

APPLIED RADIO PHYSICS

LASER ANEMOMETRY METHOD FOR PARTICLE VELOCITY MEASUREMENT IN THE BOSE-EINSTEIN CONDENSATE

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Studying of physical and engineering conditions of the process of atom velocity measurement in Bose-Einstein condensate is performed in the paper. In order to provide for the metrological support of the particle laser cooling process it is suggested the laser anemometry method based on measuring the Doppler frequency shift due to scattering of laser radiation by the moving particles to be cooled. The laser anemometry method for estimation of the particle velocity during the particle laser cooling process and the interferential model of the laser Doppler anemometry are provided. The requirements set to technical specifications of the laser Doppler anemometer are determined. The results of the paper form the basis of providing for the metrological support of the particle laser cooling process performed in order to create new frequency standards, the Bose-Einstein condensate and the quantum memory.

KEY WORDS: *laser cooling of the particles, Bose-Einstein condensate, velocity measurement, laser Doppler anemometry*

1. INTRODUCTION

Performing of scientific experiments must have due metrological support, and namely – measurements of the values have to be carried out using the tested or calibrated measuring instruments, the measuring techniques and estimation of their errors (uncertainties) must be based on mathematical and physical postulates, which are maximally correspondent to the physics of investigated objects and systems.

To implement the principles of metrological support of physical investigations the authors of this paper create a new special theory of measurements (the non-linear metrology) [1-3]. It is based on the key provisions of the theory of open systems, dynamic chaos, theory of information, synergy and the methods of topological and fractal analysis. The theory contains a principally new approach to measurements and assessment of the interval values measurement results in the dissipative systems with a

To measure the atom motion velocity in the “optical molasses” it is proposed to apply the laser Doppler anemometer [10]. In the general case, the optical diagram of the anemometer, (Fig. 1), includes: the light source – 1 (one-frequency, single-mode laser [11]); beam forming unit – 2; the unit for splitting the radiation in two probing beams – 3; the rotating mirrors unit – 4 directing the beams into the area of investigation – 5; the device used for collection of the scattered radiation in the measured volume – 6 into the photoreceiver – 7. The dimension of the measured volume is determined by the diameter of the beam focal waists and the angle of the beam crossing – 2θ .

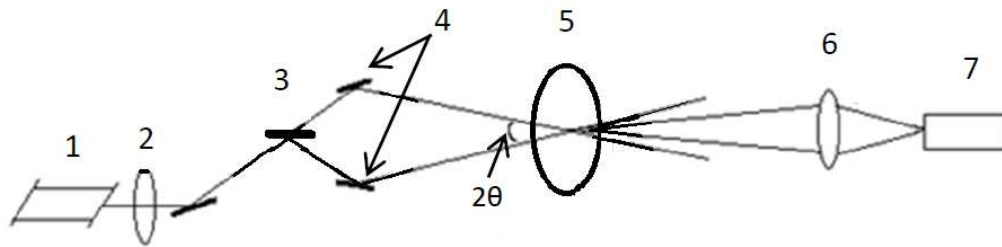


FIG. 1: Simplified optical diagram of LDA

Scanning of the BEC cloud is executed by means of rotation of the mirrors in the optical and mechanical system. At that it should be taken into consideration that decreasing of the angle 2θ between the probing beams results in losing of the measurement locality. Considering that BEC is placed into the vacuum chamber, the laser system must be positioned outside of its boundaries providing for measuring the atom motion velocity along several directions.

To influence upon the atoms at their cooling there are applied, as a rule, semiconductor lasers having the wavelength in keeping with the absorption line of the substance to be cooled. To provide for the one-frequency single-mode radiation it would be necessary to apply the lasers with the Littmann or Littrow resonator [12].

To measure the atom motion velocity, LDA uses the Doppler frequency shift of the laser field scattered by the moving atoms. The moving atoms are considered as the receivers of the light waves from the fixed source and simultaneously as the receivers and re-transmitters of the optical radiation to the fixed observer (the photoreceiver). The relation between the atom motion velocity \bar{u} and the scattered radiation frequency ν in the point of observation is expressed as:

$$\nu = \frac{\nu_0}{1 - (\bar{u} \cdot \bar{l}) / \bar{n}}, \quad (2)$$

where ν_0 is the radiation frequency of the source; c is the light velocity and \bar{l} is the unit vector directed into the point of observation.

Therefore, the value of the Doppler frequency shift ν_D considering that $|u| \ll c$ is:

The Doppler frequency of the signal arriving at the photoreceiver input depends on the wavelength (the wavelength value stability) of the laser radiation, atom velocity and the optical system geometry. The formula (4) represents the basic LDA equation; its error amounts to less than $10^{-5}\%$ [7]. At the atom motion velocity of about 20 cm/s the frequency shift (4) corresponds to the value close to 400 Hz. This estimate allows establishing the experimental conditions related to measuring the atom motion velocity.

In order to measure the atom velocity in BEC it is necessary to install the laser and photoreceiver coaxially with respect to each other and fix them on the rotating platform, which allows measuring the atom velocity upon all the directions.

According to Fig. 2, crossing of the laser beams forms the interferential image, which creates the pulses of the scattered field if crossed by the atoms. These pulses are recorded by the photo receiving device; in so doing the time interval is measured between the neighboring pulses. The distance between the interferential bands is determined by the laser radiation wavelength and by the time intervals between the neighboring pulses. That is, the spatial scale is determined by stable wavelength value, and the time scale is defined by the light velocity.

3. ATOM VELOCITY MEASUREMENT

The atoms to be cooled move along the linear-piecewise trajectories. Variation of the direction of their motion is related solely to the possibility of their direct collision with each other. This imposes certain restrictions upon concentration of the atoms in the cloud. At the same time, the laser spot providing for recording of the atoms motion must be of sufficiently small dimensions and the intensity of interfering waves must be maximally possible to provide that the scattered radiation could be recorded with the photoreceiver.

The laser anemometry method is the most efficient at determining the velocity of the particles to be cooled, the dimensions of which are commensurable with the laser radiation wavelength. Unfortunately, when used as the scattering particles of atoms or ions, the amplitude functions of scattering accept very small values for the spherical particles with the diameter of $a < 0.03 \lambda$ (the Rayleigh scattering), somewhat larger for $a > 0.03\lambda$ (the Lorentz-Mie scattering) and depend upon two parameters only – the relative size of the particles $\rho = 2\pi a/\lambda$ and the angle of crossing of the beams 2θ .

Within the measured volume, which is formed by the superposition of two equally polarized waves with the amplitudes A_1, A_2 and with the same focal waist radii b , there occurs the interference with the amplitude distribution:

$$I(\vec{r}, t) = A_1^2 + A_2^2 + 2A_1A_2 \cos(\omega_m t - \vec{K} \cdot \vec{r}) e^{-2r^2/b^2}, \quad (5)$$

where $\omega_m = \omega_1 - \omega_2$, \vec{r} is the radius vector.

$$u = \frac{N\delta\tau}{\Delta t}, \quad (9)$$

where $\delta\tau$ is the width of the bands.

The time interval Δt can be measured by counting of the number of stable short pulses filling in the measured interval. There occur errors in measuring the time interval due to missing of the count pulses and extrapolation.

In the case of the ensemble of N localized, chaotically moving particles the laser radiation $I_i(A, \nu)$ with the initial frequency ν will consist after scattering of N components:

$$I(\nu) = \sum_{j=1}^N I_j(A_j, \nu_j), \quad (10)$$

the frequency of each of which ν_j will be determined (2) by the motion velocity of the j -th particle. In order to determine the Doppler shift (3) it would be expedient to apply Fourier decomposition of the resulting signal. This operation would allow obtaining the signal spectrum (Fig. 3) and determine the average particle motion velocity (1) in the cloud

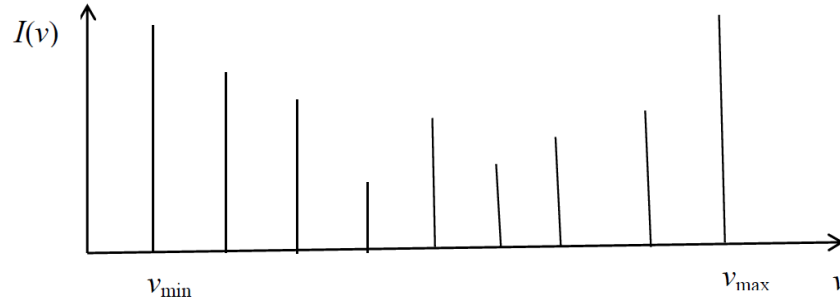


FIG. 3: The Fourier decomposition of the resulting signal: ν_{\min} , ν_{\max} are minimal and maximal values of the scattered radiation frequencies correspondent to equal and oppositely directed beam propagations and the particle motion velocity vector

4. REQUIREMENTS SET TO LDA ELEMENTS

The laser used in the anemometer must have high radiation frequency (wavelength) stability that provides for a precision measurement of the laser radiation phase shift dependent on the velocity of the atoms crossing the interferential image. The laser frequency stability is the basic parameter influencing upon the frequency shift measurement accuracy.

The focusing system positioned after the laser on the radiation line provides for formation of the beams in the measured volume of the cloud of cooled atoms. The angle of crossing of the probing beams 2θ exerts a large influence of the Doppler signal parameters. While measuring the atom velocity in the condensate with the help of LDA it is not necessary to move the operating point as it is the case with measuring the velocity of the flows. The BEC operating volume amounts to several millimeters only, so, it is sufficient to focus the laser radiation onto the cloud of cooled atoms to measure their velocity.

As a rule, this parameter of the optical diagram can be varied and selected. Its value must be optimal because the amplitude, pulse shape and the Doppler signal frequency depend on the angle of crossing. Dependence of the amplitude upon the angle is related to the dependence of the particle scattering cross-section upon the angle of crossing of the beams. Considering that for the submicron particles the scattering indicatrix is extended in the forward direction, then, the larger the angle of crossing of the beams is, the less is the Doppler signal amplitude. Dependence of the Doppler signal frequency upon the angle of crossing is determined by the basic anemometry Eq. (3): the less the angle is, the lower is the signal frequency.

To attain a high value of the signal-to-noise ratio in the photo receiving part it is necessary to decrease the laser radiation losses in the LDA optical diagram and eliminate the background noise of the photoreceiver. Main losses of the optical radiation occur due to the Fresnel refractions on the surfaces of the optical diagram elements. To eliminate the above losses the surfaces of the optical elements must be enlightened with the help of applying multi-layer selective coatings and enlightening of the working surfaces is needed. In order to prevent appearing of the background noise, the receiving optical system is manufactured in the form of the linear spatial filter.

The photomixing method or the differential method for the Doppler signal measurement is most frequently used in the photoreceiver. The radiation scattered in the cloud and the reference (from the laser) wave are directed to the photoreceiver at the photomixing method; at the differential method the scattered radiation from two probing beams is directed to the photoreceiver.

5. CONCLUSIONS

Studying of physical and engineering conditions of the process of atom velocity measurement in the Bose-Einstein condensate is performed in the paper.

In order to provide for the metrological support of the particle laser cooling process it is suggested the laser anemometry method based on measuring the Doppler frequency shift due to scattering of laser radiation by the moving particles to be cooled.

The expressions for estimation of the particle velocity during the particle laser cooling process and the interferential model of the laser Doppler anemometry are suggested.

The requirements set to technical specifications of the laser Doppler anemometer to measure the velocity of the particles to be cooled are determined.

The results of the paper form the basis of providing for the metrological support of the particle laser cooling process performed in order to create new frequency standards, the Bose-Einstein condensate and the quantum memory.

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