Photon Migration, Diffuse Spectroscopy & Optical Coherence Tomography: Imaging & Functional Assessment

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Photon Migration, Diffuse Spectroscopy, and Optical Coherence Tomography: Imaging and Functional Assessment

Stefan Andersson-Engels
James G. Fujimoto
Chairs/Editors

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Contents

Time-Gated Holographic Imaging Using Photorefractive Media

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ABSTRACT

Photorefractive holography is a whole-field, coherence-gating technique for 3-D imaging through turbid media that offers a unique mechanism to discriminate against a background of diffuse light. In contrast to the well-established technique of optical coherence tomography, it is a whole-field imaging technique and may be implemented with light sources of arbitrary spatial coherence, including low cost LEDs and broad-stripe, multimode diode lasers. One drawback of using broadband sources, such as LEDs, for off-axis holographic imaging is the "walk-off" resulting from the short temporal coherence length that limits the field-of-view. Furthermore, the non-collinear geometry required for off-axis holography can introduce significant image aberration. In this paper we discuss these design considerations for various sources. We have addressed the issue of walk-off for sources of arbitrary bandwidth and have designed an off-axis holographic imaging system based on a Michelson interferometer with a collinear beam geometry that minimizes aberration. In this paper we review our work with high-powered LEDs and discuss these issues associated with spatially incoherent sources. Also, we present a novel, spatially coherent, broadband diode-pumped laser source that may also find application in OCT.

KEYWORDS: SCATTERING, WHOLE FIELD PHOTOREFRACTIVE HOLOGRAPHY, MEDICAL IMAGING, LOW COHERENCE INTERFEROMETRY, DIODE-PUMPED BROADBAND LASER SOURCE

Introduction

Optical methods to image the internal structure or map the functional state of a biological tissue are emerging as promising and desirable tools for diagnostic purposes in biomedicine, e.g. [1, 2, 3, 4, 5]. In particular, much research is directed towards realizing non-invasive, in vivo imaging of internal structures with high resolution in real-time, with a view to continuously monitoring physiological functions using the spectroscopic properties of the structures. The conjunction of low tissue absorption and the availability of convenient solid-state laser sources in the near infra-red make this spectral region attractive for biomedical optical instrumentation. The strong scattering of near infrared radiation by biological tissue, however, degrades image quality and so much research has focused on separating the unscattered (ballistic) light component from the

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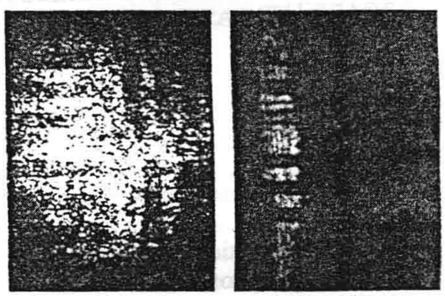
strong diffuse, scattered light background. Some methods of extracting the ballistic signal include confocal techniques [6], time-gating [7, 8, 9] and coherence-gating [10].

Coherence time-of-flight gating using holography was first proposed by Abramson [11] and later applied to biomedical imaging by Spear et al. [12]. This method, known as "light-in-flight" holography, utilizes the fact that only the image-bearing part of the light retains coherence with the reference beam and so interferes to write a hologram. Our imaging technique uses time-gated holography in photorefractive media to separate the ballistic light, that retains coherence with a reference beam, from the multiply scattered, diffuse background [13, 14, 15]. Since this coherent detection technique is, to first order, insensitive to the incoherent light background, it prevents the incoherent background from saturating the detector (CCD), thus ensuring that the dynamic range of the system is not compromised. (This is in contrast to electronic holography[16] and other techniques that record the total intensity distribution due to both ballistic and scattered light and then extract the coherent component in software.) Our technique also differs from many other ballistic light imaging techniques (such as optical coherence tomography [17]), in that it is a whole-field imaging technique: rather than scanning pixel-by-pixel, it acquires a 2-D image field in a single acquisition, which can result in extremely short (sub-ms) image acquisition times. These holographic images are acquired using back-scattered light in a time-gated reflection geometry based on low coherence interferometry and so may be used to reconstruct 3-D images. The use of reusable photorefractive holographic media, such as bulk rhodium-doped barium titanate (Rh:$BaTiO_3$) crystals or photorefractive multiple quantum well (MQW) devices, allows for fast holographic image recording and the potential for real-time read-out using a third reconstruction beam. Using MQW devices as the photorefractive recording media, we have demonstrated faster than video-rate depth-resolved image acquisition through turbid media [18]. In contrast to the well-established technique of optical coherence tomography, this whole-field imaging technique may be implemented with light sources of arbitrary spatial coherence, including low cost LEDs and broad-stripe, multimode diode lasers. There are, however, difficulties associated with using spatially coherent and incoherent sources for off-axis holography through turbid media and these are addressed in the following sections.

Speckle resulting from spatially coherent sources

Biological tissues are highly structured with building blocks ranging from a few nanometers to hundreds of microns. These structures are potential light scattering centres. Whole-field coherence-gated images of objects embedded within turbid media obtained with spatially coherent sources, such as lasers, can suffer from speckle, which is caused by unwanted interference resulting from light scattering from different transverse pixels within the turbid medium. We note that this problem does not arise if the scattering medium is dynamic, such as a liquid scattering medium. This is because the speckle noise is time-averaged within the image acquisition time by the Brownian motion of the scatterers. Speckle, also described as spatial cross-talk, can be addressed by rendering individual pixels mutually incoherent. This can be accomplished by using sources having low spatial coherence. We note that Leith et al. [16] first demonstrated the use of spatial coherence as a gating mechanism for unscattered light. A simple way to make a laser spatially incoherent is to scramble its phase by using rotating diffusers. We



(a) (b)

Figure 1. Images of a USAF test chart through sandstone obtained with (a) mode-locked, Ti:sapphire laser source of ~ 10 nm bandwidth; (b) LED of ~ 40 nm bandwidth

have demonstrated this using photorefractive holography. Alternatively, LEDs provide a cheap, spatially incoherent source with broad linewidths (e.g. > 50 nm) and high average powers (e.g. > 50 mW) [19 20]. We have demonstrated photorefractive holography with LEDs and have observed the expected reduction in speckle when imaging a US Air Force (USAF) test chart through a sample of sandstone.[21], as shown in figure 1. This figure also illustrates an inherent problem of off-axis holography using broadband sources: reduced field-of-view due to beam walk-off that results as a consequence of the very short coherence length of the source.

Limited field-of-view due to walk-off

Walk-off between two interfering beams is caused when the coherence length of the source is significantly shorter than the beam diameter. As illustrated in figure 2, this causes a delay in the arrival time of the reference beam laterally across the recording medium and, consequently, with respect to the arriving image beam. Only the central portion of the interfering beams corresponds to the interferometer arm lengths being matched to within the source coherence length and fringes are only recorded within this intersection area. Reducing the angle between the writing beams can reduce the walk-off effect, but this results in an increased grating period of the hologram. This adversely affects the angular separation between the undiffracted, zero order and the first diffracted order beams, rendering it difficult to isolate the holographic image. Placing a slit at the Fourier plane of the lens that images the first diffracted order on to the CCD provides better rejection of the undiffracted zero order beam, but there is a limit to how small the angle between the writing beams can be set. An alternative approach to increase the field-of-view is to increase the coherence length by using an interference filter (10 nm band-pass) to reduce the source linewidth. While this does eliminate the walk-off, it is at the cost of depth resolution and signal power [20].

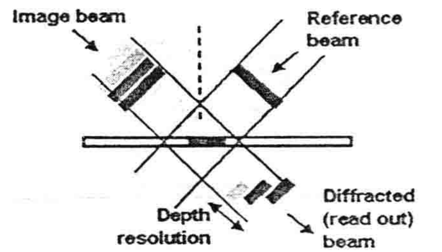


Figure 2. Schematic representation of "walk-off"

To overcome the problem of walk-off, we have exploited the observation that after a beam traverses a dispersing component such as a prism, the energy fronts in the beam becomes tilted with respect to the phase fronts [22], since the former travel at the group velocity while the latter travel at the phase velocity. We note that, while the angle at which the phase fronts intersect determines the fringe period, the fringe visibility is determined by the overlap of the energy fronts. This means that by adjusting the angle between the phase and the energy fronts in each of the beams, we can make the energy fronts collinear at the MQW and so eliminate the walk-off for radiation of almost arbitrary linewidth.

For an angle of 1.5° between the writing beams corresponding to a fringe period of 30 microns, we calculate the delay that must be induced between the energy and the phase fronts so as to make the former parallel to the MQW device. This tilt of the energy fronts may be achieved by double-passing a fused silica prism with an apex angle of 23°. Accordingly, such prisms were placed in each arm of the Michelson interferometer at the angle of minimum deviation, as shown in figure 4.

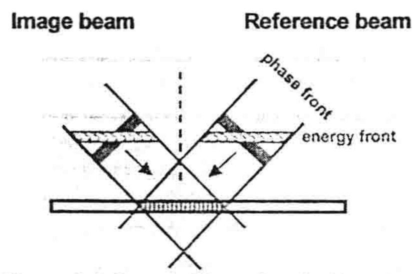


Figure 3: Schematic illustrating the idea of tilted energy fronts

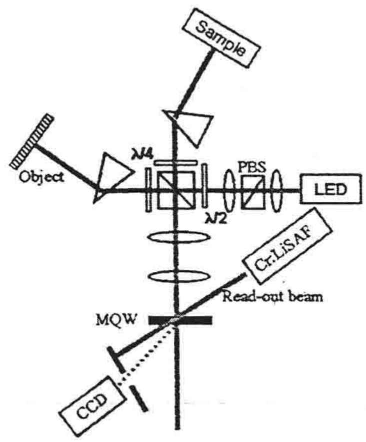
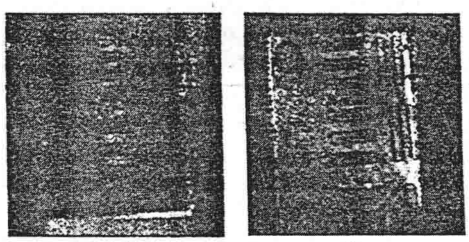


Figure 4. Schematic of the experimental set-up used for obtaining whole-field images with the LED using photorefractive holography

Using an LED of 40 nm bandwidth centred at 760 nm, we observed interference fringes spanning the entire field-of-view. Figure 5 shows the reconstructed holograms obtained without and with the prisms, illustrating the improvement in the field-of-view. Thus we are able to use off-axis holography and avoid the problems associated with walk-off. We note this approach may be applied to many interference and other wave-mixing experiments using short coherence radiation including ultrashort pulses.



(a) (b)

Figure 5. Holographic images of USAF test chart taken (a) without prisms and (b) with prisms

Off-axis holography with collinear Michelson interferometer

Eliminating walk-off does not remove all the difficulties associated with off-axis holography using spatially incoherent light. The alignment is extremely critical owing to the requirement to overlap each spatial coherence cell in the signal beam with its complement in the reference beam. This is most straightforward when the two beams are collinear. The collinear beam geometry in the Michelson interferometer also permits the use of a spatial filter to reject some of the scattered light and reduces image aberration in the optical components. Clearly off-axis holography precludes collinear writing beams and so it is desirable to ensure that our image and reference beams are collinear within the interferometer and only deviate from this at the MQW holographic recording device. We can achieve this using a Babinet compensator [23]. Figure 6 illustrates the experimental set-up.

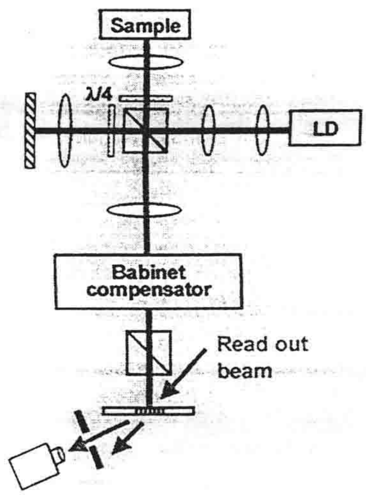


Figure 6. Holographic recording set-up using a Babinet compensator

The image and reference beams arrive collinear at the Babinet compensator with orthogonal polarizations, due to the arrangement of polarizing beam-splitter and quarter wave plates in the Michelson interferometer. Their orthogonal polarizations mean that each beam experiences a different refractive index in each prism of the Babinet Compensator. Furthermore, a transverse sweep in phase delay between the beams is introduced across the Babinet compensator [23] resulting in interference between the image and reference beams. This produces the desired sinusoidal fringe pattern across the image, the intensity distribution of which may be relayed to the MQW device to record a hologram. Figure 7 shows a holographic image obtained with a Babinet compensator placed after the collinear interferometer using a broad-stripe multimode laser diode source. The coherence length in this case was 300 μm so there was no apparent walk-off and consequently a full field-of-view was obtained without resorting to the technique described in the previous section. The Babinet compensator was made out of crystal quartz and the angle of the prisms was calculated to provide the required fringe period (30 μm.)

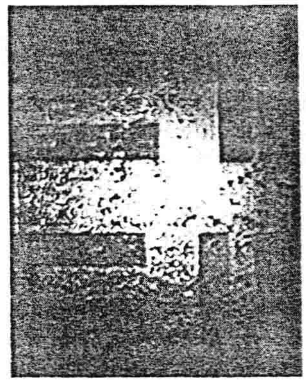


Figure 7. Holographic image of the test chart recorded with collinear beams in the interferometer and employing a Babinet compensator

Novel, broadband tunable source for low coherence interferometry

Photorefractive holography, like heterodyne detection [24] and any other whole-field coherence gated imaging technique, may be performed with light sources of arbitrary spatial coherence including low cost LEDs and broad-stripe, multimode diode lasers. This is in contrast to confocal coherence-gated imaging modalities like OCT that require spatially coherent sources which can be coupled effectively into single mode optical fibres. State-of-the-art OCT systems [25] generally rely on ultrafast laser systems such as mode-locked Ti:sapphire lasers that provide broadband radiation with high average power, but which are relatively complex and expensive. We have demonstrated a spatially coherent, broadband c.w. all-solid-state laser source that is directly diode-pumped and power-scaleable. It may be efficiently coupled into single-mode optical fibres and may be applied to all low coherence interferometric techniques.

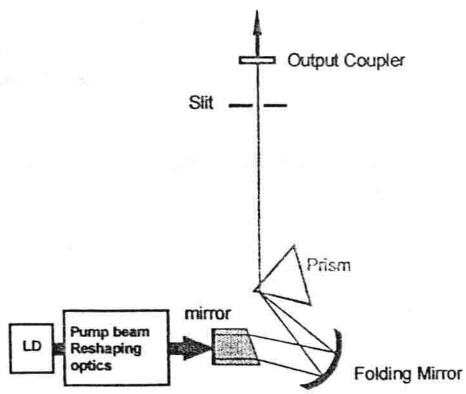


Figure 8. Schematic of diode-pumped, three mirror broadband laser: L: 100 μm 500mW stripe diode at 670 nm

Figure 8 is a schematic of this broadband laser source. An intracavity prism is used in a simple 3-mirror laser cavity (utilizing a plane/Brewster cut Cr:LiSAF or Cr:LiSGAF rod) to spatially disperse the laser mode within the laser crystal. Suitable positioning of this prism allows for different wavelength components to be collimated and collinear at the laser output, and focused but spatially separated from one another in the laser crystal. This spatial dispersion allows different wavelength components to experience separate paths in the gain medium and hence counteracts the effect of gain narrowing [26]. This cavity provides a spatially coherent high brightness broadband tunable output and is readily scaleable to higher powers. For a more detailed description of this laser the reader is referred to reference [27].

To demonstrate the utility of the above laser source for low coherence interferometry and depth-resolved imaging, it was adjusted to provide a 13 nm bandwidth and 60 mW output power and applied to depth-resolved 3-D imaging through a liquid scattering medium using photorefractive holography. Figure 9 shows depth-resolved images, acquired in real-time, of a 100 μm-stepped, 3-D test object imaged through a scattering depth of 9.8 scattering mean free paths. As expected from the measured coherence function of the source, the 100μm steps were readily resolved.

Conclusions

We have demonstrated photorefractive holography to be a whole-field, real-time coherence gated 3-D imaging technique that is compatible with sources of arbitrary spatial coherence. The use of photorefractive multiple quantum well devices provides a fast image acquisition time (typically <1 ms for a 256×256 pixel image). Furthermore, unlike OCT and other confocal imaging systems that often require expensive mode-locked, solid-state lasers for high resolution applications, photorefractive holography can be performed with cheap broadband sources such as LEDs. We have demonstrated that the 'walk-off' experienced while performing photorefractive holography with broadband radiation may be overcome and we have reported an experimental set-up that utilizes collinear beam geometry in the interferometer. We have also demonstrated a novel, spatially coherent, broadband laser source for low coherence interferometric applications (such as OCT) that is compact, cheap and simple and that can be readily coupled into a fibre. We have demonstrated the applicability of this laser source to depth-resolved, 3-D imaging through turbid media.

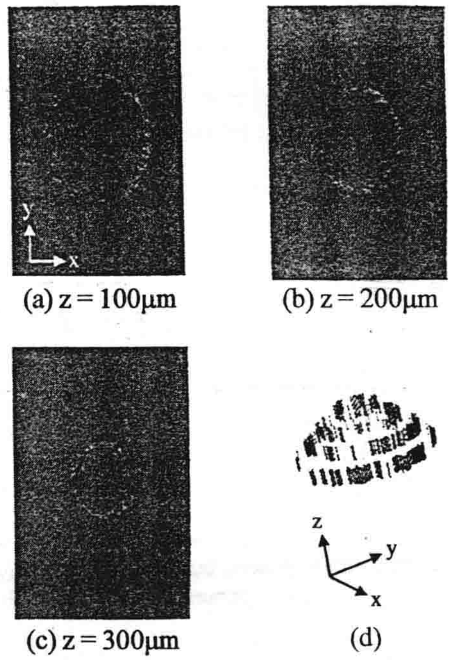


Figure 9. (a-c) holographic images and (d) reconstruction of 3-D test object acquired through ~10 mean free paths of liquid scattering medium

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A new method to perform time-resolved measurements: coherence scanning

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ABSTRACT

We explore in this paper a new method to perform time-resolved measurements of the diffuse light transmitted through a thick turbid medium. This method is based on the analysis of the speckle fluctuations due a wavelength modulated source. A time resolution of about 50ps is already achieved, and we expect to improve this result soon. This method could allow the design of low cost setups to perform such measurements.

Keywords: scattering, random media, speckle, frequency modulation, interference

1. INTRODUCTION

Light undergoes a lot of scattering events in biological tissue, and this fact cannot be ignored in the development of new non-invasive diagnostic tools. Scattering processes are very efficient on blurring every details of the structure of interest, which makes inverse problems really hard to perform on the basis of scattered light measurements. Time-domain measurements can however provide a lot of pertinent information to overcome this difficulty[1,2]. In transillumination, time-gated techniques can be used to select early-photons and thus to increase the spatial resolution of the tomography[3]. Time domain can also be used for the determination of some specific property of a medium[4], like the effective absorption coefficient. In any way, it is really difficult to bypass such information in inversion procedures Time-domain measurements however imply expensive and high-tech experiments: the classical way to perform such measurements is indeed to send a ultra-short light pulse into the medium, and to detect the scattered light with enough time resolution. As the typical transit time of light in biological tissue is of the order of a few hundreds picosecondes, the time resolution here involved has to be in the picoseconde scale, which is still yet hard to reach.

We have investigated a way to obtain the same information in a far easier way. Time resolution corresponds to the path-length distribution of the scattered light inside the turbid medium, and path-length differences can be measured using an interferometer. This fact was extensively used in optical coherence tomography (OCT), for the position determination of the different reflecting surfaces. In OCT the detected signal is restricted to the unscattered field, which is much more convenient for imaging, but is quickly attenuated and limits investigations to sub-millimeter depth. We show in this paper that it is possible to record the scattered light with an interferometric setup, by the use of a wavelength modulated source. Such a source was already used by Thompson et al[5] as a variable-coherence source, when the frequency of the modulation is much faster than the integration time of the detection. The authors have shown that the speckle contrast-ratio measured in that way was linked to path-length distribution. Our result is that the study of the speckle pattern fluctuations within the modulation period can provide much more information, and that this information can be used to completely reconstruct the scattered light path-length distribution, or equivalently to perform time-resolved measurements.

2. MEASUREMENT METHOD

2.1. Experimental setup

The experimental setup is depicted in figure 1. The source is a laser diode at 852nm, with a width in the range of 10MHz. A modulation of the injection current allows a wavelength mode-hope free modulation at a frequency f~1Hz. The resulting laser frequency modulation is:

Photon Mi[illegible] Coherence Tomography: Imaging and Functional
Assessment, St[illegible] to, Editors, Proceedings of SPIE Vol. 4160 (2000)

$$\omega(t) = \omega_0 + \Delta\Omega\cos(2\pi f t)$$

where $\Delta\Omega = 2\pi\, 15GHz$

The detector is a classical photodiode. The collection lens was chosen to have a large coherence area on the detector. The scattering medium is a 7.5mm thick homogenous slab constituted of a suspension of glass micro-spheres of 500nm diameter in a solid silicon matrix. The scattering coefficient is about $44cm^{-1}$, and the absorption coefficient is negligible.

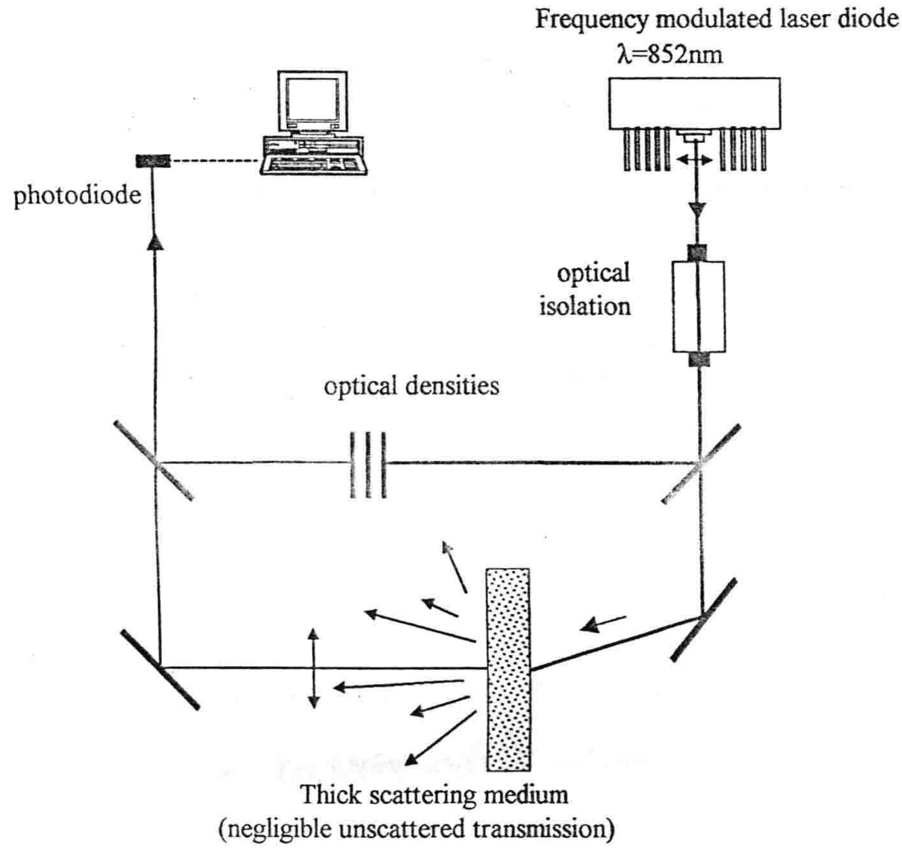

Fig. 1: Experimental setup for time resolved transmittance measurements with a frequency modulated CW laser diode and a photodiode

2.2. Signal processing

Electronic processing: The signal obtained on the detector is filtered (high pass filter at ~1Hz) and amplified to give the interference signal:

$$s(t) \propto 2Re(E_{diff}E_0^*)$$

where E_0 is the reference field and E_{diff} is the transmitted scattered field at the output surface of the medium.