Two-photon coincident-frequency-entanglement via extended phase matching

Onur Kuzucu, Marco Fiorentino, Marius A. Albota, Franco N. C. Wong, and Franz X. Kärtner
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139

We demonstrate a new class of frequency-entangled states generated via spontaneous parametric down-conversion under extended phase matching conditions. Biphoto entanglement with coincident signal and idler frequencies is observed over a broad bandwidth in periodically poled KTiOPO4. We demonstrate high visibility in Hong-Ou-Mandel interferometric measurements under pulsed pumping without spectral filtering, which indicates excellent frequency indistinguishability between the down-converted photons. The coincident-frequency entanglement source is useful for quantum information processing and quantum measurement applications.

PACS numbers: 03.67.Mn, 42.50.Dv, 03.65.Ud, 03.67.-a

Improvement in measurement accuracies beyond the classical limits is one of the most attractive applications of quantum entanglement. For example, one can perform two-photon interferometric measurements with sensitivity better than the diffraction limit by exploiting the momentum entanglement of photon pairs generated from spontaneous parametric down-conversion (SPDC) [1]. Recently, Giovannetti et al. [2] suggested that timing and positioning measurements can be enhanced by \( \sqrt{N} \) over the standard quantum limit \( \Delta t = 1/\sqrt{N} \) if one uses the \( N \)-photon coincident-frequency-entangled state, with mean frequency \( \omega \), \( |\psi\rangle = \int d\omega \phi(\omega) |\omega + \omega_1 \rangle |\omega + \omega_2 \rangle_N \), where \( \phi(\omega) \) is the spectral amplitude, \( \Delta t \) is the timing accuracy, and \( \Delta \omega \) is the coherence bandwidth of each photon. For the simplest nontrivial case of \( N = 2 \) the coincident-frequency-entangled state \( |\psi\rangle_{c,f} = \int d\omega \phi(\omega) |\omega + \omega_1 \rangle |\omega + \omega_2 \rangle_N \) consists of a pair of entangled photons with identical but uncertain frequencies; the two photons are positively correlated in frequency, and hence anti-correlated in time. In contrast, conventional SPDC, the most common method for generating entangled photon pairs, typically yields pairs of time-entangled photons that are correlated in time but anti-correlated in frequencies as described by the state \( |\psi\rangle_{spdc} = \int d\omega \phi(\omega) |\omega + \omega_1 \rangle |\omega - \omega_2 \rangle_2 \). As a result, SPDC under conventional phase matching condition is not suitable for generating coincident-frequency entanglement.

The ability to generate a coincident-frequency entangled state also provides a solution to the problem of frequency distinguishability in pulsed SPDC. This problem is particularly relevant when pulsed pumped SPDC is used to increase temporal resolution in timing or other measurement applications. Because of the large pump bandwidth and frequency anti-correlation in the down-converted light, pulsed SPDC typically generates photon pairs with signal and idler frequency spectra that are not identical [3]. This spectral distinguishability under pulsed pumping causes Hong-Ou-Mandel (HOM) interferometric measurements [4] to have poor visibility [3]. Coincident-frequency entanglement, on the other hand, yields photon pairs with the same spectral properties, thereby restoring the HOM visibility. This type of entanglement can be used in a broad variety of applications ranging from linear optics quantum computing (LOQC) [6] to timing measurements [2].

We note that pulsed polarization entanglement with high visibility has been previously demonstrated in a dual-port SPDC configuration that separates the signal and idler fields at the output [7]. Because the signal and idler fields are not mixed, their polarization entanglement is not sensitive to the difference in their spectra, a concept that is used in bidirectionally pumped SPDC with interferometric combination [5]. However, such techniques would still show low HOM visibility under pulsed pumping because the spectra of the interfering photons are different.

Several groups recently suggested the possibility of generating a biphoto output that approximates the two-photon coincident-frequency entangled state by engineering the SPDC phase-matching function [2,10,11,12]. In this Letter we report on the experimental generation of two-photon coincident-frequency entanglement by use of extended phase matching (EPM) in type-II phase-matched periodically poled KTiOPO4 (PPKTP), as proposed by Giovannetti et al. [11,12]. We obtain high HOM visibility under pulsed pumping with a pulse width shorter than the biphoto coherence time. The EPM technique eliminates the degradation in HOM visibility associated with a long crystal under pulsed pumping. This technique should lead to better entanglement sources for quantum applications such as cryptography, teleportation, and quantum computing, as well as timing measurements.

For entanglement generation via SPDC, one is mostly interested in the frequency degenerate case in which the signal and idler frequencies are equal to half of the pump frequency. Therefore, we assume degenerate collinear down-conversion at pump frequency \( \omega_p \) with the phase mismatch \( \Delta k \equiv k_p(\omega_p) - k_s(\omega_p/2) - k_i(\omega_p/2) = 0 \), where \( k_{p,s,i} \) are the moduli of the wavevectors in the crystal for the pump \((p)\), signal \((s)\), and idler \((i)\). When the pump frequency is tuned, \( \Delta k \) is no longer zero for a frequency degenerate output. This can be rectified if we operate at a point where the phase mismatch’s first frequency derivative \( \Delta k' = \partial(\Delta k)/\partial \omega \) is also zero, which yields \( k_p' (\omega_p) = (k_s'(\omega_p/2) + k_i'(\omega_p/2))/2 \). The condi-
...tions $\Delta k = 0$ and $\Delta k' = 0$ are called extended phase matching \cite{11,12}. The consequence of EPM is that the phase-matched signal and idler frequencies remain equal as $\omega_i$ is tuned or if a pulsed pump is used. This remains true if the pump tuning range or the pump bandwidth $\Omega_p$ is smaller than the extended phase matching bandwidth $\Omega_{epm}$, which is determined by the second frequency derivative of $\Delta k$ \cite{12}. Because $k'$ is the inverse of the group velocity EPM is also known as zero group velocity mismatch in ultrafast nonlinear optics.

Our coincident-frequency entanglement generation method is conceptually simple. In addition to operating under EPM conditions, we use a long crystal of length $L$ to narrow the phase matching bandwidth whose full width at half maximum is

$$\Omega_c \approx \frac{2\pi}{|k_i' - k_i'|L}. \quad (1)$$

Type-II phase matching is used so that $k_i' \neq k_i'$ and a small $\Omega_c$ can be obtained for coincident-frequency output $\omega_i \approx \omega_i$. The phase matching bandwidth $\Omega_c$ is related to the biphonon coherence time $\tau_c = 2\pi/\Omega_c = |k_i' - k_i'|L$. The coincident-frequency entangled state $|\psi\rangle_{cf}$ is generated if \cite{12}

$$\Omega_c \ll \Omega_p \ll \Omega_{epm}, \quad (2)$$

which ensures that the HOM visibility is unaffected by pulsed pumping.

We have chosen a 10-mm long PPKTP crystal for coincident-frequency generation. Periodic poling in PPKTP allows one to use the grating period as a free parameter for phase matching at any set of operating wavelengths within the crystal’s transparency window. Thus, we can always choose a grating period to satisfy the effective conventional phase matching condition $\Delta k = 0$. For noncritical type-II phase matching with collinear propagation along the crystal’s $x$-axis, $\Delta k'$ is entirely determined by the dispersion of the crystal. Recently we have experimentally determined that for a pump wavelength $\lambda_p \approx 792$ nm the EPM conditions for degenerate collinear type-II phase matching are satisfied with a grating period of $\sim 46.15 \mu$m \cite{13}. Using this PPKTP crystal we demonstrated efficient ultrabroadband SHG over an EPM bandwidth of 67 nm centered at the fundamental wavelength of $\sim 1584$ nm. This bandwidth is nearly two orders of magnitude larger than typical SHG bandwidths.

Figure 1 shows the experimental setup for the generation of coincident-frequency entanglement and the HOM interferometric analysis. The pump was a Ti:sapphire laser (Spectra-Physics, Tsunami) that could be operated in either continuous-wave (cw) or pulsed mode without altering its output spatial mode characteristics. In pulsed operation, the mode-locked laser output had a 3-dB bandwidth of $\sim 6$ nm and an average power of 350 mW at an 80-MHz pulse repetition rate. The PPKTP crystal was antireflection coated at 792 and 1584 nm and the pump light was focused into it with a diameter of $\sim 200 \mu$m. The output was collimated and two dichroic mirrors (reflecting the 792 nm pump and transmitting the 1584 nm signal and idler) were used to eliminate the pump and no narrowband spectral filtering was used to restrict the output bandwidth. The resultant output was then focused into a single-mode polarization-maintaining (PM) optical fiber for subsequent HOM interferometric measurements.

The fiber-coupled light was sent to a fiber polarizing beam splitter (FPBS) that separated the orthogonally polarized signal and idler photons into their respective fiber channels. A half-wave plate (HWP) at the entrance to the PM fiber was used to set up the signal and idler in their appropriate fiber polarization modes. In the signal arm of the HOM interferometer was a fiber polarization rotator that was used to match the idler polarization in the second arm. The two arm lengths between the FPBS and the 50–50 fiber coupler were carefully matched by including an adjustable air gap in the idler arm. The air gap was nominally 50 mm-long and efficient coupling (>70%) between the two fibers was achieved by attaching a collimator to each fiber.

The two outputs of the 50–50 coupler were sent to two fiber-coupled custom-made InGaAs single-photon counters. The design and performance of similar devices have been described in more detail in our previous work \cite{14,15}. The InGaAs detectors were operated in Geiger mode by simultaneously sending a 20-ns gating pulse (3.9 V above the breakdown voltage) to each detector at a repetition rate of 50 kHz, yielding a detector duty cycle of $10^{-3}$. The counter D1 (D2) had a detection quantum efficiency of 16% (24%) at $\sim 1580$ nm. Under the above operating conditions we measured dark count rates of 40/s and 20/s for D1 and D2, respectively, which correspond to dark count probabilities of $8 \times 10^{-4}$ (D1) and $4 \times 10^{-4}$ (D2) per gate. The photocount outputs were amplified and sent into a high-speed AND-gate logic circuit for coincidence detection within a 1.8-ns coincidence window.

![Experimental setup showing the entanglement source and the fiber HOM interferometer used to test the coincidence-frequency entangled state. DM: dichroic mirror; HWP: half-wave plate; FPBS: fiber polarization beam splitter.](image)
For cw pumping with 350 mW pump power, we have observed average singles count probabilities of $2.3 \times 10^{-3}$ (D1) and $2.5 \times 10^{-3}$ (D2) per 20-ns gate, corresponding to count rates of 125/s and 115/s respectively (not corrected for dark counts). The probability of detecting a pair per gate is $2 \times 10^{-5}$ corresponding to a count rate of 1 coincidence/s. The low coincidence count rate is due to the interferometer losses (~65% transmissivity, measured independently), low detector quantum efficiencies, and an estimated 30% coupling efficiency into the PM fiber. From the detection efficiencies and our measurement duty cycle we estimate a single spatial fiber-optic mode pair production rate of $\sim 4 \times 10^8$/s at 350 mW of pump power.

For the HOM measurements, the coincidence counts and the two singles counts were measured as a function of the air gap distance. Accidental coincidence counts were separately measured by using the same technique described in Refs. 14 15 16. Typical accidental coincidence probabilities within the 1.8-ns coincidence window were $5 \times 10^{-7}$ per gate corresponding to 5 counts in a 200-s measurement time. Figures 2 and 3 show the data corrected for the accidental counts.

Figure 2 shows the HOM measurements under cw pumping at the pump wavelength of 792 nm, and we obtained similar results at a different pump wavelength of 787 nm. The biphoton coherence time is related to the base-to-base width of the HOM dip $l_c$ by $\tau_c = l_c/2c$. Fitting the experimental data with the HOM triangular dip expected for type-II phase matching yields a visibility of 95 ± 5% and a biphoton coherence time of 1.42 ± 0.26 ps, which is equivalent to a biphoton coherence bandwidth of 2.5 ± 0.4 nm. The measured coherence bandwidth is in excellent agreement with the 2.5 nm bandwidth calculated from PPKTP’s Sellmeier equations 13. The HOM visibility is defined by $V = 1 - C_{\text{min}} / C_{\text{max}}$, where $C_{\text{min}}$ is the coincident count at zero signal-idler time delay and $C_{\text{max}}$ is the coincident count at a long time delay (in the flat part of the HOM measurement). The fiber-to-fiber coupling efficiency of the air gap varied by ~10% over the scan, and we normalize the coincidence data to the maximum singles count rate in Figs. 2 and 3, this normalization affects the visibility by ~1%. The cw measurements represent the first demonstration of tunable SPDC without any degradation of the biphoton entanglement, a result due to the large extended phase-matching bandwidth of 67 nm. The tuning range of 10 nm centered at the wavelength of 1584 nm is 4 times larger than the coherence bandwidth. We measured that the FPBS had an extinction ratio of ~99% for both ports. A 2% reduction in the visibility is caused by the 1% leakage of the signal field into the idler channel and vice versa. This 2% loss could be eliminated by using a clean-up polarizer in each of the two output ports of the FPBS.

For the pulsed HOM measurement, the setup was identical to that used in the cw measurements, except the pump laser was set in the pulsed mode centered at 790 nm with a 3-dB bandwidth of 6 nm. Figure 3 shows the pulsed HOM measurement results with a visibility of 85 ± 7% and a biphoton coherence time $\tau_c = 1.3 \pm 0.3$ ps. This is the first observation of high HOM visibility, without spectral filtering, in pulsed SPDC in which the pump bandwidth $\Omega_p$ is much larger than the biphoton coherence bandwidth $\Omega_c$. The visibility in pulsed HOM is sensitive to deviations from the exact EPM operating conditions such as the crystal angle (affecting the effective grating period) and the pump wavelength. The slightly lower visibility in pulsed HOM results compared with the cw measurements may be caused by such deviations. Another plausible explanation for the lower visibility in pulsed HOM interferometry is the presence of higher order terms in the phase matching function that have not been considered in theoretical analyses 11 12.

We also measured the autocorrelation of the signal and idler light. The PPKTP output light was sent through a linear polarizer to pass only the horizontally polarized signal or idler light. The PPKTP output light was sent through a clean-up polarizer in each arm of the interferometer because the FPBS now served as a 50–50 beam splitter for the input signal or idler light. The PPKTP output light was sent through a 3-dB beam splitter for the input signal or idler light. The PPKTP output light was sent through a clean-up polarizer in each arm of the fiber interferometer. The fiber interferometer, as depicted in the setup of Fig. 1, became effectively a Mach-Zehnder interferometer because the FPBS now served as a 50–50 beam splitter for the input signal or idler light. The autocorrelation measurement shows a signal coherence time of 380 fs, and an idler coherence time of 350 fs which are much shorter than the biphoton coherence time of 1.3 ± 0.3 ps.

The high visibility obtained in our pulsed HOM measurements is the consequence of operating under EPM which allows for the generation of coincident frequency entanglement. The signal and idler outputs are frequency entangled if, given the generic biphoton state $|\psi\rangle_{si} = \int d\omega_s d\omega_i A(\omega_s, \omega_i)|\omega_s\rangle|\omega_i\rangle$, the spectral amplitude $A(\omega_s, \omega_i)$ cannot be factorized as $f_s(\omega_s)f_i(\omega_i)$ 10. If the two photons are not entangled, then $S_{\psi}(\omega_s) = \int d\omega_i A(\omega_s, \omega_i)\delta(\omega_s - \omega_i)$, which is the Fourier transform of the one-photon spectrum $A(\omega_s, \omega_i)$. However, we have $S_{\psi}(\omega_s) = \int d\omega_i A(\omega_s, \omega_i)|\omega_i\rangle\langle\omega_i|$ for entangled states. The Fourier transform of $A(\omega_s, \omega_i)$ is then $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$. The high visibility obtained in our pulsed HOM measurements is the consequence of operating under EPM which allows for the generation of coincident frequency entanglement. The signal and idler outputs are frequency entangled if, given the generic biphoton state $|\psi\rangle_{si} = \int d\omega_s d\omega_i A(\omega_s, \omega_i)|\omega_s\rangle|\omega_i\rangle$, the spectral amplitude $A(\omega_s, \omega_i)$ cannot be factorized as $f_s(\omega_s)f_i(\omega_i)$ 10. If the two photons are not entangled, then $S_{\psi}(\omega_s) = \int d\omega_i A(\omega_s, \omega_i)\delta(\omega_s - \omega_i)$, which is the Fourier transform of the one-photon spectrum $A(\omega_s, \omega_i)$. However, we have $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$ for entangled states. The Fourier transform of $A(\omega_s, \omega_i)$ is then $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$. The high visibility obtained in our pulsed HOM measurements is the consequence of operating under EPM which allows for the generation of coincident frequency entanglement. The signal and idler outputs are frequency entangled if, given the generic biphoton state $|\psi\rangle_{si} = \int d\omega_s d\omega_i A(\omega_s, \omega_i)|\omega_s\rangle|\omega_i\rangle$, the spectral amplitude $A(\omega_s, \omega_i)$ cannot be factorized as $f_s(\omega_s)f_i(\omega_i)$ 10. If the two photons are not entangled, then $S_{\psi}(\omega_s) = \int d\omega_i A(\omega_s, \omega_i)\delta(\omega_s - \omega_i)$, which is the Fourier transform of the one-photon spectrum $A(\omega_s, \omega_i)$. However, we have $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$ for entangled states. The Fourier transform of $A(\omega_s, \omega_i)$ is then $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$. The high visibility obtained in our pulsed HOM measurements is the consequence of operating under EPM which allows for the generation of coincident frequency entanglement. The signal and idler outputs are frequency entangled if, given the generic biphoton state $|\psi\rangle_{si} = \int d\omega_s d\omega_i A(\omega_s, \omega_i)|\omega_s\rangle|\omega_i\rangle$, the spectral amplitude $A(\omega_s, \omega_i)$ cannot be factorized as $f_s(\omega_s)f_i(\omega_i)$ 10. If the two photons are not entangled, then $S_{\psi}(\omega_s) = \int d\omega_i A(\omega_s, \omega_i)\delta(\omega_s - \omega_i)$, which is the Fourier transform of the one-photon spectrum $A(\omega_s, \omega_i)$. However, we have $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$ for entangled states. The Fourier transform of $A(\omega_s, \omega_i)$ is then $S_{\psi}(\omega_s) = \int d\omega_i |A(\omega_s, \omega_i)|^2 \delta(\omega_s - \omega_i)$.
function (solid line). Base-to-base width of the HOM dip is 
\( t_c = 0.8 \pm 0.2 \text{ mm} \) corresponding to a biphoton coherence time 
\( \tau_c = 1.3 \pm 0.3 \text{ ps} \). HOM dip visibility is 85 ± 7%.

\[ |f_x(\omega_i)|^2 \text{ and } S_\perp(\omega_i) = |f_i(\omega_i)|^2 \] 
are the fluorescence spectra, which are directly related to their coherence times. 
If the two interfering photons at the 50–50 coupler of the 
HOM setup were not entangled, such as those from two 
single-photon sources, the HOM coherence time would be 
given by the overlap integral of the two pulses, as shown 
in Refs. [7, 12]. In our case, the pulsed biphoton 
coherence time of 1.3 ps is much longer than the single 
photon coherence times which are less than 400 fs. Such a 
long biphoton coherence time would not be possible if the 
two photons were not entangled. The large difference 
between the measured biphoton coherence time and the 
gle photon coherence times suggests a significant amount 
of single photon coherence times. However, we believe that the 
output state was not maximally entangled. Such a non-
maximally entangled output state is consistent with our 
observations: a small reduction in HOM visibility and a 
slightly shorter HOM coherence time compared with the 
cw results. Further measurements and theoretical analy-
ses are needed to clarify the effects of various pump and 
crystal parameters on the amount of entanglement and 
HOM visibilities.

In summary, we have demonstrated a new technique 
of generating entangled photons with coincident frequen-
cies in parametric down-conversion under extended phase 
matching conditions. HOM interferometric measurements 
show high visibilities for cw or pulsed pumping, 
valid for a broad tuning range or pump pulse bandwidth 
that is less than the large extended phase matching band-
width. Pumping the crystal bidirectionally (as shown in [8]) under EPM would allow us to generate photons 
that are both coincident-frequency and polarization en-
tangled. Pulsed entanglement provided by this quan-
tum state suits the needs of LOQC experiments which 
require high timing resolution and high quality interfer-
ence [4]. Also, timing and positioning measurements can be 
imbproved by \( \sqrt{2} \) over the standard quantum limit if 
coincident-frequency entangled photons are used in time-
of-arrival measurements [2].

The authors would like to acknowledge J. Sickler and 
J. Gopinath for help with the fiber interferometer and T. 
Kim for help with coincidence detection circuitry. This 
work was supported by the Advanced Research and De-
velopment Activity (ARDA), administered by the Office of 
Naval Research under Grant N00014-03-1-0869.

\[ |f_x(\omega_i)|^2 \text{ and } S_\perp(\omega_i) = |f_i(\omega_i)|^2 \] 
are the fluorescence spectra, which are directly related to their coherence times. 
If the two interfering photons at the 50–50 coupler of the 
HOM setup were not entangled, such as those from two 
single-photon sources, the HOM coherence time would be 
given by the overlap integral of the two pulses, as shown 
in Refs. [7, 12]. In our case, the pulsed biphoton 
coherence time of 1.3 ps is much longer than the single 
photon coherence times which are less than 400 fs. Such a 
long biphoton coherence time would not be possible if the 
two photons were not entangled. The large difference 
between the measured biphoton coherence time and the 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{HOM interferometric measurements for a pulsed pump centered at 790 nm with a 3-dB bandwidth of 6 nm.}
\end{figure}

\[ |f_x(\omega_i)|^2 \text{ and } S_\perp(\omega_i) = |f_i(\omega_i)|^2 \] 
are the fluorescence spectra, which are directly related to their coherence times. 
If the two interfering photons at the 50–50 coupler of the 
HOM setup were not entangled, such as those from two 
single-photon sources, the HOM coherence time would be 
given by the overlap integral of the two pulses, as shown 
in Refs. [7, 12]. In our case, the pulsed biphoton 
coherence time of 1.3 ps is much longer than the single 
photon coherence times which are less than 400 fs. Such a 
long biphoton coherence time would not be possible if the 
two photons were not entangled. The large difference 
between the measured biphoton coherence time and the 
gle photon coherence times suggests a significant amount 
of single photon coherence times. However, we believe that the 
output state was not maximally entangled. Such a non-
maximally entangled output state is consistent with our 
observations: a small reduction in HOM visibility and a 
slightly shorter HOM coherence time compared with the 
cw results. Further measurements and theoretical analy-
ses are needed to clarify the effects of various pump and 
crystal parameters on the amount of entanglement and 
HOM visibilities.

In summary, we have demonstrated a new technique 
of generating entangled photons with coincident frequen-
cies in parametric down-conversion under extended phase 
matching conditions. HOM interferometric measurements 
show high visibilities for cw or pulsed pumping, 
valid for a broad tuning range or pump pulse bandwidth 
that is less than the large extended phase matching band-
width. Pumping the crystal bidirectionally (as shown in [8]) under EPM would allow us to generate photons 
that are both coincident-frequency and polarization en-
tangled. Pulsed entanglement provided by this quan-
tum state suits the needs of LOQC experiments which 
require high timing resolution and high quality interfer-
ence [4]. Also, timing and positioning measurements can be 
imbproved by \( \sqrt{2} \) over the standard quantum limit if 
coincident-frequency entangled photons are used in time-
of-arrival measurements [2].

The authors would like to acknowledge J. Sickler and 
J. Gopinath for help with the fiber interferometer and T. 
Kim for help with coincidence detection circuitry. This 
work was supported by the Advanced Research and De-
velopment Activity (ARDA), administered by the Office of 
Naval Research under Grant N00014-03-1-0869.