

Second-Order Temporal Interference with Thermal Light: Interference beyond the Coherence Time

Yong Sup Ihn[1], Yosep Kim[1], Vincenzo Tamma[2] and Yoon-Ho Kim[1†]

[1]*Department of Physics, Pohang University of Science and Technology (POSTECH), Pohang, Korea 37673*
[2]*Faculty of Science, SEES and Institute of Cosmology & Gravitation,University of Portsmouth, Portsmouth, PO1 3QL, UK*
[†]*yoonho72@gmail.com*

Abstract: We report observation of a counter-intuitive phenomenon in multi-path correlation interferometry with thermal light. The intensity correlation between the outputs of two unbalanced Mach-Zehnder interferometers (UMZI) with two classically correlated beams of thermal light at the input exhibits genuine second-order interference with the visibility of 1/3. Surprisingly, the second-order inter- ference does not degrade at all no matter how much the path length difference in each UMZI is increased beyond the coherence length of the thermal light. Moreover, the second-order interference is dependent on the difference of the UMZI phases. These results differ substantially from those of the entangled-photon Franson interferometer which exhibits two-photon interference dependent on the sum of the UMZI phases and the interference vanishes as the path length difference in each UMZI exceeds the coherence length of the pump laser. Our work offers deeper insight into the interplay between interference and coherence in multi-photon interferometry.

Two-photon interference or second-order interference, in which interference is observed only in the correlation between two detectors, has long been at the heart of quantum optics and it has its root in the Hanbury-Brown–Twiss (HBT) experiment. The quintessential effect of the HBT experiment with thermal light is that the joint detection probability of the two detectors is twice as large when the two detectors "click" simultaneously than that of the case when the two detectors "click" with a relative time delay bigger than the coherence time of the thermal light. While the HBT effect with thermal light can be explained as the correlation of intensity fluctuations, quantum mechanically, it is understood as constructive interference between two indistinguishable two-photon detection probability amplitudes. HBT interferometry in recent years has become essential for a variety of studies in quantum physics, e.g., bunching and anti-bunching of photons, electrons, and atoms.

In this work, we demonstrate experimentally a novel second-order temporal interference effect. Differently from the usual HBT effect, we show the emergence of sinusoidal second-order interference fringes which seems to contradict the common understanding of temporal coherence [1,2].

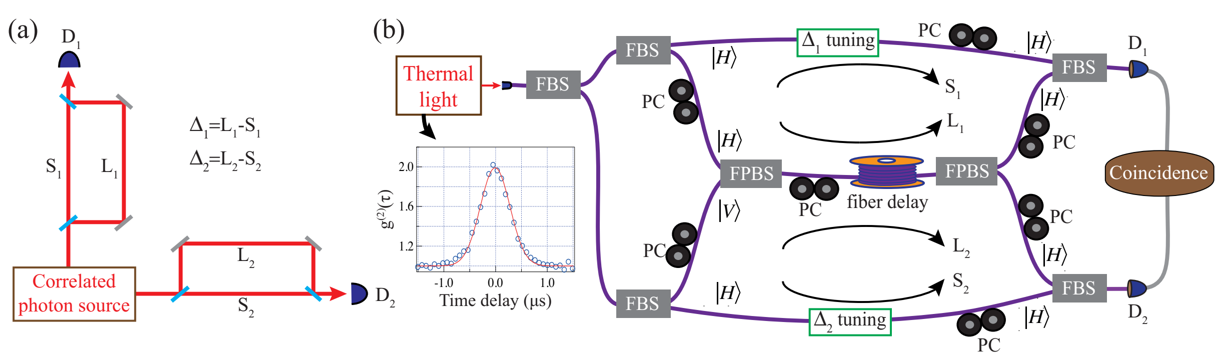

Figure 1. (a) The idea of the experiment. (b) The experimental schematic.

The essential idea of the experiment is shown in Fig. 1. A pair of classically correlated beams is generated by beam splitting of a thermal light beam. Each beam is then sent through an unbalanced Mach-Zehnder interferometer (UMZI) with the path length difference between the long and short paths larger than the longitudinal coherence length of the thermal light. The second-order correlation between the detectors placed at the output of UMZI is measured with a coincidence time window smaller than the coherence time of the thermal light. The two UMZI satisfy the following conditions. First, the path length differences Δ_1 and Δ_2 are larger than the coherence length of the thermal light. This condition ensures that there is no fist-order interference at the detectors. Second, the two UMZI are similar to each other in that the differences of the corresponding optical paths are small compared to the coherence length of the thermal light. Under these conditions, the correlation measurement picks up second-order interference due to the relative phase difference between the long path (L_1,L_2) and the short (S_1,S_2) path [3]. The second-order correlation function which is manifested in the coincidence count rate is then given by $3 + \cos((\Delta_1-\Delta_2)\omega/c)$.

In the case of the Franson interferometer, the input photon pair is energy-time entangled so that the interferometer serves as an apparatus to measure energy-time entanglement [3]. In our scheme, we consider two classically correlated beams of light, produced by beam-splitting of a thermal light beam. Nonetheless, temporal correlation between the long paths and the short paths do exist when the correlation measurement is performed at the coincidence time window smaller than the coherence time of the thermal light.

The second-order temporal interference phenomenon reported here emerges from interference of two effective probability amplitudes associated with two pairs of correlated paths (L_1,L_2) and (S_1,S_2). Interestingly, the second-order interference does not degrade at all no matter how much the path length difference in each UMZI is increased beyond the longitudinal coherence length of the thermal light. This represents a counter-intuitive manifestation of second-order temporal coherence. Indeed, this is in stark contrast to entangled-photon Franson interferometry in which the second-order interference is limited to the coherence length of the pump laser generating the energy-time entangled photons.

We however point out that these results are fundamentally of different origin from those of the entangled-photon Franson interferometer, where the second-order interference is the result of interference between probability amplitudes associated with a single pair of entangled photons taking either the (L_1, L_2) or the (S_1, S_2) path. Indeed, the Franson interferometer exhibits two-photon interference dependent on the sum of the UMZI phases, $\Delta_1 + \Delta_2$, and the interference vanishes as the path length difference in each UMZI exceeds the coherence length of the pump laser [3].

The experiment described in Ref. [1] has been demonstrated with pseudo-thermal light as shown in Fig. 1. In Ref. [2], we demonstrate that the same effect is indeed observed with a true thermal light generated from atomic spontaneous four wave mixing. The phenomenon demonstrated here, for instance, can be used to measure an unknown longitudinal phase difference between two remote locations.

3. References

[1] Y. S. Ihn, Y. Kim, V. Tamma, and Y.-H. Kim, “Second-order temporal interference with thermal light: Interference beyond the coherence time,” Phys. Rev. Lett. 119, 263603 (2017).

[2] G.-H. Lee, D.-G. Im, Y. Kim, U.-S. Kim, and Y.-H. Kim, “Observation of second-order interference beyond the coherence time with true thermal photons,” Opt. Lett. 45, 6748 (2020).

[3] O. Kwon, K.-K. Park, Y.-S. Ra, Y.-S. Kim, and Y.-H. Kim, “Time-bin entangled photon pairs from spontaneous parametric down-conversion pumped by a cw multi-mode diode laser,” Opt. Express, 21, 25492 (2013).