Direct-to-video holographic readout in quantum wells for three-dimensional imaging through turbid media

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Customized photorefractive quantum-well devices have been developed for real-time video acquisition of coherence-gated, three-dimensional images in turbid media. Large-field-of-view holographic imaging with direct video capture is now possible. We have evaluated the role of intensity-limited device performance in Fourier-plane and image-plane holography in such devices and, using near-infrared light, have imaged through turbid phantoms of 13 mean free paths' scattering depth with 50-μm transverse and 60-μm depth resolution. © 1998 Optical Society of America

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Fast recyclable holographic media have a wide range of real-time applications such as interferometry, image correlation, and three-dimensional (3-D) imaging, including through turbid media, such as biological tissue, by means of coherence gating (see, e.g., Refs. 1 and 2). Photorefractive multiple-quantum-well (MQW) devices satisfy many of the requirements for such recording media, such as high sensitivities and fast response times. In this Letter we report true real-time holographic imaging, recording directly to videotape, using significantly improved transverse field photorefractive Al₀.₁Ga₀.₉As/GaAs MQW devices that were grown at Purdue University. Both image- and Fourier-plane recording geometries have been investigated to optimize imaging performance. 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.

Both image-plane and Fourier-plane recording geometries were investigated. Photorefractive quantum-well devices must perform below maximum allowable intensities, which directly constrain holographic imaging fidelity, especially when one is working with the high dynamic range of Fourier-plane imaging. We show here, for the first time to our knowledge, that image-plane imaging is superior when one is working with intensity-limited holograms.

The experimental configuration used to record–reconstruct holograms in a MQW device by means of the Franz–Keldysh effect is shown in Fig. 1. Lens L₁ was used to relay the image beam onto the MQW device, where it interfered with the reference beam. Depending on the position of L₁, either a Fourier-plane or a direct-image hologram was produced. Intensities of 4 and 2.5 mW/cm², for the image and reference beams, respectively, were used at the MQW device. A sinusoidal ac field of peak amplitude ±5 kV/cm and frequency 3 kHz was applied to the MQW well. An ac rather than a dc voltage was applied to avoid the field inhomogeneity often seen with dc fields, which can distort the holographic images. The holograms were written at 830 nm with a mode-locked Ti:sapphire laser. The holograms were read out in the first diffracted order onto a conventional CCD camera by a 4-mw/cm²-intensity probe beam from a diode-pumped Cr:LiSAF laser tuned to the MQW device's exciton peak (~850 nm).

With the apparatus configured for image-plane holography, a U.S. Air Force (USAF) test chart was used to measure the transverse resolution of the holographic system. This resolution was determined to be 19 μm, for which the corresponding bars are

![Test chart](image-url)

Fig. 1. Schematic of the holographic imaging system: L's, lenses; PBS, polarizing beam splitter; ND's, neutral-density filters.

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shown in Fig. 2(a). This image has been corrected for static background noise by subtraction of the light field recorded in the absence of a hologram (which arises mainly from light scattered from fixed inhomogeneities in the MQW device surface). Depth-resolved 3-D imaging was demonstrated with a 3-D test object that comprised a set of cylindrical steps separated from one another by 100 $\mu$m. Figure 2(b) shows a computer-generated reconstruction of this object obtained by adjustment of the delay in the reference arm and recording of a hologram of each individual layer. These depth-resolved images were then combined by use of rendering software. The depth resolution was 60 $\mu$m (limited by the coherence length of the Ti:sapphire laser).

These new MQW devices exhibited a greatly improved optical quality across their 2-mm apertures, which, together with the improved uniformity of the applied ac field, increased the field of view by 16 times compared with our previously published results. This improved optical quality and the fast [submillisecond (Ref. 1)] response times of these MQW devices 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, as shown in Fig. 3(a), which exhibits a transverse resolution of 19 $\mu$m. An image of the background noise could also be recorded onto video and subsequently subtracted in postprocessing, resulting in the image shown in Fig. 3(b). No significant difference can be seen when one compares 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

Fourier-plane holography was investigated as a means of increasing the field of view, which, in the image-plane geometry, was limited by the aperture of the MQW device. Figure 4a shows the image of a USAF test chart transmitted through the MQW device, and Fig. 4(b) shows its corresponding Fourier-plane intensity distribution that was incident upon the MQW device. Figure 4(c) shows the image of 100-$\mu$m bars obtained by reconstruction of a Fourier-plane hologram recorded in the MQW device, and Fig. 4(d) shows the Fourier plane of this reconstructed image. The reason for the reduced image quality of Fig. 4(c) compared with Fig. 4(a) can be understood by comparison of the Fourier planes shown in Figs. 4(b) and 4(d): The lowest spatial frequencies have not been recorded in the hologram, so the reconstructed image has effectively been spatially filtered. Whereas spatial filtering may sometimes be exploited to provide edge enhancement,9 for our application this image distortion is a disadvantage.

The spatial filtering occurs in the Fourier-plane holography because it is not possible to achieve a uniform fringe modulation depth across the hologram, owing to the large difference in the intensity of the lower- compared with the higher-spatial-frequency components. For the images shown in Fig. 4 the reference intensity was matched to that of the higher-spatial-frequency components. Matching the high intensity of the low spatial frequencies
required an incident power on the MQW devices of \( \sim 1 \) W, which exceeds the damage threshold of the device. When the intensity of the image signal was reduced to match an acceptable reference beam intensity, the reconstructed image was extremely weak and the higher spatial frequencies were not recorded. A similar effect is seen in Stark geometry MQW photorefractive devices.\(^{10}\) In the image-plane geometry this problem is not encountered because the intensity across the image is roughly uniform.

The existence of a maximum allowable intensity, combined with the need to use the highest intensities for coherence tomography to get the largest penetration through the scattering medium, appears to make Fourier-plane holography less useful for this specific application. On the other hand, image-plane holography has the disadvantage that imperfections in the device will be imaged directly to the image plane of the camera. A compromise between these two extremes may be the most useful expedient, and forming the hologram between the image plane and the Fourier plane may give more-uniform illumination than the Fourier plane, while keeping device imperfections out of the image plane of video.

Holographic imaging can be applied through turbid media because it discriminates against scattered background light as a coherence gate: Any photons whose path lengths exceed 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 (nondegraded) signal is reconstructed. We investigated this conclusion by using an image-plane geometry for which a scattering cell containing an adjustable suspension of polystyrene microspheres (0.46-\( \mu \)m diameter, \( g = 0.72 \)) was placed before our test object (point \( \mathcal{A} \) in Fig. 1). Figure 5(a) shows that the USAF test chart cannot be directly viewed through a solution of 10 mean free paths’ (MFP’s) scattering depth (in double pass) because of the high amount of scattered background light. Using the holographic imaging system described above, we obtained a reconstructed image of the 50-\( \mu \)m test bars through a scattering depth of as many as 13 MFP’s, as shown in Fig. 5(b). 3-D imaging through 10 MFP’s (double pass) of scattering medium was demonstrated with the same 3-D test object as before, and a typical 3-D reconstructed is shown in Fig. 5(c). The depth resolution was again 60 \( \mu \)m.

In conclusion, we have demonstrated a real-time holographic imaging system that provides \( \sim 50-\mu \)m depth and transverse resolution. This technique uses time-gated holography in conjunction with photorefractive MQW devices to give whole field two-dimensional image acquisition without the need for pixel-by-pixel transverse scanning. Direct, depth-resolved, image acquisition to a video recorder has been demonstrated. Image-plane holography has been determined to be the optimum experimental arrangement, in spite of the limited field of view, because the large intensity variation across the Fourier plane leads to spatial filtering and its associated image degradation. We applied this system to image through as many as 13 MFP’s of scattering medium, with 50-\( \mu \)m transverse and 60-\( \mu \)m depth resolution, by means of coherence gating.

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 note that holograms can be written in the MQW devices at any wavelength shorter than that of the exciton peak; therefore it is possible to acquire spectrally resolved or color 3-D images with this technology. This possibility is the subject of ongoing research.

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