Synopsis of the PhD thesis entitled

DEVELOPMENT OF SPECKLE BASED INSTRUMENTATION & IMAGING TECHNIQUES FOR INDUSTRIAL AND BIOMEDICAL APPLICATIONS

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TITLE:

Development of Speckle Based Instrumentation & Imaging Techniques for Industrial and Biomedical Applications

ABSTRACT:

The recent technological advancement has changed the face of the tools, instruments and gadgets especially in the case of manufacturing & design industries and biomedical sciences. Many technological marvels have been invented and are functioning to provide enhanced results in their respective fields. Various techniques based on mechanical, electrical, chemical, electro-chemical, optical principles are employed for diverse applications. Every technique has its own importance, advantages and drawbacks depending on the applications. Optical techniques are more favored especially in many cases as it provides many benefits especially in applications involving the investigation of transparent and translucent materials. Although noteworthy advancements have been achieved in the imaging as well optical metrology applications, still, there is a significant demand for compact, simple, effective, rugged, cost effective optical techniques for serving the aforementioned applications. One such optical phenomenon that serves the purpose is the formation of random interference pattern known as speckles when a coherent source interacts with an optically rough surface. The laser speckles which were earlier regarded as noise can provide lot of useful information. One of the main objectives of this research work is to use speckles for measurement of various physical as well optical properties such as optical rotation (associated with Faraday Effect as well as optical activity), refractive index, concentration, temperature etc. in transparent and translucent medium by comparing the change in speckle patterns corresponding to two different states of the quantity which is to be measured. Mere use of correlation function has yielded satisfactory results in the area of optical properties. Another objective is to combine speckle phenomenon with the concepts of lens-less Fourier transform digital holography to obtain complex amplitude which yields phase contrast images of microscopic biological samples. The same technique is applied to map the change in the refractive index of macroscopic technical samples subjected to thermal stressing which helps in defect detection in transparent dielectric materials. The final objective is to obtain phase contrast images without using digital holography by employing iterative phase retrieval techniques and by using two wavelengths, contours for steep objects can be obtained thereby helping in shape measuring of objects such as lens; thus, the use of phase unwrapping is avoided keeping the experimental setup simple. Emphasis has been laid upon reducing the form factor as well as the cost of the system, keeping the functionality intact. To summarize, in this research work a sincere effort has been put forward in the direction of developing compact, simple and cost-effective techniques and instrumentation for measuring and mapping various physical and optical properties, based on laser speckles, which can be applied to various areas in the field of manufacturing industries and biomedical imaging.

INTRODUCTION:

Technological revolution has changed the face of the world's economy and has aided in raising the standard of living and life expectancy by providing proper healthcare facilities. Along with the positive outcomes the technological revolutions have also brought with it some negative consequences such as environmental hazards [1, 2]. To keep up with the pace of the advancement in industries as well as in biomedical sciences, new technologies needs to be developed along with keeping a check on the quality of the manufactured products. One of the essential factors that affect the production is the cost associated with it, especially in the developing and underdeveloped nations. Several disciplines such as electrical, mechanical, chemical, electro-chemical, optics, have come up with various measurement and inspection tools for variety of applications. Every discipline has its own advantages and disadvantages depending on the location, dimension, state and material of the object under study and the conditions in which the inspection needs to be carried out. Optical techniques are opted especially when the samples that need to be investigated are transparent or translucent. Moreover, optical techniques have many advantages such as they are non-contact in nature, immune to electromagnetic interference, signal multiplexing is possible and it can measure physical and optical parameters with high precision, accuracy and sensitivity [3-6]. Invention of laser has enhanced the optical inspection techniques as well as created a remarkable impact in the healthcare sector [7]. With the advancement in the optical metrology techniques and in the healthcare sector, need of constantly evolving and enhancing the tools has risen over the years. Especially in the under-developed countries and developing countries, an important factor that is associated with these advancements in technology is the budget and costing related to the development of a technique and its deployment in the concerned sectors.

The motivation behind carrying out this research work is providing solutions for industrial and biomedical imaging problem. The work undertaken majorly focuses on developing simple, compact and low-cost techniques for measurement of various physical and optical parameters and imaging micro-objects.

One of the most favored and widely used techniques to address the aforementioned task is Digital Holography [8-22]. Digital holography offers lot of advantages such as providing complex amplitude and the liberty to perform numerical focusing [8, 9]. As it is mentioned earlier that every technique can have some downside attached to it and so does Digital Holography. As the recording of hologram in conventional two beam digital holography setup involves superposition of coherent beams, high precision beam intensity adjustment, beam splitting and beam steering elements are required which makes the experimental setup expensive and cumbersome [23, 24]. As previously stated, the cost and the form factor can be very crucial when these tools need to be deployed especially in a non-laboratory environment. Thus, a metrology technique that is simple, compact and can be molded in a smaller form factor to be projected as a device, will really be appreciated.

After a brief literature survey, the search for the suitable technique for the research problem at hand has narrowed down to speckle phenomenon. Speckles are random interference pattern which is obtained when a coherent source interacts with an optically rough medium. Initially, the speckle phenomenon was considered to be a noise in the imaging modalities, especially when a coherent source was used [25]. But its true potential was soon realized and researchers tried to harness its potential and apply it to various applications [26-35].

We have tried to utilize the speckle phenomenon to develop simple, compact, easy-to-use and cost-effective techniques that works on correlating speckle pattern, to measure various physical and optical parameters. A simple technique that works by combining the laser speckles and the principles of lens-less Fourier Transform digital holography has also been proposed to obtain phase contrast images of microscopic samples such as Red Blood Cells (RBCs). The same technique is also applied to map the change in refractive index of a transparent dielectric material which can help in defect detection. In the final stages of this research work, effort has been put forward to use the laser speckle phenomenon along with iterative phase retrieval technique to perform contouring of steep objects using two wavelengths.

OBJECTIVES:

The main objective of the research work is to develop simple, effective and low-cost instrumentation that can be applied to the industrial as well to the biomedical and healthcare applications. This research work can broadly be classified in three sections as depending on the methodology used.

(1) Development of laser speckle-based technique to measure physical parameters such as temperature, concentration and optical parameters such as optical rotation and refractive index with the help of correlation algorithm.

(2) Applying the properties of laser speckles and the principles of lens-less digital holography to image:

(a) change in refractive index in a macroscopic dielectric object and to find defect in the same

(b) Microscopic objects such as RBCs (quantitative phase contrast imaging) using a single beam geometry.

(3) Perform contouring of steep objects such as lens and curved mirrors using volume speckle field along with the technique of iterative phase retrieval.

METHODOLOGY:

The approach adopted for this research work can predominantly be divided into following three categories as follows.

(1) Speckle Correlation Algorithm
(2) Speckles with Fourier Transform Digital Holography
(3) Speckle with iterative phase retrieval technique

(1) Speckle Correlation Algorithm

Speckle correlation algorithm works on the idea of comparing speckle pattern recorded before and after the sensor detects a change in the parameter which needs to be measured. Correlation is a statistical term which provides the measure of the extent to which two or more variables are associated with each other. The correlation coefficient provides the degree of relationship between two variables when measured in the terms of another parameter [36, 37].

Standard cross-correlation methods [38] are used to determine translations of speckle fields over time, and it becomes clear that higher spatial bandwidth gives narrower cross-correlation estimates, resulting inmore accurate lag parameters. Yamaguchi [39] has shown that bytracking speckle patterns emanating from surface elements illuminated by laser light, the surface element displacement can becalculated. The principle of tracking of speckles changes (resulting when the sensing element is subjected to the parameters which needs to be determined) by finding correlation between specklepatterns is used to measure various physical and optical parameters.

The intensity correlation between the speckle patterns at different values of the parameter (measurand) [40,41] is then used to measure that particular parameter. The correlation function of the intensity between twopoints separated in the transverse plane by radial distance of s and which are located at distance z from the diffusive object may be estimated as [42]:

$$\Gamma_{Transversal}(s) = \overline{I}^{2}\left(1+2\left|\frac{J_1(\pi\phi_s/\lambda z)}{\pi\phi s/\lambda z}\right|\right) \qquad (1)$$

where, $\overline{I}$ is the mean of the intensity in the output plane, ϕ is the diameter of the illuminating beam, J_1 is the Bessel function of first kind, λ is the optical wavelength and z is the axial distance. It can beseen from the equation that any lateral shift in the speckle pattern induced by the parameter will change s and hence the values of the correlation function. This change in correlation coefficient with the variation in the intensity of the parameter is used for our measurement.In the practical system, any change in the parameter is determined by correlatingthe intensities of the speckle pattern recorded with the sensor headexposed to that parameter with a reference speckle pattern recorded in the absence of that parameter using the relationship of [42]:

$$C = \frac{\sum_{k=1}^{N}\sum_{l=1}^{N}\left[I_R(k,l,t_0)-\bar{I}_R(t_0)\right]\left[I_O(k,l,t)-\bar{I}_O(t)\right]}{\sqrt{\left\{\sum_{k=1}^{N}\sum_{l=1}^{N}\left[I_R(k,l,t_0)-\bar{I}_R(t_0)\right]^2\right\}\left\{\sum_{k=1}^{N}\sum_{l=1}^{N}\left[I_O(k,l,t)-\bar{I}_O(t)\right]^2\right\}}} \tag{2}$$

where, $I_R(k,l,t_0)$ and $I_O(k,l,t)$ are the intensities of the speckle patterns recorded by the digital device before (at time = t_0) and after subjecting the sensor to the measurand (at time = t) respectively and $\bar{I}_R(t_0)$ and $\bar{I}_O(t)$ are their mean values. The change in correlation coefficient was computed from the obtained correlation value using theequation below [40]:

$$\Delta C = 1 - C \tag{3}$$

Therefore, to summarize, it can be said that to quantify a change in a quantity or a parameter, the speckle pattern corresponding to a reference is compared with the speckle patterns corresponding to themeasurandto obtain a correlation coefficient. The change in speckle pattern is then calibrated with the quantity or parameter which needs to be measured. Thus, we have measured the change in quantities like optical rotation, concentration and refractive and parameter like temperature in terms of change in speckle pattern.

(a) Faraday Rotation Measurement

Fig. 1 shows the experimental setup employed. In the present study, a He-Ne laser (unpolarized, 611.8 nm, maximum output power <2 mW) was used as the light source. In fact any laser (such as a diode laser) with sufficient coherence length can be used as the source. The beam was linearly polarized using a dichroic film and then passed through the sample under investigation, which was kept along the axis of a solenoid (having 175 turns/cm) used to apply axial magnetic field. On the exit side of the medium, a ground glass diffuser was placed to convert the laser beam into a volume speckle field. The objective speckle field was sampled using a CCD camera (AVT Guppy-146 C, 8-bit dynamic range, 4.65 μm pixel pitch, 512 × 512 pixels exposed) connected to a PC.

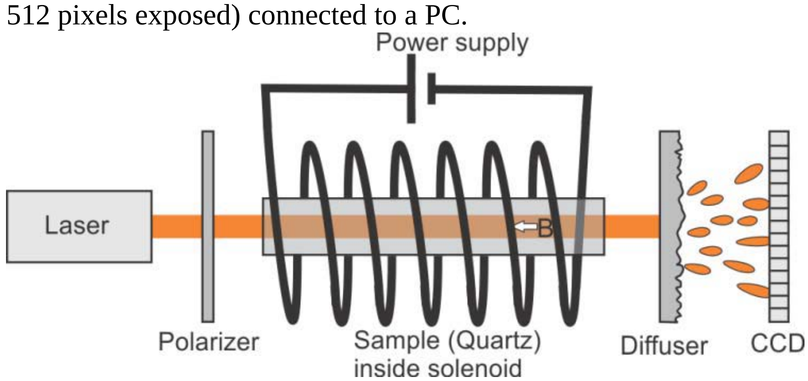

Fig. 1. Speckle-based sensor for low field Faraday rotation measurement.

Unexpanded laser beam (diameter ~ 1 mm) without spatial filtering was used and the CCD was placed 7 cm away from the diffuser so that the sampling criteria (speckle size should be twice the detector pixel size) is satisfied. Magnetic fields of different strengths were produced along the axial direction by passing different amounts of electrical current through the solenoid coil. This magnetic field rotates the plane of polarization of the incident linearly polarized light. The diffuser, which has a rough surface with random surface variations, creates spatially changing random angles of incidences for the laser beam, which can be treated as a plane wave. Since the transmittance and the reflectance of the incident beam depends upon the angle of incidence, the complex amplitude of the laser beam at the output face of the diffuser changes with polarization, hence changing the resulting speckle field [43]. Correlation coefficient of the sampled speckle patterns intensities [44] with and without the applied magnetic field can then be used as a measurement of the rotation. For each applied magnetic field, objectivespeckles patterns were recorded for 30 s at the rate of 1 Hzand stored for analysis.

(b)<u>Concentration Measurement</u>

Fig. 2 shows the schematic of the proposed technique. It comprises of a laser diode module working at 635nm with maximum output power of 4.5mW. This laser beam is linearly polarized and then is allowed to pass through the experimental cell of length 1cm. The beam after passing through the solution under investigation falls on a ground glass diffuser. The diffuser was used to convert the laser beam into a volume speckle pattern. The aperture size of the diffuser was limited to 1mm in diameter using a diaphragm. The speckle pattern generated by the diffuser was then sampled using a CMOS sensor having 1.67μm pixel pitch. The sensor was placed 4cm behind the diffuser to satisfy the sampling criteria (speckle size should be at least twice the detector pixel size). For each sugar concentration (sugar dissolved in distilled water) speckle patterns were recorded for 2s at the rate of 30Hz (total of 60 frames). Also, a reference speckle pattern with only distilled water in the experimental was also recorded for the same duration.

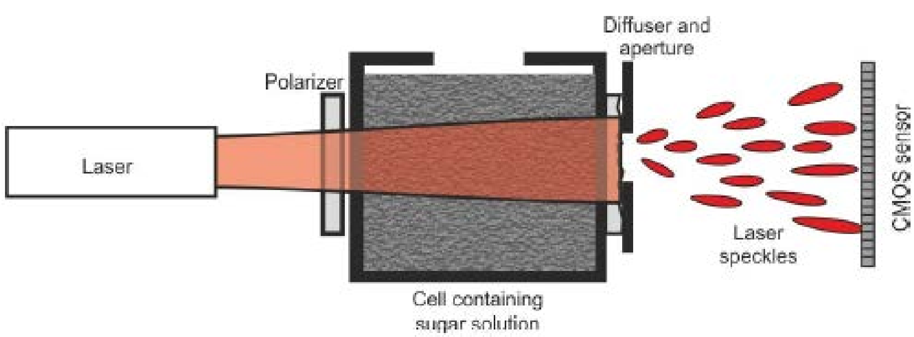

Fig. 2. Experimental setup for the measurement of sugar concentrations. Solution having different sugar concentrations were obtained by dissolving different masses of sugar in distilled water.

(c) <u>Refractive Index Measurement</u>

Fig. 3 shows the schematic of the setup used for determining the change in the refractive index. The setup comprises of a laser diode (power <5 mW, λ=650 nm, random linear polarized) which was allowed to pass through a pin hole (30 μm diameter) generating a spherical beam. This beam then passes through the chamber (volume=1 cm^3) which is made up of fused silica to contain the liquid whose refractive index is to be measured. A ground glass diffuser (1 mm×1 mm) is placed at the exit face of the chamber to generate the speckle pattern (objective speckle) which is recorded by a digital array (webcam sensor with 3.2 μm pixel pitch and 256×256 pixels exposed). During the construction of the device, the Nyquist sampling criterion is satisfied by placing the webcam 2 cm away from the ground glass diffuser so that the speckle size at the recording plane is at least twice the sensor pixel size.

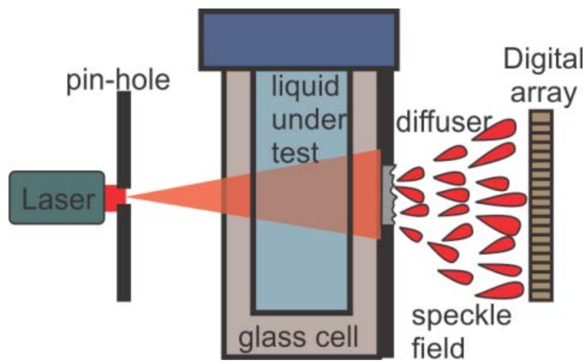

Fig.3. Schematic of the technique used for determination of change in refractive index

A 3D printer (Make3d.in, Prusa, 1.75 mm ABS filament)is employed to fabricate a frame of the device based on the proposed technique anda compact and a prototype of the stand-alone device to measure small change in refractive index was constructed. This 3D printed hand-held refractometer has length 7.5 cm, width 7 cm and height 4 cm respectively. Two batteries each of 1.5 V were used to supply the power to the laser diode. The laser diode, pinhole, chamber containing solution, webcam sensor and battery for supplying power to the laser diode were affixed at their respective positions inside the refractometer module. The idea behind using the 3D printer is to lay emphasis and attention to the small form factor achieved by the use the presented technique. Although, the optical components involved in the technique are not 3D printed, the 3D printed module serves the purpose.
Furthermore, the webcam of the device was accessed by a smartphone through an OTG cable and images (speckle patterns) can be stored in its memory. The images were transferred to a PC for further analysis. The device was tested for refractive index measurement by preparing sugar solutions corresponding to different concentrations and recording a series of speckle patterns (at the rate of 25Hz for 30s).

(d) Temperature Measurement

The optical arrangement shown in Fig. 4 is used to determine temperature changes. A heating rod (3 mm diameter) is used to produce different temperature distributions at the sensor head which is a metal (aluminum) cantilever. The heating rod was placed on a translation stage so that it can be adjusted to various distances from the sensor head leading to different temperature changes. The resulting temperature at the metal strip was also measured using a thermo-couple which is used for the calibration purpose. The illuminating light source consisted of either a<2 mW He–Ne laser (randomly polarized, with λ = 611.9 nm) illuminating a circular area of approximately 1 mm in diameter with a sufficient intensity to properly expose the CCD cameras, or a laser diode beam, having approximately the same diameter, whose output power can be selected to be less than 2 mW. This may be of importance if such systems are used in industrial environment. Due to the low power, special safety requirements are not necessary and it is easy to handle the sensor. The objective speckle field is sampled using a CCD camera (AVT Guppy-146 C, 8-bit dynamic range, 4.65 μmpixel pitch, 512 × 512 pixels exposed) connected to a PC.

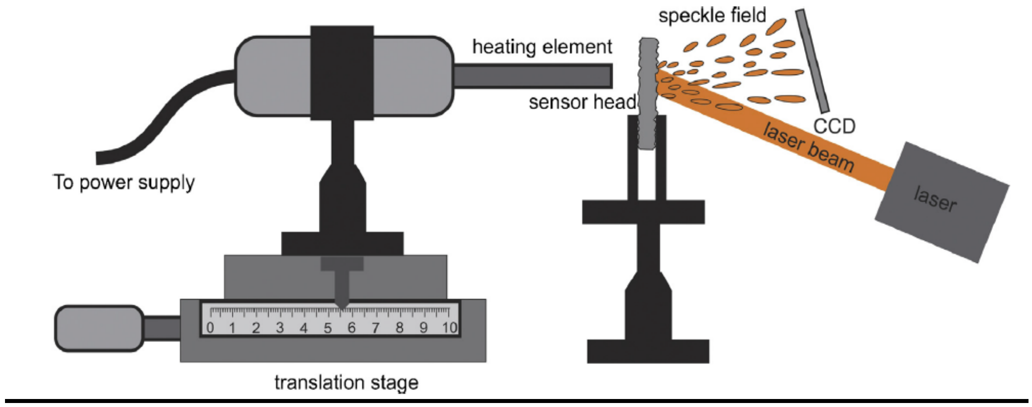

Fig 4. Experimental configuration. Heating element was mounted on a translation stage.

(2) Speckles with Lens-less Fourier Transform Digital Holography

The above mentioned speckle correlation technique works good for measuring various parameters but it cannot be applied for imaging applications. To serve this purpose, principles of digital holography is employed along with the laser speckle pattern.

The objective of using this approach is to obtain phase contrast images for (a) Microscopic objects such as RBCs (b) Mapping change in refractive index of macro objects for defect detection.

Single shot digital holographic setups require the object beam (beam interacting with the object) and reference beam, which is unmodulated by object information to interfere at an angle [8, 9, 45]. This is usually achieved using a two-beam geometry in which the object and reference beam travel along different paths [8, 9]. This geometry requires optical components for beam splitting, steering and beam recombination leading to lower temporal phase stability, which is an important aspect in the measurement of dynamic phenomena. A single beam system, in which the object and reference beam travel along the same path encountering the same optical elements, will provide a simple and more stable digital holographic geometry.

To serve the aforementioned purpose of phase contrast imaging of macro as well as micro objects and keeping the setup simple and stable, a single beam setup using a pin-hole co-located with the diffuser was devised to record lens-less Fourier transform digital holograms of phase objects such as (a) Red Blood Cells (for its phase contrast imaging) (b) Dielectric slab (for mapping heat diffusion and defect detection). The advantage of employing a lens-less Fourier Transform Holography geometry lies in the pinhole that is kept at the plan of the object which provides a Fourier Transform relation between the hologram and reconstruction plane [8, 9, 46]. Thus a single Fourier Transformation of the hologram transmittance can provide the complex amplitude of the object wavefront at the image plane. This makes the system very quick as it provides the phase information in real time. On the other hand other geometries require multiple Fourier Transforms [8, 9] which can at times be computationally exhaustive.

The general principle of lensless Fourier Transform is described as follow, where a point source that is acting as a reference beam is kept at the same distance from the sensor as the object.

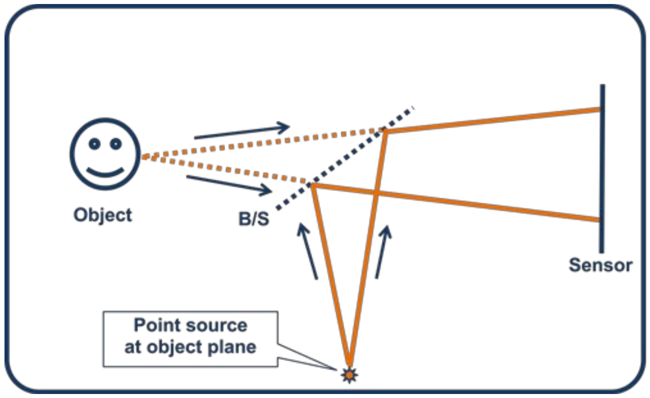

Fig 5: Principle of lensless Fourier Transform Holography

Numerical reconstruction of digital holograms is achieved by illuminating the hologram by a digital version of the reference wavefront [8]. Diffraction of the reference wavefront from the micro-structures of the hologram, which is kept perpendicular to the reference incoming beam, is described by the Fresnel-Kirchhoff integral after applying Fresnel approximation [46] according to which the complex amplitude U(x, y) of the object wavefront at any time instance is then given by [9]

$$U(x,y) = A\Im\left\{h(\xi,\eta)R(\xi,\eta)e^{i\varphi}\right\} \tag{4}$$

where A is a complex constant, $h(\xi,\eta)$ is the recorded hologram intensity and $R(\xi,\eta)$ is the digitally inputted reference wave and $e^{i\varphi}$ is a spherical function. Use of a spherical reference wave with the same curvature as the object wavefront (point source located at the object plane), the effect of the spherical phase factor associated with Fresnel transform can be eliminated and the numerical reconstruction reduces to

$$U(x,y) = A\Im\left\{h(\xi,\eta)\right\} \tag{5}$$

So, a lens-less Fourier transform hologram is reconstructed by a single Fourier transform yielding the complex amplitude distribution (an array of complex numbers) of the entire object [8, 9, 47, 48]. The intensity and the phase of the object wavefront can be determined from this complex amplitude [47, 48]. Phase of the object wavefront at any time instance is computed from the complex amplitude using

$$\phi = \tan^{-1}\left\{\frac{\mathrm{Im}\left[U(x,y)\right]}{\mathrm{Re}\left[U(x,y)\right]}\right\} \tag{6}$$

where ‘Re’ and ‘Im’ represents the real and imaginary part of the reconstructed complex amplitude distribution

(a) Single beam Fourier transform digital holographic quantitative phase microscopy

The proposed microscope is tested on static and dynamic micro-objects to reconstruct their 3D profiles. The time dependent thickness variation of red blood cells (RBCs) was studied using this technique with nanometer level temporal stability.

The schematic of the proposed microscope is shown in Fig. 6. A laser beam is directly allowed to pass through the object. The image is magnified using a microscope objective lens. A diffuser is located at the image plane of the microscope objective lens, co-located by a pinhole (Fig. 6(b)). The pinhole samples a small portion of the object beam and converts it into a spherical reference beam originating from a point source located at the diffuser plane (image plane of the microscope objective). An imaging sensor is located behind the pinhole. The diffuser allows the coupling of the image to the sensor by converting it to laser speckles (by scattering the light, coming from the image plane in the direction of the sensor). The object beam (beam from the diffuser) and the reference beam (beam from the pinhole) interfere at the sensor plane producing a hologram (interference pattern). Since the pinhole is located at the image plane, this setup generates lens less Fourier transform holograms.

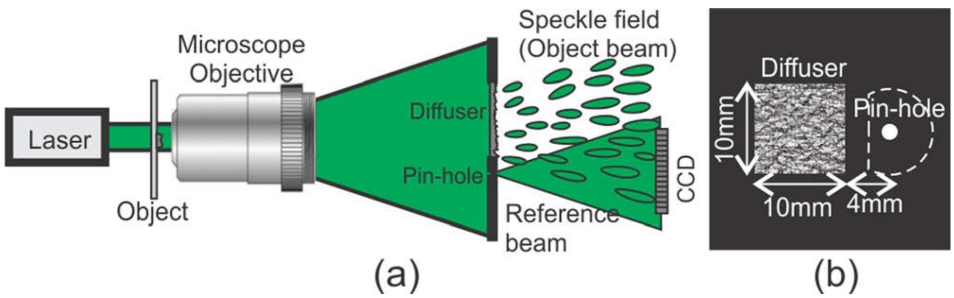

Fig 6(a) Experimental setup of single beam Lens less Fourier transform DH Microscope, (b) fabrication of wavefront division element. It consists of a ground glass diffuser co-located with a pinhole.

A thin blood smear was made on a glass slide and was covered with thin cover glass. Here, a diode laser working at 635 nm was used as the light source. A commercial grade 40x microscope objective with NA=0.65 was used for the magnification. An 8-bit CCD with 4.65 μm pixel pitch and 1392 X 1040 pixels was used for recording holograms and the sensor was kept 20 cm away from the diffuser satisfying the sampling criterion. Hologram with cells, present in the field of view, was recorded first. The slide was then moved such that there were no RBC in the field of view and a second hologram with the object beam passing through the surrounding medium (plasma) was recorded. For dynamic studies of RBCs, an oil immersion 100X microscope objective with NA=1.25 was used for magnification. The remaining microscope elements stayed the same. At first, the stability of the setup was determined from the path length variations when a microscope cover slide was used as the object. For this study, holograms were acquired at the rate of 1Hz over a period of 5 min and the path length changes were computed.

(b) __Single beam Fourier transform digital holographic quantitative phase imaging__

Fig. 7shows the schematic of the devised setup. A He-Ne laser of wavelength 611.9 nm and having maximum output power of 2mW was used as the source. Expanded and collimated output from the laser trans-illuminates the phase object under investigation and was then converted into volume speckle field by a plastic diffuser (obtained from a container) and acts as the object wavefront. Roughness of the diffuser was measured by using reflection mode digital holography [47] and was found to be 0.37 μm. A pin-hole of approximate diameter of 200 μm was made on the diffuser using a hot needle located at the diffuser plane. This pin-hole samples a portion of the wavefront falling on the diffuser creating a wavefront division geometry. Dashed lines after the diffuser in the figure represents the reference wavefront generated by the pin-hole. The object and reference wavefronts interfere at the detector plane to create the holograms, which were recorded by a CCD array (8-bit dynamic range, 4.65 μm pixel pitch).

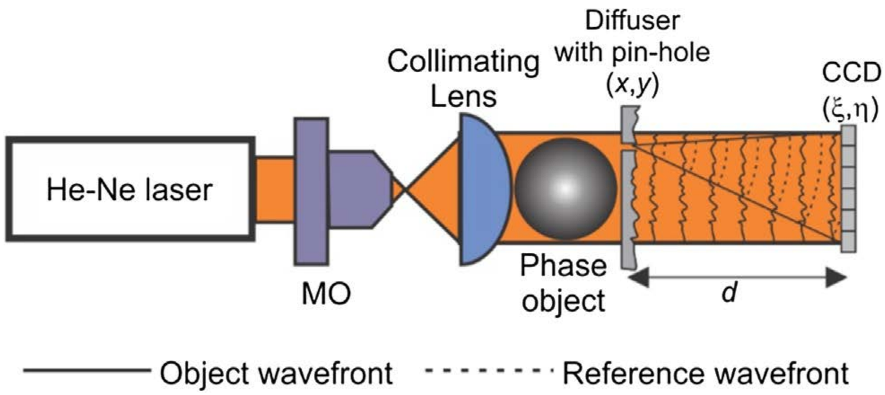

Fig. 7. Single beam lens-less Fourier transform holography setup for investigation of phase objects.

To investigate spatio-temporally evolving objects, sequence of digital holograms were recorded. This helped in mapping the heat diffusion across the object, which then help in detecting a defect.

(3) <u>Speckles with iterative phase retrieval technique</u>

The measurement of the large deformation and shape of a steep objects requires the use of inverse trigonometric functions (that are periodic in nature) for the phase reconstruction process. The periodicity causes the continuous phase information to be wrapped in a discrete wrapped phase. Thus, after the reconstruction procedure, an ambiguity will arise as the absolute phase is divided into separated regions with phase value in the region $(-\pi, \pi]$. This causes the phase images to contain large number of fringes. Thus, to get the true phase information, correct phase cycles needs to be added to each pixel for phase measurement which leads precise measurement of the phase change for steep objects. This process of getting the continuous phase information from the wrapped phase is known as Phase Unwrapping [49-51]. Recently, many researchers have developed and proposed various phase unwrapping algorithm to deal with the phase ambiguity [52-62]. Although, there are large number of options available to perform phase unwrapping, phase unwrapping algorithms encounters certain problems in the case of complex shape measurement where there is low fringe modulation, irregular surface brightness, fringe discontinuities and under sampling [52]. Another constraint while measuring steep objects is imposed by limited size of the pixel pitch of the sensor because to resolve and analyze one fringe at least two pixels are required according to the nyquist criteria [63].

Thus, in an ideal case it would be preferred not to use phase unwrapping algorithms. One of the solutions to the phase problem is to use a source with large wavelength to reduce the number of phase cycles, but it is not feasible to have a higher wavelength beyond the range 400nm-700nm in the visible regime of the spectrum. Such problems can be tackled by employing contouring techniques for shape measurement, where an image of an object is modulated by a fringe pattern corresponding to contours that represents positions of constant height or constant optical path length [64].

Holography is one of the widely used techniquesfor shape measurement and deformation quantification and so holographic contouring can be employed. Holographic contouring can broadly be achieved by two wavelength method, two refractive index method, holographic Moire interferometry, by translating illumination source or object, by light in flight recording etc [65-76]. However, the two beam off-axis holography employs lot of beam steering and beam splitting elements which makes the setup complicated and prone to mechanical disturbances. Moreover, these two beam off-axis holography setups may require adjustment of beam ratio for obtaining high contrast fringes.The Gabor inline holography setup can be thought of as an alternative geometry as it uses a single beam and fewer optical components, however it brings along with it the twin image problem and the limitation on the distribution of the object in the field of view (only sparse distributions could be imaged) and it is computationally exhaustive. [45]. Thus, a technique which employs a single beam, utilizing fewer components and yielding complex amplitude will be appreciated. One such modality is iterative phase retrieval technique, which employs a single beam, no separate reference beam and fewer components to obtain complex amplitude of the wavefront of interest. The technique majorly relies on the phenomena of diffraction, where multiple intensity patterns of the object are recorded at different axial planes for extracting complex amplitude by iteratively using scalar diffraction theory [46, 77, 78]. Considering such advantages of iterative phase retrieval technique, we have put efforts in the direction of employing it to perform contouring for steep objects by incorporating two sources with slightly different wavelengths.

The first set of experiments was conducted in the transmission mode to determine the shape of an lens which is used as a test object.Fig 8 shows the experimental setup used for the shape measurement of steep objects by two-wavelength contouring using iterative phase retrieval technique. Two He-Ne Lasers having wavelengths 611nm and 632nm are employed to obtain the longer synthetic wavelength. The maximum output power of both the lasers is 2mW. In the experiments a CCD camera having a pixel size of 4.65μm×4.65μm and 8-bit dynamic range was used. The experiment is performed for two types of objects; transparent and opaque. In the case of transparent objects as shown in fig8, the collimated light from both the laser is made to fall on the object under study (here a plano-convex lens). The area of the object exposed to the incident light was limited by a window of 2mm×2mm. A diffuser is used to generate volume speckles that convert the object wavefront in to a high frequency intensity pattern. The resulting volume speckle field was imaged at several axial planes and these intensities were stored in a PC for further processing to reconstruct the wavefront.

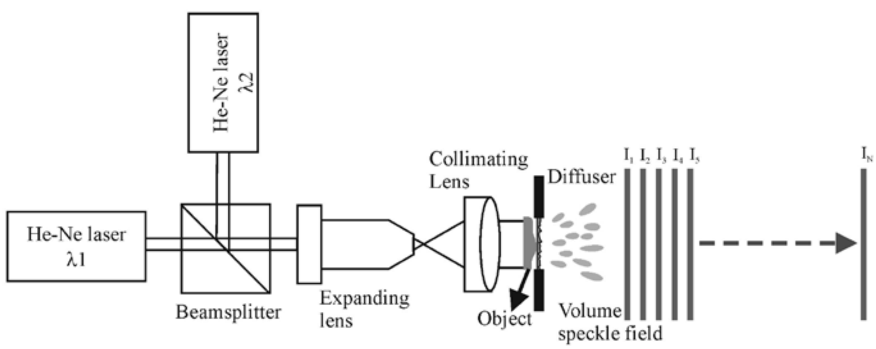

Fig 8. Transmission mode: Dual wavelength contouring setup employing iterative phase algorithm

On the other hand, the geometry slightly changes in the case of opaque objects (here a concave mirror) keeping the rest of the specifications the same, as shown in fig. 9.

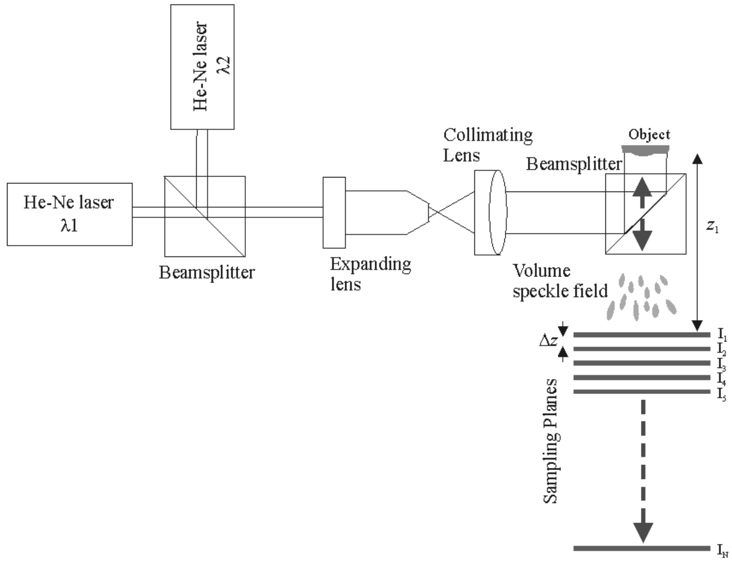

Fig 9. Reflection mode:Dual wavelength contouring setup employing iterative phase algorithm

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