Femtosecond photon-counting receiver

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AGENDA

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

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

Intensity autocorrelator

Interferometric (2nd order) autocorrelator
Correlation Function
Optical nonlinear crystal

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

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”.

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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 \(V_0(t)\) is the complex analytic signal representing the incident stationary, polarized wave, then

\[
\gamma(t) = \langle V_0^*(t)V_0(t + \tau) \rangle / |V_0(t)|^2.
\]  

(1)

Because \(\gamma(t)\) 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 \(\delta\tau\) and measuring the fringe visibility as a function of \(\tau_c\), one can readily determine \(\tau_c\) from the range of \(\delta\tau\). Although the method works well

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

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 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 \(\delta\tau\) must yield results corresponding to the first term.

The problem of measuring the coherence time \(\tau_c\) of the laser field is now reduced to the determination of \(\gamma_{00}(\delta\tau)\).

\[
\text{Count}_{\text{in}}(\delta\tau) = K \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} d\tau \langle E_1(t)E_1^*(t + \delta\tau) \rangle \times E_2(t + \tau)E_2^*(t).\]  

(4)

where \(K\) is an appropriate proportionality constant, \(T\) is the detector response time, and \(\langle \cdot \rangle_{\lambda_4}\) denotes ensemble averages with respect to \(\lambda_4\) and \(\phi(\lambda_4)\).

\[
\text{Count}_{\text{out}}(\delta\tau) = K \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} d\tau \langle E_1(t)E_1^*(t + \delta\tau) \rangle \times E_2(t + \tau)E_2^*(t)\lambda_4.
\]  

(5)

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.

The first optical pulses with interference

Baba, and M. Matsuoka

We show a plot of this function in Fig. 2. There is a decrease in the coincidence count rate at \(\delta\tau \approx 0\) 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 larger 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.
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

Absolute measurement of a long, arbitrary distance to less than an optical fringe

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Real-time product originates from: square law detector

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

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

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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

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

PicoQuant 780-nm Diode Laser

λ/2

λ/4

PZT

λ/4

λ/2

Sensl

ND Filters

2.5 GHz Oscilloscope

Sensl

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REFERENCE:


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

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

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

T = pulse width
\(\tau_c\) = coherence time
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I. Reviewed methods for forming correlator product
   1) Nonlinear crystal
   2) Heterodyne – 2\text{nd} order interferometer
   3) Photon number statistics (variance of intensity difference) - 4\text{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