Optimal detection of ultra-broadband bi-photons with quantum nonlinear SU(1,1) interference

Nir Nechushtan, Hanzhong Zhang, Mallachi Meller and Avi Pe’er

Department of Physics and BINA Center for Nanotechnology, Bar-Ilan University, Ramat Gan 5290002, Israel

* Author to whom any correspondence should be addressed.
E-mail: avi.peer@biu.ac.il

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Abstract

The visibility of nonlinear SU(1,1) interference directly reflects the nonclassical properties of entangled bi-photons and squeezed light with practically unlimited bandwidth, high efficiency and ultra-high photon flux, orders of magnitude beyond the abilities of standard photo-detectors. We study experimentally the dependence of the SU(1,1) visibility on the phase matching conditions and beam parameters in a free-space configuration, and show that maximal SU(1,1) visibility requires extreme collinear conditions, which deviate from the conditions for maximal nonlinear conversion. We demonstrate near-ideal visibility of \( \sim 95\% \) (limited only by internal loss) in an ultra-broadband SU(1,1) interferometer with over 120 THz of squeezed light bandwidth. Utilizing this analysis we demonstrate efficient detection of the spectral phase of single-cycle bi-photons and precise compensation of the dispersion over a full octave of bandwidth.

1. Introduction

Parametric amplification in a nonlinear medium by means of down conversion (PDC) or four-waves mixing, is a key source of quantum light, such as entangled photon-pairs (bi-photons) and squeezed coherent states [1, 2]. The bandwidth of parametric amplification can be very wide (over 120 THz in this work), offering a unique resource for quantum information science and technology [3–8]. Specifically, when the parametric interaction is phase matched across a wide bandwidth and pumped by a narrowband laser, an ultra-high flux of single bi-photons can be produced (up to \( 10^{14} \) bi-photons/s in this work) with extreme time–energy entanglement (or two-mode squeezing at higher power levels), which is attractive for quantum technology, such as high-speed quantum communication [3, 9–12] broadband quantum sensing [13–17], and even photonic quantum computation [18–21].

Despite their attractive properties, broadband bi-photons and squeezed light are rarely used in standard quantum technology, mainly due to the lack of efficient broadband measurement methods. Recently, parametric homodyne measurement was introduced [17], that does not rely on direct detection with photo-detectors, but rather on broadband parametric amplification and simple intensity detection of the full, ultra-high photon flux, offering a viable route to utilize the quantum bandwidth resource of broadband bi-photons. Specifically, parametric homodyne relies on the phase-dependent amplification of parametric gain, which amplifies one quadrature component of the input light field without added noise, while attenuating the other quadrature. Thus, the output field from a parametric amplifier reflects primarily one quadrature of the input field, with the pump laser acting as a local oscillator that provides the phase-reference in the homodyne scenario to the entire bi-photon bandwidth.

Consequently, measurement of a squeezed state entails two parametric amplifiers in series—the first creates the squeezed state and the second measures it, with some control of the phase in between to select the measured quadrature axis. This configuration directly reflects the well-known nonlinear SU(1,1) interference [22–24], as illustrated in figure 1, where parametric amplifiers take the place of the beam splitters in a standard Mach–Zehnder interferometer [SU(2)] [25]. Taking advantage of the squeezing that is generated within the interferometer, the SU(1,1) can achieve sub shot-noise sensitivity in phase-detection.
that is resilient to detection inefficiency and capable of handling practically unlimited optical bandwidth.

In the low gain regime, the weakly squeezed vacuum generated by the parametric amplifiers is equivalent to the random generation of photon pairs [27]. In this regime, bi-photons generated by SPDC in the first nonlinear crystal are guided along with the pump field into a second crystal, where either enhancement or annihilation of the SPDC can occur, depending on the bi-photons phase relative to the pump. After the second crystal, the photon flux (or spectrum) is measured with a standard photo-detector (or spectrometer), showing interference fringes as a function of the accumulated phase between the bi-photons and the pump. The observed fringes are due to the quantum mechanical interference between two indistinguishable pathways—a detected photon can be generated either in the first crystal or in the second. The lack of a photon could indicate either that a bi-photon was generated in the first crystal and annihilated in the second, or that no bi-photon was generated at all. Conceptually, when the interference is destructive the 2nd crystal serves as a physical detector of bi-photons, where the existence of entangled pairs is detected by attempting to annihilate them via up-conversion back into the pump.

Since up-conversion affects only bi-photons, the fringe visibility is a direct measure of the bi-photon purity [3]. If the bi-photons phase varies spectrally (non-transform-limited pairs), high-visibility interference fringes would appear on the measured bi-photons spectrum in a symmetric manner around the degeneracy point at \( \omega_p/2 \), which provides a direct holographic measurement of the bi-photons spectral phase. Moreover, a theoretical quantum analysis [3] showed that the fringe visibility can also be utilized to detect and measure loss within the SU(1,1) interferometer by the following relation:

\[
\text{Visibility} = \frac{2 t_p^2 t_{dc}^2}{t_p^2 + t_{dc}^2},
\]

where \( t_p \) and \( t_{dc} \) are the pump and down-conversion amplitude transmission coefficients respectively. Hence, the interference visibility is expected to be a valuable measurement tool, especially in the ultra-broadband regime.

However, the visibility in the experiments published so far [3, 28] did not meet the prediction of equation (1). Since the visibility of the SU(1,1) interference is important to characterize the bi-photons as explained above, understanding the sources of visibility degradation and optimizing the experiment for maximum visibility are important to establish the validity of an SU(1,1) measurement and to calibrate its outcome. In what follows, we analyze the different mechanisms for visibility degradation and present an optimized nonlinear interference, that achieves the ideal loss limit, by effective control of the pump beam parameters and phase matching conditions.

2. Analysis and optimization of the SU(1,1) interference

In our aim to optimize the SU(1,1) visibility in a free-space configuration, we examined two main parameters: the temperature of the nonlinear crystal, which controls the phase-matching condition; and the focusing of the pump beam in the crystal, which affects the efficiency of down conversion and the

Figure 1. (a) The simple SU(1,1) interferometer: generation of bi-photons by SPDC in the first medium, is followed by further enhancement or annihilation of the bi-photons in the second medium. A change in the relative phase between the pump and the down converted light governs the interference. (b) The analogy to a standard Mach–Zehnder SU(2) interferometer, where the nonlinear media represent two-photon beam splitters that couple the pump and the bi-photons beams.
Figure 2. (a) Experimental configuration: the 885 nm pump beam (black) is shaped by a variable telescope for manipulation of the beam waist, and then focused into the nonlinear PPKTP crystal with a lens ($f = 75$ mm). The temperature of the crystal is varied to adjust the phase matching condition (collinear or non-collinear). The SPDC generation (red-blue) is reflected back along with the pump by a spherical dielectric mirror (>99.5% reflectivity) for a second pass through the PPKTP crystal, forming the SU(1,1) interferometer. The spectrum of the resulting down conversion is separated from the pump by a harmonic separator (HS) mirror and observed by a home-built spectrometer composed of a prism (SF11 glass) and a CCD camera for the IR-range (Xeva-2.5-320 by Xenics). The observed spectral fringes (b) are due to the dispersion of the coating of the spherical mirror, which varies the phase of the bi-photons across the spectrum.

parametric gain. Normally, one would optimize these parameters for maximum down-conversion efficiency, adjusting the pump focus according to the Boyd–Kleinman recipe of matching the Rayleigh range of the beam to the length of the crystal [29]. However, here the optimization target is different—interference visibility and not generation efficiency, which leads to different conditions for both parameters, as we show. Specifically, the visibility is very sensitive to the spatial properties of the generation (collinear or non-collinear) in both crystals and strict collinear generation is necessary to observe near-ideal visibility, as we explain below. This dictates operation at the edge of the phase-matching condition [30] beyond the maximum efficiency point to suppress deleterious non-collinear generation. For the beam focusing the requirement is less restrictive, and optimal visibility can be obtained in a wide range of pump beam waists around the Boyd–Kleinman criterion.

To understand how the phase matching conditions affect the spatial properties of the down-converted beam, remember that spontaneous PDC is initiated by the vacuum, which is inherently incoherent and covers all modes of space and frequency. Since phase-matching basically reflects the momentum mismatch within the nonlinear medium ($\Delta \vec{k} = \vec{k}_p - \vec{k}_s - \vec{k}_i$), whose angular-bandwidth is finite and inversely proportional to the length of the crystal ($|\Delta \vec{k} \cdot \vec{l}| \leq \pi$), all wave-vectors within this angular bandwidth will contribute to the generated SPDC as analyzed in detail in [30]. Thus, in contrast to stimulated PDC, where the output spatial mode is dictated by the classical coherent seed, it is impossible for spontaneous PDC to
Figure 3. (a) SU(1,1) Visibility and SPDC intensity vs the temperature of the crystal, showing that optimal visibility does not coincide with maximum efficiency, but appears beyond it. (b) Visibility and SPDC intensity vs the pump spot diameter at the crystal (calculated from the measured beam width before the focusing lens), showing the wide tolerance of the visibility to focusing parameter around the Boyd–Kleinman criterion (vertical dashed line). The intensity value reflects the global maximum of the observed spectrum at each experimental point. The calculation of the visibility \( V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \) relies on the following: the maximum intensity \( I_{\text{max}} \) is considered as the maximum peak value, and the minimum intensity \( I_{\text{min}} \) of each fringe is the average between the two intensity minima on both sides of the peak. Since the fringe spectrum is inherently symmetric, we used for our calculation only the left-side peaks, since the right side is out of focus of the camera (due to the chromatic aberration of the CCD lens).

be purely single-mode in space (or frequency) in a free-space configuration, and its angular bandwidth will be dictated by phase matching, as we analyze below.

We employ in our experiment an SU(1,1) interferometer with an ultra-broad bi-photons spectrum, which provides simultaneous observation of the interference across many signal-idler pairs in the spectrum. To generate these broadband bi-photons, we employ a periodically-poled KTP (PPKTP) crystal (dimensions: \( 1 \times 2 \times 12 \text{ mm} \), poling period: \( 37 \mu\text{m} \)), pumped by a single-frequency laser at 885 nm. This pump wavelength was chosen to maximize the spectral bandwidth of the two-mode light by positioning the center of the bi-photons spectrum (1770 nm) near the zero-dispersion wavelength of the PPKTP crystal (1789 nm) [31], allowing an ultra-broad phase matching (>120 THz, nearly an octave) between 1.25–2.5 \( \mu\text{m} \).

Our experimental configuration (see figure 2) was based on a simple folded SU(1,1) interferometer, where a single nonlinear crystal acts as both the 1st and the 2nd parametric amplifier in opposite directions: the down conversion beam is retro-reflected along with the pump by a spherical mirror back into the nonlinear crystal, where it can be either amplified or attenuated, depending on the relative phase. Beam waist manipulation was achieved by a three-lens variable telescope [32], and measurement of the output spectrum was performed with a simple home-built prism-based spectrometer.

We first examined the temperature dependence of the interference visibility (setting the pump beam size according to the Boyd–Kleinman criterion). As expected, a symmetrical spectral interference pattern around the degenerate wavelength, \( \lambda_0 = 1770 \text{ nm} \), was observed due to the dispersion from the dielectric spherical mirror within the SU(1,1) interferometer. The dependence of both the SU(1,1) fringe visibility and the SPDC intensity on the crystal temperature is shown in figure 3(a).
Clearly the optimal fringe visibility is achieved somewhat beyond the temperature for maximum intensity, where the generation is slightly phase mismatched and dominated by collinear SPDC. This strong collinear preference can be explained by two possible mechanisms of phase variation that appear within the nonlinear medium and decrease the visibility—the intrinsic variations of noncollinear angles and the inconsistent imaging along the optical axis. The intrinsic variation is due to the fact that in a nonlinear medium of finite length the generation is not only exactly at the phase matched $k$-vectors, but also with a small spatial bandwidth around it, where the phase mismatch does not exceed $|\Delta \vec{k} \cdot l| \leq \pi$ ($l$ is the crystal length and $\Delta \vec{k}$ is the wave-vector mismatch). The phase mismatched components of the generated beam acquire a nonzero bi-photon phase $\varphi_{\Delta \vec{k}} = \frac{\Delta \vec{k} \cdot l}{2}$ according to their phase mismatch value [33], which is later imprinted onto the SU(1,1) interference. However, since $\Delta \vec{k}$ varies for various noncollinear angles across the narrow angular width of the generated beam (see figure 4(a)), the mismatch phase $\varphi_{\Delta \vec{k}}$ varies across the spatial directions of phase matching, which leads to smearing of the SU(1,1) interference fringes due to contributions of different components with different phases. This effectively decreases the fringe visibility of the detected bi-photons spectrum. An additional cause of the visibility loss is related to the imaging of the first crystal onto the second one through the intermediate mirror/lens, as illustrated in figure 4(b).

Generally, in order to maintain the same noncollinear wave interaction in both crystals, the angles between the different waves in the image should be the same as in the source, which inherently requires one-to-one imaging with unit magnification. However, since the crystals are long, the magnification is not uniform across the crystal length when imaged with a single lens. While the center of the crystal may be imaged with unit magnification, the edges of the crystal are not (one is magnified and the other demagnified). Consequently, the phase mismatch and the bi-photon phase vary longitudinally along the crystal, which causes smearing of the SU(1,1) interference and reduction of the visibility. A possible mitigation of this error may be to use telecentric imaging with two lenses (or mirrors) separated by $2f$ distance (telescope), which yields a uniform unit-magnification along the optical axis.

Since the above mechanisms degrade the interference only with non-collinear generation, the optimal interference visibility is obtained with our free space interferometer when the noncollinear components are suppressed, which naturally occurs at the very edge of the phase matching range, just before the intensity starts to decrease. On the other hand, in terms of pump focusing in the nonlinear crystal, we found that the optimal visibility is rather tolerant to focus variation around the Boyd–Kleinman optimum. Specifically, the visibility remains high even with bigger spot sizes, which indicates high flexibility in choosing the beam parameters. The observed dependence in figure 3(b), where we set the temperature to the optimal value of figure 3(a) (80 ºC), the interference pattern with the optimal parameters in figure 2 shows ~95% fringe visibility. Adapting the SU(1,1) quantum interference analysis of [3], this visibility matches well the theoretical prediction when assuming the pump transmission as 90% (measured) and ~95% for the down-conversion transmission (estimated) of our nonlinear crystals. We conclude that our fringe visibility is indeed near its ideal theoretical limit at our current level of loss.
Figure 5. (a) Collinear SPDC generated in the first PPKTP crystal is sent to double pass through (b) a prism-pair configuration with an intermediate 4f telescope consisting of two spherical mirrors which allows effective negative distance between the prisms. The correct selection of the negative distance R and the prims-penetration H will compensate two orders of dispersion across the SPDC spectrum. The compensated light beam returns from the prism-pair configuration at a slightly lower height than the input and directed into (c) second PPKTP crystal followed by our home-built spectrometer. All mirrors are coated by protected silver for low dispersion.

Figure 6. Dispersion compensation results: various output spectra were taken at the optimal point of compensation with varying pump phase, showing the unison swing of the entire spectrum between constructive and destructive interference (with visibility of 55%).

3. Precision, low loss dispersion compensation for single cycle-bi photons

The above understanding of the conditions for optimal two-photon interference allowed us to demonstrate another important control dimension for broadband parametric light—precise dispersion compensation over the entire bi-photons spectrum. As illustrated in figure 5, we expanded our SU(1,1) interferometer (figures 5(a) and (c)) with a prism-based spectral phase-shaper between the crystals (figure 5(b)) that is double-passed, and consists of prism-pair with an intermediate telescope.

Practically, to fully exploit the ultra-broad bi-photon bandwidth (>120 THz), two orders of dispersion (2nd and 4th) should be precisely and independently tuned [34] and low-loss in the shaper is preferable to maintain the purity of the quantum bi-photon state, which favors a pair of Brewster prisms for compensation instead of gratings. In addition, since the bi-photons are generated in our experiment in the IR range, where the dispersion of most optical materials is anomalous (negative), a standard prism-pair (or grating pair) [35, 36] are no longer applicable, since they inherently rely on the negative dispersion of free
space between the prisms/gratings to compensate for the generally positive dispersion of optical materials. Thus, when shifting deeper into the IR range, the free space dispersion we rely on cannot compensate the material dispersion since they are both negative. In order to expand this concept to allow compensation of negative material dispersion, we utilize the intra-shaper telescope to image the first prism beyond the second prism, thereby creating a 'negative distance' between the prisms. The telescope allows therefore to swap the roles of space and material—instead of positive material dispersion that is compensated by the negative dispersion of free space propagation, we use prisms with negative material dispersion with 'negative distance' between them to introduce positive dispersion, which enables exact compensation of the dispersion [28]. By varying the two degrees of freedom of the prism-shaper (the separation R between the prism tips and the insertion H of the prisms into the beam path), two orders of dispersion (2nd and 4th in our case) can be compensated simultaneously.

By combining the above optimal parameters (figure 3) with precise nulling of the astigmatism of the spherical mirrors in the shaper, a dispersion compensated SU(1,1) interferometer was realized, where the entire octave-wide spectrum responds in unison as one fringe (!), as shown in figure 6. The visibility of the interference was $\sim 55\%$ (as opposed to 15% in previous publications [28]), again limited by the loss of the interferometer due primarily to the silver mirrors used in the shaper (total 11 mirror bounces).

4. Conclusion

We demonstrated an optimized quantum detection of bi-photons and squeezed light in free space with ultra-broadband nonlinear interference at the theoretical loss limit, taking into account the nonlinear medium (phase matching) and the beam parameters (waist and location).

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Nir Nechushtan https://orcid.org/0000-0002-1458-8330
Avi Pe'er https://orcid.org/0000-0002-2813-7194

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