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コヒーレンスゲート法を用いた強い散乱体中の吸収と画像計測
Optical imaging and absorption measurements in highly scattering media using coherence gating method

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Abstract We present a quantitative study on optical heterodyne detection measurement of absorption and scattering in strongly scattering media. Measurement result using a cw laser is compared to that obtained from the temporal scattering profiles of coherent photon migration measured with a low-coherence light source, and they are examined by the computation using the Mie theory. We show that coherence gating in optical heterodyne detection, which discriminates the diffuse light through the lost optical properties of the incident wave, including coherence, direction, and polraization, is functionally equivalent to time gating in ultrafast incoherent detection.

Recently, there is a growing number of research activities in transillumination imaging through highly scattering media, as a result of the increased interest in optical computed tomography (CT) for biomedical applications. To form image from the transmitted light that is multiply scattered in biological tissues, several detection techniques have been proposed and studied.[1] A novel technique, named coherent detection imaging (CDI), has been proposed by the last author and others.[2,3] By employing optical heterodyning in its detection scheme, CDI is a coherence gating method that discriminates against the diffuse components of transmitted light, which generally loss the properties of the incident wave, such as coherence, direction, and polarization, due to multiply scatterings.[4]

CT images of both human soft and hard tissues have been achieved by using CDI technique and continuous wave (cw) lasers in the visible and near infrared regions.[2,3,5,6] The advantages of using cw lasers in CDI, such as the wide spectral range of spectroscopic measurements, excellent dynamic range (>120 dB), very high spatial resolution, and relatively simple detection scheme,[5,7,8] are attractive for optical imaging of tissues. On the other hand, because of the long temporal coherence of the cw laser, the resulting heterodyne signal intensity is the time integration of the coherent components of the transmitted light, which may also include some diffuse components, provided that they maintain enough coherence for heterodyne detection. In this paper, we present a quantitative study on coherent photon migration through strongly scattering media. The influence of diffuse light on the quantitation of coherent detection is experimentally investigated.

Our experimental study was performed with a CDI system similar to that used previously.[8] Its schematic diagram is shown in Fig. 1. Briefly, a continuous wave (cw), single frequency, Ti: sapphire laser tuned at 850 nm was used in the laser heterodyne detection. For low coherence heterodyne detection, a 850 nm SLD with a coherence length of ~50 μm was employed. In either case, the optical beam from the light source was collimated to ~1 mm in diameter and split into two parts, the probe and the local oscillator beams. After being frequency shifted by 80 and 79.9 MHz, respectively, with acousto-optic modulators, the two beams were combined and mixed on the surface of the silicon detector for heterodyne detection. The heterodyne signal was amplified, and detected with a time constant of 0.1 msec. The incident laser power on the sample was up to 10 mW, resulting in a ~120 dB detection dynamic range. Because of the relatively low output power of the SLD, the incident power was limited to ~300 μW, and the dynamic range was measured to be ~100 dB.

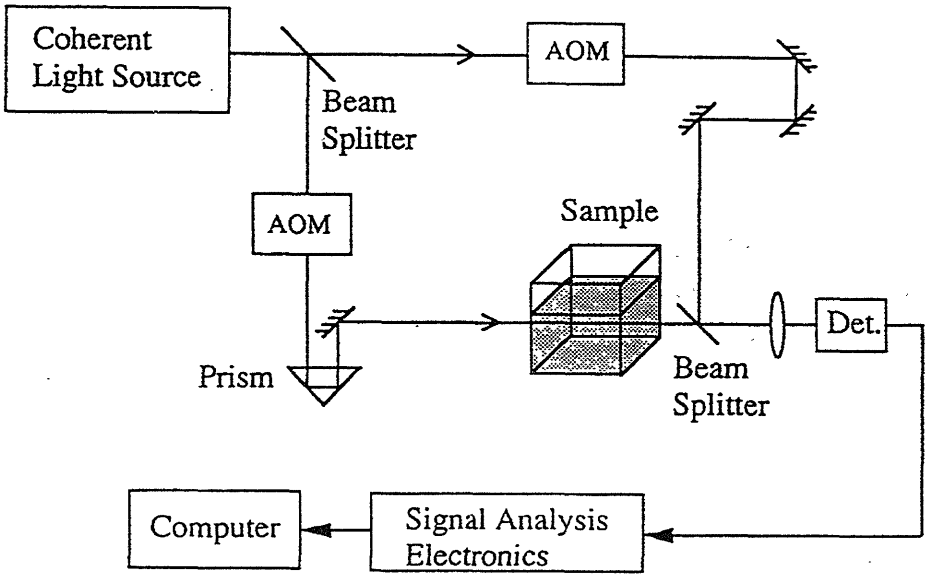
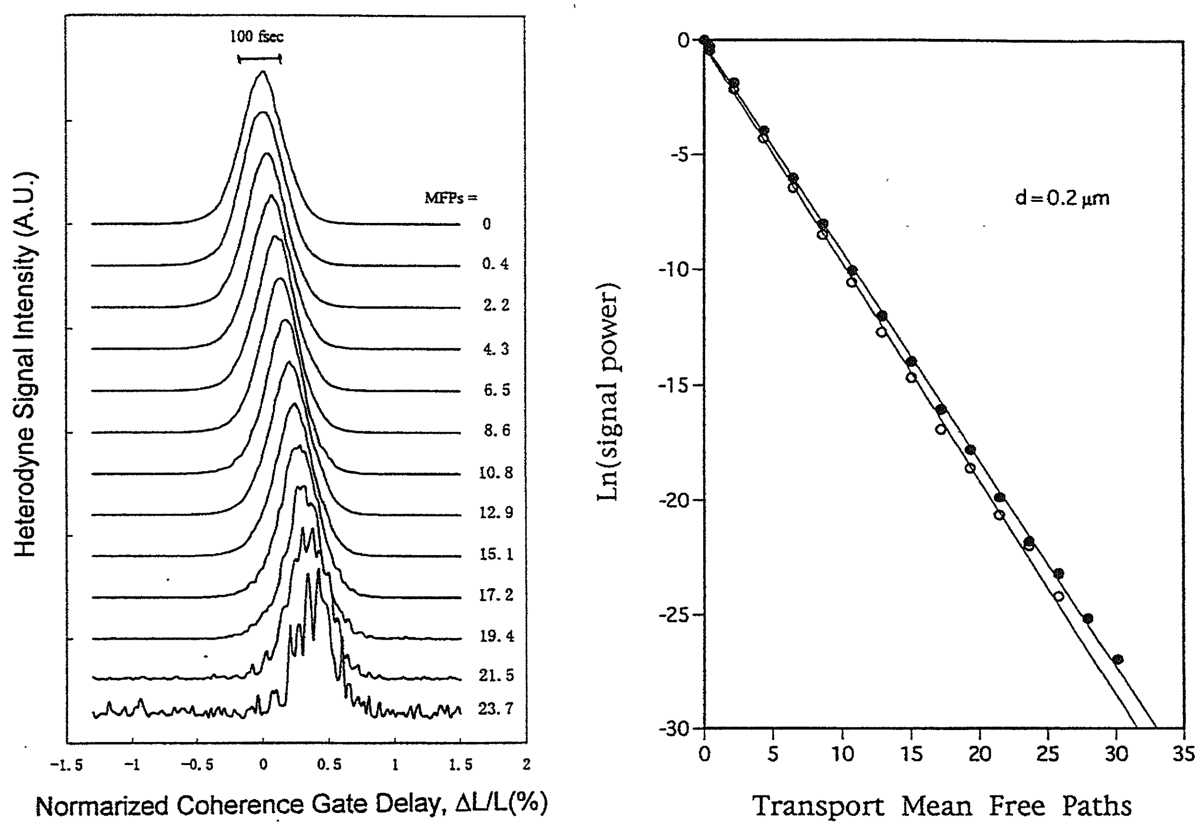


Fig. 1 Schematic diagram of the coherent detection imaging (CDI) system.

When a low coherence SLD is used in the CDI system shown in Fig. 1, heterodyne signal is detected only when the pathlength difference of the two arms of the Mach-Zehnder interferometer, ΔL, is within the coherence length of the SLD. In transillumination measurement, therefore, heterodyne signal detected with $\Delta L = 0$, i.e., zero coherence gate delay, is proportional to the number of apparently unscattered (straight-forward scattered) photons. On the other hand, heterodyne signal detected with coherence gate delay > 0 shall be proportional to the number of late arriving photons that travel an extra distance of $\Delta L/n$, where n is the refractive index of the sample. In time domain this extra distance leads to a time delay of $\Delta t = \Delta L/c$, where c is the light velocity in air. Therefore, by scanning the prism in Fig. 1 to vary the value of ΔL, temporal profile of coherent photon migration through scattering medium can be measured. For a stationary subject, this low coherence heterodyne detection method corresponds, in principle, to a time-resolved detection method that is functionally equivalent to that using ultrashort-pulse laser and fast time gating.[1] In the present experiment, the accuracy of scanning was measured to be better than 1 μm, i.e., ~7 fsec in time domain.

Figure 2(a) shows the detected heterodyne signal intensity through the highly scattering media as a function of the normalized coherence gate delay, $\Delta L/L$, where L is the sample thickness and ΔL is the measured pathlength difference. The scattering media were suspensions of 0.2-μm-diameter polystyrene microspheres (Duke Scientific Corp. Palo Alto, CA, U.S.A.) in 1-cm-thick deionized water. From Mie theory, the anisotropy factor g and scattering cross sections s of the microspheres at the wavelength of 850 nm are calculated as g = 0.17 and s = 1.0×10^{-11} cm^2. The mean free paths (MFPs) of the scattering medium, which is equal to NsL, where N is the number density of the microsheres, was increased from zero to ~24. The peak values of the temporal profiles are shown in Fig. 2(b) as a function of the calculated MFPs (open circles) in the sample cell. In Fig.2(a), however, they are normalized to the same peak for readability. From Fig. 2(a) it can be seen that despite of the increasing multiply scattering in the sample, the temporal profile of coherent photon migration remains nearly unchanged, indicating that after being coherence gated, only a negligible amount of diffuse light was detectable. As seen in Fig. 2(b), the extinction coefficient due to scattering as measured from the slope of the fitted curve is in good agreement with the calculation.



(a) (b)

Fig. 2 (a) Scattering profiles of coherent photon migration through various concentrations of 0.2-μm-diameter polystyrene microspheres in 1-cm-thick deionized water, measured by using a 850 nm super luminescent diode with a coherence length of ~50 μm and the optical heterodyne detection technique, and (b) peak values of the scattering profiles in (a) as a function of the calculated transport mean free paths (MFPs) (o). Also shown are heterodyne detection measurement results using a 850 nm cw laser (●).

By using a Ti:sapphire laser tuned at 850 nm, we repeated above heterodyne detection measurement. The results are shown in Fig. 2(b) (closed circles), together with the results using SLD. A direct comparison in Fig. 2(b) shows that the two measurement results are nearly identical; they remain linear until 30 MFPs, or an attenuation of $\sim 10^{-12}$. This is an obvious result when we recall the temporal profiles of scattering shown in Fig. 2(a), where hardly any diffuse photons were detected by the coherence gating method. The excellent agreement between the two results in Fig. 2(b) demonstrates that coherent gating is effective in both cw laser and low coherence heterodyne detection methods.

Finally, Fig. 3 shows an example of optical imaging in biological tissues by using CDI technique, where the detected two-dimensional image of a positive U.S. National Institute of Standard and Technology (NIST) test chart through a 2-cm-thick slab of chicken tissue at 1.064 μm is depicted.[9] The 65 x 30 pixel image corresponds to an actual area of 3.25 mm x 1.5 mm. As shown, each of the three 500-μm-wide bars is clearly identified. With an incident power of 15 mW from a laser-diode-pumped Nd:YAG laser at 1.064 μm and a detection time of 0.1 msec, we achieved a better than 110 dB dynamic range of detection, and were able to detect the early arriving photons transmitted through chicken tissue as thick as 4 cm. Other results of absorption measurements in highly scattering media will be presented.

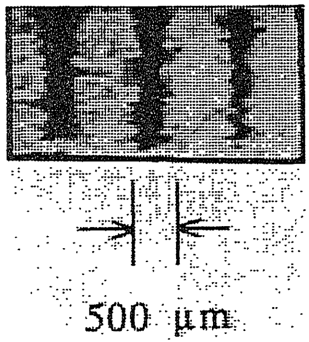


Fig. 3 Detected 2-D image of a U.S. NIST test chart through a 2-cm-thick slab of chicken tissue at 1.064 μm, using coherent detection imaging method. Each of the three 500-μm-wide bars is clearly resolved.

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