Femtosecond photon-counting receiver

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AGENDA

I. Ways to achieve CORRELATION function
II. Intensity interferometer correlator
III. Experimental results
IV. Summary
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

![Diagram of autocorrelator systems]
Correlation Function
Optical nonlinear crystal

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

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

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

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
\(|\gamma(r)|^2\) and the position of the fringe pattern is determined by
the phase of \(\gamma(r)\), where \(\gamma(r)\) is the normalized second-order
autocorrelation function of the incoming wave field. If
\(V_0(t)\) is the complex analytic signal representing the incident
stationary, polarized wave, then
\[
\gamma(r) = \frac{\langle V_0^*(t)V_0(t + r)\rangle}{|V_0(t)|^2}.
\] (1)

Because \(\gamma(r)\) 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 \(\omega\) and measuring the fringe
visibility as a function of \(\omega\), one can readily determine \(\tau_c\) from
the range of \(\omega = 0\). Although the method works well

By measuring the photoelectric correlation as a function of \(\tau_c\), we
can determine the range of \(\lambda(\tau)\) and therefore the
coherence time. In general, the ranges of \(\lambda(\tau)\) and \(|\gamma(r)|^2\)
may be quite different, however, although in the special case
of polarized light with thermal statistics \(\lambda(\tau)\) and \(\gamma(r)\) are
related by
\[
\lambda(\tau) = |\gamma(r)|^2.
\] (3)

But for other fields, such as laser beams, there may be little
connection between \(\lambda(\tau)\) and \(|\gamma(r)|^2\). 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 \(\tau_c\) much longer than
\(\tau_R\) (typically of the order of \(10^{-20}\) sec), and it becomes useless
when \(\tau_c \ll \tau_R\).

In what follows we discuss a method for measuring the
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-
locked 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

\[
\tau_c \gg \int_0^\infty \lambda(\tau) d\tau.
\] (16)

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

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

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 \(\delta \tau = \tau - \tau_0\) must yield results analogous to those


st optical pulses with interference

Baba, and M. Matsuoka

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We show a plot of this function in Fig. 2. There
increase in the coincidence count rate at \(\delta \tau \sim 0\) that
is a result of two components, corresponding to the first
second Gaussian terms of Eq. (9), which in turn
duce a function back to the terms in Eq. (7). The
ponent corresponding to the first term is caused
second-order interference, which occurs only when
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.
Absolute measurement of a long, arbitrary distance to less than an optical fringe

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Heterodyne correlator

Real-time product originates from: square law detector

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

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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

\[ 0.5 \left[ \text{Var}(I_1(t) - I_2(t)) \right]^{\frac{1}{2}} \left[ \text{E}(I_1(t)) - \text{E}(I_2(t)) \right] \]
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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

\[ \lambda = 0.8 \]

\[ \lambda = 1.7 \]

\[ \lambda = 3.2 \]
Proof-of-concept experiment
REFERENCE:


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

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

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

T = pulse width
\( \tau_c = \) coherence time
Experimental RESULTS

![Graph showing micrometer position (µm) vs. delay (ps). The graph includes a black line labeled 'Theory' and blue triangles labeled '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