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The role of beam polarization on the quality of digital holograms

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ABSTRACT

Holography is an imaging technique that has attracted much attention since its inception due to its potential of recording three-dimensional images. As a result, the technique has been applied in fields like interferometry. However, its recording relied on the use of non-polarized sensitive materials which have been limited to the isotropic materials. In this study, we report the role of beam polarization on quality of holograms in respect to important parameters such as the distance of the Charge Coupled Device from the object and variation of polarization angle. By varying the distance of the camera from the object, a distance of 15cm was clearly noticed to have produced holograms with a more comprehensive set of light wave characteristics, intensity, phase, and polarization state. We have also managed to record and reconstruct holograms at different polarization angles with significant impact on holograms at 0^O, 15^O, 30^O and 45^O whose amplitude and phase information were extracted at an optimum distance of 15cm. By comparing the results from these angles, holograms at 45^O were of high quality. This advancement not only enhances the visibility of objects that are otherwise obscured or low contrast but also broadens the application of holography beyond isotropic materials.

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1. INTRODUCTION

Holography is a technique in which light wavefronts from the object are recorded in a hologram and later reconstructed by the same original light field producing three dimensions (3D) images of an object. This was invented by Dennis Gabor in 1948 while working on electron microscope resolution and throughout all this time, the invention was limited due to lack of coherent source of light [1] [2] [3]. The holograms are recorded based on the interference phenomenon in which beam from the laser is split into reference beam and object beam. During reconstruction, a laser beams identical to reference beam used during recording is used to illuminate the hologram resulting to retrieval of the amplitude and phase. Since the hologram acts as diffraction grating, the reference beam undergoes diffraction producing real image in front of the object and virtual image formed in the original position of the object and this is as a result of one of diffracted waves which appear to diverge from the hologram [4]. A part from its application in imaging, holography has been applied in different areas such as medicine, data storage and many other areas. However, many potential applications have been limited by many factors including; the challenge of a material to be recorded and inability to retrieve all light wave characteristics [4], [5], [6], [7], [8]. Traditional holographic technique is capable of recording and reconstructing the parameters of the wave front which include intensity distribution of the two waves, phase and the amplitude involved. However, it ignores the actual polarization state components of the two interfering waves hence paving away for polarization holography. Polarization state is an important property applied in writing light field in an optical storage tasks and by overlooking the polarization information of the light, the reconstructed light intensity is of low magnitude [10], [11], [12], [13], [14]. These limitations have been solved by application of polarization holographic technique resulting to holograms of enhanced applications [5], [10]. In polarization holography fundamental properties of light which include polarization information of light (actual polarization states), amplitude and phase are recorded which is compromised by conventional holography since the amplitude is disregarded [15]. Its ultimate goal is to record all characteristics of light wave. The first method of recording a polarized hologram was first proposed by Lohmann in 1965, in which the polarized states of light with two orthogonal polarized beams formed an interference field on a photo-anisotropy. Foumey in 1968, verified Lohmann's theory by coming up with an experimental method to record and reproduce the polarized information of light [16], [17]. Polarization optics plays an immeasurable role in areas such as diffractive, refractive and emerging flat optics where advanced polarization manipulation leads to robust control of the direction of light. Polarization holography may also be applied in generating vortex beam, complex beam and polarization grating among others [18], [19], [20], [21].

Jones matrix formalism was then adopted in order to describe the recording and reproduction process of polarization holography. This theory was confined under some conditions like the two polarization interference lights were to be approximately parallel indicating that the angle between the two lights that interfere should be small and thus these results were limited under paraxial approximation which was eliminated later eliminated by development of tensor based polarization holographic theoretical model [22]. The theoretical model involved changing the holographic recording plane, analyzing the polarization combining, comparing and also analyzing the difference between the reconstructed results from the holographic optical elements. It was noted that, before polarization matching, the diffraction efficiency recorded by linear polarization was 63% and the intensity of light reconstructed in reference to 183.9 μmW was 151.9 μmW. For the right- and left-handed circular polarization, it was 60% and the intensity of light being 110.38 μmW.

Experimental research on improving the diffraction efficiency of phase holograms was also carried out in 2023. The research was on exposure time, processing chemical composition, objective beam orientation and the optimization of these parameters established that, phase hologram image of around diffraction efficiency of 16%. When the objective beam polarization was altered by rotating the half wave plate at 45º, a minimum diffraction efficiency was recorded. Holograms with maximum diffraction efficiency of 21% were obtained at 0º and 90º [1]. Clarity in fringe visibility translated to enhanced image quality. Research on high conversion efficiency was obtained when the angular range of tolerance narrows and thus decreases the plateau of homogenous. The laser power constant, intensity and crystal length were found to affect the angular acceptance. When the intensity and crystal length were increased, there was an increase in the conversion efficiency. The high-quality results dictated that; the nonlinear crystal should have a broad angular acceptance. For example, a conversion efficiency of 30% was recorded for a 9mm long Potassium Titanyl Phosphate (KTP) at a lower angular acceptance while conversion efficiency of 8.5% 2mm long KTP [23].

To increase its applications in field of holography, this paper therefore proposes on the way of improving the image quality of the polarized holograms by carrying out experimental research on impact of the beam polarization on the quality of holograms and the key parameters being; the effect of varying charge coupled device (CCD) camera positioning and also manipulation of the polarization angles of both reference and objective beam. Holograms were recorded from distances of 0cm to 16.5cm while noting the characteristics. It was realized that, a lot of noise was observed at distances 0cm to 14cm due to over-exposure of the camera to excess beam light. When the distance of 15cm was considered, it gave the best results basing on observation on holograms as compared to the rest of the distances. A range of 15.5cm to 16.5cm and also beyond had a lot of information of holograms lost. By manipulating polarization angle of both beams from 0^O to 90^O, the clear holograms were obtained at an angle of 45^O. Through identification of specific angle and optimum distance, effect of beam polarization on the quality of the hologram have been pointed out with best and viable results realized which will increase its applications in holography.

2. RESEARCH METHOD

2.1 Recording of a digital hologram

Coherent mixing of object beam $E_O(x,y)$ and reference beam $E_R(x,y)$results to the recording of digital hologram. The object and reference beams can be expressed using the following equations [24].

$$E_O(x,y) = \mathrm{a}_O(x,y)\exp(-j\varphi_O(x,y)) \quad (1)$$

$$E_R(x,y) = \mathrm{a}_R(x,y)\exp(-j\varphi_R(x,y)) \quad (2)$$

Where α_O and φ_O are the amplitude and phase distributions of the object beam respectively. α_R and φ_R are the amplitude and phase distributions of the reference beam respectively. During their mixing object and reference beam create an interference pattern with $I_H(x,y)$ being the intensity. This is represented using the following equation in hologram plane;

$$I_H(x,y) = \{E_O(x,y) + E_R(x,y)\}\{E_O(x,y) + E_R(x,y)\}^* \quad (3)$$

$$I_H(x,y) = |E_O(x,y)|^2 + |E_R(x,y)|^2 + E_O(x,y)\{E_R(x,y)\}^* + \{E_O(x,y)\}^* E_R(x,y) \quad (4)$$

Where the first two terms in equation (4); $|E_O(x,y)|^2 + |E_R(x,y)|^2$ are constant terms of intensity while $E_O(x,y)\{E_R(x,y)\}^* + \{E_O(x,y)\}^* E_R(x,y)$ represent the complex amplitude of object beam and its complex conjugate. I_H is then recorded in the computer as intensity distribution which can then be reconstructed using several methods among them is convolution method, angular spectrum method, Fresnel method and others [25].

The holographic recording set-up is as shown in Figure 1. The Mach-Zehnder interferometer holographic experimental setup was used and the holograms captured using a CCD camera with numerical reconstruction and propagation performed using convolution integral method (CIM). The recording was carried out in a darkroom where all sources of light have been blocked with minimized movements. A 24mW linearly polarized He-Ne laser of wavelength 632.8nm was used as the source of coherent light. The alignment was done both near field and far field with its vertical height of 11cm from the optical table. The beam from He-Ne laser was spatially filtered with a help of microscope objective, pinhole, iris and collimating lens. It was later split into two beams; object beam (the beam from beam splitter that was made incident on Number 5 on ruler whose hologram was to be recorded) and reference beams (the beam reflected from the beam splitter and was incident on CCD camera where the two beams interfered to form a hologram). To record the hologram, the two beams were superimposed on CCD camera as observed on computer screen. The camera had megapixels of 1440 X 1080 with pixel pitch of 3.45μm X 3.45μm. The object therefore, was supposed to be within the range of imaging area 4.968mm X 3.726mm. Holograms were then recorded from 0^O to 90^O at an interval of 15^O with reconstruction done simultaneously and their images analyzed to obtain best optimum distance for recording, specific angle of recording and phase information retrieved. An optimum distance was achieved by getting a distance greater than the minimum distance obtained suing the equation below [26].;

$$d(d_o) = \frac{(d_o + N\Delta\xi)\Delta\xi}{\lambda} \quad (5)$$

Where *do* is the size of an object, *N* is the longer pixel size, $\Delta\xi$ is total pixel pitch, λ is the wavelength of the laser.

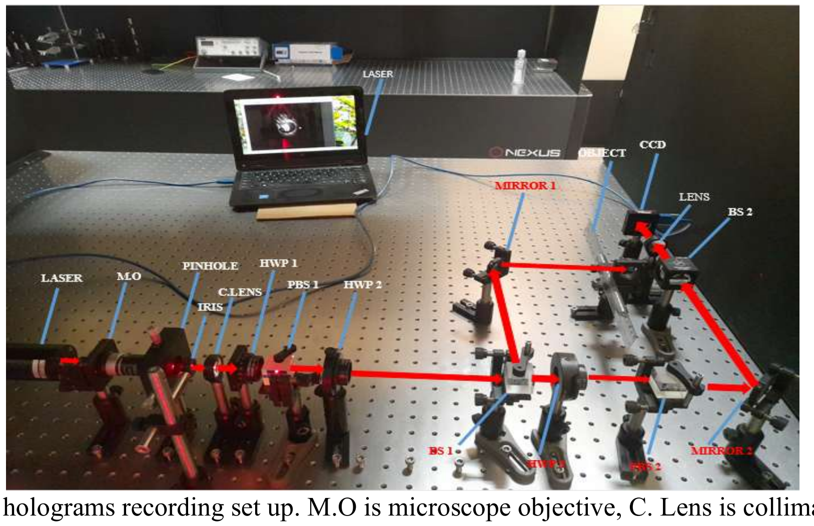

Figure 1. Digital holograms recording set up. M.O is microscope objective, C. Lens is collimating lens, HWP 1 is half wave plate 1, PBS 1 is polarizing beam splitter 1, HWP 2 is half wave plate 2, HWP 3 is half wave plate 3, PBS 2 is polarizing beam spliter 2 and BS 2 is Beam spliter 2.

The experiment involved introduction of HWP 1 in main beam path to regulate the power intensity of s- and p- polarized beams which emerged from PBS 1. HWP 2 was then introduced to re-introduce the s- and p- polarization components of the beam so that they are used in the experiment. When the first hologram was recorded, it was noticed from the screen that, there was a lot of noise in it. To minimize this noise, HWP 3 and PBS 2 were introduced in the reference beam with the fast axis of HWP 3 kept at 90^O with PBS 2 only allowing p-polarized component to be used thus the hologram recorded as observed had minimal noise.

2.2 CCD camera distance from the object

This is one of the key parameters that was considered during recording to establish the effect it has on the quality of the digital hologram. In the experimental set-up, ranges of distances of CCD camera from the object were considered. The ranges were from 0cm to 14cm, 14.80cm to 15.3cm and 15.5cm to 16.5cm and beyond. During recording, spacing between the fringes was observed, effect on depth of field, angular sensitivity and resolution and the signal-to-noise ratio (SNR) which played a key role in the quality of the hologram. Out of all the distances, an optimum distance was established for recording and reconstruction of digital hologram.

2.3 Varying polarization angles of both beams and object beam

To accomplish this, HWP 2 was placed in the main beam path which was used to vary the angles of polarization of both beams. At first, before recording, the fast axis of HWP 3 was placed at 90^{O} with PBS 2 whose task was to reduce the noise noted earlier on holograms. HWP 2 was then rotated at an interval of 15^{O} as the holograms are recorded. After varying the polarization angle of both beams, HWP 2 was then transferred to the object beam where its orientation was the only one varied with Fast Axis of HWP 3 remaining at 90^{O}. Holograms were then recorded at an interval of 15^{O} in HWP 2 and the results compared to those collected when varying the polarization of both beams.

3. RESULTS AND DISCUSSIONS

3.1 CCD camera- object propagation distance

To analyze the effect of propagation distance on digital holograms, investigation on appropriate distance was carried out. From the range of distances, distances of 14cm, 15cm and 16.5cm were chosen. During recording, some of the distances used resulted to missing of key angular information which is essential for a full 3D reconstruction and thus to avoid this, an optimum distance had to be considered. To calculate a suitable distance for recording, equation (5) was used thus resulting to the distance of 0.1356m which was too close to the CCD leading to over exposure hence noisy hologram was recorded. To avoid aliasing, a distance greater than 13.56cm was to be chosen. By observing the results obtained, a distance of 15cm was preferred.

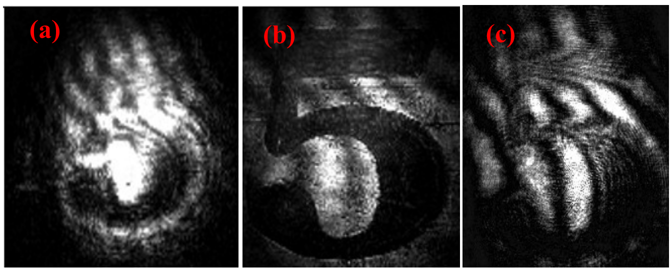

Figure 3. The reconstructed images of object recorded at different distance from the CCD camera. (a) 14.00cm (b) 15.00cm (c) 16.50cm.

In Figure 3a the hologram was reconstructed at a distance of 14.00cm. The CCD camera was close to the object thus the interference fringes were too hard to detect thus reducing the clarity of the hologram that has been reconstructed. The quality of the hologram had been compromised also by a reduced depth of field in which the parts of the object that has been recorded appeared blurry with a lot of over-exposure to the CCD camera. Sensitivity to vibrations and movements was more prominent at this distance thus affecting the quality of hologram recorded.

Figure 3b shows a hologram reconstructed at 15.00cm. This is an optimum distance in which the hologram had comprehensive features as compared to the rest. At this distance, the interference fringes were well spread-out with wide field of view capturing a large portion of the details of the object. The light intensity captured by the sensor was balanced with reconstructed image having minimal contrast and noise recorded hence resulting to high signal-to-noise ratio. With these factors in place, the quality of the hologram was improved.

Figure 3c shows a hologram reconstructed at 16.50cm. At this distance, the resolution of the image has been reduced with a broader view of it and therefore making the finer details of the image to be less visible. This is also attributed by decreased magnification as a result of increased distance. The resultant hologram is also due to a spread out of interference fringes which play a key role in the quality of the image. Due to the size of our object, wider field of view resulted to a hologram of low resolution since the sensor captured large part of the hologram but with decreased magnification.

3.2 Impact of varying polarization angle of the reference and object beam in respect to distance

Polarization angle plays an important part in the quality of holograms recorded through interaction of light and object by use of half wave plates in the beam paths. Holograms were recorded at different distances [see fig3] to identify specific angle in which the hologram was of high resolution.

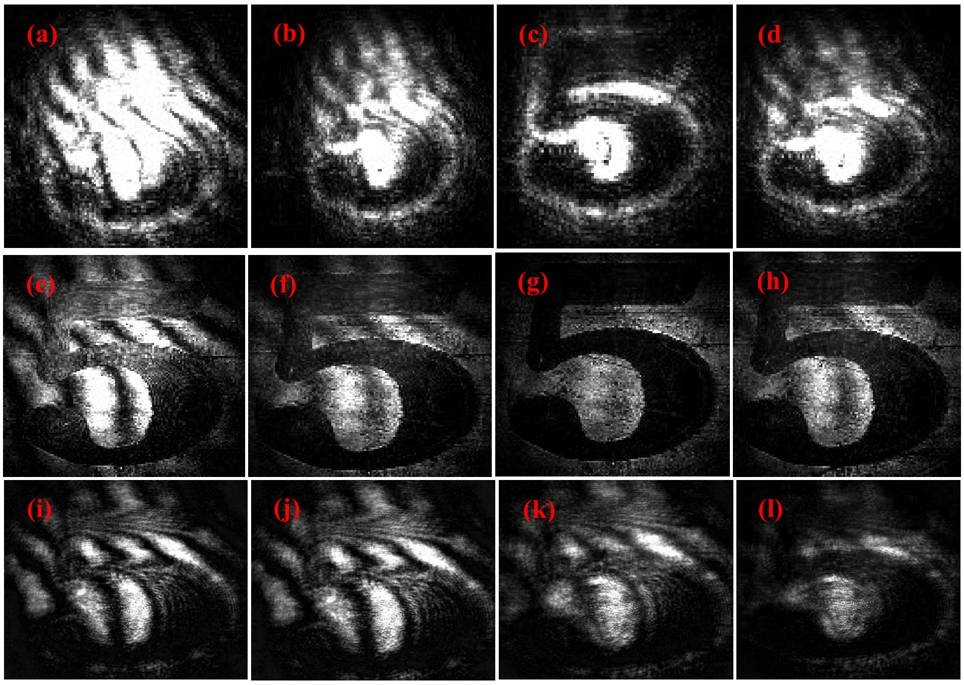

Figure 4. The reconstructed images of object recorded at different polarization angles and distance. Fig (a), (e) and (i) at 0^{O}, fig (b), (f) and (j) at 15^{O}, fig (c), (g) and (k) at 30^{O} and fig (d), (h) and (l) at 45^{O}. Figures (a) - (d) recorded at 14.00cm, (e) - (h) recorded at 15.00cm and (i) - (l) recorded at 16.50cm.

Figure 4(a), (e) and (i) are the reconstructed images of holograms recorded at 0^{O}. Orientation of HWP at 0^{O} does not affect the polarization of the beam (linearly polarized). At this angle, the contrast of interference is maximum since the beams have same polarization. However, at the distance of 14.00cm, the hologram was too distorted due to the closeness of the CCD camera to the object. At 15.00cm the hologram was very clear because at this angle, the polarization was well aligned thus clarity and details of the object were well captured hence high resolution of the image. Clarity of the image was also attributed to the fact that 15.00cm was an optimum distance for recording holograms. At 16.50cm, the orientation in HWP did not change the polarization state of the image. However, the fringes were still well spread and the details of the image captured well.

Figure 4(b), (f) and (j) are the reconstructed images recorded at 15^{O}. As the angle of polarization increases, the image also reconstructed becomes clear. More details of the object were well captured, since the angle allowed for better interaction of light and object resulting to a holographic image with improved resolution. The clarity of these images also suggested the fact that, the SNR had been greatly improved due to noise reduction when altering the polarization angle of both beams by 15^{O}. Again, when considering the clear hologram in figure 4b, hologram reconstructed at 15cm becomes the most preferred due enhanced depth perception, reduced noise and optimum distance chosen.

Figure 4(c), (g) and (k), are the reconstructed images at 30^{O}. As it is observed, the images at this angle are clear as compared to those of 0^{O} and 15^{O}. At this polarization orientation, details of the object were still captured. The noise had been greatly reduced which also improved the SNR of the holograms. Due to its ability to capture object's surface by multiple perspectives and interaction of more light with the object, the depth perception of the hologram especially at 15.00 cm was enhanced hence becoming more distinct as compared to the rest.

Figure 4(d), (h) and (l) are the reconstructed holograms at 45^{O}. At this angle, there is a balance between the interference effects recorded in the hologram. It is a significant angle where the hologram is very clear due to improved SNR as a result of reduced noise. The unwanted scattered light had been greatly reduced at reconstructed with well captured depth information due large amount of light interacting with an object. In this angle, there is an improved 3D property of an image. The other holograms are still affected by the distance of the CCD camera from the object. However, the features of the hologram are still observable due to contribution of the angle of polarization.

From figure 4, it is worth noting that the holograms at Figure 4(d), (h) and (l) had distinct features with a high SNR, deep depth information and well captured details of the object hence making it a specific angle of recording holograms alongside the respective distances.

When comparing these results to the ones obtained by varying polarization orientation of object beam only, the holograms had a lot of noise especially at 14.00cm distance thus not recommended for holograms recording. At 16.50cm the holograms were somehow clear since most of its information was lost. For 15.00cm distance, the results were very clear, proving that it was the best distance that can be used for recording. However, unlike for the results when varying both beams at 15^{O}, 30^{O} and 45^{O}, the results for the angles of 0^{O}, 15^{O} and 30^{O} were of good quality as shown by figure 5;

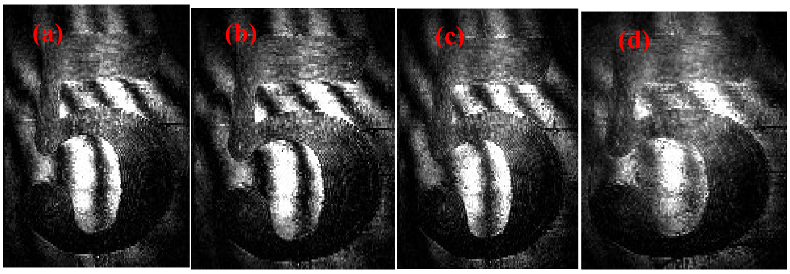

Figure 5. The reconstructed images of object recorded when varying the orientation of the object beam. (a) 0^{O}, (b) 15^{O}, (c) 30^{O} and (d) 45^{O}.

3.3 Phase information of the reconstruction hologram

Polarization angle plays an important role when extracting phase information of an object. Varying the beam polarization results to phase shift and also an influence in interference fringes. The phase information of holograms recorded at polarization angle of 0^{O}, 15^{O}, 30^{O} and 45^{O} at a distance of 15cm are shown in Figures 6 and 7.

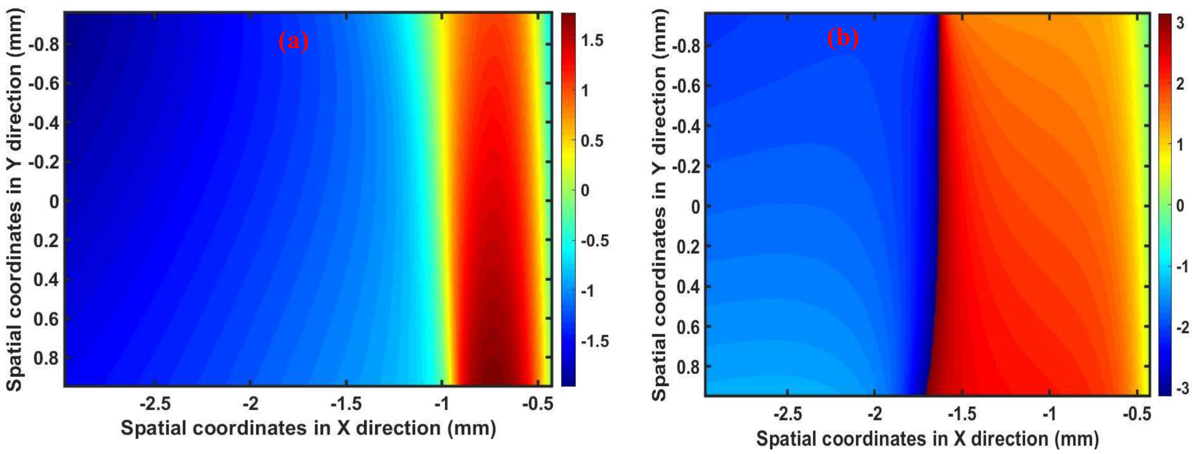

Figure 6. The phase of the reconstructed hologram at different object beam. (a) 0^{O} and (b) 15^{O}.

Figure 6a is phase information of hologram reconstructed at 0^{O}. At this angle, there is slight change in polarization of the beam. The phase shift is much dependent on the surface of the object and therefore much of information captured in the hologram by the beam will only reflect the interaction of light with the object. This is depicted by spatial coordinates in x direction where there was a very low amount of phase information reconstructed ranging from -3.0mm to -1.0mm (blue color region). This is as a result of delayed light wave interaction with the object. At -1.0mm to -0.5mm, there was interaction of object with the beam of light and due too slight change in polarization, phase information covered a narrow and small section. In y-axis, a region with values of -1.0mm to -0.2mm had minimum intensity which was an indicator of low phase values as compared to values ranging from 0.4mm to 1.0mm where the phase values were very high. The low values are because of the nature of the parts of the object in which the flat section was the only part in which the object interacted with light. The region of high phase value has been attributed by the fact that the beam interacted with curvy parts of our object hence clearly demonstrating a region of high light intensity. Figure 6b shows the magnitude and phase of reconstruction at 15^{O}. The phase shift is slightly titled as compared to that at angle of 0^{O} thus resulting to a shift in the interference fringes. The electric field having components of x and y is in direct interaction with the object. Since the components have been altered, there is a change in phase information thus resulting to an increase in phase information. In x-axis, the width of the region has increased to a range of -1.75mm to -0.5mm becoming a region containing high phase values due to high amount of light interacting with the object (more complex interaction of polarization of light and the surface of the object). It is also due to the fact that, the interference fringes were more localized in a region where the surface variations in path length were stronger. The strength of the intensity in this region is in a range of 1-2 as shown in the key with a slight balance between the region of low phase values and high phase values. Region of low phase values (-3.0 mm to -1.5mm) might have been contributed by the weak interaction between the light and the surface of the object and also the interfering beams which might have been nearly in phase or even out of phase throughout the entire image.

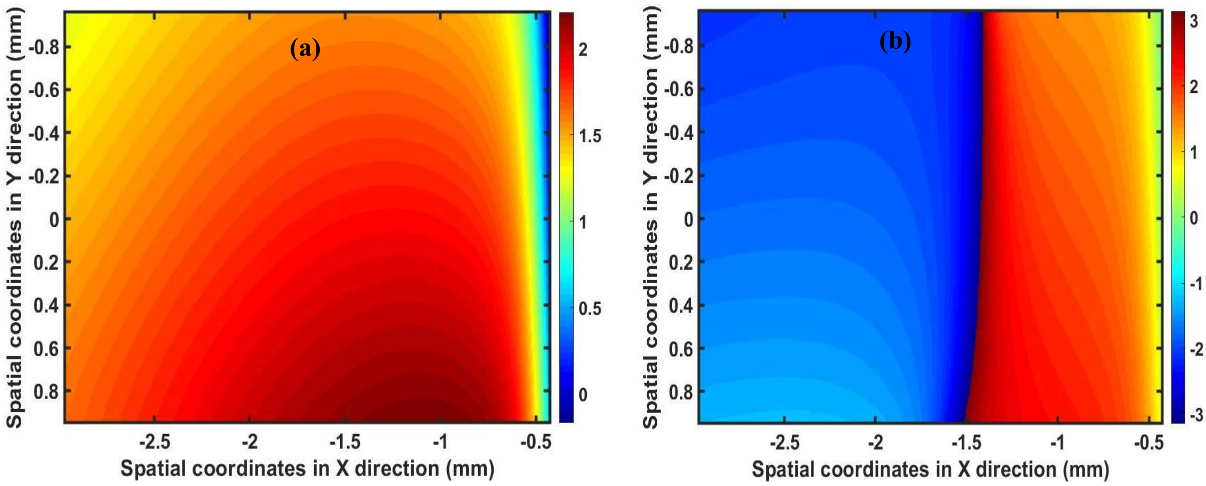

Figure 7. The phase reconstructed values of object recorded at different polarization angles. (a) 30^{O} and (b) 45^{O}.

Figure 7a shows a phase reconstructed from hologram recorded at 30^{O}. As the angle increases there is a more pronounced change in phase information reconstructed hence resulting to a more complex object and reference beam attributed by the sensitivity of our object to polarization of light. The region covered by phase information in x-axis was from -3.0mm to -0.5mm indicating that the object had interacted fully with beam of light. High phase values as observed in region -2.0mm to -0.5mm in x-axis are as a result of well alignment of reference beam and object beam with optical axes of the object. Region of low phase values was minimal due to the fact that, there was a slight reduced intereference fringe visibility hence lower contrast which ends up creating a region of low phase values. At this angle also, the path difference nearly remains constant between the reference beam and object beam which may contribute to the small region of low phase values. In Figure 7b, the polarization has been phase shifted diagonally by 45^{O} so that there is mixing up of the x and y components of electric field. At this angle there is a significant change and pronounced contrast in phase due to interaction of the object with light. Region of high phase values is from -1.5mm to -0.5mm while -3.0mm to -1.5mm is a region of low phase values. High phase values are due to full interaction between the object and polarized light resulting to constructive intereference. The constructive interference can also occur when the direction of polarization light matches well with the object beam hence resulting to regions of high phase values. Region of low phase values is caused by destructive interference as a result of poor polarization matching which ends up canceling the phase information. Some parts of the object might not have been exposed to light also thus causing minimal interaction of the object with light. This results to a very little shift in phase hence disrupting light.

4. CONCLUSION

In this study, we have experimentally investigated the role of beam polarization on the quality of digital holograms and examined key factors such as polarization angle as well as optimum recording distance. Our findings show that beam polarization significantly impacts on depth information, fringe patterns and hologram contrast. This is important in achieving high quality reconstruction. By varying the polarization direction of reference and object beams, holograms of enhanced resolution have been achieved at angles of 0^{o}, 15^{o}, 30^{o} and 45^{o}. Additionally, clear and well-defined holograms were recorded by varying the polarization orientation of object beam at 0^{o}, 15^{o} and 30^{o}. Furthermore, an optimum recording distance of 15cm achieved to be the appropriate distance of recording holograms of high resolution. By establishing optimal polarization and recording parameters, this work provides fundamental understanding of digital holography by providing practical guidelines for developing more efficient holographic systems across diverse applications.

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