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The superluminal velocities as the consequence of non-classical states of electromagnetic field

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ABSTRACT

It was shown within the framework of conventional quantum electrodynamics, and without using perturbation theory, the presence of superluminal signals, transferring the information, while investigating the scattering of quantum electromagnetic field by excited atom. The superluminal signals are impossible in the theory of free fields, but their existence is predicted by the theory of interacting fields.

1. Introduction

Let the atom placed in vacuum is affected by electromagnetic pulse with the sharp wave front. The scattered light due to inertial properties of atom electrons cannot change the wave front speed. Such an effect does not depend on the number of scattering atoms. Therefore, the wave front speed of electromagnetic wave inside of all substances in accordance with the classical physics is equal to the electromagnetic wave speed in vacuum [1]. In quantum physics in accordance with the reciprocal principle the situation is the same for "quantum averages" $\langle \hat{E} \rangle$ (E^{ν}-electric strength of electromagnetic field) that have classical analogy. The behavior of fluctuating components $\langle \hat{E}^{\nu}\hat{E}^{\nu} \rangle - \langle \hat{E}^{\nu} \rangle \langle \hat{E}^{\nu} \rangle$ requires the special analysis that was made in this work. This analysis was based on the conventional equations of quantum electrodynamics solved by conventional methods. It was shown that superluminal signals exist due to non-classical states of electromagnetic field described by the wave function in the configuration space.

Last years the interest to the optical superluminal signals has risen supplementary. In the first experimental work [2] the wave packet speed was found to be several times larger than the speed of light in vacuum. The physical interpretation of the results obtained was presented in [2] as well. The comprehensive theory of the effect discovered was present in papers [3,4]. The fact is that in gain-assisted media the shape of light pulse is distorted that leads to displacing of pule maximum in motion direction. Such a displacement imitates the superluminal signal. The results of the work [2] were repeated in experimental works [5–7] and in a recent work [8].

The interest to subject was risen supplementary after experimental work [9]. Its authors used the double frequency pump to avoid the distortion of the signal shape and the explanation proposed in [3,4] becomes not valid. Since the shape of the pulse was not changed the authors of the work [9] used the theory developed in [10]. According to this theory medium possess abnormal dispersion without changing the speed of wave front may form anomaly large and even negative group speed.

Further other authors did not use of the double frequency pump [11,12]. But the theory of superluminal signals practically was the same [13]. All authors agreed with the theory of relativity and with impossibility of transmitting information with superluminal speed [14].

The last affirmation was doubt in theoretical work [15]. If in the works mentioned above and in the work [16] one investigates the group wave speed in the classical electromagnetic fields the author of the present work investigates the wave front speed in accordance with quantum electrodynamics. The main difference of work published in [15] from all other works is in the consideration namely quantum states of electromagnetic field. In such consideration one could show that in excited (not necessary in inversional excited) media another mechanism of superluminal signal generation could exists. The wave front speed due to the correlation properties of quantum wave functions may exceed light speed in vacuum. This could open the possibility of superluminal transportation of information.

In present paper we did the theoretical study of elementary example that is believed to prove the correctness of our hypothesis.

Let us denote the wave function of total quantum system in interaction representation: electromagnetic field plus scattering atom after scattering process by $\Psi(t)$. Let us represent this function as a set of the total system of scattering atom wave functions ψ_i

$$\Psi(t) = f_0(t)\psi_0 + \sum_{i\neq 0} f_i(t)\psi_i = f_0\psi_0 + (\Psi - f_0\psi_0)$$

where the initial state of scattering atom ψ_0 is written separately. The

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scalar product

$$\langle f_0\psi_0|\Psi - f_0\psi_0\rangle = 0$$

turns to zero due to orthogonality of atom wave functions. We name the scattering channel as the coherent one if after scattering the atom rests in its initial state [15]. This channel is connected with wave function of electromagnetic field f_0. If initial atom state ψ_0 is the excited state then we could show that the function f_0 describes the superluminal signals. If the atom state is changed due to the scattering process then such a channel is named as non-coherent one.

The experimentally observed values could be calculated as "quantum average" values of correspondent quantum operators. For instance if we are interested in the electric strength of electromagnetic field then we can write

$$E^\nu = \langle \hat{E}^\nu(\mathbf{r},t)\rangle = \langle\Psi|\hat{E}^\nu(\mathbf{r},t)|\Psi\rangle = \\ = \langle f_0\psi_0|\hat{E}^\nu(\mathbf{r},t)|f_0\psi_0\rangle + \langle\Psi - f_0\psi_0|\hat{E}^\nu(\mathbf{r},t)|\Psi - f_0\psi_0\rangle = \hat{E}^{\nu(c)}(\mathbf{r},t) \\ + \hat{E}^{\nu(n)}(\mathbf{r},t) \quad (1)$$

where in rationalized Gauss unit system

$$\hat{E}^\nu(\mathbf{r},t) = i\sum_{\mathbf{k}\lambda}\sqrt{\frac{\hbar ck}{2V}}e^\nu_{\mathbf{k}\lambda}(\hat{\alpha}_{\mathbf{k}\lambda}e^{i\mathbf{kr}-ickt} - \hat{\alpha}^+_{\mathbf{k}\lambda}e^{-i\mathbf{kr}+ickt}), \quad (2)$$

$\hat{\alpha}_{\mathbf{k}\lambda}$ and $\hat{\alpha}^+_{\mathbf{k}\lambda}$ are respectively the annihilation and creation photon operators in their states describing by wave vector $\mathbf{k}$ and by polarization index λ, $V = L_xL_yL_z$ quantized volume. These operators satisfied the commutation relations

$$[\hat{\alpha}_{\mathbf{k}\lambda};\ \hat{\alpha}^+_{\mathbf{k}'\lambda'}] = \delta_{\mathbf{kk}'}\delta_{\lambda\lambda'}.$$

The electromagnetic field is supposed to be traversal polarized $\lambda = 1, 2$. Unit vectors of linear polarization are denoted by $\mathbf{e}_{\mathbf{k}\lambda}$. The electric strength operator $\hat{E}^\nu(\mathbf{r},t)$ is connected with vector potential operator $\hat{A}^\nu(\mathbf{r},t)$ by the gouge condition with scalar potential equal to zero [17] as $\hat{E}^\nu(\mathbf{r},t) = -\partial\hat{A}^\nu(\mathbf{r},t)/c\partial t$.

The first term in the right hand side (1) describes the coherent scattering while the second one describes the non-coherent scattering. It is worth to emphasize that the crossed terms in (1) vanish due to orthogonality of atom wave functions $\langle\psi_0|\psi_i\rangle = 0$.

We say that there is no quantum interference between coherent and non-coherent channels associated with phase values of total system wave functions Ψ. This interference vanishes due to the properties of atom wave functions that influences on the properties of scattered electromagnetic field. Such a connection between scattered photons and atom electron in classical physics does not exist.

On the other hand, due to presence of the sum $\hat{E}^{\nu(c)}(\mathbf{r},t) + \hat{E}^{\nu(n)}(\mathbf{r},t)$ in the Eq.(1) the conventional (classical) interference between $\hat{E}^{\nu(c)}(\mathbf{r},t)$ and $\hat{E}^{\nu(n)}(\mathbf{r},t)$ does exists in spite of the fact that the phases of $\Psi(t)$ functions are vanished by evaluating the "quantum mean values". So one has to distinguish two sorts of interference in quantum electrodynamics.

Using Lorentz –invariant equations of quantum electrodynamics and convenient methods of their solutions we made the calculations that have shown that the superluminal signals were present in both fields $\hat{E}^{\nu(c)}(\mathbf{r},t)$ and $\hat{E}^{\nu(n)}(\mathbf{r},t)$. The superluminal signals appeared in intermediate calculations only in fields scattered by an excited atoms. Only due to "classical" interference of scattering channels the superluminal signals vanished in the sum $\hat{E}^{\nu(c)}(\mathbf{r},t) + \hat{E}^{\nu(n)}(\mathbf{r},t)$, and we received well-known conventional result. This result could be obtained using the quasi-classical theory without the second quantized formalism of electromagnetic field.

One could ask the question: is it possible by breaking the interference between coherent and no coherent channels to create the superluminal signals not in the virtual but in the real states? The answer is: Yes.

Let to estimate the bilinear products of electromagnetic field operators $\langle\hat{N}(\hat{E}^\nu)^2\rangle$ that determine field energy characteristics. Here $\hat{N}$ is the normal-product operator. It could be estimated as follows. Let to consider inequality

$$\left\langle \sum_{\mathbf{k}\lambda}\sqrt{k}\,e^\nu_{\mathbf{k}\lambda}e^{-i\mathbf{kr}+ikct}(\hat{\alpha}^+_{\mathbf{k}\lambda} - \langle\hat{\alpha}^+_{\mathbf{k}\lambda}\rangle)\cdot\sum_{\mathbf{k}'\lambda'}\sqrt{k'}\,e^\nu_{\mathbf{k}'\lambda'}e^{i\mathbf{k}'\mathbf{r}-ik'ct}(\hat{\alpha}_{\mathbf{k}'\lambda'} - \langle\hat{\alpha}_{\mathbf{k}'\lambda'}\rangle)\right\rangle \\ \geq 0,$$

where operators $\hat{\alpha}_{\mathbf{k}\lambda}$ and $\hat{\alpha}^+_{\mathbf{k}\lambda}$ are Hermit-conjugated.

Then

$$\sum_{\mathbf{kk}'\lambda\lambda'}\sqrt{kk'}\,e^\nu_{\mathbf{k}\lambda}e^\nu_{\mathbf{k}'\lambda'}e^{-i(\mathbf{k}-\mathbf{k}')\mathbf{r}+i(k-k')t}\langle\hat{\alpha}^+_{\mathbf{k}\lambda}\hat{\alpha}_{\mathbf{k}'\lambda'}\rangle \\ \geq \sum_{\mathbf{k}'\mathbf{k}\lambda\lambda'}\sqrt{kk'}\,e^\nu_{\mathbf{k}\lambda}e^\nu_{\mathbf{k}'\lambda'}e^{-i(\mathbf{k}-\mathbf{k}')\mathbf{r}+i(k-k')t}\langle\hat{\alpha}^+_{\mathbf{k}\lambda}\rangle\langle\hat{\alpha}_{\mathbf{k}\lambda}\rangle.$$

Let the electromagnetic field has characteristic frequency ω_0 and wave length $\lambda\!\!\!^-_0$. Here we are interested in time and distance values larger than $1/\omega_0$ and $\lambda\!\!\!^-_0$ respectively. Then after averaging of intervals $\Delta t\sim 1/\omega_0$ and $|\Delta\mathbf{r}|\sim 1/\lambda\!\!\!^-$ one get

$$\langle(\hat{\alpha}_{\mathbf{k}\lambda}e^{i\mathbf{kr}-ickt})^2\rangle + c.\ c. << \langle\hat{\alpha}^+_{\mathbf{k}\lambda}\hat{\alpha}_{\mathbf{k}\lambda}\rangle.$$

It is not difficult to show that

$$\langle\hat{N}(\hat{E}^\nu(\mathbf{r},t))^2\rangle \approx \sum_{\mathbf{kk}'\lambda\lambda'}\frac{\hbar c}{V}\sqrt{kk'}\,e^\nu_{\mathbf{k}\lambda}e^\nu_{\mathbf{k}'\lambda'}\langle\hat{\alpha}^+_{\mathbf{k}\lambda}\hat{\alpha}_{\mathbf{k}'\lambda'}\rangle e^{-i(\mathbf{k}-\mathbf{k}')\mathbf{r}+ick(t-t')} \geq \\ \geq \sum_{\mathbf{kk}'\lambda\lambda'}\frac{\hbar c}{V}\sqrt{kk'}\,e^\nu_{\mathbf{k}\lambda}e^\nu_{\mathbf{k}'\lambda'}\langle\hat{\alpha}^+_{\mathbf{k}\lambda}\rangle\langle\hat{\alpha}_{\mathbf{k}'\lambda'}\rangle e^{-i(\mathbf{k}-\mathbf{k}')\mathbf{r}+ick(t-t')} \approx \langle\hat{E}^\nu(\mathbf{r},t)\rangle^2. \quad (3)$$

Values of $\langle\hat{E}^\nu\rangle$ allows to estimate from the low values the construction $\langle\hat{N}(\hat{E}^\nu)^2\rangle$. The correctness of inequality (3) does not depend on the states over witch the quantum averaging is made and has no relationship with perturbation theory. If the inequality (2) is applied to each term of the right part of equality

$$\langle\hat{N}(\hat{E}^\nu)^2\rangle = \langle f_0\psi_0|\hat{N}(\hat{E}^\nu)^2|f_0\psi_0\rangle + \langle\Psi - f_0\psi_0|\hat{N}(\hat{E}^\nu)^2|\Psi - f_0\psi_0\rangle$$

one can get

$$\langle\hat{N}(\hat{E}^\nu)^2\rangle \geq \langle f_0\psi_0|\hat{E}^\nu|f_0\psi_0\rangle^2 + \langle\Psi - f_0\psi_0|\hat{E}^\nu|\Psi - f_0\psi_0\rangle^2. \quad (4)$$

Both terms in the right part of inequality (4) are positively defined and the superluminal signals can't be mutually compensated. Thus it impossible to ignore superluminal signals in the theoretical consideration.

It should be emphasized, that if the scattered light would have the classical structure, instead of (4) we should have $\langle\hat{N}(\hat{E}^\nu)^2\rangle = \langle E^\nu\rangle^2$ and superluminal signal would be absent. Now superluminal signal is present due to non-cancelation effect of the superluminal components in the bilinear product of field operators.

The inequality (4) could be rewritten as follows

$$\langle\hat{N}(\hat{E}^\nu)^2\rangle \geq \langle f_0\psi_0|\hat{E}^\nu|f_0\psi_0\rangle^2 + (\langle\Psi|\hat{E}^\nu|\Psi\rangle - \langle f_0\psi_0|\hat{E}^\nu|f_0\psi_0\rangle)^2,$$

This inequality underscores the important role of the coherent scattering channel if the scattered electromagnetic signal is not the classical one and $\langle\hat{N}(\hat{E}^\nu)^2\rangle \neq \langle\hat{E}^\nu\rangle^2$. It opened another way to estimate $\langle\hat{N}(\hat{E}^\nu)^2\rangle$ without investigating the non-coherent scattering channel. The expression $\langle\Psi|\hat{E}^\nu|\Psi\rangle$ can be evaluated using conventional quasi-classical theory operating with non-quantum electromagnetic field. The calculation of $\langle f_0\psi_0|\hat{E}^\nu|f_0\psi_0\rangle$ could be made using only coherent channel of scattering. It could be done even in extended medium using only the wave functions without matrix density formalism [18].

Below we present the explicit calculations and their results.

2. Formulation of the problem

Let the monochromatic plane electromagnetic wave defined by wave vector $\mathbf{k}_0$ and unit vector of linear polarization $e^\nu_{\mathbf{k}_0\lambda_0}$ spreads along the z axis. This wave has a sharp wave front placed in point $z = 0$ at