Direct-to-video holographic 3-D imaging using photorefractive multiple quantum well devices

R. Jones, M. Tziraki, and P. M. W. French,

Femtosecond Optics Group, Department of Physics, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, U.K.

richard.jones@ic.ac.uk

K. M. Kwolek and D. D. Nolte,

Department of Physics, Purdue University, West Lafayette, Indiana 47907-1396

M. R. Melloch

School of Engineering, Purdue University, West Lafayette, Indiana 47907-1396

Abstract: Customised photorefractive quantum well devices have been developed for real-time video acquisition of coherence-gated, three-dimensional images. Holographic imaging with direct video capture has been demonstrated. The technique has been applied to 3-D imaging through turbid media with 50 μm transverse and 60 μm depth resolution being achieved using near infrared light through a phantom of 13 mean free paths scattering depth. Spectrally-resolved holographic imaging has also been demonstrated.

OCIS codes: (090.0090) Holography; (110.6880) Three-dimensional image acquisition; (170.1650) Coherence imaging

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References and links

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#4055 - $15.00 US Received November 28, 1997; Revised April 30, 1998

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Introduction

Fast recyclable holographic media have a wide range of real time applications such as interferometry, image correlation and 3-D imaging, including imaging through turbid media, such as biological tissue, via coherence gating e.g. [1,2]. Photorefractive multiple quantum well (MQW) devices satisfy many of the requirements needed for such recording media, such as high sensitivities [3] and very fast response times [4]. In this paper we report true real-time holographic imaging, recording directly to videotape, using significantly improved transverse field photorefractive $Al_{0.1}Ga_{0.9}As/GaAs$ MQW devices which were grown at Purdue University [5]. Both image and Fourier plane recording geometries have been investigated in order to optimise imaging performance [6]. We expect that the rapid image acquisition and 3-D sectioning capability of this technology will find application in microscopy and in real-time imaging technologies including in-vivo biomedical imaging.

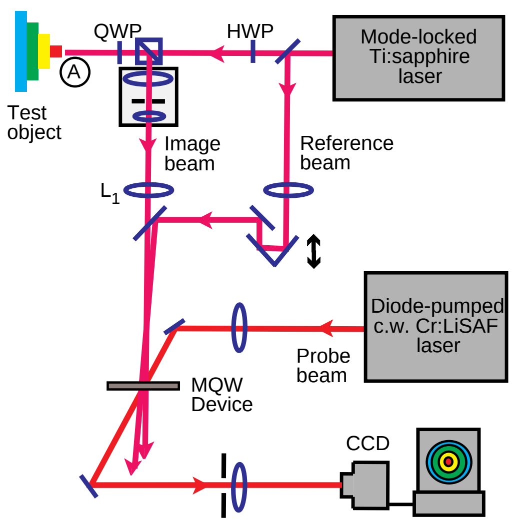


Fig. 1. Schematic of the holographic imaging system (QWP-quarter wave plate, HWP-half wave plate)

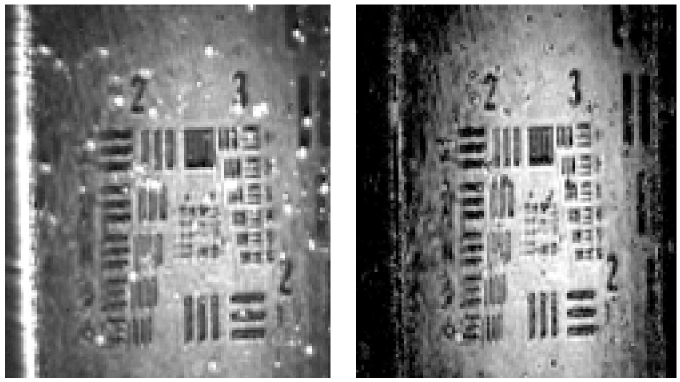
The experimental configuration used to record/reconstruct holograms in a MQW device via the Franz-Keldysh effect [7] is shown in Fig.1. Lens L_1 was used to relay the image beam onto the MQW device where it interfered with the reference beam. Depending upon the position of L_1 either a Fourier plane or direct image hologram was produced. For the results presented here, we have recorded only image plane holograms, typically using intensities of 4 mW/cm^2 and 2.5 mW/cm^2, for the image and reference beam respectively at the MQW device. A sinusoidal AC field of peak amplitude ± 10 kV/cm and frequency 3 kHz was applied to the MQW well. The apertures of the MQW devices used varied from 1-3 mm. The holograms were written at 830 nm using a mode-locked Ti:sapphire laser (Tsunami, Spectra-Physics). Any writing wavelength may be used as long as the MQW devices are excited above their band-gap (i.e. ≤ 850 nm). This permits multi-wavelength (i.e. colour) and/or spectrally-resolved holographic imaging. The holograms were read out in the first diffracted order onto a conventional CCD camera (Pulnix PE 530, pixel size 8.6x8.3 µm), at 15 or 30 frames per second, using a 4 mW/cm^2 intensity probe beam from a home-made diode pumped Cr:LiSAF laser tuned to the MQW device's exciton peak (~ 850 nm). For video recording, we acquired the signal from the CCD camera directly into a domestic video cassette recorder (VCR). The video clips in this paper were thus recorded in this manner in real time. Subsequently the output signal from the VCR was played into a frame grabber (Video Logic Captivator) and movies were recorded as xxx.avi files. The video acquisition software used (Vidcap) captured images at rate of 15 frames/sec, ~ 50 % were dropped. These were then converted to Quicktime video clips (xxx.mov files) using Smartvid.

Real-time depth-resolved imaging

This latest generation of MQW devices exhibited a greatly improved optical quality across their 2 mm aperture, which, together with the improved uniformity of the applied AC field, increased the field of view by 16 times compared to our previously published results [1]. Fig. 2 shows a reconstructed image of a USAF test chart which was used to measure the transverse resolution of the holographic system. This was determined to be 19 µm, for which the corresponding bars are shown. This image has been corrected for static background "noise" (which arises from light scattered from fixed inhomogeneities in the MQW device surface, the edges of the aperture and other components) by subtracting the light field recorded in the absence of a hologram.

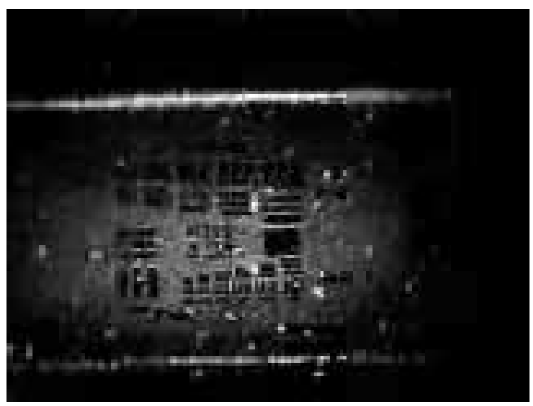
Fig. 2. (a) Holographic reconstruction of USAF test chart showing 50 µm bars.

The improved optical quality and the fast (sub-ms [1]) response times of these MQW devices, however, allowed us to record useful depth-resolved images directly from the CCD camera to a conventional video cassette recorder without any background subtraction or other signal processing, such as is shown in Fig. 3(a). An image of the background noise could also be recorded onto video and subsequently subtracted from Fig. 3(a), resulting in the image shown in Fig. 3(b). No significant difference can be seen comparing the background-subtracted, frame-grabbed, image of Fig. 2 (a) and the image shown in Fig. 3 (b). The truly real-time depth resolved imaging illustrated in Fig. 3(a) is possible because no computational signal processing is required, as is the case for e.g. electronic holography [8]. This is further illustrated by the real-time video clip shown in Video 1 which shows the reconstructed image of the USAF test chart view in real time while being translated in the recording plane. For all the video clips shown here no background subtraction has been done, and so there is some static noise arising from scattering centres in the MQW devices themselves.



(a) (b)

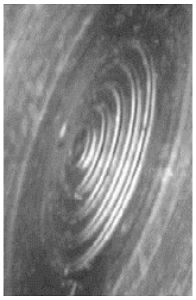
Fig. 3. (a) Holographic reconstruction of USAF test chart recorded direct to video. (b) Fig. 3 (a) with background noise subtracted.



Video. 1. Real-time reconstructed image of USAF test chart.

Real-time depth-resolved imaging of moving 3-D objects

Depth resolved 3-D imaging was demonstrated using a 3-D test object, which comprised a set of cylindrical steps, separated by 100 µm. Fig. 4 (a) shows a video picture of this 3-D test object and Fig. 4 (b) shows a computer generated reconstruction of this object obtained by adjusting the delay in the reference arm and recording holograms of each layer. These depth-resolved images were then combined using rendering software. The depth resolution was measured to be 60 µm (limited by the coherence length of the Ti:Sapphire laser).


(a)

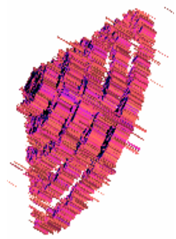
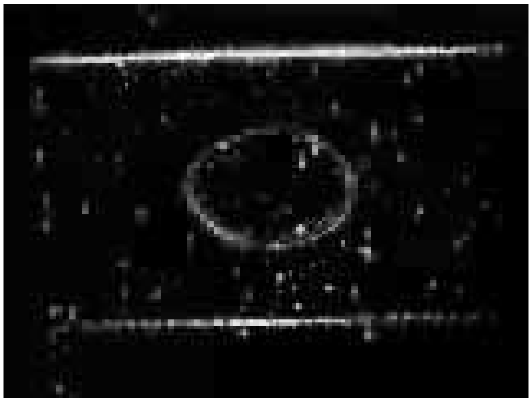

(b)

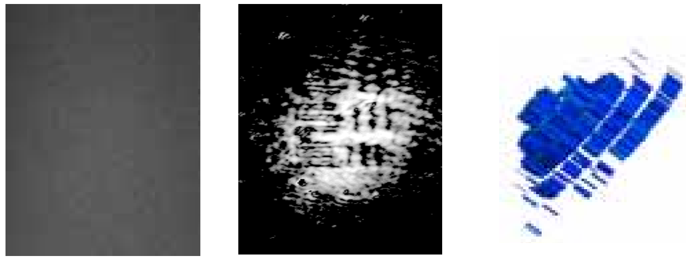
Fig. 4. (a) Video image of 3-D test object and (b) computer reconstruction of 3-D test object.

The individual depth-resolved images may be seen in Video 2 which shows the various layers of the 3-D test object as it was scanned through the holographic recording reference plane corresponding to matched pathlengths for the object and image beams. It should again be noted that Video 2 is a real-time video recording showing the real-time reconstructed image of the 3-D object as it is being translated in the longitudinal and transverse directions. This demonstrates that the extremely fast response of the MQW devices permits holograms of moving 3-D objects may be recorded and reconstructed. We anticipate applications, including microscopy and endoscopy, for which real-time depth-resolved objects of dynamic living subjects is required.


Video 2. Real-time reconstructed image of moving 3-D test object.

Depth-resolved imaging through turbid media

Holographic imaging may be applied through turbid media because it discriminates against scattered background light as a coherence gate: any photons whose path length exceeds that of the ballistic signal by more than the coherence length will not write any interference fringes. Thus, when the hologram is read-out, essentially only the unscattered (non-degraded) signal is reconstructed. We investigated this using a scattering cell containing a suspension of polystyrene microspheres (0.46 μm diameter, g = 0.72) which was placed before our test object (point A in Fig. 1). Approximately 500 mW was incident upon the scattering cell in an area of 0.25 cm^2.

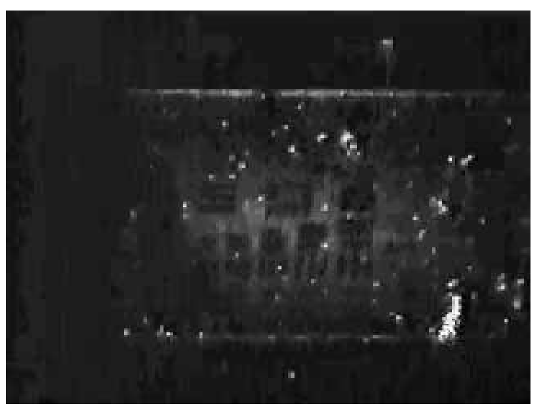


(a) (b) (c)

Fig. 5: (a) Direct "image" through 10 MFP (double pass) of scattering media. Holographic reconstruction of (b) USAF test chart through 13 MFP showing 50 μm bars; (c) 3-D test object showing 100 μm depth resolution through 10 MFP (double pass).

Fig. 5 (a) shows that the USAF test chart may not be directly viewed through a solution of 10 scattering mean free paths (MFP) (in double pass) due to the high amount of scattered background light. Using the holographic imaging system described above, a reconstructed image of the 50 μm test bars was obtained through up to 13 MFP scattering depth, as shown in Fig. 5 (b). 3-D imaging through 10 MFP (double pass) of scattering medium was demonstrated using the same 3-D test object as before, a typical 3-D reconstruction is shown in Fig. 5 (c). The depth resolution was measured to again be 60 μm.

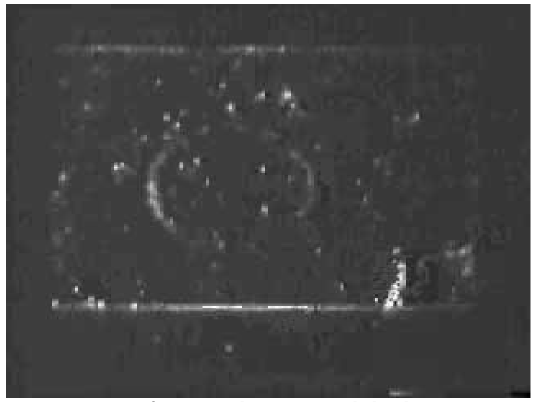
We also recorded depth-resolved holograms of the test chart and the moving 3-D test object through a scattering phantom. Video 3 shows the real-time reconstructed image recorded as the USAF test chart was translated behind a scattering solution of 8 MFP scattering depth. All the video images shown here through scattering media have degraded resolution and contrast when compared to the images seen on a monitor or the single frame grabbed images. This is due to the lower intensity of the reconstructed beam and the limited dynamic range and pixel size of the video file types used.



Video 3. Real-time reconstructed image of USAF test chart moving behind a scattering phantom of 8 MFP (double pass).

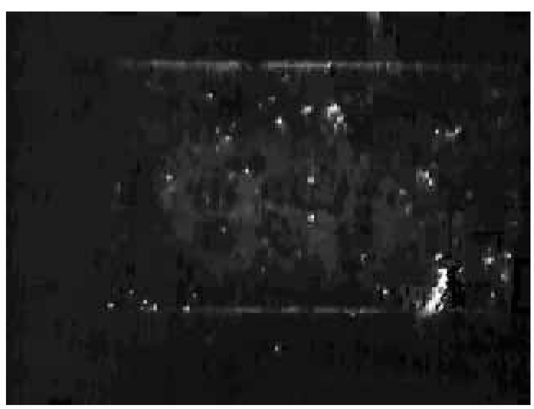
Video 4 shows the real time depth-resolved image of the 3-D test object moving behind a scattering solution of 8 mfp scattering depth. The reasons for the degraded image quality are not fully understood at present. In general we note that as the scattering depth of the obscuring phantom is increased, the signal to noise ratio of the reconstructed image is degraded but the spatial resolution is maintained.

#4055 - $15.00 US Received November 28, 1997; Revised April 30, 1998



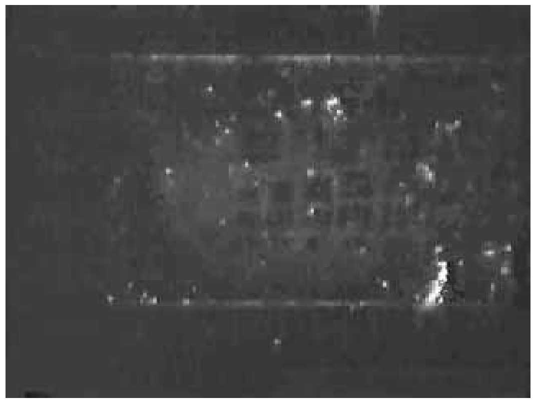
Video 4. Real-time reconstruct of 3-D test object moving behind an 8 MFP scattering phantom

The physics underlying the ability of our photorefractive holographic technique to image through turbid media has been discussed in depth in reference [9]. Scattered light which has an extra pathlength of less than the coherence length will instantaneously write unwanted fringes which are averaged over the finite acquisition time of the holographic recording medium. For a 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. Because photorefractive media respond to the spatial derivative of intensity, rather than to its magnitude, this uniform background will not contribute to the reconstructed image. For a static scattering phantom, the "instantaneous" noise fringe patterns would not time-average to a uniform background and so can degrade the reconstructed image. This can be considered as "inter-pixel cross-talk" and is a problem for *all* whole-field imaging systems. Any *coherent* imaging system, however, can take advantage of the time-averaging when imaging through dynamic (e.g. liquid) scattering media, this is illustrated by Video 5 and 6. Video 5 shows the USAF test chart imaged through a *solid* scattering phantom of 8.6 MFP (double pass). This phantom was made using a suspension of silicon microspheres in araldite resin in a manner similar to Firbank et al. [10]. The phantom is stationary and only bars larger than the 150 μm bars may be resolved and there is evident speckle on the reconstructed image.



Video 5. Real-time reconstructed image of USAF test chart behind a static scattering phantom of 8.6 MFP (double pass).

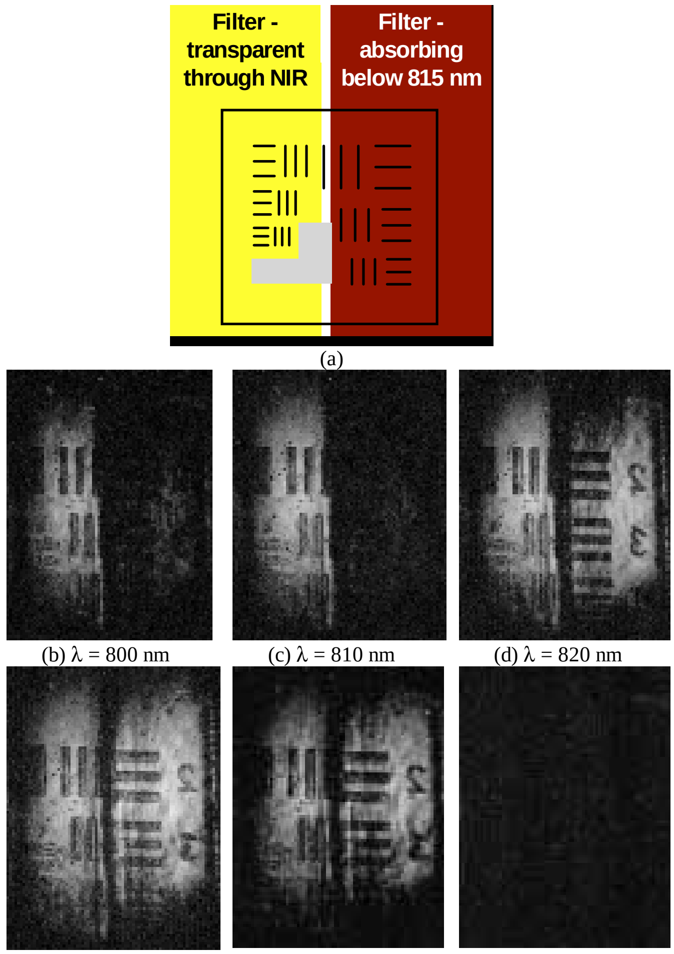
In Video 6 the phantom is shaken to introduce some time-averaging of the scattered light. This reduces the deleterious effects of speckle due to the inter-pixel cross-talk and now the 115 μm bars may be resolved. The reduced image resolution here compared to the single frame grabbed images is again due to the video capturing software being used. The experimental set-up is unaltered between these two videos - the only difference is the movement of the scattering media. To image through truly static phantoms, *all* coherent imaging systems must address the issue of inter-pixel cross-talk. This may be approached using spatial incoherence, e.g. [11] and is the subject of ongoing work.



Video 6. Real-time reconstructed image of USAF test chart behind a moving scattering phantom of 8.6 MFP (double pass).

Spectrally-resolved holographic imaging

One of the most important features of optical imaging modalities is that they can provide spectroscopic information. This may ultimately lead to chemically-specific or functional imaging. Using MQW devices as our holographic recording medium permits images to be recorded at any wavelength below the MQW exciton peak at 850 nm. This is demonstrated in Fig. 6 which shows a series of reconstructed images of a USAF test chart half of which was covered by a cut-off filter which only transmitted radiation above 815 nm, and half by a filter transparent to all the wavelengths used (to match the path length across the image). The images were recorded as the operating wavelength of the Ti:Sapphire laser was tuned from 800 to 860 nm. Below 815 nm, only the portion of the test chart beneath the transparent filter is seen, while above the exciton peak wavelength of 850 nm, no hologram is recorded. It should be noted that any visible radiation could be used to record the holograms and that, given red, green and blue recording radiation, RGB images could be recorded and read out (using the same read-out beam) onto the CCD camera. This would permit full colour reconstructed depth-resolved images of 3-D objects, including moving (living) subjects. The high speed response of the MQW devices means that it would be quite feasible to record the depth-resolved RGB images sequentially.



(a)

(b) λ = 800 nm (c) λ = 810 nm (d) λ = 820 nm

(e) λ = 840 nm (f) λ = 850 nm (g) λ = 860 nm

Fig.6. (a) Schematic of USAF test chart partially covered by cut-off filter and (b)-(g) reconstructed images as the recording radiation was tuned from 800 nm to 860 nm.

Conclusions

In conclusion, we have demonstrated a real-time holographic imaging system that provides ~ 50 μm depth and transverse resolution. This technique uses time-gated holography in conjunction with photorefractive MQW devices to give whole 2-D image field acquisition without the need for pixel by pixel transverse scanning. Direct depth-resolved image acquisition to a video recorder has been demonstrated. We anticipate many applications for rapid high resolution 3-D imaging including 3-D microscopy e.g. of living subjects, motion analysis, process monitoring and as an input device for 3-D animation. To these ends, further improvements in the field of view and optical quality are anticipated as the technology matures.

We have applied this system to image through up to 13 MFP of scattering medium, with 50 μm transverse and 60 μm depth resolution, via coherence gating. We note that 13 scattering MFP "penetration depth" corresponds approximately to a depth in tissue of ≥ 0.7 mm. This could be increased in practice by using a higher incident intensity at the tissue or by optimising the wavelength of the radiation, e.g. [12]. Because holograms may be written in the MQW devices at any wavelength shorter than that of the exciton peak, it is possible to acquire spectrally-resolved or colour 3-D images using this technology. This has been demonstrated and is the subject of ongoing research.

Acknowledgements

Funding for this research was provided by the UK Engineering and Physical Sciences Research Council (EPSRC). R. Jones acknowledges an EPSRC studentship. We also acknowledge funding from the Defence Evaluation and Research Agency (DERA). M. Tziraki acknowledges an EU TMR studentship.