Apparent superluminal advancement of a single photon far beyond its coherence length

Simone Cialdi, Ilario Boscolo, Fabrizio Castelli and Vittoria Petrillo

Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica, Università di Milano, Via Celoria 16, 20133 Milano, Italy
E-mail: fabrizio.castelli@mi.infn.it

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Abstract. We present experimental results relative to superluminal propagation based on a single photon traversing an optical system, called a 4f-system, which acts singularly on the photon’s spectral component phases. A single photon is created by a continuous wave (CW) laser light down-conversion process. The introduction of a linear spectral phase function will lead to the shift of the photon peak far beyond the coherence length of the photon itself (an apparent superluminal propagation of the photon). Superluminal group velocity detection is done by interferometric measurement of the temporally shifted photon with its correlated untouched reference. The observed superluminal photon propagation complies with causality. The operation of the optical system allows the origin of the apparent superluminal photon velocity to be elucidated. The experiment foresees a superluminal effect with single-photon wavepackets.

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1 Author to whom any correspondence should be addressed.
1. Introduction

Einstein’s theory of special relativity establishes that the velocity $c$ of light in a vacuum is invariant under a reference frame change [1]–[3]. Superluminal single objects under Lorentz transformations lead to violation of the relativistic causality principle, and in turn, to the paradox of effect preceding its cause [4]. Nevertheless, many experiments with faster-than-$c$ light propagation have been performed and discussed [5]–[7] ([8] and references therein). In fact, special relativity theoretical framework stands even without assuming that $c$ is the highest possible speed [9]–[12].

Research on superluminality refers mostly to barrier tunneling by radiation pulses [5, 6] or by single photons [7], and to active media crossing ([13] and references therein). Barrier tunneling of light pulses is substantially governed by very low transmission coefficients and by an almost linear spectral component time delay $\tau_d = d\phi(\omega)/d\omega$. Some authors state that the outgoing light pulse after crossing the barrier is so much weaker than the incoming one (or the photon crossing probability is so scarce) that any possible information carried by the pulse is destroyed, therefore the causality principle is not broken [7, 8, 14]. Winful [15] maintains that no propagation can occur inside the barrier, hence it is not the case to speak about advancing velocity. In optical pulse propagation experiments within the so-called fast-light media, that is media with anomalous dispersion [7, 8] (precisely, with gain-assisted linear anomalous dispersion), pulse shape is preserved and phase varies almost linearly with frequency in the region of interest. The slope of the graph $dn/d\omega$ leads to a group velocity $v_g$, which exceeds the speed of light in vacuum and can even become negative [7, 8]. A superluminal experiment carried out with a microwave pulse crossing a birefringent two-dimensional crystal resulted in a clear superluminal group velocity. This was measured using the interference of pulses that had traveled along the two crystal axes [14, 16] set in such a way that the pulse polarization of the incident and detected fields relative to the crystal fast axis could be well controlled.

The experimental results on these systems renewed the debate about superluminal propagation and information velocity. The discussion focuses on the concept that the speed of a light pulse crossing a medium is not precisely defined because a pulse is an ensemble of optical components traveling at different and well-defined phase velocities $v_p = c/n(\omega)$, where $n(\omega)$ is the refractive index of the optical material at a given frequency. The pulse peak usually travels at the group velocity $v_g = c/n_g$, where $n_g = n + \omega dn/d\omega|_{\omega=\omega_0}$ is the group index and $\omega_0$ is the wavepacket central frequency [17]. The wave nature of the wavepacket allows superluminal light propagation. Arguments concentrate on the fact that $v_g$ does not coincide with the information velocity $v_i$ and there is a debate about the nature of these velocities [4, 7, 8]. Since the analysis of the problem by Sommerfield and Brillouin, it is discussed that the ‘front’ velocity of a square pulse does not exceed $c$, and Garrison et al [4], Steinberg et al [7] and Stenner et al [18] suggest a non-analytic point of the pulse amplitude as transporting information, by observing that this is a generalization of the ‘front’ point of the pulse.

In all experiments carried out so far, the temporal forward shift of the pulse or of the single-photon wavepacket is much smaller than the total length involved, and this necessarily poses interpretation problems. In this respect, the definition of the information velocity as the propagation speed of a particular point in the profile [18] leads to information velocities always less than or equal to $c$.

Experiments show that the characteristic of a light pulse for providing superluminal effects is its nature of being a superposition of monochromatic waves. Within this view, the
possibility of a superluminal effect with a single photon lies in the fact that a photon is always a superposition of monochromatic Fock states $|1, \omega\rangle$ (encompassing a frequency bandwidth due to the Heisenberg principle and the fact that the photon is generated in a definite space region). We would like to underline that in quantum mechanics any single particle is a superposition of many states (another example, a moving electron is a superposition of momentum eigenstates $|k\rangle$), even if they are detected in the laboratory as a single event (i.e. a single click). Therefore, quantum mechanics allows superluminal propagation of single particles.

We are going to present and discuss an experiment where a single photon, created in a nonlinear crystal by the down-conversion of continuous wave (CW) laser light [19], is operated through its spectral components in such a way that a clear temporal shift with respect to the non-acted upon photon is detected via an interferometric measurement. This experiment pertains to the class of superluminal experiments. The way we carry out the experiment (acting upon one of the two generated photons only) does not allow us to claim strictly that we are operating with one single-photon wavepacket. The description of the interference between optical components can also be done by viewing the observed light temporal shift as a result of the interference of very weak light beams with femtosecond coherence length. Anyway, for simplicity and convenience, we will use the view of running photons.

In our experiment, the photon velocity can become apparently superluminal as a result of the interference of photon optical components whose phases are acted upon by the optical system described below. Because of the interference process, the observed result is not at odds with causality. In order to avoid issues about the kind and the physical meaning of the different definitions of velocity, we set the experiment in such a way that the shift between the normal and ‘superluminal’ photons is notably wider than the width of the corresponding coherence length.

2. The experiment

In figure 1 we show the experimental device consisting, in sequence, of a CW pump laser, a nonlinear BBO crystal that generates photons via parametric down-conversion, a half-wave plate (HWP) for inducing a polarization rotation, a 4f-system with a phase mask (a spatial light modulator (SLM)) in the middle providing a time delay between optical components of the horizontally polarized photon beam [20]–[22], and finally an interferometer followed by a single-photon detector for measuring the time delay. A pair of photons, usually called signal and idler photons, is generated by a parametric noncollinear down-conversion [19] of CW 40 mW 405 nm almost monochromatic laser radiation within a nonlinear 3 mm thick BBO crystal. The state of this photon pair can be written as [23]

$$|\psi_0\rangle = \int d\omega f(\omega)|H, \omega\rangle|H, -\omega\rangle,$$

where $\omega$ is the frequency shift with respect to the central frequency $\omega_0$ and $H$ indicates the horizontal polarization. The function $f(\omega)$, defined in [24], gives the probability amplitude. The signal photon enters the 4f-system, where the required linear delay $\tau_d$ is generated by the mask. The 4f-system consists of two gratings with 1200 lines mm$^{-1}$ and of two 100 mm focal lenses. By means of this device the photon spectral components are spatially dispersed in a linear way by the first grating, and then focused onto the liquid crystal mask array of pixels (our mask is composed of 640 pixels 100 $\mu$m wide) capable of setting the relative phases almost at will. Finally, the optical components are again synthesized by the second grating.
The transmission coefficient of the 4f-system depends on the efficiency of the two gratings, and in our apparatus it is around 50%. This device is more flexible than a fast-light medium and, more importantly, allows the manipulation of each single optical component. In this context we observe that our setup allows us to act separately, almost at will, upon the photon optical component phases, contrary to all other experiments in the literature where a dispersion law is imposed by a medium. In our case, the entering light is opened up along a plane by means of the Fourier components’ spatial expansion, whereas in the other experiments the components were forced to propagate along the same original line within the acting medium.

Now, we analyze the propagation of the signal photon along the experimental apparatus. A HWP set in front of the 4f-system rotates the photon polarization by a suitable angle $\theta$ (see below), hence the state of the entering photon is changed into a superposition of a horizontal and a vertical polarized states:

$$|H, \omega\rangle \rightarrow \cos(\theta)|H, \omega\rangle + \sin(\theta)|V, \omega\rangle. \quad (2)$$

Then the signal photon propagates through the 4f-system. The spectral phase function that we introduce is applied only on the horizontal polarization, whereas the vertical polarization experiences only the delay due to the transit through the mask pixels, becoming therefore our time reference. Considering only the path sections that have different optical thicknesses for H and V polarizations, we obtain the two phase variations:

$$\begin{align*}
\phi^m_H(\omega) &= (\omega_0 + \omega)\tau^m_H + \phi_{SLM}(\omega_0 + \omega), \\
\phi^m_V(\omega) &= (\omega_0 + \omega)\tau^m_V,
\end{align*} \quad (3)$$

where $\phi_{SLM}(\omega_0 + \omega)$ is the spectral phase function imposed by mask pixels. In our case we introduce a linear function $\phi_{SLM}(\omega_0 + \omega) = (\omega_0 + \omega)\tau$, with $\tau$ being a constant parameter.
The times $\tau^m_H$ and $\tau^m_V$ are the time delays due to the pixel slab crossing. We found experimentally that $\Delta \tau^m = \tau^m_H - \tau^m_V = 10$ fs. Incidentally, in the setting of the diagnostic system we also had to take into consideration the fact that the two transmission coefficients $t_H$ and $t_V$ of the 4f-system are different (this is due to the different transmission efficiencies of the gratings for the two polarizations).

The interferometer placed after the 4f-system to detect the signal photon at the optical system output is made by two calcite crystals, an HWP and a polarizer set at $45^\circ$. This device, described in [25], interchanges the two polarizations and causes a time delay which can be changed simply by rotating the second crystal. We also have to take into account a certain dispersion introduced by the crystals because they are relatively long. However this dispersion, described by the parameter $\beta$, can be assumed to be nearly equal for the two paths to a very good approximation. The photon state propagation within crystals is then described by the following spectral phase variation:

$$\phi^d_H(\omega) = (\omega_0 + \omega)\tau^d_H + \frac{1}{2} \beta (\omega_0 + \omega)^2,$$

$$\phi^d_V(\omega) = (\omega_0 + \omega)\tau^d_V + \frac{1}{2} \beta (\omega_0 + \omega)^2.$$  \hspace{1cm} (4)

The last step to be analyzed is the propagation through the polarizer placed at $45^\circ$. This is a crucial element in the photon detection. In fact, the polarizer mixes up the H and V polarization states with the result that the two states interfere and a pattern of fringes within the coherence length is created. Summing up the state evolution along the entire path, the signal component $|H, \omega\rangle$ at the output reads

$$|H, \omega\rangle \Rightarrow \frac{1}{\sqrt{2}} \left[ t_H \cos(\theta) e^{i(\phi^0_H(\omega)+\phi^d_H(\omega))} + t_V \sin(\theta) e^{i(\phi^0_V(\omega)+\phi^d_V(\omega))} \right] |45^\circ, \omega\rangle = A(\omega) |45^\circ, \omega\rangle.$$  \hspace{1cm} (5)

The probability of having one count relative to the signal photon, ignoring the idler one, is given by the trace of the density matrix $|\Psi_p\rangle \langle \Psi_p|$ where

$$|\psi_p\rangle = \int d\omega f(\omega) A(\omega) |45^\circ, \omega\rangle |H, -\omega\rangle.$$  \hspace{1cm} (6)

After some mathematics we get

$$P(\tau, \Delta \tau) = t^2 \int d\omega |f(\omega)|^2 \left[ 1 + \text{Re} \left\{ e^{i(\Delta \tau^m + \Delta \tau)(\omega_0 + \omega)} \right\} \right],$$  \hspace{1cm} (7)

where $t = t_H = t_V$ is obtained with a proper rotation of the HWP set in front of the 4f-system, and $\Delta \tau = \tau^d_H - \tau^d_V$ is the time delay introduced by the interferometer.

This result accounts for our experimental data shown in figure 2. Curve (a) is the reference case $\tau = 0$ (which sets the origin of the time scale). Curves (b) and (c) present a lead and a lag of $\tau = \mp 100$ fs, respectively. All data show that the interference fringes occur within a coherence length of $30$ fs $< |\tau|$.

3. Discussion of the experimental results

Considering the transit time of the photon light from the source up to the end of the apparatus (that is looking at the optical system as a long black-box), we observe that the horizontal and vertical polarized parts take different time intervals. The two parts travel at the same velocity.
Figure 2. The interference records of the advanced (b) and retarded (c) photon wavepackets, referred to the reference $\tau = 0$ (a). The top frame shows an expanded view of the interference fringes.

within the vacuum sections and within the lenses (which are isotropic), hence we may say that their velocities are different within the mask slab of $\ell_m = 10 \mu m$ thickness. Using the delay between V and H states measured at the end of the apparatus, we may define the group velocity of the horizontal polarization as

$$v_{gH} = \frac{\ell_m}{v_{gV} + \Delta \tau + \tau},$$

where $v_{gV} = c/1.488$ is the group velocity of the vertical polarization, derived from the manufacturer mask characteristics. The group velocity defined in this way would be greater than $c$ when $\tau$ is lower than $-30\, fs$ and even negative for $\tau < -60\, fs$. We must observe that this overall view of the light transmission would raise problems with respect to the causality principle [26], because of a photon propagation that is mathematically superluminal, and does not consider the real physics of the phenomenon.

The overall result is readily explained by following the spatially sectioned sub-light-packets crossing the mask pixels. Each one of these sub-packets has a limited spectrum selected by the pixel dimension. That portion of the spectrum corresponds to a coherence length of 3 ps. These sub-packets have subluminal velocity in every part of the device, including the mask. According to this view, the recombination of the sub-packets on the second grating leads to either the forward or backward shift of the photon with respect to the non-acted photon.
state, depending on the setting of the component phases. This superluminal effect was already observed in [14, 16].

The question of the information velocity in our experiment does not fit either the discussion presented so far or the debate in progress about the matter, that is, within the models of pulse reshaping and consideration of peculiar points of the pulse (such as front or non-analytic ones). In our experiment photon reconstruction may occur within the entire 3 ps coherence length of a sub-wavepacket, which means a shift backwards or forwards of the reconstructed envelope which is very far from the tail of the reference one. An observation is in order: the delay introduced by the lenses, which is about 30 ps, is larger than the 3 ps maximum advance allowed, and this does not allow direct measurement of ‘superluminality’ downstream of the 4f-system. However, in principle, one could substitute the refractive optics with parabolic mirrors [27], thus eliminating the causes of the delay.

The propagation of the spectral sub-light-packets crossing the pixels is certainly in agreement with causality. In fact, considering Kramers–Kronig relations for the sub-packets, we can represent the evolution by means of a Green function that satisfies the requirements of causality. For different pixels they are independent of one another, so the phase of each pixel can be programmed at will. There is no contradiction, then, in saying that the propagation is causal, although the photon moves far ahead of its coherent length. From this analysis one can infer that the relevant time is not the coherence time of the photon, but the coherence time of the sub-packet that reaches the single pixel.

4. Conclusions

We have performed an experiment on a superluminal shift wider than the coherence length, hence more noticeable than those observed in all other experiments carried out so far. The overall result of figure 2 indicates clearly that we have induced a large superluminal group velocity on the radiation traveling inside the apparatus. Our experiment can also be described by considering a single photon propagating within the apparatus. The superluminal group velocity is such that the preserved photon envelope shows up at distances from the vacuum site that are much larger than the photon coherence length, a result that is not possible with the other experimental layouts. This result was obtained with an optical system capable of managing the single-component phases of the radiation independently, at variance with all other previous experiments. We have shown that our observations are consistent with the principle of causality even if the nominal group velocity is highly superluminal.

By considering this experiment extendable to single photons, we observe that the results would have a physical content different in essence with respect to the complementary result obtained with sub-picosecond laser pulses [5, 6]. In fact, while the detection of the propagation speed of particular points of a light pulse profile (as for instance the front edge) can be in principle experimentally measured, it cannot be considered in the case of a single photon because a point within its wavepacket profile is meaningless, and represents only the probability amplitude of obtaining a click (i.e. of detecting the photon). The superluminality experiment with single photons could be carried out neatly, thanks to the exploitation of the particular technique of the spatial light modulator which allowed the spectral components to be managed while substantially maintaining their amplitudes.
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