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All-optical shaping of a three-dimensional self-induced transparency soliton in ^{87}Rb vapors

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Subject of study**. Three-dimensional solitons of the theory of self-induced transparency of laser pulses with a converging cylindrical wavefront and different transverse spatial profiles of the pulse field in ^{87}Rb vapor (resonant transition D_2, wavelength 780.24 nm) are studied.** ***Aim of study*****. The aim is the experimental study of three-dimensional solitons of self-induced transparency of laser pulses for the development of new device prototypes for resonant quantum microwave photonics using laser signal processing methods in the microwave region of the spectrum.** ***Method*****. In the caustic of a focused beam of a laser pump pulse with a cylindrical wavefront, a transverse spatial profile of the electric field strength of a special shape is created. The computer-generated holograms developed by us can be used to create an arbitrary profile.** ***Main results*****. The properties of a three-dimensional self-induced transparency soliton are studied for various detuning frequencies of the input pulse field with respect to atomic resonance. The maximum laser pulse power is 8.5 mW, the pulse duration is 4–5 ns, and the time resolution of the recording system is 27 ps. It is shown that the all-optical control of the carrier frequency of the input pulse determines the properties of the output pulse: compression of the pulse duration (generation of a strobe pulse), the value of the soliton delay in time, and the time shift of the carrier frequency of the soliton.** ***Practical significance*****. The results obtained in this study of the properties of three-dimensional self-induced transparency solitons will serve as the basis for the development of prototypes of signal processing devices using low-power laser diodes.** © 2023 Optica Publishing Group

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1. INTRODUCTION

Self-induced transparency (SIT) is a classical effect of quantum optics [1]. According to the McCall–Hahn area theorem [1], the "area" of a resonant optical pulse propagating in an extended absorbing resonant medium asymptotically tends to one of the values 0π, $\pm 2\pi$, or $\pm 4\pi$, depending on its initial "area." A significant simplification of the SIT theory is the assumption that the input pulse has an ideal plane wavefront (WF), and thus, the problem becomes one-dimensional. However, in real experiments, laser beams have a finite diameter, and this must be taken into account in the generalized three-dimensional SIT theory.

The first experiments [2,3] highlighting significant differences in the shape of experimental pulses and SIT solitons were reported in 1972. Then, it was theoretically shown (see, for example, [4]) that the solitons of the classical SIT theory are unstable when working without the plane wave approximation.

Three-dimensional SIT solitons were first experimentally studied in detail in [5] for a converging spherical WF of the pulse. In subsequent theoretical works, the theory of three-dimensional solitons for such a WF with the distribution of the field strength along the transverse radial coordinate in the form of a Gaussian function was developed in [6–10]. Considering the ultrasmall attenuation of the pulse energy during propagation, the effect was called "*supertransparency.*"

Subsequently, it was shown that two- and three-dimensional SIT solitons are stable under certain conditions [11].

It was shown that the McCall–Hahn SIT soliton in the form of a 2π pulse arises as a special case of the generalized 3D SIT theory when the spherical WF of the input laser pulse transforms into a plane WF. In accordance with the experiment [5], it was shown that the carrier frequency of the input pulse shifts to the long-wavelength region of the atomic transition of the resonant medium, after which the pulse changes its shape and propagates in the resonantly absorbing medium over long distances with virtually no loss of energy.

It was also shown that the governing physical effects leading to new soliton solutions of the problem are related to the effects of nonstationary resonant self-focusing and defocusing and have been studied in significant detail (see, for example, [12,13]). The mechanism of stability of a three-dimensional SIT soliton was called dispersion-diffraction and is not described by the concepts of the nonlinear susceptibility of the medium (nonlinear refractive and absorption coefficients). For a correct description of the dynamics of spatiotemporal phase modulation of a pulse, it is necessary to consider the propagation of a short pulse based on the coupled Maxwell–Bloch equations [1].

Systematic study of three-dimensional SIT solitons has attracted significant interest with the development of methods for all-optical formation of laser pulse characteristics for signal processing problems in quantum resonant microwave photonics. Interest in the use of spatially modulated pump pulses in a dense resonant medium is also associated with the discovery of a number of new effects and their applications [14–16].

The purpose of this work is to study the properties of three-dimensional SIT solitons, which is necessary for the development of novel resonant microwave photonics device prototypes using laser signal processing methods in the microwave spectral range.

Below, we provide experimental data on the properties of new three-dimensional SIT solitons with a cylindrical WF with a spatial distribution of the field of the following forms: $E(t,x)=E(t)f(x)$ in the form $f(x)=\exp[-(x/\sigma)^2]$, a Gaussian function, or $f(x)=\sin(\beta x)/\beta x$. Here x is the transverse coordinate in the focal plane of a positive cylindrical lens focusing the laser beam into a cell with a resonant medium, and E is the electric field strength.

2. EXPERIMENTAL SETUP

The laser pulse generator is constructed according to the "master oscillator-amplifier" scheme. The characteristics of the master oscillator are given in [17].

In this experiment, the master oscillator frequency was tuned stepwise within ±3500 MHz near the resonance of the D_2 ^{87}Rb line by modulating the laser diode injection current. The current modulation method was set programmatically in the NI USB-6363 data acquisition device in the LabVIEW environment.

Continuous radiation from a laser diode was directed along a single-mode optical fiber to an SOA-780-14BF pulsed semiconductor laser amplifier, which was excited by a nanosecond current generator. The amplifier generated pump pulses with a duration of 4–5 ns and a maximum pulse power of 10 mW. The pulse energy did not exceed 40 pJ. The pulse repetition frequency was 200 kHz.

After the amplifier, the radiation was collimated by a collimator in the form of a parallel Gaussian beam with a diameter of 800 μm and was directed to an optical slit with a variable width. The required transverse profile of the laser pump beam $f(x)$ with a cylindrical WF was formed in the focal plane of a cylindrical lens with a focal length of 100 mm. With a spatial profile in the form of a Gaussian function, the size of the focused beam was 20 μm along the transverse coordinate x. The distribution $f(x)$ in the beam caustic had the form $f(x)=\exp[-x/\sigma)^2]$, with $\sigma=0.017$ mm.

When the transverse spatial profile of the field $f(x)$ was formed with a lens in the form of a diffraction pattern on the optical slit $f(x)$ in the focal plane of the lens, it had the form $f(x)=\mathrm{sinc}(\beta x)$, with $\beta=24.3\ \mathrm{mm}^{-1}$.

The generated pump laser pulse was directed to a cell containing a vapor of isotopically pure rubidium ^{87}Rb. The concentration of Rb atoms was controlled by the temperature of the cold offshoot of the cell and varied from $1.87\times10^{10}\ \mathrm{cm}^{-3}$ (temperature 32.0°C) to $4.08\times10^{12}\ \mathrm{cm}^{-3}$ (98.0°C); the cell length was 75 mm. The laser pulse was focused at a distance of 5 mm from the exit window of the cell.

The laser pulse leaving the cell was focused by an objective into a single-mode optical fiber of 10-μm diameter and directed to an avalanche photodiode to detect single photons.

The avalanche photodiode pulses from single photons were sent to a multichannel time analyzer. The analyzer had 4096 time channels and generated an oscillogram of the laser pulse in the form of a time histogram of registered photons, i.e., the number of photons per time channel. The time resolution of the recording system was 27 ps.

3. EXPERIMENTAL RESULTS

Three-dimensional soliton-like SIT pulses were detected under conditions when the laser pump pulses had a spatial profile in the form of a Gaussian function $f(x)=\exp[-(x/\sigma)^2]$, with $\sigma=0.017$ mm. The concentration of rubidium atoms was $8.93\times10^{11}\ \mathrm{cm}^{-3}$.

Three-dimensional SIT solitons were also observed in the case of a spatial field profile of the form $f(x)=\mathrm{sinc}(\beta x)$, with $\beta=24.3\ \mathrm{mm}^{-1}$. The concentration of rubidium atoms was $4.08\times10^{12}\ \mathrm{cm}^{-3}$.

The pulses that passed through the cell with rubidium were analyzed at an angle $\varphi=0$. Figure 1 shows a series of output laser pulses at different detunings $\Delta\nu$ of the laser frequency in the long-wavelength region of the spectrum from the D_2 ^{87}Rb resonance frequency.

As seen in the data in Fig. 1, a three-dimensional soliton-like SIT pulse is formed on the long-wavelength wing of the D_2 transition with a rapidly growing leading edge, time delay, and duration compression by a factor of 3–4 (Fig. 2). The energy of the output pulse is equal to the energy of the input pulse with an accuracy of several percent.

The time delay (Δt) of the soliton decreases monotonically due to the increase in $\Delta\nu$ (Fig. 3). Accordingly, the soliton velocity increases from $c/30$ ($\Delta t=8$ ns) to $c/6$ ($\Delta t=1.5$ ns), where c is the speed of light in vacuum. With a subsequent increase in $\Delta\nu$, the transition of the time profile of the SIT soliton to the shape of the incident pulse is observed (Fig. 1 and curve *2* in Fig. 2).

In accordance with the generalized SIT theory (for the case when the input pulse has a converging spherical WF), when the laser carrier frequency is tuned to the short-wavelength wing of the D_2 line, the SIT soliton should not be formed. Indeed, as follows from the data presented in Fig. 4, the formation of a SIT soliton is not observed even in the case when the pulse has a

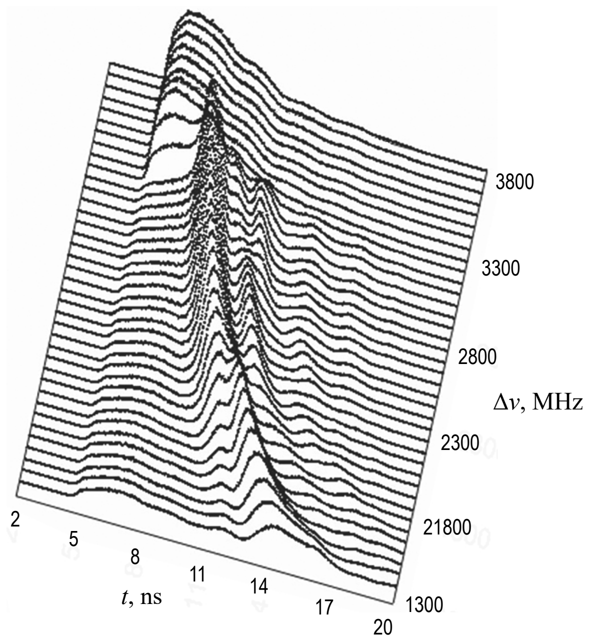

Fig. 1. Dependence of the shape of the output pulses with increasing detuning $\Delta\nu$ of the pump pulse. For $\Delta\nu > 0$, the carrier frequency of the pulse is in the long-wavelength region of the spectrum of the resonance line D_2 ^{87}Rb. Full Doppler linewidth D_2 is $\Delta\nu_D \approx 500$ MHz.

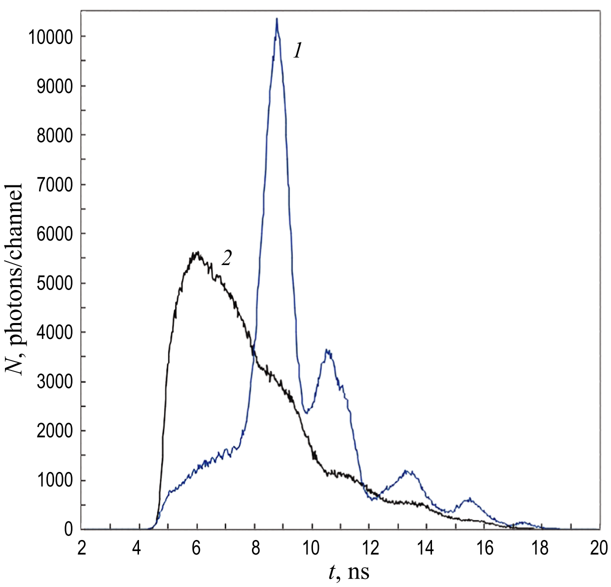

Fig. 2. Output pulse shapes from the cell with ^{87}Rb at detunings (*1*) 2692 and (*2*) 3414 MHz. (*1*) At $\Delta\nu = 2692$ MHz, a three-dimensional self-induced transparency soliton is formed; (*2*) at $\Delta\nu = 3414$ MHz, the self-induced transparency soliton is not formed. The ordinate shows the number of photons per time channel of the pulse analyzer.

cylindrical WF. As the carrier frequency of the pulse approaches the frequency of the atomic resonance, only an abrupt decrease in the rate of rise of the pulse front is observed. In this case, additional oscillations appear at its trailing edge and the total pulse energy decreases.

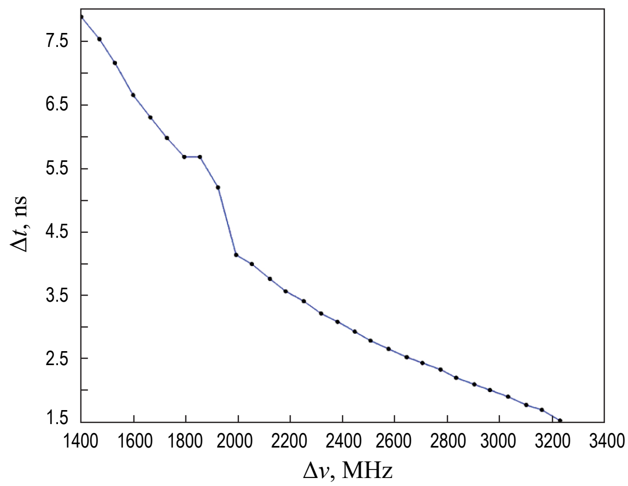

Fig. 3. Dependence of the delay Δt of the output pulse from the cell with ^{87}Rb on the pulse frequency detuning $\Delta\nu$.

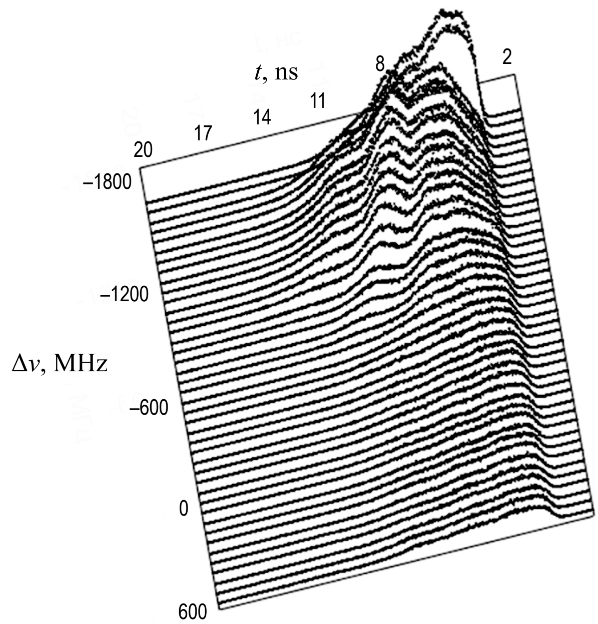

Fig. 4. Dependence of the output pulse shapes for different values of the pump pulse detuning $\Delta\nu$. For $\Delta\nu < 0$, the carrier frequency of the pulse is in the short-wavelength region of the resonance line D_2 ^{87}Rb spectrum.

It should be noted that, in accordance with the classical SIT theory, the McCall–Hahn 2π pulse should appear at the input laser pulse with a plane WF only in the case of an exact resonance of the field frequency and atomic transition frequency ($\Delta\nu = 0$). However, as seen in the data in Fig. 4, at $\Delta\nu = 0$ the soliton is not observed in the experiment.

Moreover, as shown in the data in Fig. 1, for an input laser pulse with a cylindrical WF, a three-dimensional SIT soliton is formed on the long-wavelength wing of the D_2 resonance line of rubidium.

4. CONCLUSION

To the best of our knowledge, a generalized theory of the effect of self-induced transparency for the three-dimensional case exists only for input pulses with a converging spherical wavefront with a Gaussian distribution of the field amplitude along the transverse radial coordinate. The fundamental theory of three-dimensional solitons of self-induced transparency for the general case has not been developed.

As can be inferred from the experimental data, the effect of the formation of three-dimensional soliton-like pulses of self-induced transparency can be observed under wider experimental conditions. It is shown that the effect of self-induced transparency is also observed in the case of pulses having a converging cylindrical wavefront. Moreover, for at least two different transverse spatial profiles $f(x)$—$f(x) = \exp[-(x/\sigma)^2]$ in the form of a Gaussian function and $f(x) = \sin(\beta x)/\beta x$—the case of an arbitrary transverse profile of the pump field $f(x)$ can also be considered.

To create such a profile, it is convenient to use computer-synthesized holograms output on a spatial light modulator. The algorithm for calculation developed here shows that it is possible to form an arbitrary field profile $f(x)$ with a dynamic range of radiation intensity reaching 10^3.

The data presented show that the full optical control of the input pulse carrier frequency determines the temporal characteristics of the output pulse: pulse duration compression (strobe pulse generation), soliton time delay, and temporal shift of the pulse carrier frequency.

The properties listed above should aid in the development of new devices for quantum resonant microwave photonics that use fully optical laser methods for processing signals in the microwave frequency range of the spectrum.

Thus, the obtained data on the properties of three-dimensional self-induced transparency solitons will serve as the basis for the use of laser diodes of low power (of the order of 10 mW) and low pulse energy (of the order of 40 pJ) in order to develop prototypes of various devices for signal processing in quantum resonant microwave photonics.

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