Measurement-dependent erasure of distinguishability for the observation of interference in an unbalanced SU(1,1) interferometer

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Abstract: We report a method of homodyne detection that can recover otherwise lost interference effect in an unbalanced SU(1,1) interferometer. The indistinguishability due to amplitude measurement and slow detection is responsible for the recovery of interference. © 2022 The Author(s)

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It is well-known that the occurrence of quantum interference phenomena relies on whether it is possible to distinguish the interfering paths. This quantum complementarity principle is demonstrated in the phenomenon of induced coherence without induced emission [1,2] in parametric processes where one (first) of the generated twin photons can be used for path distinguishability of the other twin photon (second). It seems that the disappearance of interference is predetermined by the possibility of distinguishing the first photon even without the actual act for distinction on the photon. Nevertheless, such distinguishability can be erased by projective measurement of the first photon to recover interference of the second photon [3,4].

![Fig. 1: (a) A pulse train-pumped SU(1,1) interferometer in which parametric amplifiers (PA1, PA2) function as beam splitters. A delay of a full pulse duration is introduced to the signal arm for an unbalanced interferometer. Direct intensity measurement (PD) and homodyne measurement (HD) are performed simultaneously at two output ports, respectively. (b) An unbalanced SU(1,1) interferometer with asynchronized signal arm. LO consists of two pulses to measure the asynchronized signal field for amplitude addition. Half waveplates (HWPs) are used to rotate the polarization of delayed signal and its corresponding LO pulse train by 90 degree.](image)

We create such distinguishability in an unbalanced SU(1,1) interferometer, as shown in Fig.1, where two parametric amplifiers are used as beam splitters [5], and indeed observe no interference in the direct photodetection of the outputs when a delay is introduced in the signal path, as shown in Fig.2(a) when the phase of the interferometer is scanned. However, different from the quantum eraser scheme where distinguishability is erased with a projective measurement [3,4,6], we implement a method of homodyne detection that can also recover interference effect, as shown in Fig.2 (b) when the phase of the interferometer is scanned.

![Fig. 2: (a) Direct intensity measurement yields no interference. (b) Interference is recovered in homodyne measurement with slow detectors.](image)

The disappearance of interference in direct power (intensity) measurement is straightforward because the SU(1,1) interferometer is a variation of the interference experiment of induced coherence without induced emission [1,2]: with the delay in signal arm, the signal photon cannot induce coherence in idler photon due to temporal distinguishability. However, the recovery of interference in homodyne detection is a total surprise based on the above argument of distinguishability. To explain the result, we calculate the photo-current from homodyne detection with a full quantum theory and it has the following result:
\[ i_{\text{HD}}(t) = \left| e_0 \right| \sum_j k(t - j \Delta T) \left[ \hat{X}_{\text{det}}^{(j)}(\phi - \theta) \cosh K_1 + \hat{X}_{\text{det}}^{(j)}(\theta - \phi) \sinh K_1 \right] \cosh K_2 + \left| k(t - j \Delta T) \right| \left[ \hat{X}_{\text{det}}^{(j)}(\phi) \sinh K_1 + \hat{X}_{\text{det}}^{(j)}(-\phi) \cosh K_1 \right] \sinh K_2 \]

where $\Delta T$ is the delay in the unbalanced interferometer, $K_1$, $K_2$ are the gain parameters of PA1 and PA2, and $k(t)$ is the response function of the detectors used for the homodyne detection. $\hat{X}_{\text{det}}^{(j)}$, $\hat{X}_{\text{LO}}^{(j)}$ are the quadrature-phase amplitudes of input signal and idler fields. $\theta$ is the phase of the interferometer. $\phi$ is the phase and $e_0$ is the amplitude of the local oscillator (LO) of the homodyne detection. The sum is over a whole pulse train labeled by $j$. From above, we find that when $k(t)$ is wider (slow detector) than the delay $\Delta T$, the quantum nature of homodyne detection and the detector's slow response time give rise to the indistinguishability in amplitude between $j$th and $(j-1)$th pulses that leads to the recovery of interference. More specifically, we derive quantitatively the visibility of interference for the homodyne measurement as

\[ V_{\text{HD}}(\Delta T) = \frac{\sinh 2K_1 \sinh 2K_2}{1 + 2 \sinh^2 (K_1 - K_2) + \sinh 2K_1 \sinh 2K_2} \left[ \int dt k(t - \Delta T) / \int dt k^2(t) \right]. \]

The dependence of visibility on response function is obvious above.

The difference in the observation of direct power (intensity) measurement and homodyne measurement is that the former is intensity measurement which, in the unbalanced case, gives intensity addition due to distinguishability, whereas the latter is amplitude measurement which, even in the unbalanced case, results in amplitude addition from different pulses due to the slowness of detectors and thus cannot distinguish from which pulse the photon comes. In the latter case, interference occurs because of photon indistinguishability in homodyne measurement process even though there is distinguishability in photon generation in PA1 and PA2. This recovery of interference is different from the quantum eraser schemes [3,4,6] where distinguishability in photon generation is erased by projection measurement on the other correlated photon. It demonstrates that the outcome in the observation of a quantum system is highly dependent on the measurement process and quantum interference occurs in the measurement processes.

To further prove that amplitude addition by homodyne detection is what leads to the recovery of interference, we make a variation of the unbalanced interferometer by setting the delay ($T_{\text{delay}}$) of the signal arm not equal to a multiple of the pump pulse separation but some arbitrary number (see Fig. 1(b)). In this case, the PA2 will not interact the delayed signal field generated in PA1 with the corresponding idler field because the pump pulse train to PA2 is not synchronized with the delayed signal field. Moreover, we rotate the polarization of the delayed signal field by 90 degree by inserting a half waveplate. In this way, there is no interference in direct intensity measurement no matter what is done. To perform homodyne detection measurement, we make an extra pulse in the LO and the corresponding LO also has its polarization rotated 90 degree (see Fig. 1 (b)) to match the delayed signal so that the HD still measures the amplitude of the asynchronous signal field and adds it with the amplitude of the signal field which is generated by PA2 and is synchronous to the pump of PA2. This leads to interference pattern similar to that observed in Fig. 2(b).

It should be pointed out that the observed interference effect only depends on the phase of the interferometer ($\theta$) and is independent of the phase of LO ($\phi$ in Eq.(1)) although homodyne detection involves the mixing of LO with the field to be measured. The role of LO is to solely make an amplitude measurement. Furthermore, since the pump field is in the form of short pulses in a train, the generated signal and idler fields together with the matched LO are all in broad band and thus are suitable as a probe field for sensing. With no need for path compensation, the unbalanced interferometers studied here should have practical applications in quantum metrology and remote sensing.

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