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

II. Intensity interferometer correlator

III. Experimental results

IV. Summary
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AGENDA

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Correlation Function
Definition

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

Intensity autocorrelator

Interferometric (2\textsuperscript{nd} order) autocorrelator

April 17, 2016
SPIE DCS 2016
Correlation Function
Optical nonlinear crystal

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

Real-time product originates from:
2\textsuperscript{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”.
equal intensity in each arm the fringe visibility is given by
\(|\gamma(\tau)|\) and the position of the fringe pattern is determined by
the phase of \(\gamma(\tau)\), where \(\gamma(\tau)\) is the normalized second-order
autocorrelation function of the incoming wave field. If \(V_0(\tau)\) is the complex
analytic signal representing the incident stationary, polarized wave, then
\[ \gamma(\tau) = |\langle V_0^*(\tau) V_0(\tau + \delta\tau) \rangle| = |\langle |V_0(\tau)|^2 \rangle|^2. \] (1)

Because \(\gamma(\tau)\) is of second order in the field amplitude, we refer to this
procedure as second-order interferometry and to the corresponding coherence
time \(\tau_c\) as the second-order coherence time.

By varying the path difference and measuring the fringe visibility as a function of \(\tau\), one can readily determine \(\tau_c\) from the range of \(\tau\) in which the method works well.

By measuring the photoelectric correlation as a function of \(\tau\), we can determine the range of \(\lambda(\tau)\) and therefore the correlation time. In general, the ranges of \(\lambda(\tau)\) and of \(|\gamma(\tau)|\)
may be quite different, however, although in the special case of polarized light with thermal statistics \(\lambda(\tau)\) and \(\gamma(\tau)\) are related by
\[ \lambda(\tau) = |\gamma(\tau)|^2. \] (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 \(\tau_R\) of the detectors and the electronics to fourth-order correlation times \(\tau_4\) that are much longer than
\(\tau_R\) (typically of the order of \(10^{-8}\) sec), and it becomes useless when \(\tau_4 \ll \tau_R\).

In what follows, we shall discuss a noise-reduction scheme for measuring both the coherence time and
the pulse duration time of the input optical field, with virtually no limit on time resolution. Measurement
is made at photon-counting intensity levels and is applicable to a wide range of wavelengths.

We have tested our scheme by applying it to the
measurement of the output pulses of a cw mode-lockedback dye laser. The results are in good agreement
with values obtained by the conventional second-
harmonic (SH) autocorrelation technique.

The scheme is illustrated in Fig. 1. Let us assume that the incident optical field is a pulse train of
polarized light and that each pulse can be expressed by the complex field

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

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

\[ \Gamma_M = 2RT(R^2 + T^2)(I_0)^2 \tau_R \left[ 1 - \frac{RT}{R^2 + T^2} |\gamma(\tau_0)|^2 \right], \] (17)

where \(\gamma(\tau_0) = \Gamma_{00}(\tau)/\langle I_0^2 \rangle\) 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 \(\gamma(0) = 1\) by definition, it follows that a measure-
ment of the correlation \(\Gamma_M\) as a function of the variable time
delay \(\delta\tau\) must yield results summed to those obtained with

\[ \text{Count}_{\text{inst}}(\delta\tau) = K \int_{-\tau_R}^{\tau_R} \int_{-\tau_R}^{\tau_R} d\tau_1 d\tau_2 \langle E_1^*(\tau_1) E_2^*(\tau_2) E_1(\tau_1 + \delta\tau) E_2(\tau_2 + \delta\tau) \rangle. \]

\[ K \text{ is an appropriate proportional constant, } T_R \text{ is the detector response time, and } \langle \cdot \rangle_{\text{det}} \text{ denotes ensemble averages with respect to } A(t) \text{ and } \phi(t). \]

The optical pulses with interference

Baba, and M. Matsuoka

1993 / Vol. 18, No. 11 / OPTICS LETTERS

We show a plot of this function in Fig. 2. There
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
reduce back to the two terms in Eq. (7). The narrow
component corresponding to the first term is called
second-order interference, which occurs only when
the variable delay \(\delta\tau\) is smaller than the pulse field coherence time.
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.
Conventional (2\textsuperscript{nd} order) interferometer
Heterodyne correlator

Real-time product originates from: square law detector

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

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Var(X) = E[(X - E[X])^2] = E[X^2] - (E[X])^2

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

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

$$0.5 \left[ \text{Var}(I_1(t), I_2(t)) \cdot \text{E}(I_1(t)) \cdot \text{E}(I_2(t)) \right]$$
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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

\[ \lambda = 0.8 \]
\[ \lambda = 1.7 \]
\[ \lambda = 3.2 \]

April 17, 2016

SPIE DCS 2016
Proof-of-concept experiment
REFERENCE:


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

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

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

T = pulse width

\( \tau_c = \) coherence time
Experimental RESULTS

Micrometer position (μm)

Variance of difference

Delay (ps)

Theory

Experiment
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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