Paper:

Development of a Non-Contact Focusing Probe for the Measurement of Micro Cavities

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The measurement of microcavities is a challenging task if the cavity is smaller than the diameter of the micro touch-trigger probe. This paper presents a non-contact method using a blue-ray DVD pickup head as the sensor. It is based on a focusing principle holding that reflected light intensity is maximal when the tested surface is at the focus point of the probe. When a focused beam scans the edge of the cavity, reflected light intensity is gradually reduced. Theoretical analysis is used to derive the light intensity equation for when the focused beam is passing along the edge. Experimental tests of the developed probe were carried out in association with a nanopositioning stage. The edge position is obtained up to a resolution of 1 nm and a standard deviation of about 30 nm. This performance is beyond the diffraction limit of optical microscopes.

Keywords: micro cavity detection, blue-ray pick-up head, non-contact measurement, nano-positioning stage.

1. Introduction

Conventional form-error measurement of a hole is carried out by a coordinate measuring machine, image processing, or a roundness tester. These conventional methods are becoming more and more difficult to use, however, as advances in processes such as MEMS and micromachining make the holes to be measured smaller and smaller.

Microprobes are thus designed in order to enter the inner diameter of microholes. Kim et al [1] designed a vibrating probe with a probe ball 50 μm in diameter to measure microholes of 100 μm in diameter. Muralkrishnan et al [2] used a NIST fiber probe with a ball diameter of 113 μm to measure a hole of 130 μm diameter. Cho and Thielecke [3] used a microscope to measure microhole-based cell chips 8 μm in cell diameter, but resolution is limited by the optical diffraction limit. Chen et al [4] developed a capacitance probe to measure holes 1 mm in diameter with 0.78 μm repeatability. Lin et al [5] employed a confocal microscope to measure laser-drilled microholes 10 μm in diameter with an optical resolution to 0.5 μm. Recently, microcontact probes [6–8] are being developed for micro- and nano-coordinate measuring machines. Although contact probes have many advantages, they also have shortcomings that are difficult to overcome, such as workpiece damage, probe wear, contact deformation, and the inability to measure microcavities due to a limited probe diameter.

In contrast, noncontact methods using optical microscopy are free from contact force; however, but lateral resolution is limited to 0.5 μm, which is the limit of optical diffraction.

In this paper, a newly developed focusing probe, modified from a blue ray DVD pickup head, is presented to detect noncontact edges of microcavities. It is based on the intensity variation of the reflected laser beam scanning across the microcavity edge, which is moved by a nanopositioning stage. Lateral resolution is determined by the nanopositioning stage, which achieves a lateral resolution of 1 nm. Theoretical analysis of edge detection is derived. Current experimental results show that the cavity edge position is obtained to a resolution of 1 nm and a standard deviation of 30 nm can be successfully measured.

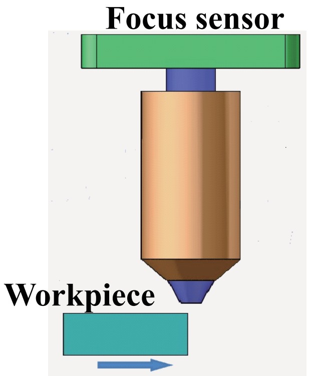
2. Measurement Principle

2.1. Theoretical Analysis

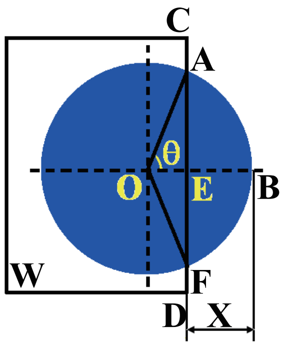
The edge detection principle is based on light reflection theory. When a beam spot is focused on a reflective surface, all light is reflected back to the receiver. While the spot is moved across the surface, only part of the light is reflected back. **Fig. 1(a)** shows the focus sensor on top of the moving workpiece. **Fig. 1(b)** shows a situation in which the beam spot, in blue, passes distance (x) from edge (CD) of surface W. The amount of reflected light is proportional to the remaining spot area on the surface. Let the radius of the spot be r ($x<2r$).

$$\text{Sector area of OABF} = r^2\theta \quad (1)$$

$$\text{Triangular area of OAF} = r\,(r-x)\sin\theta \quad (2)$$



(a) System configuration



(b) Beam spot on the surface

Fig. 1. Geometrical relationship of spot area across the edge.

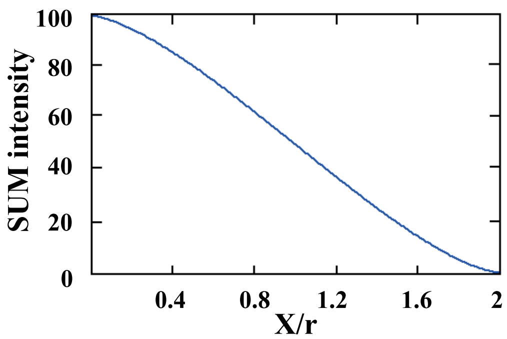


Fig. 2. Optical intensity of received light.

Area of the spot remaining on the surface is then

$$A(x) = \pi r^2 - r^2\theta + r(r-x)\sin\theta \quad . \quad . \quad . \quad . \quad (3)$$

Total light intensity received by the photodetector is proportional to the reflected area of the spot. Its relationship is plotted in **Fig. 2**. It shows that when the spot is on the surface, received light intensity is 100%. This intensity decays gradually and vanishes when the spot has completely gone from the surface. The theoretical slope of this characteristic curve is plotted in **Fig. 3**. It can be seen that the ideal edge position corresponds to minimal slope point ($x = r$).

In actual experiments, however, the characteristic curve of the intensity response was not so smooth. With the occurrence of inevitable noise disturbance, it is not possible to obtain the ideal slope curve to find the minimal slope point. However, an invariant pattern of the intensity curve assures that the edge point must be at the midpoint of the curve if the spot shape, either purely circular or elliptical, is symmetrical in the direction of movement. In the present study, a method is determined to find the edge point corresponding to the average intensity of maximal and minimal intensities of reflected light. In practice, measured intensity is in a discrete form with respect to the step size of scanning in the X direction. The edge point is found by linear interpolation of two adjacent points between which the midpoint lies. Theoretical analysis shows that if the midpoint is within a region of 0.9 and 1.1 of the X/r ratio, linearity error is within $+0.15$ and -0.1, as shown in **Fig. 4**. Estimated error is 0.15% of the X/r value. The ideal diameter of the focused spot of a blue-ray DVD pickup head is about 500 nm. Theoretical estimated error by linear interpolation should be less than 1 nm.

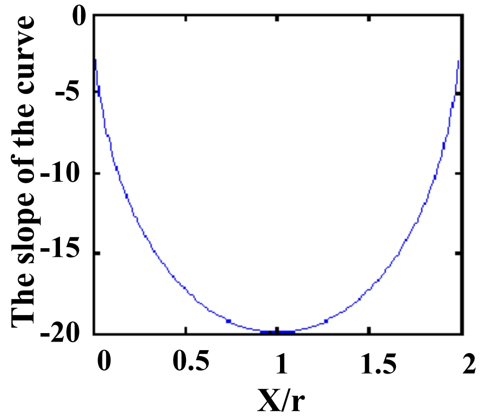


Fig. 3. Slope of the intensity curve.

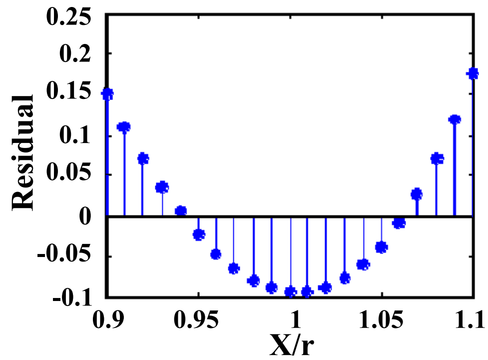


Fig. 4. Linearity error in the region of (0.9, 1.1) of X/r.

2.2. Focus Sensor

The DVD pickup head is used to detect binary signals stored on the DVD track with the focused laser spot based on the astigmatic principle. **Fig. 5** shows the optical system of a commercial DVD pickup head. The laser diode emits a beam through a grating. The beam then is split into three beams that pass through the polarization beam splitter, quarter wavelength plate, collimator lens, and objective lens and finally focus on the disc surface. The reflected beam passes along the same original path and, after two polarizations by the quarter wavelength plate,

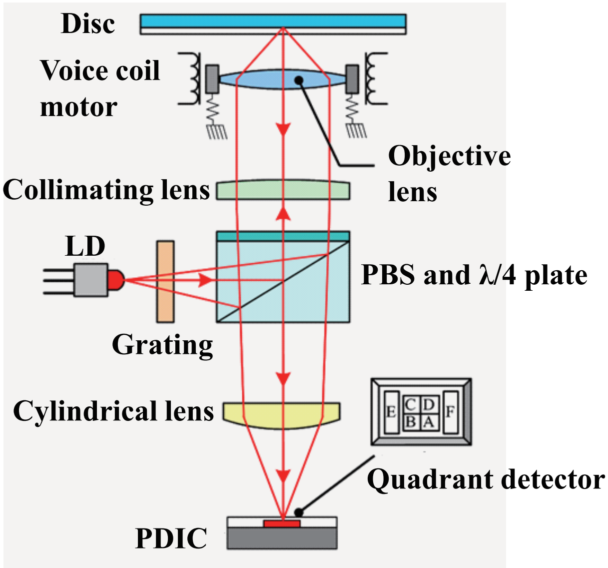


Fig. 5. Optical structure of a DVD pick-up head.

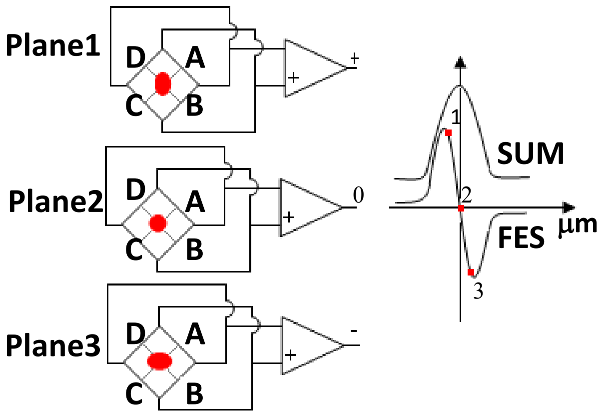


Fig. 6. Spot shape within the FES and SUM range.

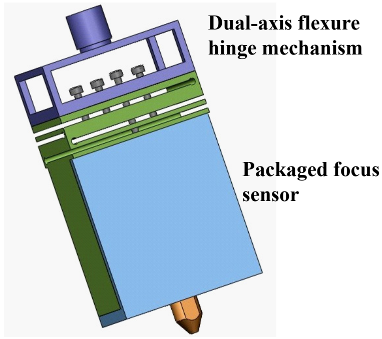
is projected onto the quadrant detector through the cylindrical lens. The photodiode outputs Focus Error Signals (FES) based on the astigmatic principle, as expressed by Eq. (4) and total light intensity signal (SUM) is expressed by Eq. (5).

$$FES = (V_A + V_C) - (V_B + V_D) \quad \quad (4)$$

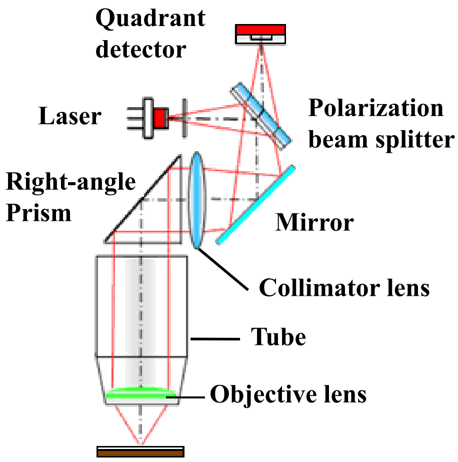
$$V_{sum} = V_A + V_B + V_C + V_D \quad \quad (5)$$

The photodiode outputs FES if the measured surface is located close to the focal point. The image of the beam on the photodiode becomes elliptical in different orientations (see planes 1 and 3 in **Fig. 6**). If the measured surface is in focus, the image becomes circular (see plane 2 in **Fig. 6**). The range of SUM also is shown in **Fig. 6**, where it can be seen that when the measured surface is in focus, FES reaches midpoint (FES = 0) and SUM reaches the maximal point. The FES signal is often used to detect variation in the surface profile of a measured object [9]. In the present study, it is used to detect total light intensity

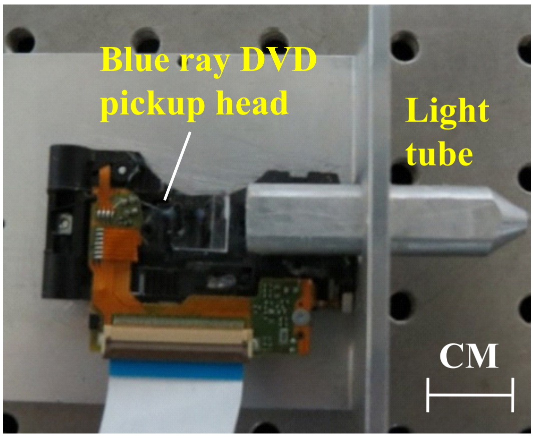
(Note that the voice coil motor in the DVD pickup head is not used in this study. It was therefore removed from the assembly. The grating was also removed).



(a) CAD design of the probe



(b) Configuration of the optical system



(c) Assembly of the DVD probe in the case

Fig. 7. Developed focusing probe.

In order to reduce overall size, the probe is designed in the CAD form of **Fig. 7(a)**. The optical axis of the pickup head is bent 90 degrees by a right-angle prism, as shown in **Fig. 7(b)** in which a tube is designed to fix the objective lens in place. **Fig. 7(c)** shows the internal assembly of the pickup head in the probe case. A flexure mechanism, shown in **Fig. 7(a)**, is attached to the probe case to easily adjust the optical axis normal to the tested surface in two angular directions.

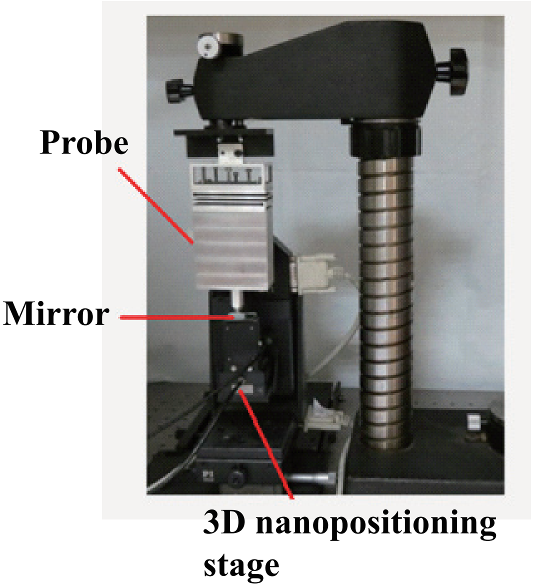


Fig. 8. Experimental setup of the measurement system.

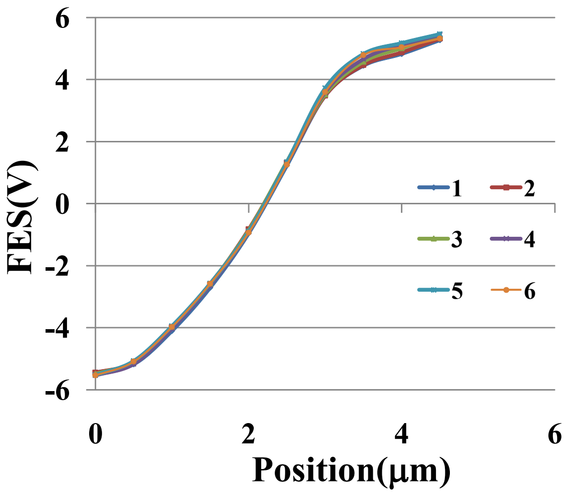


Fig. 9. FES curve of the probe.

3. Experiments

3.1. Edge Detection

The experimental setup of the measurement system is shown in **Fig. 8**. A mirror was used as the test piece. A 3D nanopositioning stage (PI Co. model P753.1) was adopted to position the mirror on the focal plane of the probe. Adjusting the flexure mechanism, a good FES curve was obtained with quite good repeatability, as shown in **Fig. 9**. It can also be seen that linearity from 1 μm to 3 μm is good. Let the position be that at which FES $=0$ is the trigger point. As soon as FES reaches the midpoint, i.e., the trigger point, a signal is sent to the nanopositioning stage to stop the probe from moving vertically. **Table 1** lists trigger data with standard deviation of less than 12 nm. In experiments on edge detection, the mirror is positioned at the focal point of the probe and laterally moved by the nanopositioning stage at an incremental

Table 1. Trigger positions (unit: nm).

Six trigger positions	Average position	Standard deviation
2314, 2291, 2283 2292, 2304, 2285	2294.8	11.9

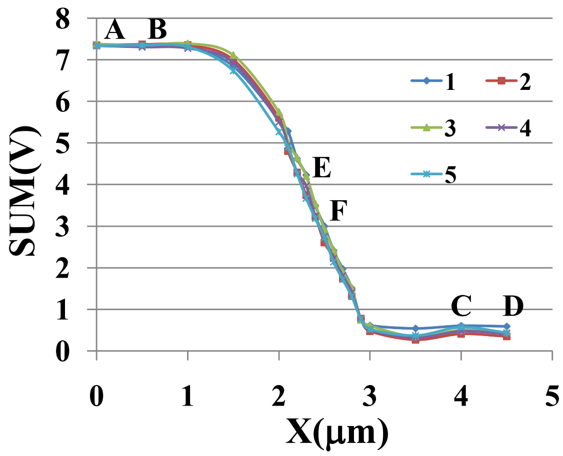


Fig. 10. Measured light intensity across the edge.

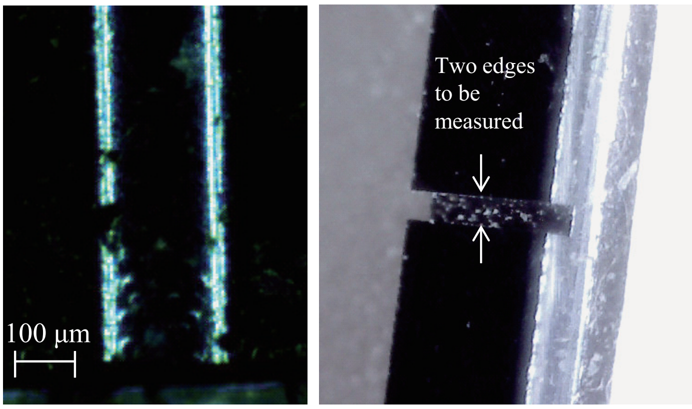
Table 2. Calculated edge positions (unit: nm).

Five calculated edge positions	Average position	Standard deviation
2327, 2281, 2264 2296, 2337	2301	30.7

step size of 0.1 μm. Intensity variation in scanning across the edge of the mirror shows quite good repeatability for 5 times of experiments, as shown in **Fig. 10**. The average intensity value, corresponding to the theoretical edge point, was calculated from the midpoint between two end points V_A and V_D of the SUM curve. In comparison, it was found that this edge point fell in the region of two consecutive steps E and F. A linear interpolation operation for this region then obtains the exact edge position. **Table 2** listed edge positions calculated 5 times. The average value is 2301 nm and standard deviation is 30.7 nm. This experiment demonstrates the capability of this non-contact measurement system to detect the edge position of a rectangular cavity to a resolution of 1 nm with about 60 nm repeatability (two standard deviations). It has broken through the diffraction limit conventionally measured by an optical microscope.

3.2. Rectangular Trench Measurement

A rectangular trench fabricated by a MEMS process shown in **Fig. 11** was then measured. The plate is about 1 mm thick. The top view was measured by an optical microscope, which shows obvious diffraction on both sides that cause difficulty in determining the real edge position. The isometric view was taken by a microscopic



(a) (b)

Fig. 11. Rectangular trench: (a) top view, (b) isometric view.

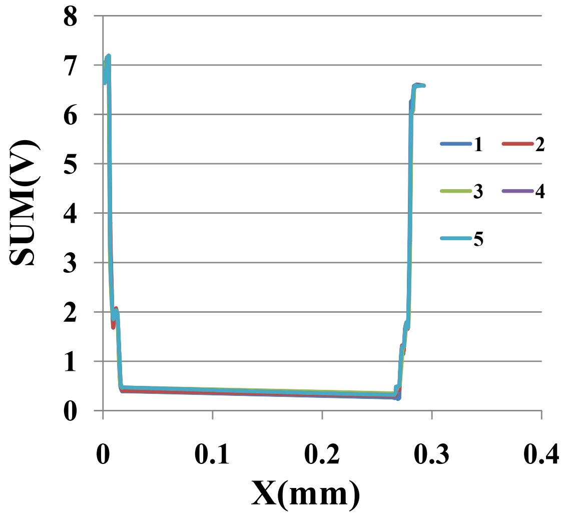


Fig. 12. Measured light intensity across the trench.

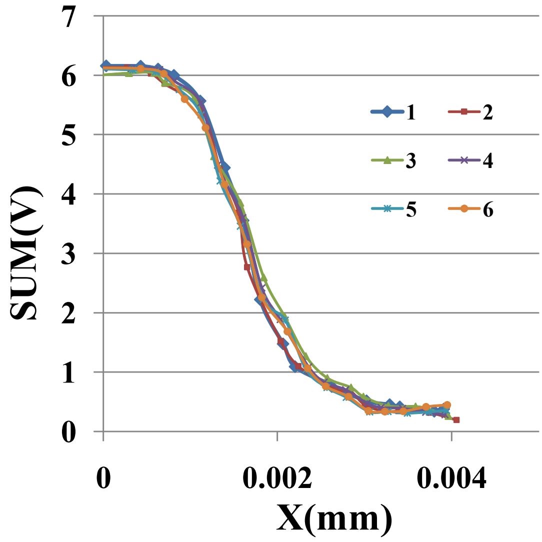


Fig. 13. Measured light intensity across the left edge.

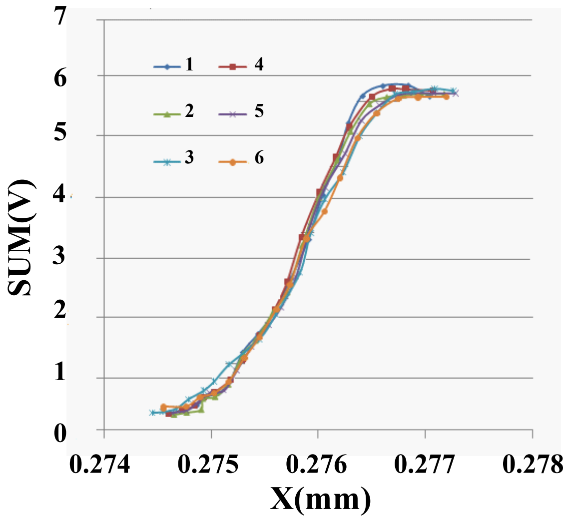


Fig. 14. Measured light intensity across the right edge.

camera but without a scale indicator. The optical microscope, moreover, measures only a submicron resolution due to the diffraction limit. It is seen from **Fig. 11(a)** that the two edges have broken-line defects and are quite rough. To the best of our effort with an optical microscope, the width of the rectangular trench was measured at 264.5 μm. Using the developed focus probe system, intensity variation is shown in **Fig. 12**. **Figs. 13** and **14** show repeatability of 6 detections of the left and right edges, respectively. **Table 3** listed calculated width. The average calculated width is 274.188 μm with a standard deviation of 55.8 nm.

3.3. Microhole Measurement

A small pinhole of 100 μm in nominal diameter was used for measurement. As shown in **Fig. 15**, the area surrounding the hole is seriously damaged in the machining process, so the surface is dented and very rough. The edge scanning path for four-point detections reveal only the damaged circle. **Table 4** shows that the measured diameter is 174.951 μm with a standard deviation of 74 nm.

Table 3. Calculated trench width (unit: μm).

Six measured widths	Average width	Standard deviation
274.216, 274.212, 274.094 274.113, 274.175, 274.102	274.152	0.0558

4. Error Analysis

4.1. Circuit Noise

It is necessary to magnify weak signals detected by means of an operational amplifier circuit. The operational amplifier circuit not only enlarges useful signals, however, but also increases noise. It generates a new circuit noise, moreover, that adversely affects signal quality, such as resistances, capacitances, power supply, etc. In experiments, noise amplitude is 120 mV. In order to reduce the effect of noise on signals, moving average software was developed in signal processing.

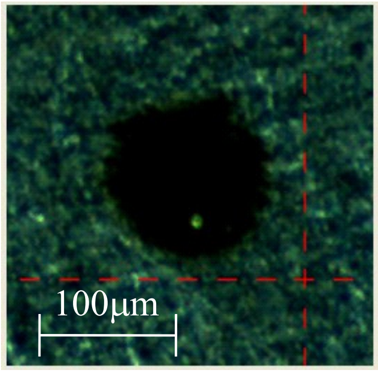


Fig. 15. 100 μm pinhole with a damaged edge.

Table 4. Microhole measurement (unit: μm).

Three measured diameters	Average diameter	Standard deviation
175.016, 174.871 174.967	174.951	0.074

4.2. Temperature

4.2.1. Effect of Temperature on the Laser

Laser output power is sensitive to temperature change. Any change in laser power also changes FES voltage.

4.2.2. Effect of Temperature on the Mechanical Structure

Temperature changes cause thermal deformation in mechanical structures that directly affects measurement accuracy.

Experiments therefore have to be carried out in a temperature-controlled environment.

5. Conclusions

A noncontact type of focus probe has been developed in this study for microcavity edge detection. It is based on the light reflection principle in scanning across the cavity edge. Assisted by a nanopositioning stage, the measurement system detects the edge position at 1 nm of resolution with about 30 nm standard deviation. Applications to the rectangular trench and micropinhole measurement show standard deviation to be below 75 nm. Compared to the conventional optical microscope, this breaks through the diffraction limit. Further work will be continued to measure the dimension and form error of microcavities smaller than 100 μm in diameter that cannot yet be measured, for example, by a microstylus.

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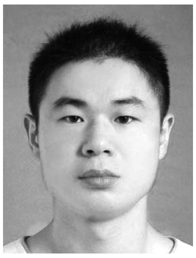

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