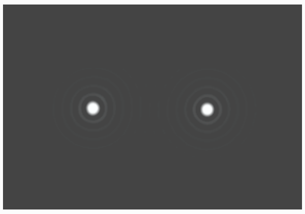
Design Rules for Quantum Imaging Devices

Experimental Progress Using CMOS Single Photon Detectors



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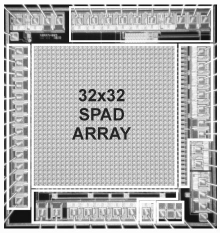

Paper 6305-23
Quantum Communications and Quantum Imaging IV
SPIE Optics & Photonics
San Diego Convention Center, San Diego, California, August 14, 2006

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When we left our story ...

Gunther and Beretta, "Towards Practical Design Rules for Quantum Communications and Quantum Imaging Devices," Paper 5893-32, *Quant. Comm. and Quant. Imaging III*, **SPIE** (2005)

- Proposed *qualitative* quantum design rules (QDRs)
- Future need as we move toward VLSI optical integration
- Based on quantum path integral (QPI) formulation of photon
- QPI provides unification between classical optics and photonics
- Exposed flaw in YAW interferometer design using our QDRs

Developing *quantitative* QDRs requires experimental validation

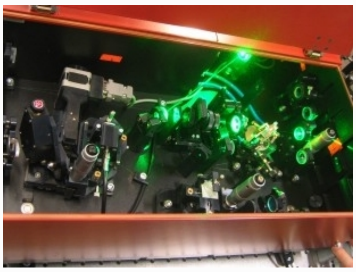
Paper 6305-23 is a progress report on that effort

Here, I will present mostly theoretical developments

Our Experimental Subsystems

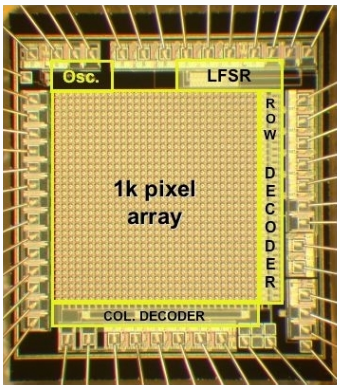
Sources: Femtosecond laser

- Ti:Sapphire mode-locked
- $\lambda = 800$ nm, 500 mW
- 100 fs pulses @ 93 MHz rep rate
- Harmonic generator $\lambda = 267$ nm, 35 mW
- BBO subsystem being prescribed

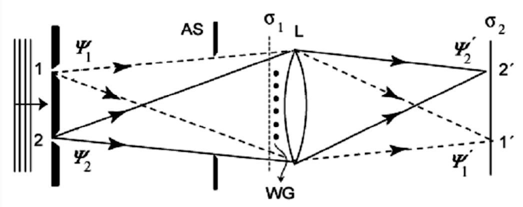


Detectors: Single photon

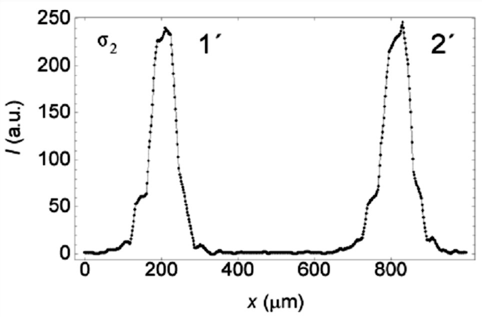
- Single photon avalanche diode (SPAD)
- 2-D SPAD array with 32×32 pixels
- $0.8\,\mu m$ CMOS technology
- VLSI integration for photonic devices
- Economies of scale cost-benefit



YAW Interferometer Paradox



YAW interferometer arrangement



Data from APD detectors at $1'$ and $2'$

- Flawed interferometer design. See Afshar, *SPIE*, **5866** (2005).
- Claims to resolve WW path info (2 image spots) in presence of interference. Violates Bohr but where is the design error?
- QPI analysis shows *photon-twinning* negates this claim (See Slide 9).
- What does the YAW image plane look like? Can we calculate such a complex device using QPI technique?

Coherent QPI Imaging

QPI Green's function expresses *amplitude* superposition:

$$\psi(x_2, t_2) = \int G(x_2, t_2 | x_1, t_1)\, \psi(x_1, t_1)\, dx_1 \tag{1}$$

Can reduce to 2-d time-independent Green's function:

$$\psi(\mathbf{x}_2) = \int G(\mathbf{x}_2 | \mathbf{x}_1)\, \psi(\mathbf{x}_1)\, d^2 x_1 \tag{2}$$

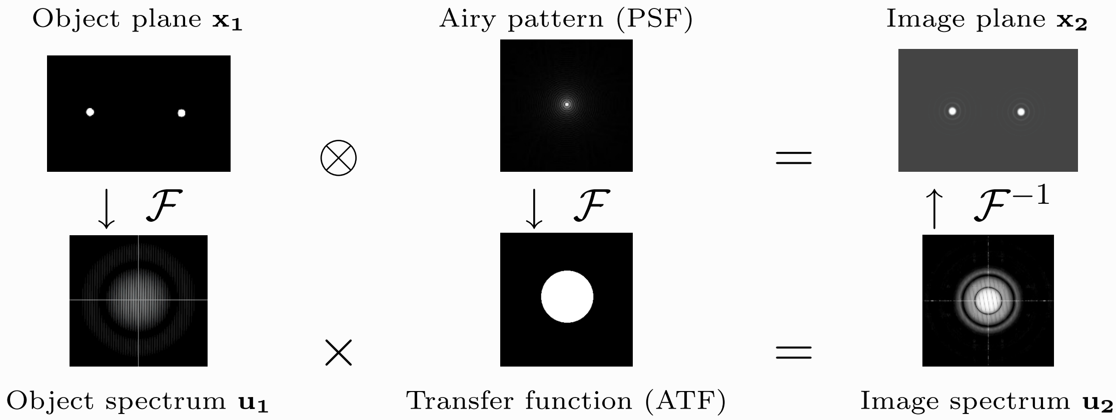
- $\psi(\mathbf{x}_1)$ is complex amplitude in *object* plane
- $\psi(\mathbf{x}_2)$ is complex amplitude in *image* plane
- Propagator $G(\mathbf{x}_2|\mathbf{x}_1)$ is *Point Spread Function* (PSF)

Eliminates usual distinction between *amplitudes* and *intensities*:

$$\mathcal{I}(\mathbf{x}_2) = |\, G(\mathbf{x}_2|\mathbf{x}_1) \otimes \psi(\mathbf{x}_1)\,|^2 \tag{3}$$

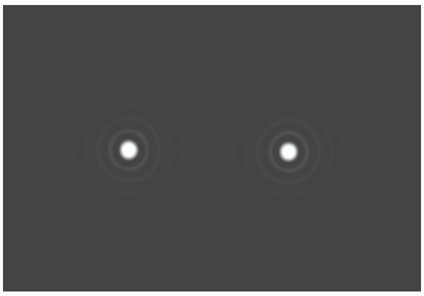
always; consistent with QDR # 8. (*Example of higher-level QDR*)

Convolution and Fourier Optics



Finite lens acts as low-pass LSI filter: $\psi(x_2) = G(\mathbf{x}_2|\mathbf{x}_1) \otimes \psi(x_1)$.
Point spread function (PSF) $\equiv$ impulse response function: $h(\mathbf{x})$.
Pupil function $\equiv$ amplitude transfer function (ATF): $H(\mathbf{u}) = \mathcal{F}[h(\mathbf{x})]$.
Image intensity: $\mathcal{I}(\mathbf{x_2}) = |G(\mathbf{x}_2|\mathbf{x}_1) \otimes \psi(x_1)|^2$ from QPI ... or
Image intensity: $\mathcal{I}(\mathbf{x_2}) = |\mathcal{F}^{-1}[\mathcal{F}[G(\mathbf{x}_2|\mathbf{x}_1)] \cdot \mathcal{F}[\psi(x_1)]]|^2$ in Fourier space.

Computed YAW Images



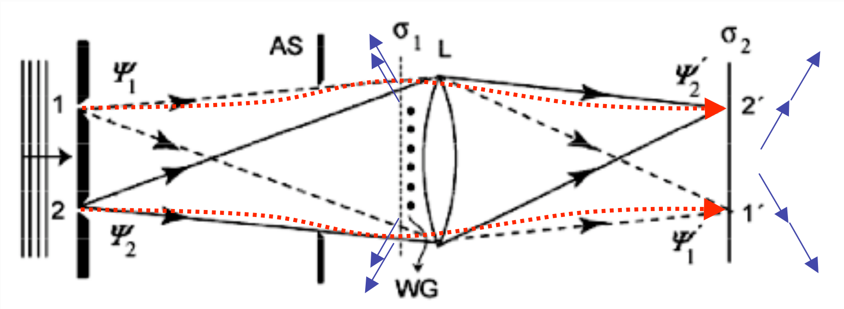
Without wire comb:

- Shown in low contrast
- Two central spots
- Concentric rings from aperture
- Not shown in YAW plots

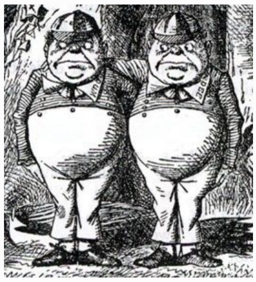
With wire comb:

- Same as above, high contrast
- Concentric rings not apparent with higher contrast
- Slight scattering off wires
- Possibly some numerical artifacts

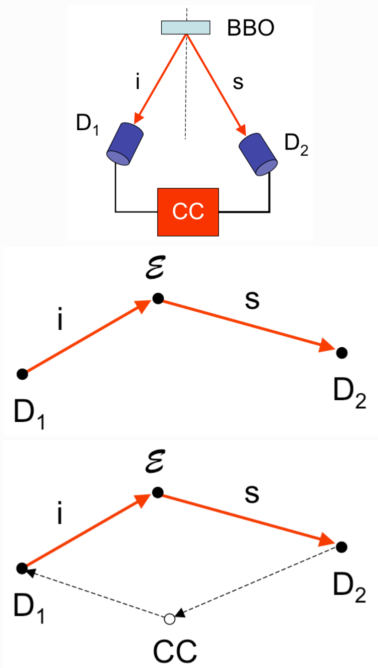
Photon Phase Twinning



Each QPI amplitude phase $\nwarrow$ rotating at $\omega = 2\pi c/\lambda$
One QPI from each source e.g., $\downarrow$ at 1 and $\nearrow$ at 2
Phase twins at σ_1 *identical* or *fraternal* at σ_2?
Twice as many quantum paths as classical geometric-rays
Identical twins $\nearrow\nearrow$ if they met at fringe maxima in σ_1
Fraternal twins cancel $\searrow\nwarrow$ at $2'$ if fringe minima in σ_1
Gives quantum corrections to Abbe-Rayleigh imaging theory



QPI for Entangled Biphoton

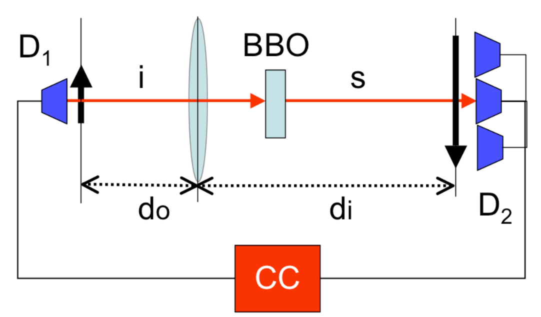


Standard production method for entangled photons is SPDC of pump laser to produce entangled photon pairs (biphotons). The *idler* (i) and *signal* (s) must satisfy certain matching conditions. Need two detectors (D_1 and D_2) to see each member of the correlated pair in coincidence counts (CC).

Biphoton is a formal product of two single-photon states that cannot be factored as direct product. In QPI, intrinsic correlation becomes *product* of 2 propagators i.e., $G_s \times G_i$. But this looks like **QDR # 6** for a path segmented by event $\mathcal{E}$ (e.g., BBO) and *idler* going backwards from D_1 to its source! (cf. Klyshko 1988)

Together with the coincidence counter (CC), the QPI paths form a kind of *closed circuit* in contrast to single photon detection which is an *open* circuit.

QPI Circuit for Quantum Ghost Imaging



Quantum ghost-imaging device is topologically equivalent to QPI closed circuit with the idler going backwards from detector D_1 to the source.

Classical optics *thin lens* equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

holds even though the image is only seen in coincidences (ghost). Also independent of which side of the source the lens is placed.

Klyshko, *Sov. Phys. JETP*, **67**, 1131 (1988)
D'Angelo and Shih, *Laser Physics* (2005)

Next Steps

- Ultimate goal is quantitative QDRs and heuristics
- Installed Ti:Sapphire laser and frequency tripler
- Acquiring BBOs for SPDC entangled photons
- Experimental program:
  - Calibrate SPAD detector arrays
  - Assess QDR tolerances in various devices
  - Investigate corrections to Abbe-Rayleigh theory

Once all the subsystems are in place, we hope to report a number of new results in rapid succession.

Stay tuned ...