Shot noise detection of the ultrasound tagged photon in ultrasound-modulated optical imaging.

M. Gross and P. Goy
Laboratoire Kastler Brossel
Departement de Physique de l'Ecole Normale Superieure
24, rue Lhomond F-75231 Paris cedex 05, France

M. Al-Koussa
Physical Department. Damascuss University. Damascuss. Syria
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We propose a new detection method for ultrasound-modulated optical tomography, which allows to perform, using a CCD camera,a parallel speckle detection with an optimum shot noise sensitivity. Moreover,we show that making use of a spatial filter system allows us to fully filter off the speckle decorrelation noise. This method being confirmed by a test experiment.

Ultrasound-modulated optical tomography is a new non invasive and non ionizing biological tissues imaging technique. In this technology an ultrasonic wave is focused into a diffusing medium that scatters the incident optical beam. Due to the ultrasonic vibration of the medium, some of the diffused photons are shifted in frequency on an ultrasonic sideband. These are the so called tagged photons [1], which can be selected to perform imaging. The advantage of the method is its combination of optical contrast and ultrasonic resolution.

Many groups have worked on that field. Marks et al. [2] investigated the modulation of light in homogeneous scattering media with pulsed ultrasound. Wang et al. [3] performed ultrasound modulated optical tomography in scattering media. Lev and al. made scattering media study in the reflection configuration [4]. Wang and Ku [5] developed a frequency chirp technique to obtain scalable imaging resolution along the ultrasonic axis by a 1D Fourier transform. Leveque and al. [1] performed parallel detection of multiple speckles on a video camera and demonstrated an improvement of the detection signal to noise ratio on 1D images of biological tissues. This parallel speckle detection (PSD) is considered to be "so far, the most efficient technique for ultrasound modulated optical tomography" [10], and is now extensively used in the field, combined [6, 7, 8] or not [9, 10] with the frequency chirp technique.

By analysing the PSD detection process, we show nevertheless that the PSD sensitivity is far from optimum. Moreover, as noticed by Leveque et al. [1], PSD is sensitive to the "decorrelation of the speckle pattern, which reduces the signal and increases the noise" (see also [9, 10]). In this letter, we propose to solve these two problems by adapting our heterodyne technique [11] to PSD, i.e. by performing heterodyne PSD (or HPSD). In HPSD, the LO beam passes outside the sample. The LO field is thus much larger, and the detection sensitivity is much better. It is then possible to reach the optimum shot noise limit. On the other side, the HPSD LO beam is a plane wave. One can then separate the k-space components of the detected field. By using a proper optical arrangement, which reduces the k-space extend, we can fully filter off the decorrelation noise.

Let us analyse the PSD detection process. The focus point of the ultrasonic wave can be considered as a source of ultrasonic tagged photons, which are detected coherently by heterodyne detection. For a single pixel detector, the coherent detection selects the field within the spatial mode that fits with the pixel considered as an antenna. The collection efficiency can be characterized by its "optical etendue", defined as the product of the emitting area by the emission solid angle, which is the two-dimensional generalization of the usual Lagrange invariant of geometrical optics. Due to diffraction, for one single mode, the etendue is about λ^2. For a N pixels detector, since each pixel is able to perform coherent detection within its mode, the etendue is about $N\lambda^2$. On the emission side, the etendue is about πS, since each point of the sample external surface of area S diffuses photons in all outgoing directions (solid angle $\sim \pi$). The collection efficiency η, which is the ratio of the etendues is very low : $\eta \approx N\lambda^2/\pi S$. For a $2cm \times 2cm \times 2cm$ diffusing sample, $\eta \approx 10^{-10}$ for 1 pixel, and $\eta \approx 10^{-4}$ for $N = 10^6$ pixels. The meaning of η is quite simple. Forget et al. [8] explained that, in order to detect the speckles efficiently, it is necessary to "position ... the camera ... to match the size of a grain (of speckle) with the size of a pixel". The camera must be thus placed quite far away from the sample, and the photons, which are diffused by the sample in all directions, have a probability $\sim \eta$ to reach the CCD.

On the CCD surface, each photon is converted into a photo electron with a probability equal to the CCD quantum efficiency Q. In the optimal case, the heterodyne detection noise is related to the shot noise of the local oscillator. Accounting of the heterodyne gain, this noise corresponds to 1 photo electron per pixel during the measurement time [12] (since both shot noise and heterodyne gain are proportional to the LO amplitude). PSD is far from this optimum for two reasons. Firstly, the PSD LO beam is obtained by amplitude modulation of the main laser. The noise is thus related to the total intensity (car-

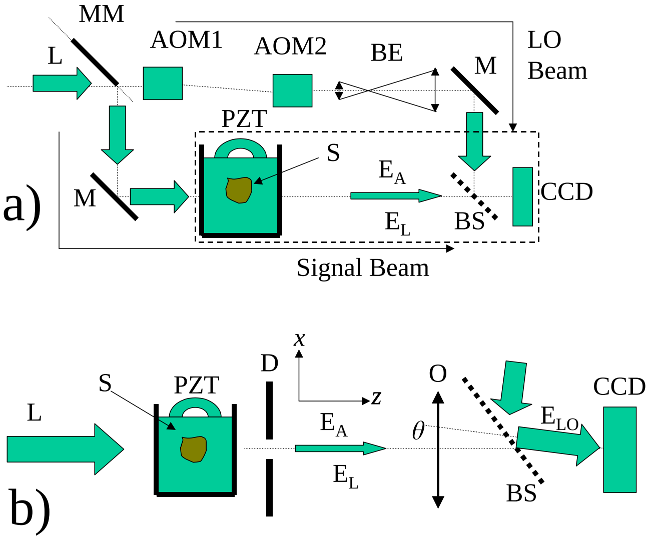

FIG. 1: a) Experimental setup. L: main laser, MM: moving mirror, AOM1 et AOM2: acousto optic modulators, BE: beam expander, M: mirror, PZT: ultrasonic transducer, S: sample, BS: beam splitter and CCD: CCD camera. b) Spatial filter system. E_L : beam diffused by the sample, E_A: tagged photon beam, E_{LO}: LO beam, S: sample, D: diaphragm with rectangular aperture, O: lens and CCD: CCD camera.

rier + sideband), while the gain depends on the sideband only. Secondly, the LO beam passes through the sample and is diffused in many modes, which do not match with the mode of the detector. Neglecting absorbtion, and back reflection (which are also present), one looses here a factor η on the LO useful intensity. The LO intensity is then too small to get enough heterodyne gain for efficient detection.

To improve the sensitivity, we propose to perform HPSD with the Fig.1 a) setup. This setup is similar to the Toida et al. [13] one, but with a CCD camera in place of the mono pixel detector [11]. The main laser L is a $\lambda = 850nm$, $20mW$ Newport 2010M laser followed by an optical isolator. The mirror MM splits the laser into two beams. The low intensity LO beam is shifted in frequency by Δf by the 2 acousto optic modulators AOM1 (80 MHz) and AOM2 (80 MHz $+\Delta f$). It is expanded by BE ($20\times$) in order to get a plane wave (diameter 1.5 cm) larger than the CCD area. On the other side, the high intensity signal beam irradiates the sample in a $13cm$ width water vessel.

The PZT ultrasonic transducer (Parametrics: $f_a = 2.2MHz$, diameter $35mm$, focal length: $50mm$) generates an ultrasonic wave that is focused into the sample. The signal beam that is diffused toward the CCD (z direction) at both the optical carrier frequency (field E_L) and at the ultrasonic sidebands (field E_A) interferes with the LO beam (beam splitter BS) on the CCD camera. Accounting of the optical isolator, BS and water losses, the measured laser power reaching the sample is 2.5 mW.

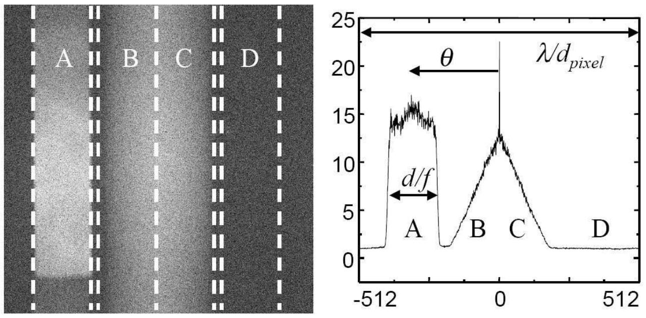

FIG. 2: Left hand side: k-space tagged photon intensity $\tilde{I}(k_x, k_y)$. Right hand side: 1D plot of $\mathcal{I}(k_x)$. Vertical scale is normalized with shot noise (noise in D zone).

The CCD camera (PCO Pixelfly: 1280×1024 pixels of $6.7 \times 6.7\mu m$, $f_c = 12.5\ Hz$, $12bit$ digital, 2.2% measured quantum efficiency at $850nm$) records in real time the interference pattern on a PC computer. MM is adjusted to get an average of 2000 shots per pixels (1/2 full scale) for the LO beam, which remains ever much larger than the signal beam that is strongly attenuated and diffused by the sample. To measure the tagged photons field complex amplitude, we have chosen $\Delta f = f_a + f_c/4$.

According to the camera gain given by PCO (2.2 electrons for 1 LSB: low significant bit), we have measured, without signal beam, a noise corresponding to 1 signal photo electron per pixel (within 10%). Our HPSD setup performs thus a optimal, shot noise limited, heterodyne detection.

Consider now the speckle decorrelation noise. We have first to notice that HPSD is less sensitive to this noise than PSD: the noise is the same in both cases, but the signal is larger in HPSD, because the heterodyne gain is higher. We will see now how to filter off this noise. The setup (Fig.1a dashed rectangle) is modified as shown on Fig.1b. The lens O (focal length $f = 250\ mm$) and the diaphragm D ($\simeq 25 \times 5\ mm$ located in the O focal plane) collimate the field diffused by the sample (E_L and E_A), and reduce the k-space extend in the k_x direction. By this way, the speckle grains are enlarged in x and extended over several CCD pixels. Moreover, the LO beam is slightly tilted (in the x, z plane) making a angle θ with the z direction, so that the tagged photons versus LO beam interference exhibit vertical fringes (along y). It is then possible to separate the tagged photon signal (fringes) from the decorrelation noise (no fringes) by a simple Fourier calculation.

To illustrate this point, we have studied the field diffused by a 3.5 cm phantom sample with a 15 Vpp (Volt peak to peak) $2MHz$ excitation of the PZT. From 4 successive CCD images signal I_1,I_2...I_4 (where I_i is proportional to $I = |E|^2$) we have calculated the 4-phases complex signal $S = (I_1 - I_3) + j.(I_2 - I_4)$ where $j^2 = -1$. We have calculated $\tilde{S}(k_x, k_y) = FFT\,(S(x, y))$ by making a 1024×1024 truncation over the $S(x, y)$ data mea-

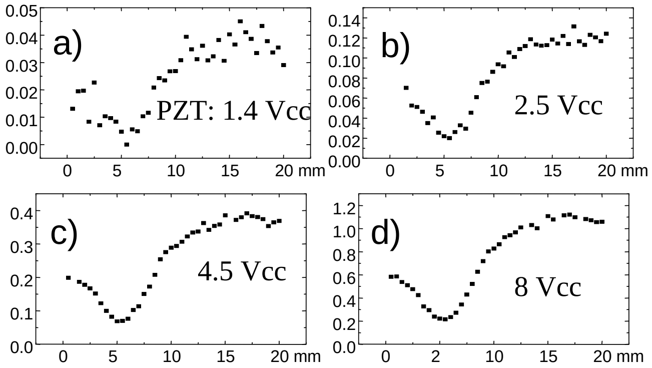

FIG. 3: $\mathcal{I}_{AD}/\mathcal{I}_D$ as a function of the sample position for different ultrasonic excitation: 1.4 (a), 2.5 (b) , 4.5 (c), and 8 (d) Vpp on the PZT transductor. Laser equivalent power $2.5mW$. CCD quantum efficiency 2.2%. Measurement time $0.96s$ per point.

sured on the CCD (1280 × 1024) followed by a Fast Fourier Transform (FFT). The $\tilde{I}(k_x, k_y) = |\tilde{S}|^2$ matrix (1024 × 1024) is imaged on Fig.2 (left hand side) with logarithmic arbitrary gray scale. The sum over the column $\mathcal{I}(k_x) = \sum_{k_y} \tilde{I}((k_x, k_y))$ is also plotted (right hand side). One can separate here the contributions of the product terms of $I = E.E^*$ (where $E = E_{LO} + E_L + E_A$: E_{LO} being the LO field, E_L the field diffused at the carrier frequency and E_A the ultrasonic sideband tagged photons field). The tagged photon heterodyne term $E_{LO}.{E_A}^*$ evolves fast is space (fringes). It yields to the A rectangular bright zone for $\tilde{I}$, and to the A peak for $\mathcal{I}$ (angular width d/f, angular offset θ). The speckle decorrelation noise corresponds to the fluctuations on the $E_L.{E_L}^*$ term, which evolves slowly in space (no fringes). It yields to the bright zone in the center of the k-space image ($k_x \approx k_y \approx 0$), and to the triangular (convolution of 2 rectangles) peak in the plot (B and C). The fluctuations of the $E_{LO}.{E_{LO}}^*$ term yield to the very narrow peak visible on the 1D plot ($k_x = 0$). The other terms give very small contributions. For example, the $E_{LO}.{E_L}^*$ and $E_L.{E_A}^*$ terms evolve fast in time ($2MHz$) and are filter off by the CCD. As seen, a proper choice of the θ tilt allows us to separate in the k-space the tagged photon (A) and the speckle decorrelation noise (B and C) contributions to signal. For control purpose, we have considered the zone D, symmetric to A, where the shot noise only contributes.

We have performed a test experiment with the diffusing PSD sample already studied in [8] (see Fig.2 of [8]). In the sample, a $4mm$ diameter vertical (x direction) cylindric black inked zone absorbing the light. The sample is slightly compressed in the z direction and its width is $15mm$. To get a pertinent information we have summed $\tilde{I}(k_x, k_y)$ in the A (tagged photons + shot noise) and D (shot noise alone) zones: $\mathcal{I}_A = \sum_{k_x \in A} \mathcal{I}(k_x)$. We have calculated $\mathcal{I}_{AD} = \mathcal{I}_A - \mathcal{I}_D$ (tagged photons alone), and plotted $\mathcal{I}_{AD}/\mathcal{I}_D$ (tagged photon signal normalized with respect to shot noise). The Fig.3a, b, c and d show the plots obtained by moving the sample ($x = 0...20mm$ with $0.5mm$ steps) with 1.4, 2.5, 4.5, and 8 Vpp on the PZT respectively. Each point corresponds to 3 successive acquisitions of 4 images ($0.96s$). The black inked zone near $x = 5mm$ is clearly seen. As seen, outside the absorbing zone, $\mathcal{I}_{AD}/\mathcal{I}_D$ ($\simeq$ 0.035, 0.12, 0.37 and 1.2) is proportional to the square of the PZT applied voltage (i.e. to the ultrasonic power). By making $\Delta f = f_c/4$, with no ultrasonic wave, we have measured the carrier field E_L signal $\mathcal{I}_{AD}/\mathcal{I}_D \simeq 700$. The maximum ($8Vpp$) ultrasonic conversion factor is then 1.7×10^{-3}. As seen, curves c and d exhibit roughly the same S/N (signal/noise) ratio. The technical noise is then the limiting factor. On the other side, on curves a and b, the tagged photon signal is lower and the S/N goes down. The shot noise becomes thus the limiting factor. With 2 zones (A and D), with $n_{pix} \approx 2.10^5$ pixels per zone, one expects for $\mathcal{I}_{AD}/\mathcal{I}_D$ a shot noise of $\pm\sqrt{2/n_{pix}} = \pm 0.003$, in good agreement with the noise observed on curve a. This shows that the sensitivity obtained by our technique is truly limited by shot noise.

As seen above, our HPSD detection method presents many advantages for ultrasound-modulated tomography. It allows to perform parallel speckle detection of the ultrasound-modulated component with an optimum shot noise sensitivity, and to fully filter off the speckle decorrelation noise. At the end, many controls are possible on the data. One can measure , for example, both the ultrasound-modulated signal (zone A), the shot noise (zone D) and the speckle decorrelation noise (zone B and C).

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