Applied Physics Letters

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Cite as: Appl. Phys. Lett. **69**, 1674 (1996); https://doi.org/10.1063/1.117024
Submitted: 29 April 1996 . Accepted: 06 July 1996 . Published Online: 05 August 1998

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Reconstruction of diffuse photon-density wave interference in turbid media from time-resolved transmittance measurements

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(Received 29 April 1996; accepted for publication 6 July 1996)

We demonstrate an improved technique to precisely localize inhomogeneities in turbid media by means of reconstructing diffuse photon-density wave interference from time-resolved transmittance measurements applying the Fourier transform. This interference can also be obtained in the reverse mode, that is using a single source and combining the signals detected at several locations. This increases the collection efficiency and the possibility for postprocessing and allows one to evaluate the data from one measurement in different ways to make the analysis more robust. © *1996 American Institute of Physics.* [S0003-6951(96)02538-7]

The detection and localization of inhomogeneities hidden inside highly scattering media is presently a topic of intense research, due to the possible applications in noninvasive tissue diagnosis.[1,2] Several techniques have been introduced, among them the method of studying diffuse-photon-density-wave propagation.[2–11] When a light source is intensity modulated, it will launch a photon-density wave that travels through the medium. If two light sources are sinusoidally modulated so that their two photon-density waves have opposite phase, there will be destructive interference in the plane midway between them. An object in the medium with optical properties different from the rest of the medium will affect this interference and can thus be detected and localized with high accuracy.[6–11]

The general principle of the interference between two diffusive photon-density waves has already been shown. In this letter, we utilize the fact that this is not an interference phenomenon of the electromagnetic fields, but rather an additive effect of two photon density waves, whose amplitude and phase can be measured separately. We also demonstrate here that this phenomenon can be studied for a wide range of different modulation frequencies performing the measurements in the time domain and analyzing the results in the frequency domain using a Fourier transform algorithm. By utilizing these observations the measurements of diffuse photon density wave interference can be simplified and advanced analysis and postprocessing of the data be employed.

The verifying experiments consisted in sending very short laser pulses through a tissue phantom containing some sort of inhomogeneity, and recording the time-resolved transmission curves with a time-correlated single photon counting system, as described elsewhere.[9] The light source was an Ar-ion laser pumped mode locked Ti:sapphire laser (Coherent Mira 900) operating at 790 nm with 100 fs long pulses. An average power of 50 mW was used in the measurements. For both delivery and detection, 60 cm long fused silica fibers with a core diameter of 600 μm were used. The temporal response function for the system was ~55 ps FWHM, which provided signals at all modulation frequencies of interest in the analysis.

The tissue phantom consisted of a 0.75% (solid fraction) solution of Intralipid, with black ink added in a concentration of 1.3×10^{-5}:1. The liquid was contained in a $300\times250\times50$ mm^3 tank, and its tissuelike optical properties were determined to $\mu_s'=7$ cm^{-1} and $\mu_a=0.06$ cm^{-1} using time-resolved reflectance measurements, where μ_s' is the reduced scattering coefficient and μ_a the absorption coefficient, respectively. As inhomogeneities we used either a 5 mm totally absorbing black aluminum rod, or 4 mm solid rods produced adding 1% agar to an aqueous solution of Intralipid and ink with known optical properties. Two agar rods were used, one with twice the scattering coefficient ($\mu_a=0.12$ cm^{-1}, $\mu_s'=6$ cm^{-1}) and one with four times the absorption coefficient ($\mu_a=0.06$ cm^{-1}, $\mu_s'=28$ cm^{-1}). The rod was always placed in the central plane of the tank.

The principle of the measurements is displayed in Fig. 1. The sample is moved stepwise at intervals of 1 mm along the x axis. For each sample position, two independent measurements were performed, flipping the source between two fixed positions, 30 mm apart and equidistant from the detector. The interference between the two sources can be reconstructed at the analysis level summing the two time-dispersion curves for each sample position and applying the Fourier transform. If one of the two curves is time shifted with respect to the other, this will produce a phase shift in the frequency domain. In particular, it is possible to obtain two photon-density waves dephased by π for a chosen modulation frequency v_c, applying a time shift of $\Delta t=1/2v_c$. This procedure is repeated for each pair of mea-

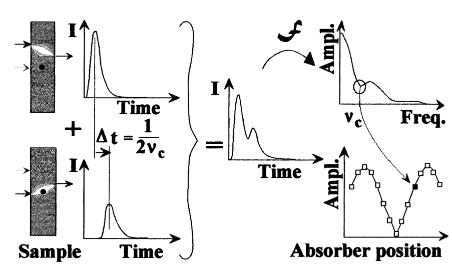

FIG. 1. For two different source positions, a light pulse is sent through the phantom and the transmitted time-dispersion curve recorded. On software level, one of the curves was delayed in time to correspond to a phase shift of π for a chosen modulation frequency v_c, and added to the other curve. After Fourier transformation, the amplitude for the chosen frequency was extracted. The sample was moved to a new position and the procedure was repeated. Phase data were extracted in the same way.

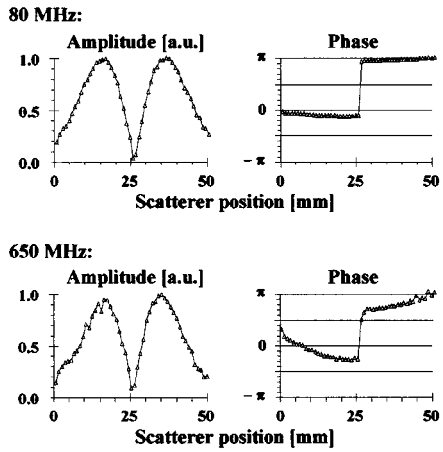

FIG. 2. Scan across a sample containing a black cylinder, 5 mm in diameter. The sample was scanned while the detector was fixed midway between the two source positions. The absorber caused two amplitude peaks as it passed the two sources, respectively, and a phase transition as it passed the midplane.

surements, and the resulting amplitudes and phases are plotted as a function of the sample position.

By extending the results of Kaltenbach *et al.*[12] to two sources, one delayed Δt with respect to the other, the experimental data obtained from the midplane between the two sources can be theoretically described by Eq. (1), if the diffusion approximation is valid and a homogeneous, infinite sample is assumed:

$$\mathscr{F}\left[\frac{c}{(4\pi cDt)^{3/2}}\exp\left(-\mu_a ct-\frac{r^2}{4cDt}\right) + \frac{c}{[4\pi cD(t-\Delta t)]^{3/2}}\exp\left(-\mu_a c(t-\Delta t) - \frac{r^2}{4cD(t-\Delta t)}\right)\right] = \frac{1}{4\pi Dr}\exp\left(-\sqrt{\frac{\mu_a c+i2\pi\nu}{cD}}\,r\right)\times[1+\exp(-i2\pi\nu\Delta t)], \qquad (1)$$

where c is the velocity of light in the medium, $D=[3(\mu_a+\mu_s')]^{-1}$ is the diffusion coefficient, g is the scattering anisotropy factor, r is the distance between the source and detector fibers (the same for both sources), and finally ν is the modulation frequency. This formula shows that the Fourier transform $\mathscr{F}(\nu)$ of the fluence rate at the detector, being the sum of the dispersion curves for the two sources, is equal to the sum of two damped sinusoidally modulated waves. By choosing Δt equal to $1/2\nu_c$, destructive interference results in the midplane between the sources.

The experimental results for the total absorber are shown in Fig. 2. In the figure, the amplitude and phase of the detected signal are plotted as a function of the position of the inhomogeneity, for two different frequencies. The detector served as a sensitive indicator of inhomogeneities in the phantom. As can be seen in the figure, the symmetry in the system was disturbed as the absorbing cylinder was closer to either of the sources. This resulted in a displacement of the

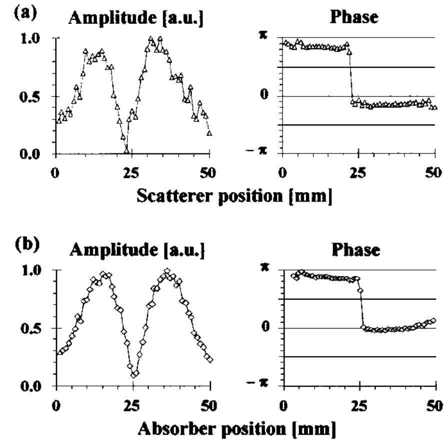

FIG. 3. Data as in Fig. 2 for a 4 mm diam inhomogeneity with (a) 2 times the scattering, (b) 4 times the absorption as the surrounding medium.

plane of destructive interference from the detector plane. Hence the curves show an amplitude null and a sharp phase transition by π as the inhomogeneity passes the midplane between the two source positions, i.e., when the system is symmetric. The results from the same type of measurement using inhomogeneities with twice the scattering and four times the absorption coefficient are shown in Figs. 3(a) and 3(b), respectively.

The fact that the amplitude and phase can be measured for the two waves and added first at the analysis stage, also opens other possibilities. It is, for example, feasible to use the reverse setup, where the source is fixed and the detector is flipped between two positions. In Fig. 4, the result of a reverse experiment is shown to be the same as in the direct setup used above. The source was fixed, the sample was scanned, and for each sample position the detector was flipped between two fixed positions, 30 mm apart. These results thus show that it is possible to improve the light economy by using one source and many detectors, while keeping the advantage of the high spatial resolution offered by the diffuse photon-density wave interference technique.

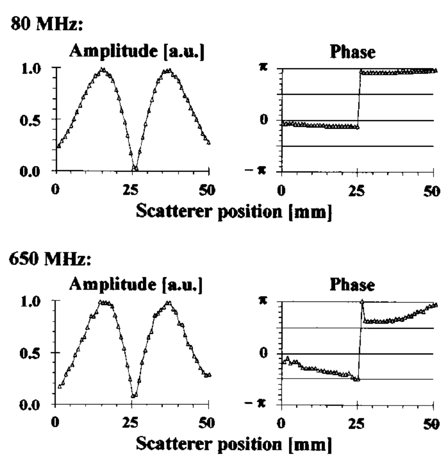

FIG. 4. Measurement with the reverse setup, where the source is fixed and the detector is flipped between two positions. The sample contained a 5 mm diam black cylinder.

Also, the detectors could be positioned in a two-dimensional pattern so that by combining them in different ways during the analysis after the measurement, the plane of destructive interference could be constructed in different directions. Then an absorbing object hidden inside the sample could be more efficiently localized.

So far we have dealt with measurements performed in the time domain. Still, these concepts hold true for the frequency domain as well. There is a perfect correspondence in the physics of the two domains, also for the interference phenomena, as we have shown. In particular, it is possible to achieve a measurement in the frequency domain using the ''reverse'' setup previously described. This can be accomplished for example by feeding the light collected from the two different points to the detector using fibers of different lengths that dephase the two signals by π.

In summary, we have studied the additive effect of photon-density waves and we propose a new technique for multifrequency examination of turbid media to accurately localize an inhomogeneity. This technique is based on adding time-domain recordings and analyzing the results in the frequency domain. The proven additivity also simplifies measurements, as it is technically easier to balance the signals correctly if one is using the same source in the two positions. We explored the additive effect further by proving that the same results can be achieved in the reverse mode by exchanging source and detector. This gives a great improvement of the light economy and acquisition time.

We believe that interference between diffuse photon density waves can be a powerful technique to detect and accurately localize inhomogeneities in turbid media. More sophisticated, time consuming, and less robust tomographic reconstruction algorithms can then be applied once an inhomogeneity is detected and its location well known.

Financial support by the Swedish Natural Science Research Council, the Swedish Research Council for Engineering Sciences as well as from the European Commission under Grant No. ERBCHBGCT940657 is gratefully acknowledged.

[1] A. Yodh and B. Chance, Phys. Today **48**, 34 (1995).
[2] R. R. Alfano, ed., *Advances in Optical Imaging and Photon Migration, OSA Proceedings Series* (Optical Society of America, Washington, DC, 1994), Vol. 21.
[3] J. B. Fishkin and E. Gratton, J. Opt. Soc. Am. A **10**, 127 (1993).
[4] M. S. Patterson, B. W. Pogue, and B. C. Wilson, SPIE **IS11**, 513 (1993).
[5] B. J. Tromberg, L. O. Svaasand, T.-T. Tsay, and R. C. Haskell, Appl. Opt. **32**, 607 (1993).
[6] M. Schmitt, A. Knüttel, and J. R. Knutson, J. Opt. Soc. Am. A **9**, 1832 (1992).
[7] A. Knüttel, J. M. Schmitt, and J. R. Knutson, Appl. Opt. **32**, 381 (1993).
[8] B. Chance, K. Kang, L. He, J. Weng, and E. Sevick, Proc. Natl. Acad. Sci. **90**, 3423 (1993).
[9] C. Lindquist, R. Berg, and S. Andersson-Engels, Proc. SPIE **2326**, 31 (1994).
[10] M. A. O'Leary, D. A. Boas, B. Chance, and A. G. Yodh, Opt. Lett. **20**, 426 (1995).
[11] K. A. Kang, B. Chance, D. F. Bruley, and J. Londono, Proc. SPIE **1888**, 340 (1993).
[12] J.-M. Kaltenbach and M. Kaschke, Proc. SPIE **IS11**, 65 (1993).