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

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

Intensity autocorrelator

Interferometric (2\textsuperscript{nd} order) autocorrelator
\[ R(t) = f(t)g(t) \]  

Real-time product originates from:  
\(2^\text{nd} \) 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 $|\gamma(\tau)|$ 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

$$\gamma(\tau) = \frac{\langle V_0^*(t)V_0(t+\tau) \rangle}{\langle |V_0(t)|^2 \rangle}. \quad (1)$$

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 $\tau$ and measuring the fringe visibility as a function of $\tau$, one can readily determine $\tau_c$ from the range of $|\gamma|\neq 0$. Although 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

$$\lambda(\tau) = |\gamma(\tau)|^2. \quad (3)$$

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 $\tau_c$ that are much longer than $\tau_0$ (typically of the order of $10^{-9}$ sec), and it becomes useless when $\tau_c \ll \tau_0$.

In what follows we shall be concerned simply with 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 modelocked 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

$$A(t) = \int_{-\infty}^{\infty} \alpha(t) \exp(j\omega t) dt,$$

where $\alpha(t)$ and $\beta(t)$ are the complex envelopes of the electric and magnetic field, respectively, of the field. We show a plot of this function in Fig. 2. There is an 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 are back to the two terms in Eq. (7). The narrow component corresponding to the first term is caused by the 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

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

But to implement:
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IDEA!
Use Statistics “DEFINITION”

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

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

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

\[ \lambda = 0.8 \quad \lambda = 1.7 \quad \lambda = 3.2 \]
Proof-of-concept experiment

[Diagram of optical setup with labeled components: PicoQuant 780-nm Diode Laser, λ/2, λ/4, Sensl, ND Filters, 2.5 GHz Oscilloscope, PZT, Sensl, and SPIE DCS 2016 details.]
REFERENCE:


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

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

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

\( T = \text{pulse width} \)

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