Information losses when recording the stimulated echo-hologram in gas media

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Abstract. Considered is the impact of collisions with the change of the particles velocity in the \textsuperscript{174}Yb vapor exerted on the information reproducibility in the stimulated echo hologram response, encoded in the temporal form of the second object laser pulse. It was manifested that such collisions result in the increase of the “spurious” information, serving the background for loosing information introduced into the object laser pulse in the stimulated echo hologram response.

1. Introduction

The process of echoholograms formation in gas media is qualitatively different from its analog in a solid body \cite{1-6}. Differences are associated with the “working” particles movement, which causes the need of accounting collisions and random reorientations of particles which occur at formation of optical coherent responses of the media. The velocity of individual particles in gases is a vector quantity. Thus, each point of such a sample is associated with its own direction in space (the directed nature of the Doppler effect). Therefore, the amplitude and phase information containing in the object wave turns out to be “encoded” in streams of particles moving with certain velocities. In addition, phasing of individual dipole moments in gas at the time of the echo formation does not necessarily take place at each point of the sample, but there occurs phasing of individual velocity “packages” of particles moving with different velocities. This paper considers the impact of collisions with the velocity change of particles in gas on the reproducibility of information in the stimulated echohologram (SEH) response at the $^{1}S_{0}(6s^{2})-^{3}P_{1}(6s6p)$ junction in \textsuperscript{174}Yb vapor, encoded in the temporal form of the second object laser pulse. Obtained is the dependence of differential information entropy of the SEH response temporal form at the change in the time interval between the first and the third laser pulses due to collisions with change in the velocity of gas particles, as well as at different \textsuperscript{174}Yb vapor pressure.

2. The basic equation

For description of the echo hologram formation in a gas, it is necessary to simultaneously account the Doppler shifts in the particles radiation frequencies, the changes in their position and orientation in space, the collision of particles, as well as the degeneration of their energy levels by over some quantum number. In the case of a shock mechanism of broadening the resonance transition line the
equation for the single-particle density matrix with the streaming members in the laboratory coordinate system have the form [2,3]:

\[
\left( \frac{\partial}{\partial t} + \frac{\partial \Delta \vec{r}}{\partial t} \right) \rho_{\alpha \beta}^{J_{z_1} J_{z_2}} \left( 1 - \frac{n}{c} \frac{\partial \Delta \vec{r}}{\partial t} \right)^{-1} = \frac{i}{\hbar} \left( H_{J_{z_1}}^\alpha - H_{J_{z_2}}^\beta \right) \rho_{\alpha \beta}^{J_{z_1} J_{z_2}} + 
\]

\[ + \frac{i}{\hbar} \sum_{\beta} \left( V_{\alpha \beta} J_{z_1} J_{z_2} - V_{\beta \alpha} J_{z_1} J_{z_2} \right) - N \left( \nu \left( \sigma_{\alpha \alpha}^\prime - i \sigma_{\alpha \alpha}^\prime \right) \right) \rho_{\alpha \beta}^{J_{z_1} J_{z_2}} \]  

(1)

where \( J_i \) is the total moment of \( i \)-th level, indexes \( \alpha, \beta, \gamma \) denote sublevels degenerate levels, \( \Delta \vec{r} \) is the displacement of the particle due to its movement on the considered time interval, \( \vec{n} \) is the direction of propagation of the laser excitation pulse, \( V_{\alpha \beta}^{J_{z_1} J_{z_2}} \) are the matrix elements of the interaction operator of the atom with electromagnetic radiation, \( H_{J_{z_1}}^\alpha \) is Hamiltonian of the unperturbed atom, \( N \) is the concentration of the perturbing particles, \( \nu \) is the relative velocity of the atom and the perturbing particle, \( \sigma^\prime \) and \( \sigma'' \) are cross-sections for the broadening and shifting of the corresponding spectral line, \( c \) is the velocity of propagation of the excitation laser pulse in the medium.

Let us consider the SEH formation in gas system considering the effect of particle motion. The best mode for recording and reproducing an echo hologram in a gas is possible in case when the sample (cells) dimensions are small as compared with the distance to the object. In this case, an decomposition of the object laser pulse field over plane waves shall become possible. The electric field amplitude of the SEH response will be:

\[
E \sim \sum_j \int W(\vec{v}) d\vec{v} \left( \vec{d}_{ij} \right) \times \vec{n}_n \times \vec{\bar{n}}_n \]  

(2)

where \( \vec{n}_n \) are the unit vectors in the direction of plane waves propagation, \( W(\vec{v}) \) - the particle velocity distribution function, \( \vec{d}_{ij} = t - \frac{\vec{R}_0 - \vec{n}_n}{c} + \frac{\vec{r}_j - \vec{n}_n}{c} \), \( \vec{R}_0 \) - the radius vector of the observation point, and \( \vec{r}_j \) - the radius vector of the \( j \)-th optical center location, \( \vec{d}(t') = SP \left( \vec{d}(t') \right) = \vec{d}_+ \rho_{ij}^{(1)}(t') + c.c. \) where \( \rho_{ij} \) - are the matrix elements of the density matrix have been obtained in [7].

The recording of an SEH in a gas is possible in case the conditions of spatial phase synchronism have the form

\[
\vec{n}_{0n} - \vec{n}_1 + \vec{n}_{2n} - \vec{n}_3 = 0 \]  

(3)

It was shown in [8, 9] that elastic collisions with the change in the direction of the particle velocity in gas result in spectral diffusion within the inhomogeneous broadened line, which affects the temporal form of the SEH response. Let us consider the case when the information is stored in the temporal form of the second object laser pulse at the SEH recording. The pulse sequence at excitation of a stimulated echo hologram is shown in figure 1.
Figure 1. The sequence of pulses at SEH excitation. \( \Delta t_i \) - is the duration of the \( i \)-th resonant laser pulse, \( t_e \) - is the time of appearance of the SEH response, \( \tau = t_2 - t_1 \) and \( \tau_1 = t_3 - t_1 \) are the time intervals between the exciting pulses, \( t_i \) - moment of the \( i \)-th laser pulse impacts, \( P_1, P_2, P_3 \) - resonance laser pulses.

The electric field amplitude of the SEH response in case of the linear polarization of the exciting laser pulses will be determined by an expression similar to the one obtained in [8]:

\[
E \sim \int_{-\infty}^{\infty} \frac{\sin(\theta_1(\Delta))\sin(\theta_2(\Delta, \delta\varphi_r(\Delta)))\sin(\theta_3(\Delta, \delta\varphi_{r_1}(\Delta)))}{\theta_1'(\Delta)\theta_2'(\Delta, \delta\varphi_r(\Delta))\theta_3'(\Delta, \delta\varphi_{r_1}(\Delta))} \times \tilde{S}_1(\Delta)\tilde{S}_2(\Delta)\tilde{S}_3(\Delta) \exp \{i\Delta[t \cdot \cos(\delta\varphi_r(\Delta)) - \tau \cdot \cos(\delta\varphi_{r_1}(\Delta)) - \tau_1 \cdot \cos(\delta\varphi_{r_1}(\Delta))]\} g(\Delta)d\Delta, \tag{4}
\]

where

\[
g(\Delta) = \left(1/\Delta_D \sqrt{2\pi}\right)\exp\left(-\frac{(\Delta/\Delta_D)^2}{2}\right) \quad \theta_1(\Delta) = \theta_1'(\Delta)\delta_1, \quad \theta_2(\Delta, \delta\varphi_r(\Delta)) = \theta_2'(\Delta, \delta\varphi_r(\Delta))\delta_2, \quad \theta_3(\Delta, \delta\varphi_{r_1}(\Delta)) = \theta_3'(\Delta, \delta\varphi_{r_1}(\Delta))\delta_3.
\]

\( \theta_1', \theta_2', \theta_3' \) are the Fourier spectra of pulses, \( \delta\varphi_r(\Delta), \delta\varphi_{r_1}(\Delta) \) is the average random increase in the angle between the velocity of the molecule and the direction of observation during the corresponding time interval and the corresponding isochromes of the Doppler-broadened line, \( \Delta_D \) is the width of the heterogeneously (Doppler) broadened line, \( \tau \) is the time interval between the first and the second pulses, \( \tau_1 \) - time interval between the 1st and 3rd pulses.

Numerical calculation of the expression (4) at information encoding in the temporal form of the object pulse for the SEH response is shown in figure 2 (a, b), at changing the temporal interval between 1 and 3 pulses.
From the analysis of the figures it follows that the information display in the SEH response encoded in the temporal form of the second object pulse deteriorates at changing the time interval between 1 and 3 pulses on the $^{17}$Yb $^{1}S_{0}(6s^{2})-^{3}P_{1}(6s6p)$ transition of the $^{17}$Yb vapor. Note that an increase in pressure results in a similar effect [8, 9]. We introduce differential information entropy in order to describe the number of reproduced and recorded information which stored in the temporal form of the object laser pulse.

3. Classical differential information entropy of object laser pulse and seh response

The differential informational entropy of the temporal form of the object laser pulse is defined as:

$$J'_{c} = J_{c} - J_{c0}$$  \hspace{1cm} (5)$$

where

$$J_{c} = -\int_{0}^{\Delta t} p(t) \log_{2} p(t) dt - \lim_{\Delta t \to 0} \frac{\log_{2} \Delta t}{\Delta t}$$  \hspace{1cm} (6)$$

$$J_{c0} = -\int_{0}^{\Delta t'} p_{o}(t) \log_{2} p_{o}(t) dt - \lim_{\Delta t' \to 0} \frac{\log_{2} \Delta t'}{\Delta t'}$$  \hspace{1cm} (7)$$

$\Delta t$ - pulse duration, $\Delta t'$ - normalization pulse duration, $p(t)$ - the probability density of the distribution of amplitude (or intensity) of the electric field of pulse, $p_{o}(t)$ is the probability density of the distribution of amplitude (or intensity) of the electric field of the normalizing pulse, chosen against the information encoding type in the object pulse.

Differential information entropy of the temporal form of the SEH response is determined similarly to (5) with allowance for (6), where $p(t)$ is the probability density of the distribution of amplitude of the electric field of the response.
A numerical calculation of the expression (5) with allowance for (4, 6-7) is shown in figure 3(a) with a change in the temporal interval between the 1st and 3-rd pulses, and in figure 3(b) under the change of \(^{174}\text{Yb}\) vapor pressure.

![Graphs](image)

**Figure 3.** The change of the differential information entropy of the stimulated echo hologram response a) the dependence on the time interval between the 1-st and 3-rd laser pulses due to collisions with a change in the velocity of the gas particles; b) the dependence on the vapor pressure value of \(^{174}\text{Yb}\).

The change of value of differential information entropy for the stimulated echo hologram response a) dependence of value of differential information entropy on the time interval between the 1-st and 3-rd of exciting laser pulses due to collisions with a change in the velocity of the gas particles; b) dependence of value of differential information entropy on the vapor pressure value of \(^{174}\text{Yb}\).

Analysis of figure 3 shows that collisions with changes in the velocity of gas particles lead to the increase in “spurious” information, serving the background for losing in the SEH response of information introduced into the object laser pulse.

**4. Conclusions**

In the considered numerical experiments, it was found that collisions with a change in the velocity of gas particles have an impact on the temporal form of the SEH response, which results in the destruction of the recorded information in gas media. In addition, such collisions result in an increase in “spurious” information, serving the background for information losing in the SEH response that which must be taken into account when creating optical memory devices and echo processors.

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**References**

[1] Zuykov V, Nefed'ev L, Samartsev V 1982 *Applied questions of holography* (L.: LINF) p 179

[2] Nefed'ev L 1985 *Opt. and Spectrosc.* **59** 841
[3] Nefed'ev L 1986 *J. Appl. Spectr.* **44** 664
[4] Nefed'ev L 1986 *Opt. and Spectrosc.* **61** 387
[5] Evseev I, Rubtsova N and Samartsev V 2009 Photon echo and phase memory in gases (Kazan: Kazan State University Press) p 490
[6] Rubtsova N, Ishchenko V, Khvorostov E, Kochubei S, Khvorostov E and Yevseyev I 2004 *J. Phys. Rev.* **70** 023403
[7] Akhmedshina E, Nefediev L and Garnaeva G 2016 *Opt. and Spectrosc.* **121** 405
[8] Akhmedshina E, Nefediev L and Garnaeva G 2015 *J. Appl. Spectr.* **82** 669
[9] Akhmedshina E, Nefediev L, Garnaeva G, Shigapova E 2017 *J. of Phys.: Conf. Series* **859** 1