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# Stochastic Digital Holography for Visualizing Strongly Refracting Transparent Objects

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**Abstract:** This paper presents a digital holographic method to visualize and measure refractive index variations, convection currents, or thermal gradients, occurring inside transparent but strongly refracting object. The proof of principle is provided through the visualization of refractive index variation inside a lighting ampoule. Comparison with transmission and reflection holography is also provided.

**OCIS codes:** (090.1995) Digital holography, (090.2880) Holographic interferometry, (090.5694) Real-time holography, (120.5050) Phase measurement

## 1. Introduction

Visualizing flows inside a transparent but strongly refracting object remains an open problem. For example, objects as a glass ball, an ampoule, a glass container, a glass flask, ..., are not opaque but they are strongly refracting light and measuring inside is not straightforward. It follows that observing phenomena, such as refractive index variations, convection currents, or thermal gradients, occurring inside the object requires specific methods. Different experimental methods are usually used to investigate fluids and to visualize/measure dynamic flows [1-3]. Nevertheless, these approaches are appropriated when the envelope including the flow is relatively smooth and transparent (i.e. not strongly refracting). A suitable experimental method should be able to exhibit the phase changes inside the object without suffering from any image distortion. This paper proposes an experimental approach based on stochastic digital holography to investigate flows inside a strongly refracting envelope. It leads to the measurement of the phase change inside the object, so as to get a quantitative measurement. Experimental results are provided in the case of the visualization of refractive index variations inside an ampoule.

## 2. Proposed method

The approach that can be quite adapted to visualize inside a strongly refracting object is describes in Fig. 1. The sensor includes  $N \times M = 1920 \times 1440$  pixels with pitches  $p_x = p_y = 3.65 \mu\text{m}$ . The main feature is that a diffuser is used to illuminate the object to provide a stochastic back illumination. The set-up exhibits some similarity compared to a classical transmission microscope, although, no microscope objective is used and the illuminating wave is quite a speckled wave. A negative lens is put in front of the cube to virtually reduce the object imaged by this lens. This leads to a more compact system compared to the case where the lens is not used. For example, for an object size of 10-15cm, the distance  $d_0$  in Fig. 1 has to be greater than 2m. The use of the negative lens produces a smaller image of the image, which position is close to the sensor [4,5]. Thus the distance than has to be used in the algorithm is  $d'_0$  (see Fig. 1). The optimization of the off-axis the set-up has to follow the basic rules about the Shannon conditions [6].

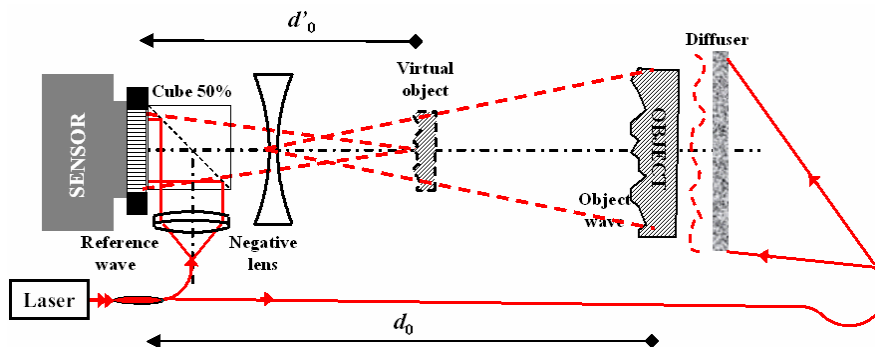


Fig. 1. Digital holographic set-up

Particularly, the focal length of the lens has to be judiciously chosen. Especially, the criterion is the observation angle from the sensor, which has to fulfil this condition:

$$\theta_{\max} = -\frac{\lambda}{(4 - 2\alpha)\max(p_x, p)} \quad (1)$$

where  $\alpha$  is the accepted tolerance in the superposition of the useful +1 order and the 0 order. In this paper, the diffuser (considered here as a “stochastic screen”) is sized 10cm×20cm and a superposition tolerance of  $\alpha=20\%$  is accepted. The evaluation of the focal length and distance leads to  $d_0=800\text{mm}$ ,  $d'_0=100\text{mm}$  and  $f=-150\text{mm}$  (equations not given). Holograms can be reconstructed by the adjustable magnification method described in [7] or by the discrete Fresnel transform [3,4,6]. After reconstruction of the complex amplitude in the virtual object plane, an amplitude image and a phase image can be calculated. The amplitude image is related to the image of the object given by the lens, whereas the phase is useful to investigate refractive index variations, convection currents, or thermal gradients, occurring inside the object. For this, one has to evaluate the temporal phase difference at different instants. A quantitative measurement can be obtained after unwrapping the phase differences. Since the refractive index variations are encoded in the unwrapped phase, the use of the Gladstone-Dale relation allows determining density variations.

#### 4. Proof of principle

We are interested in applying the proposed method to the visualisation and analysis of small air jet inside a molten glass at high temperature during its manufacturing process. Since this study is under some confidentiality, we present in this paper a proof of principle that was obtained by using a light ampoule. This ampoule was submitted to a current to produce light and holograms were recorded at different instants after its lighting. Fig. 2 shows preliminary results. Fig. 2(a) shows the recorded hologram when the ampoule is off and Fig. 2(b) shows the amplitude image obtained with the discrete Fresnel transform. In Fig. 2(b) the stochastic screen and the ampoule can be clearly seen. Note also the slight superposition of the useful order with the 0 order ( $\alpha \neq 0$ ). Fig. 2(c) and 2(d) shows respectively the modulo  $2\pi$  and unwrapped phase differences obtained between two instants (light off and light on). The “numerical fringes” observed in Fig. 2(c) exhibits the refractive index variations integrated in the glass container.

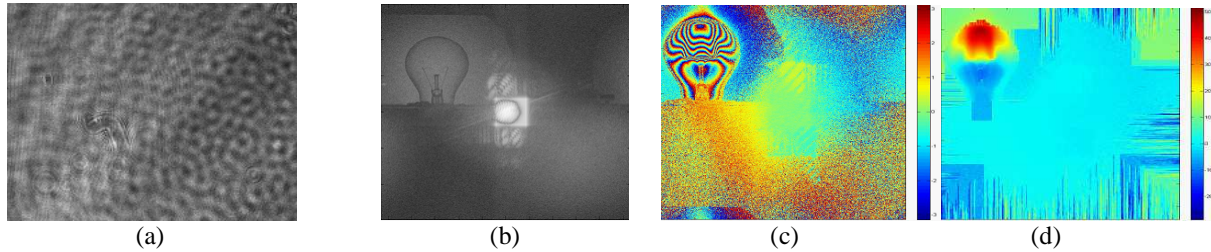


Fig. 2. (a) recorded hologram, (b) full field amplitude image, (c) modulo  $2\pi$  phase difference, (d) unwrapped phase difference

These results show that the set-up is quite adapted to the visualization of the physical phenomena occurring inside the ampoule. Furthermore, the light emission is not a limiter since it does not produce any loss of information.

#### 5. Comparison with analogue image holography

In order to check for the quality of the results obtained with the proposed method, results obtained with analogue image-holography were compared [8]. The set-up is described in Fig. 3 and can be either transmission holography or reflection holography. Fig. 3(a) shows the transmission holography mode and Fig. 3(b) that for reflection holography. Note that the set-ups require the use of photographic plates [9] and that the diffuser is also used to get a stochastic screen to illuminate the object. The process is as follows: record a transmission or reflection hologram, apply the chemical treatment to the plate to develop and bleach, dry the plate, put the holographic plate in the set-up anew (exactly at the same location), at this step the holographic image of the ampoule is observable, adjust the camera lens to produce a focused image, then record real-time interferences between the initial ampoule and that currently submitted to the current. Note that only the luminous intensity of interference fringes can be obtained, and not the phase image as it is the case for the digital holographic approach.

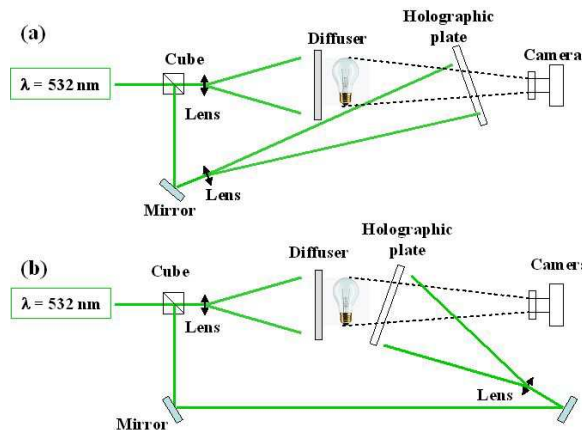


Fig. 3. (a) analogue transmission holography, (b) analogue reflection holography

Fig. 4 shows a comparison between results obtained with digital holography and those obtained with analogue holography. Fig. 4(a) shows the image obtained with the amplitude and phase change measured by digital holography, after calculating the intensity  $I=A(1+\cos(\Delta\varphi))$ , where  $\Delta\varphi$  is the phase change and  $A$  the amplitude image. Fig. 4(b) shows the interference fringes obtained with the set-up of Fig. 3(a) and Fig. 4(c) shows those obtained with the set-up of Fig. 3(b). A very good agreement can be observed. Furthermore, the image quality given by each method can be appreciated. Analogue holography provides the best spatial resolution: the strand of the lamp can be clearly seen in Fig. 4(b)(c). However, digital holography is more flexible since no chemical processing is required and a phase image can be obtained.

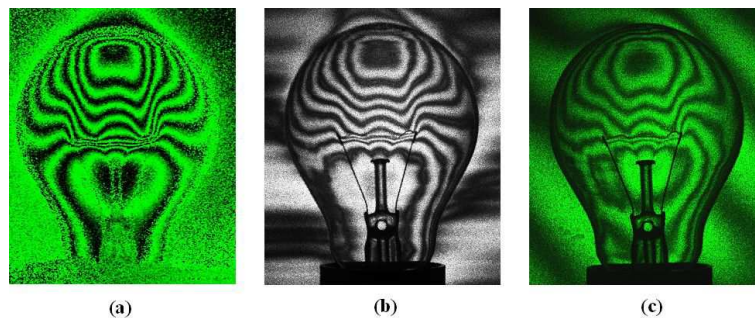


Fig. 4. Comparison between intensity of fringes, (a) fringes calculated with digital holography, (b) fringes obtained with transmission holography, (c) fringes obtained with reflection holography

As a conclusion, this paper proposes a digital holographic method to visualize and measure refractive index variations, convection currents, or thermal gradients, occurring inside transparent but strongly refracting object. The proof of principle is provided through the visualization of refractive index variation inside a lighting ampoule. Comparisons with transmission and reflection holography demonstrate the high image and phase quality that can be extracted from the stochastic digital holographic set-up.

## 7. References

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