January 01, 2007

Superconducting Single-Photon Detectors (SSPDs) for OCT and QOCT

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Abstract

Classical optical coherence tomography (OCT) and quantum OCT measurement methods are important for characterizing thickness of very thin reflective biological samples. Measurement resolution for both methods is enhanced by the use of a broadband short coherence length light source that must be detected over the full spectral range.

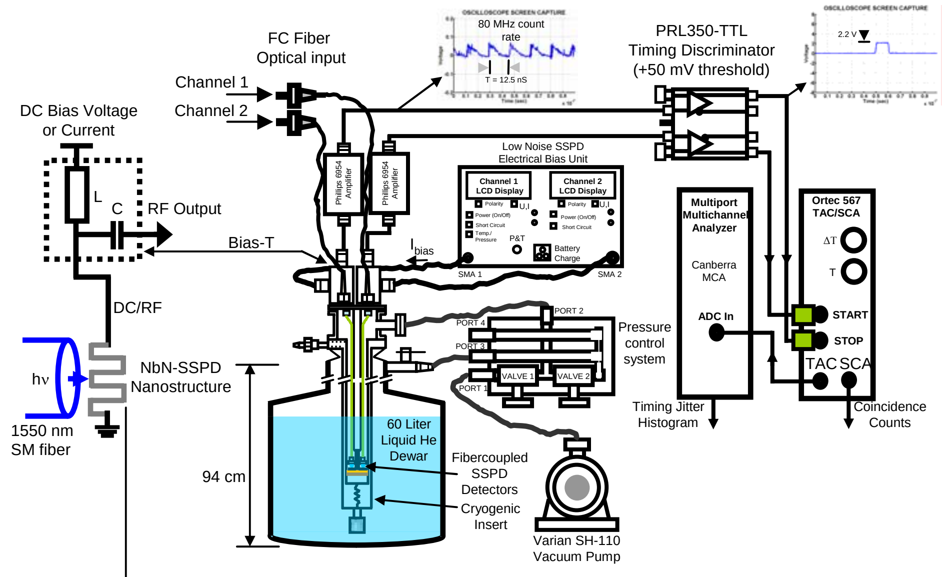
Classical OCT:
- Reflective biological sample is placed in one arm of a Michelson interferometer and a single detector records intensity. $I(\tau) \propto \Gamma_0 + 2\mathrm{Re}\{\Gamma(\tau)e^{-i\omega\tau}\}$ as function of optical delay τ as the mirror in the reference arm is scanned.

Quantum OCT:
- Biological sample is placed in one arm of an HOM beamsplitter interferometer and two detectors record the coincidence counting rate $C(\tau) \propto \Lambda_0 - \mathrm{Re}\{\Lambda(2\tau)\}$ at the output of the beamsplitter as an optical delay τ is scanned in the other arm.

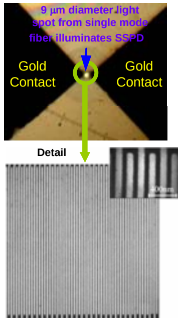
Detector Technology for OCT and QOCT:
- Silicon Avalanche Photodiode (APD)
  - Maximum count rate is 5-10 MHz; quenchtime limited.
  - Bandgap limited long wavelength cutoff at 1100 nm.
- Superconducting single-photon detector (SSPD)
  - E-beam patterned NbN light sensitive nanostructure operates at 2.0 °K with low darkcount rate and high sensitivity over a broad spectral range.
  - We have demonstrated with our detectors maximum count rate of 80 MHz and high quantum efficiency at 810 nm and 1550 nm wavelength.

Both OCT and QOCT measurement methods will have increased axial resolution if SSPDs are used for detection of the broadband light source.

TCOPRS-1 Two Channel SSPD Photon Registration System

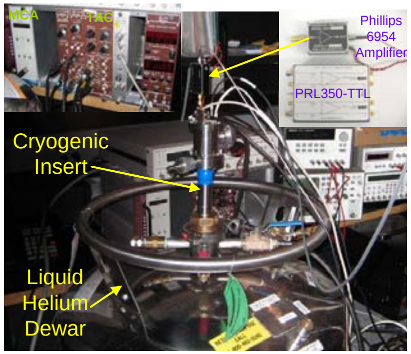


SSPD Device



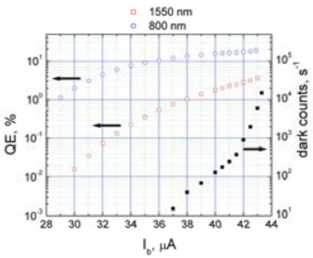
E-beam patterned NbN constitutes SSPD active area

SSPD Photon Registration System

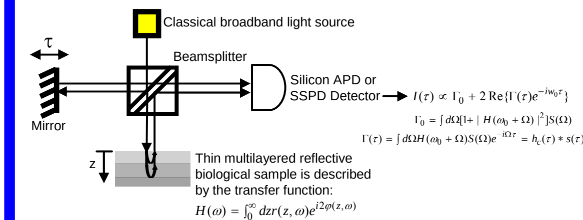


System Detection Efficiency

DE = 20% at 810 nm
DE = 3% at 1550 nm



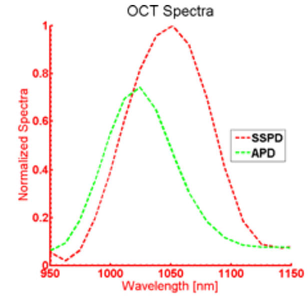
Optical Coherence Tomography (OCT) Measurement System using Michelson Interferometer



$$I(\tau) \propto \Gamma_0 + 2\,\mathrm{Re}\{\Gamma(\tau)e^{-i\omega_0\tau}\}$$
$$\Gamma_0 = \int d\Omega [1 + |H(\omega_0+\Omega)|^2] S(\Omega)$$
$$\Gamma(\tau) = \int d\Omega H(\omega_0+\Omega) S(\Omega) e^{-i\Omega\tau} = h_c(\tau) * s(\tau)$$
$$H(\omega) = \int_0^\infty dz\, r(z,\omega) e^{i2\varphi(z,\omega)}$$

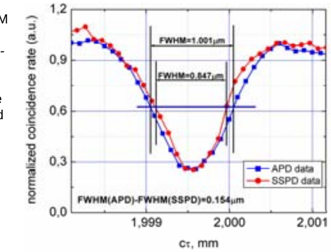
A central wavelength of 1064 nm is optimal for broadband OCT light sources to minimize scattering from the sample below 700 nm wavelengths while avoiding water absorption for wavelengths beyond 1600 nm.
- Broadband light was generated by the non-linear optical process of spontaneous parametric downconversion using a 532 nm monochromatic pump beam incident on a 1.5 mm thick BBO crystal aligned for non-collinear degenerate Type-I downconversion.
- Scans were made using APD and SSPD detectors and the experimental curves are shown below.

- At the optimal central 1064 nm wavelength, the SSPD captures more of the spectrum from downconversion than the APD.



- QOCT measurements using HOM interference at a beamsplitter also benefit from detecting broad-band light.
- By detecting broadband light, the width of the HOM dip is narrowed thereby enhancing the axial resolution of the measurement method.

As detected optical bandwidth increases the width of the coincidence dip narrows



Gordon-CenSSIS is a National Science Foundation Engineering Research Center supported in part by the Engineering Research Centers Program of the National Science Foundation (Award # EEC-9986821)