A compact holographic optics-based interferometer

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A compact holographic optics-based interferometer involving the use of minimal bulk optical components is described. The optical arrangement in the proposed system involves a simple alignment procedure, and conventional holographic recording material is used in the formation of holographic optical elements. Recording schemes for the formation of holographic optical elements and related techniques for the realization of the proposed interferometer along with typical experimental results are presented. The interferometer is quite suitable for performing optical test studies on phase (transparent) objects in real time.

Optical test techniques are increasingly finding use in various precision-measurement-related fields. Several kinds of optical test studies have been performed using different types/configurations of optical interferometers. There is one class of interferometers that directly maps the aberrated wavefront, such as Twyman–Green and Mach–Zehnder interferometers in which the aberrated wavefront is made to interfere with a reference wavefront. There is another class of shearing interferometers in which the aberrated wavefront is made to interfere with a replica of itself, after it has been sheared by some amount in some direction. The conventional optical interferometers generally use expensive, 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 conventional optics can drastically reduce the bulkiness and high cost factors. Because of the several attractive features offered by holographic optical elements (HOEs), such as light weight; compactness; ease of fabrication; containing multiple optical functions in the single element, their use provide the advantage in the construction of compact optical systems. The replacement of conventional optics with HOEs can drastically reduce the bulkiness, high cost factors and provide the optical systems with improved functionality. HOEs are increasingly finding their applications for performing various kinds of optical test studies and also in several specialized applications. The applications of HOEs have, however, been largely reported in the area of shearing interferometry. In recent years, there has been a renewed interest in using optical interferometers for carrying out phase visualization and measurement studies. In this communication, we describe a simple method for making a compact holographic optics-based interferometer, which is suitable for performing optical test studies of phase (transparent) objects in real time.

The method reported here is based on the formation of three holographic optical elements separately, in two recording steps, on two different recording plates (Figure 1). For the formation of these three holographic optical elements, the upper, lower and middle portions of a collimated beam (labelled as object beams O1, O2, and O3 respectively) are used separately. The first recording step of the method involves the formation of two spatially separated holographic optical elements (HOE1 and HOE2) on the first recording plate (H1), where HOE1 is formed by using O1 in conjunction with another collimated beam (labelled as reference beam R1) and HOE2 is formed by using O2 in conjunction with a second collimated beam (labelled as reference beam R2). These two permanently recorded holographic optical elements on H1 provide two inbuilt collimated beams for subsequent recording. In the second recording step of the method, diffracted-order of beams R1 and R2 (which are the replica of R1 and R2 respectively) are generated from HOE1 and HOE2 with the illuminating beams O1 and O2 respectively. The so-generated beams R1 and R2 are used independently, in two separate holographic exposures, in conjunction with the common beam O3 for the formation of two different but overlapped holographic optical elements on the second recording plate (H2). After processing, H2 is repositioned at the same location at which it was recorded. These two holographic plates (H1 and H2), when placed in this configuration and illuminated with the beams O1 and O2 (where beam O3 is blocked by a stopper (ST), serve as a versatile two-beam interferometer (Figure 2). Here HOE1 and HOE2 (formed on the plate H1), upon illumination with the beams O1 and O2 respectively, provide two different illuminating beams R1 and R2 for H2. H2 is thereafter illuminated with the so-generated illuminating beams R1 and R2. These two illuminating beams (R1 and R2) further provide from H2, two diffracted-order of beam

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Figure 2. Schematic of a compact holographic optics-based interferometer.

\( O_3 \) (which are a replica of \( O_1 \)) overlapping each other. The portion of any one of the two collimated beams 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 careful alignment procedure, would yield an infinite-fringe interferogram. In this setting, optical test studies on a phase (transparent) object can be performed in real-time by placing it in any one of the test arms.

The complex amplitude distribution of the three object-plane wavefronts and the two reference-plane wavefronts can be considered as \( O_1, O_3, O_1, R_1, R_2 \) respectively. The resultant intensity at the recording plate \( H_1 \) is given by

\[
I = |O_1 + R_1|^2 + |O_2 + R_2|^2.
\]

The amplitude transmittance of the processed \( H_1 \) is

\[
t_1 \sim |O_1 + R_1|^2 + |O_2 + R_2|^2.
\]

For the formation of two different and overlapped holographic optical elements on \( H_2 \), \( HOE_1 \) and \( HOE_2 \) (formed on plate \( H_1 \)) are illuminated with beams \( O_1 \) and \( O_2 \) respectively (as was used in the first recording step). The complex amplitude of the transmitted field from \( H_1 \) is

\[
U_1 \sim O_1[|O_1 + R_1|^2] + O_2[|O_2 + R_2|^2]
\sim R_1[O_1]^2 + R_2[O_2]^2 + O_1[R_1]^2 + O_1[R_2]^2 + O_2[O_2]^2 + R_2[O_2]^2.
\]

We can consider \( |O_1|^2 \) and \( |O_2|^2 \) to be constant across \( H_1 \), as plane beams \( O_1 \) and \( O_2 \) are used for the illumination of \( HOE_1 \) and \( HOE_2 \) respectively, on plate \( H_1 \). Thus, only the 2nd and 6th terms on the right-hand side of eq. (3) are of interest to us, as they represent the diffracted-order of beams \( R_1 \) and \( R_2 \) (which are the replica of the original reference beams \( R_1 \) and \( R_2 \) respectively), i.e.

\[
|O_1|^2 R_1 + |O_2|^2 R_2 = \text{Constant. } R_1 + \text{Constant. } R_2.
\]

(4)

These two generated reference beams (\( R_1 \) and \( R_2 \)) are further used independently in two separate holographic exposures, in conjunction with a common collimated beam \( O_3 \) for the formation of two different but overlapped holographic optical elements on \( H_2 \) in the second recording step. After processing, \( H_2 \) is repositioned at the same location at which it was recorded. The amplitude transmittance of the processed \( H_2 \) is

\[
t_2 \sim |R_1 + O_3|^2 + |R_2 + O_3|^2.
\]

In this configuration, when \( HOE_1 \) and \( HOE_2 \) (formed on plate \( H_1 \)) are illuminated with beams \( O_1 \) and \( O_2 \) respectively, they provide illuminating beam \( R_1 \) (from \( HOE_1 \)) and \( R_2 \) (from \( HOE_2 \)) for the two independently recorded holographic optical elements on \( H_2 \). The complex amplitude of the transmitted field from \( H_2 \) is

\[
U_2 \sim R_1[|R_1 + O_3|^2] + R_2[|R_2 + O_3|^2]
\sim R_1[|R_1|^2 + |O_3|^2] + R_2[|R_2|^2 + |O_3|^2] + |R_1|^2 O_3
+ |R_2|^2 O_3 + R_2^3 O_3^n + R_2^3 O_3^n.
\]

(6)

In the right-hand side of eq. (6), the first term represents the undiffracted-order of beam \( R_1 \) and the second term represents the undiffracted-order of beam \( R_2 \). Similarly, the third term represents the diffracted-order of beam \( O_1 \) (generated due to \( R_1 \) illuminating beam) and the fourth term represents the diffracted-order of beam \( O_2 \) (generated due to \( R_2 \) illuminating beam) and is overlapping the above diffracted-order of beam \( O_2 \). These two beams thus provide two overlapped interfering beams in the observation plane \( OP \) (Figure 2). A typical finite-fringe interferogram obtained in the observation plane with this setup is given in Figure 3a. By applying a simple alignment procedure in repositioning of \( H_2 \), results in an infinite-fringe interferogram (Figure 3b) 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 beam for performing optical test studies on phase (transparent) objects. Typically, if a phase object \( S = \exp[i\phi] \) is introduced in one of the test arm, say \( R_3 \), then the complex amplitude of the transmitted field from \( H_2 \) (containing two independently recorded holographic optical elements) is given by

\[
U_3 \sim R_3[|R_3 + O_3|^2] + R_2 S[|R_2 + O_3|^2]
\sim R_3[|R_3|^2 + |O_3|^2] + R_2 S[|R_2|^2 + |O_3|^2] + |R_3|^2 O_3
+ |R_2|^2 S + R_2^3 O_3^n + R_2^3 O_3^n S.
\]

(7)

In the right-hand side of eq. (7), the third term represents the diffracted-order of beam \( O_1 \) (generated due to \( R_1 \) illuminating beam) and the fourth term represents the diffracted-order of beam \( O_2 \) (generated due to \( R_2 \) illuminating beam). The amplitude transmittance due to these two overlapped interfering beams is

\[
U_4 \sim |R_3|^2 O_3 + |R_3|^2 O_3 S.
\]

The intensity distribution of the interference pattern in the observation plane is
the observation plane, depends only on the phase variation introduced by the phase object (S) into the test arm (R2) between H1 and H2.

In our experimental arrangement (Figure 1), a 3 mW He–Ne laser system was used in the first and second recording steps of the method for the formation of H1 and H2. Light from the laser (L) is split by a variable beam splitter (BS1) into two components. The transmitted component is further split into two components by another variable beam splitter (BS2). The transmitted and reflected components from BS2 are used for the generation of object beams (O1, O2 and O3) and reference beam (R1) respectively. The reflected component from BS1 is used for the generation of another reference beam (R2). Collimated reference beams (R1 and R2) are generated through beam expanders (BE1 and BE2) in conjunction with 30 mm diameter-collimating lenses (C1 and C2 respectively). Collimated object beam is generated through a beam expander (BE3) in conjunction with a 100 mm diameter collimating lens (C3). The upper and lower portions (O1 and O2) of the object beam are used separately for the formation of two spatially separated holographic optical elements on H1 in the first recording step. The middle portion (O3) of the object beam is used separately for the formation of two different but overlapped holographic optical elements, involving two separate holographic exposures, on H2 in the second recording step. The shear plate interferometric technique was applied to ensure the optical quality of the collimated beams, which were used for forming the holographic optical elements on H1 and H2. Standard Kodak D-19 developer and R-9 bleach bath solutions are used for Agfa-Gevaert 8E75HD plates (having spatial resolution power of more than 3000 mm−1) to give high efficiency and low noise grating holograms. Holographic optical elements with almost uniform diffraction efficiency were generated using these holographic recording plates with exposure energies of the order of 160–180 μJ/cm². It is to be noted that in order to realize the proposed

\[ I_r \sim U_4 U^2 \]
\[ \sim |O_3|^2 |R_1|^2 + |R_3|^2 |O_3|^2 S^2 + |R_1|^2 |R_3|^2 |O_3|^2 (S + S^*) \]

\[ I_s \sim A + B \cos \phi, \] (8)

where A and B are constants. It is thus seen that the intensity distribution of the interference pattern, recorded in
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 pro-
cedure. However, since in our recording scheme the re-
spective interfering beams used for the formation of
holographic optical elements on both $H_1$ and $H_2$ plates
have permanently been frozen, repositioning became
much simpler. We could achieve it by merely mounting
the $H_2$ plate on a holder having the capabilities of provid-
ing tilt motion to the plate in horizontal and vertical di-
rections. Using a simple alignment procedure, an infinite-
fringe interferogram is easily obtained in the observation
plane. Optical test studies on phase objects were per-
formed by inserting them in either of the test arms ($R_1$

or $R_2$) between $H_1$ and $H_2$. Figure 4 shows a typical interfer-
ence pattern due to heat flow of a burning matchstick.
The optical arrangement with this method is quite suit-
able for performing optical test studies on phase objects
in real time. The optical quality of a microscope cover
slide plate was tested by inserting it in one of the test
arms and the typical interference pattern obtained is
given in Figure 5a. Figure 5b shows a typical interference
pattern in real time due to heat flow from an active elec-
tronic resistor. The results presented here have been
captured frame-by-frame to show the versatility of the
proposed interferometer. Using hologram-copying tech-
iques, holographic copies of $H_1$ and $H_2$ can be generated
in large numbers that can further facilitate the production
of cost-effective, simple and compact, holographic, op-
tics-based interferometers.

We have described a simple method for making a com-
 pact, holographic, optics-based interferometer, 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 simple alignment procedure and
a portion of either of the collimated beams (i.e. $R_1$ or $R_2$)
generated between $H_1$ and $H_2$ can be used as a test arm
for studying the phase objects. It may be seen from Fig-
ures 4 and 5 that this interferometric method, in infinite-
fringe mode set-up, gives high-contrast interference pat-
terns on insertion of a phase object in any one of the two
test arms. Quantitative evaluation of the phase change
may be performed by phase-shifting interferometry. It is
possible to acquire a series of interferograms from this in-
ferometer by introducing an arbitrary phase delay in a
series of steps using suitable optical elements (e.g. quar-
ter-wave plate, half-wave plate, etc.) between the refer-
ence and the test waves, without varying the physical
lengths of the optical paths. Wavefront distortions caused
due to emulsion shrinkage/swelling and substrate, etc. get
cancelled as both the interfering beams pass through the
same portion of $H_2$. This interferometric method, in infi-
te-fringe mode set-up, facilitates studies of phase ob-
jects in real time. Further, the described geometry of the
interferometer is 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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Theoretical design for a light-driven molecular motor based on rotaxanes

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We suggest a design for a light-driven molecular motor, which is different from the existing designs. It is a rotaxane molecule, having identical `stations' and an asymmetric `shuttle'. We argue that the molecule would exhibit unidirectional rotational/translational motion continuously, upon shining with light of just one frequency. With this design, it should be possible to synthesize a light-driven single-molecular motor in the near future.

There has been considerable interest in the design and fabrication of molecular devices. Of particular interest are molecular motors in which the components are forced to move past each other by external stimuli. Recent insights into the working of biological motors have stimulated a surge of papers on such artificial molecular motors. Rotaxanes are the most widely studied as they offer the possibility of long range translational motion of a threaded `shuttle' along a molecular wire or `rail track'. The shuttle can be driven chemically, electrochemically or photochemically.

Natural molecular motors are usually driven by chemical energy and are believed to have high efficiency, often close to unity. One of the most efficient natural motors, the ATP synthase, rotates 15–20 times per second. Though chemically driven motors are plentiful in biology, their components are rather large molecules and it does not look as if an artificial molecular motor of comparable efficiency satisfying the three desirable features will be made in the near future. Any synthetic molecular motor should have the following desirable characteristics:

(a) It should draw energy from a source and produce mechanical work, with high efficiency, hopefully comparable to those of natural molecular motors.
(b) The motion produced should be on a time scale, faster or at least comparable to those of natural molecular motors.
(c) Its operation should not, if possible, lead to the formation of waste products.

In an interesting paper, unidirectional rotational motion in a mechanically interlocked catenane molecule has been reported. The authors have studied a `three-station' [2]catenane and a `four-station' [3]catenane. 'Stations' are the binding sites in the macrocyclic ring of the catenane assembly. In these systems, there is a large macrocycle with the binding sites and smaller macrocycles which are bound to these sites. It was found that in response to external stimuli, the small ring in the three-station [2]catenane moves sequentially between the binding sites. In the four-station [3]catenane there are two smaller macrocycles and one of them blocks the backward Brownian movement of the other macrocycle, effectively making the rotation unidirectional.

The chemically driven motors that have been synthesized recently are of great interest, though they have rather low efficiency and rotate by 360 degrees on a rather long time scale (for example, one day). They are in no way near the goals that one would like to achieve. The existing attempts based on rotaxanes have not put the ideas from Brownian motors to maximum use to get an efficient molecular motor.

Here, we suggest a design that we believe will lead to machines that satisfy all the three requirements above. It is to be stressed that the ideas that we use are well known.