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Non-Contact No-Moving Parts Surface Height Measurement Sensor using Liquid Crystal-based Axial Scanning Confocal Optical Microscopy

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ABSTRACT

An analog liquid crystal lens-based axial scanning confocal microscope is demonstrated as a 48 μm continuous range optical height measurement sensor used to characterize a 2.3 μm height Indium Phosphide twin square optical waveguide chip.

Keywords: Instrumentation, measurement, and metrology; Height measurements; Liquid crystals; Confocal microscopy; Scanning microscopy

1. INTRODUCTION

Height sensing or surface profiling is a very important aspect of electronic, optical, and optoelectronic device fabrication and testing. Typically, these measurements require tens of microns of height dynamic range with nanometer scale resolutions. Over the years, a number of techniques have been proposed to measure device heights that include both non-contact (e.g., optical and ultrasonic) and contact methods (e.g., Atomic Force Microscopy, Scanning Tunneling Microscopy). Of utmost importance is measurement repeatability over many years of operations. Here all-mechanical and/or contact methods are limited in terms of cost and performance such as via hysteresis effects in piezoelectric motion stages or wear and tear of probe tips or cost of sample preparations and sample handling. Hence the use of optics has been pursued to realize an electronically controlled no-moving parts non-contact optical profiler with no sample preparation requirements [1-4]. These key optical precision height sensors rely on the use of broadband light to enable height measurements, thus possess inherent limitations such as possible errors due to wavelength dependent effects, both in the sample and the sensor optics.

Proposed in this paper is a height sensor that uses a single wavelength laser, thus eliminating the limitations of using a widely broadband source, yet performing accurate and repeatable electronically controlled no-moving parts height profiling of an optically reflective sample. The proposed sensor takes advantage of an earlier demonstrated no-moving-parts three dimensional (3-D) free-space laser beam scanning technique using liquid crystals (LCs) [5-7]. Specifically, the use of agile focus tunable optics using LCs and optical Micro-Electro-Mechanical Systems (MEMS) technology was proposed to realize various axial scanning confocal microscopy (ASCM) architectures [8-9]. To the best of our knowledge, for the first time, shown is the design and proof-of-concept experimental demonstration of one of these LC-based no-moving-parts ASCM's as a surface height sensor [10]. A powerful attribute of this sensor is that it is an all-analog sensor that allows smooth and high resolution surface profiling mainly limited by the detection electronics and signal processing. Such a height sensor can be useful in device fabrication and test industries.

2. NON-CONTACT SURFACE HEIGHT MEASUREMENT SENSOR DESIGN

Fig.1 shows the proposed height sensor or profiler design that uses a LC lens to continuously move the focal spot along the axial direction. By monitoring the optical surface reflected optical power that returns via the detection pin-hole, surface profile measurements are achieved. Maximum light throughput will occur when a tightly focused spot on the optical sample is provided by controlling the LC lens focal length. The proposed system is calibrated using a mirror placed on a precision x-y-z translation stage and motion controller Model FiberAlign 130 from Aerotech, Pittsburgh, PA. The details of the LC lens from OKO Tech., Netherlands are described in Ref.7 and Ref.10. Note that because the LC lens is an analog device controlled by an analog electrical drive signal that controls the smooth analog molecular rotation of the LC molecules, super-precise focal motion is possible.

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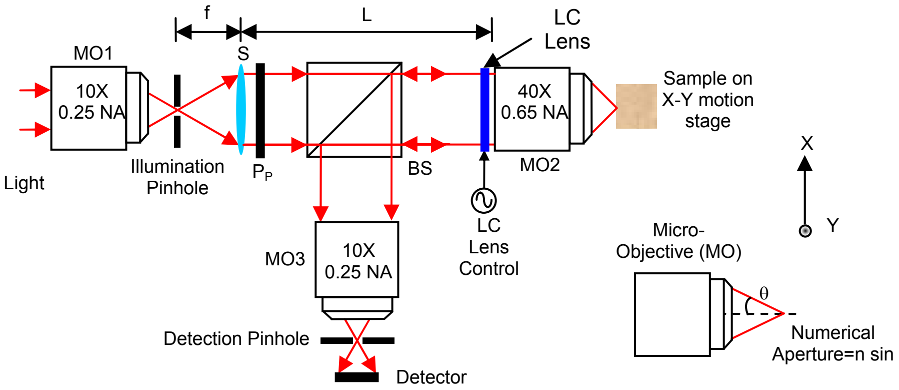

Fig. 1. Proposed LC lens-based Height Measurement Sensor, S: Spherical lens, Pp: linear polarizer along horizontal or p-axis, BS: Beam Splitter, MO1/ MO2/ MO3: Micro-Objective (MO) lenses.

3. EXPERIMENTAL RESULTS

For the proof-of-concept experiment, the Fig. 1 reflective ASCM is designed and assembled in the laboratory. A 15 mW He-Ne laser at 633 nm wavelength is used as the illumination source. The laser beam is spatially filtered using a 10 µm pinhole and a Micro-Objective (MO) labeled MO1 which is a 10X 0.25 NA lens assembly. The beam is then collimated using a 5 cm focal length spherical lens S, producing a 1/e2 Gaussian beam waist diameter of 5 mm at the S lens plane. A linear polarizer Pp is placed after S so that light is horizontally or p-polarized. The LC lens used is a 5 mm diameter device with an LC layer thickness of 50 µm. The LC device nematic director is aligned along the horizontal or p-direction. The sampling 40X microscope objective MO2 used has a NA of 0.65 and a 5 mm clear aperture. With 100 nm step height motion used for the Aerotech Stage, the ASCM axial 3-dB resolution is determined to be 3.1 µm.

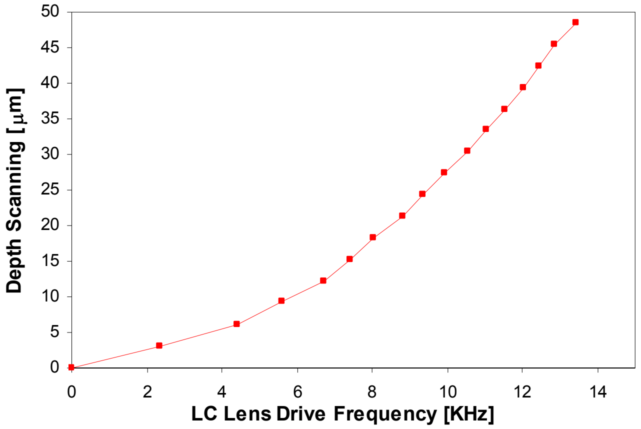

Fig. 2. Demonstrated 48 µm profiling range for the LC lens based surface height sensor. Shown is the ASCM classic 3-dB confocal resolution limited axial scanning transfer characteristics as a function of the LC lens drive frequency.

Using a flat aluminum mirror placed in the sample arm, the LC lens drive frequency and voltage is changed to cause the combined focal length of the 40X microscope and LC thin lens to change over the expected profiling range. Figure 2 shows the measured 3-dB confocal resolution limited axial scanning 48 µm profiler range. To determine the finest focal plane shift possible using the present Fig.1 profiler, the drive signal to the LC lens is finely varied. Then the shift of focal plane in the axial direction is measured by mechanically translating the sample in sub-micron sized steps using the precision motion controller while tracing the optical power maxima on the photo-detector.

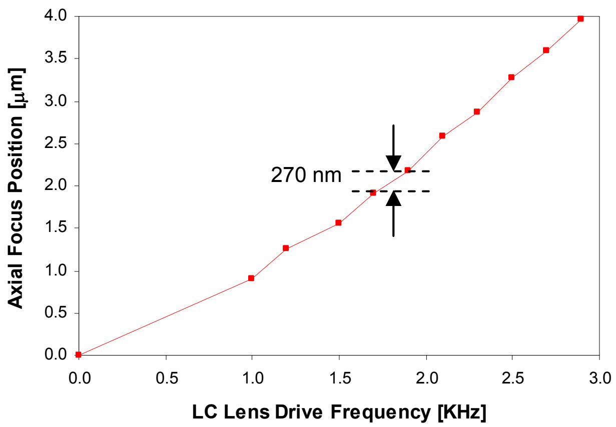

Fig. 3. Super-fine axial scanning resolution transfer characteristics of the demonstrated LC lens-based surface height measurement sensor.

The resulting plot in Fig. 3 shows that the LC lens is capable of scanning in sub-depth-of-focus steps as shown by the 270 nm resolution achieved in this case. To determine the transverse resolution of the profiler, a semiconductor sample with dual InP square waveguides is deployed. Each waveguide has 2.3 μm width and 2.3 μm height with a 7.9 μm inter-waveguide gap as measured by a Scanning Electron Microscope (SEM); see line-scanned SEM image of sample in Fig. 4. Three different planes in the waveguide chip were imaged to show profiler discrimination. The Aerotech stage is used to produce line scan images as shown in Fig.4, but with different planes in focus. First, with LC lens off, the stage is moved to its OFF position in the axial direction so the light is focused on the top surface of the waveguides. Then the stage is moved to its ON position such that the light is no longer focused on the top surface of the waveguides and a new line scan image is generated. Finally, without further moving the axial direction stage, the LC lens is turned on and drive signal adjusted to get a maximum optical signal over the waveguide top surface locations (bottom scan in Fig.4). The analog traces of these line scans confirm the SEM measured waveguide pitch and width values to within 0.1 μm. In addition, the LC lens calibration data and measured Fig.4 data confirm the waveguide height to 2.3 μm with 270 nm measured height repeatability.

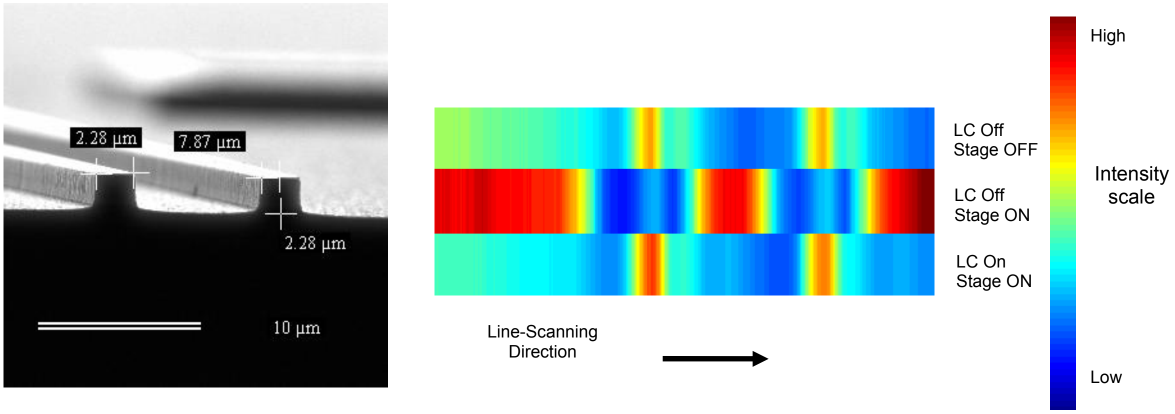

Fig. 4. (Left) SEM image of the InP test sample. (Right): Experimental profiler line-scanned optical intensity plots obtained for the InP waveguides sample. The top and bottom gray-scale optical power traces correctly show the line scans matching the SEM scan.

Confocal microscopy can also be realized as an interferometer. Essentially, one interferes the focused confocal sensing signal beam from the sample with a fixed reference plane wave optical beam coming from a mirror to realize an interference confocal microscope [11]. Fig.5 shows a modified novel surface profiler design using this ref. 11 coherent optical detection technique providing height profiling with a wavelength/2 scale.

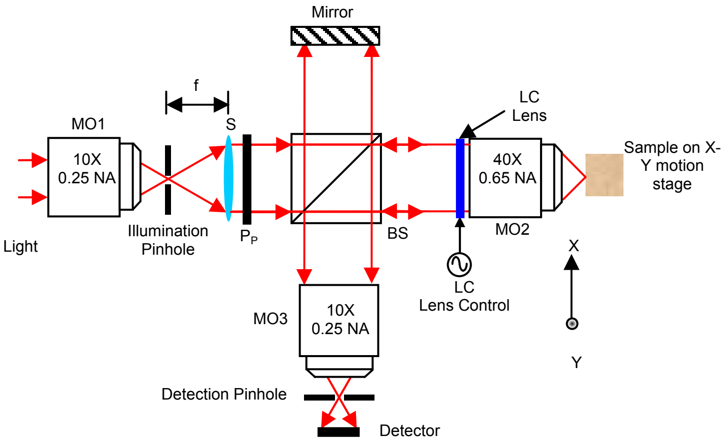

Fig. 5. Proposed Higher Resolution LC lens-based Optical Height Measurement Sensor using a coherent optical design, S: Spherical lens, Pp: linear polarizer along horizontal or p-axis, BS: Beam Splitter, MO1/ MO2/ MO3: Micro-Objective (MO) lenses.

4. CONCLUSION

Demonstrated is a novel non-contact no-moving parts height measurement sensor using LCs. Initial experiments show the power of this all-analog sensor with presently 48 μm continuous height mapping range with 270 nm resolution. Transverse motion of the laser beam can be accomplished by also deploying LC deflectors [6,7], thus making a fully electronic height measurement sensor suited for chip-scale characterizations. The proposed sensor can also be implemented using transmit/receive single-mode fiber (SMF) optics to realize a compact fiber-remoted design to deploy in hard to access zones. Future work relates to improving the resolution of the proposed sensor to nano-meter scales and implementing a compact sensor engineering prototype.

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