We demonstrate a new biphoton manipulation and characterization technique based on electro-optic intensity modulation and time shifting. By applying fast modulation signals with a sharply peaked cross-correlation to each photon from an entangled pair, it is possible to measure temporal correlations with significantly higher precision than that attainable using standard single-photon detection. Low-duty-cycle pulses and maximal-length sequences are considered as modulation functions, reducing the time spread in our correlation measurement by a factor of five compared to our detector jitter. With state-of-the-art electro-optic components, we expect the potential to surpass the speed of any single-photon detectors currently available. © 2015 Optical Society of America

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As is now well established, the optical regime of the electromagnetic spectrum offers unique capabilities in high-speed information transfer; compared to conventional all-electronic solutions which are limited at best to the picosecond level, the extremely high carrier frequencies of optical fields can support temporal features only a few femtoseconds in duration. Yet characterizing such ultrabroadband signals in practice presents its own difficulties because, in exceeding the speed of fast electronics, ultrafast optical fields naturally cannot be resolved through direct photodiode detection. For that reason, a variety of reconstruction techniques based on nonlinear mixing have been developed, from fairly basic intensity correlation to more sophisticated tools such as frequency-resolved optical gating (FROG) for complete field characterization [1,2]. Likewise, the field of all-optical signal processing [3,4] continues to extend the use of photonics from information transmission to processing, with the goal of circumventing altogether the speed limitations imposed by electronics.

Identical considerations hold for nonclassical light, particularly in the field of quantum information, where speed is often limited by single-photon detection rather than the intrinsic bandwidth of quantum fields. Indeed, in some sense, the situation is even worse than the classical case because detectors responsive to single photons suffer from large timing jitters typically on the order of several hundred picoseconds. At best, jitters of only around 35 ps have been realized, either with optimized Si photon counters for visible light [5] or superconducting nanowire detectors at telecom wavelengths [6]. Such values are still significantly slower than state-of-the-art analog photodiodes [7], which can attain bandwidths in the range of 100–300 GHz, corresponding to jitters of only a few picoseconds. This inability to reach even the limits imposed by electronic processing hints at the existence of a potentially valuable intermediate regime, wherein well-chosen microwave solutions can furnish substantial speed improvements over direct photon detection. While not as fast as nonlinear optical techniques such as entangled-photon mixing [8–12], short-pulse upconversion [13,14], and time-to-frequency conversion [15,16], electronics benefits from robustness and simplicity, providing a bridge between slow (but straightforward) direct detection and ultrafast (but elaborate) nonlinear optical processing.

A concrete example of such intermediary microwave processing of quantum light was developed [17] and demonstrated [18] by Harris and colleagues. Each photon from an entangled pair is separately propagated through sinusoidal intensity modulation; then coincidences between the two outputs are measured with slow integrating detectors. By maintaining phase synchronization as the modulation frequency is swept, it is possible to extract the Fourier spectrum of the Glauber correlation function \(G^{(2)}(\tau)\). The maximum measurable bandwidth is then limited not by detector jitter, but by the speed of the electro-optic modulators. Although the first proof-of-principle experiment considered frequencies up to only 30 MHz [18], state-of-the-art 100 GHz modulators [19] could, in theory, resolve temporal features shorter than 5 ps. Unlike Hong–Ou–Mandel interference, which can provide a measure of ultrafast biphoton synchronization without nonlinear optics [albeit not of \(G^{(2)}(\tau)\) directly] [20], the photons need not mix spatially, making this approach consistent with nonlocal detection as well. In this Letter, we extend on Harris’s work, proposing and experimentally demonstrating a new technique for biphoton measurement based on high-speed electro-optic
intensity modulation with arbitrary microwave waveforms. Our measurements are found to be related to the modulators’ temporal cross-correlation, with periodic revivals controlled by the repetition rate. Moreover, by propagating the biphoton through various lengths of optical fiber, we demonstrate sensitivity to temporal spreading and shifting beyond the capabilities of our single-photon avalanche photodiodes (SPADs). Thus, our approach makes use of temporal cross-correlation rather than Fourier transformation to resolve fast features, and we expect the idea to contribute to the characterization of high-speed quantum information-processing systems.

To theoretically describe our modulation procedure, we consider an input correlation function \(G(\tau) = G_0(t_1 - t_2)\) which, when properly normalized, gives the probability density for joint detection of the signal photon at time \(t_1\) and the idler at time \(t_2\) [21,22]. We have assumed a monochromatic pump, so that the temporal correlations depend only on the difference \(t_1 - t_2\). Each photon is subsequently intensity modulated by \(T\)-periodic functions: the signal by \(M_s(t_1 + \tau)\), the idler by \(M_i(t_2)\), with \(\tau\) a tunable time shift. Coincident arrivals are then recorded within a temporal window much longer than the initial correlation time of \(G_0(t_1 - t_2)\). Following a development similar to that in [18], we arrive at the final coincidence rate,

\[
R_c(\tau) = K \int_{-\infty}^{\infty} dt G_0^{(2)}(t) \gamma_s(t + \tau),
\]

where \(K\) is a constant, and

\[
\gamma_s(t) = \int_{t_0}^{t_0+T} dx M_s(x + t) M_s(x)
\]

is the circular intensity correlation between the two modulators. In this way, we see that the modulator cross-correlation supplants any detector characteristics in the overall temporal response function, and we observe two important limiting cases. (Case 1) When the initial correlation function \(G_0(\tau)\) is much narrower than \(\gamma_s(t)\), we recover \(R_c(\tau) \propto \gamma_s(\tau)\); that is, the coincidence pattern reflects the modulator cross-correlation. (Case 2) On the other hand, when the modulators are much faster than \(G_0(\tau)\), the coincidence rate becomes \(R_c(\tau) \propto G_0(\tau)\) for \(\tau \in (-\frac{T}{2}, \frac{T}{2})\), assuming a modulator period much longer than the biphoton correlation time. This second case is the motivation for our method, revealing how electro-optic modulation can recover photon correlations too fast for the available SPADs. Both extremes are considered in the experiments below, although we employ the more precise Eq. (1) in all theoretical curves rather than these approximations.

These relationships hold only for a narrowband pump whose coherence time exceeds all other relevant temporal scales—easily satisfied with megahertz-class linewidths and gigahertz modulators. In the more general case, e.g., with a pulsed pump source, the biphoton correlation function varies with both \(t_1\) and \(t_2\) (rather than through their difference alone), and Eq. (1) must be replaced by a more complicated two-dimensional integral. Nevertheless, the basic principle of applying fast electro-optic modulation for resolution enhancement would still hold, with the additional requirements of independent delay control on both modulators and synchronization with the photon source itself. Overall, the main difference between our approach and that of [17,18] is that instead of maintaining fixed modulator timing and sweeping the modulation rate, thereby giving coincidences as a function of frequency, we keep the period unchanged but sweep the relative delay. With sufficiently fast modulation, both approaches recover \(G_0^{(2)}(\tau)\) either through Fourier synthesis or temporal sampling.

To explore these ideas experimentally, we utilize the setup in Fig. 1. Entangled photons are created via degenerate, type-0 spontaneous parametric downconversion (SPDC) of a continuous-wave laser at \(\sim 775\) nm in a 67 mm long periodically poled lithium niobate (PPLN) waveguide. (Although we consider degenerate biphotons here, the method would apply equally well to nondegenerate signal–idler pairs, as long as each modulator accepts the full bandwidth of its respective photon.) The generated photon flux is estimated at \(\sim 10^8/s\), corresponding to a pair occupation probability of about 0.1 per 1 ns coincidence window used below; this reduces the effects of multipair emission and ensures we are operating in the single-photon detection regime. We remove residual pump light with three color glass filters (Schott RG1000) and couple the remaining photons centered at 1550 nm into optical fiber, the amount of which varies between tests. To separate the co-polarized and degenerate signal and idler photons, we make use of a 50/50 fiber beam splitter; with 50% probability, the photons in a given pair will exit along separate paths and can contribute to coincident arrivals. An electronic arbitrary waveform generator (Tektronix AWG7122B) provides the desired 20 GS/s microwave drive signal, which is then split, amplified, and applied to each intensity modulator (EOSpace AX-0K5-10-PFU-PFU-UL). A series of microwave delay stages precedes the electrical input of the signal modulator to control the relative delay \(\tau\). The modulated photons are then detected by a pair of gated InGaAs SPADs (Aurea SPD_AT_M2), and coincidences within a 1 ns window are determined by an event timer (PicoQuant HydraHarp 400). The modulation speed is limited by the bandwidths of the waveform generator (7.5 GHz) and the modulators themselves (10 GHz). Although sufficient for an initial experiment, significantly faster modulation could be realized with, e.g., 100 GHz modulators and photonically generated drive signals [23,24].

As a first test, we drive each modulator with a length-4 sequence consisting of one high and three low voltages. In practice, imperfections in the waveform generator limit the purity of the applied modulation, and the modulator bandwidth reduces the extinction ratio. Figure 2(a) shows the experimental modulator functions \(M_s(\tau)\) (signal) and \(M_i(\tau)\) (idler), obtained by sending a continuous-wave laser through each and measuring the temporal response with an analog photodiode and sampling oscilloscope. To give the most accurate measure of the optical throughput, we average 2000 traces and remove...
the combined impulse response of the photodiode and oscilloscope through deconvolution. (The exact form of the impulse response was previously obtained by exciting the diode with ∼100 fs laser pulses and recording the electrical output, showing a full width at half-maximum of 18.2 ps.) With these patterns applied, we then send entangled photons through each modulator and measure the coincidence rate as the delay of the drive signal to \( M_i \) is shifted. The precise value of the delay \( \tau \) (apart from an unimportant overall offset) is determined by tapping off a portion of the time-shifted signal and observing its relative position on an oscilloscope. The coincidence results are presented in Fig. 2(b), normalized to idler detections to parti-
relative position on an oscilloscope. The coincidence results are subtracted in the results of Fig. 2(b). The solid curve

-\[ \text{deviation. Accidentals are determined by measuring coinciden-
-\[ \text{tials are subtracted in the results of Fig. 2(b). The solid curve}
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described dispersive spreading in Figs. 3(a) and 3(b), these results

<table>
<thead>
<tr>
<th>Amplitude [mV]</th>
<th>Time [ps]</th>
<th>Coincidences/Idler</th>
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<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>2</td>
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<td>5</td>
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<td>10</td>
<td>400</td>
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Fig. 2. Coincidence measurements with pulse-like modulation.
(a) Modulation functions and (b) corresponding coincidence rate
when a 25%-duty-cycle sequence is applied by a waveform generator.
(c) Intensity modulation and (d) associated coincidence rate for a
12.5%-duty-cycle pattern. For comparison, the red dotted curve in
d gives the measured coincidence spread when the modulators are
bypassed and the photons are detected directly, binned into 32 ps time
slots. For the modulation results in (b) and (d) [left axis], the error bars
show experimental results; the solid curves give theoretical predictions.

coincidence measurement are shown in Fig. 2(d) [left axis].
We have again subtracted accidentals and included the theoretical
prediction as a solid line. Sharp 73.5 ps correlation peaks
repeating at the 400 ps period are observed, but now the con-
trast has increased to 6.7:1. The fluctuations between peaks
derive from the oscillations present in the modulator functions of
Fig. 2(c) and could be eliminated with higher-bandwidth electronics.
These results highlight a key advantage of this tech-
nique: the ability to arbitrarily extend the periodicity and en-
sure temporal separation of the measured correlation peaks. As
reference, also included in Fig. 2(d) is the correlation pattern
measured via direct electronic coincidence detection with our
InGaAs SPADs and without any modulation, delay shifted for
visual comparison with the modulated case; at 353 ps, the jiter-
limited FWHM is approximately five times wider than that
obtained from our new technique.

In the previous examples, the biphoton correlation time is
significantly less than the modulator correlation width, so that
\( G_0(t) \) is effectively sampling \( \gamma_2(t) \) in Eq. (1). Accordingly, the
measurements in Figs. 2(b) and 2(d) provide upper bounds on
the width of the input temporal correlations, but not a direct
measure thereof. Thus, to confirm that this modulation ap-
proach is sensitive to modifications of \( G_0(t) \), we next consider
additional fiber links optimized for two different cases: in the
first, we make use of long links to show the method’s ability to
resolve dispersive spreading (second-order spectral phase); in
the second, a series of shorter patch cords are inserted into the
idler path to demonstrate sensitivity to linear delay shifts
(first-order spectral phase). For the dispersion tests, we insert
optical fiber after the collimator and before the coupler in Fig. 1;
the results for 50 and 200 m of additional fiber for the length-8
sequence in Fig. 2(c) are presented in Figs. 3(a) and 3(b), re-
spectively. The photonic correlations spread in good agreement
with theory, with the extra dispersion significantly modifying the
coincidence peak widths. At 50 m, the background-subtracted
FWHM has increased to around 100 ps; for 200 m of fiber, it
has spread nearly beyond recognition, with a theoretical duration
of about 270 ps. Proceeding to the delay tests, we remove the long
fiber links and add short fiber patches in the idler arm prior to
modulator \( M_i \) in Fig. 1. Figure 3(c) shows the coincidence rates
for added lengths of 41.9 cm (solid blue), 43.7 cm (dotted black),
and 46.0 cm (dashed red). The correlation peaks are shifted by
about 100 ps and are clearly separated. Combined with the ob-
served dispersive spreading in Figs. 3(a) and 3(b), these results
verify sensitivity to biphoton transformations significantly smaller
than the combined ∼350 ps resolution of our electronic detectors.

The modulation functions considered thus far consist of low-
duty-cycle return-to-zero pulses, a natural choice for obtaining
well-resolved correlation peaks. Yet alternative patterns with
more sophisticated properties can also furnish useful character-
istics. For the single-pulse examples earlier, the complexity of the
measured biphoton correlation function is related to the duty
cycle; the period specifies the longest discernible features (any-
thing longer overlaps with the next peak), and the modulation
width gives the sharpest observable correlations. To increase the
ratio of the two—i.e., the maximum time-bandwidth product
the system can resolve—one necessarily must reduce the duty
cycle which, in turn, lowers the transmitted flux.

A binary pattern which can ideally decouple loss and reso-
lution is the maximal-length sequence (M-sequence) [25]. The
circular autocorrelation of one such length-(2^N - 1) phase
sequence (with \( N \) an integer and elements equal to \( \pm 1 \)) produces a peak value of \( 2^N - 1 \) at every multiple of \( 2^N - 1 \), while at every other offset, \(-1\) is obtained. Since temporal phase modulation is unobservable in our detection scheme, we must consider an amplitude-only version, in which any minus-ones are replaced by zeros. Defining the sequences so that \( M \)-sequences give maximal transmission and \( -M \)-sequences give minimal transmission, we are high transmission and low transmission, respectively. Every other offset, \( N \) bits pass incoming photons implies minimal reduction in flux as compared to the values obtained in our low-duty-cycle experiments. Experimentally, we consider the resolution improved. As \( \Delta t \) increases, the probability for transmitting a photon asymptotically approaches 1/2, rather than zero as in the single-pulse case. Experimentally, we consider the length-15 M-sequence \([010110010001111]\), which at our 20 GS/s sampling rate corresponds to a period of 750 ps. The measured coincidence rate under this modulation follows in Fig. 3(d); the peak-to-background contrast is near the ideal value of 2:1, and the background-subtracted FWHM is 83.6 ps, comparable to the values obtained in our low-duty-cycle experiments.

This situation bears analogy to a previous experiment in which Hadamard sequences were used to infer the frequency correlation of entangled photons [26]. There, the relevant quantity was the product of signal–idler spectral filters, for which intensity Hadamard codes give 2:1 contrast for matched and mismatched cases, contingent on strong frequency entanglement. On the other hand, in this Letter, the relevant quantity is the cross-correlation of the signal–idler modulation functions, for which M-sequences give 2:1 contrast provided the photons are strongly entangled in time. Accordingly, we can view the approaches as Fourier complements, relying on biphoton correlations in the conjugate observables of either time or frequency.

In conclusion, we have realized an approach for temporal biphoto measurement based on high-speed electro-optic intensity modulation and tunable electronic delay. Our proof-of-principle experiment attains a timing resolution of 75 ps, showing sensitivity to both temporal spreading and delay. Moreover, with pseudorandom M-sequence codes, we provide a means by which the time-bandwidth product of the measurement can be increased without significantly lowering throughput. Either technique can improve the temporal sensitivity of a given pair of SPADs and, more excitingly, could reduce timing uncertainty well beyond even the fastest photon detectors by using state-of-the-art >100 GHz intensity modulators. More generally, our results provide yet another example of the value of high-speed classical technologies in quantum information.

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