Femtosecond photon-counting receiver

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AGENDA

I. Ways to achieve CORRELATION function

II. Intensity inteferometer correlator

III. Experimental results

IV. Summary

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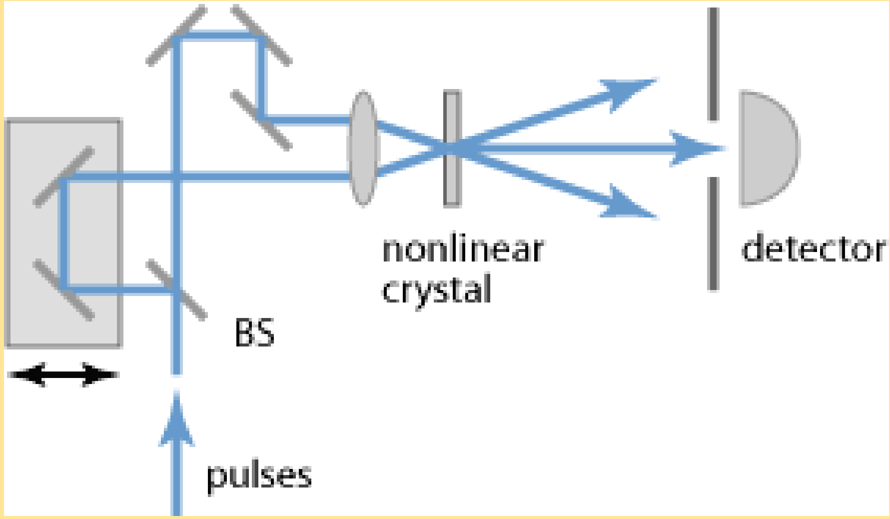
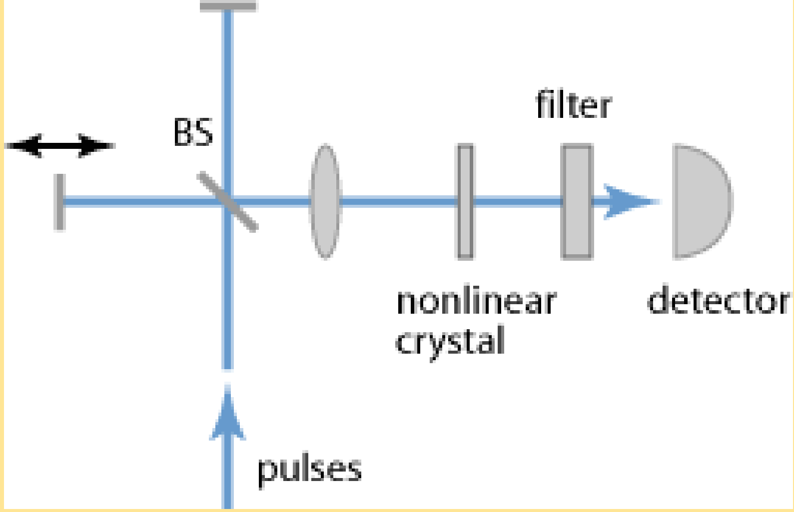
Correlation Function Definition

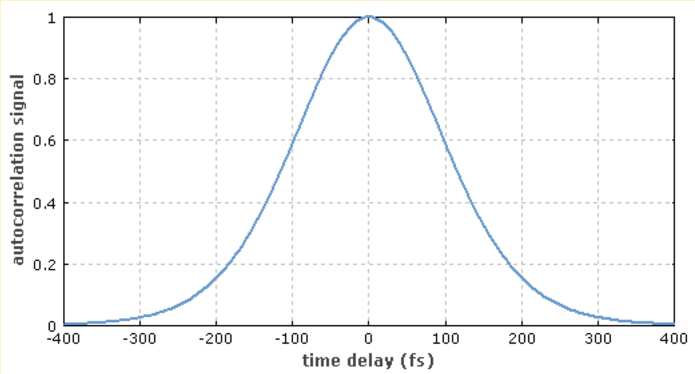
$$R(\tau) = \int f(t)\,g(t - \tau)\,dt$$

Correlation Function
Optical Implementation

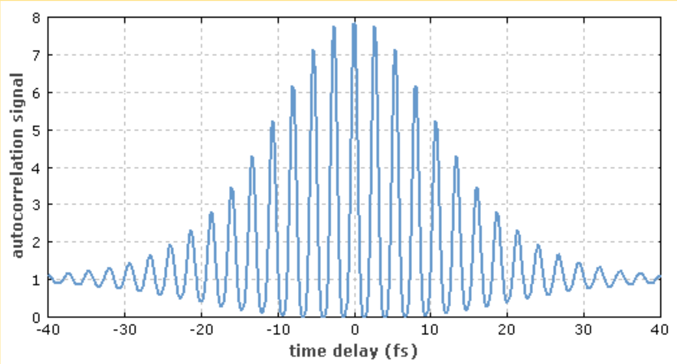




Intensity autocorrelator



Interferometric (2^{nd} order) autocorrelator



Correlation Function
Optical nonlinear crystal

$$R(\tau) = \int f(t) g(t - \tau) dt$$

Real-time product originates from:

2nd harmonic crystal: $\chi^{(2)}$

$$P^{NL} = \chi^{(2)} f(t) g(t - \tau)$$

But to implement:

We step the delay (τ) and calculate at each step.

NOT “real-time”.

4^{th} order Interferometer (Using coincidence detection)

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1989

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[1]

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

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 τ_c as the second-order coherence time.

By varying the path difference $c\tau$ and measuring the fringe visibility as a function of τ, one can readily determine

By measuring the photoelectric correlation as a function of τ, 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[3]

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

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 τ_R of the detectors and the electronics to fourth-order correlation times τ_c that are much longer than τ_R (typically of the order of 10^{-9} sec), and it becomes useless when $\tau_c \ll \tau_R$.

$$\tau_R \gg \int_{-\infty}^{\infty} \lambda(\tau)\mathrm{d}\tau. \quad (16)$$

Hence for large τ_R Eq. (12) simplifies to

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

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 Γ_M as a function of the variable time

1993

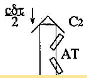
scheme for measuring both the coherence time and the pulse duration time of the input optical field, with virtually no limit on time resolution. Measurement is made at photon-counting intensity levels and is applicable to a wide range of wavelengths.

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

$$\mathrm{Count}_{12}(\delta\tau) = K\int_{t_1}^{t_2}\mathrm{d}t\int_{-T_R/2}^{T_R/2}\mathrm{d}\tau\langle E_1^*(t)E_2^*(t+$$
$$\times E_2(t+\tau)E_1(t)\rangle_{A,\phi}.$$

K is an appropriate proportional constant, T_R is detector response time, and $\langle\rangle_{A,\phi}$ denotes ense averages with respect to $A(t)$ and $\phi(t)$.



st optical pulses with nterference

Baba, and M. Matsuoka

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

e show a plot of this function in Fig. 2. There crease in the coincidence count rate at $\delta\tau \sim 0$ t ists of two components, corresponding to the fi second Gaussian terms of Eq. (9), which in tu e back to the two terms in Eq. (7). The narr ponent corresponding to the first term is caus econd-order interference, which occurs only wh is smaller than the pulse field coherence time

Two photon interference for short pulse (1987)

Goddard Space Flight Center

resolving time of the photodetector to intervals of order 100 ps or longer.[5]

We wish to report an experiment in which the time interval between signal and idler photons, and by implication the length of a subpicosecond photon wave packet, produced in parametric down-conversion was measured. The technique is based on the interference of two two-photon probability amplitudes in two-photon detection, and is easily able to measure a time interval of 50 fs, with an accuracy that could be 1 fs or better.

An outline of the experiment is shown in Fig. 1. A coherent beam of light of frequency ω_0 from an argon-ion laser oscillating on the 351.1-nm line falls on an 8-cm-long nonlinear crystal of potassium dihydrogen phosphate, where some of the incident photons split into two

5×10^{12} Hz, corresponding to a coherence time for each photon of order 100 fs. Needless to say, the two-photon probability amplitudes at the detectors D1,D2 are expected to interfere only if they overlap to this accuracy or better. We start by examining how this interference arises.

Let us label the field modes on the input sides of the beam splitter by 01,02 and on the output sides by 1,2 and suppose first that the light is monochromatic. If we take the state at the input resulting from one degenerate down-conversion to be the two-photon Fock state $|1_{01},1_{02}\rangle$, then one can show from general arguments[7] that the state on the output side of the beam splitter is

Position of beam splitter (μm)

FIG. 2. The measured number of coincidences as a function of beam-splitter displacement $c\,\delta\tau$, superimposed on the solid theoretical curve derived from Eq. (11) with $R/T=0.95$, $\Delta\omega=3\times10^{13}$ rad s^{-1}. For the dashed curve the factor $2RT/(R^2+T^2)$ in Eq. (11) was multiplied by 0.9. The vertical error bars correspond to one standard deviation, whereas horizontal error bars are based on estimates of the measurement accuracy.

time spread of the photoelectric pulses and the slewing of the discriminator pulses, a range of time intervals centered on zero delay was obtained with a spread of several nanoseconds. For the purpose of the measurement, pulse pairs received within a 7.5-ns interval were treated as "coincident." Pulse pairs received within an interval of 35 to 80 ns were regarded as accidentals, and when scaled by the factor 7.5/45 provided a measure of the number of accidental coincidences that occur within any 7.5-ns interval.

The results of the experiment are presented in Fig. 2,

"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 be- comes less e%cient for more intense pulses of light, be- cause 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 (2nd order) inteferometer

May 15, 2004 / Vol. 29, No. 10 / OPTICS LETTERS 1153

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

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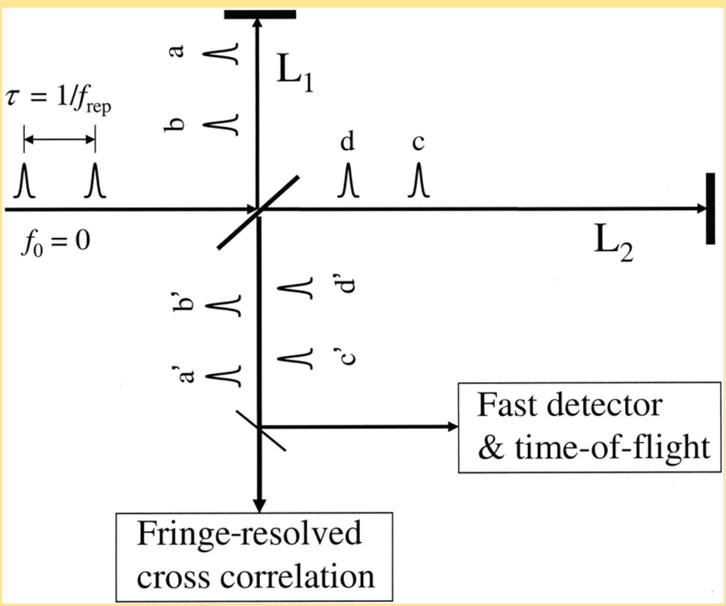

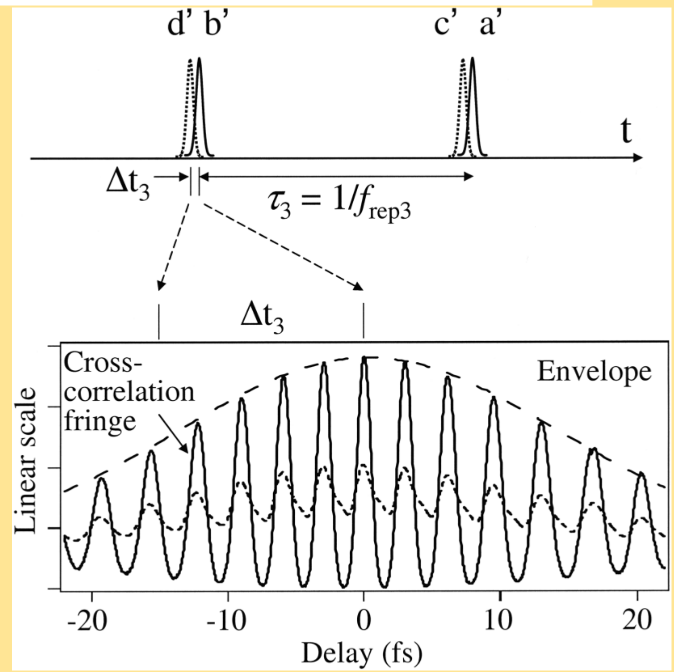

Heterodyne correlator

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Real-time product originates from: square law detector

$$[f(t)+g(t - \mathbf{t})]^2 => f(t)g(t - \mathbf{t})$$

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NOT “real-time”.

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IDEA!
Use Statistics "DEFINITION"

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

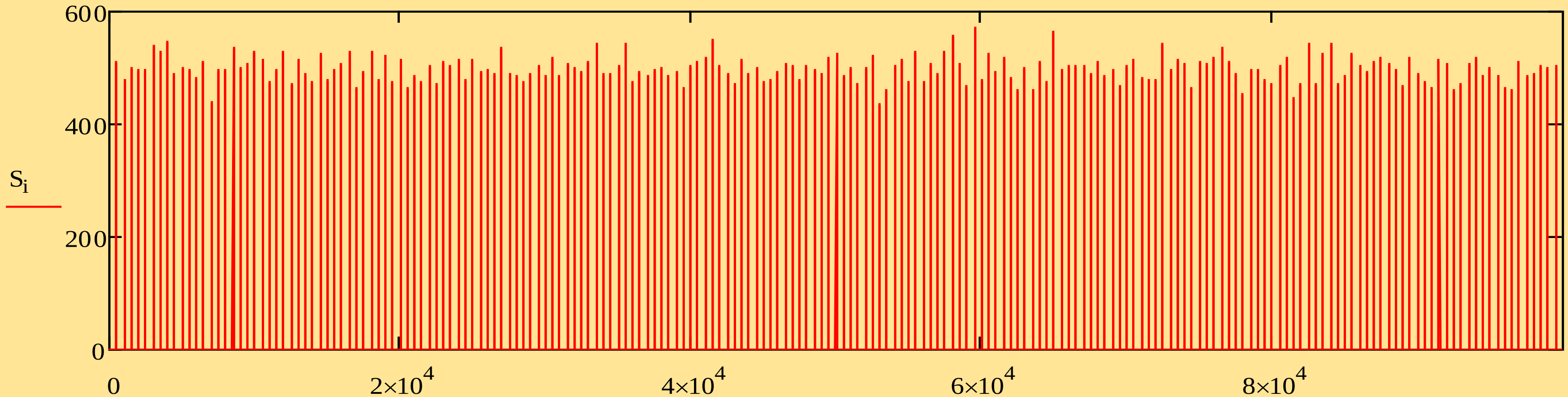
IDEA: Use Intensity interferometer (a.k.a. fourth order)

$$Var(I_1(t) - I_2(t)) = E[(I_1(t) - I_2(t))^2] - (E[I_1(t) - I_2(t)])^2$$

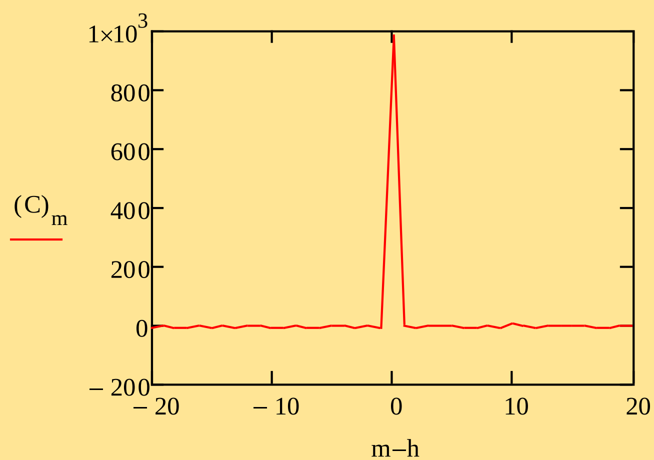
Calculated product originates from: Variance DEFINITION

MathCad "intensity" simulation

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



$$-0.5\left[Var(I_1(t) - I_2(t)) - {}^{i}\, E(I_1(t)) - E(I_2(t))\right]$$



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Sensl Silicon APD Array

Detector: Sensl MicroFM-SMA-10020
Lot # 131218

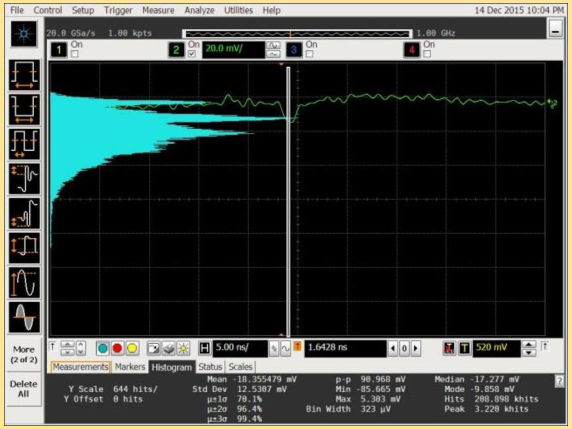
Active Area: 1mm x 1mm
# of Cells: 1144
Fill Factor: 48%

Biased at -32V unless noted otherwise

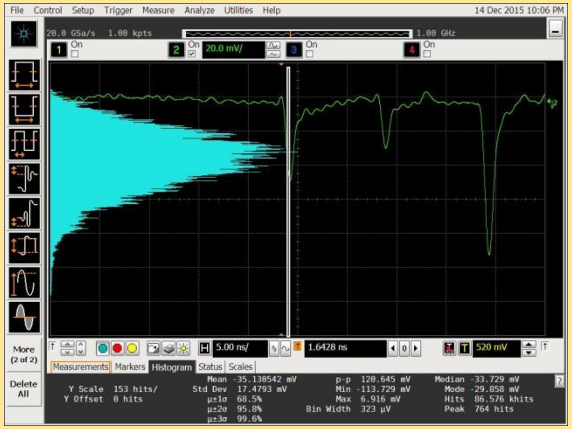
NOTE: New "Red" version available with higher near-IR QE. NOT used in these tests.

Detected photon number discrimination

$\lambda = 0.8$

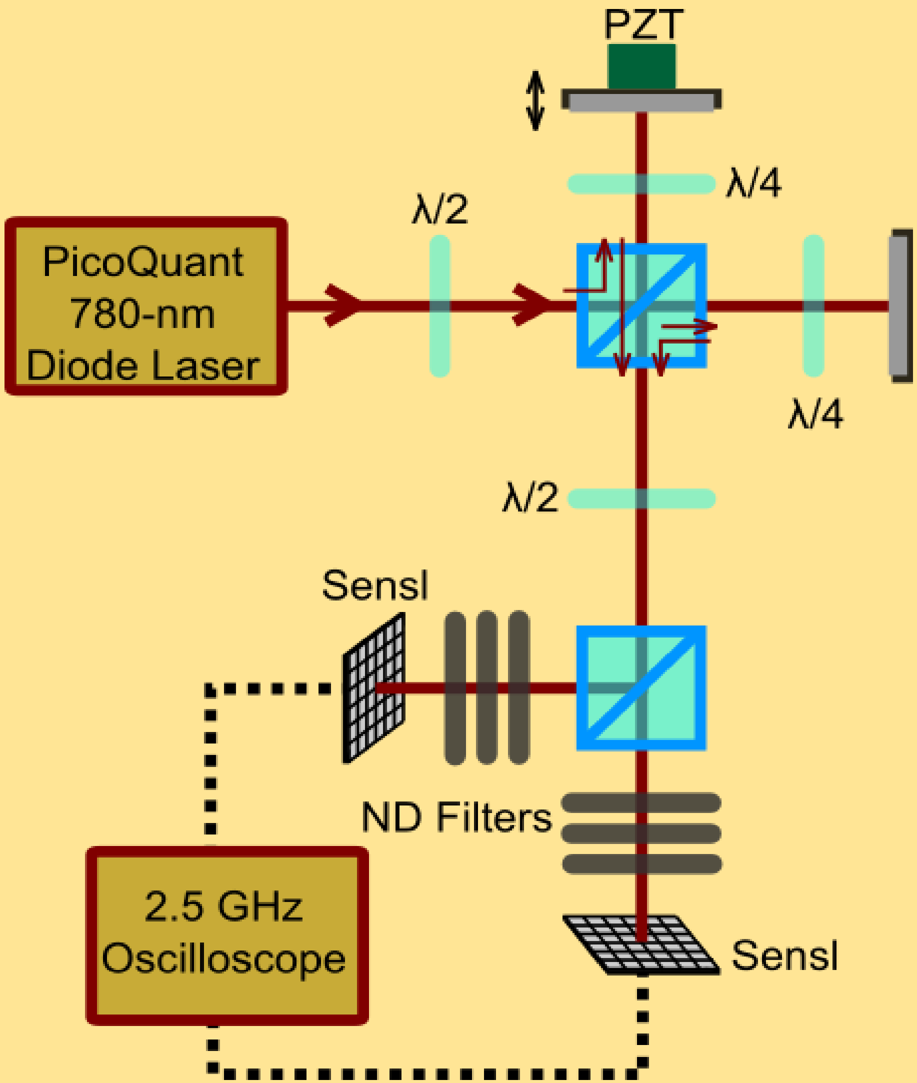


$\lambda = 1.7$



$\lambda = 3.2$

Proof-of-concept experiment



Intensity Interferometer Correlator (Macroscopic Hong-Ou-Mandel)

REFERENCE:

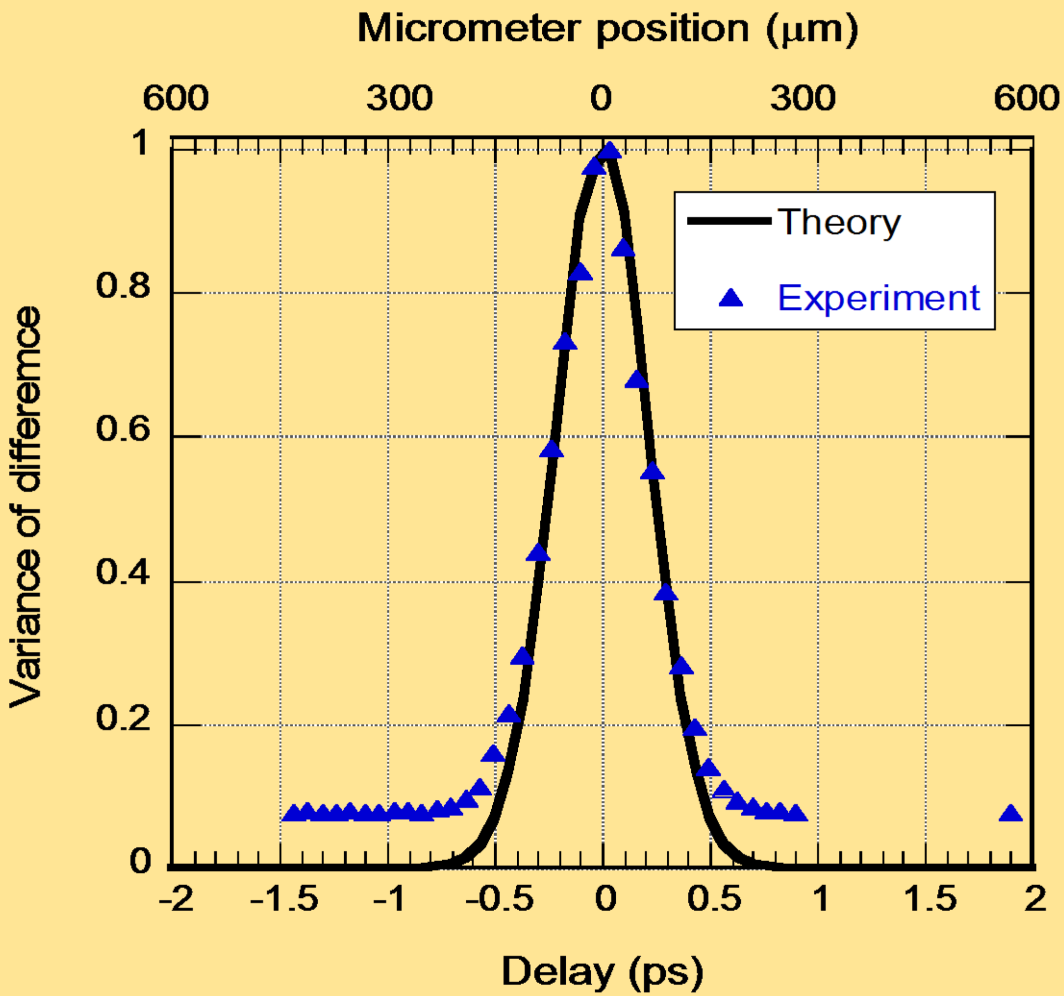
Iskhakov, T. Sh; Spasibko, K. Yu; Chekhova, M. V.; et al.
"Macroscopic Hong-Ou-Mandel interference,"
New Journal of Physics Vol. 15, 093036 (2013)

$$\frac{Var\left(N_{-}(\tau)\right)}{\langle N_{+}\rangle} = \frac{1}{2}\langle N_{+}\rangle \exp\left[-2\ln 2\,\frac{\tau^{2}}{\Delta\tau^{2}}\right]$$

$$\langle N_{+}\rangle = N_{1} + N_{2} \qquad \frac{1}{\Delta\tau^{2}} = \frac{1}{\tau_{c}^{2}} + \frac{1}{T^{2}}$$

T = pulse width
τ_c=coherence time

Experimental RESULTS



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SUMMARY

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

II. Experimental demonstration of intensity inteferometer 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