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Realization of an optical interferometer based on holographic optics for real-time testing of phase objects

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Abstract. The paper describes a simple and cost effective method for the realization of an optical interferometer based on holographic optics, which use minimal bulk optical components. The optical arrangement in the proposed method involves a very simple alignment procedure and inexpensive holographic recording material is used in the formation of holographic optical elements. The proposed interferometer set-up is quite suitable for performing optical test studies on phase (transparent) objects in real-time. Recording schemes for the formation of holographic optical elements and the related technique for the realization of the interferometer set-up along with the experimental results have been presented.

Keywords. Interferometry; holography; optical testing instruments.

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1. Introduction

Different types of optical interferometers [1] are in use for performing various kinds of optical test studies in several precision-measurement related fields. The conventional optical interferometers generally use expensive and precise custom-made bulky optics and also involve rather tedious and time-consuming alignment procedures, which make them impractical in some applications. The use of holographic optical elements instead of the conventional optics can drastically reduce the bulkiness and high cost factors. Holographic optical elements are in use for performing various kinds of optical test studies [2–5] and also in several specialized applications [6,7]. The applications of holographic optical elements have, however, been largely reported in the area of shearing interferometry [8,9]. Holographic optical elements have several attractive features such as light weight; compactness; ease of fabrication; presence of multiple optical functions in a single element and so their use provide an advantage in the construction of compact optical systems and their high functionality compared with conventional bulky optics. Recently there has been a renewed interest in using optical interferometers for carrying out phase visualization and measurement studies [10–13]. In this paper, we describe a simple method for the realization of an optical interferometer based on holographic optics which is suitable for performing optical test studies on phase (transparent) objects in real-time.

2. Principle of the method and experimental details

The method reported in this communication is based on the formation of two holographic optical elements (HOEs) separately, in two recording steps, on two different recording plates (figure 1). The first recording step of the method involves the formation of three spatially separated holographic optical elements, where three different collimated beams (labeled as object beams O_1, O_2 and O_3 respectively) are used in conjunction with a common collimated beam (labeled as reference beam R) on the same recording plate (H_1). These three permanently recorded holographic optical elements on H_1, formed by a common reference beam, provide three in-built [14] collimated beams for subsequent recording. In the second recording step of the method, diffracted-order of beams O_1, O_2 and O_3 (which are replica of O_1, O_2 and O_3 respectively) are generated from H_1 with a single reference beam. Out of these so generated beams, O_1 and O_3 are used independently, in two separate holographic exposures, in conjunction with the common beam O_2 for the formation of two different but overlapped holographic optical elements on the second recording plate H_2 (figure 2). After processing, the plate H_2 is repositioned at the same location at which it was recorded. These two holographic plates (H_1 and H_2) when

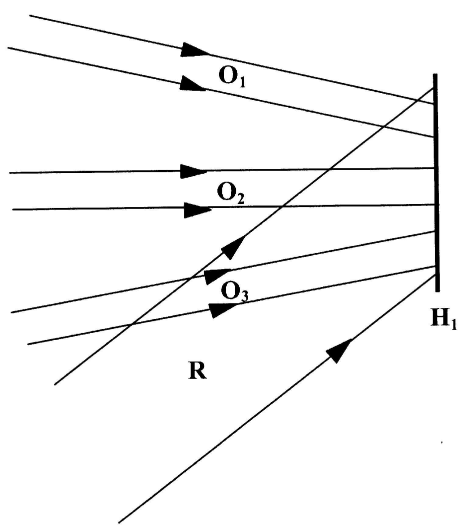

Figure 1. Recording scheme for the generation of holographic optical elements on plate H_1.

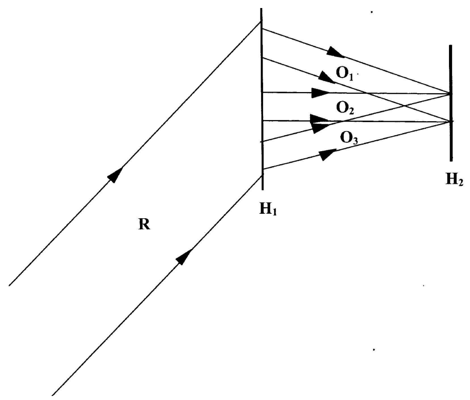

Figure 2. Recording scheme for the generation of holographic optical elements on plate H_2.

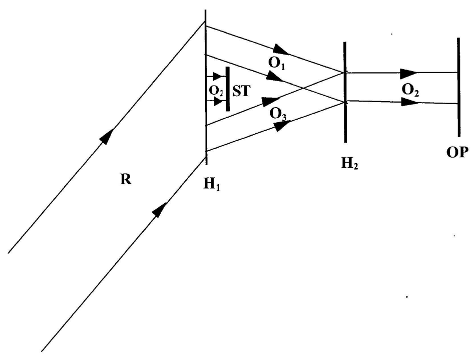

Figure 3. Schematic configuration for forming holographic optics-based interferometer.

placed in this configuration and illuminated with a single reference beam R, provide diffracted-order of beams O_1, O_2 and O_3 from H_1. Out of these diffracted-order beams, the beam O_2 is blocked by a stopper (ST) and the beams O_1 and O_3 are allowed to illuminate the plate H_2. The two holographic plates (H_1 and H_2) when used in this configuration serve as a versatile two-beam interferometer (figure 3). In this case, the two illuminating beams O_1 and O_3 further provide from H_2, two diffracted-order of beam O_2 (which are replica of O_2) overlapping each other. The portion of any one of the two collimated beams O_1 and O_3 generated between H_1 and H_2 can be used as a test arm. Repositioning of H_2 results in a finite-fringe interferogram, which with a little more careful alignment would yield an infinite-fringe interferogram. In this setting, optical test studies on phase (transparent) objects can be performed in real-time by placing it in any one of the test arms.

In our case, for forming three spatially separated holographic optical elements (HOE_1, HOE_2 and HOE_3) on H_1 in the first recording step, three collimated object beams in conjunction with a common collimated reference beam is used. The complex amplitude distribution of three object plane wavefronts and the reference plane wave-front can be considered as O_1, O_2, O_3 and R respectively. The resultant intensity at the recording plate H_1 is given [15] by

$$I = |O_1 + R|^2 + |O_2 + R|^2 + |O_3 + R|^2. \tag{1}$$

The amplitude transmittance of the processed H_1 is

$$t_1 \sim |O_1 + R|^2 + |O_2 + R|^2 + |O_3 + R|^2. \tag{2}$$

For forming two different and overlapped holographic optical elements on H_2, HOE_1, HOE_2 and HOE_3 (formed on plate H_1) are illuminated with the collimated reference beam R. The complex amplitude of the transmitted field from H_1 is

$$\begin{aligned} U_1 &\sim R \cdot t_1 \\ &\sim R|O_1|^2 + R|R|^2 + O_1|R|^2 + O_1^* R^2 + R|O_2|^2 + R|R|^2 \\ &\quad + O_2|R|^2 + O_2^* R^2 + R|O_3|^2 + R|R|^2 + O_3|R|^2 + O_3^* R^2. \end{aligned} \tag{3}$$

We can consider $|R|^2$ to be constant across H_1, as a plane beam R is used for illumination of H_1. Thus only 3rd, 7th and 11th terms on the right-hand side of eq. (3) are of interest to us as they represent the diffracted-order of beams O_1, O_2 and O_3, i.e.

$$\begin{aligned} O_1|R|^2 + O_2|R|^2 + O_3|R|^2 = {} & \text{Constant} \cdot O_1 + \text{Constant} \cdot O_2 \\ & + \text{Constant} \cdot O_3. \end{aligned} \tag{4}$$

Out of these so generated beams, O_1 and O_3 are used independently, in two separate holographic exposures, in conjunction with the common beam O_2 for the formation of two different but overlapped holographic optical elements on the second recording plate H_2 in the second recording step. The amplitude transmittance of the processed H_2 is

$$t_2 \sim |O_1 + O_2|^2 + |O_3 + O_2|^2. \tag{5}$$

In this configuration, when HOE_1 and HOE_3 (formed on plate H_1) are illuminated with beam R, they provide illuminating beam O_1 from HOE_1 and O_3 from HOE_3 for the two independently recorded holographic optical elements on H_2. The complex amplitude of the transmitted field from H_2 is

$$\begin{aligned} U_2 &\sim O_1[|O_1 + O_2|^2] + O_3[|O_3 + O_2|^2] \\ &\sim O_1[|O_1|^2 + |O_2|^2] + O_3[|O_3|^2 + |O_2|^2] \\ &\quad + |O_1|^2 O_2 + |O_3|^2 O_2 + O_1^2 O_2^* + O_3^2 O_2^*. \end{aligned} \tag{6}$$

In right-hand side of eq. (6), the first term represents the undiffracted-order of beam O_1 and the second term represents the undiffracted-order of beam O_3. Similarly, the third term represents the diffracted-order of beam O_2 (generated due to O_1 illuminating beam) and the fourth term represents the diffracted-order of beam O_2 (generated due to O_3 illuminating beam) overlapping the above diffracted-order of beam O_2. These two beams thus provide two overlapped interfering beams in the observation plane OP (figure 3). A typical finite-fringe interferogram obtained, in

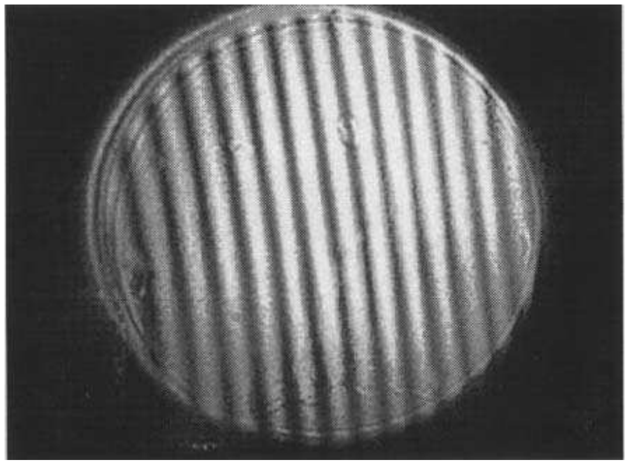

Figure 4. Photograph of a typical finite-fringe interferogram.

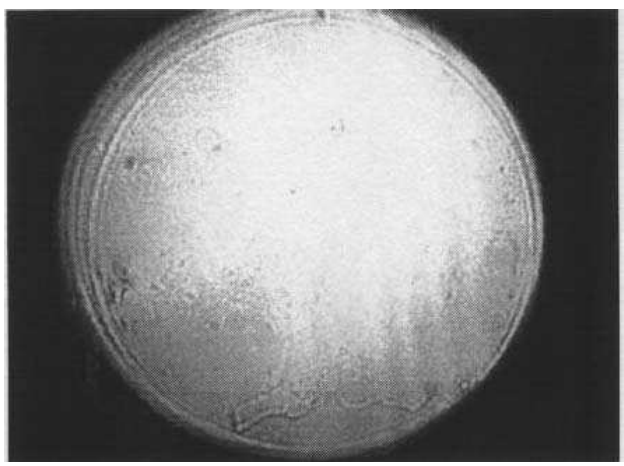

Figure 5. Photograph of a typical infinite-fringe interferogram.

the observation plane, with this set-up is given in figure 4. By applying a simple alignment procedure in repositioning of H_2 results in an infinite-fringe interferogram (figure 5) in the observation plane. In this configuration, portion of any one of the two collimated beams generated between H_1 and H_2 can be used as a test arm for performing optical test studies on phase (transparent) objects. Typically, if a phase object $S = \exp[i\theta]$ is introduced in one of the test arm, say O_3, then the complex amplitude of the transmitted field from H_2 is given by

$$\begin{aligned} U_3 &\sim O_1[|O_1 + O_2|^2 + O_3 S[|O_3 + O_2|^2] \\ &\sim O_1|O_1|^2 + O_1|O_2|^2 + |O_1|^2 O_2 + O_1^2 O_2^* + O_3 S|O_3|^2 \\ &\quad + O_3 S|O_2|^2 + |O_3|^2 S O_2 + O_3^2 S O_2^*. \end{aligned} \tag{7}$$

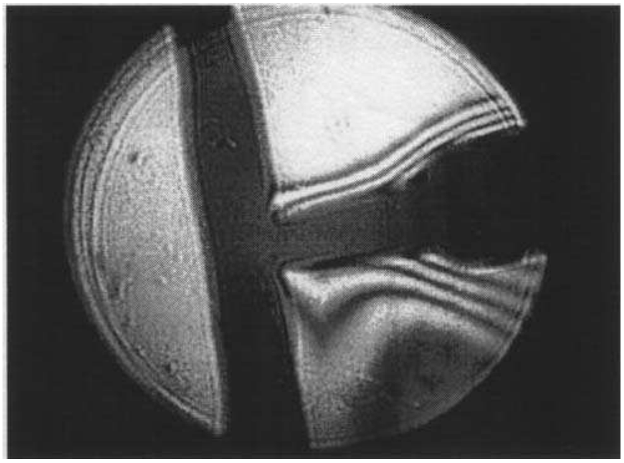

Figure 6. Photograph of typical interference pattern of heat flow obtained by inserting a hot soldering gun with a vertical metallic sheet in the test arm.

In the right-hand side of eq. (7), the third term represents the diffracted-order of beam O_2 (generated due to O_1 illuminating beam) and the seventh term represents the diffracted-order of beam O_2 (generated due to O_3S illuminating beam). The amplitude transmittance due to these two overlapped interfering beams is

$$U_4 \sim |O_1|^2 O_2 + |O_3|^2 S O_2.$$

The intensity distribution of the interference pattern in the observation plane is

$$\begin{aligned} I_r &\sim U_4 U_4^* \sim |O_1|^4 |O_2|^2 + |O_1|^2 |O_3|^2 S |O_2|^2 \\ &\quad + |O_1|^2 |O_3|^2 S^* |O_2|^2 + |O_3|^4 |S|^2 |O_2|^2 \\ &\sim A + B\cos\theta, \end{aligned} \tag{8}$$

where A and B are constants. It is thus seen that the intensity distribution of the interference pattern, recorded in the observation plane, depends only on the phase variation introduced by the phase object (S) into the test arm (O_3) between H_1 and H_2.

In our experimental arrangement, a 3 mW He–Ne laser system was used in the first and second recording steps of the method for forming H_1 and H_2. A collimated reference beam and three collimated object beams were generated by using a 100 mm-diameter and 30 mm-diameter collimating lenses respectively. The shear plate interferometric technique was applied to ensure the optical quality of the collimated beams, which were used for forming holographic optical elements on H_1 and H_2. Standard Kodak D-19 developer and R-9 bleach bath solutions are used for Agfa-Gevaert 8E75HD plates to give high efficiency and low noise grating holograms on H_1 and H_2. It is to be noted that in order to realise the proposed interferometer set-up, the processed H_2 plate is required to be repositioned at the same location at which it was formed. Normally one can accomplish it by performing an *in-situ* processing of the exposed H_2 plate or by employing a tedious and time-consuming/cumbersome alignment procedure. However, since in our recording

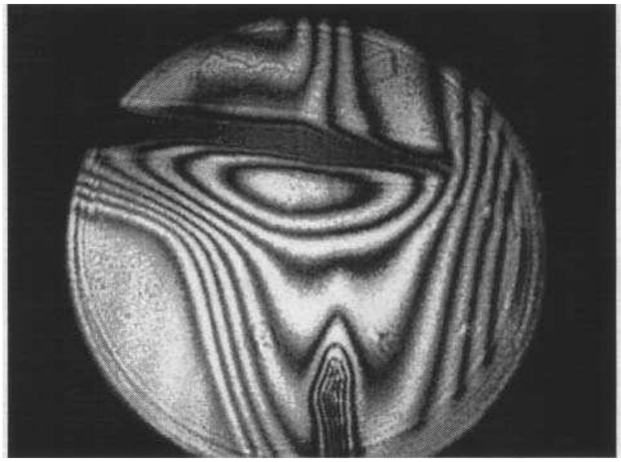

Figure 7. Photograph of typical interference pattern of heat flow obtained by inserting a metallic sheet over a burning candle in the test arm.

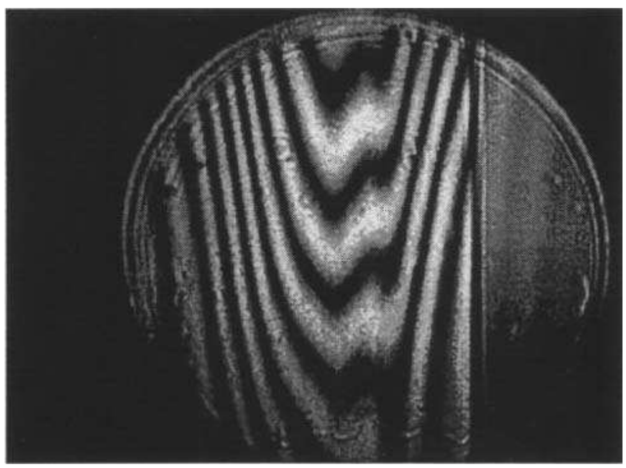

Figure 8. Photograph of interference pattern obtained by inserting a microscope cover slide plate in the test arm.

scheme the two interfering beams have permanently been frozen on a single element (H_1), the repositioning became much simpler. We could achieve it by merely mounting the H_2 plate on a holder having the capabilities of providing tilt motion to the plate in horizontal and vertical directions. By using a simple alignment procedure, an infinite-fringe interferogram is easily obtained in the observation plane. Optical test studies on phase objects were performed by inserting it in any one of the test arms in the above described interferometer set-up. Typical interference pattern of heat flow caused by inserting a hot soldering gun in the test arm is shown in figure 6. Figure 7 shows typical interference pattern in real-time as a metallic sheet is introduced over the flame of the burning candle in the test arm. The optical quality of a microscope cover slide plate was also tested by inserting it in the test arm and the typical interference pattern obtained is given in figure 8. The results presented here have been captured frame by frame to show the versatility of the realized interferometer set-up. The optical arrangement with this interferometer set-up is suitable for performing optical test studies on phase objects in real-time. By using hologram copying techniques [16], holographic copies of H_1 and H_2 can be generated in large number that can further facilitate in the production of cost effective and simple holographic optics-based interferometer.

3. Conclusion

We have described a simple method for making an optical interferometer utilizing holographic optics, which is suitable for performing optical test studies on phase (transparent) objects. The advantage of this method lies in the fact that the proposed optical arrangement of the interferometer involves a very simple alignment procedure and portion of either of the collimated beam (i.e. O_1 or O_3) generated between H_1 and H_2 can be used as a test arm for studying the phase objects. It may be seen from figures 6, 7 and 8 that this interferometric method, in infinite-fringe mode set-up, gives high contrast interference patterns on insertion of a phase object in any one of the two test arms. Quantitative evaluation of the fringe pattern may also be performed by phase shifting interferometry. It is possible to acquire a series of interferograms from this interferometric set-up by introducing an arbitrary phase delay in a series of steps using suitable optical elements (e.g. quarter-wave plate, half-wave plate etc.) between the reference and the test waves without varying the physical lengths of the optical paths [17]. Further, this two-beam interferometric set-up is relatively sturdy and any perturbation caused in any one of the test arms does not have any effect on the other arm. Wave-front distortions caused due to emulsion shrinkage/swelling and substrate etc. gets cancelled as both the interfering beams pass through the same portion of H_2. This interferometric method, in infinite-fringe mode set-up, facilitates studies of phase objects in real-time. Further, the described geometry of the interferometer is very simple and can be realized with relative ease and the vital components of the interferometer could be produced in great numbers using hologram-copying methods.

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