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# Speckle decorrelation in Ultrasound-modulated optical tomography made by heterodyne holography

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Ultrasound-modulated optical tomography (UOT) is a technique that images optical contrast deep inside scattering media. Heterodyne holography is a promising tool able to detect the UOT tagged photons with high efficiency. In this work, we describe theoretically the detection of the tagged photon in heterodyne holography based UOT, show how to filter the untagged photon discuss, and discuss the effect of speckle decorrelation. We show that optimal detection sensitivity can obtain, if the frame exposure time is of the order of the decorrelation time.

OCIS codes: 170.1650, 170.3660, 290.7050, 090.0090, 170.7050

Light scattering prevents optical imaging from achieving high resolution inside scattering media deeper than about 1 mm in tissue. Ultrasound-modulated optical tomography (UOT)[1, 2] also called acousto-optic imaging [3], has been developed to overcome this limit by combining ultrasonically defined spatial resolution and optical contrast (i.e. sensitivity to the bulk optical properties like absorption). One of the purpose of the technique is to use the optical contrast to detect breast tumors that cannot be seen with ultrasound, because the ultrasonic contrast is too low. In an UOT experiment, the light scattered through a diffusing sample crosses an ultrasonic beam, and, due to the acousto-optic effect, undergoes a frequency shift equal to the ultrasonic frequency [4, 5]. By detecting the frequency-shifted photons, called tagged photons, and by plotting their weight as a function of the ultrasonic beam geometry, 2D or 3D images of the sample can then be obtained with ultrasonic spatial resolution.

Various methods have been developed to detect the very low tagged photons signal out of a large background of untagged photons [2, 3]. First experiments use single-pixel detector and detection of the tagged photon AC modulation at the ultrasonic frequency [4, 6, 7]. Since each speckle grain oscillates with a different phase, the single pixel method detects, with a good efficiency, no more than one speckle grain. This severely limits the detection etendue (defined as the product of the detection area and the acceptance solid angle). To increase the detection etendue without reducing the modulation depth, three types of methods have been developed. The first type relies on incoherent detection with a narrow spectral filter ( $\sim$ MHz) that filter out the untagged light. A large-area single-pixel detector can be used. Examples include Fabry-Perot interferometers [8–10] and spectral-hole burning [11–13] based methods. These techniques require bulky and expensive equipment. The second and third types of method use interferences and are thus sensitive to the signal phase decorrelation due to the living tissue inner motions, and to the corresponding Doppler broadening. For breast, this broadening is 1.5 kHz [14]. The second method is based on a photorefractive crystal, which records the volume hologram of the sample scat-

tered field. This hologram can be then used to generate a diffracted field able to interfere with the scattered field on a large area single-pixel detector [15–18]. The method has a large optical etendue ( $\sim 10^8$  speckle), but is somewhat sensitive to decorrelation, since the response time of the crystal is usually much longer than the speckle correlation. Promising results are expected with Sn<sub>2</sub>P<sub>2</sub>S<sub>6</sub>:Te and Nd:YVO<sub>4</sub> crystals, because of their short response times [19, 20].

The third type of method uses a pixel array, i.e., a camera, to detect the UOT tagged photons [21–24]. The optical etendue ( $\sim 10^5$  to  $10^6$  speckle) is then related to the number of pixels of the camera. The camera method has been improved by adapting the heterodyne holography technique [25] to the tagged photon detection [26]. By tuning the LO beam frequency near the ultrasonic sideband, and by using a properly adjusted spatial filter, the tagged photons were detected selectively. Moreover, optimal noise detection was obtained, since shot noise is the dominant noise in heterodyne holography [27–29]. The reference [26] experiment was nevertheless performed with a phantom sample, whose decorrelation is low, and it is generally considered that the heterodyne holography UOT method cannot be used with a living sample, whose speckle decorrelation time  $\tau_c$  is shorter than the time needed to record four camera frames (where  $\tau_c = 0.1$  ms for the light scattered "in vivo" through a woman's breast [14]). Resink et al. [3] wrote, for example, "all frames of the one to four phases [i.e. the four frames of the camera] should be taken within the speckle decorrelation time".

In this work, we analyzed theoretically the heterodyne holography UOT detection scheme, and we calculated how untagged photons, speckle noise, shot noise, decorrelation and etendue, affect the UOT signal. By adjusting the calculation parameter, we got results very similar to the ones of [26]. By comparing results obtained with and without decorrelation, we showed that the Resink et al. remark is not valid, and that heterodyne holography remains, with decorrelation, an optimal detection scheme of the tagged photons. Note that this point was already demonstrated for the detection of the untagged photon in experiments done without ultrasound [30–35].

To introduce our theoretical discussion, let us consider

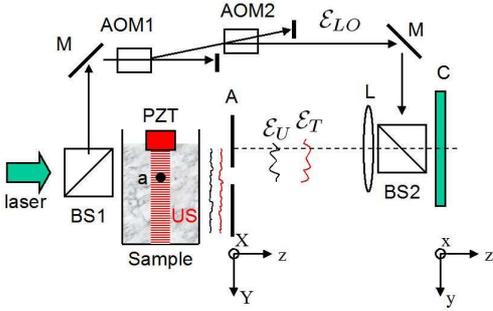


FIG. 1. Typical UOT setup: BS1, BS2: beam splitter; M: mirror; AOM1, AOM2: acousto optic modulator; PZT: piezoelectric transducer that generates the ultrasonic beam US; a: absorber embedded in the diffusing sample; A: rectangular aperture; L: lens of focal  $d$ ; C: camera;  $\mathcal{E}_{LO}$ ,  $\mathcal{E}_T$ ,  $\mathcal{E}_U$ : LO, tagged and untagged fields.

a typical heterodyne holographic UOT setup (Fig. 1). A laser of frequency  $\omega_L$  is split by the beam splitter BS1 into a signal beam and a local oscillator (LO) beam. The signal beam travels through the diffusing sample S and is scattered by it. The sample is explored by an ultrasonic beam US of frequency  $\omega_{US}$ . The light transmitted by the sample exhibits components. The first component at  $\omega_T = \omega_L + \omega_{US}$  is weak ( $\sim 10^{-2}$  to  $10^{-4}$  in power), and corresponds to the tagged photons that have interacted with the ultrasonic (US) beam. The second component at  $\omega_U = \omega_L$  is the main one ( $\simeq 100\%$  in power). It corresponds to untagged photons which have not interacted with US.

A rectangular aperture A, located off axis near the sample, controls the size and location of the zone of the sample where the tagged and untagged fields  $\mathcal{E}_T$  and  $\mathcal{E}_U$  are detected. The  $\mathcal{E}_T$  and  $\mathcal{E}_U$  fields are mixed with the LO field  $\mathcal{E}_{LO}$  by the beam splitter BS2, and the camera C records a sequence of  $M$  frames  $I_m$  (with  $m = 0 \dots M-1$ ) corresponding to the interference pattern:  $\mathcal{E}_T + \mathcal{E}_U + \mathcal{E}_{LO}$ ,  $I_m$  being recorded at time  $t_m = m\Delta t$ , where  $\Delta t = 2\pi m/\omega_C$  is the pitch in time, and  $\omega_C$  is the camera frame frequency. The hologram  $H_C$  of the aperture A (that is back illuminated by  $\mathcal{E}_T$  and  $\mathcal{E}_U$ ) is calculated, in the camera plane C, by combining frames  $I_m$ . The hologram  $H_A$ , in the aperture plane A, is then calculated from  $H_C$ . The signal of interest (tagged or untagged photon) is calculated from  $H_A$ .

To analyze theoretically the Fig.1 experiment, let us define, in plane A and C, the untagged, tagged and LO fields and their respective complex amplitudes, which are slow varying with time  $t$ :

$$\begin{aligned} \mathcal{E}_{A,U}(X, Y, t) &= E_{A,U}(X, Y, t) e^{j\omega_L t} + \text{c.c.} \\ \mathcal{E}_{A,T}(X, Y, t) &= E_{A,T}(X, Y, t) e^{j(\omega_L + \omega_{US})t} + \text{c.c.} \\ \mathcal{E}_{C,U}(x, y, t) &= E_{C,U}(x, y, t) e^{j\omega_L t} + \text{c.c.} \\ \mathcal{E}_{C,T}(x, y, t) &= E_{C,T}(x, y, t) e^{j(\omega_L + \omega_{US})t} + \text{c.c.} \\ \mathcal{E}_{C,LO}(x, y, t) &= E_{LO} e^{j\omega_{LO} t} + \text{c.c.} \end{aligned} \quad (1)$$

where c.c. is the complex conjugate. Here,  $X, Y$  are the coordinates in plane A, and  $x, y$  in plane C. To simplify theory, we have considered here that  $E_{LO}$  do not depend on  $x, y$  and  $t$ . In plane A, the tagged and untagged photon fields are fully developed speckle. The complex fields  $E_{A,T/U}(X, Y, t_m)$  are thus random Gaussian complex quantities uncorrelated from one pixel  $X, Y$  to any other  $X', Y'$ . The random amplitudes  $E_{A,T/U}(X, Y, t_m)$  do not depend on  $t_m$  without decorrelation, and are uncorrelated from one frame (i.e.  $m$ ) to the next (i.e.  $m+1$ ) with decorrelation.

A lens  $L$ , which is located near the camera, and whose focal plane is close to plane A, collects the fields. Because of  $L$ , the tagged and untagged fields in planes C and A are related by a Fourier transform

$$E_{A,U/T}(X, Y) = \tilde{E}_{C,U/T}(k_x, k_y) = \text{FFT}(E_{C,U/T}(x, y))$$

where  $(X, Y) = (k_x, k_y) \times |CA|/k$  with  $k = 2\pi/\lambda$ . To simplify calculations, the discrete Fourier transform (FFT) is made within a calculation grid that fits with the camera pixels in plane C. The pitch  $\Delta x$  of the discrete coordinates  $x, y$  is thus equal to the size of the pixel of the camera. Because of the FFT, the pitch  $\Delta X$  in plane A is

$$\Delta X = 2\pi|CA|/(Nk\Delta x) \quad (2)$$

where  $N$  is the number of pixels of the camera ( $N = 1024$  typically). The detection etendue is thus  $G = S_A S_D/|CA|^2 = N^2 \lambda^2$ , where  $S_A = |N\Delta X|^2$  and  $S_C = |N\Delta y|^2$  are the areas of the calculation grid in plane A and C. The number of modes or speckle grains that can be detected is thus equal to the number of pixels of the camera  $N^2$ .

The frame signal  $I_m$  corresponds to the sum of the tagged, untagged and LO photons. To detect the tagged photons,  $\omega_{LO}$  is made close to the tagged photon frequency  $\omega_L + \omega_{US}$ . The LO and the tagged photons thus interfere (and are summed in fields), while the untagged photons do not interfere (and are summed in intensities). We have thus:

$$I_m(x, y) = |E_{C,T}(x, y, t_m) + c^m E_{LO}|^2 + |E_{C,U}(x, y, t_m)|^2 \quad (3)$$

where  $c = e^{j(\omega_{LO} - \omega_{US} - \omega_L)\Delta t}$  is the LO versus tagged photon shift of phase. On the other hand, to detect the untagged photons,  $\omega_{LO}$  is close to  $\omega_L$ , and  $I_m$  is given by an equation similar to Eq. 3, where the indexes  $U$  and  $T$  are exchanged, and where  $c = e^{j(\omega_{LO} - \omega_L)\Delta t}$ . Because of the random nature of light emission and camera photo conversion, the frame signal  $I_m$  is affected by shot noise yielding  $I'_m$ :

$$I'_m(x, y) = I_m(x, y) + s(x, y, m)\sqrt{I_m(x, y)} \quad (4)$$

where the term  $s\sqrt{I_m}$  accounts for shot noise. Here,  $I_m$  must be expressed in photo electron Units per pixel and per frame, while  $s$  is a real Gaussian random variable of

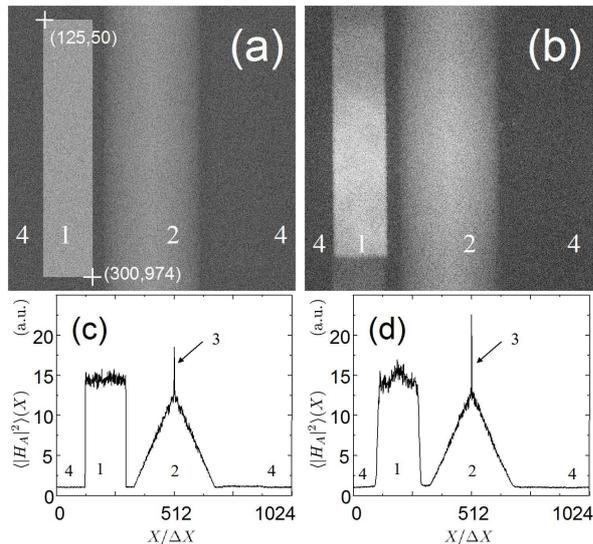


FIG. 2. Tagged intensity images  $|H_A(X,Y)|^2$  (a,b) and curves  $\langle |H_A(X)|^2 \rangle$  (c,d) obtained by calculation (a,c) and from ref.[26] experiment (b,d). The images  $|H_A(X,Y)|^2$  (a,b) are displayed in an arbitrary logarithmic scale. The curves  $\langle |H_A(X)|^2 \rangle$  (c,d) are normalized with respect to the background.

variance  $\langle s^2 \rangle = 1$  uncorrelated with pixels (i.e.  $X, Y$ ) and with frames (i.e.  $m$ ).

The hologram  $H_C$  is then calculated from  $I'_m$ . Without decorrelation, four phase detection of the tagged photons is made. We have thus:  $H_C = \sum_{m=0}^M j^m I_m$  (where  $M$  frames is a multiple of four) and  $\omega_{LO} = \omega_L + \omega_{US} + \omega_C/4$  yielding  $c = j$  in Eq. 3. With decorrelation, two phase detection with two frames is made:  $H_C = I_0 - I_1$ , and  $\omega_{LO} = \omega_L + \omega_{US} + \omega_C/2$  yielding  $c = -1$ . In  $H_C$ , the holographic term of interest:  $E_{C,T} E_{LO}^*$  (where  $*$  is the complex conjugate operator), is proportional to the field  $E_{C,T}$ . Because of L, the holograms  $H_A$  and  $H_C$  in planes A and C are related by a Fourier transform

$$H_A(X, Y) = \tilde{H}_C(k_x, k_y) = \text{FFT} ( H_C(x, y) ) \quad (5)$$

We have calculated, without decorrelation, the tagged photon hologram  $H_A$  for  $M = 12$  frames (like in [26]). The calculation is made with  $|E_{LO}|^2 = 10^4$ ,  $\langle |E_{A,U}|^2 \rangle = 1.33$  and  $\langle |E_{A,T}|^2 \rangle = 3 \times 10^3$  photo electron per frame and per pixel, where  $\langle \rangle$  is the average over  $X$  and  $Y$  within the aperture. Note that tagged and untagged energies ( $\sum_{\text{pixels}} |E|^2$ ) are the same in planes A and C, because Eq.2 conserves energy. The coordinates of the upper left and bottom right aperture corners were (125, 50) and (300, 974).

We have displayed in Fig. 2 the arbitrary logarithmic scale intensity image  $|H_A(X,Y)|^2$  obtained by calculation (a), and in experiment (b) [26]. Note that the calculation parameters were chosen here to fit with [26]. To further compare our calculation with [26], we have

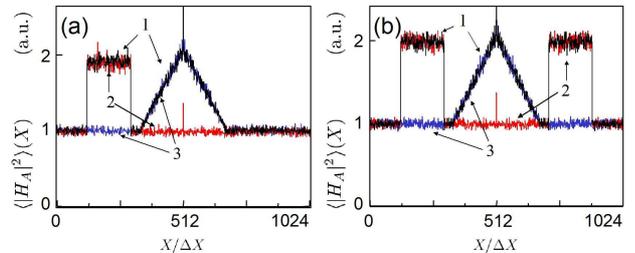


FIG. 3. Curves  $\langle |H_A(X)|^2 \rangle$  calculated without (a) and with decorrelation (b) by switching on and off the tagged and untagged photons signals.

calculated the curves  $\langle |H_A(X)|^2 \rangle$ :

$$\langle |H_A(X)|^2 \rangle = (1/N) \sum_X |H_A(X, Y)|^2 \quad (6)$$

Figure 2 (c,d) show the curves  $\langle |H_A(X)|^2 \rangle$  obtained by calculation (c) and from [26] (d). The curves are normalized with respect to the background that is obtained without tagged and untagged photons and that corresponds to shot noise. The good agreement with [26] validates our theoretical calculation.

In figure 2, the tagged photon signal corresponds to the image of the aperture, i.e. to the bright rectangular zone 1, which is located in the left of images (a,b), because the aperture is located of axis. The aperture corresponds also to the rectangular walls 1, in curves (c,d). On the other hand, the blurred bright zone 2, in the center of (a,b), and the triangular wall 2, in (c,d), corresponds to a parasitic detection of the untagged photon signal, which does not cancel here because of decorrelation (in experiment) and shot noise (in experiment and calculation). The parasitic detection of the LO fields yields a very narrow peak located in the center of the calculation grid, which is only visible on the curves (arrow 3). To the end, shot noise yields a flat background in all points of the images and the curve (zones 4).

To confirm this analyse of Fig.2, and to evaluate how untagged photons, shot noise and decorrelation affect the UOT signal, we have calculated the curves  $\langle |H_A(X)|^2 \rangle$  without and with decorrelation by switching on and off the tagged and untagged photons. To better compare results obtained without and with decorrelation, the tagged and untagged photon energies were measured within a time equal to the recording time of the sequence of  $M$  frames ( $2\pi M/\omega_C$ ) without decorrelation, and to the frame exposure time, which is made equal to  $\tau_c$ , with decorrelation. Calculations were made with  $|E_{LO}|^2 = 10^4$ ,  $M \langle |E_{A,U}|^2 \rangle = 10000$ ,  $M \langle |E_{A,T}|^2 \rangle = 1$  and  $M = 12$  without decorrelation, and with  $|E_{LO}|^2 = 10^4$ ,  $\langle |E_{A,U}|^2 \rangle = 250$  and  $\langle |E_{A,T}|^2 \rangle = 1$  with decorrelation. Note that the calculations are made with the same tagged photon signal with and without decorrelation (1 photo electron per pixel).

Figure 3 shows the curves obtained without (a) and

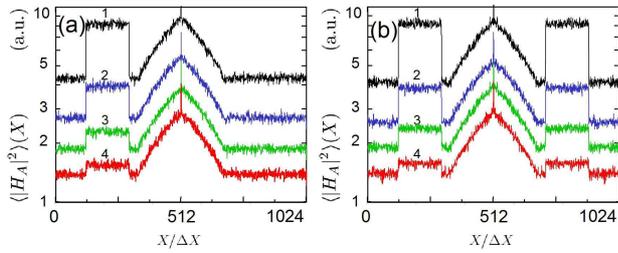


FIG. 4. Curves  $\langle |H_A(X)|^2 \rangle$  obtained without (a) and with decorrelation (b). Calculation is made with  $\alpha = 1$  (1), 0.5 (2), 0.25 (3) and 0.125 (4). Plots are made in arbitrary logarithmic scale.

with (b) decorrelation. Curves 1 (back) were obtained with tagged and untagged photons, curves 2 (red) with tagged (and without untagged) photons, and curves 3 (blue) with untagged (and without tagged) photons. As seen, the rectangular walls (located on the left side of Fig.3(a) and on the left and right sides of Fig.3(b)) correspond to the tagged photon signal. On the hand, the triangular walls (located in the center of Fig.3(a) and (b)) correspond to the untagged photons. Note that the width of triangular walls is twice the width of the rectangular walls, which is itself proportional to the width of the aperture. By a proper choice of the aperture size, here and in [26], the rectangular and triangular walls are well separated, making possible to filter off the unwanted untagged photon signal. Note that the effect of the untagged photons is much lower without decorrelation. To still visualize them in Fig.3(a), we have performed the calculation with a much larger untagged signal without decorrelation ( $\langle |E_{A,U}|^2 \rangle = 10^4$ ), than with decorrelation ( $\langle |E_{A,U}|^2 \rangle = 250$ ).

To evaluate tagged photon detection sensitivity limits, we have calculated  $\langle |H_A|^2 \rangle(X)$  curves by varying the total tagged photon energy per  $\tau_c$ . The curves are plotted on Fig.4 with decorrelation (a) and without (b). Calculations were made with  $|E_{LO}|^2 = 10^4$ ,  $M\langle |E_{A,U}|^2 \rangle = 10000$ ,  $M\langle |E_{A,T}|^2 \rangle = \alpha$  and  $M = 12$  without decorre-

lation, and with  $|E_{LO}|^2 = 10^4$ ,  $\langle |E_{A,U}|^2 \rangle = 250$  and  $\langle |E_{A,T}|^2 \rangle = \alpha$  with decorrelation, where  $\alpha$  is the number of tagged photons per pixel with  $\alpha = 1, 0.5, 0.25, 0.125$  and  $0.0625$  for curves 1 to 5. To better visualize them, the curves were plotted in log scale, and the curves were arbitrarily shifted up or down to better separate them from each other. The results of Fig.4 show that heterodyne holography UOT exhibits roughly the same sensitivity for the detection of the tagged photon with and without decorrelation. The key parameter is the tagged photon energy per pixel during the coherent measurement time with is equal to  $\tau_c$  with decorrelation, and to time  $M2\pi/\omega_C$  needed to record the sequence of  $M$  frames without decorrelation. A signal versus background ratio of 1 corresponds, with and without decorrelation, to one photo electron per pixel. By averaging over the about  $10^5$  pixels of the rectangular aperture, the sensitivity limit is improved down to about  $1/\sqrt{10^5} \sim 1/300$  photo electron. This result agrees with what observed experimentally for the detection of the untagged photons [14].

In this letter, we have proposed a theoretical model to describe the detection of the tagged photons in heterodyne holography UOT. This model, which agrees with the results of [26], has been used to calculate how untagged photons, speckle noise, shot noise, decorrelation and etendue, affect the UOT signal. For a given coherent measurement time, which is  $M2\pi/\omega_C$  and  $\tau_c$  without and with decorrelation, the model yields the same detection sensitivity, and the same noise floor (one photon electron per pixel). Heterodyne holography UOT is thus shot noise limited. By averaging over the  $K \sim 10^5$  pixels of the image of the aperture, the detection sensitivity becomes  $1/\sqrt{K}$  photo electron per speckle (i.e per etendue  $\lambda^2$ ). We hope this work will stimulate further UOT development.

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