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NONLINEAR AND QUANTUM OPTICS

Optical Echo Holography

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Abstract—The basic physics and applications of an unconventional area in holography that is based on the interference of light-induced atomic coherent superposition states in a resonant medium are discussed.

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INTRODUCTION

Echo holography is a method of recording and reconstruction of light wave fronts in which the reference, object, and reconstructed waves do not coincide in time. The radical difference of this situation from that in conventional holography (including dynamic holography in resonant media [1]) is that the reference and object beams are separated in time so that cannot directly interfere. It was shown in [2] that information on the object-field wave front can nevertheless be reconstructed some time after the effect on a resonant atomic detecting medium. Under certain excitation conditions, an atomic system can emit a time-delayed coherent response in the form of a photon echo, the wave front of which depends on not only the shapes of the wave fronts of object and reference fields, but also on the order of applying these fields to a recording medium, which makes it possible to implement space–time holography.

SUPERPOSITION STATES OF ATOMS

The fundamental physics of holography of this type is based on a combination of two necessary conditions. First, the atomic medium must contain superposition states induced upon coherent excitation of the atomic ensemble. Second, the excited atomic ensemble must possess a sufficiently long phase memory of this excitation.

Let us consider the former condition in more detail. We will start with a single atom. It is known that any atom may not only occupy its stationary states (i.e., the so-called energy levels), but also be in a linear superposition of these states. In the absence of external effects on an atom, stationary energy states with energy E_j are known to be solutions to the time-independent Schrödinger equation for the atomic wave function; these atomic states are theoretically stable. In practice, all these energy levels (except for the ground one) are quasi-stable. Specifically, a minor effect from the atomic environment (vacuum fluctuations, external electric and magnetic fields, phonon oscillations, collisions, etc.) can make the atom relax from this state to the ground level. During this relaxation, the atom passes successively through the continuous spectrum of superposition states corresponding to a given energy transition. Generally, these states are determined for the atom by the wave function that is a solution to the time-dependent Schrödinger equation and depends on time:

$$|\Psi(t)\rangle = \sum_{j=1}^{m} c_j(t)|j\rangle, \tag{1}$$

where $|j\rangle$ are the eigenfunctions corresponding to the stationary energy levels and probability amplitudes $c_j(t) = a_j e^{-i\frac{E_j}{h}t}$ are harmonic functions determining the temporal behavior of the dipole moment acquired by the atom in the superposition state.

The basic property of the superposition state is its fundamental instability [3]. An atom excited in a particular way into this state, with all channels of external effect switched off (for example, in the absence of external fields and all relaxation factors suppressed), nevertheless immediately starts relaxing the lower equilibrium state because of the presence of internal forces.

This instability of superposition states becomes very important when we pass on to consideration of coordinated oscillations of an entire atomic ensemble. Naturally, one has to deal with a large number of atoms in practice, and in holography we are interested in specifically coherent properties of a particle ensemble. Having excited this ensemble coherently, one can transfer each of its atoms simultaneously to the same superposition state. This collective state of the ensemble is referred to as a pure coherent superposition state. After the excitation, its motion will be coordinated for some time. Specifically in view of the instability of the superposition state of an individual atom, when pumping by external field is over, each atom starts relaxing to equilibrium at the same time. In other words, since the atoms existing in a pure superposition state must have identical dipole moments, all dipoles will have identical initial phases. Naturally, this could not be implemented if all atoms were transferred (even coherently) into one of stationary states. Atoms can relax from these states to lower ones only under random external effects, thus forming a mixed superposition state; therefore, a pure coherent superposition state of the entire ensemble is impossible in this case. Therefore, the initial phases of oscillations of individual dipoles cannot coincide. Correspondingly, interference of collective coherent superposition states of atoms cannot occur.

The second necessary condition is the existence of phase memory of the recording medium. When a material is exposed to a short coherent light pulse separated in time, interaction between waves is possible only through the medium and only when the material has a sufficiently long phase memory. In this situation, each pump field pulse transfers information on its wave characteristics to the medium, this information being retained in it until the next pump pulse arrives. Therefore, when we refer to nonsimultaneous interaction, this does not mean violation of causal relations, despite the fact that optical pump waves do not encounter each other and, therefore, cannot interfere directly. In this case, the recording medium is a peculiar wave bridge, which connects the wave characteristics of optical pump fields in time and space.

Pure coherent superposition states of a medium obtained as a result of its irradiation by a coherent light pulse decay gradually during the transition period after the end of the pulse due to different relaxation processes. This process is accompanied by gradual passage of the atomic ensemble to a mixed state, which leads to irreversible loss of phase memory. In this state, each atom retains the dipole moment induced in it by the perturbation caused by the excitation field; nevertheless, macroscopic polarization of the medium caused by coherent collective oscillations disappears and only the spontaneous component of polarization remains. In this case, the intensity of spontaneous radiation of an atomic ensemble is smaller than the intensity caused by the coherent component of polarization by a factor of N (N is the concentration of excited centers in the material). The concentration of active centers in different materials is rather high (10^8–10^{20} cm^{-3}). Thus, one can easily imagine how efficiently the processes of light–matter interaction occur in the stage of the transition process where the phase memory of the atomic ensemble is not violated. In this situation, various transient quantum optical phenomena (the so-called transients) may occur: self-induced transparency [4], optical nutation [5], superradiance [6], photon echo [7], generation of spatial gratings in materials by optical fields separated in time [8], etc. [9].

It is important in dynamic echo holography to retain correct information on the spatial distribution of the object-field phase in a medium to the instant of arrival of reference-wave pulse. Therefore, we will dwell on the reasons for the destruction of the macroscopic polarization induced by the object field in the medium. If an ensemble consists of atoms with the same intrinsic radiation frequency, the phase difference of individual-dipole oscillations could be retained to the end of the transition process in the absence of external effects (i.e., until all atoms pass to the equilibrium state). However, there are always perturbing external effects, which change the phase of individual-dipole oscillations by a statistical random change in the instantaneous intrinsic frequency of dipole oscillations. These changes occur irreversibly, are statistically identical for each atom, and lead to homogeneous broadening of the emission spectrum of the entire ensemble. This broadening is responsible for the reduction of the macroscopic polarization of the medium because of the gradual extraction of individual atoms from the coordinated emitting ensemble.

Thus, the phase memory time can be characterized in this case by an inverse of the homogeneous broadening of a given atomic transition (so-called transverse relaxation time T_2). Here, the homogeneous broadening is known to be a sum of natural radiative broadening and the component due to various external effects. Therefore, to decrease homogeneous broadening (i.e., to make the phase memory longer) it is necessary to suppress external effects. For example, cooling a crystal from room to low temperatures (several tens of kelvins) allows one to elongate the memory of a homogeneously broadened ensemble from 10^{-13} to 10^{-7} s. Homogeneous broadening in gases is caused by collisions and is less considerable. Therefore, the phase memory time in gases, especially molecular, is fairly long. The time during which macroscopic polarization becomes irreversibly destroyed may reach several hundreds of microseconds.

There is another, radically different mechanism of macroscopic polarization decay in the situation in which an ensemble is additionally inhomogeneously broadened. At this broadening, different atoms in an ensemble have different intrinsic frequencies (for example, because of local crystal-field inhomogeneities in crystals or due to the Doppler effect in gases). Therefore, after the forced transfer of a group of atoms to a pure superposition state using a short coherent-field pulse, when the field is switched off, the atoms emit field at their intrinsic frequencies in the presence of the same phase at the instant when the pump is over. In this case, collective oscillations are misphased not only because of irreversible random changes in the intrinsic frequency, but are also caused by the phase shift $\delta\omega t$ during time t, where $\delta\omega$ is the spread of the isochromates involved in the process near the pump frequency. This de-phasing of macroscopic polarization is in principle reversible, and polarization can be reconstructed at some instant after this process is started by irradiation with additional light pulses. Specifically, this reversibility property is used to generate coherent responses by an atomic system (optical transients) [9] and for holographic time–space recording of optical information.

TRANSFORMATION OF OPTICAL WAVE FIELDS IN ECHO HOLOGRAPHY

Recording, reconstruction, and transformation of light wave fronts can be performed both in homogeneously broadened atomic ensembles and in the case of inhomogeneous broadening using optical transients of a system. In this case, information on the phase perturbation of the medium formed by an object wave is fixed both in nonequilibrium polarization waves and in the pattern of local distortions in the pattern of local curving of layers of the periodic structure of a population density (transient induced gratings).

In the former case, information about the object can be reconstructed in signals of self-diffraction [10], free polarization, and primary photon echo [2, 11]. The primary (double-pulse) photon echo is the response arising after applying the second pump pulse. Its delay time coincides with the interval between the first two pump pulses. Here, the information storage time is limited by transverse relaxation parameter T_2. At the same time, using gratings in a solid, one can perform longer-term information storage. Decay of the state inversion grating is determined by the destruction time of the longitudinal component of the Bloch vector (longitudinal-relaxation time T_1), which significantly exceeds T_2 in solids. In this case, the information can be reconstructed either in linear diffraction signals (with a probe pulse applied) or in the form of stimulated photon (three-pulse) echo, even after complete decay of the macroscopic polarization induced by object and reference fields in the medium (i.e., beyond the phase memory). The optical transient of a system to three subsequent pulses arises after the third pulse with a time delay equal to the interval between the first two pulses (object and reference fields). The possibility of recording and reconstructing light wave fronts in the photon echo geometry was considered for the first time in [2], where the term "echo holography" was introduced. Similar suggestions were later made in other works [12, 13]. Let us consider the specific features of this holography in more detail. In many practical cases, optical transitions can be studied within the two-level model of atom; the fruitfulness of this approach has been proven by many examples.

Let two time-spaced short pulses of monochromatic light with frequency ω, pulse areas θ_1 and θ_2, and wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ be incident at some angle with respect to each other on a two-level atomic system with transition frequency ω_j. If delay τ between the pulses is shorter than irreversible phase-relaxation time T_2, as was shown in [8, 14], a spatial hologram grating is induced on the atomic transition. The modulation depth of this grating depends on the degree of loss of the "phase memory" by the instant of second-pulse arrival. The simplest pattern is observed at exact resonance between the pump frequency and the frequency of the working transition in the medium, provided that the pulse is short in comparison with transverse relaxation time T_2.

In this situation, a population grating (immobile in space) is formed during the second pulse. When this pulse is over, the grating decays with longitudinal-relaxation time T_1:

$$\Delta N(\mathbf{r},t) = N_o\{1 + (A-1)e^{\frac{\tau-t}{T_1}}\}, \quad (2)$$

where N_o is the particle concentration, $A = \cos\theta_1\cos\theta_2 - e^{-\tau/T_2}\sin\theta_1\sin\theta_2\cos\phi(\mathbf{r})$, $\phi(\mathbf{r}) = \delta\mathbf{kr} + \omega\tau + \varphi_1(\mathbf{r})$ is the phase, $\delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$ is the grating vector, and the function $\varphi_1(\mathbf{r})$ is the phase information present in the weak perturbation of the first-pulse (object-field) wave front. Here, it is assumed that the second pulse is a plane wave (reference field). It can be seen that this hologram is formed only when atoms are transferred to a superposition state. If at least one of the pulses inverts the system (for example, at θ_1 or θ_2 equal to π) or returns it to the ground state (at θ_1 or θ_2 equal to 2π), the spatial modulation depth of the grating in (2) is zero. The most efficient hologram is formed at the $\left(\frac{\pi}{2}, \frac{\pi}{2}\right)$ interaction, when each pump pulse transfers the system to the state with a maximum dipole moment, and the delay is much shorter than the transverse relaxation time.

In the more general case, where an atomic system is inhomogeneously broadened (i.e., consists of many spin packets), a series of traveling frequency-shifted isochromatic polarization waves is induced in the medium. The character of spatial modulation becomes more complex. In particular, the inversion of transitions has the form of a set of gratings with parameters depending on the detuning from resonance, $\Delta = \omega - \omega_j$, where ω_j is the frequency of the jth isochromate,

$$m(\Delta,t) = D(\Delta,t) + C(\Delta,t)e^{-\tau/T_2}\cos[\delta\mathbf{kr} + \phi(\Delta,t)]. \quad (3)$$

Parameters $D(\Delta,t)$, $C(\Delta,t)$, and $\phi(\Delta,t)$ depend in a complicated way on the pumping conditions. Analytical expressions were obtained for them in [15] by solving the Bloch equations (modified for the optical range) without any limitations, except for the assumption that there is a rectangular shape of pulses and a large saturation parameter ($\Omega > T_2^{-1}$, where Ω is the Rabi frequency). The characteristics of these gratings change in a complicated way during pumping (gratings are formed, disappear, arise again, and travel in space). When pumping is over, the gratings cease to move and a complex interference pattern is frozen in the medium. However, it should be noted that this complex pattern, although frozen in space, decays in the course of time. In the time interval $t > T_2$, all phase collective relations are averaged. The grating decay in this stage being determined by only the energy characteristics of transition. This decay of holograms occurs with longitudinal relaxation time T_1, which determines the tendency of the system toward thermodynamic equilibrium. More detailed information on the conditions of transient-grating generation in systems with phase memory can be found in review [16].

In the cases of both homogeneous and inhomogeneous broadening, information can be extracted from these holograms using a probe wave, as in conventional holography. An inhomogeneously broadened system can independently generate an optical transient, making it possible to reconstruct the phase information in the primary and stimulated photon-echo signals. This is possible because the dynamics of hologram formation is closely related to the polarization induced in the medium, which has the form of traveling perturbation waves. Under certain conditions, the latter can be phased in space.

In the general case of multipulse pumping, a system evolves in such a way that any polarization wave existing in the medium by the instant of any applied pulse arrival serves as a source of two new polarization waves. The number of new waves and gratings increases nonlinearly with an increase in the number of pump pulses. After the nth pulse of a field with wave vector $\mathbf{k}_n$ at arbitrary instant t_0, these polarization waves have the form

$$p_n(t - t_0) \approx \{m_{n-1}(t_o)\sin\theta e^{i(\mathbf{k}_n\mathbf{r} - \pi/2)} + p_{n-1}(t_0)\cos^2(\theta/2) + p^*_{n-1}(t_0)\sin^2(\theta/2)e^{i(2\mathbf{k}_n\mathbf{r} - \pi)}\}e^{i\omega_j(t - t_0)}. \quad (4)$$

Step-by-step joint use of (3) and (4) at an arbitrary number of pump pulses allows one to trace the evolution of the system, creation and annihilation of polarization waves and level-population gratings, excitation transfer from one wave to another, etc. The evolution of a system under multipulse pumping was studied in detail in [17], where it was shown that, after the effect of n pulses, 3^{n-1} polarization waves and $\frac{(3^{n-1} - 1)}{2}$ inversion gratings are formed in the medium in the general case. For example, Fig. 1 shows the character of evolution of an atomic system under three-pulse pumping.

In addition to conventional gratings, intermodulation gratings can also be formed under these conditions. These are products of multiwave interaction (an example is the grating with vector $\delta\mathbf{k} = \mathbf{k}_3 - 2\mathbf{k}_2 + \mathbf{k}_1$ in Fig. 1). This mechanism makes it possible to generate (under certain conditions) polarization waves with a large modulus of the wave vector, thus yielding a unique possibility of forming gratings with an ultralow period (with a step smaller than the half wavelength of the pump radiation used) [18].

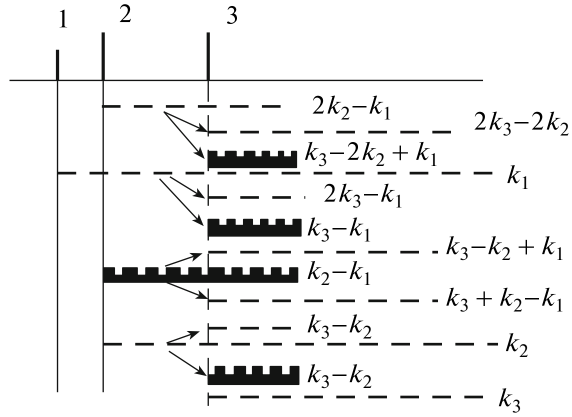

Fig. 1. Evolution of an atomic system under resonant pumping by three short light pulses (dashed lines indicate traveling polarization waves; immobile inversion gratings are shown as combs).

When the phase matching condition is satisfied, polarization waves are sources of coherent electromagnetic waves (responses of the system). For example, after the irradiation by the second pulse with a delay τ, along with the inversion grating three polarization waves are generated in the medium (see Fig. 1). The third polarization term in the isochromate ω_j in (4) is the result of interference of superposition states. Specifically, the re-phasing of oscillations for all isochromates of the form

$$p_3 = p^*(\tau)\sin^2(\theta_2/2)e^{2i(\mathbf{k}_2\mathbf{r} + \varphi_2)}e^{i\omega_j(t - \tau)} \quad (5)$$

at the instant $t = 2\tau$ is the source of primary photon echo. Indeed, the factor in (5) has the form $p^*(\tau) = \sin\theta_1 e^{-\tau/T_2}e^{-i(\omega_j\tau + \mathbf{k}_1\mathbf{r} + \varphi_1)}$; i.e., it is a wave complex conjugate to the polarization wave that was induced in the previous stage by the first pump pulse and contained phase information about its wave front. As can be seen in (5), at instant $t = 2\tau$, the dependence of p_3 on isochromate frequency ω_j disappears. This means that all isochromates have the same phase at this instant. This leads to re-phasing of oscillations of all atoms involved in emission, i.e., to the occurrence of hyperpolarization at this instant. In this case, the macroscopic-polarization amplitude, after averaging over the statistical ensemble [15], has the form of primary-echo pulse $p_3(t) \sim e^{-[(t - 2\tau)\delta\omega]^2}$ emitted in direction $2\mathbf{k}_2 - \mathbf{k}_1$ with deviation from plane wave front $\varphi_{pe}(\mathbf{r}) = 2\varphi_2(\mathbf{r}) - \varphi_1(\mathbf{r})$. When the phase-matching condition is satisfied, the light field generated by this polarization contains information on the phases of the wave fields of both pump pulses. In this stage, the shape of the echo wave front depends on the sequence in which these pulses arrive.

Let us consider particular cases of different reconstruction and transformation of wave fronts for different sequence orders of pump pulses.

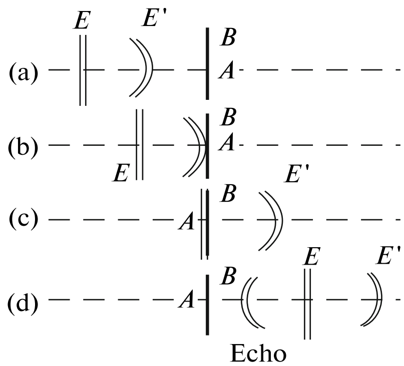

Fig. 2. Phase conjugation in the primary photon-echo signal under sequential collinear pumping of a resonant medium by object and reference pulse fields: (a, b) before and (c, d) after pumping.

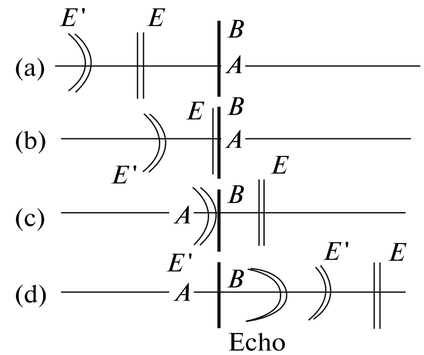

Fig. 3. Doubling of the wave front of primary photon echo under collinear pumping of a resonant medium by a sequence of reference and object fields.

Let the first pulse be an object wave with information laid in phase perturbation $\varphi_1(\mathbf{r})$. The second pulse is a plane reference wave, i.e., a wave with $\varphi_2(\mathbf{r}) = 0$. In this case, $\varphi_{pe}(\mathbf{r}) = -\varphi_1(\mathbf{r})$; i.e., the photon echo has a wave front complex conjugate with the object wave front.

A change in the sequence order of pulses (when the plane reference wave with $\varphi_1(\mathbf{r}) = 0$ arrives first and is followed by an object wave with information $\varphi_2(\mathbf{r})$) leads to a change in the primary echo front. Now, the front echo has a doubled (in comparison with the object wave) phase perturbation: $\varphi_{pe}(\mathbf{r}) = 2\varphi_2(\mathbf{r})$. This dynamic doubling of fronts can be used to increase the sensitivity of interferometric measurements of weak phase inhomogeneities (for example, nonstationary gas flows at low pressures). A similar concept of increasing measurement sensitivity was implemented in [19], where a front with doubled curvature was formed in the second diffraction order at reconstruction from a conventional hologram recorded in a medium with a nonlinear exposure characteristic.

The character of front reconstruction in primary-echo signals can be clarified by the following simple considerations. Let reference and object waves propagate in the same direction ($\mathbf{k}_2 = \mathbf{k}_1 = \mathbf{k}$). Then the echo will also propagate in this direction ($\mathbf{k}_{pe} = 2\mathbf{k}_2 - \mathbf{k}_1 = \mathbf{k}$). Let a divergent object wave E' act before the plane reference wave E (Fig. 2a). When approaching the recording medium, the object wave excites sample atoms located in different regions of the medium at different instants (Fig. 2b). All particles located in the vicinity of point **A** are excited before the particles located in the vicinity of point **B**. Since pumping of the particles situated near point **A** also ceases earlier, misphasing of dipole oscillations (which starts when pumping is over) near point A will also begin earlier than near point **B**. Therefore, when the plane waves arrive simultaneously at points **A** and **B** (Fig. 2c), the dipoles at these points have different phases (the misphasing at point **B** is smaller than at point **A**). After passage of wave E, the reverse process of dipole dephasing starts simultaneously at points **A** and **B**. It will take more time for the dipoles at point **A** (as compared with the dipoles at point **B**) to be phased after time τ and generate an echo signal. Therefore, echo will arise earlier at point **B** (Fig. 2c), which should lead to bending of the wave front in the opposite direction. Thus, there will be three waves to propagate behind the hologram: E', E, and convergent wave E_{pe} in the form of echo (Fig. 2d).

Let us consider the reverse sequence of pump pulses (Fig. 3), where plane wave E is first to come, while object wave E' arrives after time τ. Here, misphasing will begin simultaneously at all sample points after the reference-wave passage and dephasing at point **B** will be delayed by the time $(\tau_B - \tau_A)$ in comparison with that at point **A**. Therefore, an echo will arise at point **A** earlier (by the time $2(\tau_B - \tau_A)$) than at point **B**, which will double the wave front perturbation. Other, different situations can be explained similarly. For example, if the pump pulse fronts are chosen to be self-conjugate ($\varphi_1(\mathbf{r}) = -\varphi_2(\mathbf{r}) = \varphi(\mathbf{r})$), the echo wave front will have a triple perturbation of reverse curvature with respect to the first pulse: $\varphi_{pe}(\mathbf{r}) = -3\varphi(\mathbf{r})$.

One of the drawbacks of double-pulse echo holography is that it does not allow one to reconstruct the wave front of the object wave exactly. In addition, in the case of a complex wave front shape, when the spatial-frequency spectrum is wide, there is a distortion at a large angle between the pump beams. The reason for this is that the wave-matching condition for the high-frequency components of the Fourier spectrum of object-wave spatial frequencies becomes violated. The distortions are minimum only at angles between the object-wave components with higher spatial frequencies and a reference wave no larger than 3° [2, 8]. These limitations are removed upon multiwave nonsimultaneous interaction, i.e., when the case in point is the wave front of the echo response of a system to three or more pulses. For example, an exact copy of the object-wave front can be obtained in three-pulse (stimulated) photon echo signals, when the sequence of pump pulses corresponds to that shown in Fig. 4 (the first pulse is a plane reference wave, and the second one is an object wave). Here, application of pulses *1* and *2* results in freezing of spatially misphased immobile holographic inversion gratings (see formula 3 and Fig. 1) with vectors $\mathbf{k}_{12} = \mathbf{k}_2 - \mathbf{k}_1$ in a medium with memory. The photon-echo pulse arising after their irradiation by plane waves *3* is an exact replica of the object wave.

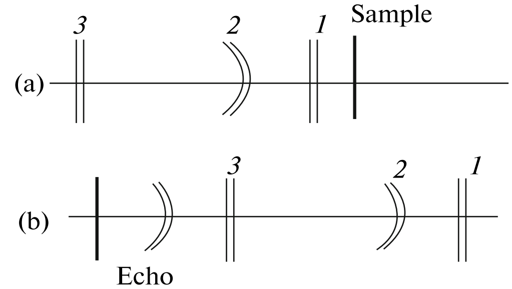

Fig. 4. Exact reconstruction of the wave front in a stimulated photon echo signal under collinear pumping: (a) before pumping and (b) after excitation of the medium by three pulses.

In the more general case of noncollinear pumping and an arbitrary shape of the reference-wave front, each component of the spatial Fourier spectrum of the object wave in the thus-formed stimulated-echo signal propagates in directions $\mathbf{k}_{se} = \mathbf{k}_3 + \mathbf{k}_2 - \mathbf{k}_1$, for which the wave-matching condition is exactly satisfied. The wave front can also be exactly reconstructed in the situation where a medium is first exposed to a nonplanar reference wave with phase perturbation $\varphi_1(\mathbf{r})$; it is followed by an object wave with $\varphi_2(\mathbf{r})$; and, finally, a reading wave which should be a copy of the reference wave, i.e. to have the same direction $\mathbf{k}_3 = \mathbf{k}_1$ and the same wave front $\varphi_3(\mathbf{r}) = \varphi_1(\mathbf{r})$. In this case, each spatial-spectrum component will be reconstructed without distortions.

Here, we are dealing with a more general (in comparison with the conventional holography) principle of recording and reconstruction of wave fronts, because, along with the memory of the wave front, this hologram stores information on the sequence order of the object and reference waves and the delay of the object wave with respect to reference.

Stimulated echo, as well as primary echo, also yields a complex-conjugate replica of the object wave. This occurs when an object wave arrives first and is successively followed by two more waves. Here, complete phase conjugation can be obtained if the second and third waves have exactly opposite directions ($\mathbf{k}_2 = -\mathbf{k}_3$) and complex-conjugate wave fronts. In this case, similarly to the well-known simultaneous four-wave mixing in the presence of a standing wave, both the direction and wave front of stimulated echo are phase-conjugate with respect to the first (object) wave. The only difference is that the phase-conjugate wave is delayed in time after the reading-pulse arrival.

Phase-conjugate backward photon echo was experimentally observed for the first time in [8] and then investigated in detail in [20, 21]. In these studies, the resonant medium was a ruby crystal with a concentration of Cr^{3+} ions of 0.03%. The sample had a cubic shape with a 10-mm edge; it was cooled to 2 K to elongate the phase memory of the medium. A resonance at the $^4A_2(\pm 1/2) - {}^2E(\bar{E})$ transition (with wavelength $\lambda =$ 6934 Å at 2 K) was excited by a ruby laser. To obtain generation on the second component of the same doublet ($\lambda = 6933.97$ Å), this laser was cooled to 77 K and generated a 10-ns pulse with a power of 1 MW.

The sample was irradiated with two light pulses separated by time interval τ along the crystal optical axis. The angle between these beams was 5°, which provided spatial separation of the pump wave and echo signal. The signal was amplified by applying a weak (to 250 Oe) longitudinal magnetic field to the sample in order to remove degeneracy of ground state $^4A_2$. A phase-conjugate photon echo was observed in direction *4* (see scheme in Fig. 5) following sample pumping by pulses *1* and *2* separated in time.

The second pulse, reflected from plane mirror M (with a controlled delay), was used as the third (reading) pulse *3*. A system of conjugate lenses with focal length $f = 50$ cm made it possible to align the caustics of all beams in the overlap region and enhance their intensity. In fact, phase-conjugate echo *4* had a direction opposite to that of beam *1* and reverse divergence, i.e., had a complex-conjugate wave front.

The phase-conjugation quality was verified by introducing an aberration into signal beam *1* using transparent etched plate FM, which played the role of spatial phase modulator. After the first pulse passed through this plate, its wave front became distorted and the divergence of radiation significantly increased (see Fig. 6a, *1*). The introduced wave front aberrations were completely compensated for in the wave of phase-conjugate photon echo after its passage through the same phase plate FM but in the opposite direction (Fig. 6b, *1*). This is direct evidence that the echo front is complex-conjugate with respect to the front of the first pump wave transmitted through the modulator FM. For comparison, Fig. 6a (*2*) shows the shape of beam *1* after its reflection by a plane mirror installed instead of the phase plate FM. It can be seen that, when the object wave has a wider spatial-frequency spectrum (a phase plate is introduced), the echo (Fig. 6b, *1*) reproduces more the pump beam geometry correctly (Fig. 6a, *2*). The reason for this is the more favorable mixing of spatial frequencies in the

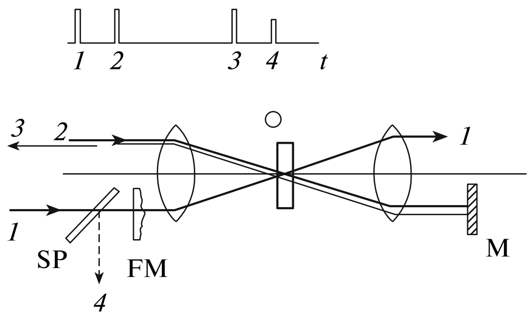

Fig. 5. Schematics of the experiment.

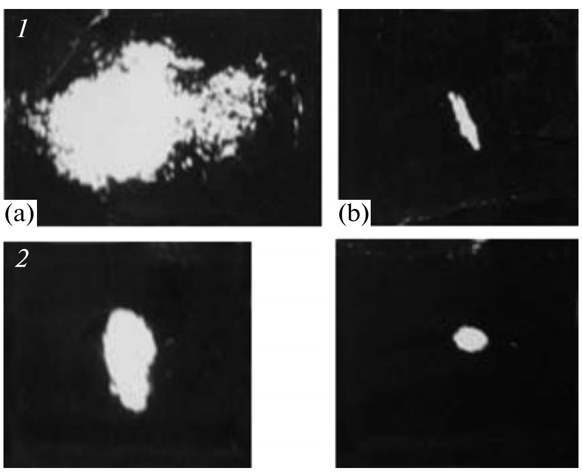

Fig. 6. Spatial-frequency spectrum for a reflected beam: (a) reflection of beam *1* by a plane mirror mounted directly after FM (see Fig. 5) and (b) reflection by a phase-conjugate echo mirror (*1*) with and (*2*) without a phase plate.

beam-overlap region, due to which caustic filling becomes more complete and the sample is excited homogeneously. Another consequence of this principle of phase conjugation is the transformation of the divergent first pump beam (Fig. 6a, *2*) into a convergent photon-echo beam (Fig. 6b, *2*).

The exact compensation of the distortion of the object-beam wave front (caused by introduction of a phase plate) using the above-considered scheme makes it possible to consider such a system as a phase-conjugate echo mirror. In this case, phase conjugation of the wave fronts involved in hologram recording is caused by the above-described peculiar time reversal. In the sample points where dipole oscillations are leading in phase, irradiation by the third pulse causes a lag in phase by the same value. In accordance with the general principle of holography, this leads to formation of a pseudoscopic image of an object.

Generally, the instant of dipole phasing depends on many conditions. For example, in the case of pumping by long pulses, when the dipole de-phasing during the time when a field acts on the atomic system cannot be neglected, an additional shift of echo in time is observed [15]. Under certain conditions, this may lead to undesirable distortion of the wave front in the complex-conjugate replica of the object field.

CONCLUSIONS

To conclude, we can indicate some prospects of using this method of time–space data recording on induced transient dynamic gratings.

The formation of dynamic echo holograms in multilevel atomic systems opens wider possibilities for carrying out various transformations of light wave fronts. This is especially important when passing from one wavelength to another or, for example, from the optical range to acoustic and vice versa. Acousto–optic transformation of wave fronts in echo holography allows one to visualize information laid in an acoustic wave. For example, in the situation where an acoustic plane wave comes first; then, an acoustic object wave arrives; and, finally, a plane light wave is supplied, the wave front of stimulated photon echo repeats the shape of the acoustic wave front [22]. One of the interesting properties of echo holograms is the possibility of separating reconstruction of information about the leading and trailing wave fronts of pulse object field [23].

In addition, echo holography makes it possible to perform recording and complete reconstruction of information about the character of transient processes. For example, a cw light beam rapidly scanning over the sample surface can be used as one of the pump waves. In this case, either a forward- or backward-scanning track (depending on the sequence order of pump pulses) can also be reconstructed in a stimulated echo. Another interesting aspect of the application of transient gratings is the study of the relaxation and spectroscopic characteristics of atomic transitions (measurement of dipole moments, transverse and longitudinal relaxation times, weak level splitting, etc.) in order to establish fundamental regularities of the interaction between coherent light and matter.

Recently, much attention has been paid to three-level quantum systems, which open new possibilities for controlling quantum coherence of atoms [24–27]. Here, one should expect the occurrence of new interesting properties for implementing dynamic echo holography; the above-considered problems are very closely related to the development of optical quantum memory [27–29].

New achievements in the field of photon echo [28, 30–38] that make it possible to retain (with a high efficiency) the quantum information present in a large number of light modes appear to be very promising for developing optical quantum memory and quantum holography. The first experimental results showed the possibility of obtaining record quantum efficiency (87%) [39], recording and effective reconstruction of 1060 light modes [40], and preserving light quantum states [41, 42]. All this gives grounds to expect progress in the development of optical quantum computers [43], the operating speed of which is based specifically on the combination of spatial and temporal characteristics of transformation of fields upon their coherent interaction with matter.

Finally, we should note that the formation of interference patterns by waves separated in time is of fundamental scientific importance. Indeed, the modern theory of interferometry in classical optics considers the formation of interference patterns with allowance for only coherent properties of optical fields and disregards the phase memory of recording media. Therefore, it is accepted that, to obtain interference patterns, the delay between interfering beams should not exceed the coherence length of the radiation source used. This limitation is removed in the presence of phase memory. It appears that consideration of this circumstance should expand significantly and generalize the theory of interferometry, which, in turn, will facilitate the development of interferometric methods.

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