (at 1 kHz) on U_0 is shown in Fig. 3 for different fringe spacing Λ. The best fit of the theoretical expression for the first harmonic of the output signal (assuming a negligible saturation of impurity traps), when an external dc field

$$\frac{U_S}{U_{SO}} = \frac{2\pi\mu\tau[1 + (\Lambda_0\Lambda)^2]\{[1 + (\Lambda_0/\Lambda)^2](\Lambda_0{}^2/2\pi\mu\tau\Lambda) - (2\pi/\Lambda)\mu\tau E_0{}^2\}}{(\Lambda_0{}^2/\Lambda)\{[1 + (\Lambda_0/\Lambda^2)]^2 + (4\pi^2/\Lambda^2)\mu^2\tau^2E_0{}^2\}} \quad (3)$$

is applied to our experimental data, is reached for $\mu\tau = 4.6 \times 10^{-5}$ cm^2/V.[7,9] This value is close to 4.0×10^{-5} cm^2/V obtained from Einstein's relation ($L_D{}^2 = D\tau = \mu\tau k_BT/e$) and the diffusion length L_D given above. Note that in Eq. (3), U_{SO} is the signal in the absence of the external voltage $U_0 = E_0d$, μ is the mobility, and τ is the recombination time of photocarriers.

The curves obtained for different fringe spacings demonstrate a remarkable growth of signal amplitude with increasing external voltage. The absence of decay in these curves at high external voltages confirms our assumption of quasi-neutrality (i.e., nonsaturation of the traps). One can also see that the signal maximum also moves toward lower fringe frequencies with growing U_0 (Fig. 4). However, the output signal is limited by the condition that the fringe spacing should be much smaller than the interelectrode separation (d = 1.5 mm in our case). The position of this maximum for high external voltages can be deduced from Eq. (3):

$$\Lambda_M = 2\pi\mu\tau E_0. \quad (4)$$

The best fit of our experimental results (with ≤3% errors for U_0 > 10 V) was obtained by using the relation $\Lambda_M{}^{-1}$ (mm^{-1}) = 35/U_0 (V). This relation agrees with Eq. (4) to a factor of 1.75.

It was also found that in the intensity range of 10^{-2}–1 mW/mm^2 the signal amplitude (at 1 kHz) exhibits a linear dependence on the light intensity and grows quadratically with the fringe contrast up to $m = 1$, as is expected from relation (1).

The linear dependence of the first harmonic of the output signal on the vibration amplitude was experimentally observed at low excitation voltages of the piezo mirror, U_g < 20 V (Fig. 5).

The theoretical results of Ref. 7 predict that the output signal amplitude U_{SO} is given by

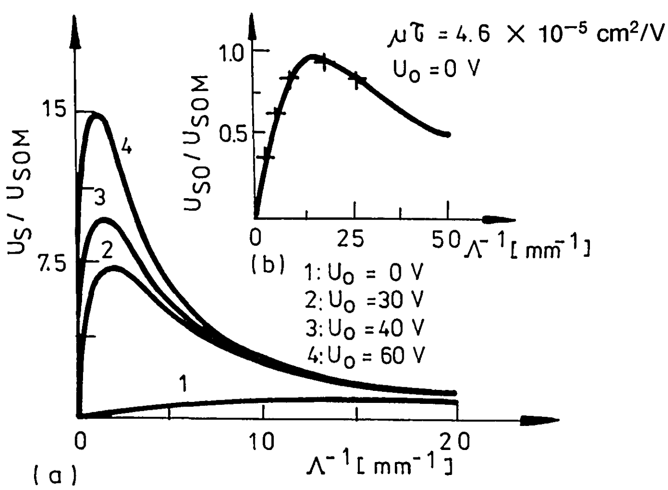

Fig. 4. (a) Dependence of the absolute amplification ratio U_S/U_{SOM} on fringe frequency Λ^{-1}. (b) Normalized response of the device for U_0 = 0 V on the fringe frequency Λ^{-1} (λ = 633 nm, f = 1 kHz, U_g = 10 V, L_D = 10.6 m, $\mu\tau = 4.6 \times 10^{-5}$ cm^2/V).

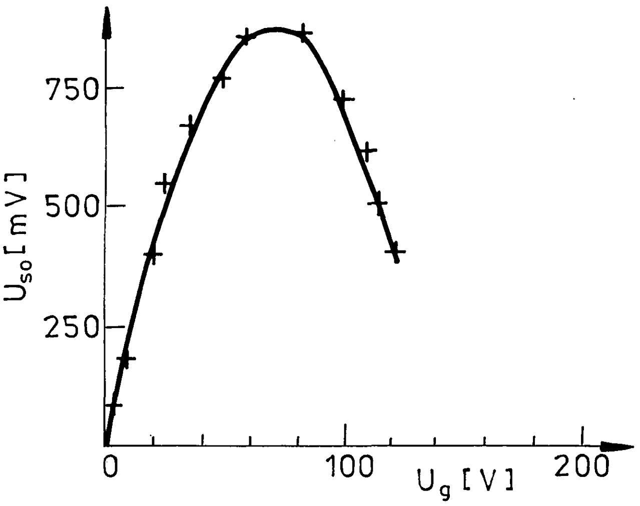

Fig. 5. Experimental dependence of the signal amplitude U_{SO} (first harmonic) on the piezo mirror excitation voltage U_g ($\lambda = 633$ nm, $f = 1$ kHz, $U_0 = 0$ V, $\Lambda^{-1} = 15$ mm^{-1}).

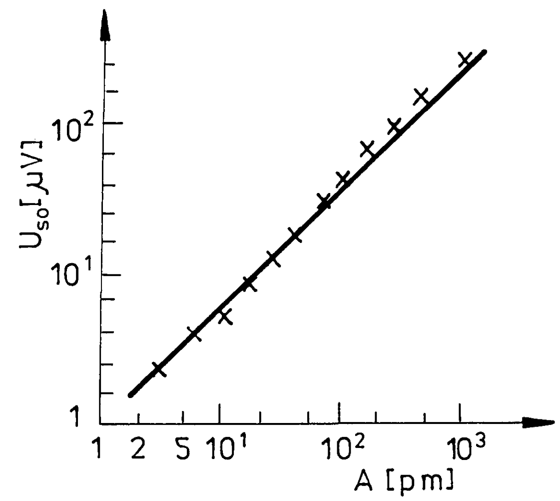

Fig. 6. Experimental measurements of small vibration amplitudes, A. The data were calibrated by the self-calibration procedure.

$$U_{SO} = k_1 J_0(2\pi A/\lambda) J_1(2\pi A/\lambda), \tag{5}$$

where J_0 and J_1 are Bessel functions.

The first maximum of the output signal is obtained for $A_M \simeq \lambda/2\pi \simeq 0.1$ μm. In our experiments this maximum was obtained for an excitation voltage of the piezo mirror, $U_{gM} = 70$ V.

For vibration amplitudes $A < 0.2$ μm, the linear dependence $A = k_2 U_g$ holds both theoretically and experimentally. (This was verified also by another interferometric method.) Then $k_2 = (A_M/U_{gM}) = 1.43 \times 10^{-3}$ μm/V.

In the range of small vibration amplitudes, $A < 30$ nm, where Eq. (5) becomes linear, $U_{SO} = k_1(\pi A/\lambda)$. The following self-calibration procedure is valid: for an arbitrary excitation voltage, U_{g1} (<20 V), the output signal amplitude $(U_{SO})_1$ is measured; a vibration amplitude $A_1 = k_2 U_{g1}$ corresponds to U_{g1} so that $k_1 = (\lambda/\pi)(U_{SO})_1/A_1$ can be found. In our case, $k_1 = 2.785$ μV.

The high cutoff frequency of GaAs:Cr makes this device insensitive to low-frequency noise. As was shown,[14] all major noise sources are several orders of magnitude less important in the vicinity of 1 kHz than at low frequencies. Thus the frequency response fortunately matches this frequency range, in which such small vibration amplitudes are usually measured.[14]

We emphasize that this type of laser vibrometer can also operate with irregular interferometric patterns, in particular, with specklelike signal beams produced, for example, by a diffusely reflecting object. Experimentally we have measured vibration amplitudes as small as $A = 100$ pm for such objects.

To summarize, we have demonstrated the interferometric measurements of picometer vibration amplitudes, using dynamic light gratings in semi-insulating GaAs:Cr. For the optimum regime of operation, the new technique described here is simpler than the conventional homodyne or heterodyne techniques. It does not require mechanical or electronic control of the interferometric working point and inherently filters out low-frequency components. It also can work with irregular interferometric patterns (i.e., specklelike patterns). Self-calibration of this vibrometric system is another useful feature. We expect that the sensitivity of our device can be increased by technological improvements and modification of the operating mode up to the level limited by the short noise. Another promising application of this novel device for detection of moving fringe patterns includes its use in high-sensitivity interferometric fiber-optic sensors and for characterization of the photoconductor and semiconductor crystals.[5–7]

References

1. A. M. Glass, A. M. Johnson, D. H. Olson, W. Simpson, and A. A. Ballman, Appl. Phys. Lett. **44,** 948 (1984).
2. M. B. Klein, Opt. Lett. **9,** 350 (1984).
3. G. Albanese, J. Kumar, and W. H. Steier, Opt. Lett. **11,** 650 (1986); Opt. Commun. **63,** 191 (1987).
4. B. Imbert, H. Rajbenbach, S. Mallick, J. P. Herriau, and J. P. Huignard, Opt. Lett. **13,** 327 (1988).
5. G. S. Trofimov, S. I. Stepanov, M. P. Petrov, and M. V. Krasinkova, Sov. Tech. Phys. Lett. **13,** 265 (1987).
6. M. P. Petrov, S. I. Stepanov, and G. S. Trofimov, Sov. Tech. Phys. Lett. **12,** 379 (1986).
7. G. S. Trofimov and S. I. Stepanov, Sov. Phys. Solid State **28,** 1559 (1986).
8. I. A. Sokolov, G. S. Trofimov, and S. I. Stepanov, Sov. Phys. Tech. Phys. **33,** 261 (1988).
9. V. I. Vlad, D. Popa, I. Apostol, M. P. Petrov, S. I. Stepanov, and G. S. Trofimov, preprint LOP-72-89 (CIP Press, Bucharest, 1989).
10. G. E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. **10,** 2495 (1971).
11. Y. Ohtsuka, Opt. Commun. **7,** 244 (1973).
12. R. L. Forward, Phys. Rev. D **17,** 379 (1978).
13. M. Bassan and S. Ciliberto, Opt. Acta **27,** 1253 (1980).
14. A. Rudiger, R. Schilling, L. Schnupp, W. Winkler, H. Billing, and K. Maischberger, J. Phys. (Paris) Suppl. C8 **42,** 451 (1981).
15. M. Tanaka and K. Nakayama, Jpn. J. Appl. Phys. **22,** L233 (1983).
16. K. P. Birch and M. Okaji, J. Phys. E **19,** 361 (1986).