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Incoherent off-axis Fourier holography for different colors using a curved mirror

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ABSTRACT

Herein we describe an incoherent off-axis Fourier holographic system that uses a curved mirror in conjunction with color filters to capture holograms. Conceptually, our system is similar to both the Fourier incoherent single channel holography (FISCH) and the incoherent off-axis Fourier holographic (IOFH) systems. Our proposed system, which is termed incoherent off-axis Fourier holography with curved mirror (IOFH-CM), is not as robust in its response to environmental changes when compared to single channel light systems because it relies on dual light pathways. However, IOFH-CM and IOFH have the same three advantages over FISCH. First, replacing the spatial light modulator (SLM) with a curved mirror makes it cost-effective and simple. Second, its light throughput is high; and the third advantage is its ability to capture holograms of samples placed on an optical axis by tilting one mirror. A fourth advantage, compared to IOFH, is its use for different colors because, IOFH-CM requires only a filter change to capture different colors and no other movements of any optical component or camera is necessary. Here, we demonstrate the holographic capabilities of IOFH-CM using three different color filters.

1. Introduction

Incoherent holography has been used in the past [1,2], and can be implemented in different forms using a variety of setups, including radial shear holography [3], rotational shear holography [4], conoscopic holography [5], and optical scanning holography [6,7]. Also, among the more recent developments are Fresnel incoherent correlation holography (FINCH) [8–11] and Fourier incoherent single channel holography (FISCH) [12,13].

For both FINCH and FISCH, the two interfering beams follow the same channel and are resilient to environmental changes (e.g. temperature, pressure, air flow etc.) that can cause phase distortions. These two methods make use of a spatial light modulator (SLM) and are categorized as single channel systems.

FINCH, like every other inline Fresnel holographic system, has unwanted contributions from zero order term and twin image term. To remove these term, at least three holograms must be combined through the phase shift method to form one complex hologram. The FINCH system has already implemented using dual path systems [14,15], which also has the limitation of capturing at least three holograms to remove zero order and twin image contributions. These dual path systems also have another limitation of being more sensitive to environmental changes when compared to single channel systems. However, eliminating the SLM makes them more simple and cost-effective. The introduction of the single short off-axis Fresnel holographic system [16], which is also conceptually similar to FINCH, has eliminated the need to capture at least three holograms.

FISCH is used for incoherent Fourier holography and has one drawback, which was mentioned in [12], that is related to sample position. FISCH can only be applied to samples that have placed completely on one side of the optical axis (i.e. the half plane). Previously, our incoherent off-axis Fourier holographic (IOFH) system [17] implemented the concept of FISCH by replacing the SLM with an optical lens. When compared to FISCH, the IOFH system is cost-effective, simple, and has holographic capability even for samples present on its optical axis.

One drawback of the IOFH system is that it cannot capture different colors without physically moving the lens that is attached to an arm of a modified Michelson interferometer. This limitation caused by light dispersion introduced by the lens. An alternative technique known as incoherent off-axis Fourier triangular color holography (IFTCH) was recently introduced [18]. When compared to FISCH, IFTCH has the advantage of being off-axis. However, this technique has two limitations. First, axial movement of the camera is required for capturing

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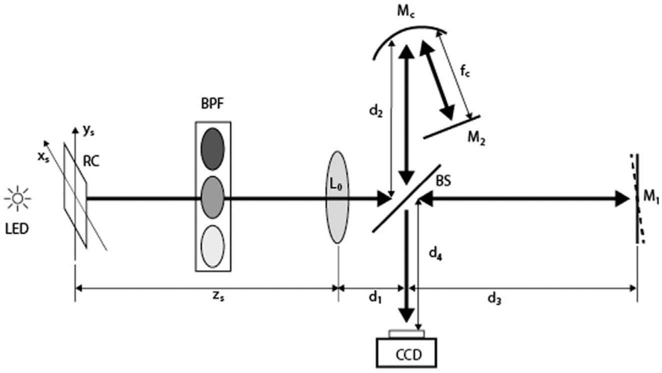

Fig. 1. Schematic of the dual path color robust incoherent off-axis Fourier holographic (IOFH-CM) system,*RC* resolution chart,*BPF* band pass filter, L_o lens, M_c curved mirror,*BS* beam spliter, M_1, M_2 mirrors,*CCD* charge-coupled device.

different colors. Second, the two interfering beams are not of equivalent magnification, which reduces its performance.

Here, we have implemented the concept of FISCH by using a curved mirror. Similar to our previous IOFH system, our proposed IOFH-CM is also a dual channel system, and it shares the same three advantages that IOFH has over FISCH. First, IOFH-CM is simple and cost-effective because the need for the SLM is eliminated; second, it has high light throughput; and third, it is an off-axis system that can be applied to samples placed on its optical axis. The use of IOFH-CM to capture different colors without any axial movement for any optical component or camera contributes to its novelty. With these advantages, our system has potential for contributing to the development of a Fourier incoherent color holographic microscope.

2. System design and methodology

The design of the IOFH-CM system is illustrated in Fig. 1. Here we describe the system in transmission mode, but it can be modified to capture reflected or fluorescent light. White light, after interacting with the sample, is passed through a band pass filter (BPF) to select one color. This quasi-monochromatic light, after passing through the achromatic lens L_o, is divided into two beams by a beam splitter, and enters into a modified Michelson interferometer. One arm of the interferometer has a curved mirror M_c, and the beam that enters this arm is focused by M_c, which is reflected back by mirror M_2. The other beam that is reflected from tilted mirror M_1, interferes with the first beam on the surface of the CCD.

Conceptually, IOFH-CM is similar to FISCH and our previously described IOFH system [12,17]. A diverging spherical beam coming from point $p(\vec{r}_s, z_s)$ at $z_s = f_o$ where $\vec{r}_s = (x_s, y_s)$ is radial position of point and f_o is the focal length of lens L_o. This diverging beam is collimated by lens L_o and is split into two beams. Eq. (1) describes the beam that is reflected by the tilted mirror M_1 when it reaches the capture position:

$$B_1(x, y; \vec{r}_s, z_s) = c_1(\vec{r}_s, z_s)A_s \cdot Q\left(\frac{1}{f_s + d}\right) \cdot L\left(\frac{-\vec{r}_s f_s}{z_s(f_s + d)}\right) \cdot L(x, y; \vec{r}_s), \tag{1}$$

where A_s is the amplitude, $c_1(\vec{r}_s, z_s))$ is a complex constant, $Q(\xi) = \exp[i2\pi\xi\lambda^{-1}(x^2 + y^2)]$ and $L(\xi) = \exp[i2\pi\lambda^{-1}(\xi_x x + \xi_y y)]$ are the quadratic and linear phase functions, respectively. The linear phase function $L(x, y; \vec{r}_s)$ is introduced by tilted mirror M_1. The other parameters are $f_s = \frac{f_o z_s}{f_o - z_s}$ and $d = d_1 + 2d_3 + d_4$. The second reflected beam, which is focused by curved mirror M_c and is reflected back by plane mirror M_2 at the capturing position, is given by Eq. (2) and a detailed derivation is described in IOFH [17]:

$$B_2(x, y; \vec{r}_s, z_s) = \left[c_2(\vec{r}_s, z_s)A_s \cdot L\left(\frac{ab}{a + 2f_c}\right) \cdot Q\left(\frac{-(b + f_c)}{f_c(b + 2f_c)}\right)\right] * Q\left(\frac{1}{d_{24}}\right), \tag{2}$$

where $a = \frac{-\vec{r}_s f_s}{z_s(f_s + d_{12})}$, $\frac{1}{b} = \frac{f - f_s - d_{12}}{f(f_s + d_{12})}$, $d_{12} = d_1 + d_2$, $d_{24} = d_2 + d_4$.

$$B_2(x, y; \vec{r}_s, z_s) = c_2(\vec{r}_s, z_s)A_s \cdot L\left(\frac{EF}{F + d_{24}}\right) \cdot Q\left(\frac{1}{F + d_{24}}\right), \tag{3}$$

where $E = \frac{ab}{a + 2f_c}$, $\frac{1}{F} = \frac{-(b + f_c)}{f_c(b + 2f_c)}$.

The resulting interference intensity of beam B_1 and B_2 is given by Eq. (4).

$$I(x, y; \vec{r}_s, z_s) = |B_1 + B_2|^2. \tag{4}$$

$$I(x, y; \vec{r}_s, z_s) = |B_2|^2 + |B_2|^2 + B_1 \cdot B_2^* + B_1^* \cdot B_2. \tag{5}$$

Due to the incoherent nature of light, the resulting hologram is an incoherent summation of contributions from all points and is given by Eq. (6).

$$H(x, y) = \iiint I(x, y; \vec{r}_s, z_s) dx_s dy_s dz_s. \tag{6}$$

We will analyze only one term $B_1 \cdot B_2^*$ from Eq. (5) which has complete sample information.

$$B_1 \cdot B_2^* = c_1 c_2 A_s^2 \cdot Q\left(\frac{1}{f_s + d}\right) \cdot Q\left(\frac{-1}{F + d_{24}}\right) \cdot L\left(\frac{-\vec{r}_s f_s}{z_s(f_s + d)}\right) \cdot L\left(\frac{-EF}{F + d_{24}}\right) \cdot L(x, y; \vec{r}_s). \tag{7}$$

Here we briefly mention the reconstruction process, described in detail in FISCH [12], which depends on the location of the sample. For sample plane at the focus of lens L_o, only inverse Fourier transform is required and both the image and twin image are in focus in the same plane at different locations. For off-focus sample planes, the reconstruction procedure involves extra field propagation in free space after inverse Fourier transform with only the image or twin image in focus depending on the propagation direction. The reconstruction for off-focus locations is given by Eq. (8)

$$O(x, y, z_r) = F^{-1}\{H(\alpha x, \alpha y)\} * Q\left(\frac{1}{z_r}\right), \tag{8}$$

where $\alpha = \frac{1}{\lambda f_r}$ is the scaling factor and f_r is the focal length of reconstruction lens. The free space propagation distance for off-focus object location is z_r and its value derived from Eqs. (7) and (8) is given below.

$$z_r = \left(\frac{1}{f_s + d} - \frac{1}{F + d_{24}}\right) f_r^2. \tag{9}$$

3. Results and discussion

The implementation of IOFH-CM is shown in Fig. 1. A white mounted LED (MWWHL3, Thorlabs, NJ, USA) was used as a light source to illuminate the negative resolution chart (RC). The light beam, after diffraction from the target, was filtered using three different filters (λ=650 nm, $\Delta\lambda$=10 nm, λ=600 nm, $\Delta\lambda$=10 nm, λ=550 nm, $\Delta\lambda$=10 nm) to capture holograms at different wavelengths. The other parameters of the systems are f_o=200 mm, d_1=23 mm, d_2=160 mm, d_3=260 mm, d_4=60 mm and f_c=100 mm.

First, to demonstrate the Fourier holographic properties of the IOFH-CM system, we used only one filter (λ=600 nm, $\Delta\lambda$=10 nm) with RC at different axial locations. The first hologram, shown partially in Fig. 2(a), was captured by placing the target on the optical axis at the focus of lens L_o ($z_s = f_o$=200 mm). The resulting reconstructed image, obtained by just a single inverse Fourier transform, is shown in Fig. 2(b). Both image and twin image are in focus at the same plane but are spatially at different locations due to the off-axis nature of the system.

To demonstrate the 3D information capturing capability of IOFH-CM, a portion of a second hologram captured using the same filters