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Control of image reproducibilty in a response of a stimulated echo hologram

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Abstract. **We consider image recording and reproduction using a reversed stimulated echo hologram, with a recording medium exposed to pulses of nonresonant electromagnetic standing waves. It is shown that the spatial intensity distribution in a stimulated echo hologram response depends on the electric field strength of nonresonant standing waves, which makes it possible to control reconstructed images.**

Keywords: *information recording, information reproduction, reversed regime, stimulated echo hologram, standing wave, control of a reconstructed image.*

1. Introduction

Recording coherent optical images using stimulated echo holograms (SEHs) is a promising technology in view of the possibility of implementing their ultrafast image processing. The latter is of key importance in many practical cases where a large number of images must be simultaneously saved, analysed and processed. A noteworthy feature of SEHs is their ability of reconstructing or reversing wavefronts and the temporal shape of object laser pulses, which can be used in online data processing systems. Note that the methods of image processing using SEHs were experimentally considered for the first time in [1]. The experiments performed in [1–3] demonstrated (also for the first time) the potential of SEHs in reproduction, convolution and correlation of images embedded in excitation laser pulses. Thus, an SEH makes it possible to record, reproduce and transform an image by recording simultaneously several images embedded in excitation laser pulses.

A promising way to design optical storage devices and echo-processors is to apply echo-holographic data processing, which provides an efficient mechanism of data erasure and associative sampling. It was shown in [4] that the most promising approach in this field is to use the effect of echo-holographic information locking, i.e., provide conditions under which recorded information cannot manifest itself as a response of a resonant medium; these conditions can be implemented by violating the frequency–time correlation of the inhomogeneous broadening of the resonant line in different time intervals. The frequency–time correlation of an inhomogeneously broadened line of a resonant transition is related to the rigid correspondence of individual line isochromates in different time intervals. Each isochromate of an inhomogeneously broadened line is formed by a set of optical centres that exist under identical conditions and, at the same time, are randomly distributed over the sample volume. The formation of photon echo responses consists of two main stages: misphasing of oscillating dipole moments of optical centres and their subsequent phasing, which leads to the occurrence of macroscopic polarisation of the medium, observed in the form of a coherent response. A slight violation of the rigid frequency–time correlation of inhomogeneous broadening in different time intervals should significantly reduce the response intensity. In other words, the case in point is the reversible destruction of the phase memory of a resonant medium, with a possibility of reconstructing it. This effect can be implemented by affecting a resonant medium (in different time intervals) by different spatially inhomogeneous external perturbations, leading to random shifts or splittings of the initial isochromates of the inhomogeneously broadened line.

The effect of locking a long-lived photon echo (LLPE) in a LaF_3Pr^{3+} crystal ($^3H_4$ – $^3P_0$, transition, λ = 477.7 nm), affected by an inhomogeneous electric field in the interval between the first and second laser pulses, was theoretically predicted and experimentally verified in [4]. A similar effect occurs in the presence of external nonresonant standing electromagnetic waves. In this case, the LLPE response intensity depends strongly on the mutual orientation of the excitation pulse wave vectors with respect to the direction along which a standing electromagnetic wave is formed [5]. This effect can be used to filter images recorded with the aid of the LLPE, which provides additional possibilities for their processing. It was shown in [6, 7] that the exposure to pulses of nonresonant electromagnetic standing waves between excitation laser pulses during the formation of an SEH leads to the wavefront transformation in its response.

In this paper, we report the results of studying the influence of nonresonant electromagnetic standing waves on the reproducibility and filtering of an image in an SEH response, with the first excitation laser pulse playing the role of the object one.

2. Phase matching of a stimulated echo hologram

Let us consider the SEH formation in the case when a transparency with an image forms a spatial distribution of the light wave corresponding to the first object pulse, and the spatial

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distribution of the light waves corresponding to the second and third pulses is formed by transparencies without images.

The electric field strength of the ηth excitation laser pulse can be written as

$$E_\eta(\boldsymbol{r},t) = U_\eta(\boldsymbol{r})\mathrm{e}^{\mathrm{i}\omega t} + \mathrm{c.c.} \quad (0 \leqslant t \leqslant \Delta t_\eta), \tag{1}$$

where Δt_η is the duration of the ηth excitation laser pulse and $U_\eta(\boldsymbol{r})$ describes its spatial structure.

Let us analyse the approximations in which $U_\eta(\boldsymbol{r})$ can be expanded in spherical or plane waves. The image on the transparency will be considered as a set of points with radius vectors $\boldsymbol{r}_n$. Each such point emits a spherical wave. Then the electric field strength of the ηth excitation laser pulse at point $\boldsymbol{r}_{0j}$ of the sample can be written as

$$E_{\eta j} = \sum_n A_{nj}^{(\eta)} \frac{\exp[\mathrm{i}k_{\eta n}(\boldsymbol{r}_{0j} - \boldsymbol{r}_n) - \mathrm{i}\omega t + \mathrm{i}\varphi_n]}{|\boldsymbol{r}_{0j} - \boldsymbol{r}_n|}, \tag{2}$$

where $\boldsymbol{k}_n = (\omega/c)\boldsymbol{n}_n$; $\boldsymbol{n}_n = (\boldsymbol{r}_{0j} - \boldsymbol{r}_n)/|\boldsymbol{r}_{0j} - \boldsymbol{r}_n|$; φ_n are the initial phases of spherical waves; note that $\exp(\mathrm{i}\varphi_n)$ can be included in complex amplitudes $A_{nj}^{(\eta)}$. If $|\boldsymbol{r}_{0j} - \boldsymbol{r}_n|$ greatly exceeds the sample size, expansion (2) in spherical waves is transformed into an expansion in plane waves:

$$E_{\eta j} = \sum_n \varepsilon_{\eta n} \exp(\mathrm{i}\boldsymbol{k}_{\eta n}\boldsymbol{r}_{0j} - \mathrm{i}\omega t), \tag{3}$$

where $\varepsilon_{\eta n}$ are the electric field amplitudes of waves from individual points of the ηth transparency.

Since the spatial distribution of the light wave of each excitation laser pulse is formed by the corresponding transparency, the spatial phase matching during the SEH response formation takes the form

$$\boldsymbol{k}_{\mathrm{e}n} = -\boldsymbol{k}_{1n'} + \boldsymbol{k}_{2n''} + \boldsymbol{k}_{3n'''}, \tag{4}$$

Figure 1 shows the mutual arrangement of the wave vectors of the light waves of excitation laser pulses at which the spatial phase matching conditions are satisfied in the case of the SEH formation.

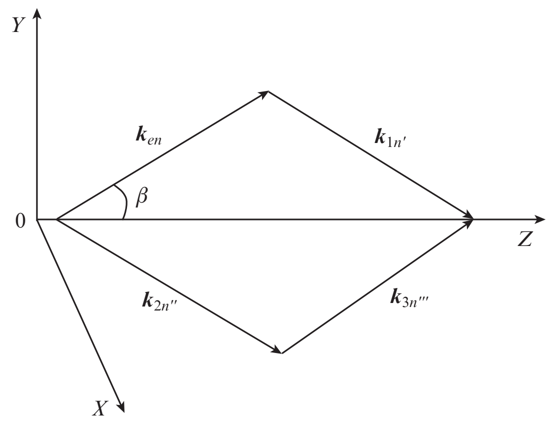

Figure 1. Spatial phase matching in the case of the SEH formation.

3. Control of the angular distribution of amplitudes of a stimulated echo hologram response

In the case of an echo hologram response, amplitudes $A_{nj}^{(\eta)}$ or $\varepsilon_{\eta n}$, which are related to the propagation direction of the spatial components of the object laser pulse, may be functions of angles $\beta_{\eta n}$ of mutual orientation of vectors $\boldsymbol{k}_{\eta n}$ with respect to the direction in the sample along which an artificial anisotropy of additional frequency shifts of isochromates of an inhomogeneously broadened resonant line is induced [5]. When the object laser pulse is the first excitation pulse, the electric field strength of the SEH response has the form

$$E(R_0, t) \sim \mathrm{Re}\sum_{n'} \varepsilon_{1n'}'^{*}(\beta_{1n'}) \exp(-\mathrm{i}\boldsymbol{k}_{1n'}R_0). \tag{5}$$

As a result, there occurs a spatial energy redistribution and, correspondingly, image transformation in the response ($\boldsymbol{R}_0$ is the radius vector of the observation point). The most efficient mechanism of the influence on the amplitudes of expansion in plane waves of the SEH response electric field may be photon echo locking using standing nonresonant electromagnetic waves. In this case, one can observe a change in the $\varepsilon_{1n'}'(\beta_{1n'})$ values at angles $\beta_{1n'}$ as small as several hundredths of degree [6, 7].

To calculate the $\varepsilon_{1n'}'^{*}(\beta_{1n'})$ values, we will consider the formation of an SEH recorded by a sequence of three resonant pulses and nonresonant electromagnetic standing waves acting between the first and second excitation laser pulses and after the third pulse. The equation for the single-particle density matrix in a rotating coordinate system can be written as

$$\frac{\partial\tilde{\rho}}{\partial t} = \frac{\mathrm{i}}{\hbar}[B,\tilde{\rho}], \tag{6}$$

where $B = \tilde{H}_{0m} + \tilde{V} - \hbar A$; $\tilde{H}_{0m} = \mathrm{e}^{\mathrm{i}At}H_{0m}\mathrm{e}^{-\mathrm{i}At}$; $\tilde{V} = \mathrm{e}^{\mathrm{i}At}V\mathrm{e}^{-\mathrm{i}At}$; A is the matrix of the transition to a rotating coordinate system; V is the interaction operator of a resonant system with excitation laser pulses; and H_{0m} is the Hamiltonian of an atom in an external spatially inhomogeneous nonresonant electromagnetic field (standing nonresonant electromagnetic waves acting in the time interval τ_1). In the case of a two-level system, $A = P_{22}\omega$ (P_{ij} is a projective matrix, with ijth elements equal to unity and other elements equal to zero),

$$\mathrm{e}^{\pm\mathrm{i}At} = P_{11} + P_{22}\mathrm{e}^{\pm\mathrm{i}\omega t}, \ \tilde{H}_{0m} = \hbar(f(\tau_1,r))P_{22},$$

$$\tilde{V} = P_{12}V_{12}\mathrm{e}^{-\mathrm{i}\omega t} + P_{21}V_{21}\mathrm{e}^{\mathrm{i}\omega t},$$

$$V_{ij} = \frac{1}{2}d_{ij}U(\boldsymbol{r})\exp(\mathrm{i}\omega t) \approx \frac{1}{2}d_{ij}\sum_n \varepsilon_n \exp(-\mathrm{i}\boldsymbol{k}_n\boldsymbol{r} + \mathrm{i}\omega t),$$

where ω is the laser frequency; d_{ij} is the dipole moment of the resonant transition; $\boldsymbol{r}$ is the radius vector of the optical centre; and $f(t_1, \boldsymbol{r})$ is the shift of an isochromate of the inhomogeneously broadened line in an external spatially inhomogeneous electromagnetic field.

The dependence of $f(\tau_1, \boldsymbol{r})$ on the optical centre location in the sample is due to the spatial inhomogeneity of nonresonant laser radiation. This inhomogeneity arises, for example, under the impact of a standing wave. In this case, we have the following relation for each propagation direction of plane waves in expansion (3) [8, 9]

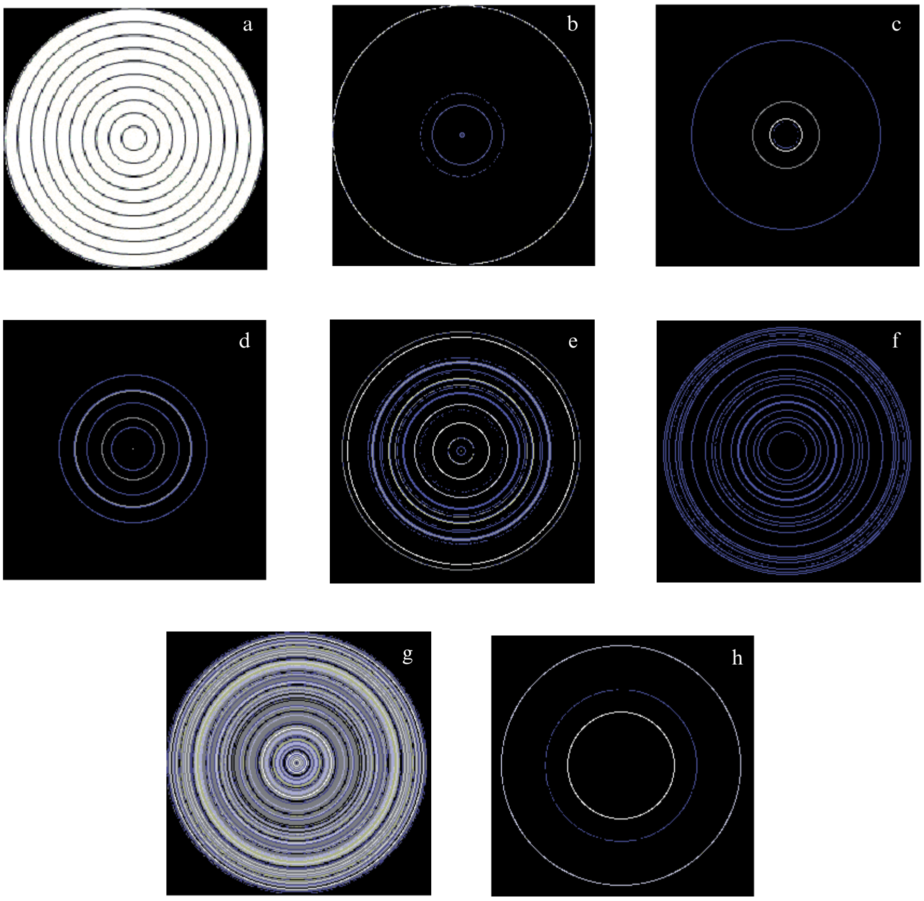

Figure 2. Images ($L \times L$ in size) in the response of a stimulated echo hologram at $E_2 = 0$ and E_1 = (a) 0, (b) 2600, (c) 1700, (d) 3500, (e) 2050, (f) 5400, 350 (g) 350 and (h) 1200 V cm^{-1}.

$$f(\tau_1, \boldsymbol{r}) = \varDelta + C_\mathrm{D} E_{01}^2 \cos^2\left(\frac{2\pi z \cos\beta_{1n'}}{\lambda}\right), \quad (7)$$

where $\varDelta$ is the frequency of the inhomogeneously broadened line; C_D is the constant of the dynamic Stark effect; E_{01} is the electric field amplitude for a standing wave of a nonresonant laser pulse; z is the axis in the laboratory coordinate system along which a standing wave is formed; and λ is the nonresonant laser wavelength.

A solution to Eqn (7) for a two-level system was obtained in [5]. In this case, the phase part of the electric field strength of the SEH response has form (3) and

$$\varepsilon_{1n'}'^{*}(\beta_{1n'}) \sim \int_0^L \mathrm{d}z \int_{-\infty}^{\infty} g(\varDelta)\, \mathrm{d}\varDelta \exp\{\mathrm{i}[\varDelta(t - \tau_2) - f(\tau_1, \boldsymbol{r})\tau_1]\}, \quad (8)$$

where L is the sample size in the direction of the z axis; $g(\varDelta)$ is the frequency distribution function for the inhomogeneously broadened line of the resonant transition; τ_1 is the time interval between the first and second laser pulses; and τ_2 is the time interval between the first and third laser pulses.

To illustrate the influence of nonresonant electromagnetic standing waves on the reproducibility and filtering of an image in the SEH response, the transparency with an image forming the light wave spatial distribution corresponding to the first object pulse will be set in the form presented in Fig. 2a.

The results of numerical calculation of the SEH response intensity distribution on a screen, $I \approx |E(R_0, t)|^2$, with allowance for expressions (8) and (5), are shown in Fig. 2. Figure 2a demonstrates the image in the SEH response in the absence of nonresonant standing waves.

An analysis of the data in Fig. 2 shows that, depending on the electric field strength of the standing wave, the radiation is concentrated in certain parts of the screen at some electric field strengths of nonresonant standing waves, due to which the image in the SEH response can be controlled. This leads to selection (filtering) of certain rings in the image, depending on the nonresonant standing wave parameters, and can also be used to design optical storage devices and echo processors based on echo-holographic data processing.

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