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A single micro-LED manipulation system based on micro-gripper

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ABSTRACT

Micro-LEDs (μLEDs) have advantages in terms of brightness, power consumption, and response speed. In addition, they can also be used as micro-sensors implanted in the body via flexible electronic skin. One of the key techniques involved in the fabrication of μLED-based devices is transfer printing. Although numerous methods have been proposed for transfer printing, improving the yield of μLED arrays is still a formidable task. In this paper, we propose a novel method for improving the yield of μLED arrays transferred by the stamping method, using an innovative design of piezoelectrically driven asymmetric micro-gripper. Traditional grippers are too large to manipulate μLEDs, and therefore two micro-sized cantilevers are added at the gripper tips. A μLED manipulation system is constructed based on the micro-gripper together with a three-dimensional positioning system. Experimental results using this system show that it can be used successfully to manipulate μLED arrays.

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KEYWORDS

Micro-gripper, Micro-LED, Transfer printing, Manipulation

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I. INTRODUCTION

In recent years, Apple, Samsung, Sony, and other companies have initiated research into micro-LEDs (μLED),[1,2] which represent a promising new approach in the development of display technology, particularly with regard to displays in smart devices.[3,4] μLED technology is based on miniaturization and matrixing, with high-density and micro-sized LED arrays being integrated on a chip, with a pixel size generally less than 100 μm. Images of an μLED array as observed with a field emission scanning electron microscope (SWM, Zeiss Sigma 300) are shown in Figs. 1(a) and 1(b), and the corresponding surface texture obtained using white light interferometry is shown in Figs. 1(c) and 1(d).

The main advantage of μLEDs is that each pixel cell can be individually controlled and driven. In terms of brightness, contrast ratio, power dissipation, resolution, and other parameters, they are superior to conventional LEDs while meeting standard requirement with their characteristic micrometer-scale pixel spacing. μLEDs provide brighter illumination than competing technologies, even under low-power conditions. Specifically, for a given brightness, they consume 90% less power than LCDs and 50% less than OLEDs. Accordingly, if smart phones were to use μLED displays, their battery life would be greatly improved—a critical requirement for portable devices. Furthermore, the response time of μLEDs is in the range of nanoseconds. This quick response is faster than those of LCDs (in the millisecond range) and OLED (in the microsecond range), making μLEDs the best choice for virtual reality (VR) applications of 5G technology.[2] In another words, μLEDs are at the forefront as technology enablers for display applications in the 5G era.[3,4]

To transfer μLEDs, the most commonly used techniques are the stamp method,[5–14] the roller method,[15–18] the laser method,[19–22]

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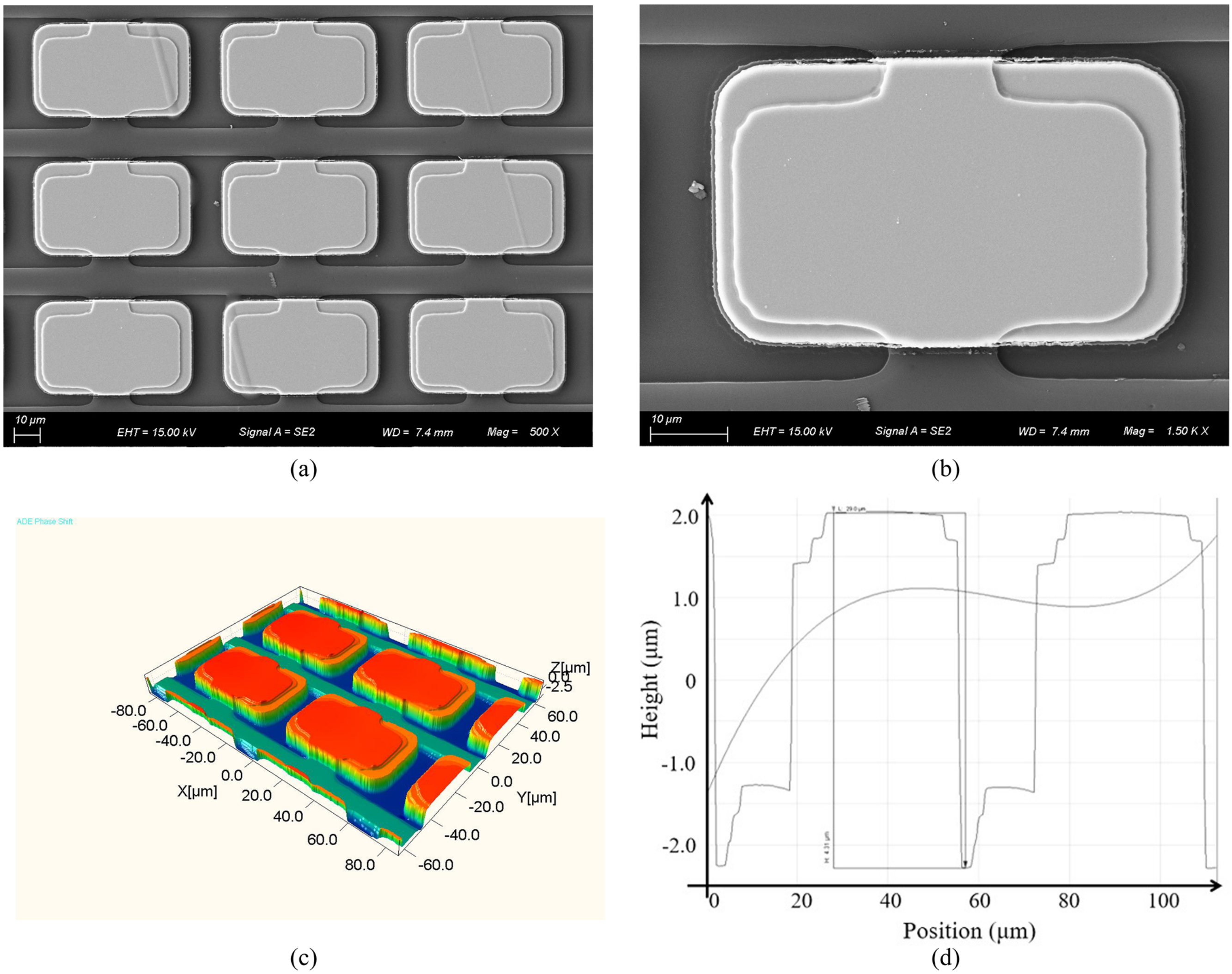

FIG. 1. (a) and (b) SEM images of an array of μLEDs with magnifications of 500× and 1500×, respectively. (c) and (d) Surface texture of μLED array captured by a white light interferometer.

the electrostatic method,[23–27] the magnetoelectric method,[28] and the fluid method.[29–31] Among these, the most commonly used is the stamp method (also known as transfer printing), in which the μLEDs comprising the array are picked up from the donor substrate on which the μLEDs were formed and transferred to the receiving substrate in parallel using an elastomeric stamp with a microstructured surface. Park *et al.*[5] have proposed the use of such stamps made of polydimethylsiloxane (PDMS)-based materials. In this transfer method, the adherence and release of the μLEDs is achieved by controlling the speed of the stamp. When the stamp moves rapidly, the μLEDs adhere to the stamp owing to van der Waals forces. When the stamp moves slowly, the μLEDs detach from it and adhere instead to the receiving substrate. The Korea Institute of Machining and Materials has proposed a transfer technique based on the use of barrel seals,[15–19] with which it is possible to achieve transfer speeds reaching 10 000 μLED crystals per second.

However, differences between the roughness of the stamp surface and that of the donor substrate will lead to a large mismatch error, as shown in Fig. 2. Local temperature inhomogeneities could also contribute to mismatch error. The thermal coefficient of PDMS is about 340 ppm/°C, while the thermal coefficient of the donor substrate (Si) is about 5–9 ppm/°C. There would be a mismatch error of 33 μm between stamp and μLED array for a stamp of side length 100 mm if the ambient temperature changed by 1 °C. Such errors contribute to the low yield rate of stamp transfer printing. In view of this low yield rate, we propose here a micro-gripper[32] to manipulate μLED arrays and thereby improve the yield of micro-stamp transfer.

The micro-gripper is aimed at fixing mismatch errors associated with the stamp method in mass production. It should be possible for a μLED to be picked up and released with highly accurate guidance of the positioning system. However, it is hard

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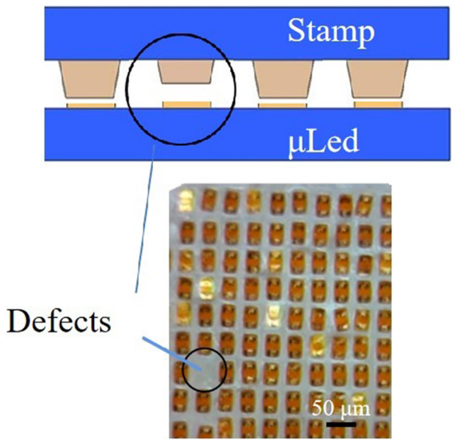

FIG. 2. Mismatch error associated with the stamp method.

for traditional methods to obtain high accuracy in positioning the μLED and the receiving substrate. In a previous study,[33] we proposed a highly precise method for depth measurements using a 3D microscope system that can be used to determine the positions of both the μLED and the receiving substrate. Owing to the small size of μLED crystals, it is necessary to employ specially designed mechanical grippers to handle them. Mechanical clamping has an advantage over other clamping methods in that it can be used in conjunction with a microscope camera for determining the position of the μLED. Figure 3(a) shows a piezoelectrically driven asymmetric micro-gripper.[34–36] However, on its own, such a gripper is too large to manipulate μLEDs. Therefore, to meet the needs of μLED crystal clamping and transfer, two micro-sized cantilevers, shown in Fig. 3(b), are added at the tips of the gripper as shown in Fig. 3(c).

II. GRIPPER-BASED MANIPULATION SYSTEM FOR μLED

A. Design of gripper

μLEDs have already been cleaved from their donor substrate before they are transferred. The micro-gripper only needs to overcome the adhesion between μLED and substrate, which is about 2 μN. The micro-gripper can be used to carry out micromanipulations such as clamping, transfer, and release. Previous work on micro-gripper has been reviewed in Refs. 37 and 38.

The structure of the proposed gripper based on the asymmetric clamping mode is shown in Fig. 4(a). The clamping arm on one side is attached rigidly to the frame of the gripper. The clamping arm on the other side is connected to the lever mechanism via the output end of the gripper. This structure ensures stability during clamping and avoids instability caused by manufacturing error. At the same time, it makes operation of the gripper easier. In practical operation, only a piezoelectric drive is needed to control the displacement of the clamping arm to grip the object.

The movable clamping arm of the micro-gripper moves in a translational mode. The two clamping arms are always in a parallel alignment and the Y displacement is approximately zero. This ensures that when the gripper clamps an object, even if there is interference by external forces, the clamped object will not slip off. In addition, this gripper uses a parallelogram mechanism as an amplifying mechanism for the final stage. When the angle of rotation of the parallelogram mechanism is small, the displacement generated by the system in the horizontal direction is much greater than that generated in the vertical direction. The relationship between the vertical displacement y and the angle of rotation θ is as follows:

$$y = l(1 - \cos\theta), \tag{1}$$

where l is the length of the moving part of the parallelogram mechanism. It can be seen from Eq. (1) that when the angle of rotation

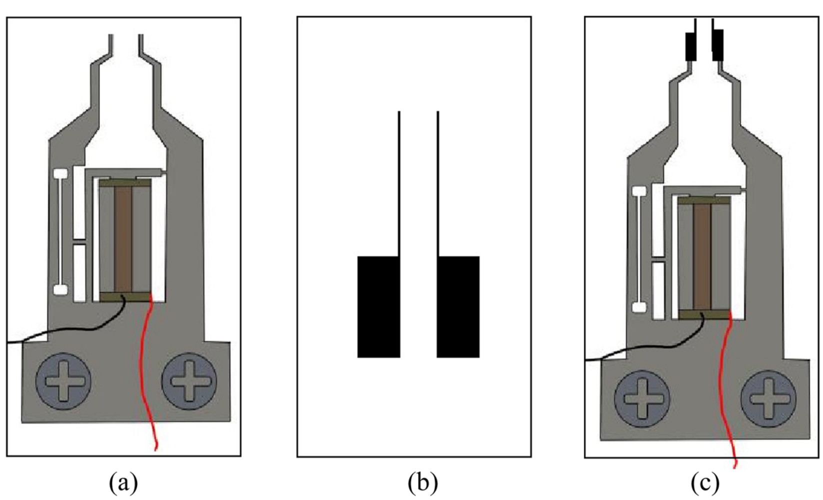

FIG. 3. Schematic of a gripper-based μLED manipulation system.

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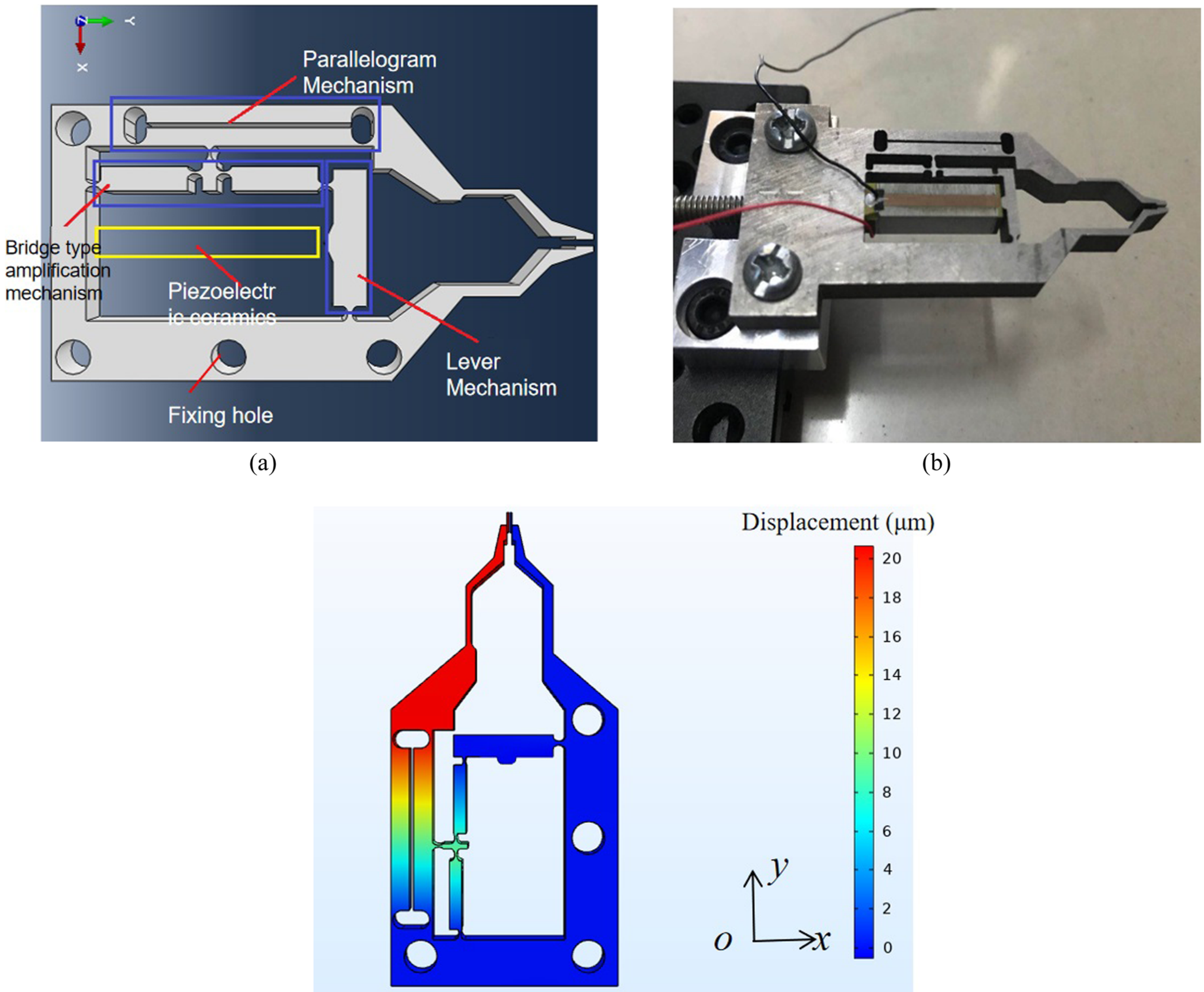

FIG. 4. Micro-gripper: (a) diagram of gripper; (b) photograph of gripper; (c) finite element simulation model of gripper for an input displacement of 2 μm.

is extremely small, and so $\cos\theta$ is close to 1, the vertical displacement is close to zero. The parallelogram mechanism is connected directly to the output end of the micro-gripper, which ensures parallel movement of the clamping end of the micro-gripper.

This micro-gripper is driven by stacked of piezoelectric ceramics where the output displacement of the gripper depends on the input displacement of the piezoelectric ceramics. We simulated the displacement amplification ratio of different depths by finite element method as shown in Fig. 4(c).

To simulate the output of the gripper, the input displacements are set at positions on the piezoelectric ceramic of 2 μm, 4 μm, 6 μm, and 8 μm. The X and Y displacements of the movable clamping arm of the micro-gripper under different inputs are recorded. The results show that the displacement in the Y direction is much less than that in the X direction. The displacement amplification is the ratio of output displacement to input displacement and for this gripper is about 10.2. The data from the simulation are shown in Table I.

B. Design of gripper tip

The selection of the size of the cantilever beam is extremely important. The stress introduced by the cantilever when the μLED crystal is clamped needs to be assessed to ensure that the clamping end will not damage the μLED during the clamping process. According to Euler's formula, the thickness of the cantilever has the greatest influence on the magnitude of the stress introduced by the micro-gripper. Therefore, the finite element method is used to simulate the

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TABLE I. Displacement amplification of gripper according to simulation.

Input displacement (μm)	X (μm)	Y (μm)	Y/X	Displacement amplification ratio
2	20.438	0.183	0.008 95	10.219
4	40.876	0.367	0.008 99	10.219
6	61.313	0.551	0.008 97	10.219
8	81.751	0.734	0.008 98	10.219
10	102.200	0.918	0.008 98	10.220

stress conditions of cantilevers of different thickness when they hold and transfer μLED crystals.

Considering the size of the μLED crystals, the length of the cantilever is set at 100 μm and the width at 30 μm. Cantilevers with thicknesses of 0.5 μm, 1.0 μm, and 1.5 μm are selected. The maximum stress at the movable end when clamping is simulated under different input displacements at the cantilever tip. Thereby, the working ranges of cantilevers with different thicknesses are determined. The simulation results are shown in Fig. 5.

Both the cantilever and μLED are fabricated from silicon, which has a yield strength of 503 MPa. To prevent damage to the μLED and cantilever, the maximum clamping force is set at one-tenth of this yield strength, i.e., 50.3 MPa. The simulation results show that for cantilevers of thicknesses 0.5 μm and 1 μm, the maximum stress at the tip remains below the yield strength throughout the entire working range of 10 μm. Thus, even in extreme cases, neither the clamping end of the micro-gripper nor the μLED will be damaged by excessive stress during the manipulation procedure. The proposed method is robust enough to be used repeatedly.

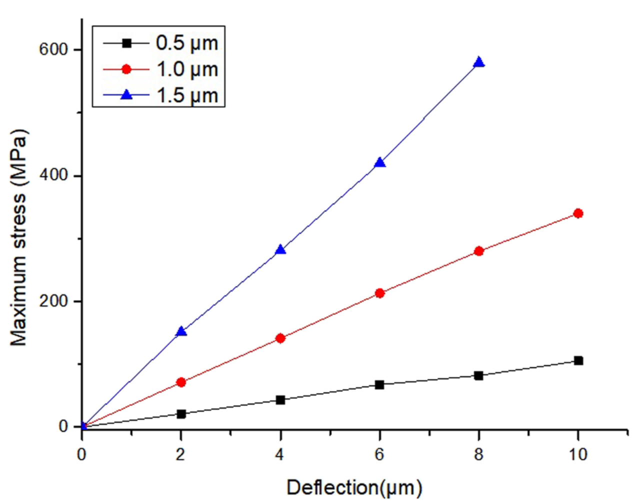

FIG. 5. Simulated maximum stress at the tip of the gripper vs deflection.

For a cantilever of thickness of 1.5 μm, when the input displacement is 8 μm, the maximum stress will exceed the yield strength and thus cause damage. Although this cantilever would be damaged in the extreme case where the μLED crystal was immovable, irreversible damage would only occur when the input displacement reached 7.5 μm. By then, the micro-gripper would have covered three-quarters of the working range. Also, in actual operation, the driving voltage applied to the piezoelectric ceramic end of the micro-gripper increases slowly from low to high. Therefore, it can be considered that a cantilever of thickness of 1.5 μm performs well under extreme conditions and will not cause any damage. Thus, the above analysis indicates that the ideal thickness of the cantilever of the micro-gripper should be 1.5 μm.

III. RESULTS AND DISCUSSION

A. Characteristics of micro-gripper

To investigate the performance characteristics of the micro-gripper, the voltages at both ends of the piezoelectric ceramic are applied from 0 to 120 V in steps of 10 V. The input voltage is converted into the corresponding input displacement of the piezoelectric ceramic. The relationship between the voltages and the displacement has been calibrated by the manufacturer. At the same time, the output displacement of the micro-gripper is measured by a laser interferometer. The ratio of the output displacement of the clamping arm to the input displacement of the piezoelectric ceramic is the amplification factor of the gripper. The data are shown in Table II.

The experimental results show that the displacement amplification ratio of the micro-gripper is about 7.5.

B. μLED clamping experiment

The setup of the clamping experiment is shown in Fig. 6(a) and consists of three parts: the micro-gripper, a 3D microscope system for depth measurement, and an adjustable displacement table.

The procedure for manipulation of a single μLED using the micro-gripper consists of the following steps.

Step 1. Depth measurements are performed using the 3D microscope system, and the images obtained while recording the clamping

TABLE II. Displacement amplification ratio of micro-gripper.

Input voltage (V)	Input displacement (μm)	Output displacement (μm)
0	0	0
20	2.67	21.31
40	5.33	42.78
60	8.00	59.38
80	10.67	80.23
100	13.33	94.86
120	16.0	112.63

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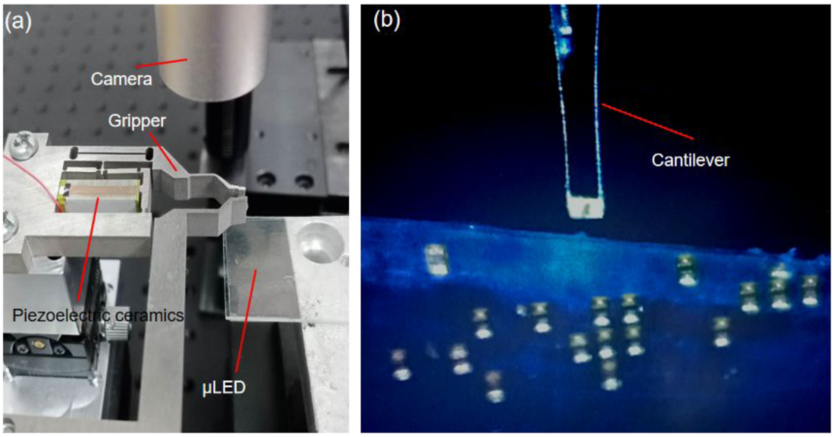

FIG. 6. Experimental manipulation of a μLED by the micro-gripper. (a) Experimental setup. (b) Manipulation of a single μLED by the micro-gripper.

process are saved in real time. The accuracy of positioning can reach 1 μm. The advantages of the micro-gripper is that it can be used in conjunction with visual methods to achieve high-precision position control.

Step 2. After positioning has been performed using the visual system, the micro-gripper performs its clamping function and manipulates the μLED under control by the piezoelectric system.

Step 3. The displacement table and the visual positioning system are used together to transfer the micro-gripper to its target position.

Step 4. The micro-gripper releases the μLED under control by the piezoelectric system.

To investigate the performance of the micromanipulation system, the experimental setup shown in Fig. 6(a) was used to manipulate a μLED of length of 40 μm, width 20 μm, and thickness 4 μm as shown in Fig. 6(b). It can be seen that the micro-gripper was able to achieve a stable clamping state. Meanwhile, it was found that the difference in Y position of the two clamping arms before and after clamping was very small, thus enabling parallel clamping. It should be noted that the micro-gripper used in this study was designed with one clamping arm fixed and the other movable. The fixed clamping arm was used as the position reference in the experiment, which greatly reduced the positioning time and improved the experimental efficiency.

IV. CONCLUSIONS

Current μLED handling and transfer methods are limited by their low yield. In this paper, a micro-gripper has been designed to manipulate and transfer μLED arrays with improved yield. The next step should be to investigate the application of this micro-gripper on an industrial scale, for example by developing a new method for repairing μLED arrays taking advantage of the inherent low speed of the micro-gripper-based manipulation system.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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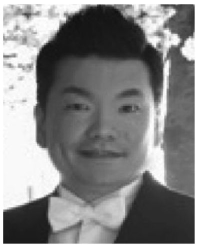

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