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Microscopic TV Holography and Interferometry for Surface Profiling and Vibration Amplitude Measurement in Microsystems

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ABSTRACT

The micro-electro-mechanical systems (MEMS) technology requires a robust non-contact quantitative measurement system for the characterisation of their performance, reliability and integrity. A TV holographic system with long working distance microscope is developed for the static, dynamic and 3-D surface profile characterisation of microsystems. The system can be operated either in continuous or stroboscopic illumination mode of operation. The usefulness of the system for measurement of deflection, discontinuities, resonance mode shapes and vibration amplitudes on both smooth and rough micro samples is discussed and demonstrated.

Keywords: TV holography, interferometry, microsystems, surface profiling, resonance-mode, deflection

NOMENCLATURE

I_o	Bias intensity
φ	Phase
A	Vibration amplitude
z	Profile height
λ	Wavelength
V	Contrast
n	n-frame
P	Applied pressure
f	Frequency
α	Known phase shift

ABBEREVATIONS

AOM	Acousto optic modulator
BS	Beam splitter
CCD	Charge coupled device
CL	Collimating lens
CW	Continuous wave
FG	Function generator
LDM	Long working distance microscope
MTVH	Microscopic TV holography
MEMS	Micro electro mechanical systems
NDF	Neutral density filter
PZT	Lead Zirconate Titanate
PC	Personal computer
SF	Spatial filtering
TVH	TV holography

1. INTRODUCTION

Progresses in micro-electro mechanical systems (MEMS) technology promise a lot of new applications in industry and research. In recent years, microsystems such as MEMS are finding applications in various fields such as telecommunication, digital projectors, high speed devices, computers, aerospace, automobiles, biomedical, micro-optics etc. The emphasis on Microsystems development is of miniaturised mechanical, electro-mechanical, opto-mechanical, and micro-fluidic systems[1,2]. These Microsystems can offer significant advantages over conventional systems, such as small form factors, highly robust construction and low power consumption. The technology of fabricating Microsystems has been adopted by a number of industries to produce sensors, actuators, visual display components, AFM probe tips, semiconductor devices, micro-lens array, etc., aided by photolithography and other novel methods, large number of devices have been fabricated. The materials behavior in combination with new structural design cannot be predicted by theoretical simulations. Further in micro structures, the materials behavior is noticeably affected by the production technology. As a consequence, the demand for sensitive and robust measurement techniques for characterising the fabrication and performance of Microsystems has also been increased. Full field and non invasive interferometric methods are desirable to get access to spatially resolved material properties and parameters. Therefore simple and robust optical measuring systems for characterisation of the Microsystems under static and dynamic conditions are highly desired. The measuring systems should have the following conditions. First it should not alter the integrity and the mechanical behaviour of the device. Since the MEMS components have an overall size up to a millimeter, a high spatial resolution interferometric measuring system that can evaluate rough as well as smooth micro components is required. Further the surface profile, deflection, motion or vibration amplitude of microsystems are typically in the nanometer to a few microns range which requires a high sensitive system. Interferometric based evaluation methods have been received considerable attention in this regard, since it provides high speed, high accurate, whole field, non-contact characterisation of MEMS[3-7]. The

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interferometric techniques for Microsystems analysis relay on microscopic imaging systems with the combination of different magnification objective lens.

The MEMS specimen surfaces can be optically rough or smooth, hence require a microscopic imaging setup that can be used for both. In this paper, we present a microscopic TV holographic (MTVH) system for characterisation of rough as well as smooth microsystems. The method is based on TV holography (for rough surfaces) and laser interferometry (for smooth surfaces) and it is capable of static and dynamic deformation, and 3-D surface profile characterisation of small scale objects such as MEMS. Phase shifting technique[8] has been incorporated for quantitative fringe analysis. The procedures involved for quantitative fringe analysis include

(a) Storing the phase shifted patterns,
(b) Raw phase evaluation from the stored phase shifted patterns,
(c) Digital filtering and smoothening to reduce the noise,
(d) Phase unwrapping and
(e) 3-D profiling.

The development of the microscopic imaging system and its applications for static, dynamic and surface profile measurement on small scale objects is presented.

2. MICROSCOPIC TV HOLOGRAPHIC SYSTEM

Figure 1 represents the schematic arrangement and photograph of a microscopic TV holography (MTVH) and Interferometry. The system can be operated either in continuous or stroboscopic illumination mode of operation. Continuous illumination allows the measurement of static deformation, surface profiling and time visualization of resonance modes. The system consists of three units;

(a) Special illumination system using an acousto-optic modulator (AOM) modulator with an OPTO-DYNAMIC+ synchronizer controller which can generate either a continuous or a stroboscopic illumination,
(b) Microscopic imaging system, a phase shifter unit, and
(c) Software program for automatic data acquisition and data evaluation.

A narrow 50 mW laser beam from a diode pumped solid state mini 532 nm CW Nd:YAG laser (Compass TM 315M-Coherent Inc.) is allowed to pass through an acousto-optic modulator (AOM). A variable neutral density (VND) filter in front of the laser controls the power of the laser beam. When the AOM is active, it generates a diffraction pattern. The AOM is oriented so as to direct most of the beam power from zero order to first order. The first order beam is than expanded using a spatial filtering (SF) setup and collimated with the support of a 150 mm focal length collimating lens (CL). An iris in front of the lens is used to adjust the size of the collimated beam. The collimated laser beam illuminates the object and a reference mirror via a cube beam splitter (BS). A neutral density filter (NDF) in front of the reference mirror allows to control the intensity ratio between the object and reference wave. The specimen is mounted on a 3-axis stage for alignment. The microscopic imaging system consists of a Thales-Optem zoom 125C long working distance microscope (LDM) with extended zoom range and a mega pixel JAI (BB-500GE) 2/3 inch colour CCD camera. The CCD is interfaced to a PC with an NI PCIe-8231, GigE Vision Board with Vision Acquisition frame grabber card. The zoom LDM provides a 12.5:1 zoom ratio, at working distance of 89 mm with 1.0X objective. The zoom ratio in the system can be further increased by using the higher magnification objective lens. However the working distance will reduce for higher zoom ratio. In the present setup the magnification can be varied in steps (1.0X to 12.5X) and the specimen dimensions of 8.4 mm x 6.3 mm at low magnification (1.0X) and 0.68 mm x 0.51 mm at high magnification (12.5X) cover the full area of the 2/3 inch CCD. The system is fitted with a fiber based white light illumination (VSI 220 Illuminator, 220V/150W) for initial alignment and focusing of the test specimen onto the CCD camera. A PZT driven reference mirror (PIEZOMECHANIK Model No. STr 25/150/6 PZT) is used for introducing the phase shifts between the object and reference waves. The PZT is driven by an amplifier A_1 (LE150 Amplifier) which is interfaced to a PC with a NI6251 DAQ card.

An external function generator (Tektronix AFG 3022B) is used to apply the frequency ($Clock_{in}$) to the synchronizer. The synchronizer generates two signals called $Gate_{out}$ and f_{out}. $Gate_{out}$ is connected to the AOM for activation and f_{out} is connected to the object through an amplifier (A_2) for excitation. An oscilloscope (Tektronix DPO 2012) is connected to the monitor out of the controller unit to monitor and record the AOM Trigger pulse and the object excitation wave. The synchronizer controller has a provision to generate a series of short pulses of width in a range from 1^o to 90^o and a special function to adjust the phase from 0° to 360^o. The system can be operated either in continuous or stroboscopic illumination mode of operation. Continuous illumination allows measurement of static deformation, surface profiling and time visualisation of resonance modes. Continuous beam can be achieved by switching the CW button ON (continuous wave illumination) and OFF (stroboscopic wave illumination) on the front panel of the controller. The controller generates both a continuous wave illumination (for shape, static or vibration investigation by the time-average method) and a stroboscopic illumination (for vibration fringe analysis) without changing any optical arrangement in the setup.

For diffusing specimen, the system works on the principle of TV Holography[6]. The scattered object wave from the rough specimen and the smooth reference wave from the PZT driven mirror are recombined coherently onto the CCD plane via a cube beam splitter and microscopic imaging system. For smooth specimens, it works on the principle of conventional Interferometry[8]. In the present arrangement, the collimated illumination and the observation beams are in-line and hence the sensitivity vector is perpendicular to the test object. Therefore the system is predominantly sensitive for the measurement of out-of-plane deformation. LabVIEW and MATLAB based software programs have been developed for visualization, storing and analyzing the data.

3. THEORY

3.1 Static fringe analysis

For static deformation and 3-D surface profile analysis, the system is used in continuous mode of operation. Continuous illumination can be achieved by switching the CW button ON in the OPTO-DYNAMIC+ synchronizer controller. The object beam from the specimen and the smooth reference beam from the PZT driven mirror are recombined coherently onto the CCD plane via a cube beam splitter and microscopic imaging system. For rough specimens, the system works on the principle of TV Holography, while for smooth specimens, the interference is between the two smooth surfaces; in which case one can usually observe a visible interference fringe pattern.

The reflected beam from the rough micro-specimen is a scattered object beam known as a random speckle pattern[6]. The interference pattern generated from the scattered object beam and the smooth reference beam will be again a random speckle pattern and hence no fringe pattern is visible. However by storing and subtracting the two random speckle patterns that represent the initial state and the deformed state of the rough micro-specimen under study, we obtain a speckle correlation fringe pattern. If the micro-specimen is optically smooth, the interference between the micro-specimen and the reference generates a visible fringe pattern. For quantitative fringe analysis we have used a five step phase shifting algorithm[9].

For rough surface analysis, the method involved in recording the identical five π/2 phase shifted frames before and after loading the object to generate the individual phase maps. The subtraction between the two phase maps yields the desired phase map corresponding to the object deformation. The intensity distribution of the five π/2 phase shifted frames for the initial and the deformed state of the object respectively can be expressed as

$$I_{Bn} = I_O + I_R + 2\sqrt{I_O I_R}\cos(\phi_B + (n-1)\frac{\pi}{2}) \tag{1}$$

$$I_{An} = I_O + I_R + 2\sqrt{I_O I_R}\cos(\phi_A + (n-1)\frac{\pi}{2}) \tag{2}$$

where I_O and I_R are the intensities of the scattered object and reference waves respectively, ϕ_B is the random speckle phase of the initial state of the object before deformation. ϕ_A is the random speckle phase after object deformation and $\phi_A = \phi_B + \Delta\phi$, $\Delta\phi$ being the phase change due to object deformation. n is the number of phase shifted frames (n = 1 to 5).

The speckle phase distribution ϕ_i can be obtained from a five phase step algorithm as[9]

$$\phi_i^5 = \arctan\left(\frac{2(I_2 - I_4)}{-I_1 + 2I_3 - I_5}\right) \tag{3}$$

where *i* represents the initial B or deformed state A of the object.

Since the interference pattern is a speckle pattern, no fringes will be observed from the individually generated phase maps. However, the subtraction between the two yields the phase map $\Delta\phi$ and one can observe the visible phase map fringes[6].

The use of five step algorithm eliminates completely the speckle phase term ϕ_B. The method is more suitable for static deformation quantitative analysis.

From the optical configuration, the phase $\Delta\phi$ can be related to the out-of-plane deformation as

$$\Delta\phi = \frac{4\pi}{\lambda} w \tag{4}$$

where *w* is out-of-plane deformation and λ is wavelength of laser used.

If the micro-specimen is a smooth surface, the interference between the test and the reference surfaces gives a visible fringe pattern. Such a pattern can be used to extract the information about the microelement 3-D surface profile[7]. The analysis needs to remove the rigid body tilt to yield the pure 3-D surface profile. Under this condition, we can relate the phase $\Delta\phi$ to surface depth z as

$$\Delta\phi = \frac{4\pi}{\lambda} z \tag{5}$$

The calculated relative phase change is wrapped between –π and π due to the fact that the phase is calculated by an arctangent function. In TV holography, the raw wrapped phase map is noisy. The noise could be optical, electrical, and speckle de-correlation. Since both the speckle noise and the 2π discontinues (a sawtooth function) in the phase maps are characterised by high spatial frequencies, applying a filter not only reduces the noise, but also smears out the discontinuities. This problem is solved by calculating the sine and cosine of the wrapped phase map and then apply filtering to the two state of data. This is known as sine-cosine filtering scheme[10,11]. The sine and cosine fringe patterns are filtered individually by applying a median filter. In median filtering, the value of each pixel is replaced by the median of the values in a neighborhood of that pixel. From the filtered sine and cosine fringe patterns the phase map is re-calculated by the four-quadrant inverse tangent of the sine and cosine patterns. This process is usually repeated few times depending upon the applications.

The smoothened wrapped phase is to be unwrapped to make the phase continuous for quantitative information. The process is carried out by adding or subtracting 2π each time the phase map presents a discontinuity. Numbers of sophisticated algorithms have been proposed[12-14]. Unwrapping is the procedure which removes these 2π phase jumps (discontinuities) and the result is converted into desired continuous phase function[15]. The next step is to unwrap the data to yield the 2-D and 3-D profiles.

3.2 Vibration Fringe Analysis

For measurement of amplitude of object excitation resonant frequencies, the system is used in stroboscopic illumination mode of operation by switching the CW button OFF (Fig. 1) in the OPTO-DYNAMIC+ synchronizer controller. The OPTO-DYNAMIC+ synchronizer controller shown in Fig. 1 plays an important role to control and synchronize the stroboscopic illumination with the object excitation signal, to control the trigger position (PHASE) and pulse width (GATE). For this it is necessary to vary the Phase and Gate values in the controller. When CLOCK-IN is applied to the controller, it generates two synchronized signals. The high frequency (110 MHz) signal coming from GATE-OUT is in a pulsed form and is send to the AOM for activation. When the AOM is

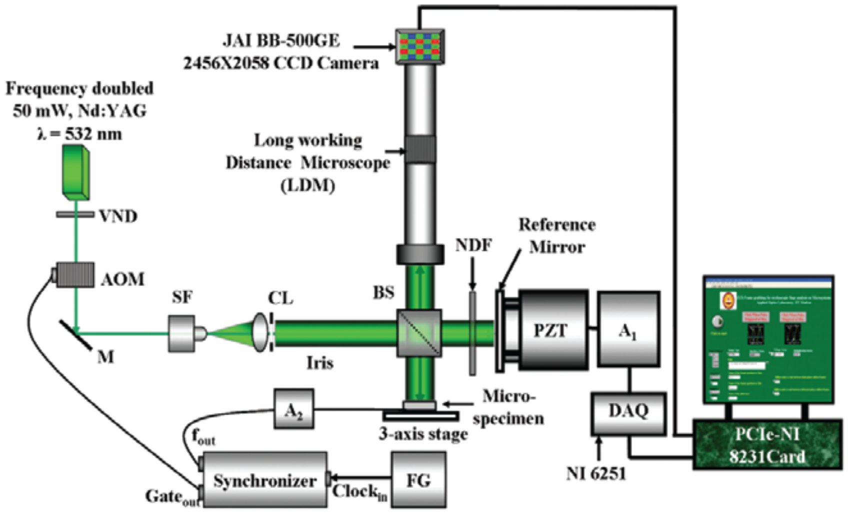

Figure 1. Schematic microscopic TV holographic system: Variable neutral density filter (VND), Acousto-optic Modulator (AOM), Mirror (M), Spatial filtering (SF), Collimating lens (CL), Cube beam splitter (BS), Neutral density filter (NDF), Amplifier (A), Function generator (FG), and Data acquisition system (DAQ).

active, the laser beam mainly stays in the direction of the first order of diffraction. After the trigger duration, the vibrating phase grating of the AOM returns to a neutral resting position, and the laser light in this case stays in the direction of zero order. After 360 input pulses (i.e. the complete sine period), the procedure is repeated. With this method, a synchronized stroboscopic illumination with an adjustable trigger position and pulse width can be generated. Usually, the pulse width should be as short as possible for greatest accuracy, but the actual working width is dependent on the power of the laser. The pulse width can be adjusted by varying the GATE adjustment knob of the controller front panel. Similarly the phase between the stroboscopic illumination trigger pulse and the object excitation signal can be controlled with the help of PHASE adjustment knob. An oscilloscope (Tektronix DPO 2012) is connected to the Monitor out of the controller unit to monitor and record the AOM Trigger pulse signal and the object excitation signal.

Synchronization between the illuminating and excitation signal helps in freezing the vibrating object in different states of object excitation. It allows to adopt the conventional phase shifting procedure as described for static fringe analysis. For measurement of amplitude of object excitation at resonant frequencies[14] it is necessary to use the subtraction of the phase evaluated when the pulse is triggered at the maximum of the object excitation signal (e.g., at α phase) and the second evaluated phase when the pulse is triggered at the minimum (e.g., at α+180° phase) as shown in Fig. 2. The subtracted phase is related as to the out-of-plane amplitude (A) of the object vibration from the maximum position to the minimum position (Fig. 2) as

$$\Delta\phi = \frac{4\pi}{\lambda} A \qquad (6)$$

4. APPLICATIONS TO MICROSYSTEMS METROLOGY

4.1 Out-of-plane Deflection Measurement on Rough Surfaces

The microscopic TV holographic system is used for static out-of-plane deflection analysis on a circular MEMS pressure sensor. The diaphragm area, 1.5 mm in diameter and 25 µm thick, is etched on a silicon substrate. The sensor area is zoomed-in to measure the deflection as a function of applied pressure. We have used 2.0X magnification by adjusting the magnification control knob of the LDM. For static fringe analysis, eight phase shifted frames before and after applying the external pressure to the sensor[12] is stored in the PC. Then the phase before and after deformation are evaluated individually using the Eqn. (3). No fringes are observed from the individual phase maps. By subtracting the phase maps, one can observe the visible phase map fringes. The raw phase map fringes are noisy. A simple digital sine\cosine median filtering with a 3x3 window is used to smoothen out the noise. The phase distribution, is the wrapped or modulo 2π phase map, which range from –π to π. The wrapped phase is then unwrapped to get the desired continuous amplitude phase. The unwrapped phase is scaled using the Eqn. (4) to generate the out-of-plane deflection (w) profile. The MEMS pressure sensor sample along with the experimental results is shown in Fig. 3. It can be noticed from the analysis the deflection is predominantly in the circular membrane area, while the silicon wafer region remains unchanged.

4.2 Measurement of Vibration Amplitude on Rough Surfaces

The stroboscopic illumination method makes use of an AOM in the setup (Fig. 1). The stroboscopic first order beam helps in freezing the vibrating object in different states of object excitation. It allows using the conventional phase shifting procedures for the measurement of amplitudes of vibration at

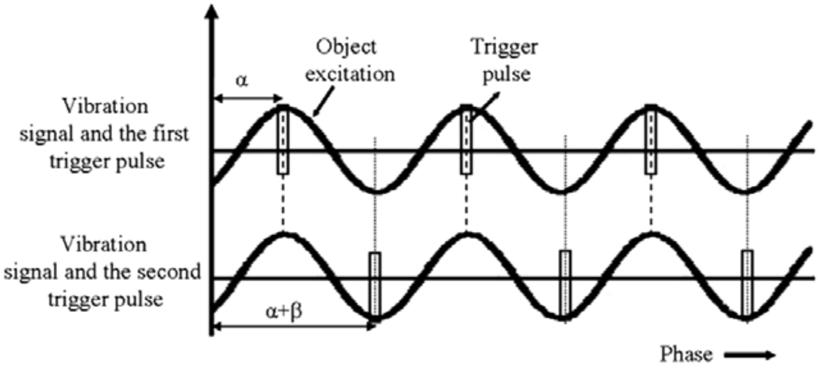

Figure 2. Object sinusoidal excitation and the stroboscopic trigger pulse: (a) first trigger pulse at maxima, and (b) second trigger pulse at minima of the object excitation.

resonant frequencies. We have carried out stroboscopic fringe analysis on a (i) thin circular membrane of diameter 5 mm and thickness 10 µm and (ii) cantilever beam (2x 2.5 X 0.1 mm^3). For the visualization of the vibration fringes, we first capture the speckle pattern at the maximal displacement in the positive direction at the first trigger position and the maximal displacement in the negative direction at the second trigger position of the excitation signal. The difference between the two frames creates an amplitude speckle correlation fringes. For quantitative measurement, five phase shifted frames are stored at maximal and minimal positions. The fringe analysis carried out using the Eqns. (3) and (6) on both these samples are represented in Figs 4 and 5 respectively.

4.3 3-D Surface Profiling on Samples with Smooth Surfaces

Many micro-components have a reflective surface-for example, MEMS mirrors, MEMS switches etc. used in the telecommunications industry. The surface profile is an important parameter that influences the optical characteristics such as the insertion loss. One of the applications of the system developed here is to measure the surface profile of such samples. In the setup shown in Fig. 1 and assuming that the specimen surface has been adjusted to be perpendicular to the surface of the reference mirror and the reference mirror is absolutely flat, then the phase distribution follows the 3-D surface profile (z)

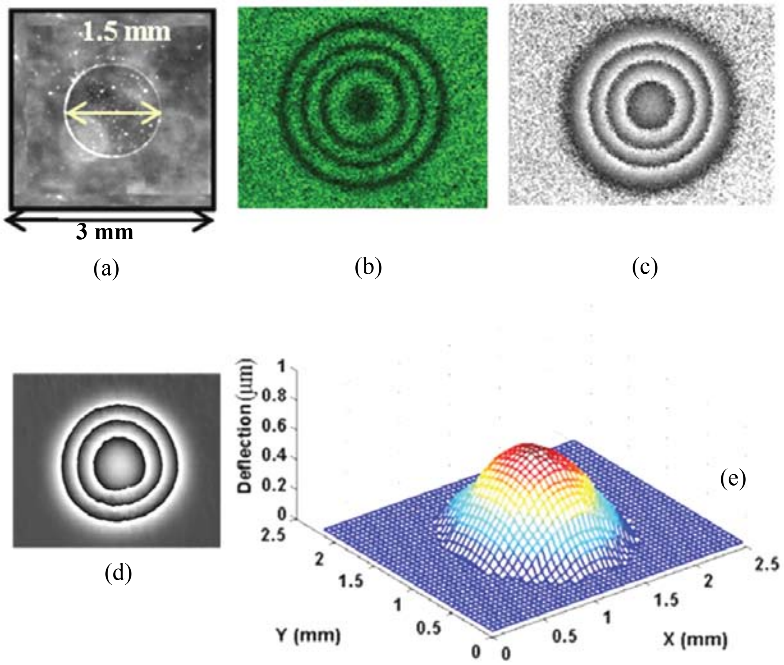

Figure 3. Deflection measurement on a circular MEMS pressure sensor: (a) white light image, (b) speckle fringes at P=25 kPa, (c) raw phase map, (d) filtered phase map, and (e) 3-D deflection profile.

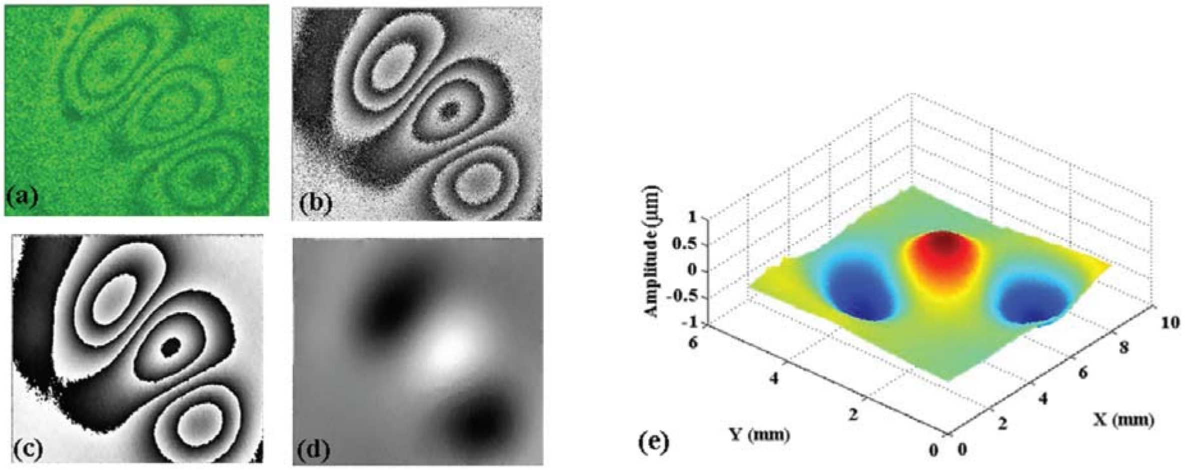

Figure 4. Vibration measurement at a resonant frequency 12.2 kHz: (a) Fringe pattern, (b) Raw phase map, (c) Filtered wrapped phase map, (d) unwrapped phase, and (e) 3-D view of the mode shape. The set values are :Gate=20° and Phase, α =82° and α+180° = 262° (82° +180°).

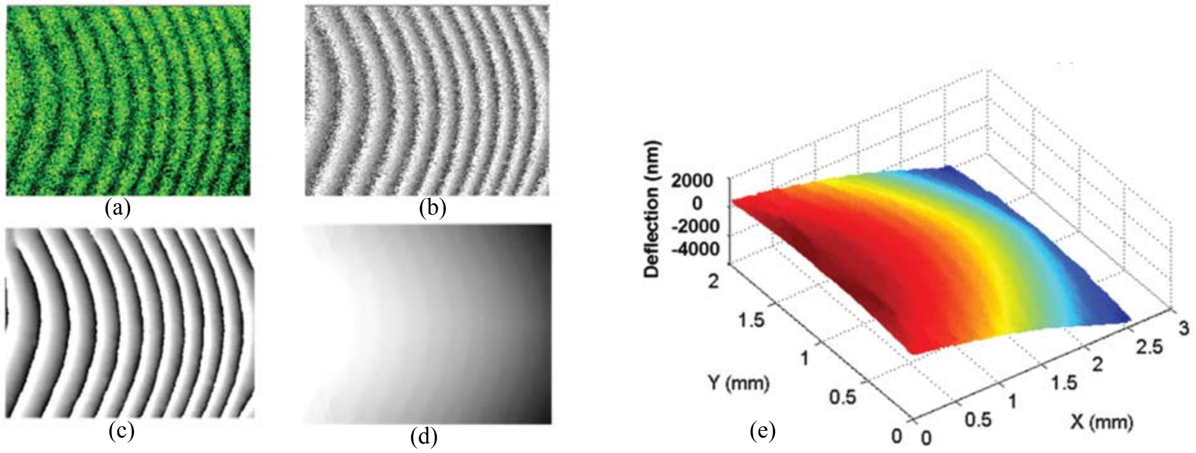

Figure 5. Vibration analysis on a cantilever beam at a resonant frequency 1.4 kHz :(a) Fringe pattern, (b) Raw phase map, (c) Filtered phase map, (d) unwrapped phase map, and (e) 3-D view of the mode shape. The set values for the measurement are: Gate: 20°, and Phase, α =20° and α+180° = 200° (20° +180°).

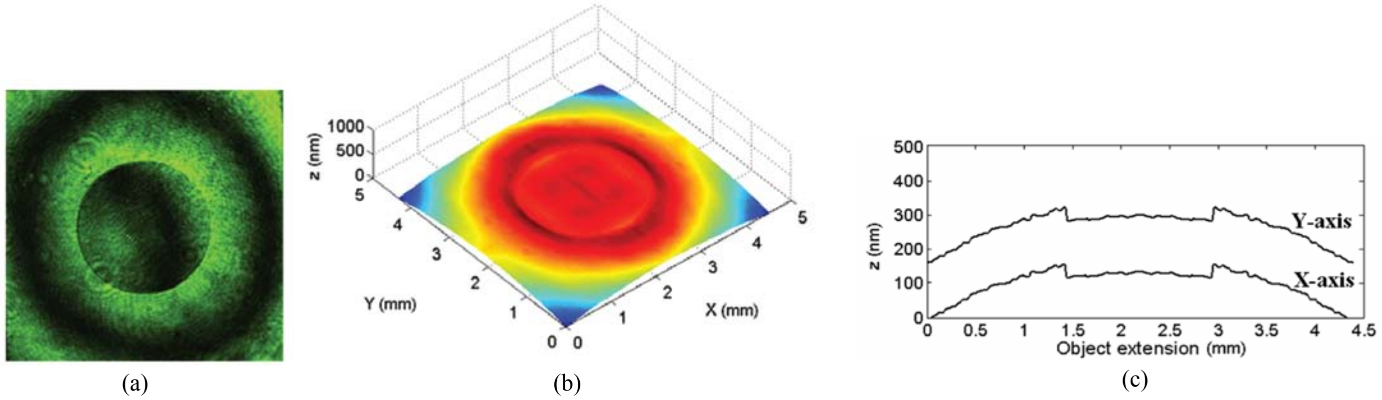

Figure 6. 3-D surface profiling on a circular MEMS pressure sensor: (a) fringe pattern, (b) 3-D plot, and (c) line scan along central x-,y-direction. The steeped part in the middle is the diaphragm.

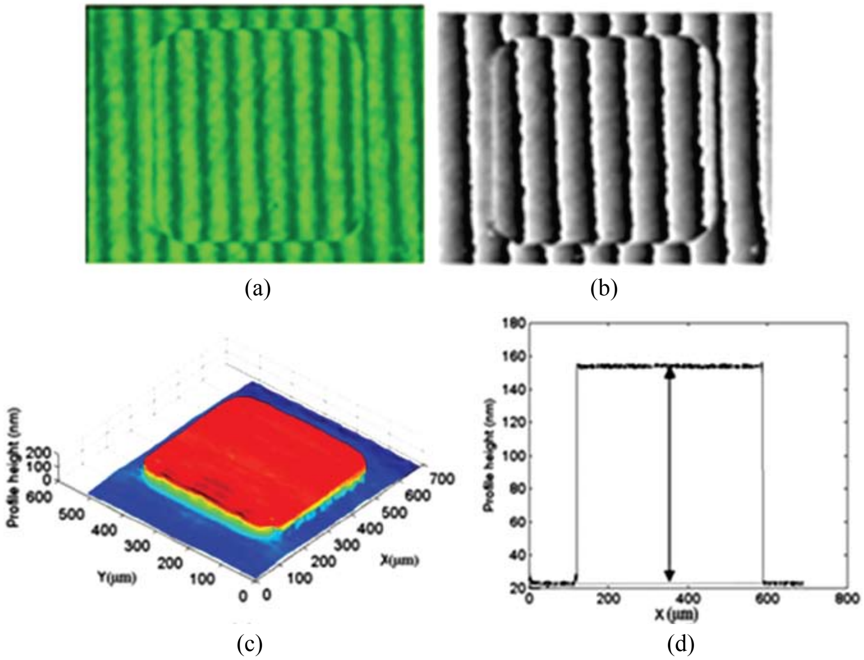

Figure 7. Measurement of discontinuity on a silicon sample with small step: (a) fringe pattern, (b) phase map, (c) 3-D plot, (d) line scan profile of 130 nm height along central x-axis.

of the micro specimen as given in Eqn. (5).

As explained earlier, the setup shown in Fig. 1 can be also be used as a microscopic interferometer for smooth surfaces. Here the interference between the test and the reference surfaces result in a conventional interference pattern. The circular pressure sensor used in Section 4.1 has a smooth surface. The sample is placed on the three axes stage and aligned to optically flat reference mirror to obtain an interference fringe pattern as shown in Fig. 6(a). In the experiment a larger area of the specimen, which include the 1.5 mm diaphragm in the middle, is observed. Accordingly the fringes are seen over a large area. The 3-D surface profile is shown in Fig. 6(b). Figure 6(c) represents the corresponding line scan along the central x-, y-direction. The steeped part in the center is the etched area at the center to create a circular diaphragm of diameter 1.5 mm and thickness 25 μm. The sensor area is almost flat whereas the overall substrate area is weakly spherical in shape.

The system can be used for the measurement of step height on smooth surfaces as shown in Fig. 7. Figure 7(a) shows the fringe pattern generated on a silicon sample with a small step. The corresponding wrapped phase map is shown in Fig. 7(b). The 3-D view of the step of height 130 nm is shown in Fig. 7(c). But the step heights greater than half a wavelength cannot be measured unambiguously using single wavelength data. This problem can be solved by incorporating multiple (RGB) wavelength method which can extend the measurement range as well as retain the single wavelength resolution[17-19]. Further the multiple wavelength method can also be used for rough surface 3-D surface profiling[20,21].

5. CONCLUSIONS

A TV holographic system for the static, dynamic and 3-D surface profile characterisation of Microsystems is presented in this paper. It is capable of investigating the rough as well as smooth specimens. The size of the samples that can be studied using the system ranges from few hundred micro meters to around 6 mm with the 2/3 inch CCD camera. The analysis is automatic, quantitative, full-field, non-contact, simple, and rapid.

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