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A New Scheme for Single-Photon Emission Using Surface Acoustic Wave Solitons

- Particle-Wave Dual Nature of Solitons and Quantum Fluctuations of Photon Generation Processes -

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Abstract: We investigate quantum-mechanical aspects of a new scheme for single-photon emissions utilizing electrons transported by surface-acoustic-wave solitons. Within the framework of dipole approximation, it turns out that the single-photon emission probabilities distribute in time at about the emission center, reflecting the underlying particle-wave dual nature of interacting surface-acoustic-wave solitons.

1. Introduction

In the field of quantum information sciences such as quantum cryptography and quantum teleportation, the realization of highly efficient single-photon sources has been one of the key prerequisites for information processing based on the quantum mechanical principles [1]. For practical use of such single-photon sources, photons should be generated into a periodic photon stream and preferably into the same quantum state.

In the previous paper [2], we have proposed a novel scheme for generating a single photon by using Korteweg-de Vries (KdV) solitons as shown in Figure 1. Suppose that a potential energy in Schrödinger equation is given by a soliton solution of the KdV equation, i.e., the soliton potential can move stably through this system where bound states are naturally formed. Thus, an electron can be captured in the soliton potential and transported through the media [3]. When an empty soliton interacts with a soliton having a captured electron, the electron relaxes between bound states in merged soliton potential at the soliton interaction center and simultaneously generates a single photon. The features of the emitted single photon can be controlled by designing interacting solitons such as soliton amplitudes, configurations, and so on. Therefore, this soliton scheme can provide tunable single-photon sources.

In this study, we investigated quantum mechanical aspects of the emission processes in view of the underlying particle-wave dual nature of solitons.

2. Theory: the system Hamiltonian

The system Hamiltonian we consider here is written as

$$\hat{H} = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + u(x,t) \qquad (1)$$

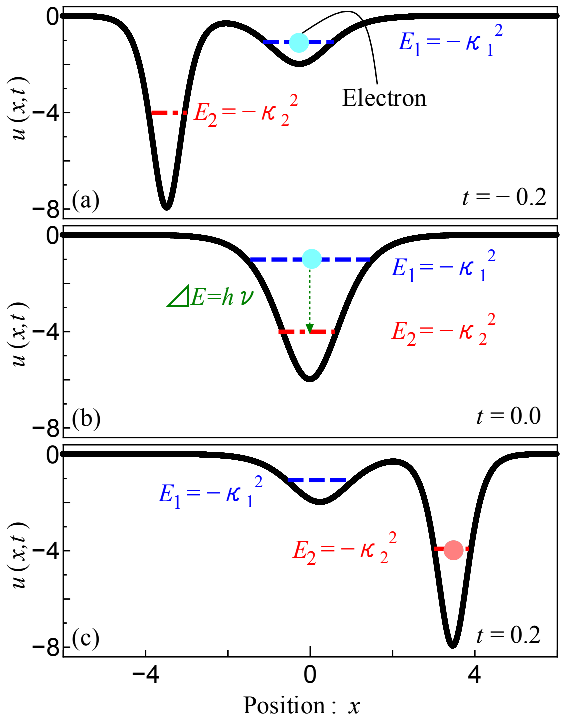

Figure 1: Schematics of single-photon emission processes using an electron transported by KdV saw solitons (κ_1=1.0, κ_2=2.0). (a) An empty deep soliton approaches a shallow soliton having an electron (blue solid circle). (b) The two solitons interact and merge into one soliton. The electron relaxes from the excited state to the ground state, resulting in a photon emission. (c) After the interaction, the electron is transported by the deep soliton.

where m is the electron mass and $\hbar$ is the Dirac constant, respectively. $u(x, t)$ is a time-dependent potential energy governed by the KdV equation

$$\frac{\partial u(x,t)}{\partial t} - \alpha u(x,t)\frac{\partial u(x,t)}{\partial x} + \beta\frac{\partial^3 u(x,t)}{\partial x^3} = 0 \qquad (2)$$

where α and β are the system parameters[3]. The KdV equation has soliton solutions which behave like an extended object without any distortion in the dispersive media. There-

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fore, this Hamiltonian describes an electron captured in the moving attractive KdV soliton potentials.

3. Results and discussion

Figure 2 shows a color map for the depth of the KdV soliton potentials. The dashed line and the dash-dotted line in the figure are trajectories of the excited state and the ground state, respectively. It is found that the deeper the soliton potential is, the faster the potential moves, and that the fast-moving soliton potential overtakes the slower (shallow) one at the origin. At that time, the trajectories bent due to a nonlinearity of soliton potentials. It can also be seen that the trajectories of the bound states curve along the potential minima which caused by nonlinear interaction of underlying soliton potentials.

To see how the relaxation process from the excited state to the ground state depends on time t, we numerically evaluate the matrix element

$$A(t) = \int_{-\infty}^{\infty} \psi_g x \psi_e \, dx \qquad (3)$$

because the transition amplitude is proportional to $A(t)$ within the framework of the dipole approximation.

Figure 3 shows the time dependence of the transition amplitude $A(t)$. It is indicated that $A(t)$, and hence the photon emission probability, distributes at about the center of soliton-soliton interaction. The transition amplitude is essentially proportional to the overlap of wave functions. This distribution can qualitatively be explained by the classical rectangular model [4,5] that resulted from the particle-wave dual nature of the underlying KdV soliton potentials.

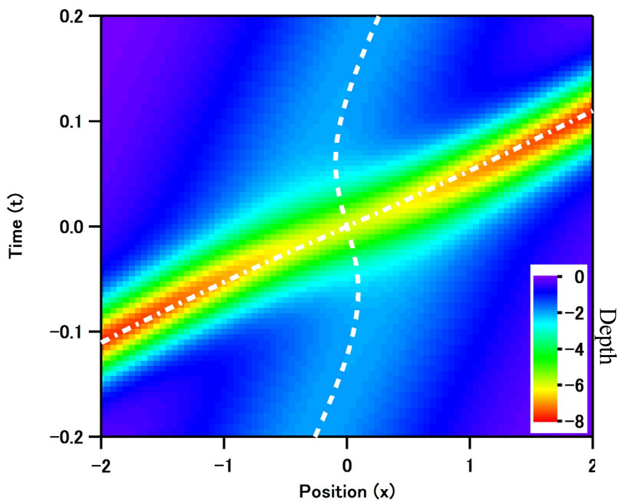

Figure 2: Color map for the depth of the soliton potentials. The dashed line and the dash-dotted line are trajectories of the excited state and the ground state, respectively.

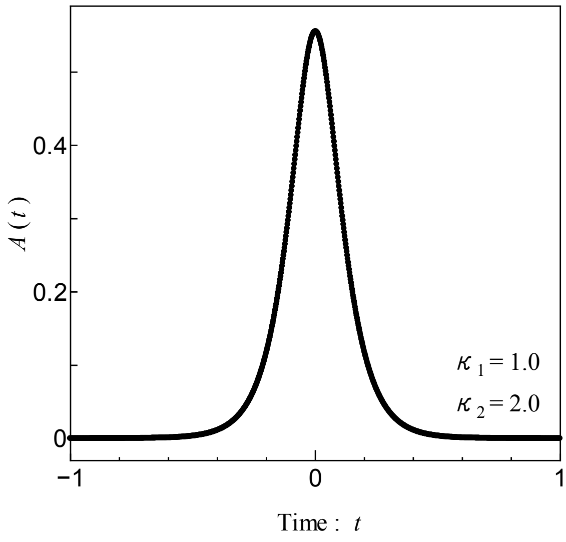

Figure 3: Time dependence of the transition amplitude $A(t)$. It distributes at about interaction center, $t = 0$.

4. Conclusions

In this study, we have investigated quantum-mechanical aspects of single-photon emission processes from a view point of the extended nature of KdV solitons. Within the framework of the dipole approximation, we have found that the photon-emission probabilities distribute in time at about the center of soliton-soliton interaction. We have revealed that the distribution is governed soliton's particle-wave dual nature.

Acknowledgment

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