How to divert current research in classical optics to quantum avenues

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Content

- Introduction to the Applied Optics Group research
- 3 examples of potential avenues
- Conclusions

What is

Optical Coherence Tomography?

A low coherence interferometer + Lateral scanner

NOISE STUDEIS IN OPTICAL COHERNCE TOMOGRAPHY

Balanced versus non balanced OCT configurations

- Unbalanced configuration:

$$\langle \Delta I_p{}^2 \rangle = 2eB\langle I \rangle + (1 + \Pi^2)\frac{B}{\Delta v_{\mathrm{eff}}}\langle I \rangle^2 = \langle \Delta I_{\mathrm{sh}}{}^2 \rangle + \langle \Delta I_{\mathrm{ex}}{}^2 \rangle. \quad (1)$$

SN **EPN**

- Balanced configuration:

$$\langle \Delta I_p{}^2 \rangle = 2eB\langle I \rangle + 2(1 + \Pi^2)\frac{B}{\Delta v_{\mathrm{eff}}}\langle I_{\mathrm{FER}} \rangle \langle I_{\mathrm{REF}} \rangle = \langle \Delta I_{\mathrm{sh}}{}^2 \rangle + \langle \Delta I_{\mathrm{ex}}{}^2 \rangle. \quad (2)$$

When the optical power is larger than 2e optical bandwidth, EPN > SN

$$\langle \Delta I_p{}^2 \rangle = 2eB\langle I \rangle + (1 + \Pi^2)\frac{B}{\Delta v_{\text{eff}}}\langle I \rangle^2 = \langle \Delta I_{\text{sh}}{}^2 \rangle + \langle \Delta I_{\text{ex}}{}^2 \rangle. \quad (1)$$

SN

EPN

Quantum efficiency, in Silicon, a = 0.5 InGaAS , a = 1

e = 1.6 10 -19, Bandwidth 10 THz, Current = 1.6 μA

Silicon, P> 3.2 microwatts

InGaAS , P>1.6 microwatts

EPN dominates, Bose Einstein more than Poisson

Bunching of photons, g2 > 1

Photon statistics analyze the particle-like fluctuations in the number of photons within light, classifying light sources based on how photons arrive, such as:
Poissonian (lasers),
sub-Poissonian (single-photon emitters),
or super-Poissonian (thermal light).

These statistics are crucial for quantum optics, characterizing light-matter interaction through photon counting,
bunching,
or anti-bunching behavior

•Poissonian Statistics (Coherent Light): Photons are completely uncorrelated, typical of a well-stabilized laser.

•The variance equals the mean

Super-Poissonian Statistics (Thermal/Thermalized Light): Photons tend to "bunch" or arrive together, following Bose-Einstein statistics, such as light from a bulb or star.

Variance is greater than the mean. In OCT, the excess of noise in top of the mean is called excess photon noise.

Sub-Poissonian Statistics (Non-classical Light): Photons are anti-bunched, arriving more regularly than random, common in single-photon sources. Variance is less than the mean

Second-order Correlation $g^{(2)}(\tau)$: Quantifies photon correlations, with $g^{(2)}(0) < 1$ indicating anti-bunching (non-classical) and $g^{(2)}(0) > 1$ indicating bunching.

Applications: Essential for quantum communication, improving imaging resolution, and enhancing precision in quantum metrology

Photon Bunching: Photons tend to arrive in pairs or groups (e.g., in thermal light).

Antibunching: Photons arrive at separate intervals, characteristic of single-photon emitters.

Shot Noise: The fundamental limit of measurement noise caused by the discrete nature of photons.

Thermal sources, Tungsten lamp, Xenon lamp, SLDs, Supercontinuum source

Tunable very narrow band lasers

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The pioneering experiments by Hanbury-Brown and Twiss, and the subsequent development of the quantum theory of electromagnetic radiation by Glauber and Sudarshan, raised the interest in the question of photon statistics. It followed from their theories that states of the electromagnetic field which can only exist in a quantum treatment.

These nonclassical states show up in photon statistics through the phenomenon of antibunching. Later, further nonclassical states of the radiation field were found in the so-called squeezed fields, which are fields with phase-sensitive quantum fluctuations .

In order to achieve squeezing of laser radiation, various forms of nonlinear optical interactions can be used.

Noise of supercontinuum sources in spectral domain optical coherence tomography

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In this paper, we investigate the effect of pulse-to-pulse fluctuations of supercontinuum sources on the noise in spectral domain optical coherence tomography (OCT) images. The commonly quoted theoretical expression for the OCT noise is derived for a thermal light source, which is not suitable if a supercontinuum light source is used. We therefore propose a new, measurement-based OCT noise model that predicts the noise without any assumptions on the type of light source. We show that the predicted noise values are in excellent agreement with the measured values. The spectral correlation evaluated for the photodetected signal when using a supercontinuum determines the shape of the OCT noise floor, which must be taken into account when characterizing the sensitivity roll-off of a supercontinuum-based OCT system. The spectral correlations using both conventional supercontinuum sources and low-noise all-normal dispersion supercontinuum sources are investigated, and the fundamental physical effects that cause these correlations are discussed.

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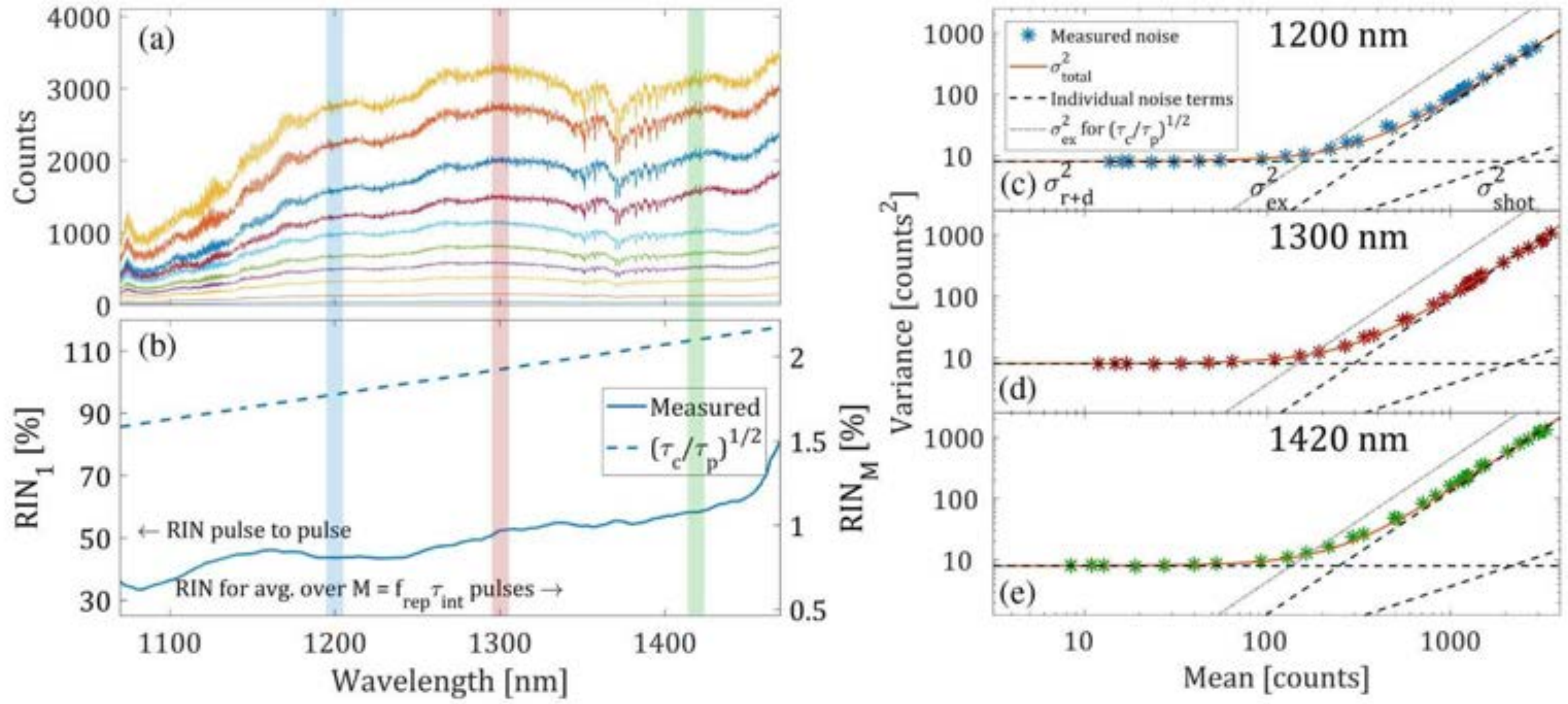

Fig. 2. (a) Mean spectra averaged over 1024 read-outs for selected power levels. (b) RIN calculated according to Eq. (2) using the series of s with the highest intensity in (a) and $(\tau_c/\tau_p)^{1/2}$ from Eq. (6). (c)–(e) show the variance in counts versus the mean counts at 1200 nm, 1300 nr 1420 nm, respectively, within the spectral colored bands in (a) and (b).

Limitation of the achievable signal-to-noise ratio in optical coherence tomography due to mismatch of the balanced receiver

Carla Carmelo Rosa and Adrian Gh. Podoleanu

Owing to the limited spectral response of the fiber directional coupler used in a balanced optical coherence tomography configuration, the spectra are different in the two outputs. This affects unfavorably operation of the balanced photodetector unit. Excess photon noise makes a larger contribution than a directional coupler with a flat spectral response. A theoretical model is developed that shows that an optimum set of parameters may be defined to maximize the achievable signal-to-noise ratio. The model leads to a redefinition of the effective noise bandwidth, which takes into account the nonflat response of the directional coupler used. The model also predicts a limitation on the signal-to-noise ratio even when the stray reflectances in the interferometer are brought to zero. © 2004 Optical Society of America
OCIS codes: 110.4500, 110.4280, 110.2350, 120.3890, 110.1650, 190.4160.

1. Introduction

Noise analysis is of prime importance in optimizing optical coherence tomography (OCT) setups to achieve a penetration depth that is as high as possible. The signal-to-noise ratio (SNR) analysis is based on elements developed in low-coherence interferometry. First attempts to maximize the SNR dealt with measuring the low reflectivity of waveguides cut at an angle in balanced configura-

lasers, when launched into photonic crystal fiber or tapered fiber, can exhibit linewidths in excess of 200 nm.[8] The high power means that other noise terms are much higher than shot noise. The large linewidth means that optical elements of a large bandwidth are required in the OCT setup.

It is known that the noise power is inversely proportional to the effective noise bandwidth of the optical source used in OCT, and the larger the

$$\langle \Delta i_{EPN}{}^2 \rangle = 2B\left\{\frac{\langle P_1\rangle\langle P_2\rangle}{\Delta\nu_0} + \frac{\langle P_1\rangle^2 + \langle P_2\rangle^2}{\Delta\nu_1}\right\}, \quad \text{(A28)}$$

where the effective frequencies are now given by

$$\Delta\nu_0{}^{-1} = \frac{4\times 64\int_0^\infty \gamma(\nu)[1-\gamma(\nu)]G_1(\nu)G_2(\nu)\mathrm{d}\nu}{2\times 4^2\int_0^\infty G_1(\nu)\mathrm{d}\nu\int_0^\infty G_2(\nu)\mathrm{d}\nu} = \frac{8\int_0^\infty \gamma(\nu)[1-\gamma(\nu)]G^2(\nu)\mathrm{d}\nu}{\left[\int_0^\infty G(\nu)\mathrm{d}\nu\right]^2}, \quad \text{(A29)}$$

$$\Delta\nu_1{}^{-1} = \frac{32\int_0^\infty [1-2\gamma(\nu)]^2 G_1{}^2(\nu)\mathrm{d}\nu}{2\times\left[4\int_0^\infty G_1(\nu)\mathrm{d}\nu\right]^2} = \frac{32\int_0^\infty [1-2\gamma(\nu)]^2 G_2{}^2(\nu)\mathrm{d}\nu}{2\times\left[4\int_0^\infty G_2(\nu)\mathrm{d}\nu\right]^2} = \frac{\int_0^\infty [1-2\gamma(\nu)]^2 G^2(\nu)\mathrm{d}\nu}{\left[\int_0^\infty G(\nu)\mathrm{d}\nu\right]^2}. \quad \text{(A30)}$$

Evaluation of effective noise bandwidth for broadband optical coherence tomography operation

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Key noise parameters in optical coherence tomography (OCT) systems employing splitters with a nonflat spectral response are evaluated using a supercontinuum fiber laser source with a spectrum of 450 nm–1700 nm and a time domain OCT architecture based on 1300 nm fiber splitters. The spectral behavior of the splitter leading to balanced detection is measured over a range of 300 nm. Because of spectrally different signals at the balanced detector input a residual excess photon noise term results. A rigorous treatment of this noise term [Appl. Opt. **43**, 4802 (2004)] introduced two new quantities that take into account the spectral properties of the coupler. In this report, we have evaluated these two noise bandwidth quantities and comparatively assessed the noise behavior predicted by the classical theory with the theory based on the two new noise bandwidths. We show that under certain operating parameters, the additional excess photon noise is twice that predicted for a coupler with a flat spectral response.

OCIS codes: 120.0120, 230.0230, 030.4280, 060.2270, 060.2430, 110.4500.

itten as a sum of two terms as in

$$\langle \Delta i^2_{\mathrm{EPN}} \rangle = 2\alpha^2 B \left\{ \frac{\langle P_1 \rangle \langle P_2 \rangle}{\Delta \nu_0} + \frac{\langle P_1 \rangle^2 + \langle P_2 \rangle^2}{\Delta \nu_1} \right\}$$

$$\Delta \nu^{-1} = 2 \frac{\int_0^\infty G^2(\nu) \mathrm{d}\nu}{\left[\int_0^\infty G(\nu) \mathrm{d}\nu \right]^2}.$$

$$\langle \Delta i^2_{\mathrm{EPN}} \rangle = 2\alpha^2 B \left\{ \frac{\langle P_1 \rangle \langle P_2 \rangle}{\Delta \nu} \right\}.$$

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Statistics of the depth-scan photocurrent in time-domain optical coherence tomography

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We derive the time-variant second-order statistics of the depth-scan photocurrent in time-domain optical coherence tomography (TD-OCT) systems using polarized thermal light sources and superluminescent diodes (SLDs). Since the asymptotic-joint-probability-distribution function (JPDF) of the photocurrent due to polarized thermal light is Gaussian and the signal-noise-ratio in TD-OCT is typically high (>80 dB), the JPDF of the depth-scan photocurrent could be approximated as a Gaussian random process that is completely deter-

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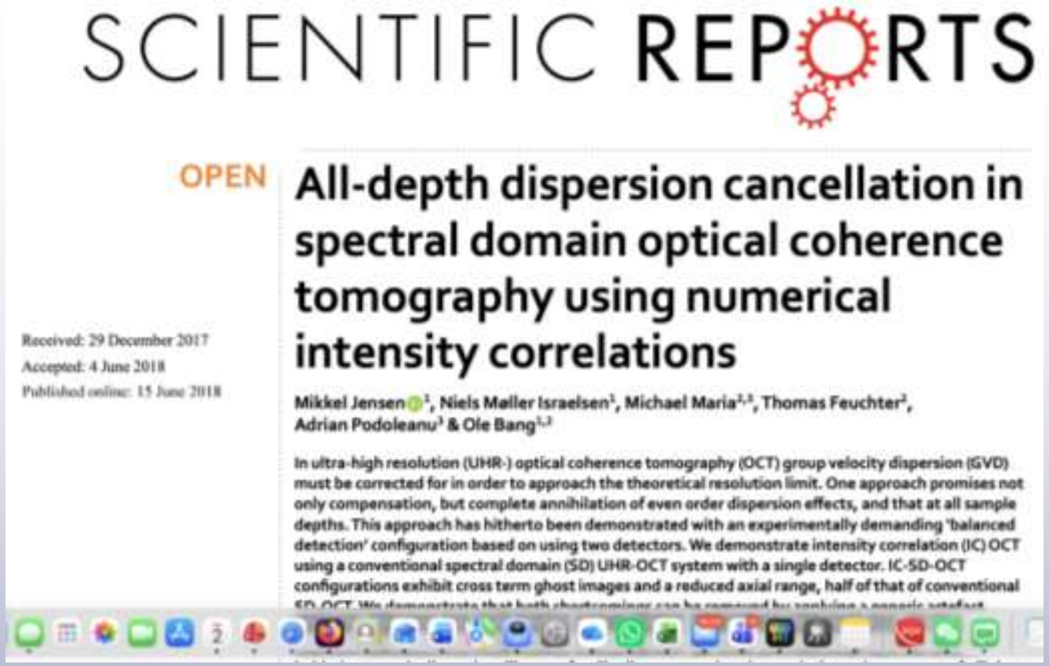

SCIENTIFIC REPORTS

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All-depth dispersion cancellation in spectral domain optical coherence tomography using numerical intensity correlations

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In ultra-high resolution (UHR-) optical coherence tomography (OCT) group velocity dispersion (GVD) must be corrected for in order to approach the theoretical resolution limit. One approach promises not only compensation, but complete annihilation of even order dispersion effects, and that at all sample depths. This approach has hitherto been demonstrated with an experimentally demanding 'balanced detection' configuration based on using two detectors. We demonstrate intensity correlation (IC) OCT using a conventional spectral domain (SD) UHR-OCT system with a single detector. IC-SD-OCT configurations exhibit cross term ghost images and a reduced axial range, half of that of conventional

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in contrast with its classical counterpart,

QOCT provides resolution enhancement and dispersion cancellation.

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Interference effects in quantum-optical coherence tomography using spectrally engineered photon pairs

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Optical-coherence tomography (OCT) is a technique that employs light in order to measure the internal structure of semitransparent, e.g. biological, samples. It is based on the interference pattern of low-coherence light. Quantum-OCT (QOCT), instead, employs the correlation properties of entangled photon pairs, for example, generated by the process of spontaneous parametric downconversion (SPDC). The usual QOCT scheme uses photon pairs characterised by a joint-spectral amplitude with strict spectral anti-correlations. It has been shown that, in contrast with its classical counterpart, QOCT provides resolution enhancement and dispersion cancellation. In this paper, we revisit the theory of QOCT and extend the theoretical model so as to include photon pairs with arbitrary spectral correlations. We present experimental results that complement the theory and explain the physical underpinnings appearing in the interference pattern. In our experiment, we utilize a pump for the SPDC process ranging from continuous wave to pulsed in the femtosecond regime, and show that cross-correlation interference effects appearing for each pair of layers may be directly suppressed for a sufficiently large pump bandwidth. Our results provide insights and strategies that could guide practical implementations of QOCT.

SEQUOIA is a Horizon Europe project to research the development of optical coherence tomography (OCT) using quantum techniques. OCT is a key imaging technology, allowing non-contact high resolution 3D imaging which has been successfully used for decades in fields from medicine to industrial testing.

What could QOCT offer?

State-of-the-art OCT seems to have reached its limit at ~1 micron axial resolution. Theory suggests that quantum OCT (QOCT) could half this to 0.5 microns and greatly reduce dispersion. In addition, control of the quantum property of orbital angular momentum (OAM) reduces noise and improves edge and surface profile definition and discrimination of chiral objects.

SEQUOIA

No.	Short name	Name	Country
1	NKT	NKT PHOTONICS A/S	DK
2	PTB	PHYSIKALISCH-TECHNISCHE BUNDESANSTALT	DE
3	MPD	MICRO PHOTON DEVICES SRL	IT
4	NOR	NORBLIS APS	DE
5	TUD	TECHNISCHE UNIVERSITEIT DELFT	NL
6	DTU	DANMARKS TEKNISKE UNIVERSITET	DK
7	NCU	UNIWERSYTET MIKOLAJA KOPERNIKA W TORUNIU	PL
8	UPV	UNIVERSITAT POLITECNICA DE VALENCIA	ES
9	ARD	ARDITEC	FR
10	VIV	VIVID COMPONENTS GERMANY UG	DE
11	WWU	WESTFAELISCHE WILHELMS-UNIVERSITAET MUENSTER	DE

Modern OCT Technologies are based on encoding path onto the optical spectrum:

- **Spectrometer based (interferometer + spectrometer) SPECTRAL OCT**

- **Tuning laser based (interferometer + tunable laser) SWEPT SOURCE OCT**

COHERENCE GATING

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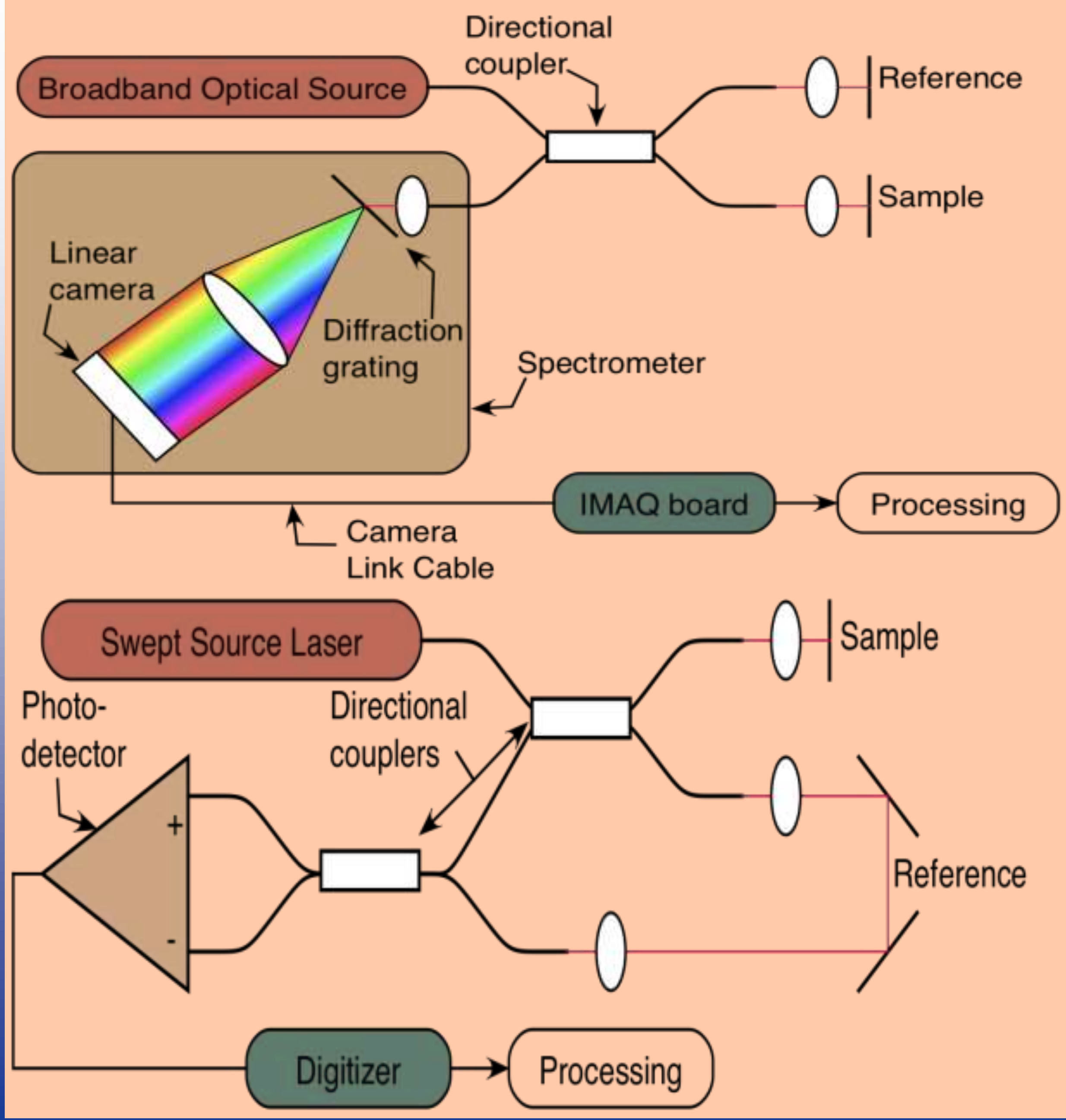
Spectral Domain-OCT

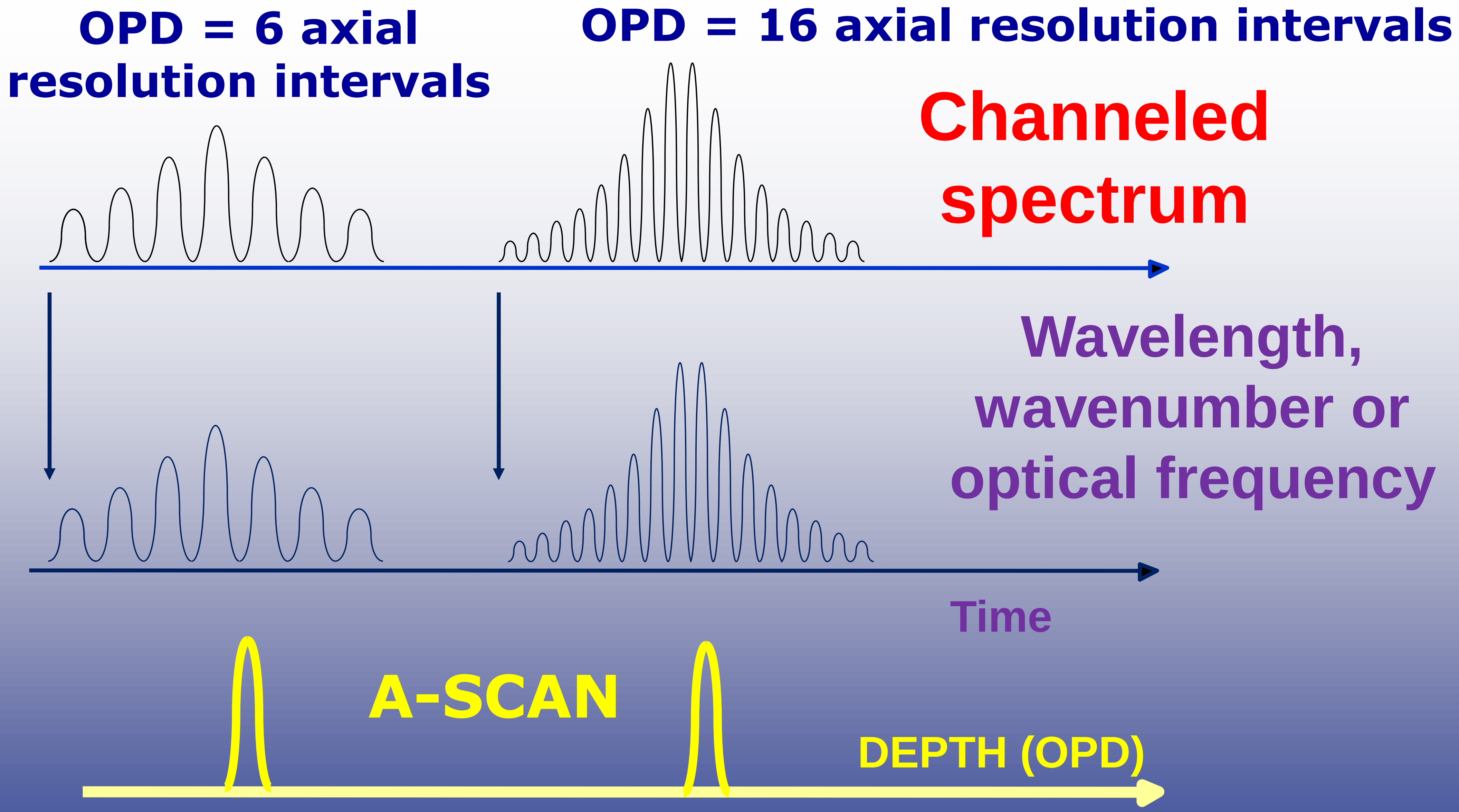
Generic Camera based (Spectral) OCT system



BROADBAND (High axial resolution) MAX. 300 KHz

Generic Swept Source (Swept source) OCT system

ULTRA HIGH SPEED Over 100 MHz



A FOURIER TRANSFORM OF THE ELECTRICAL SIGNAL DELIVERED BY A SPECTROMETER OR A PHOTODETECTOR LEADS TO A REFLECTIVITY PROFILE IN DEPTH: A-SCAN

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This detection scheme is based on the concept of dispersive Fourier transformation, where a fiber introduces a wavelength-dependent time delay measured by a single-pixel detector, usually a high-speed photoreceiver.

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Optics Letters

Quantum-inspired detection for spectral domain optical coherence tomography

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Intensity levels allowed by safety standards (ICNIRP or ANSI) limit the amount of light that can be used in a clinical setting to image highly scattering or absorptive tissues with optical coherence tomography (OCT). To achieve high-sensitivity imaging at low intensity levels, we adapt

[4]. It has already been used in OCT to time-stretch light from a supercontinuum source [5] and Ti:sapphire laser [6] at the input of the interferometer and perform swept-source-like OCT at axial scan rates of up to 90 MHz.

Here, we propose a spectral detection scheme, which is

Here, a fast superconducting single-photon detector SSPD as a single-pixel detector and obtain images of a glass stack and a slice of onion at the intensity levels of the order of 10 pW.

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(Scontel) whose detection range is 350–2300 nm and

with a peak quantum efficiency approximately 65% at 1550 nm

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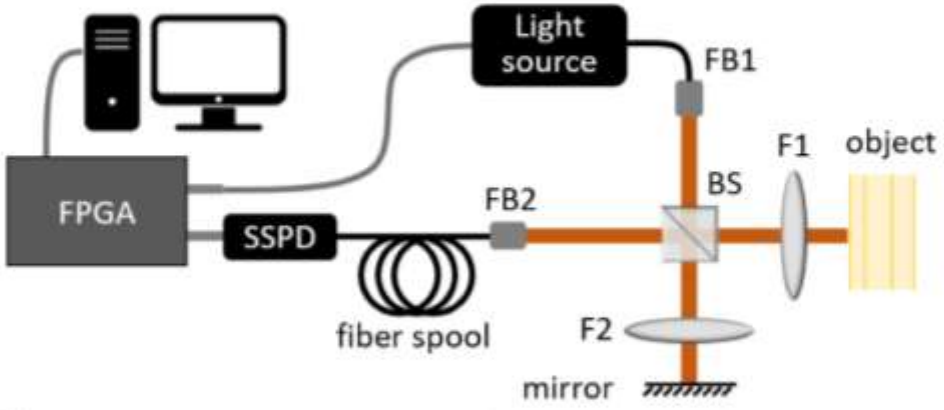

Fig. 1. Experimental setup. The light source is a pulsed laser attenuated to a level of single photon per pulse. Pulses are coupled to a fiber (FB1) and propagate in a Linnik–Michelson interferometer. The input wave packet (pulse) is then split at a beam splitter (BS) into two arms. In the object arm, one wave packet interacts with the object and acquires an additional phase; in the reference arm, the other one is reflected from the mirror. They both overlap at the beam splitter, and the output is coupled to a single-mode fiber spool using a fiber coupler FB2. The time-resolving superconducting single-photon detector (SSPD) together with the long dispersive fiber spool work as a spectrometer. Time reference is provided by a photodiode signal from the light source. The data are collected using an FPGA time-stamping electronics. F1 and F2, lenses.

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CONCLUSIONS

AOG can be engaged in Quantum research, via:

1. analysis of photon statistics:

2. Spectral OCT using attenuation of light until single photons are photodetected and spectrum modulation is obtained from time of flight statistics; missing superconducting SPD

3. QOCT using entangled states: missing SPONTANOEUS PARAMETRIC DOWN CONVERSION crystal.