Linear and nonlinear Zeno effects in an optical coupler

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(Received 7 October 2010; published 12 April 2011)

It is shown that, in a simple coupler where one of the waveguides is subject to controlled losses of the electric field, it is possible to observe an optical analog of the linear and nonlinear quantum Zeno effects. The phenomenon consists in a counterintuitive enhancement of transparency of the coupler with an increase of the dissipation and represents an optical analog of the quantum Zeno effect. Experimental realization of the phenomenon based on the use of chalcogenide glasses is proposed. The system allows for observation of the crossover between the linear and nonlinear Zeno effects, as well as the effective manipulation of light transmission through the coupler.

DOI: 10.1103/PhysRevA.83.043811 PACS number(s): 42.65.Wi, 03.65.Xp

I. INTRODUCTION

Decay of a quantum system, either because it is in a metastable state or due to its interaction with an external system (say, with a measuring apparatus), is one of the fundamental problems of quantum mechanics. More than 50 years ago it was proved that the decay of a quantum metastable system is, in general, nonexponential [1,2] (see also the reviews in Refs. [3,4]). Years later it was pointed out in Ref. [5] that a quantum system undergoing frequent measurements does not decay at all in the limit of infinitely frequent measurements. Misra and Sudarshan termed this remarkable phenomenon the quantum Zeno paradox. The Zeno paradox, i.e., the total inhibition of decay, requires, however, unrealistic conditions and manifests only as the Zeno effect, i.e., a decrease of the decay rate by frequent observations, either pulsed or continuous. The Zeno effect was observed experimentally by studying the decay of continuously counted beryllium ions [6], the escape of cold atoms from an accelerating optical lattice [7], the control of spin motion by circularly polarized light [8], the decay of an externally driven mixture of two hyperfine states of rubidium atoms [9], and the production of cold molecular gases [10]. There is also the opposite effect, i.e., the acceleration of decay by observation, termed the anti-Zeno effect, which is even more ubiquitous in quantum systems [11].

It was argued that the quantum Zeno and anti-Zeno effects can be explained from a purely dynamic point of view, without any reference to the projection postulate of quantum mechanics [12]. In this respect, Refs. [13,14] show that the Zeno effect can be understood within the framework of a mean-field description when the latter can be applied, thus providing the link between purely quantum and classical systems.

The importance of the Zeno effect goes beyond quantum systems. An analogy between the quantum Zeno effect and the decay of light in an array of optical waveguides was suggested in Ref. [15]. Namely, Longhi found an exact solution that showed a nonexponential decay of the field in one of the waveguides. Modeling the quantum Zeno effect in the limit of frequent measurements using down-conversion of light in the sliced nonlinear crystal was considered in Ref. [16]. The effect has been mimicked by the wave process in a $\chi^{(2)}$ coupler with linear and nonlinear arms since in the strong-coupling limit the pump photons propagate in the nonlinear arm without decay. The analogy between the inhibition of losses of molecules and the enhanced reflection of light from a medium with a very high absorption was also noticed in Ref. [9].

At the same time, in the mean-field models explored in Refs. [13,14], interatomic interactions play an important role, leading to nonlinear terms in the resulting dynamic equations. The nonlinearity in turn introduces qualitative differences in the Zeno effect, in particular, by dramatically reducing the decay rate [14] compared to the case of noninteracting atoms. In Ref. [14] this phenomenon of the enhancement of the effect by the interatomic interactions was termed the nonlinear Zeno effect (since, when the nonlinearity is negligible, it reduces to the usual linear Zeno effect).

Mathematically, the mean-field descriptions of a Bose-Einstein condensate (BEC) and the light propagation in Kerr-type media are known to have many similarities due to the same (Gross-Pitaevskii or nonlinear Schrödinger) equation describing both phenomena. Furthermore, the linear Zeno effect is observable not only in pure quantum systems, but also in systems described by the mean-field approximation [14]. This immediately suggests that detection of the Zeno dynamics is possible in classical systems and, in particular, in nonlinear optics, thus offering different possibilities for managing light [17]. Namely, one can expect the counterintuitive reduction of attenuation of the total field amplitude (which would correspond to a reduction of losses of atoms in the BEC case) by increasing the losses in some parts of the system (which is analogous to increasing the removal rate of atoms in the case of a BEC).

The main goal of the present paper is to report on a very basic system where analogs of linear and nonlinear Zeno effects can be observed and exploited. More specifically, we explore the mathematical analogy of the semiclassical dynamics of a BEC in a double-well potential subject to the removal of atoms [14] with light propagation in a nonlinear optical coupler in which one of the arms is subject to controllable losses.

The paper is organized as follows. In Sec. II we consider two well-known models of dissipative oscillators that illustrate the classical analogs of the Zeno phenomenon (originally introduced in quantum measurement theory). In Sec. III we discuss possible experimental settings that allow observation of the phenomenon in optics. In Sec. IV the theory of the optical nonlinear Zeno effect is considered in detail. Section V is devoted to a comparative analysis of the linear and nonlinear Zeno effects. The results are summarized in Sec. VI.

II. TWO TRIVIAL EXAMPLES

Before going into the details of the optical system, we provide basic insight into the pure classical origin of the phenomenon of inhibition of the field attenuation by strong dissipation. We recall the well-known fact that an increase in the dissipation α of an overdamped ($\alpha \gg \omega$) oscillator $\ddot{x} + \alpha\dot{x} + \omega^2 x = 0$ results in a decrease in the attenuation of the oscillations. Indeed, the decay rate $R \approx \omega^2/\alpha$ approaches zero as the dissipation coefficient α goes to infinity. The amplitude of the oscillations in this case is also nearly zero. However, the coupling of another linear oscillator to the dissipative one,

$$\ddot{x}_1 + \alpha\dot{x}_1 + \omega^2 x_1 + \kappa x_2 = 0, \quad \ddot{x}_2 + \omega^2 x_2 + \kappa x_1 = 0,$$

allows one to observe an inhibition of attenuation due to strong dissipation by following a finite amplitude x_2. Indeed, the characteristic equation

$$\lambda = \frac{\lambda^4 + 2\lambda^2\omega^2 + \kappa^2 - \omega^4}{\alpha(\lambda^2 + \omega^2)}$$

evidently has the small root $\lambda \approx (\kappa^2 - \omega^4)/\alpha\omega^2$, which appears for $\alpha \gg \kappa^2/\omega^2 - \omega^2 > 0$. Thus one of the dynamic regimes of the system is characterized by the decay rate that goes to zero in the overdamped case. Moreover, the relation between the amplitudes of the damped and undamped oscillators reads $|x_1/x_2| \to \omega^2/\kappa < 1$ as $\alpha \to \infty$. In other words, strong dissipation in one of the oscillators can attenuate the energy decay in the whole system. The last example illustrates that if the coupling is of the same order as the eigenfrequencies of the subsystems, the energy is distributed between the two subsystems in approximately equal parts. This does not allow for a further decrease of the decay rate of the energy because its large part is concentrated in the damped subsystem.

The phenomenon described above for the linear oscillators can be viewed as a classical analog of the linear Zeno effect. The nonlinearity changes the situation dramatically. This case, however, no longer allows for a complete analytical treatment, which is why we now turn to a specific nonlinear system, which we study numerically. We consider an optical coupler composed of two Kerr-type waveguides, one arm of which is subject to relatively strong field losses. We show that such a coupler mimics the quantum Zeno effect, which allows one to follow, in a simple optical experiment, the crossover between the linear (weak intensities) and nonlinear (strong intensities) Zeno effects, thus providing an analogy between the effects of dissipation in the classical and quantum systems. In particular, we show that strong losses of the field in one of the waveguides can significantly enhance the transmittance of the coupler as a whole.

III. THE COUPLER AND A POSSIBLE EXPERIMENTAL SETTING

The optical fields in the two tunnel-coupled nonlinear optical fibers [18] (alternatively one can consider two linearly couple waveguides [19]) are described by the system

$$-i\frac{da_1}{dz} = (\beta_1 + i\alpha_1)a_1 \pm \gamma|a_1|^2 a_1 + \kappa a_2, \qquad (1a)$$

$$-i\frac{da_2}{dz} = (\beta_2 + i\alpha_2)a_2 \pm \gamma|a_2|^2 a_2 + \kappa a_1. \qquad (1b)$$

Here $a_{1,2}$ are the properly normalized fields in each arm of the coupler, κ is the coupling coefficient measuring the spatial overlap between the channels, the plus-minus signs correspond to the focusing (+) and defocusing (−) media, β_j ($j = 1,2$) are the modal propagation constants of the cores, $\gamma = 2\pi n_2/\lambda A_{\mathrm{eff}}$, n_2 is the Kerr nonlinearity parameter, A_{eff} is the effective cross section of the fiber, λ is the wavelength, and the loss coefficient $\alpha_j > 0$ stands for the field absorption in the jth waveguide.

Our aim is to employ manageable losses, i.e., control over the coefficients $\alpha_{1,2}$, in order to observe different regimes of light transmission through the coupler. Since in optics one cannot easily manipulate z, i.e., the length of the coupler, we are interested in realizing different dynamic regimes with a single given coupler (rather than using several couplers having different characteristics). This contrasts with the BEC case where the propagation variable z corresponds to time (see, e.g., Ref. [14]) and can be easily varied. For this reason the most suitable experimental setting could be with a coupler whose properties strongly depend on the wavelength of the input beam (alternatively one can consider a flexible change of the optical properties using temporal gradients, active doping, etc.).

An experimentally feasible realization of the nonlinear directional coupler described can be based on the use of As_2Se_3 chalcogenide glass. For this material the intrinsic nonlinearity can be up to three orders of magnitude greater than that of pure silica fibers [20–22]. More specifically, one can consider material losses in chalcogenide glasses, where the Kerr nonlinearity parameter is $n_2 = 1.1 \times 10^{-13}\mathrm{cm}^2/\mathrm{W}$, which is 400 times greater than the nonlinearity of fused silica fiber. However, what is even more important for our aims is that the absorption rate of at least one of the coupler arms can be changed dramatically during the experiment. For example, in chalcogenide glass the coefficient α can be on the order of a few dBm and is very sensitive to the wavelength. Thus practical control over the absorption can be performed by using the dependence of the loss coefficients $\alpha_{1,2}$ on the wavelength of the incident light.

To implement this idea it is necessary to produce the arms of the coupler using chalcogenide glasses of different types. In particular, one can consider the standard sulfide fiber in one arm of the coupler and the lowest-loss sulfide fibers [23] in the other arm. Such sulfide fibers have a particularly narrow attenuation peak at wavelength $\lambda_0 \approx 3\ \mu$m. The behavior of the absorption coefficient α in the vicinity of this peak can be modeled by the Lorentzian curve (here we use the experimental results reported in Ref. [24]):

$$\alpha_1(\lambda) = \alpha_{1,0} + \frac{\alpha_{1,1}\Gamma^2}{(\lambda - \lambda_0)^2 + \Gamma^2}, \qquad (2)$$

where $\Gamma \approx 0.5$–1μm and $\alpha_{1,0} \approx 0.5$ dBm and $\alpha_{1,1} \sim 5$ dBm for a typical sulfide fiber. By varying the wavelength about $\lambda_0 \approx 3\ \mu$m in the interval $\lambda_0 \pm 0.5\ \mu$m the loss can be varied in the standard sulfide fiber by 0.5–5 dBm and in the lowest-loss sulfide fiber in the interval 0.05–0.2 dBm. Even larger attenuation can be achieved for chalcogenide fibers $Ge^{30}As^{10}Se^{30}Te^{30}$, where the chosen attenuation is on the order of 5–30 dBm for $\lambda \approx 4.5\ \mu$m.

IV. THE NONLINEAR OPTICAL ZENO EFFECT

As a result of the preceding discussion we consider the situation when one of the waveguides (waveguide 1) is subject to controllable losses (as discussed above) while another one (waveguide 2) is operating in the transparency regime, i.e., when $\alpha_1 \gg \alpha_2$. We simplify the problem by setting $\alpha_2 = 0$ in the following.

We start with an estimate of the effective losses, designated below as $\tilde{\alpha}_2$, in the transparent arm of the coupler, which occur due to the energy exchange between the arms. For $z \gg \alpha_1^{-1}$, one can adiabatically eliminate a_1 from the system [Eq. (I)]. Moreover, if we assume that $\alpha_1 \gg \kappa$ we obtain $|a_1|^2 \approx \frac{\tilde{\alpha}_2}{\alpha_1}|a_2|^2 \ll |a_2|^2$ and

$$-i\frac{da_2}{dz} \approx (i\tilde{\alpha}_2 + \tilde{\beta}_2 + \tilde{\gamma}|a_2|^2)a_2. \qquad (3)$$

Here $\tilde{\beta}_2 = \beta_2 + \tilde{\alpha}_2(\beta_2 - \beta_1)/\alpha_1$ and $\tilde{\gamma} = \gamma\,(1 + \tilde{\alpha}_2/\alpha_1)$, with the effective z-dependent attenuation rate:

$$\tilde{\alpha}_2 = \frac{\alpha_1\kappa^2}{(\beta_2 - \beta_1 + \gamma|a_2|^2)^2 + \alpha_1^2}. \qquad (4)$$

First we observe that $\tilde{\alpha}_2$ decays with an increase of the difference $\beta_2 - \beta_1$ or the nonlinearity (the term $\gamma|a_2|^2$ in the denominator). This behavior is natural because the difference in the propagation constants $\beta_{1,2}$ results in an incomplete energy transfer between the arms, whereas the nonlinearity effectively acts as an additional amplitude-dependent detuning. In practical terms, however, the effect due to the constant linear detuning is negligible because $\beta_2 - \beta_1$ is typically too small, whereas the nonlinearity can result in an appreciable effect. Thus the effective attenuation rate $\tilde{\alpha}_2$ decays either with an increase of the absorption $\alpha_1 \to \infty$ (the linear Zeno effect) or (for given losses α_1) with the intensity of the light in the transparent arm, tending to zero in the formal limit $|a_2|^2 \to \infty$ (the nonlinear Zeno effect).

Moreover, the optical analog of the anti-Zeno effect, i.e., of the increase of the attenuation (and the associated dynamics of the field distribution in the coupler) with the growth of the loss coefficient α_1, can also be observed merely due to the presence of a strong nonlinearity. Such an effect, however, is not counterintuitive in our setup. In fact, it is obvious that for $\gamma|a_2|^2 \gg \alpha_1$, Eq. (4) tells us that the ratio $|a_1|^2/|a_2|^2 \approx \tilde{\alpha}_2/\alpha_1$ is independent of α_1, which means that, in the Zeno regime $z \gg \alpha_1^{-1}$, increasing the loss coefficient must increase the actual attenuation.

In order to perform a complete numerical study of the coupler we introduce the real amplitudes and phase of the fields, $a_j = \rho_j \exp(i\phi_j)$, with $j = 1,2$; the relative difference in the energy flows in the two arms $F = (|a_1|^2 - |a_2|^2)/(|a_1|^2 + |a_2|^2)$; the total energy flow in the coupler $Q = (|a_1|^2 + |a_2|^2)/P_0$, normalized to the input flow $P_0 = |a_{10}|^2 + |a_{20}|^2$; as well as the phase mismatch $\phi = \phi_1 - \phi_2$. Then the original system [Eq. (I)] is reduced to

$$F_Z = -g(1 - F^2) + 2\sqrt{1 - F^2}\sin(\phi), \qquad (5a)$$

$$\phi_Z = \frac{(\beta_1 - \beta_2)}{\kappa} \pm 4\delta F Q - 2\frac{F}{\sqrt{1 - F^2}}\cos(\phi), \qquad (5b)$$

$$Q_Z = -gQ(1 + F), \qquad (5c)$$

where $g = \alpha_1/\kappa$, $\delta = P_0/P_c$, and the distance is normalized on the linear coupling length $L = 1/\kappa$, i.e., $Z = z/L = z\kappa$. Here we also introduce the critical power $P_c = 4\kappa/\gamma$, which separates the regimes with a periodic energy exchange between the arms for $P < P_c$ and the localization of energy in one of the waveguides if $P > P_c$ [18]. For a fiber based on the chalcogenide glass described above, the critical power $P_c \sim$ 1W and the coupling length L varies in the interval 0.1–1 m.

Notice that mathematically the system [Eq. (5)] coincides with the one describing a BEC in a double-well trap subject to elimination of atoms from one of the wells [14]. The coupler mimics the nonlinear Zeno effect in a BEC in a double-well trap, where time is replaced by propagation distance in the coupler and the electric fields in the arms of the coupler correspond to the number of quantum particles in the potential wells. The system [Eq. (5)] also resembles the evolution of a Bose-Hubbard dimer with a non-Hermitian Hamiltonian [25].

V. LINEAR VERSUS NONLINEAR ZENO EFFECTS

We now proceed to the numerical study of the system [Eq. (5)] to estimate that, for length L on the order of 1 m, the value of the absorption coefficient g can be changed in chalcogenide fibers by up to 20 times. In the empiric formula [Eq. (2)] the values of the dimensionless parameters are $g_{1,0} = \alpha_{1,0}/\kappa \sim 1$ and $g_{1,1}\alpha_{1,1}/\kappa \sim 10$–$20$, while $\delta = P_0/P_c$ is in the interval 0–2.5.

Our main results are summarized in Fig. 1. Three different regimes are evident in Figs. 1(a) and 1(b), where we show the dependence of the output signal versus the coupler length. At small distances from the coupler input, $Z \lesssim 0.2$, the standard exponential decay occurs. This stage does not depend significantly on the intensity of the input pulse (i.e., on δ in our notation). At larger distances, $0.2 \lesssim Z \lesssim 2$, the system clearly reveals powerlike decay. The power of the decay, however, appears to be sensitive to the magnitude of the input power, i.e., to the nonlinearity of the system. The decay is much stronger at lower powers ($\delta \approx 0$), corresponding to the linear Zeno effect, and much weaker for the input intensities above the critical value ($\delta = 2$), in which instance it may be termed the nonlinear Zeno effect. In all the cases the output beam is concentrated in the waveguide without losses [Fig. 1(a)] and the output power is still sufficiently high above 70% of the input power. We also notice that, while we have chosen a relatively large g, the phenomenon is also

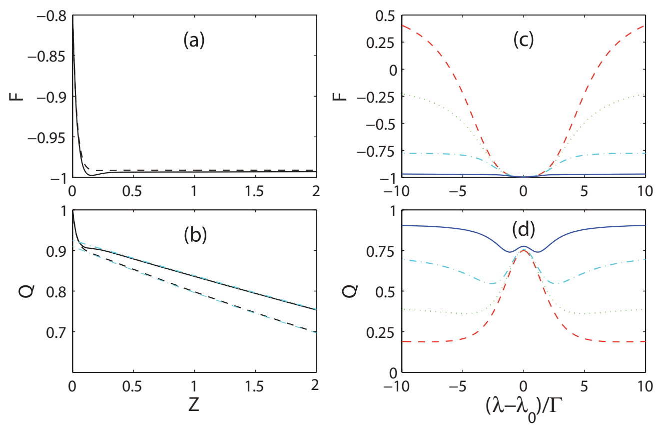

FIG. 1. (Color online) (a) Relative and (b) total energy flows vs the propagation distance Z. Here $F(0) = -0.8$, $\phi(0) = 0$, $\beta_2 = \beta_1 = 0$, $g = 15$, $\delta = 0$ (dashed lines), and $\delta = 2.5$ (solid lines). The dash-dotted lines in (b) show the reduced rate attenuation given by Eq. (3) (also obtained by numerical simulations). Also shown are (c) the output energy distribution F and (d) the total output energy flow Q in the coupler of length $Z = 2$ as functions of the deviation of the input light wavelength from the attenuation pick intensity λ_0. The output results for different values of δ [$\delta = 0$ (dashed lines), $\delta = 0.5$ (dotted lines), $\delta = 1$ (dash-dotted lines), and $\delta = 2.5$ (solid lines)] demonstrate the linear and nonlinear Zeno effects.

observable (although less pronounced) for lower levels of light absorption.

In practice, however, Figs. 1(a) and 1(b) will not correspond to a real experiment with an optical coupler because in the standard settings its length, i.e., Z, is fixed. Instead, as mentioned above, observation of the Zeno effects can be achieved by varying the wavelength of the light. From Fig. 1(b) one concludes that the best observation of the phenomenon can be achieved at some intermediate lengths of the coupler, where, on the one hand, the powerlike decay is already established and, on the other hand, the output power is still high so that the system is still in the nonlinear regime (we do not show the transition to the linear regime, which for the data used in Fig. 1 occurs at $Z \approx 0.3$). In our case the coupler lengths satisfying the above requirements correspond to the interval $0.2 \lesssim Z \lesssim 2$. By choosing $Z = 2$ in Figs. 1(c) and 1(d) we show how the output intensity depends on the wavelength of the incident beam, which can be manipulated experimentally. In particular, in Fig. 1(d) one is able to see clearly the linear Zeno effect as a dramatic increase of the output power (the transparency window of the coupler) exactly at the pick attenuation (note the dashed curve) achieved at the wavelength λ_0, as well as practically lossless propagation of the field in the nonlinear case (cf. the solid line with the dashed curves). Remarkably, for the strongly nonlinear case we also observe a local increase of the output power, which, however, is preceded by a small decay of the power. The local decay of the intensity appears when the input power is approximately equal to the critical one ($\delta \approx 1$).

So far we have considered the case of the zero-phase mismatch between the two arms of the coupler. In Fig. 2 we show the dependence on the phase mismatch between the two cores. One observes that the input phase mismatch does not destroy the phenomenon, but it can affect the output energy flow by an order of 10% (the relative energy distribution being practically unchanged).

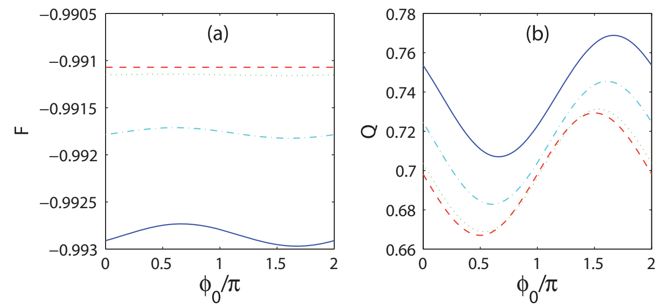

FIG. 2. (Color online) (a) Output energy distribution F and (b) total output energy Q vs the relative input phase $\phi(0)$. Here $F(0) = -0.8$, $g = 15$, $Z = 2$, and $\beta_2 = \beta_1 = 0$. The lines correspond to different values of δ, representing the nonlinear Zeno effect: $\delta = 0$ (dashed lines), $\delta = 0.5$ (dotted lines), $\delta = 1.5$ (dash-dotted lines), and $\delta = 2.5$ (solid lines).

VI. CONCLUSION

To conclude, we have shown that by using a simple optical coupler subject to the wavelength-dependent absorption of the light in one of the arms one can observe linear and nonlinear Zeno effects. The phenomenon consists in an increase of the output energy with an increase of the absorption coefficient of one of the arms. The linear Zeno effect shows an especially strong dependence on the wavelength of the input signal, as expected from the design of the system. The nonlinear Zeno effect, which is observed at intensities above the critical one, is characterized by a much larger transparency of the system and, consequently, is accompanied by a much weaker dependence on the input wavelength.

The effect of light localization in a linear coupler with strong losses in one waveguide has been observed recently [26]. Guo *et al.* attributed this phenomenon to the parity-time ($\mathcal{PT}$) symmetric configuration of their passive coupler (to which it can be reduced by the proper change of variables). Since the presence of nonlinearity rules out a change of variables, the present work proposes an alternative explanation of the experiment reported in Ref. [26] and, moreover, shows that this is a quite general phenomenon (not necessarily related to the $\mathcal{PT}$ symmetry), which can be observed in linear and nonlinear systems and offers possibilities for the manipulation of light transmission by means of controllable absorption by making the absorption either intensity or wavelength dependent.

ACKNOWLEDGMENTS

The authors gratefully acknowledge stimulating discussions with Alex Yulin. F.K.A. and V.V.K. were supported by the 7th European Community Framework Programme under Grant No. PIIF-GA-2009-236099 (NOMATOS). V.S.S. was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico or Brazil.

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