Project R1A1

Entangled 2-Photon Imaging

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Source emits photons in pairs (twins):

- Simultaneous in time \( t_1 = t_2 \)
- Each is broad band, but frequencies are anti-correlated \( \omega_1 + \omega_2 = \omega_p = \text{constant} \)
- Each is multidirectional, but directions are anti-correlated \( k_1 + k_2 = k_p = \text{constant} \)
- Each is of random polarization, but polarizations are anti-correlated
<table>
<thead>
<tr>
<th>Topic</th>
<th>References</th>
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Quantum OCT (QOCT) = OCT based on two-photon interferometry

If the photons are indistinguishable, the alternatives of reflection-reflection & transmission-transmission at the beamsplitter cancel out and the coincidence = 0

Compared to OCT, QOCT has x2 higher resolution for same bandwidth
The interference term is insensitive to GVD.

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Quantum OCT (QOCT)

= OCT based on two-photon interferometry

Optics Express, 12, 1353 (2004)

Source of simultaneously emitted photon pairs

Beamsplitter interferometer

If the photons are indistinguishable, the alternatives of reflection-reflection & transmission-transmission at the beamsplitter cancel out and the coincidence = 0

Compared to OCT, QOCT has x2 higher resolution for same bandwidth

The interference term is insensitive to GVD.
The QOCT setup

The QOCT setup involves a setup that includes a laser, a nonlinear crystal, a mirror, and a sample. The diagram illustrates the process of axial and transverse scanning, resulting in a measurement of $C(z)$.
2004 Experiment: Four Boundaries + dispersive medium in-between

\[ \beta'' \approx 4.5 \times 10^{-25} \text{ s}^2 \text{m}^{-1} \]

Initial Challenges:

- Not enough photons (long run time). 3D imaging is not viable
- Poor axial resolution (19 μm). Source bandwidth too narrow
- Not certain about quantum entanglement in the nonplanar scattering media such as biological samples
Subsequent Improvements

- **Source:** Increased bandwidth by use of periodically-poled crystal (QPM) & chirped crystals

Resolution 19 $\mu$m to 1 $\mu$m

Detector: Used superconducting single-photon detectors SSPD (greater bandwidth)

Submicron Resolution

- **Configuration**: miniaturization, use polarization components to avoid photon loss at beamsplitters (factor of 4)
- **Sample**: enhance reflection by gold nanoparticles
- **Transverse focusing**: use a lens in each path to obtain 3D images

These enhancements were used in the biological experiment reported today. But recent techniques for ultrahigh resolution QOCT have not yet been implemented in biological imaging.
Experiment: 3D QOCT imaging of biological sample

Optics Comm. 282, 1154 (2009)
Sample: Onion-skin tissue coated with spherical gold nanoparticles

Surface topography was measured by Reflection Confocal Microscopy (RCM)

C-Scans

- Untreated (bare) onion skin
- Incubated for 48 hrs in solution of pegylated gold nanoparticles
- Incubated for 48 hrs in solution of solid gold nanoparticles with attached bovine serum albumin (BSA)
Typical QOCT A-Scan of top surface

5-second accumulation time

7.5 μm
3D contours of constant reflectance

Sample coated with BSA-functionalized nanoparticles

Position (μm)

C = 0.90
QOCT B-Scans

75 µm x 30 µm x 100 µm

1.00

0.95

0.90

0.85

30 µm

100 µm
Conclusions

• First demo of viability of quantum metrology in biological imaging environment (nonplanar layers, scattering, diffusion)

• Axial resolution ($7.5 \mu m$) can be improved to $1 \mu m$. Transverse resolution ($12 \mu m$) can also be improved.

• Scan time (150 sec per A-scan) is too long (pump power was only 2 mW, corresponding to 0.5 pW of downconverted photons or $10^6$ photon pairs/sec). Higher power may be used & downconversion efficiency may be improved by use of better sources. Better detectors may also help.

• Sample reflectance was enhanced by use of gold nanoparticle — a new paradigm in quantum imaging

• Advantages of QOCT include x2 resolution enhancement & dispersion cancellation.

• The low photon flux, which is the principal challenge of QOCT, may be an advantage for imaging photon-intolerant specimens with SNR greater than classical techniques