Femtosecond photon-counting receiver

Michael A. Krainak, Timothy M. Rambo, Guangning Yang, Wei Lu, Kenji Numata

NASA Goddard Space Flight Center, Greenbelt, MD USA 20771
I. Ways to achieve CORRELATION function
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I. Ways to achieve CORRELATION function

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IV. Summary
Correlation Function
Definition

\[ R(t) = \int f(t)g(t - t) \, dt \]
Correlation Function
Optical Implementation

Intensity autocorrelator

Interferometric (2\textsuperscript{nd} order) autocorrelator
Correlation Function
Optical nonlinear crystal

\[ R(t) = \int f(t)g(t) \, dt \]

Real-time product originates from:
2\text{nd} harmonic crystal: \( \chi^{(2)} \)

\[ P^{NL} = \chi^{(2)} f(t)g(t) \]

But to implement:
We step the delay (\( \tau \)) and calculate at each step.

NOT “real-time”.
**4th order Interferometer**

(Using coincidence detection)

1989

1993

By measuring the photoelectric correlation as a function of \( \tau \), we can determine the range of \( \lambda(\tau) \) and thereby the correlation time. In general, the ranges of \( \lambda(\tau) \) and \( |\gamma(\tau)| \) may be quite different, however, although in the special case of polarized light with thermal statistics \( \lambda(\tau) \) and \( |\gamma(\tau)| \) are related by

\[
\lambda(\tau) = |\gamma(\tau)|^2. \tag{3}
\]

But for other fields, such as laser beams, there may be little connection between \( \lambda(\tau) \) and \( |\gamma(\tau)| \). One weakness of the intensity-correlation technique is that it is limited by the resolving time \( \tau_0 \) of the detectors and the electronics to fourth-order correlation times \( \tau \) that are much longer than \( \tau_0 \) (typically of the order of \( 10^{-9} \text{ sec} \)), and it becomes useless when \( \tau \ll \tau_0 \).

In what follows, we shall treat the polarized-light problem. The correlations are given by

\[
\tau_R \gg \int_{-\infty}^{\infty} \lambda(\tau) d\tau. \tag{16}
\]

Hence for large \( \tau_R \), Eq. (12) simplifies to

\[
\Gamma_M = 2RT(R^2 + T^2)\langle I_0 \rangle^2 \tau_R \left[ 1 - \frac{RT}{R^2 + T^2} |\gamma_{00}(\delta\tau)|^2 \right], \tag{17}
\]

where \( \gamma_{00}(\tau) = \Gamma_{00}(\tau)/\langle I_0 \rangle \) is the normalized second-order correlation function of the incident optical field. Although, for simplicity, we have treated a polarized field, a similar equation can be derived even for unpolarized light when certain symmetry conditions are satisfied.

Since \( \gamma_{00}(0) = 1 \) by definition, it follows that a measurement of the correlation \( \Gamma_M \) as a function of the variable time delay \( \tau \) must yield results equal to the direct product

\[
\text{Count}_{12}(\delta\tau) = K \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} d\tau \gamma_{02}(\tau)E_2(t + \tau)E_2(t)E_2(t + \tau + \delta\tau),
\]

where \( K \) is an appropriate proportional constant, \( T_h \) is the detector response time, and \( \langle I_\lambda \rangle \) denotes ensemble averages with respect to \( A(\lambda) \) and \( \phi(\lambda) \).

\[\begin{array}{c}
\text{Optical pulses with interference} \\
\text{Baba, M. Matsuoka} \\
\text{1993 / Vol. 18, No. 11 / OPTICS LETTERS}
\end{array}\]

We show a plot of this function in Fig. 2. There is a noticeable increase in the coincidence count rate at \( \delta\tau \sim 0 \) that consists of two components, corresponding to the first and second Gaussian terms of Eq. (9), which in turn go back to the two terms in Eq. (7). The narrow component corresponding to the first term is caused by second-order interference, which occurs only when \( \tau_0 \) is smaller than the pulse field coherence time.
Two photon interference for short pulse (1987)

Unlike second-order interference, this method does not require that path differences be kept constant to within a fraction of a wavelength. The method is applicable to other situations in which pairs of single photons are produced, but becomes less efficient for more intense pulses of light, because the "visibility" of the interference is then reduced and cannot exceed 50% at high intensities. In principle, the resolution could be better than 1 pm in length or 1 fs in time.
Absolute measurement of a long, arbitrary distance to less than an optical fringe

Jun Ye

JILA, National Institute of Standards and Technology, and University of Colorado, Boulder, Colorado 80309-0440
Real-time product originates from: square law detector

\[ \left[ f(t) + g(t - \tau) \right]^2 \Rightarrow f(t)g(t - \tau) \]

But to implement:
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Heterodyne correlator
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IDEA!
Use Statistics “DEFINITION”

\[ \text{Var}(X) = E[(X - E[X])^2] = E[X^2] - (E[X])^2 \]

**IDEA: Use Intensity interferometer (a.k.a. fourth order)**

\[ \text{Var}(I_1(t) - I_2(t)) = E[(I_1(t) - I_2(t))^2] - (E[I_1(t) - I_2(t)])^2 \]

Calculated product originates from: Variance DEFINITION
MathCad “intensity” simulation

Pulse train – $I(t)$ - with Poisson intensity distribution

$$0.5 \left[ \text{Var}(I_1(t)) \right. \left. - I_2(t)) \right]^{\dagger} \left[ E(I_1(t)) - E(I_2(t)) \right]$$
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Sensl Silicon APD Array

Detector: Sensl MicroFM-SMA-10020
Lot # 131218

Active Area: 1mm x 1mm
# of Cells: 1144
Fill Factor: 48%

Biased at -32V unless noted otherwise

NOTE: New “Red” version available with higher near-IR QE. NOT used in these tests.
Detected photon number discrimination

$\lambda = 0.8$  \hspace{1cm} \lambda = 1.7  \hspace{1cm} \lambda = 3.2$
Proof-of-concept experiment
REFERENCE:


\[ \text{Var}\left(\frac{N}{\langle N_+ \rangle}\right) = \frac{1}{2} \langle N_+ \rangle \exp \left[ -2 \ln 2 \frac{T^2}{2} \right] \]

\[ \langle N_+ \rangle = N_1 + N_2 \]

\[ \frac{1}{2} = \frac{1}{c^2} + \frac{1}{T^2} \]

T = pulse width

\( \tau_c = \text{coherence time} \)
Experimental RESULTS

Micrometer position (µm)

Variance of difference

Delay (ps)
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SUMMARY

I. Reviewed methods for forming correlator product
   1) Nonlinear crystal
   2) Heterodyne – 2\textsuperscript{nd} order interferometer
   3) Photon number statistics (variance of intensity difference) - 4\textsuperscript{th} order interferometer

II. Experimental demonstration of intensity interferometer correlator for laser ranging
   1) Optical delay interferometer
   2) Moving mirror => to “wash out” second order interference effects
   3) Commercial (Sensl Inc.) Geiger-mode silicon APD array (photon number) detector.
   4) Demonstrated tens of micron level accuracy of Photon Counting Ranging

III. Future

Femtosecond-pulse Carbon-nanotube mode-locked frequency-doubled fiber laser source