Sub-100-μm depth-resolved holographic imaging through scattering media in the near infrared

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We discuss the compromise between depth and transverse spatial resolution for photorefractive holographic imaging through turbid media. Results from an optimized geometry for a 45°-cut rhodium-doped barium titanate photorefractive crystal are presented, demonstrating two-dimensional imaging through turbid media with both sub-100-μm depth and transverse spatial resolution.

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Optical imaging through turbid media may provide safe, chemically specific medical diagnostics. The relatively low absorption of tissue in the near infrared provides a suitable transmission window, but unfortunately the scattering cross section at optical wavelengths is high and the scattered light severely degrades images of embedded objects. Scattered light, however, loses coherence, so by selecting only the light that remains coherent with its source one may filter out the scattered light. This technique has been shown to effectively reduce the deleterious effects of scatter and provide high-resolution images through turbid media.1–8 Coherent detection for biological imaging is limited to samples less than ~4 mm deep,1 because the number of coherent photons decays exponentially as the photons propagate through the tissue. However, high-resolution optical imaging through modest (<1-mm) tissue depths can still provide a clinically useful tool, e.g., for detecting and monitoring skin cancer and perhaps for dermatological applications such as burn assessment.

Many of the recent coherence gated imaging systems, while achieving high resolution and sensitivity, have employed confocal imaging, which requires pixel-by-pixel transverse scanning to build up a two-dimensional (2D) image. Confocal imaging is effective at reducing the amount of off-axis scattered light, but the scanning inevitably increases the acquisition time. A technique has been developed for rapid 2D scanning with acousto-optic deflectors,2 but currently it is restricted to a limited transverse range. Some other techniques do allow single-measurement 2D image acquisition, which can significantly reduce acquisition times. These include synchronously pumped Raman amplifiers,9 Kerr gating,10 optical parametric amplifiers,3 and holographic imaging.4–7

We previously reported a coherence gating technique based on holographic imaging in photorefractive crystals to achieve depth-resolved images of 2D planes through a turbid medium in a single measurement. A schematic of a typical experimental setup is shown in Fig. 1. Transverse resolution of 30 μm and depth resolution of 2 mm were achieved with 760-nm light, which lies within the transmission window for tissue.4 More recently we demonstrated 50-μm depth and transverse spatial resolution by using 450-nm light in the blue,8 which may have applications for imaging through sea water. Depth resolution is achieved in both experiments by a ranging technique, described by Abramson11 as “light-in-flight,” based on low-coherence holography. The hologram is written with low-coherence light such that only light arriving at the holographic medium from a distinct depth within the object will temporally overlap and be coherent with the reference beam. Delaying the reference pulse, by adjustment of its arm length, facilitates imaging at different depths in the object.

In this Letter we discuss the factors determining the resolution of the holographic imaging system and the compromise between spatial and depth resolution. An optimized imaging geometry is used to experimentally demonstrate 100-μm depth and 80-μm transverse spatial resolution through 8 mean free paths (mfp) (on a double pass) of turbid medium in the near infrared.

The spatial resolution of the holographic imaging system is ultimately limited in the transverse direction to the diffraction limit and in the longitudinal direction to the coherence length of the light source.
In practice, however, the depth and the transverse spatial resolution are also limited by the imaging geometry. The transverse resolution of a hologram, written with cw beams, is limited by the numerical aperture of the collection optics and by the resolution of the holographic medium. However, when short-coherence-length light is used, the volume of the hologram is reduced if the coherence length of the light is much shorter than the beam diameters, as shown in Fig. 2(a). If the recording medium lies in the Fourier plane, the restricted hologram width will act as a spatial filter and limit the transverse resolution parallel to the plane of incidence. In a geometry in which the object is imaged into the crystal, the restricted hologram width limited the field of view. For this research we have considered only the Fourier holography geometry.

The depth resolution of the hologram is determined by the coherence length of the source and by the angle between the writing beams. The angular separation of the beams causes a variation in arrival time of the reference pulse across the surface of the holographic medium and therefore with respect to the arriving image signal. Thus the reconstructed hologram contains image information from a broad depth region in the object, the extent of which is determined by the angle between the writing beams, as shown in Fig. 2(b). This decreases the depth resolution, and it is further decreased for increasing angular separation of the beams.

Our previous experiment on holographic imaging in the near infrared showed limited depth resolution (2 mm) because of the large angular separation of the writing beams. The large angle was required for the hologram grating vector to be matched close to the optimum for the photorefractive crystal (which was cut at 0° to the c axis) and so achieve sufficient sensitivity in the near infrared. To reduce this penalty, we used light at 450 nm, increasing the sensitivity and permitting nonoptimum small angles to be used, achieving a double-pass scattering thickness as much as 14 mfp. For the present study a Rh:BaTiO₃ crystal with faces cut at 45° to the c axis was used (supplied by Sandoz Huningue S.A.), which has been shown to yield much higher diffraction efficiency, particularly for small angles between the writing beams. We now demonstrate that this permits high depth and transverse spatial resolution holographic imaging in the near infrared.

As shown in Fig. 1, the light source for the experiment was a mode-locked Ti:sapphire laser (Spectra-Physics Tsunami), which produced ultrashort pulses with a coherence length of ~70 μm at a wavelength of 760 nm. The imaging setup consisted of an interferometer with the object to be imaged in one arm and an adjustable delay in the reference arm. The beam in the object arm was expanded to 7-mm diameter and reflected from the polarizing beam splitter through a quarter-wave plate and a scattering cell onto the object. The object consisted of five concentric solid cylinders of aluminum, ranging in diameter from 1 to 5 mm in 1-mm steps and displaced in depth by 100 μm. This object reflects ~8% of the incident light. The scattering cell, which obscured the object, consisted of a 0.3% solution of 0.46-μm polystyrene spheres, which, from Mie theory, is calculated to be 8 mfp of scattering medium in a double pass. On reflection from the object the light double passed the scattering cell and quarter-wave plate and, having incurred 90° polarization rotation, passed through the polarizing beam splitter. The light was then collected by a 4-F imaging system, consisting of two 150-mm focal-length lenses, and imaged onto a standard CCD camera (Pulnix PE5530). The 0.65-mm-deep, 45°-cut Rh:BaTiO₃ photorefractive crystal was placed in the 4-F system at the intersection of the object and the reference beams. The angle between the writing beams was ~5.6°. The object was imaged end on, so the different depths within the object have different arm lengths in the interferometer. We recorded the depth-resolved images by matching the reference arm to the arm length of the desired layer of the object and exposing the photorefractive crystal for ~10–20 s. To read out the recorded image, we blocked the object beam and used the reference beam to construct the image into the CCD array. Our calculations for this experimental geometry predicted that 100-μm depth resolution, 80-μm transverse resolution parallel to the plane of incidence, and 40-μm resolution perpendicular to the plane of incidence should be possible.

The sensitivity of the imaging system can be improved in software by image subtraction. This eliminates the main noise source, the scattering of light from the reference beam into the CCD array from inhomogeneities in the holographic crystal. This was achieved by recording two image, one of the scattered reference beam noise before any hologram was written in the crystal and one of the noise and diffracted image after the crystal had been exposed to both beams. The subtraction of the images permits very weak diffracted images to be recovered, limited only by the dynamic range and random noise of the CCD array.

The results of imaging the three-dimensional test object through 8 mfp of scattering medium are shown in Fig. 3. Figure 3(a) shows a video picture of the object, and Fig. 3(b) shows the object imaged directly though 8 mfp of scattering medium. Figures 3(c)–3(e), which incorporate image subtraction, show holographic images, clearly resolving the different layers of the object, which were separated by 100 μm. Figure 3(f) shows Fig. 3(e) before the subtraction. Since only one ring...
was ever visible on the holographic images for any delay of the reference arm, the depth resolution is better than 100 μm. To test the transverse resolution we imaged a U.S. Air Force test chart through 8 mfp of scattering solution, as shown in Fig. 4. Bars of 88-μm width (group 2, element 4) can be resolved parallel to the plane of incidence, whereas in the perpendicular direction bars of 70 μm (group 2, element 6) can clearly be resolved and it is just possible to resolve the 31-μm bars (group 4 element 1). These figures closely match the calculated resolution limit.

In conclusion, we have demonstrated, for the first time to our knowledge, sub-100-μm depth and transverse spatial resolution through a turbid medium by using depth-resolved holographic imaging in the near infrared. The compromise among sensitivity, depth, and transverse spatial resolution has been discussed, and an optimized configuration for high-resolution imaging with a 45°-cut Rh-BaTiO₃ crystal has been demonstrated. The system could be extended to provide continuous real-time readout with a Bragg-matched beam and faster photorefractive media. Further improvements in the depth resolution and spatial resolution could be achieved by use of photorefractive materials with high sensitivity at an even smaller angular separation between the writing beams, e.g., semiconductor multiple-quantum-well structures. The maximum imaging depth is limited by the detector sensitivity (i.e., of the photorefractive medium and the CCD camera) and by noise that is due to scattered photons incident as the detector. The detector sensitivity will be improved by optimization of the photorefractive medium and the recording wavelength.⁸ We note that all coherent detection systems suffer noise penalties from scattered photons arriving at the detector. Our future research will include a signal-to-noise analysis of this technique.

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