Thin holographic camera with integrated reference distribution

Joonku Hahn, Daniel L. Marks, Kerkil Choi, Sehoon Lim, and David J. Brady*
Department of Electrical and Computer Engineering and The Fitzpatrick Institute for Photonics, Duke University, Durham, North Carolina 27708, USA
*Corresponding author: david.brady@duke.edu

Received 21 March 2011; revised 18 July 2011; accepted 22 July 2011; posted 25 July 2011 (Doc. ID 144536); published 18 August 2011

Off-axis digital holography typically uses a beam splitter to combine reference and object waves at an angle matched to the sampling period of the sensor array. The beam splitter determines the thickness of the recording system. This paper describes and demonstrates a total internal reflection hologram that replaces the beam splitter and enables hologram recording over a large aperture with a thin camera. © 2011 Optical Society of America

OCIS codes: 090.1995, 090.2890, 260.6970.

1. Introduction
Off-axis holography is typically implemented by using an beam splitter to combine an object wave and a collimated reference beam with constant amplitude and phase varying linearly in space. The linear phase ramp enables isolation of the object field from its twin and autocorrelation by Fourier analysis [1]. As shown in Fig. 1(a), the thickness of this holographic recording assembly is dominated by the beam splitter, which is generally at least as thick as the sensor array aperture. This is unfortunate because, in contrast with focal imagers, there is no fundamental reason that the thickness of a holographic system should grow with aperture size.

This paper describes how total internal reflection (TIR) holograms can be used to reduce the thickness of holographic sensors by replacing the combination of the collimator and the beam splitter used in a conventional off-axis holographic system, as illustrated in Fig. 1(b). TIR holograms were pioneered by Stetson [2]. This technique has been broadly studied for applications for lithography patterning and microscopy. A unique advantage of TIR distribution is that the undiffracted wave is confined to the hologram, which allows a structured illumination from a hologram without crosstalk from the undiffracted zeroth order. Another benefit of TIR holograms is that compact optical systems can be designed by folding the optical path, as in the edge-illumination geometry proposed by Upatnieks [3–5]. This geometry has been analyzed by Phillips and co-workers [6,7].

Our goal in this paper is to show that a TIR hologram plate can be directly attached to two-dimensional (2D) sensor arrays to distribute a reference plane wave for thin digital holographic cameras. Figure 2 illustrates the concept of our TIR hologram module. The reference signal is folded into a glass plate by a right-angle prism. The reference is reflected from the back surface of the glass plate and is then collimated by a hologram recorded in a surface emulsion to create a reference beam for a digital holographic camera. The function of each component is described in the next section.

2. Recording and Characterization of a TIR Hologram Module
We used a glass plate with red sensitive silver halide emulsion (PFG-01) from Integraf L.L.C. [8] to construct the TIR hologram plate. Figure 3 shows the structure of the TIR hologram plate and accompanied optics for creating the input field entering the TIR hologram plate. In Fig. 3(a), an optical path is
formed by the combination of a beam shaper, a right-angle prism with an optical stop, and the TIR hologram plate. The beam shaper is composed of a ferrule connector for a single mode fiber, a linear polarizer to filter out improperly polarized light, and a cylindrical lens generating an ellipsoidal beam.

Since the beam enters the hologram material inside a glass with an oblique angle, if a circular beam enters the TIR hologram plate, the reflected beam forms an elongated ellipsoidal beam. Since this beam can be much larger than the sensor area, the power efficiency is not optimal. To mitigate suboptimality, we design the beam input to the TIR hologram as an ellipsoidal beam that becomes a circular (reference) beam whose area is about the same as the complementary metal-oxide semiconductor (CMOS) sensor area when the reference beam is retrieved.

Figure 3(b) shows a photograph of a CMOS sensor with the TIR hologram plate. The CMOS sensor is attached after the recording of the TIR hologram is complete. The sensor used here is Lumenera Corp. Model Lu105. The array consists of 1280 × 1024 elements with pixel pitch being 5.2 μm. Figure 4 shows the dimension of this module. The thickness of the TIR hologram plate is 2 mm, and the incident angle of a beam incident on hologram material is designed as 84.5°. The gap between the TIR hologram plate and the CMOS sensor is 5 mm and this gap is regarded to be reducible without an appreciable problem. Even though the thickness of the whole system is 33.0 mm, most of this is due to the CMOS sensor control board and the frame holding the plate. The optical system is only 7 mm thick and could be further reduced to 2 mm in packaging that reduces the gap between the plate and the sensor. The key issue in making a holographic camera compact is to replace a beam splitter with a thin element since a beam splitter needs a thickness compatible to the sensor aperture, but the TIR plate thickness is independent of aperture size. At that point, the thickness of the plate is remarkably small in comparison to that of a beam splitter.

The TIR hologram plate is recorded by exposing a beam, through a beam shaper, and a plane wave to the hologram material on the front side of the plate. The recording plane wave covers a 15 mm × 15 mm area matched to the dimensions of the CMOS sensor. After the exposure, the hologram is developed by a JD-2 processing kit that contains potassium dichromate. After the development, the hologram material can undesirably shrink. This is a well-known problem of silver halide material under a wet process [9–11]. This is a main reason of an aberration of a
retrieved reference wave. As another reason, the recording condition can be considered since the coupling of light dynamically changes during recording a hologram in material. So, the properties of a reference wave may be different depending on recording conditions. To account for these effects, as well as aberrations induced by the recording optics, we characterize the TIR reference wave after recording.

The intensity profile of the retrieved reference beam is measured by the CMOS sensor attached to the TIR hologram plate without an object wave, and it is shown in Fig. 5(a). The phase profile of the retrieved reference beam is measured by recording a digital hologram of a plane wave signal. The incident angle of the probe beam is \( \theta_x = -1.6^\circ \), and \( \theta_y = 1.1^\circ \). The probe beam is modulated by a piezo stage, and its relative phase is shifted by an interval of \( \pi/2 \) for using a four-step phase-shifting algorithm. Then a resultant phase profile of the retrieved reference beam is shown in Fig. 5(b).

Using the characterization results, the autocorrelation \( I_R(x,y) \) of the reference wave and its phase profile \( \phi_R(x,y) \), the reference wave can be expressed as

\[
U_R(x,y) = \sqrt{I_R(x,y)} \exp\{j\phi_R(x,y)\}. \tag{1}
\]

An object wave is measured by an off-axis hologram with a carrier frequency defined as an angle between the reference and object waves. The off-axis hologram intensity \( I_H(x,y) \) that is measured by using the TIR hologram plate can be expressed as

\[
I_H(x,y) = |U_R(x,y) + U_O(x,y)|^2 \\
= I_R(x,y) + |U_O(x,y)|^2 \\
+ 2 \text{Re}\{U_R^*(x,y)U_O(x,y)\}. \tag{2}
\]

In Eq. (2), modulation of the object wave by the thin hologram plate is assumed negligibly small. Since the angle between wave vectors applied to record a hologram is almost 90°, the period of interference fringes are small enough in comparison of the pixel pitch of a CMOS sensor. Therefore, the modulation by a thin hologram makes perturbation in the object wave with much higher spatial frequencies than that measurable by the CMOS sensor. But, practically, the thin hologram may generate unexpected perturbation with low spatial frequencies and, in that case, there is room for improvement in reconstructing the object wave.

The bandwidth of the reference wave can be computed from Eq. (1). Figure 6(a) shows the Fourier transform of the reference field. Its cross-sectional plots along the \( f_x \) and \( f_y \) axes are shown in Figs. 6(b) and 6(c). The maximum bandwidth of the CMOS sensor with pixel pitch \( p \) is given by

Fig. 4. (Color online) Dimensions of the module with (a) front view and (b) cross-sectional view.

Fig. 5. (Color online) Reference wave retrieved by TIR hologram plate and its (a) intensity profile and (b) phase profile.

\[
U_R(x,y) = \sqrt{I_R(x,y)} \exp\{j\phi_R(x,y)\}. \tag{1}
\]

Fig. 6. (Color online) (a) Fourier transform of the retrieved reference \( U_R(x,y) \), its cross section along (b) the \( f_x \) axis and (c) the \( f_y \) axis. Here, the amplitude value of the band in the vertical axis is represented in arbitrary units.
\[ B_x = B_y = 1/2p. \] (3)

If we choose the bandwidth of the reference wave as half the maximum value, its bandwidth is about 0.012B_x \times 0.14B_y. However, it is more reasonable to choose the critical value defining the bandwidth comparable to the signal value of an object wave. This will be discussed in detail in Section 3.

The off-axis hologram shifts the band of an object wave off the undiffracted term by a carrier frequency of the reference wave, and the signal band is separated from its autocorrelation and twin. The measurable bandwidth of the object wave is limited by the requirement that each component must be separable in Fourier space. From Eq. (2), the Fourier transform of the off-axis hologram intensity \( I_H(x,y) \) is given by

\[
F\{I_H(x,y)\} = F\{I_R(x,y)\} + F\{|U_O(x,y)|^2\}
+ F\{2\text{Re}(U_R^*(x,y)U_O(x,y))\}. \tag{4}
\]

Here, the first term on the right-hand side can be obtained from Eq. (1). So the limit at which an object wave can be measured is determined from the separation of the second and third terms. The third term has a signal that is an object wave. After separation of this term, an object wave is obtained by division by the conjugate of the characterized reference wave.

3. Experimental Results

An experimental setup for performing the off-axis digital holography using the designed TIR hologram plate is shown in Fig. 7. In this setup, a piezo stage to which a mirror is attached for phase shifting is used solely for the characterization of the reference wave. The reference arm is composed of a single mode fiber, a beam splitter, and a TIR hologram plate. The signal arm is split from the reference arm in front of an He–Ne laser, and the beam in the object arm diverges by a lens and illuminates a transparent object on which a diffuser is attached. The object, a transparency showing the word “Optics,” is placed 209 mm away from the CMOS sensor.

The measured off-axis hologram and its Fourier transform are shown in Figs. 8(a) and 8(b), respectively. Figure 8(c) shows the difference between the Fourier transforms of the intensity of a reference wave and the off-axis hologram: \( F\{I_H(x,y)\} - F\{I_R(x,y)\} \). In Figs. 8(a) and 8(b), the brightness is adjusted to show the band of the object wave clearly since the amplitude values of this band are weaker than the autocorrelations of object and reference waves. As discussed in Section 2, it is proper to consider the bandwidth of the reference depending on the amplitude value of signal. In Fig. 8(b), the bandwidth of the reference wave along the \( f_y \) axis is over the half-bandwidth of the CMOS sensor, and the band of the reference wave overlaps the band that is a product of an object wave and the conjugate of a reference wave. Figure 8(c) shows that the difference \( F\{I_H(x,y)\} - F\{I_R(x,y)\} \) is helpful for separating the signal from its twin and autocorrelation because the autocorrelation of a reference wave has been removed.

For a sensor maximum spatial frequency of \( B_F \) and a reference carrier frequency of \( B_R \), the maximum measurable bandwidth \( B_O \) of an object wave is determined by

\[
B_O = \begin{cases} 
B_F/2 - B_R/2 & \text{for } 0 \leq B_R < B_F/3 \\
B_F - 2B_R & \text{for } B_F/3 \leq B_R \leq B_F/2.
\end{cases} \tag{5}
\]

After the separation of the product of an object wave and the conjugate of a reference wave, the object wave is obtained by division using a reference wave in Eq. (1).

The original object may be estimated by backpropagation according to the angular spectrum method [12]:

\[
U_O(x,y;z') = U_O(x,y;z) \bigotimes h(x,y;z' - z), \tag{6}
\]

where \( \bigotimes \) is a convolution operator and \( h \) is a backpropagation kernel, and Fourier transform of this propagation kernel is given by

![Fig. 7. (Color online) Experimental setup for off-axis digital holography with TIR hologram plate.](image-url)
\[ F\{h(x,y;z' - z)\} = \exp\left[j(z' - z)\sqrt{k^2 - k_x^2 - k_y^2}\right]. \quad (7) \]

The convolution in Eq. (6) is computed by a fast Fourier transform.

The object field reconstructions and a photograph of the object are shown in Fig. 9. Figure 9(a) shows the backpropagation result of the product of the conjugate of a reference wave and an object wave. Figure 9(b) shows the backpropagation result of an object wave obtained by removing the reference wave. Figure 9(c) shows the backpropagation result of an object wave obtained by removing the reference wave.
obtained in the characterization process. It was observed that the effect of phase correction is much stronger than that of the intensity correction.

To test the mechanical stability of our thin holographic camera, we recorded a digital hologram of three-dimensional (3D) object 50 days after the experiment of Fig. 9. The original calibration model for the reference was found to become inaccurate. Figure 10 shows the new measured TIR reference field. The phase profile in Fig. 10(b) shows a distinct change compared to the phase profile in Fig. 5(b). While further study is needed, we suggest that this change may be due to aging of the holographic material or mechanical distortion of the mounting components.

Figure 11 shows an experimental setup for imaging a 3D object. The 3D object is composed of symbols “×” and “+” at different distances, as shown in Fig. 11(b). These two symbols are positioned with a 30 mm gap; one is located at $z = 292$ mm and the other is located at $z = 322$ mm.

The measurement of the 3D object is shown in Fig. 12(a). The Fourier transform of the off-axis hologram itself, $F(I_H(x,y))$, and the Fourier transform of the subtraction between the off-axis hologram and the intensity of a reference wave, $F(I_H(x,y)) - F(I_R(x,y))$, are shown in Figs. 12(b) and 12(c), respectively. There is an overlap between a signal and the autocorrelation of a reference wave, as shown in Fig. 12(b). Figure 12(c) shows that the autocorrelation of the reference wave is removed.

Figure 13 shows reconstructed images before and after elimination of the irregular intensity and phase aberration of reference wave. (a) and (b) show the reconstruction images before elimination at distances $z = 292$ mm and $z = 322$ mm, respectively. (c) and (d) show the reconstruction images after elimination at distances $z = 292$ mm and $z = 322$ mm, respectively.

4. Conclusion

We demonstrated the design and the characterization of a thin hologram plate based on the TIR hologram for creating a reference beam for off-axis holography for compact sensors. With this TIR
hologram reference module, 2D and 3D objects are measured and their object waves are reconstructed by backpropagation. We have shown that, when the fabrication of the hologram is imperfect, the performance can be improved by characterizing the reference wave.

This research was supported by the Defense Advanced Research Projects Agency (DARPA) under United States Air Force Office of Scientific Research (AFOSR) contract FA9550-06-1-0230. The authors thank James Fienup for helpful suggestions.

References