Real-Time 3-D Holographic Imaging Using Photorefractive Media Including Multiple-Quantum-Well Devices

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Abstract—We discuss a real-time coherence gated three-dimensional (3-D) imaging system, based on photorefractive holography with ultrashort pulses, which has been applied to imaging through turbid media with a view to developing biomedical instrumentation. Sub-100-μm depth-resolved images of 3-D objects embedded in a scattering medium have been obtained. Using a long integration time in rhodium-doped barium titanate (Rh:BaTiO₃), an image of a test chart has been obtained through 16 mean-free paths of scattering medium. Real-time depth-resolved imaging through 13 mean free path wavelengths of scattering medium has been demonstrated using a fast response time (<0.4 ms) photorefractive multiple quantum well device. This latter system can acquire depth-resolved images direct to video with no requirement for frame grabbing or signal processing. We discuss the tradeoffs and limitations of these photorefractive media for this application.

Index Terms—Biomedical infrared imaging, holography, photorefractive materials.

I. INTRODUCTION

NEAR-INFRARED radiation offers the potential for medical diagnostic and functional imaging in biological tissue since the absorption of typical biological tissue in this spectral region is at a minimum. The use of optical radiation, rather than X-rays or ultrasound, provides the opportunity to make spectroscopic measurements in biological tissue which can be of significant diagnostic value. Furthermore, this spectral window overlaps the tuning ranges of semiconductor laser diodes, Ti:sapphire lasers, and diode pumped Cr:LiSAF lasers [1], which makes near-infrared laser-based instrumentation viable. At these wavelengths, however, biological tissue exhibits a high scattering cross section that usually results in severe image degradation due to multiple scattering. Much research has focused on methods to recover the image information in the presence of this scattered light. In particular, various schemes have been devised to form images using ballistic (unscattered) light which normally is obscured by the diffuse background noise. These include spatial filtering [2], confocal imaging [3], time gating [4]–[6] and coherence gating [7]–[9]. When imaging with a reflection geometry, i.e., using back-scattered light, time-gating can also provide depth-resolved (time-of-flight) image information which may be used to reconstruct three-dimensional (3-D) images. Time-gating may be realized using an incoherent time-resolved detector [4], a nonlinear optical time-of-flight gate [5], [6], [10], or by low coherence interferometry [9]. This approach to imaging therefore provides a potential application for compact ultrafast laser technology.

It should be noted that all systems which form images through turbid media using the unscattered ballistic light are inherently limited to small scattering (tissue) depths since ballistic signals suffer exponential attenuation on passage through scattering media. Hee et al. [11] estimated that for reasonable powers of tissue irradiation in the infrared, the unscattered ballistic component of the light will be reduced to the shot noise detection limit after propagating through approximately 36 scattering mean free paths (MFP) of a scattering medium. This corresponds to a “typical” tissue thickness of ~4 mm (~2-mm tissue depth in a reflection geometry) and is potentially useful for clinically relevant applications such as skin cancer screening, diagnosing and/or monitoring other dermatological conditions, imaging of the eye and endoscope-based imaging systems.

The work reported here has been motivated by a desire to develop imaging systems for in vivo applications such as screening for skin cancer, for which rapid image acquisition time is a priority. To this end, we have concentrated on developing “whole-field” imaging techniques, which acquire all the pixel information in parallel, thereby accepting compromises in achievable resolution and sensitivity compared to confocal scanning techniques. We note that this approach may also prove fruitful in fast acquisition 3-D imaging including microscopy of living or other moving objects. Our technique uses time-gated holography in photorefractive media [12] as a means of achieving depth resolution and discriminating in favor of the unscattered light which retains coherence with a reference beam. It is related to coherence gating techniques previously reported by various groups including optical...
heterodyne detection [13] and optical coherence tomography (OCT) [14], as well as to conventional, electronic and light-in-flight holography [15], [16]. It fundamentally differs from other techniques, however, in that this coherent detection system is, to first order, insensitive to an incoherent diffuse (uniform) light background which, therefore, does not saturate the detector. (This is in contrast to electronic holography and other techniques which record the total intensity distribution due to both ballistic and scattered light and then extract the coherent component.) The whole-field imaging aspect of our technique differentiates it from many of the previously reported coherent imaging systems that scan pixel by pixel, and therefore require rather longer image acquisition times. Our 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 readout using a third reconstruction beam which may be adjusted independently to those writing the hologram and so be optimized for detection by a charge-coupled device (CCD) camera.

In the following sections we review the first demonstration of time-gated photorefractive holography using Rh:BaTiO$_3$ and the current implementation using photorefractive MQW devices. We discuss some of the limitations of this technology and the scope for future work.

II. DEPTH-RESOLVED IMAGING USING RHODIUM-DOPED BARIUM TITANATE

Time-gated holography, known as light-in-flight holography, was first proposed by Abramson [15], and later applied to biomedical imaging by Spears et al. [17] We first demonstrated depth-resolved photorefractive holography using the apparatus shown in Fig. 1, using a mode-locked Ti:sapphire laser producing 3 ps [18] or 100 fs [19] pulses as the source. The holographic recording medium, which replaces the photographic film used in conventional holography, was a crystal of rhodium-doped barium titanate, which permitted the hologram to be read out by a Bragg-matched beam and recorded on a CCD camera. This could be done in real time using a dedicated readout beam, or the signal arm may be blocked and the reference beam used to read out the hologram. As with any holographic imaging system, holograms can only be written when the interferometer arm lengths were matched to within the coherence length of the source (100 µm with femtosecond pulses) and so using a short coherence length source provides depth resolution. It is interesting to note that ultrashort pulse mode-locked lasers are not strictly needed for this application since the optical source need only have a short coherence length (i.e., broad spectral bandwidth) to achieve the time-of-flight-gating and hence the depth resolution. In principle any broad-band radiation source could be used but in practice, when imaging through turbid media which strongly attenuates the ballistic signal, mode-locked lasers are the most convenient source of high-power broad-bandwidth light. We speculate, however, that high average power incoherent sources based on diode-pumped fiber lasers and amplifiers [20] may provide a compact and more powerful alternative to ultrafast solid-state lasers.

To demonstrate depth-resolved imaging we used a 3-D test object, consisting of a series of concentric aluminum cylinders, ranging from 1 to 5 mm in diameter and separated in depth by 100 µm, as shown in Fig. 2(a). This object was unpolished and provided no significant specular reflection, but back-scattered ~8% of the incident light. When viewing this object directly through 8 MFP of a scattering medium containing an aqueous suspension of polystyrene spheres, no significant image can be recognized, as shown in Fig. 2(b). Using our technique of time-gated photorefractive holography to image through the scattering medium, we obtained the images shown in Fig. 2(c)–(e). For each whole-field image acquisition, the delay of the reference arm was adjusted such that the reference beam pulse arrived at the crystal at the same time as light back-scattered from the particular layer of interest in the object. By varying the delay of the reference arm between each acquisition, a set of images sufficient to reconstruct a 3-D image of the object could be obtained. The power incident on the sample was approximately 500 mW over a 4-mm diameter area (an intensity of ~2.5 W/cm$^2$) and the reference beam power was approximately 20 mW. Each depth-resolved image was recorded in approximately 1 s and then transferred to the computer for rendering, a 3-D computer reconstruction of the object as seen through 8 MFP is shown in Fig. 2(f). The depth resolution of the images was 100 µm, while the transverse spatial resolution was approximately 30 µm. This initial experiment demonstrated that photorefractive holography can be used for depth-resolved imaging through turbid media with better than 100-µm depth and transverse spatial resolution.

A study was made of the sensitivity of this technique to evaluate its potential to image through scattering media. Since increasing the scattering depth of the turbid medium will
Fig. 2. Depth-resolved holographic images showing (a) a picture of the 3-D test object, (b) image of test object when viewing directly through 8 MFP of scattering medium, (c)–(e) Depth-resolved images of each of the top three layers, (f) 3-D computer rendering of depth resolved images.

To decrease the ballistic signal available to record the hologram, we investigated the dependence of the minimum signal power required to record a useful hologram, i.e., one which could be read out and detected by our CCD camera. When writing holograms with low powers in Rh:BaTiO$_3$, it is necessary to integrate for as long as tens of minutes before a detectable hologram is recorded (the photorefractive response time taken to reach this detectable hologram is a function of the intensity of the writing beams). In any clinical practice, such a long integration time would of course be unacceptable, but for these proof of principle experiments we used integration times of up to 300 s. In order to maximize the “strength” (i.e., the diffraction efficiency) of a hologram recorded in a shorter time than that required to reach the steady state, it is possible to increase the power in the reference arm and therefore increase the rate at which the steady-state is approached. Unfortunately, increasing the ratio of the intensity of the reference beam compared to the signal beam means that the modulation depth (and therefore the diffraction efficiency) of the hologram will be decreased. There is therefore an optimum intensity for the reference beam for a given integration time. Fig. 3(a) shows how the minimum signal intensity required to record a useful hologram varied as a function of reference beam intensity. Fig. 3(b) shows how, for a fixed reference beam intensity, the minimum signal intensity required to write a useful hologram varied as a function of the readout beam intensity. The hologram diffracts a fraction of the reference beam into the CCD camera to record an image and so, for a given CCD camera sensitivity, increasing the power in the readout beam should permit a “weaker” recorded hologram to be used. Increasing the readout beam will not, however, continue indefinitely to reduce the minimum required signal

![Figure 3](image-url)
intensity as eventually the light diffracted off the recorded hologram will be less than that scattered by inhomogeneities in the Rh:BaTiO₃ crystal. Also, the readout beam tends to erase the hologram as it is read out and there will be no advantage in increasing the readout beam power past the value at which it erases the hologram in a time comparable to the integration time of the CCD camera. For image integration times of 60 and 300 s, respectively, the minimum signal intensities required to record a hologram were 100 and 10 nW/cm² for a reference beam intensity of 40 nW/cm² and a readout beam intensity of 200 mW/cm².

Having optimized the beam intensity ratios, a holographic image of the USAF test chart was obtained through 16 MFP of scattering solution. The direct image of the test chart through the imaging system, as seen at the CCD camera when there was no scatterer present is shown in Fig. 4(a). The reduced definition of the bar patterns is a consequence of the spatial filters used in this experiment. A holographic image of the test chart acquired through 16 MFP of scattering medium is shown in Fig. 4(b). This clearly shows the 100-μm bars of the test chart.

The integration time for the holographic recording of the image obscured behind 16 MFP was ~5 min. Translating the test chart longitudinally established that the depth resolution was 100 μm, as predicted from the pulse duration and beam geometry [21]. We also imaged the 3-D test object through more strongly scattering media. Fig. 5 shows 3-D images recorded through a scattering medium of (a) 0, (b) 12, and (c) 14 MFP scattering depth. It will be seen that while the signal to noise ratio of the image decreases with scattering depth, the spatial resolution does not.

For the range of scattering phantoms used in our experiments, the minimum required ballistic signal was not affected by the amount of scattered light but remained constant [19]. This illustrates one of the key advantages of photorefractive holography: a (uniform) diffuse background will not write a hologram in a photorefractive medium because a photorefractive medium does not respond to the intensity distribution of an optical signal but only to the spatial derivative of that intensity distribution. The effect of an incoherent diffuse background is only to act as an erasing field which will reduce the modulation depth of a recorded hologram. This was investigated quantitatively using the experimental configuration represented in Fig. 6. Essentially a hologram was written using a train of 100-fs pulses and an incoherent scattered light background simulated by a third beam, for which 100-fs pulses were delayed by more than their coherence length relative to the signal and reference beam pulses. It was possible to record a useful hologram in the presence of an incoherent background which was 10⁶ times more intense than the signal beam. This figure was ultimately limited by scattering from inhomogeneities in the crystal and by beam fanning. This
provides a means to provide depth-resolved images at 80 keV to Ga may at 160 keV and 5 m 100-˚AA l Ga 10 As stop-etch layer GaAs buffer layers. Deep 10 cm /cm As/75-˚A GaAs MQW, was used to relay the image beam onto the...imaging system.

Fig. 6. Experimental setup used to investigate the dynamic range of Rh:BaTiO 3 imaging system.

dynamic range is equivalent to 20 b and exceeds that of most photodetectors such as CCD cameras. Our experiments show that the depth of scattering medium through which we can image is, therefore, not limited by the scattered light background but by the minimum required ballistic signal at the recording medium and, therefore, by the power incident at the scattering medium.

It is seen that time-gated photorefractive holography using Rh:BaTiO 3 provides a means to provide depth-resolved images through turbid media. The ability to employ high power readout beams means that extremely weak holograms may be detected and so signal intensities as low as 10 nW/cm 2 may be used. Unfortunately, the long response time of Rh:BaTiO 3 means that image acquisition times as high as hundreds of seconds must be used when imaging through strong scattering media and this is clearly unacceptable for most biomedical applications. There is therefore a requirement to use photorefractive media with a much faster response. Two such media are bulk semiconductors such as cadmium telluride (CdTe) and photorefractive GaAs–AlGaAs multiple-quantum-well (MQW) devices. The latter have been the subject of our recent research which is described in the next section.

III. DEPTH-RESOLVED IMAGING USING PHOTOREFRACTIVE GaAs–AlGaAs MQW DEVICES

Compared to bulk semiconductors, the strong, narrow excitonic absorption features of MQW’s lead to a large optical nonlinearity [22] when an electric field is applied, parallel or perpendicular to the wells. The nonlinearity is due to the Franz–Keldysh effect [23], or the quantum-confined Stark effect [24], according to whether the electric field is applied parallel or perpendicular to the wells, respectively. Their photorefractive properties are derived from a low-electrical conductivity, which is typically achieved by proton bombardment which allows the construction of two-dimensional (2-D) devices without the need for pixellation. Semiconductors usually have sensitivities many orders of magnitude greater than oxide materials [25] and their high-carrier mobilities lead to very fast response times [26]. We have measured the response time of these devices while imaging through scattering media to be faster than 0.4 ms [27]. This permits images to be captured much faster than standard (30 frames/s) video rate and so images can be directly recorded on a conventional video cassette recorder, which we have recently demonstrated. All of the images presented here using our MQW device imaging system have been visible in real-time.

In this paper, the MQW devices were used in the transverse Franz–Keldysh geometry [21], [22], which requires a large applied field of the order of tens of kilovolts per centimeter to be applied in the plane of the quantum wells, parallel to the optical grating vector being written. As in normal photorefractive behavior, carriers are produced in the bright regions which then drift to shield the applied field in these regions. The large applied field will produce a broadening of the exciton peak via field ionization, this is known as the Franz–Keldysh effect. In bright regions, where carriers have shielded the applied field, the absorption will remain unchanged. Conversely, the dark regions, where the applied field is still strong, will exhibit a decrease in absorption at the exciton peak. Hence the optical interference pattern is mapped to an absorption distribution, which is equivalent, via a Kramers–Kronig transformation into a refractive index distribution.

Our photorefractive MQW devices were grown at Purdue University in a Varian GEN-II molecular beam epitaxial chamber on a GaAs substrate. The STG 10% Al barrier structure, grown at 600 °C, consists of an Al 0.5 Ga 0.5 As stop-etch layer beneath a 1.5-μm 100-Å Al 0.4 Ga 0.6 As/75-Å GaAs MQW region sandwiched between Al 0.3 Ga 0.7 As buffer layers. Deep defects were introduced by proton implantation at a double dose of 10 12/cm 2 at 160 keV and 5 × 10 11/cm 2 at 80 keV to make the device semi-insulating throughout the MQW region. The defects provide traps for photorefractive space-charge gratings. The MQW surface was protected with wax and liftoff of the film was performed using a highly selective (>10 8) 12% HF etch to dissolve the AlAs layers. The sample was then van der Waals bonded to a glass substrate. Two gold contacts were evaporated on the top of the sample to apply a transverse electric field parallel to the QW layers.

Fig. 7 shows the experimental set-up used to record and reconstruct 3-D holograms using the MQW devices. The output of a mode-locked Ti:sapphire laser (~100-fs pulses at 830 nm) passed through a beam splitter in order to produce an image and reference beam. The image beam travelled through a cell filled with the scattering media, reflected off the test object and passed once more through the scattering cell. A quarter wave-plate and polarizing beam splitter pair then separated this reflected, image-bearing, light from the incident beam. A half wave-plate was added before the polarizing beam splitter so that the image beam and reference beam have the same polarization. A 3:1 demagnifying telescope and a 1:1 imaging lens, L 1, was used to relay the image beam onto the 2-mm-wide aperture of the MQW device where it interfered.
with the reference beam. Intensities of 4 and 2.5 mW/cm² for the image and reference beam respectively were typically used at the MQW device to write these holograms. In these experiments the writing beams were separated by an angle of 1.4°, which corresponds to a grating spacing of 31 μm at 830 nm.

A sinusoidal ac field of peak amplitude ±7.5 kV/cm and frequency 3 kHz was applied to the MQW well. This provides a more homogeneous electric field across the device aperture than a dc field and so gives a more uniform hologram recording. Reconstruction of the hologram was performed using a tunable Cr:LiSAF diode pumped laser tuned to the MQW device’s exciton peak (~850 nm) to maximize the hologram diffraction efficiency. The hologram was reconstructed by imaging the −1 or +1 diffraction orders of the readout beam onto a CCD camera.

To evaluate the transverse resolution of the holographic system, holograms of the USAF test chart were recorded in the absence of any scattering media. The reconstructed image was measured to have a transverse resolution of 13 μm. The depth resolution of the reconstructed image was measured by imaging the same 3-D test object described in the previous section. The different layers of the object were individual imaged and then computer rendered into a 3-D volume. The depth resolution was determined by the range of delays of the reference arm over which a single step of the object remained visible and was found to be 60 μm. This is limited by the coherence length of the laser and the angle of the writing beams (and therefore the grating period) at the MQW device.

The capability of the system to image through turbid media was next investigated. The image acquired when viewing a USAF test chart directly through a double pass of 13 MFP scattering solution is shown in Fig. 8(a), no image is readily seen due to the high amount of scattered background. Using the holographic system described above the image shown in Fig. 8(b) is obtained showing a transverse resolution of 50 μm.

The 3-D test object was then imaged through a scattering solution corresponding to 10 MFP. Fig. 9(a) shows a 3-

D image reconstructed from 2-D images taken using the holographic setup through 0 MFP and Fig. 9(b) shows the computer reconstructed image through 10 MFP. The depth resolution was measured to be 60 μm.

An attractive feature of the MQW devices is that, although the wavelength of the readout beam is constrained to the exciton peak (~850 nm), any writing wavelength may be used as long as the MQW devices are excited above their band-gap (i.e., ≤850 nm). This permits multiwavelength (i.e., color) and/or spectrally resolved holographic imaging. This is illustrated in Fig. 10 that shows a series of depth-resolved holographic images of a USAF test chart that was partially obscured by an edge filter that transmitted radiation at wavelengths longer than 815 nm and absorbed below this wavelength. These images were recorded and readout from a MQW device as the wavelength of the writing beams was tuned from 800 to 860 nm. As the writing wavelength is increased, the initially obscured portion of the test chart becomes visible until, at writing wavelengths longer than the exciton peak at 850 nm, no image is recorded.

The sensitivity of the MQW devices as photorefractive media was investigated by measuring the minimum image (signal) intensity needed to write a useful hologram of the USAF test chart as a function of the reference and the probe
intensities, Fig. 11(a) and (b) show the results when varying the reference and the readout beam intensities respectively. For low reference beam intensities the signal intensity needs to be large to reach the saturation intensity [see Fig. 11(c)]. For higher intensities of the reference beam the saturation intensity of the writing beams is reached independently of the signal intensity but the need for a large modulation depth requires that the signal intensity be sufficiently high. To investigate the dependence of the minimum required signal on the readout beam intensity, the reference intensity was kept constant at 250 μW/cm² such that saturation in intensity was always reached. At low readout intensities, the diffraction efficiency of the hologram needs to be large enough to produce a detectable diffracted beam: this demands a large modulation depth and hence a large signal beam intensity. At the higher readout intensities, the hologram is being erased by the readout beam and so the minimum signal needed to reach a given modulation depth is increased. It should be noted, although the minimum signal intensity required to write a useful hologram is greater for MQW device compared to the Rh:BaTiO₃ crystal, the hologram in the latter had not reached steady state after 60-s integration. On the other hand, the MQW device reached steady state and recorded a hologram in ≤0.4 ms—in fact, it required fewer photons to record the useful hologram.

The dynamic range of the MQW device, i.e., the ratio of the maximum erasing intensity-to-signal intensity, was measured in an experiment analogous to that described in the previous section. A third writing beam was introduced which was collinear with the signal but incoherent with it. This beam acted as an erasing beam and simulated light scattered outside the coherence length of the illuminating pulse. As it is indicated in Fig. 12, the maximum dynamic range of the MQW device is 1260, which is significantly smaller that the dynamic range of the Rh:BaTiO₃. This difference is believed to be associated with the fast response time of the MQW devices compared to the Rh:BaTiO₃, and to the fact that the holograms in the MQW devices are being constantly exposed (and therefore erased) by the readout beam during the writing process. Improving the dynamic range and sensitivity of the MQW device holography is a subject of our ongoing research.

IV. CONCLUSION AND FUTURE WORK

We have demonstrated the use of a photorefractive holographic imaging system as a coherence gate to discriminate against scattered light and provide depth-resolved images through turbid media. Using Rh:BaTiO₃ as a hologram recording medium, we have recorded depth-resolved images through
up to 16 MFP of turbid media, with sub-100-μm depth and transverse spatial resolution. The sensitivity and the dynamic range of the Rh:BaTiO₃ have been investigated and the later found to be as high as $10^6$. However, the long integration times required with this photorefractive bulk crystal medium are a disadvantage for real-world applications although the high damage threshold is attractive because it permits the use of high-power readout beams and tolerance to large incoherent backgrounds. As discussed in our earlier work [19], carrier mobility of this crystal leads to an optimum grating period of $\sim 1 \mu m$ which degrades the achievable spatial resolution, and the requirement for Bragg-matching of a separate readout beam increases the experimental complexity.

These issues have led us to the use of MQW devices as the holographic recording medium. We have demonstrated 3-D holographic imaging through up to 13 MFP of scattering medium with transverse and depth resolution of $\sim 50 \mu m$. The use of an applied field means that the optimal grating period does not impose a practical limit to the achievable spatial resolution. While the response time of these devices, which has been measured to be less than 0.4 ms [27], makes them suitable for real-time imaging. Unfortunately, their ability to discriminate against a background of diffuse scattered light appears to be less favorable than that the Rh:BaTiO₃ and we are currently working to maximize the sensitivity of the holographic recording process. We anticipate perhaps an order of magnitude improvement by optimizing the readout of the holograms. Work is also underway to increase the field of view of the devices and to shift the exciton peaks to longer wavelengths to extend the spectral coverage of this imaging system.

Bulk semiconductor crystals, such as CdTe, may offer a useful compromise between the two previously discussed holographic media. They retain the rapid response time advantage and high carrier mobility of the MQW devices while exhibiting higher damage threshold. Unfortunately, Bragg-matching is required for the readout beam while their spectral response is limited to wavelengths longer than $\sim 800$ nm. This spectral response is adequate for the near infrared wavelengths needed for biomedical imaging but limits their use to non-visible wavelengths for other applications. We have recently demonstrated depth-resolved imaging through turbid media using a Mn,V: CdTe crystal, supplied by Brimrose Corporation, which has response time of $< 10^{-5}$ ms at 1 W/cm$^{-2}$. Fig. 13 shows a depth-resolved holographic image of a USAF test chart recorded, in real time, through (a) 0 MFP and (b) 4 MFP of scattering medium. The measured transverse and depth spatial resolutions were 55 and 60 μm, respectively. This is very much a preliminary result but it shows the potential for this medium which will be investigated in future work.

Finally, we are studying the capability of photorefractive holography to image through static (solid) scattering media, with a view to imaging through living biological tissue. To date, most experiments reporting the use of coherence-gated (holographic) imaging techniques have used liquid (dynamic)
scattering phantoms such as aqueous suspensions of polystyrene microspheres or intralipid solutions. In general, weakly scattered light, which has an extra pathlength compared to the reference beam of less than the coherence length, will instantaneously write unwanted fringes that are averaged over the finite-acquisition time of the holographic recording medium. For a dynamic (liquid) scattering phantom, the Brownian motion of the scattering centres results in time-varying noise fringe patterns which average to a uniform background level over the image acquisition time. Any coherent imaging system can take advantage of this time-averaging when imaging through dynamic (e.g., liquid) scattering media. Photorefractive media have the advantage that they respond to the spatial derivative of intensity, rather than to its magnitude, and so this uniform background is not recorded and will not contribute to the reconstructed image. If an intensity-dependent recording medium (such as a CCD camera) is used, this incoherent background is recorded and must be removed to recover the image. For a static scattering phantom, the “instantaneous” noise fringe patterns do not time-average to a uniform background and so can degrade the reconstructed image. This can be considered as “interpixel crosstalk” and is a problem for all whole-field imaging systems. To image through static phantoms, however, all coherent imaging systems must address the issue of interpixel crosstalk. This may be approached using spatial incoherence, e.g., [28], and this will be the subject of future experiments.

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