Temporal coherence of an optical field in the presence of entanglement

Yunxiao Zhang 1, Nan Huo 1, Liang Cui 1, Wen Zhao 1, Xueshi Guo 1, Xiaoying Li 1* Z. Y. Ou 2*

(1) College of Precision Instrument and Opto-Electronics Engineering, Key Laboratory of Opto-Electronics Information Technology, Ministry of Education, Tianjin University, Tianjin 300072, P. R. China
(2) Department of Physics, City University of Hong Kong, Kowloon, Hong Kong, P. R. China

Author e-mail address: *xiaoyingli@tju.edu.cn; jeffou@cityu.edu.hk

Abstract: Using an unbalanced SU(1,1) interferometer, we study the dependence of interference upon filter bandwidth. We find that under some conditions depending on entanglement, the coherence time does not change when optical filtering is applied. © 2022 The Author(s)

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In classical coherence theory, coherence time is typically related to the bandwidth of the optical field. Narrowing the bandwidth will result in the lengthening of the coherence time. This will erase temporal distinguishability of photons due to time delay in pulsed photon interference. However, this is changed in an SU(1,1)-type quantum interferometer [1,2] where quantum entanglement is involved. As shown in Refs. [3,4], we need to consider the effect of quantum entanglement when we discuss how distinguishability affects interference effects. In this paper, we investigate how the temporal coherence property of the fields in a pulse-pumped SU(1,1) quantum interferometer changes with the bandwidth of optical filtering. We find that under some conditions, because of quantum entanglement [3,4], the coherence property does not change when optical filtering is applied, in contrary to the classical coherence theory.

Fig. 1: (a) A pulse train-pumped SU(1,1) interferometer (SUI) with filtered detection. The parametric amplifiers (PA1, PA2) function as beam splitters. The delay relative to the time slot of pump pulse (Δt or Δε) is introduced to the signal or idler arm for an unbalanced interferometer. Power detection (PD) measurement are performed at the signal and idler outputs, respectively. (b) The interference pattern observed at one output port when the phase of the pump P2 is varied. (c) The visibility of interference in idler output as a function of delay Δε when the bandwidth of filter (Fε) is 0.05, 0.1 and 0.5 THz, respectively. The measurement results are obtained under the condition of Δt=0 (or Δε=0) while changing Δt (or Δε).

The pulse pumped SU(1,1) interferometer (SUI) is shown in Fig.1(a), where two parametric amplifiers (PA1 and PA2) are used as beam splitters [1]. When the signal and idler arms between two PAs are carefully balanced for all the fields involved, interference is observed in the idler output [2]. We then introduce delays (Δε, Δt) in either of the arms so that interference disappears due to temporal distinguishability. We next place narrow optical filters at the idler output port in front of the detector with the intention to lengthen the coherence time of the detected field and erase the temporal distinguishability for the recovery of interference.

Figure 1(b) shows a typical set of interference pattern measured at one output port when the phase of the pump P2 is varied by scanning a piezoelectric transducer (not shown in Fig. 1(a). In the first experiment we set Δε = 0. Fig. 1(c) presents the visibility of interference versus delay Δε when the bandwidth of filter (Fε) is varied. According to the results in Fig. 1(c), we can extract the coherence time of the filtered idler field by assuming Gaussian shape and fitting data to a linear regression of log V vs. Δε2, as shown in Fig. 2(a). The results as the blue data in Fig.2(c) show that the coherence time Tε of the idler output field increases almost linearly with the inverse of filter bandwidth (1/ε), which is the same as classical optical fields.

In the second experiment, we set Δε = 0 but vary Δt. So, the idler pulses have complete overlap and should lead to maximum interference according to classical theory. However, as we see from Fig.2(b), the visibility drops as Δt increases. This is due to entanglement between signal and idler field [3] and temporal distinguishability of the signal photon. Now, the question is whether we can erase this distinguishability by filtering the detected field, as we have done in Fig.2(a). We make similar measurement as Fig.2(a) but now change Δε while setting Δt = 0. The results are shown in Fig. 2(b) and the best fit time constant Tε is plotted as the green data points in Fig.2(c). It can be seen that filtering does not improve the coherence of the idler field.
Fig. 2 The measured visibility as a function of the square of \( \Delta \) in (a) with \( \Delta = 0 \) or \( \Delta \) in (b) with \( \Delta = 0 \) for various filter bandwidths \( \sigma \). The best fit time constants are plotted as a function of reciprocal bandwidth \( 1/\sigma \) in (c).

To understand Fig. 2, we write the photon state in a single mode as
\[
|\psi\rangle = A_1|s_1, i_1\rangle + A_2|s_2, i_2\rangle
\]
(1)
where \( A_1, A_2 \) are related to the pump fields of PA1 and PA2, respectively. When the delay in the signal arm is zero, i.e., \( \Delta = 0 \), signal photon states are identical: \( |s_1\rangle = |s_2\rangle = |s\rangle \), and Eq. (1) becomes
\[
|\psi(\Delta = 0)\rangle = (V_1|i_1\rangle + V_2|i_2\rangle)|s\rangle
\]
(2)
which is a product state with no entanglement (concurrence \( C = 0 \)). Then interference observed at the idler output port is related to the indistinguishability in the idler field between \( |i_1\rangle \) and \( |i_2\rangle \), which can be altered by the optical filtering of the idler field. This corresponding to the classical case, as shown by the result in the blue data in Fig. 2(c). On the other hand, if there is a delay in the signal field \( (\Delta \neq 0) \) \( |s_1\rangle \neq |s_2\rangle \), the temporal distinguishability in the signal field leads to no interference of the idler field and this cannot be erased by optical filtering at the idler field. In this case, the classical concept of coherence time does not apply.

Quantitative understanding of Fig. 2 needs a full quantum description of the process, which gives an output two-photon state of the form:
\[
|\Phi_2\rangle = \int d\omega_1 d\omega_2 [\Phi(\omega_1, \omega_2)e^{i\omega_1\Delta_1 e^{i\omega_2\Delta_2}} + \Phi'(\omega_1, \omega_2)] \times \hat{a}_1^\dagger(\omega_1)\hat{a}_2^\dagger(\omega_2)|\text{vac}\rangle
\]
(3)
where \( \Phi(\omega_1, \omega_2), \Phi'(\omega_1, \omega_2) \) are the two-photon wave functions for the two-photon states produced by PA1 and PA2 respectively. Assuming the two PAs are identical, we can derive the time constants \( T_i, T_s \) for Fig. 2(c), which can be expressed as:
\[
T_i^2 \equiv \frac{1}{\sigma_i^2} + \frac{4}{\sigma_i^2 + 2\sigma_0^2}
\]
(4)
\[
T_s^2 \equiv \frac{\sigma_0^2 + 2\sigma_i^2 + 4\sigma_0^2}{\sigma_0^2 + 2\sigma_i^2 + 4\sigma_0^2}
\]
(5)
where \( \sigma_i \) and \( \sigma_0 \) are the bandwidths of filter and pump, respectively. \( \sigma_0 \) denotes the bandwidth of the phase matching function in each PA. In the extreme case of using single frequency continuous wave laser as pump, we will have \( T_s = T_i \). We calculate \( T_i \) and \( T_s \) by substituting the experimental parameters into Eqs. (4) and (5), respectively, as shown by the solid line and curves in Fig. 2(c), respectively. The results show the experimental data well agree with theoretical predictions.

In conclusion, we demonstrate experimentally that when there is quantum entanglement involved, the classical concept of coherence time does not apply and interference effect also depends on quantum entanglement [3,4].

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