Detection of dust grains vibrations with a laser heterodyne receiver of scattered light

Yuriy Serozhkin, Olexiy Kollyukh, and Yevgen Venger

V. Lashkaryov Institute of Semiconductor Physics
41 Nauky Prospect, Kyiv 03028, Ukraine
Tel./Fax: +38 (044) 525 61 79; e-mail: yuriy.serozhkin@zeos.net

Abstract

A laser heterodyne receiver of scattered light was used to detect dust grains vibrations. We made experiments for estimation of the technique sensitivity. The vibrations were excited in cigarette smoke with a loudspeaker. The results obtained indicate that dust grains vibrations with amplitude of about 30 nm can be detected.

1 Introduction

Heterodyne detection of scattered light is one of the most informative techniques used for investigation of the static and dynamic characteristics of micron and submicron particles. The parameters of modern laser heterodyne receivers of scattered radiation make it possible to detect nanoparticles and nanoclusters [1]. Application of heterodyne detection of scattered light when studying various biological objects *in vivo* seems very promising [2].

The objective of our work is to estimate feasibility of investigation of the dynamic characteristics of microparticles with a laser heterodyne detector of scattered radiation. We determined the potentialities of this technique and carried out pilot experiments on determination of vibrational amplitude for microparticles (cigarette smoke, colophony smoke) exposed to external actions.

2 Estimation of technique sensitivity

Let us estimate the laser heterodyne receiver capabilities when measuring vibrations of dust grains. The signal-to-noise ratio (S/N) of heterodyne detector peaks under conditions when its sensitivity is determined by shot noise [4, 5]:

$$(\mathrm{S/N})_{\mathrm{power}} \approx \frac{\eta P_s}{h\nu\Delta F}. \tag{1}$$

Here P_s is the detected signal power, h Planck's constant, ν radiation frequency, η detector quantum efficiency, and ΔF pass bandwidth of the receiver. Then the expression for the minimal detected signal power $P_{s,\,\mathrm{min}}$ (S/N = 1) is

$$P_{s,\ \mathrm{min}} \approx \frac{h\nu}{\eta}\Delta F. \tag{2}$$

When the wavelength is 0.6328 μm, η =0.5, losses in the receiving optical system up to 60%, and pass bandwidth of the receiver 10 kHz, then one obtains $P_{s,\ \mathrm{min}} \approx 1\times10^{-14}$ W. If the entrance aperture cross section is 1 cm^2, probing radiation power 1 mW, and distance to the scattering surface 50 cm, then the power coming to the detector input will be about 6×10^{-8} W (with the assumption that the surface scattering is isotropic and albedo is 0.8). Thus, a signal scattered from a surface with albedo of about 1×10^{-5} can be detected at a distance of 50 cm. If the scatterer is an assembly of 5 μm grains, with single albedo of 0.5 and the distance between particles of about 100 μm, then the resulting albedo of a layer about 0.5 mm thick will be 0.6×10^{-2}. In this case, the signal from radiation scattered by the dust layer will be 600 times the threshold of sensitivity, so one obtains S/N = 0.6×10^3. It can be shown that the S/N ratio at a frequency of scattering surface vibration is determined by the following expression:

$$(\mathrm{S/N})_{\omega_i \pm \Omega} \approx \left(\frac{2\pi}{\lambda} a\right)^2 \frac{P_s}{P_{s,\ \min}} . \tag{3}$$

Here ω_i is the difference between the heterodyne and probing radiation frequencies, a amplitude of scattering surface vibrations, and Ω vibrational frequency of the surface. For vibrational amplitude of 10 nm, the ratio S/N ≈ 6; this means that one can easily detect in-phase vibrations of particles in a layer of about 0.5 mm thick.

3 Experimental setup

The threshold of sensitivity of our detector was 2×10^{-14} … 2×10^{-12} W (depending on the pass bandwidth); the detector sensitivity to vibrations of a surface (with albedo of 0.8) at a distance of 1 m was no worse than 0.1 nm (in the 10 kHz band). The probing and heterodyne beams of the detector were formed with acoustooptical shift of laser radiation frequency in the same direction by the frequencies Fs and Fh, respectively. As a result, the information signal (which is formed when the frequencies of the radiation from heterodyne and that scattered by particles are mixed in the photodetector) is a phase-modulated signal whose carrier frequency $F_s - F_h$ is about 10 MHz.

Digitization of that phase-modulated signal was made with a two-channel A/D converter AD6600. Extraction of quadrature components digital heterodyning, decimation and filtration were performed with a digital filter/receiver AD6620. The information on phase value and rate (and consequently on the scattering surface displacement and velocity) was extracted by calculating the modified function atan2 of the ratio between the in-phase and quadrature components of a phase-modulated signal.

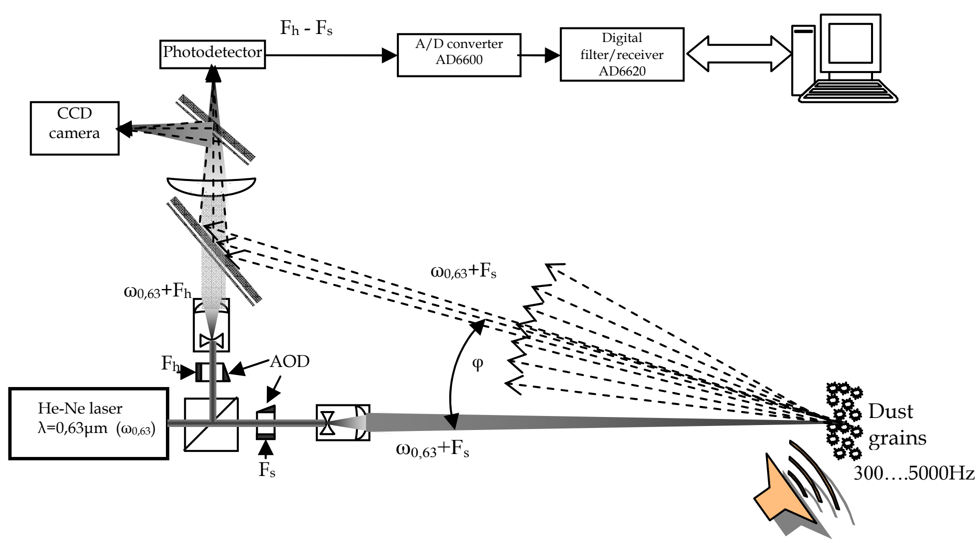
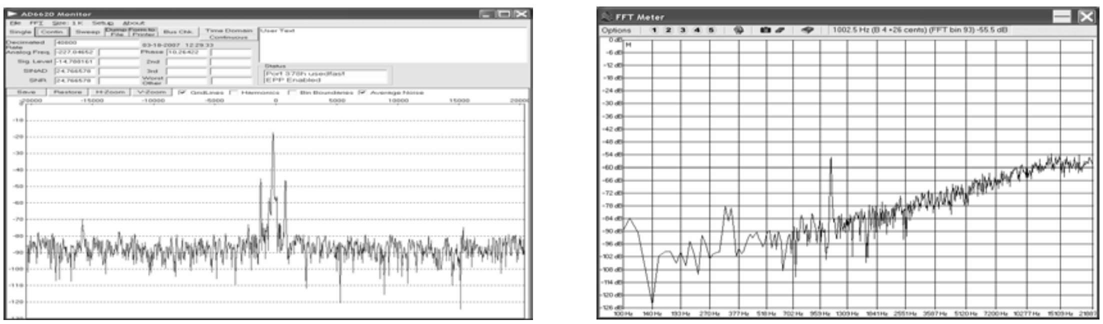


Figure 1: The experimental setup.

The experimental setup (Figure 1) involved a laser heterodyne receiver and a volume for dust component (cigarette smoke, colophony smoke) bleeding. A loudspeaker (to excite vibrations of air with dust component) was located in the above volume. A probing laser beam was focused (through a window) at a chosen point inside the dust cloud at a distance of about 50 cm from the collecting aperture. The focal spot diameter was 100…200 µm. A TV camera was used for visual focusing at a chosen region of the dust cloud. The detector was a bistatic optical system (with an angle $\varphi \approx 5^{\circ}$ between the transmission and reception optical axes), so there was a depth of focus for such detector: object shifting led to change in the scattered spot position relative to the heterodyne spot, thus resulting in signal decrease. For the angle of about 5° and distance of 50 cm, the depth of focus was 0.25…0.5 mm. One can state that the information signal was formed by scattering from those particles which occupied a region whose cross section was equal to the focal spot diameter and whose length was about five times that diameter.

4 Experimental results

Before measuring particle vibrations, we have measured piezoelectric cell vibrations (of the known amplitude) to refine the measurement procedure and receiver calibration. Shown in figure 2a is the spectrum of the $F_s - F_h$ signal obtained at scattering from the vibrating surface of piezoelectric cell (vibrational amplitude of 10 nm and frequency of 1 kHz). Figure 2b presents the signal spectrum after phase recovery and attenuation of low frequencies with a 6th order filter (the cutoff frequency of 200 Hz). Such measurements were performed for different frequencies and amplitudes of surface vibrations.



a) b)

Figure 2: Frequency spectrum signal from light, scattered by piezoelectric cell vibrations

When measuring particles vibrations, the probing beam was focused at a point inside the dust cloud at a distance of several millimeters from the inlet window. Shown in figure 3 are trails of the probing beam in the dust cloud and heterodyne spot (in center, a 10^4-fold attenuation). After the information collection area is chosen and detector is set, the heterodyning intensity is increased up to the operating level (about 50 μW). The diameter of the beam entering the dust cloud is 0,3 mm. The bright spots on the right are formed due to scattering from the inlet window surfaces.

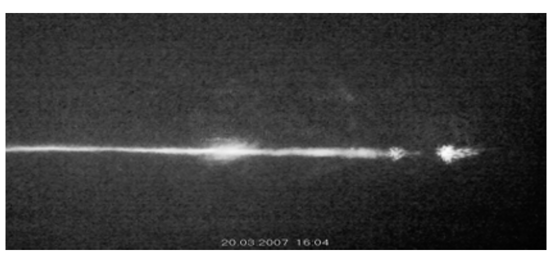
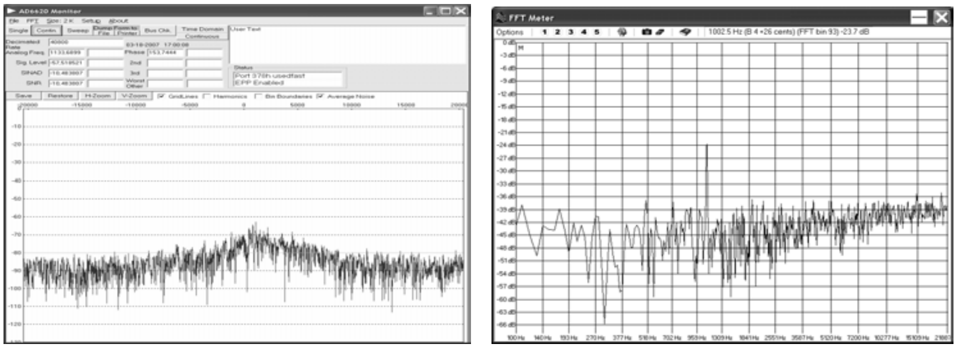


Figure 3: Trails of the probing beam in the dust cloud

Figure 4a presents the spectrum of the $F_s - F_h$ signal obtained at scattering from cigarette smoke exposed to sound action from a loudspeaker (power of 0.1 W at a frequency Ω = 1 kHz). The components with the above frequency appear in the spectrum of the $F_s - F_h$ signal (Fig. 4a). The spectrum is broadened considerably due to chaotic motion of the particles. Figure 4b presents the signal spectrum after phase recovery and attenuation of low frequencies with a 6th order filter (the cutoff frequency of 200 Hz). Such measurements were performed for different frequencies and power of loudspeaker.



4a 4b

Figure 4: Frequency spectrum signal from light, scattered by smoke

From figure 4b it is visible, that the noise level at measuring a scattering from a smoke makes quantity about 40 dB. It corresponds to vibration amplitude about 30 nm.

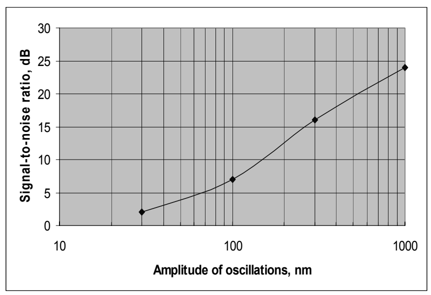


Figure 5: Signal-to-noise ratio for vibration of grains

In figure 5 is presented the dependence of the signal/noise ratio from a vibration amplitude of grains.

5 Conclusion

We developed a laser heterodyne detector of scattered radiation to be applied for investigation of the dynamic characteristics (vibrational amplitude and frequency) of dust grains in a dust cloud. Such detector makes it possible to register micron particles vibrations with amplitude of 30 nm.

References

[1] Stéphane Berciaud, Laurent Cognet, Gerhard A. Blab, and Brahim Lounis. Photothermal Heterodyne Imaging of Individual Nonfluorescent Nanoclusters and Nanocrystals, Phys. Rev. Lett. 93, 257402 (2004)

[3] Gross M, Goy P, Forget BC, Atlan M, Ramaz F, Boccara AC, Dunn AK. Heterodyne detection of multiply scattered monochromatic light with a multipixel detector. Opt. Lett. 2005 Jun 1; Vol. 30, No. 11, pp. 1357-1359.

[3] Oliver, B.M. (1961). Signal-to-noise ratio in photoelectric mixing. Proc. IEEE, 49(12):1960–1961.

[4] M. C. Teich and R. Y. Yen, "On the Signal-to-Noise Ratio for Optical Heterodyne Detection," J. Appl. Phys. **43**, 2480-2481 (1972).