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Optical Coherence Tomography based on Intensity Correlations of Quasi-Thermal Light

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Abstract: We show theoretically that the longitudinal resolution of conventional optical coherence tomography can be improved by a factor of $\sqrt{2}$ when a two-photon (as opposed to a single-photon) sensitive detector is used, and we present preliminary supporting results.

OCIS codes: (030.1670) Coherent optical effects; (040.5250) Photomultipliers; (170.4500) Optical coherence tomography

Optical coherence tomography (OCT) is a non-invasive three-dimensional interferometric imaging technique [1, 2, and references therein]. It is used to acquire high-resolution cross-sectional images through inhomogeneous samples and has found numerous applications in a number of different fields [3, 4]. In conventional time-domain OCT, a broadband light source (with a short coherence length) is split by a beam splitter. The signal beam is reflected by the sample under study while the reference beam is simply reflected by a mirror on a translation stage. The back-reflected signal and reference beams recombine and interfere on a beam splitter and are then detected. One of the important parameters of OCT is its spatial resolution. The longitudinal resolution is determined by the coherence length of the light source that is used, and for a Gaussian broadband pulse with a spectral width $\Delta\lambda$ the longitudinal resolution is given by $\Delta z = l_c/2 = (2\ln 2/\pi)(\bar{\lambda}^2/\Delta\lambda)$, where l_c, $\bar{\lambda}$, $\Delta\lambda$ are the coherence length, the mean wavelength, and the spectral width of the source respectively.

Here we consider the possibility of improving the longitudinal resolution of OCT by using a two-photon-absorption (TPA) based detection scheme and using classical broadband light. Note that a factor of two improvement in the axial resolution, in addition to even-order dispersion cancellation, can be obtained if one uses entangled photons from spontaneous parametric down conversion (SPDC), as has been shown theoretically and experimentally [5, 6]. These improvements were attributed to the quantum nature of the source, although a recent theoretical study has shown that these same features can be obtained using classical (phase-conjugate) light sources [7].

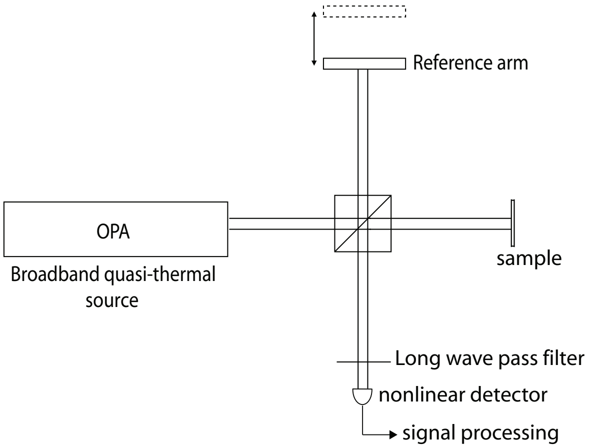

Fig. 1. Schematics of the experimental setup for the two-photon-absorption based OCT. The nonlinear detector is a two-photon-sensitive photomultiplier tube.

Conventional OCT measures Young's interference fringes, whose visibility can be quantified in terms of the complex temporal coherence function $g^{(1)}(\tau) = \langle E_r^*(t+\tau)E_s(t)\rangle$, where τ is the delay (time of flight) between the reference and signal arms, and E_r and E_s are the reference and sample fields, respectively. In time-domain OCT, the interference signal $I(\tau)$ is proportional to $\mathrm{Re}\{g^{(1)}(\tau)\}$. Instead, we have performed OCT using the intensity fluctuations

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of a quasi-thermal light source, which are described by the intensity correlation function $g^{(2)}(\tau) = \langle I_r(t+\tau) I_s(t) \rangle$, where $I_r(I_s)$ is the intensity of the field in the reference (sample) arm. For thermal light, it is well known that $g^{(2)}(\tau) = 1 + \left| g^{(1)}(\tau) \right|^2$. Because of the square, the longitudinal resolution of the intensity-correlation-based-OCT is $\sqrt{2}$ times better than that of conventional OCT.

Our experimental configuration is shown in Fig. 1. We used the output from a noise-seeded optical parametric amplifier (OPA) having a Gaussian spectrum with a central wavelength around 1500 nm as our light source. The two-photon-absorption signal resulting from the back-reflected light from the sample and the reference arms was detected by a photomultiplier tube (PMT). The sample used was a 140 μm thick microscope cover slip. A long-wave-pass filter (cut-on wavelength of 1300 nm) was placed in front of the PMT to eliminate single-photon absorption. Recently, ultra-sensitive and high-dynamic-range two-photon absorption has been shown experimental using single photon counting silicon avalanche photodiodes (SAPDs) and GaAs photomultiplier tubes (PMTs) [8, 9]. Compared to second-harmonic [10] or sum-frequency [11] based OCT systems, the detection process in two-photon-absorption based OCT is extremely simple.

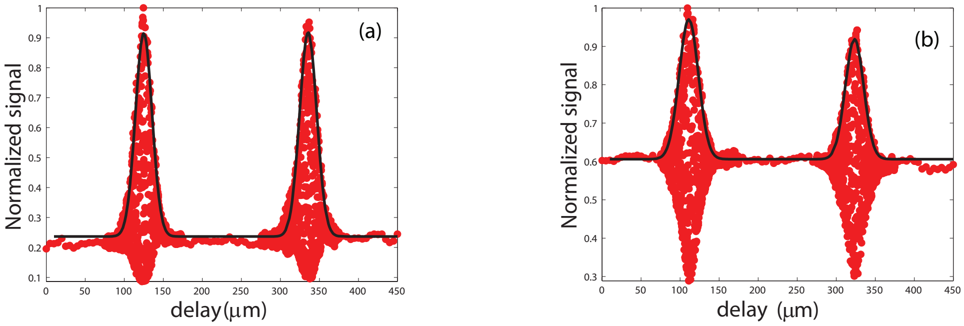

Fig. 2. (a) Intensity-correlation based and (b) conventional OCT of a microscope cover slip.

The results of the experiment on two-photon-absorption based OCT are shown in Fig. 2(a). The twin peaks result from back reflections from the front and back sides of the sample. For comparison purposes, we also show the results for conventional OCT (see Fig. 2(b)). The full width at half-maximum (FWHM) of the first peak for the two-photon and conventional OCT are 25.1 and 29.1 μm respectively. The improvement in resolution is thus a factor of 1.16. The improvement for the second peak is only a factor of 1.07. We are currently investigating the reason why the resolution improvement is less than the theoretical value of $\sqrt{2}$. Possible explanations include a deviation from Gaussian statistics of our source and dispersive effects within the glass sample.

In summary, we have shown theoretically and experimentally that the longitudinal resolution of OCT can be improved by basing the measurement on intensity correlations of the optical field and that this method can be implemented by simply replacing the detector of a conventional OCT setup by a two-photon-absorbing detector.

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