Hong–Ou–Mandel interference on free charged particles

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Abstract. The Hong−Ou−Mandel effect (HOM) is used in many fields of quantum optics and quantum technologies. It is well known that this effect occurs when two identical photons in different modes hit a beam splitter (BS) with a reflection coefficient of $R = 1/2$. The classical effect consists in the interaction of two photons and was first experimentally demonstrated by Hong and co-authors in 1987. In this paper, it was shown that this effect can be realized using free charged particles. It was determined when this effect would manifest itself. The results obtained for HOM have an analytical form, which simplifies its analysis. The Hong−Ou−Mandel effect is of fundamental importance in quantum physics and quantum computer science, as it demonstrates quantum entanglement and interference. The results of the research can be used in problems of quantum physics and quantum computer science.

Keywords: HOM effect, free electrons, photons, quantum optics

Интерференция Хонга – Оу – Манделя на свободных заряженных частицах

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Аннотация. Эффект Хонга − Оу − Манделя (ХОМ) используется во многих областях квантовой оптики и квантовых технологий. Хорошо известно, что этот эффект возникает, когда два одинаковых фотона в разных режимах попадают на светоделитель (BS) с коэффициентом отражения $R = 1/2$. Классический эффект заключается во взаимодействии двух фотонов и был впервые экспериментально продемонстрирован Хонгом и соавторами в 1987 году. В этой статье было показано, что этот эффект может быть реализован с использованием свободных заряженных частиц. Было определено, когда этот эффект проявит себя. Результаты, полученные для ХОМ-эффекта, имеют аналитическую форму, что упрощает их анализ. Эффект Хонга − Оу − Манделя имеет фундаментальное значение в квантовой физике и квантовой информатике, поскольку он демонстрирует квантовую запутанность и интерференцию. Результаты исследования могут быть использованы в задачах квантовой физики и квантовой информатики.

Ключевые слова: ХОМ-эффект, свободные электроны, фотоны, квантовая оптика

Introduction

The HOM effect was first demonstrated experimentally by Hong et al. in 1987 [1]. HOM interference appears in many contexts, both in fundamental research in quantum mechanics and in practical implementations of quantum technologies [2]. A HOM interferometer scheme was presented in [1], one of the main elements of which was a beam splitter (BS). To observe quantum interference, a BS close to 1:1 (having reflectivity $R = 1/2$ and transmittance $T = 1/2$) is chosen. The theoretical explanation of the HOM effect based on constant R and T and bosonic photon statistics is quite simple [2].

HOM is a quantum phenomenon observed when two identical photons pass together through a beam splitter. If the photons are absolutely identical in all quantum parameters, such as polarization, frequency, and phase, and arrive at the beam divider at the same time, then they will interact in such a way that both photons will exit the divider in the same direction, instead of being randomly distributed between two possible directions. This effect is a quantum analogue of binary encoding in programming, used in experiments on quantum teleportation, quantum cryptography and in the development of quantum computers.

It has recently been shown that the statistical properties of photons in the interaction of a two-mode electromagnetic field with free charged particles can be identical to a beam splitter [3]. Thus, the interaction of photons with free electrons is a new and interesting direction for research [4−7]. At present, studies related to the HOM effect in the interaction of photons with free charged particles have not been encountered in the literature and may be interesting not only as a theoretical direction, but also as an experimental one.

Materials and methods

There are many methods of entangling photons, but one way or another, all methods are reduced to the interaction of incoming electromagnetic waves with matter, in the process of such interaction, photons are entangled, and then quantum-entangled photons appear. The efficiency of generating such quantum entangled photons can vary and depends on many factors. Studies on plasmonic platforms based on the interaction of electrons with photons are considered promising. For example, plasmons can be controlled using electrons and photons, electrons can be used to change the quantum statistics of photons, and quantum statistics of photons can be transmitted to electrons. That is why free electrons are interesting from a practical point of view, since as a result of such an interaction, quantum entangled photons appear.

Thus, the study of the interaction of photons with electrons is an important part of modern physics and quantum technologies. To calculate the HOM effect, it is necessary to find the correlation function. When using free electrons, the correlation function can be obtained in the form:

$$P_{1,2} = \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} \left| \xi_1\left(t_1, t_2, \tau\right) - \xi_2\left(t_1, t_2, \tau\right) \right|^2 dt_1 dt_2,$$

$$\xi_1\left(t_1, t_2, \tau\right) = \frac{1}{2\pi} \int \phi\left(\omega_1, \omega_2\right) T\left(\omega_1, \omega_2\right) e^{-i\omega_1(t_1-\tau)} e^{-i\omega_2 t_2} d\omega_1 d\omega_2, \tag{1}$$

$$\xi_2\left(t_1, t_2, \tau\right) = \frac{1}{2\pi} \int \phi\left(\omega_1, \omega_2\right) R\left(\omega_1, \omega_2\right) e^{-i\omega_2(t_1)} e^{-i\omega_1(t_2-\tau)} d\omega_1 d\omega_2,$$

where τ is the delay time of photons between themselves in modes 1 and 2, $\phi(\omega_1, \omega_2)$ is the spectral function, $R(\omega_1, \omega_2)$ and $T(\omega_1, \omega_2)$ is the coefficient of reflection and transmission of photons on free electrons, which looks like:

$$R = \frac{\sin^2\left(\Omega t_{BS} / 2\sqrt{1+\varepsilon^2}\right)}{\left(1+\varepsilon^2\right)}; \; \varepsilon = \frac{\omega_2 - \omega_1}{\Omega},$$

$$T = 1 - R, \; \Omega = \frac{8\pi u_1 u_2}{\left(\omega_1 + \omega_2\right)V}, \tag{2}$$

where V is the quantization volume, u_1 and u_2 are the polarizations of the first and second photons with frequencies ω_1 and ω_2 respectively, t_{BS} is the interaction time of photons with free electrons.

Results and Discussion

Next, the spectral function was chosen in the form:

$$\phi\left(\omega_1, \omega_2\right) = Ce^{-\frac{(\omega_1+\omega_2-\Omega p)^2}{2\sigma_p^2}} e^{-\frac{(\omega_1-\omega_{01})^2}{2\sigma_1^2}} e^{-\frac{(\omega_2-\omega_{02})^2}{2\sigma_2^2}}. \tag{3}$$

Function (3) allows to analyze the value of $P_{1,2}$ for two cases of practical interest. The first case is spontaneous parametric scattering (SPR), for example, for $\Omega p = 2\omega_0$; $\omega_0 = \omega_{01} = \omega_{02}$; $\sigma_1 = \sigma_2 = \sigma$ — SPR type I, where σ_p — beam pumping bandwidth, ω_0 and σ — The center frequency and bandwidth are respectively for both the signal and the idle beams. The second case is if $\sigma_p \to \infty$, then it will be a case of Fock states. As a result, a correlation function was obtained. The calculation of this correlation function showed that the HOM effect can be realized on free electrons. The calculation results are presented in Fig. 1.
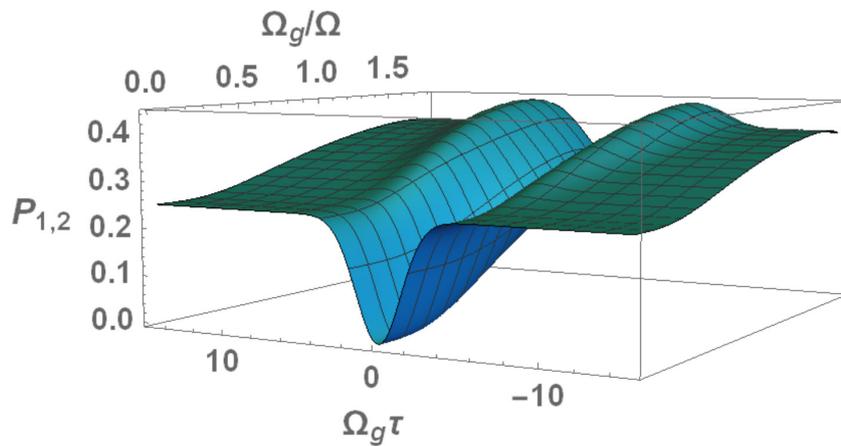

Fig. 1. Calculation of the correlation function in the case of identical photons falling on free electrons is presented. The calculation is presented in the form of two parameters: the time delay between the 1st and 2nd photons and the value determining the spectral width of the photons

In Fig. 1, the value Ω_g is defined as: $\Omega_g = \sqrt{\dfrac{4\sigma_1^2\sigma_2^2 + \left(\sigma_1^2 + \sigma_2^2\right)\sigma_p^2}{\sigma_1^2 + \sigma_2^2 + \sigma_p^2}}.$

Here Ω_g is some frequency related to the characteristics of the source itself. For example, in the case of photons in Fock states Ωp it is necessary to aim at infinity and it will turn out Ω_g the order of dispersion of incident photons. There is a minimum on the resulting graph, which drops to zero. This minimum is called the "HOM dip" and it is this minimum that identifies that the original photons are identical.

Conclusion

Thus, in this paper it is shown that the HOM effect for two photons is observed on free charged particles. In order for the HOM effect on free charged particles to be fulfilled, i.e. for $P_{1,2}(\tau = 0) = 0$, one additional condition $\Omega_g/\Omega \ll 1$ must be fulfilled compared to the theory of the HOM effect on a beam splitter. In other words, it is necessary that the spectral width of the incident photons be many times smaller than the frequency Ω. The time delay during scattering by free electrons is performed in the same way as it is done in the case of a beam splitter. The first and second photons are sent to the beam splitter with some delay. Another option is to change the distance from the electrons to the first and second detectors, which also leads to a time delay. This is an interesting conclusion, which suggests that free electrons can act as a beam splitter when interacting with photons.

This article shows that this effect is also realized on free electrons, which has not been shown before.

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