Spectrometer based on SPAD linear array with sub-nanosecond timing resolution and single photon sensitivity for quantum-assisted optical interferometers.

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Astronomy picture of the decade

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines
Radio $\bar{n} \gg 1$

Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline

Optical $\bar{n} \ll 1$

One photon at a time! Need to bring paths to common point in real time

Need path length compensated to better than $c$/bandwidth

Need path length stabilized to better than $\lambda$

Accuracy $\sim 1$ mas

Max baselines to $\sim 100$ m
Two-photon techniques
Quantum Astrometry

DOE QuantISED project

- Measure photon phase difference teleporting it to another station, similar to quantum repeaters in quantum networks
- Enables long baselines and could improve astrometrical precision by orders of magnitude
- Great impact on astrophysics and cosmology

- Photons must be indistinguishable to interfere → indistinguishable means: \( \Delta E \times \Delta t \sim \frac{h}{2\pi} \)

requires detectors with excellent time & spectral binning

\( \Delta E \times \Delta t \sim 0.1\text{nm} \times 10\text{ps} \)

DOE QuantISED project

www.quantastro.bnl.gov

P. Stankus et al, arxiv:2010.09100
A. Nomerotski et al, arxiv: 2107.09229, TIPP Proceedings

2022: benchtop verification

\[ P(cg) = P(dh) = \frac{1}{8}(1 + \cos(\delta_1 - \delta_2)) \]
\[ P(ch) = P(dg) = \frac{1}{8}(1 - \cos(\delta_1 - \delta_2)) \]
Phase dependence

- Stable setup
- See expected behavior
- Time resolution \(\sim 100\) ps
Visibility and phase

- All as expected
- Paper in preparation

![Graphs showing visibility and phase relationships](image-url)
Next step: spectral binning
Spectral binning

Two beams → diffraction grating
Based on intensified Tpx3Cam, ns time resolution

spectral resolution for Ar lines ~0.15 nm

A. Nomerotski et al. Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications, arxiv.org/abs/2210.13713, accepted to JINST
SPDC source in spectrometer

- 810 nm idler and signal
- no filter

wavelength anti-correlation for photon pairs

pump wavelength

time coincidences
Adding SPDC instead of one lamp

• As in original GJC2012 paper

• one Ar lamp + Thorlabs SPDC source

• Thorlabs source 1 MHz, 810 nm

• Spectral analysis of idler will post-select wavelength of signal photon
LinoSPAD2 linear SPAD array

- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- Fill factor ~ 40%
- DCR ~ 30 Hz /pix @ room T
- Deadtime ~ 100ns
- Asynchronous readout of pixels

Developed by AQUA group in EPFL (Switzerland)
E.Charbon et al
SPAD arrays with 50 ps resolution

Two beams from SPDC source

Time difference, $\sigma=57$ ps
Spectrometer with LinoSPAD2 (1)

Used Ar lamp coupled to SM fiber
Achieved 0.1 nm spectral and 50 ps timing resolution
Next: demonstrate HBT peaks (photon bunching) for spectral binning
On-sky measurements

- Experimenting with SM fiber coupling
- Trying adaptive optics

with active participation of BNL & SBU
Summary and outlook

• Demonstrated the idea of quantum telescopes on the bench, closing in on required instrument parameters

• Collaborative effort: BNL, SBU, U Oregon, U Illinois, SCSU, EPFL, Czech TU, NRC Ottawa

• Quantum Telescopes: one day workshop in June 2023
  • Companion meeting at Quantum 2.0 in Denver CO

• Next: sky observations, demonstration of the original idea with stars

• To be sensitive to faint sources
  • Need high intensity entangled photon sources
  • Need quantum repeaters and memories

Synergy with quantum internet roadmap

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