

Spectral correlation measurements at the Hong-Ou-Mandel interference dip

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We present an efficient tool capable of measuring the spectral correlations between photons emerging from a Hong-Ou-Mandel interferometer. We show that for our spectrally factorizable spontaneous down-conversion source, the Hong-Ou-Mandel interference visibility decreases as the photons' frequency spread is increased to a maximum of 165 nm. Unfiltered, we obtained a visibility of $92.0\% \pm 0.2\%$. The maximum visibility was $97\% \pm 0.2\%$ after applying filtering. We show that the tool can be useful for the study of spectral correlations that impair high-visibility and high-fidelity multisource interference applications. The nature of this tool also allows for arbitrary post-selective spectral filtering and high-rate multiphoton spectral correlation measurements.

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I. INTRODUCTION

Multiphoton entanglement lies at the heart of many quantum information and communication applications [1–8]. To generate the photonic states needed for these systems in a scalable manner, it is often necessary to entangle photons from different sources together. This can be accomplished by interfering two photons with one another, but the process is only successful if both photons are completely indistinguishable from one another in every degree of freedom. Such indistinguishable photons are also critical to implementations of boson sampling and quantum random walk protocols which rely on quantum interference with a high visibility [9–13]. Generating indistinguishable photons from two different sources remains a challenging open problem [14–19]. One of the most common methods of generating entangled photons is through the process of spontaneous parametric down-conversion where a parent photon splits into a pair of daughter photons, called the signal and idler. The photon pairs generated through down-conversion can possess strong spectral entanglement and correlations. It is therefore important to engineer the down-conversion process to produce photon pairs that are spectrally uncorrelated with one another [14]. To date, much effort has been spent developing ways to design spectrally pure down-conversion sources by studying different material properties, angles of emission of the photons [20,21], and the nonlinear profile of the crystal [22,23].

A standard method for measuring how distinguishable two photons are is to use a Hong-Ou-Mandel interferometer (HOM) [24]. However, a standard HOM measurement only reveals the amount of distinguishing information, but does not provide clues as to its origin. Here, we present a tool for studying the two-photon interference and indistinguishability of two photons that is well suited to analyzing the spectral properties of photons. We take two photons and interfere them on a beam splitter in a Hong-Ou-Mandel interferometer [24]. Using a fiber-based spectrometer we measure joint-spectral information from the two photons as a function of their arrival time on the HOM interferometer [18]. The fiber spectrometer allows for high-rate higher-order photon correlation

measurements since all possible coincidences are measured simultaneously. This provides detailed dynamical information about the spectral correlations not typically available in a HOM measurement. This extra information yields direct insights into the quality and behavior of the photon source. Our technique also enables us to implement arbitrary spectral filters to shape and tailor the measured joint spectrum of the two photons.

Section II reviews the theory of joint-spectral correlations emerging from the Hong-Ou-Mandel interference beam splitter. Section III describes the fiber spectrometer in detail and explains the limits and potential improvements for its spectral resolution. Section IV presents the experiment; in Sec. V we show our results and conclude with Sec. VI.

II. JOINT-SPECTRAL CORRELATIONS

We use a single down-conversion source for the demonstration of the spectrally resolved Hong-Ou-Mandel interference. The spectral intensity distribution of the two-photons $I(\omega_1, \omega_2)$ exiting from opposite ports of the HOM interferometer is given by [25,26]

$$I(\omega_1, \omega_2) \propto \frac{1}{2} |C(\omega_1, \omega_2)e^{i(\omega_1 t_1 + \omega_2 t_2)} - C(\omega_2, \omega_1)e^{i(\omega_2 t_1 + \omega_1 t_2)}|^2, \quad (1)$$

where $C(\omega_1, \omega_2)$ is the complex joint-spectral amplitude (JSA) of the two-photon wave function, ω_1 and ω_2 are the signal and idler frequencies, respectively, and t_1 and t_2 are the signal and idler photon detection times. The beam splitter acts as a symmetry filter. If the joint spectrum $C(\omega_1, \omega_2)$ is symmetric under the exchange of the signal and idler frequencies, then when $t_1 = t_2$ perfect destructive interference takes place and the two photons never exit from opposite ports of the beam splitter. A typical photon generated from down-conversion comes in a wave packet containing many different frequency components. Interference of such photons leads to a rich interference spectrum that beats as the product between the relative arrival time $\delta t = t_1 - t_2$ and the frequency difference $\Delta\omega = \omega_1 - \omega_2$.

Typical single-photon detection systems integrate over all of the frequency components, leading to a coincidence detection rate of:

$$R_c = \iint d\omega_1 d\omega_2 I(\omega_1, \omega_2). \quad (2)$$

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Such a measurement ignores the additional information and complexity present in the spectrum of interference between the individual frequency components of Eq. (1). If instead the full interference spectrum $I(\omega_1, \omega_2)$ can be directly measured, then deeper insight into the dynamics of the HOM dip can be obtained. For sources where the two photons are not indistinguishable, it is possible to determine exactly which frequency components in the photon wave packets contribute to the distinguishing information.

A pair of daughter photons generated from down-conversion can share strong spectral correlations. To achieve good interference visibility between the signal and idler photons from a single down-conversion event, it is necessary to engineer the JSA so that it is symmetric around the biphoton's zero detuning axis ($\omega_1 - \omega_2 = 0$) and $C(\omega_1, \omega_2) = C(\omega_2, \omega_1)$ [25,26]. When interfering two photons from different down-conversion events, the spectral correlations between the signal and idler of each pair lead to distinguishing information. Sources that will eliminate these spectral correlations will emit uncorrelated JSAs, meaning that $C(\omega_1, \omega_2) = \phi(\omega_1)\theta(\omega_2)$, in order to obtain high-visibility interference.

III. FIBER SPECTROMETER

A medium with group velocity dispersion, such as a single-mode optical fiber, allows encoding of the frequency of a photon with known creation time into time of arrival at the exit of that medium. During a parametric down-conversion event, two photons are born at the same moment. This moment is known with an uncertainty equal to the optical length of the nonlinear medium in which the photon pair was created. For single-pass spontaneous parametric down-conversion (SPDC) sources this uncertainty is small and generally in the picosecond regime. This is in contrast to when SPDC is produced, using a resonant cavity. In that case, the emerging pairs will have a temporal uncertainty given by the cavity lifetime, which can be many orders of magnitude larger than for single-pass SPDC. In addition, the timing jitter of the single-photon detector adds to the photon's arrival time uncertainty. For a fiber spectrometer, the dispersion imposed by the optical fiber must be larger than the combination of all the timing uncertainties related to the emergence of the photon pairs from the source and their detection. The ratio of photon-arrival uncertainty and fiber dispersion determines the resolution of the fiber spectrometer.

Each coincidence count between the superconducting nanowire single-photon detectors (SNSPDs) delivers one data point in the joint-spectral probability distribution, and is therefore much more efficient than a two-dimensional scanning approach, i.e., two monochromators each followed by a single-photon detector. This, along with high system detection efficiencies, leads to much shorter acquisition times for a joint-spectral probability distribution than is possible with the two-dimensional scanning approach. The rate at which coincidences are detected is given by $R_s = R_p \eta_1 \eta_2$, where R_p is the pair production rate, η_1 and η_2 are the two system detection efficiencies of both modes from the source including the detector. To illustrate, we calculate examples for a given parameter set. Assuming a pair generation probability of 0.1% per pump pulse, a laser repetition rate of 76 MHz, an

overall system efficiency of 30% for both modes, the resulting coincidence rate then is about 7 kHz.

We can now estimate the uncertainty per bin in the coincidence matrix from the counting statistics as a function of integration time and coincidence rate. Assuming 100 bins of the coincidence matrix are within the FWHM of the joint spectral probability distribution, we calculate statistical uncertainties of 5%, 1.6%, or 0.5% when integrating for 5.7 s, 57 s, or 570 s. The coincidence rate is reduced by a factor of 2 when performing the spectrally resolved HOM interference experiment owing to the 50/50 HOM beam splitter.

IV. EXPERIMENT

Here, we demonstrate a HOM interferometer that uses a fiber-based spectrometer capable of simultaneously recording all of the spectral correlations that exist. This enables us to directly observe the frequency-dependent interference between two photons at different positions in the HOM dip. To measure the two-photon frequency correlations, we send each photon through a medium with group velocity dispersion, long single-mode optical fibers in our case, and then measure the arrival time with fast superconducting nanowire single-photon detectors (SNSPDs). By accurately recording the arrival times of the photons it is then possible to determine the frequency correlations between the pair. From this information, it is possible to reconstruct the joint-spectral intensity (JSI) distribution of the two photons at different points in the HOM dip.

Our pair of photons is generated using spontaneous parametric down-conversion (SPDC) in a KTiOPO₄ (pp-KTP) crystal with a poling period of 46.15 μm [18]. The source is engineered to produce nearly pure, degenerate single photons in orthogonal polarization modes at a center wavelength of 1570 nm, and is pumped with a femtosecond-mode Ti:sapphire laser at a repetition rate of 76 MHz and a center wavelength of 785 nm [see Fig. 1(a)]. The spectral full-width half maximum (FWHM) of the Fourier transform limited pump laser pulse is 5.3 nm, and its temporal FWHM is 140 fs. We focus the pump beam to a beam waist of 57 μm FWHM using a 100-mm focusing lens in front of the pp-KTP crystal. The emerging two-mode state is collimated through a 100-mm collimation lens and sent to a polarizing beam splitter (PBS). After passing through an optical path delay, the two modes are recombined at a second polarizing beam splitter. The arrival time of idler photon can be adjusted by moving a translation stage (Δt), allowing the scan of the HOM interference dip. The combination of a half-wave plate (HWP) and a third PBS serves as a variable transmission (reflection) beam splitter. However, in this study we only use a splitting ratio of 50/50 needed for the HOM interference measurement, and a 0/100 splitting ratio for measuring the JSI of the source. The spectral output FWHM bandwidth of the source is 17.3 nm.

Photons emerging from the two output ports of the beam splitter are coupled into single-mode fibers using achromatic lenses with a focal length of 15.4 mm. We estimate the combined transmission through the free-space optics and coupling efficiency into fiber to be $42\% \pm 1\%$ and $47\% \pm 1\%$ for the

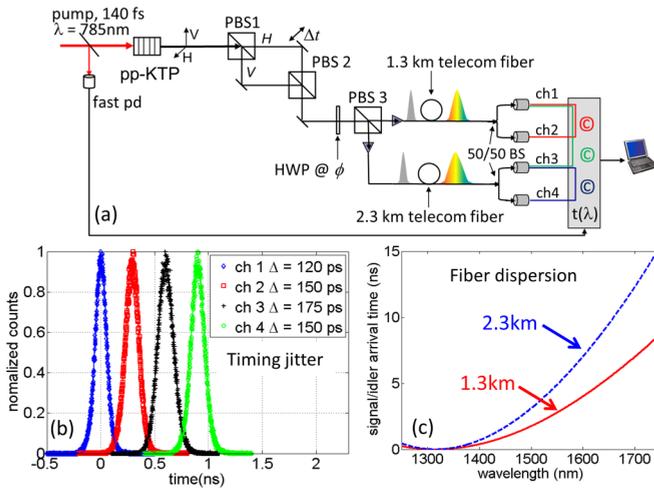


FIG. 1. (Color online) (a) Experimental setup: A femtosecond pulse, pumps a pp-KTP crystal producing type-II SPDC. PBS1 and PBS2 are sandwiched around an optical path delay Δt for the H (idler) photon. A HWP at angle ϕ and PBS3 serve as a variable beam splitter for both input modes. Two long single-mode fibers are used to encode the photons' frequency into time of arrival. Four SNSPDs probe various spectral correlations of the SPDC after the variable beam splitter. Time-stamping electronics record the arrival time of each photon; fast pd: fast photodiode (trigger). (b) Instrument response functions of all four SNSPDs. (c) Measured fiber dispersion curves for both single-mode fibers.

vertically polarized (V) signal and horizontally polarized (H) idler photons, respectively, using the Klyshko method [27].¹

We use 1.3- and 2.3-km lengths of single-mode fiber, which have an optical transmission of 77% and 87%, respectively, at 1550 nm, as the dispersive medium in our fiber spectrometer. After travelling through the fibers, the photons are sent to high-efficiency, low-jitter, superconducting nanowire single-photon detectors [28]. The time of arrival of each photon is then recorded with commercial time-stamping electronics.

Our detector system employed four SNSPDs based on amorphous tungsten-silicide (W_xSi_{1-x} , or WSi) nanowires [28]. The SNSPDs had an active area of $15 \mu\text{m} \times 15 \mu\text{m}$ and were made from 110-nm-wide nanowires. The devices were fabricated on Si substrates and embedded in an optical stack to enhance the detector absorption. The optical stack was designed to allow front-side illumination, and was composed of the following layers from top (illumination side) to bottom: TiO_2 , SiO_2 , WSi nanowires, SiO_2 , and Au. We used silicon micromachining to implement a self-aligned packaging scheme with telecom single-mode optical fibers as described in Ref. [29]. This scheme allows efficient coupling between the core of a single-mode optical fiber and the active area of the detector with $\pm 3\text{-}\mu\text{m}$ precision. The devices could be

operated in the temperature range 150 mK to 1 K without degradation of the detector performance.

The four detectors, labeled channels 1–4 in Fig. 1(a), were used with detection efficiencies ranging from 67% to 87% at 1550 nm, respectively. The timing jitter varied from 120 to 175 ps for these four detectors and, along with the fiber dispersion, determines the resolution of our fiber spectrometer. All channels had a $<1 \text{ s}^{-1}$ intrinsic dark-count rate, and background-limited count rate (BCR) of $\sim 300 \text{ s}^{-1}$. The SPDC source was single pass with a timing uncertainty of less than one picosecond, much less than the jitter in the detectors which limits the resolution of the spectrometer. Near 1570 nm, the dispersion of the 1.3-km (2.3-km) length was 24.0 ps/nm (41.9 ps/nm). Calibration of the optical fibers, shown in Fig. 1(c), was performed following the method described in Ref. [18]. Combined with the jitter of our SNSPDs [see Fig. 1(b)], this results in a finite spectral resolution for detecting a single photon and coincidence detection. The spectral resolutions are summarized in Table I. The spectral resolution of the fiber spectrometer in the coincidence basis is given by the convolution of both single-photon instrument response functions for each of the SNSPDs. In principle, the resolution can be enhanced by use of lower jitter detectors [30], by increasing the optical fiber length, or using a medium with larger group velocity dispersion. However, increasing the optical fiber length will add significant loss, and the uncertainty in the time of arrival will depend on temperature fluctuations in the fibers. We integrated each spectral correlation matrix for 10 min when measuring the frequency-resolved HOM interference.

V. RESULTS

A. Measured joint-spectral intensity

Figure 2(a) shows the raw JSI showing the photons' time-of-flight correlations. The axes represent the individual arrival times for a coincidence between signal and idler photons. The slight curvature to the spectrum is due to the wavelength-dependent dispersion of the fiber. The horizontal and vertical axes show the arrival times for photons that traveled through the 1.3- and 2.3-km lengths of fiber, respectively. After correcting for the wavelength-dependent group velocity dispersion of the individual fibers, the resulting $|JSA|$ is shown in Fig. 2(c). The log-scale plot of the JSI shown in Fig. 2(b) clearly shows the sinc-lobes associated with the phase-matching condition of our source. From the measured JSI we can compute the spectral purity, or factorizability, of our source using the Schmidt decomposition [31]. A Schmidt number of 1 corresponds to a completely factorizable source, while a large Schmidt number implies a high degree of correlation. We measure a Schmidt number of 1.07, in agreement with results reported in Ref. [18]. Note that the total measured bandwidth of the output of our source including the sinc-lobes ranges over 20 THz (165 nm).

B. Joint correlations at the Hong-Ou-Mandel interference dip

The central plot of Fig. 3 shows the measured HOM interference dip and the bunched two-state component emerging from either port of the HOM beam splitter. The insets show snapshots of the measurement, theory, predicted shape, and

¹At low pair production rates ($< 0.5\%$), we determined the ratio between coincidences and singles at a 0/100 HWP – PBS splitting ratio for signal and idler paths yielding the overall system efficiency including the detectors.

TABLE I. Summary of spectral resolution, detector jitter, and detection efficiency at 1550 nm.

Channel	Detector efficiency	Detector jitter FWHM (ps)	Single-photon spectral resolution FWHM (nm)	Channel combination	Coincidence detection spectral resolution FWHM (nm)
Ch1	87% \pm 1%	120	5.0	Ch1 and Ch2	3.9
Ch2	85% \pm 1%	150	6.3	Ch3 and Ch4	2.7
Ch3	67% \pm 1%	175	4.2	Ch1 and Ch3	3.2
Ch4	81% \pm 1%	150	3.6		

the spectral correlations of the biphotons after interference at the HOM beam splitter at various HOM delays. The complete set of data are presented in the Supplemental Material accompanying this paper [32]. The blue crosses of the central plot show the integral of each spectral correlation, equivalent to the conventional integral coincidence-counting method. The visibility of the measured HOM interference dip is $92.0\% \pm 0.2\%$. Note that all data presented in this paper are unfiltered and no background subtraction was applied.

The black dashed line in the central figure shows the theoretically predicted HOM interference based on Eq. (1) and a first-principles calculation using the Sellmeier parameters for our crystal [33]. This calculation takes into account the full phase dependence of the JSA. Based on the measured JSI, it is also possible to directly place an upper bound on the HOM interference visibility. As we only possess information about the intensity of the joint spectrum and not its phase we must make the additional assumption that the joint spectrum is real. In this case, Eq. (1) can be rewritten as $I(\omega_1, \omega_2) \propto \frac{1}{2}[C^2 + C_T^2 - CC_T e^{i\Delta\omega\delta t} - C_T C e^{-i\Delta\omega\delta t}]$, where $C = C(\omega_1, \omega_2)$ and $C_T = C(\omega_2, \omega_1)$, and are both real. This will provide an estimate of the maximum dip visibility possible: any complex phase terms between different frequency components will only serve to lower the dip visibility. The red open diamonds in the central figure show the maximum HOM dip possible directly calculated in this way from the measured |JSA|. Both calculations represent the measured HOM dip well. However, the dip visibility is not recovered in the data as predicted by the calculations. The predicted visibilities are 98.3% and 99.5% for the red diamonds and dotted black line, respectively.

Based on Eq. (1), the visibility should reach a value close to 100% if the JSA is symmetric with respect to the biphoton's zero detuning axis. In fact, our JSA is not perfectly symmetric

around the zero-detuning axis, as our focusing and collimation setup slightly biased the JSA towards larger signal and smaller idler detuning of about 0.1 THz [33]. As we will show in the following, the main source for decreased visibility lies in the sinc-lobes of the JSA, and we believe that spatial mode distinguishability originating from slight misalignments is the cause for some of the reduced visibility. The bunching of the two-photon state emerging from either beam-splitter output port is shown by the green solid and black dashed-dotted lines in the central plot. Coincidences between detector channels 1 (3) and 2 (4) detect the presence of two photons in beam-splitter output port 1 (2). The temporal shape of the two-photon bunching resembles the shape of the HOM dip, as it is to be expected.

Four different spectra are shown in Figs. 3(b)–3(f) at various HOM delays: the measured spectral correlations between the two output ports of the HOM beam splitter (lower left figure); the predicted spectral correlations between the two output ports of the HOM beam splitter based on the simplified Eq. (1) and the measured |JSA| (lower right figure); the measured spectral correlations of the two-photon state, i.e., bunching, in output port 1 (2) of the HOM beam splitter: upper left (right) figure. All figures show the predicted interference as predicted by Eq. (1). The period of the interference is proportional to $\Delta\omega\delta t$, linear with spectral detuning from the center frequency, symmetric around $\Delta\omega = 0$, and linear with HOM interference delay. High-frequency interference patterns are visible at large δt in the theoretical prediction. However, due to the spectral resolution of the fiber spectrometer, the measurements show low-frequency interference patterns at small δt only. Figure 3(g) shows the correlation spectrum of the remaining correlations in the HOM interference plotted with a different color scale than the spectrum shown in the bottom left figure of Fig. 3(c).

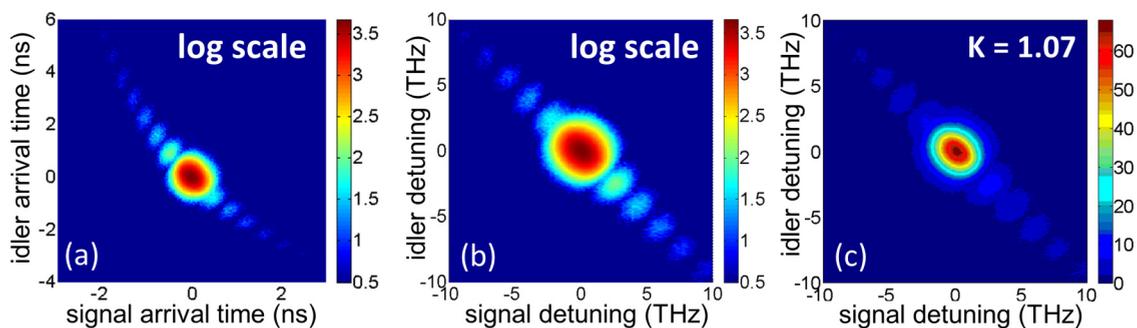


FIG. 2. (Color online) Joint probability distribution, integrated for 2 min (a) as measured, log-scale plot of the raw joint time-of-arrival probability distribution, (b) log-scale plot of the joint-spectral intensity (JSI), (c) absolute value of the joint-spectral amplitude (JSA) distribution.

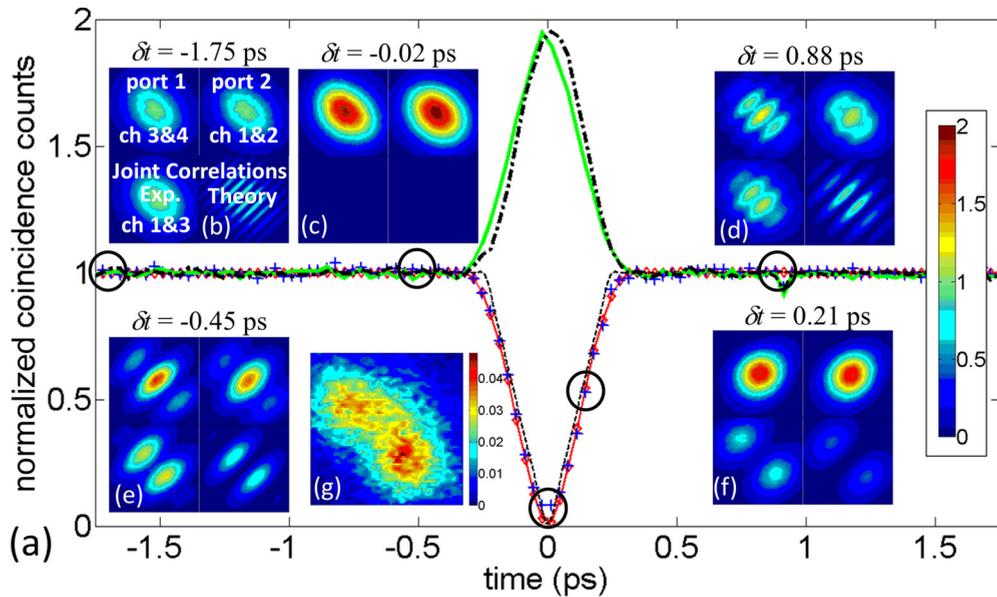


FIG. 3. (Color online) (a) HOM interference dip; blue crosses: integral of the correlation spectra as a function of HOM delay; black dotted line: first-principles calculation of the HOM interference dip based on Eq. (1); open diamonds/red line: HOM interference dip prediction based on the simplified version of Eq. (1) and the measured $|JSA|$; green solid and black dashed-dotted lines: bunching of two-photon component at either output port of the beam splitter; (b)–(f) correlation spectra at various HOM delays; each inset consists of four spectra. The scale is ± 2 THz for both axes; upper left (right): two-photon component, i.e., bunching, in output mode 1 (2), lower left: measured spectral correlation of HOM interference, lower right: spectral correlation of HOM interference based on Eq. (1) and the measured $|JSA|$. Bracket insets denote the detector channel numbers used for the measurement. Color bar on the right denotes the relative intensity color scale; (g) correlation spectrum at zero time delay showing remaining correlations [same as bottom left of Fig. 3(c) but with different color scaling].

C. Post-selective spectral filtering

Using the fiber spectrometer, we can post-select frequency components of the spectral correlations, and in the following we apply post-selective spectral filtering to investigate the origin of the reduced HOM interference visibility in the measurement. The black solid line in Fig. 4(a) shows the HOM interference visibility as a function of post-selective filter bandwidth. We chose a virtual top-hat filter around the center of the HOM spectral intensity distributions and calculated the expected HOM dip visibility by integrating the portion of the photons passing through this filter. Certainly, many other filter shapes (even those not feasible using optical

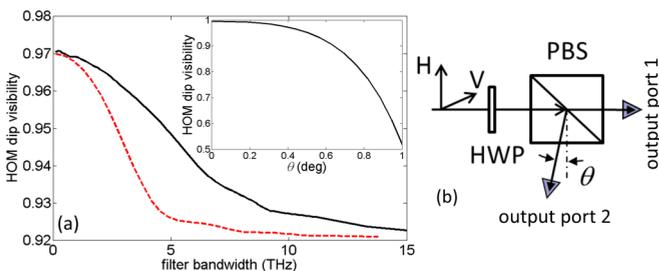


FIG. 4. (Color online) (a) Red dashed line: measured HOM dip visibility versus virtual filter bandwidth, based on a variable bandwidth top-hat post-processing filtering method. Black solid line: first-principles calculation assuming asymmetric mode fiber coupling; inset: calculation of maximum HOM visibility as function of off-optical-axis collection angle θ ; (b) schematic of the asymmetric mode coupling.

components) can be constructed based on this approach. Figure 4(a) shows the HOM interference visibility decreasing as the filter bandwidth increases. The maximum visibility for a filter bandwidth equivalent to the resolution of the fiber spectrometer (0.44 THz) is 97%. The reduced visibility at minimum filter bandwidth is most likely caused by a number of small experimental imperfections, such as dark counts, fluorescence, and double pair generation, misalignment, wavefront distortion, nonperfect 50/50 beam splitting for the center frequencies, and detector jitter causing distinguishable frequency components further away from the center to spoil the maximum visibility. The visibility drops to about 92% for the maximum filter bandwidth of 15 THz. Beyond about 5 THz bandwidth photons only exist in the sinc-lobes of the JSA. At large detunings from the center wavelength the spatial distributions of the pairs are quite different, leading to distinguishability in the HOM interference. In our setup, though, because we use a single-mode fiber, the spatial modes should be matched based on the overlap of the fiber mode with the spatial mode of the photons. If, however, the spatial overlap at the HOM beam splitter is different from the mode collected by the optical fiber, the photons are distinguishable. Figure 4(b) shows such a scenario. We assume two modes exiting from the two output ports of the 50/50 HOM beam splitter. The collection from output port 1 is aligned perfectly with the optical axis and the light collected from output port 2 has a slight misalignment with the optical axis (θ). The inset of Fig. 4(a) shows the HOM interference visibility as a function of the misalignment angle θ . A clear drop in the visibility is observed for angles smaller than 1° . The red dashed line in

Fig. 4(a) shows the anticipated HOM dip visibility as a function of virtual filter bandwidth for a misalignment angle of 0.5° . The predicted values for the HOM visibility are reduced by 3% to compensate for the experimental imperfections mentioned above. The predictions qualitatively follow the trend of the observed visibility decrease. However, the exact shape of the measured data cannot be predicted fully.

In the near future, we plan to further study the limits imposed by imperfect spatial mode overlap by implementing a fiber-based HOM beam splitter ensuring that the spatial modes are well matched for each photon pair coupled into the optical fiber.

VI. CONCLUSION

We presented a tool capable of efficiently measuring joint-spectral correlations emerging from the two output

modes of a HOM interference setup. We show that fast acquisition of the correlation spectra is possible, and that the reduced HOM interference visibility is mostly due to pairs far detuned from the center wavelength. We show that distinguishable spatial modes can be the cause of the reduced HOM interference visibility. This finding also implies that photon-source engineering should be extended to the spatial domain to allow for perfect quantum interference in photonic quantum information platforms without the need of filtering.

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