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Simultaneous generation of *N* coherent pulses of various areas under self-diffraction in ^{87}Rb vapors

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Subject of study. **The self-diffraction process of a resonant pulse in a dense extended resonant medium was studied for the first time to our knowledge. This process leads to an angular deflection of the output radiation and sequential emission of a large series of N pulses with a variable area in the range $(-3\pi, \ldots, 0, \ldots, 3\pi)$. The pulses are emitted from a small focusing region (0.1–1 mm) of the pump pulse in a dense extended resonant medium. The pulse wavelength corresponds to the resonant transition D_2 ^{87}Rb (wavelength 780.24 nm).** ***Aim of study.*** **The nonlinear effect of the self-diffraction of a laser pulse with a cylindrical wavefront is studied in an extended resonant medium of rubidium vapor to develop new resonant microwave photonics devices using laser signal-processing methods in the microwave spectrum.** ***Method.*** **A transverse spatial profile of the electric field strength of a special shape $f(x)$ is created in the caustic of a focused beam of a laser pump pulse with a cylindrical wavefront. The pump pulse must have a converging (for example, cylindrical) wavefront. Computer-synthesized holograms developed by us are used to create an arbitrary $f(x)$ profile.** ***Main results.*** **The effect of the self-diffraction of a pump pulse is studied. This is accompanied by the emission of a series of N coherent resonant pulses with different areas in the range $(-3\pi, \ldots, 0, \ldots, 3\pi)$ from a short focusing region (0.1–1 mm) of a resonant laser pump pulse. The self-diffraction of the pump pulse resulted in 16 emitted pulses with different areas. The distribution of series pulses over the diffraction angle was observed in the angle range from $-5°$ to $+4°$. The nonlinear generation of 0π-pulses was observed at some angles. The results verify the nonlinear generation of 0π-pulses over a short interaction length between light and a resonant medium for the first time to our knowledge.** ***Practical significance.*** **The obtained results on the effect of the self-diffraction of a resonant pulse with a transverse spatial profile $f(x)$ will serve as a basis for the development of prototype devices for signal-processing problems using low-power laser diodes.**

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1. INTRODUCTION

Recently, significant progress has been made in the field of ultrafast processing of wideband optical signals. New all-optical laser methods of information processing and signal control have enabled a fundamentally different approach to solving problems that are inaccessible to electronic signal-processing methods. For example, the fast, fully optical deflecting of laser pulses along the propagation angle was proposed to solve the problem of the analog-to-digital conversion of nano- and picosecond optical pulses.

Laser-pulse deflecting along an angle with a high angular velocity is relevant for controlling optical signals and the temporal analysis of short laser pulses [1]. We recently proposed and implemented a new method for the fast deflecting of laser radiation that uses the coherent effects of the interaction between laser radiation and a resonant medium [2,3]. The operating principle of a coherent deflector is based on the creation of a dynamic light-induced transverse diffraction grating of resonant polarization using a medium with a time-varying spatial pitch. Hence, the self-diffraction angle of light in a resonant medium changes during the pump pulse under the action of the input pulse field $E(t, x, y, z)$ and is controlled by its current "area" [4] $\theta(t, x, y, z)$.

Thus, the solution is reduced to obtaining a controlled profile of the resonant polarization of the medium $P(t, x, y, z)$, which is achieved by modulating the input pump pulse in time and space. In this study, we consider a simple case in which the spatial profile of the pump field depends on only one coordinate $x - E(t, x) = \mathrm{E}(t) f(x)$. Here, $f(x)$ is the unit function describing the transverse profile of the pump field. In these experiments, $f(x)$ has a simple Gaussian function $f(x) = \exp[-(x/s)^2], s = 0.017$ mm.

Previously, laser pulses shaped in time in a special manner (modulation according to a certain temporal law of amplitude, frequency, or phase) were shown to increase the rate of multiphoton transitions upon the excitation of atoms, molecules, and quantum dots [5–8]. Moreover, a single pulse in the absence of special amplitude and phase modulation is not optimal [7]. A particular sequence of pulses with phase modulation can enable this transition at a lower total energy. This feature can reduce the energy of the pump pulse by 6–8 orders of magnitude if we additionally utilize the excitation of the parametric collective resonances of an ensemble of atoms and the field in the cavity [9,10].

This study proposes the application of this approach to the spatial coordinates describing the pulse field (modulation of the spatial phase and wave vector of the wave), which can be used in special problems in all-optical signal processing and quantum technologies.

In the traditional problem formulation of the nonresonant pumping of a single two-level quantum system by a specially prepared pulse, it is necessary to identify the pump-field profile $E(t, x, y, z)$ at which the quantum transition occurs at the minimum pulse energy. The problem is solved by determining the trajectory of the Bloch vector along the Bloch sphere [4] during the transition between the initial and final states $(u', v', w') \rightarrow (u'', v'', w'')$ of the atomic system. Here, u, v, and w are projections of the Bloch vector.

We consider a more complex process: $(u', v', w') \rightarrow (u'', v'', w'') \rightarrow (u', v', w')$. For example, the transition of a quantum system from a pure lower state to a superposition quantum state with maximum polarization and back to its initial state—$(0, 0, -1) \rightarrow (0, \pm 1, 0) \rightarrow (0, 0, -1)$—during the pump pulse. This is because the medium polarization radiation pulses should not have a long "tail" that slows the signal processor and reduces its clock frequency.

According to the McCall–Hahn area theorem [4], the 0π- and 2π-pulses have such properties. When a pulse propagates in an extended resonant medium, each atom returns to its original (ground) state after the end of the pulse. However, if approached from a practical point of view, the advantages of 0π-pulses over solitons based on the theory of self-induced transparency, i.e., 2π-pulses, are easily observed. In practice, the laser beam has a finite diameter; therefore, the wavefront of a soliton based on the theory of self-induced transparency must differ from the ideal plane front, which is considered in the classical McCall–Hahn theory of self-induced transparency [4]. As the generalization of the theory of self-induced transparency for the three-dimensional case shows, when propagating in an extended resonant medium, a 2π-pulse with a non-plane wavefront becomes unstable and decays. Moreover, in the three-dimensional case, a 0π-pulse with an arbitrary wavefront propagating in an extended medium changes the shape of $E(t)$ but maintains an "area" equal to 0. When a 0π-pulse propagates in a medium with a degenerate resonant transition or a transition with an inhomogeneous type of broadening, its area of 0 is also preserved, in contrast to that of the 2π-pulse.

An arbitrary pulse with an initial area $\theta < \pi$ asymptotically transforms into a 0π-pulse as it propagates in an extended resonant medium [4,11–13]. Because this effect has a phase nature, the transformation of the input pulse into a 0π-pulse can be achieved in a dense resonant medium of considerable length. In the gas phase, the required interaction distances may be tens of centimeters.

The 0π-pulse is formed as a long decaying train of pulses with a periodic change in the carrier phase by π. From a physical perspective, this corresponds to the process of multiple absorptions and periodic re-emissions of the medium in the form of superradiance pulses without population inversion. Thus, this process is called "optical ringing."

Single-photon input pulses propagating in an extended medium were shown to transform into single-photon 0π-pulses [14,15]. However, despite the ease of obtaining 0π-pulses in this manner, the long oscillating process at their trailing edge makes them unsuitable for use in a high-speed signal processor.

The temporal properties of laser pulses can also be formed by linear optical systems based on two diffraction gratings. Reviews of modern linear methods of pulse formation are given in [16,17]. In this method, the amplitude spectrum of the input pulse $E_{\mathrm{in}}(t)$, which is limited by its duration, is localized in the focal plane of the first lens. An amplitude-phase spatial light modulator is located in this plane, and it modifies the amplitude spectrum of the input pulse based on its amplitude-phase transmission function.

The second lens and diffraction grating combine the Fourier components of the modified spectrum in space to obtain the output pulse $E_{\mathrm{out}}(t)$ of the required shape.

The amplitude-phase spatial light modulator can be implemented based on controllable liquid-crystal matrices or matrices of micromirrors. The described linear method of forming a pulse of the required shape was recently implemented using such a modulator in the form of a metasurface, which is a surface with vertically arranged nanorods [18].

Notably, this method works well with femtosecond pulses with a wide frequency Fourier spectrum but becomes inefficient in the case of nano- and picosecond pulses with a narrow spectrum.

Therefore, we propose a different nonlinear method for generating 0π-pulses that maintains a short pump-pulse duration at a short nonlinear-interaction length between the pulse and a resonantly absorbing medium.

Thus, the aim of this study is to investigate the nonlinear effect of the self-diffraction of a laser pulse with a cylindrical wavefront in an extended resonant medium of Rb vapor, which can be used in special problems in all-optical signal processing and quantum technologies to develop new resonant radio-photonics devices.

2. EXPERIMENTAL SETUP

A simplified scheme of the experimental setup is shown in Fig. 1. The complete installation scheme is given in [3].

The laser-pulse generator was set up based on the “master oscillator-amplifier” scheme. The master oscillator TLD-799.8-14BF is a continuous single-frequency laser diode with a linewidth of 0.1 MHz that can be tuned near the frequency of the resonance line D_2 of ^{87}Rb atoms (wavelength $\lambda = 780.24$ nm). The master oscillator frequency was at the D_2 ^{87}Rb line resonance frequency within ±100 MHz and was controlled by varying the laser-diode injection current. Under the experimental conditions, the total Doppler linewidth D_2 was $\Delta\nu_D \approx 500$ MHz.

Continuous radiation from a laser diode was directed along a single-mode optical fiber to a SOA-780-14BF pulsed semiconductor laser amplifier, which was excited by a nanosecond current generator. The amplifier generated pump pulses with a duration of 5.15 ns and maximum pulse power of 10 mW. The pulse energy did not exceed 40 pJ, and the total “area” of the pulse was $\theta_{\text{in}} = 3\pi$. The pulse repetition frequency was 200 kHz.

The laser pulse had a linear polarization, and the direction of the electric-field-strength vector **E** was horizontal.

After the amplifier, the laser radiation was formed by a collimator and exhibited the form of a parallel Gaussian beam with a diameter of 800 μm.

The generated pump-laser pulse was directed to a cell containing isotopically pure ^{87}Rb vapor. The concentration of Rb atoms was controlled by the temperature of the cold offshoot of the cell and corresponded to $N_o = 2.72 \times 1012\ \text{cm}^{-3}$. The temperature of the cell offshoot and cell windows was controlled by thermocouples with an accuracy of 0.1°C, and the cell length was 75 mm.

The laser pulse was focused by a lens at a distance of 5 mm from the exit window of the cell. The length of the nonlinear-interaction region between the pump pulse and Rb atoms was 0.1–1 mm.

The required transverse profile of the laser pump beam $f(x)$ with a cylindrical wavefront was formed in the focal plane of a cylindrical lens with a focal length of 100 mm. Thus, the necessary profile of the pump-laser beam $f(x)$ was formed in the resonant cell with Rb vapor on the x-axis (Fig. 1) in the focal plane of the lens.

The focused beam had a spatial profile in the form of a Gaussian function and a size of 20 μm along the transverse coordinate x. The distribution $f(x)$ in the beam caustic had the form $f(x) = \exp[-(x/s)^2], s = 0.017$ mm.

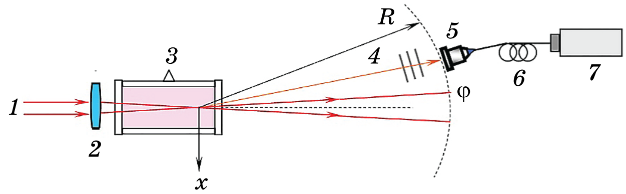

Fig. 1. Simplified scheme of the experimental setup. (*1*) Pump pulse, (*2*) cylindrical lens, (*3*) cell with ^{87}Rb vapor, (*4*) neutral attenuation filters, (*5*) collimator, (*6*) single-mode fiber, (*7*) MPD PD-050-CTD-FC single-photon avalanche diode.

Laser pulses emerging from the resonant medium at an angle of φ were directed by a collimator into a single-mode fiber. To achieve this, the collimator was moved along a circle with a radius $R = 500$ mm (Fig. 1).

The laser pulses resulting from the self-diffraction of the pump pulse were directed to an avalanche photodiode to detect individual photons of the output pulse.

In front of the collimator, the light flux was attenuated by neutral-density filters such that the probability of registering one photon did not exceed 1/4–1/5 per laser pulse.

Pulses with single photons were transmitted to a BH SPC130 multichannel time analyzer. The analyzer had 4096 time channels and generated an oscillogram of a laser pulse in the form of a time histogram of detected photons—the distribution of the number of photons per time channel. The time resolution of the entire registration system was 27 ps.

3. EXPERIMENT RESULTS

Two pulse histograms were recorded during the experiment: a signal histogram $S_1(t)$ (with a cell with Rb vapor) and a reference $S_2(t)$ (in its absence). The method used to further process histograms $S_1(t)$ and $S_2(t)$ is described in [3]. When analyzing the experimental histograms, the time dependence of the medium polarization re-emission field $E_p(t)$ can be extracted in the form $S_1(t) - S_2(t) \approx 2E_{\text{in}}(t)E_p(t)$, where $E_{\text{in}}(t)$ is the known time profile of the pump pulse at the entrance of the medium.

For this problem, the method of presenting the experimental data must determine the strength of the medium polarization field $E_p(t)$ instead of the intensity $|E_p(t)|^2$, and it must retain information about the sign of the $E_p(t)$ envelope. Thus, the pulse area $E_p(t)$ can be determined from the processed experimental data.

The semiclassical Maxwell–Bloch equations were solved numerically to simulate the effects of pulse self-diffraction, and the given field of the pump pulse had the form $E_{\text{in}}(t, x) = E_{\text{in}}(t)f(x)$. A resonant two-level medium with a uniformly broadened transition was considered in the calculations. The value of the function $2E_{\text{in}}(t)E_p(t)$ was calculated, and it had a shape similar to that of the processed experimental signal.

The calculation considered the realistic shape of the pump-laser pulse $E_{\text{in}}(t)$ versus time, which was determined in terms of the number of photons per time channel of the pulse analyzer $E_{\text{in}}(t) \sim (N_{\text{ph/channel}})^{1/2}$. In the calculations, the area of the pump pulse was $\theta_{\text{in}} = 3\pi$, which corresponded to the experimental values. The calculation results for various self-diffraction angles φ are shown in Fig. 2. The results show that, by using the nonlinear method to form the time profile of the pulse, the resonant medium can simultaneously emit N coherent resonant pulses with different areas $(-3\pi, \ldots, 0, \ldots, 3\pi)$ at different self-diffraction angles φ.

Experimental data for the same self-diffraction angles are shown in Fig. 3. A series of generated pulses with different areas was divided by the propagation angle in the range of −5° to +4°. The number of recorded self-diffraction angles reached 16.

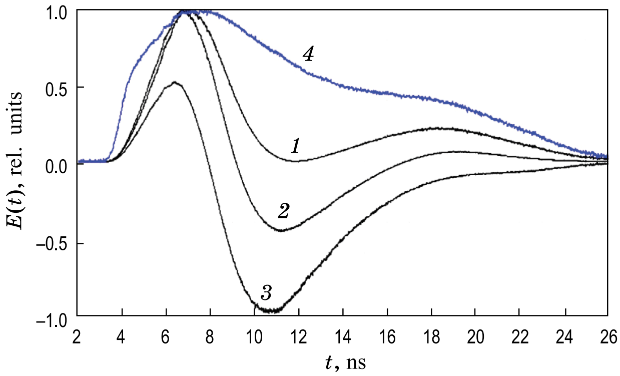

Fig. 2. Solution of the Maxwell–Bloch equations for the normalized function $2E_{\text{in}}(t)E_p(t)$. (*1*) Registration of pulses $E_p(t)$ at an angle $\varphi = 0.78°$ (pulse area $\theta > 0$), (*2*) at an angle $\varphi = 1.82°$ (pulse area $\theta = 0$, 0π-pulse), (*3*) at an angle $\varphi = 2.86°$ (pulse area $\theta < 0$), (*4*) experimental pulse shape $E_{\text{in}}(t)$.

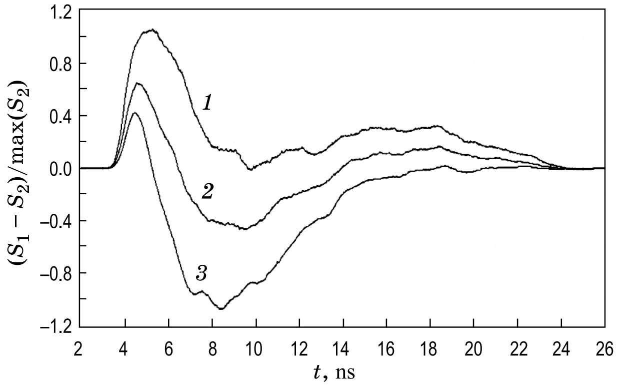

Fig. 3. Measurement results of the function $2E_{\text{in}}(t)E_p(t)$. (*1*) Registration of pulses $E_p(t)$ at an angle $\varphi = 0.78°$ (pulse area $\theta > 0$), (*2*) at an angle $\varphi = 1.82°$ (pulse area $\theta = 0$, 0π-pulse), (*3*) at an angle $\varphi = 2.86°$ (pulse area $\theta < 0$).

As shown in Figs. 2 and 3, the corresponding time profiles of the calculated and measured functions $2E_{\text{in}}(t)E_p(t)$ are in qualitative agreement.

Notably, using this method of forming pulses with the required area, the duration of the resonant 0π-pulses (at $\omega = \omega_{12}$) is equal to that of the pump pulse; i.e., the task of maintaining a short pulse duration was achieved.

The radiation of the 0π-pulses occurred in a small region of nonlinear interaction between the pump pulse and the atomic medium (on the x-axis in Fig. 1) with a size of 0.1–1 mm; i.e., the task of creating a compact generator of 0π-pulses was also achieved.

4. CONCLUSION

The proposed nonlinear method for generating a series of pulses with different areas enables the following for controlling the temporal shape and area of the output pulse:

– adjustable transverse pulse profile $f(x)$,

– variable profile and an amplitude of the pump pulses in time $E_{\text{in}}(t)$,

– variable pulse registration angle φ.

The effect of the nonlinear formation of pulses with the required area is observed when using laser diodes of low power (10 mW) and pulse energy (40 pJ). This simplifies the development of prototypes of quantum electronics devices for processing optical signals and controlling their characteristics in time and space.

The proposed method for generating 0π-pulses differs from established methods in that the radiation pulses $E_p(t)$ of nonlinear polarization of the medium occur in a small volume of the medium at a short nonlinear-propagation distance (0.1–1 mm) of the pump pulse.

In this study, we used the spatial pulse profile in the form of a Gaussian function $f(x) = \exp[-(x/s)^2]$. To create an arbitrary $f(x)$ profile, it is convenient to use computer-generated holograms. After calculation, the hologram was output to an amplitude or phase spatial light modulator. The proposed method of mathematical calculation of the computer-generated holograms enabled the control of an arbitrary function $f(x)$ of the distribution of the field amplitude along the x-axis with an intensity ratio max/min of the order of 10^3.

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