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Investigation of the Cause of a Malfunction in a Display Package and Its Solution

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***Abstract*—A piezo-actuated display package (PADP) with deformable mirror arrays is proposed for handheld applications of a micro-beam projection display. Temperature change is a critical factor affecting the performance of a PADP. To analyze temperature-related malfunctions, electrical, mechanical, and thermal analyses of the package are conducted simultaneously. A temperature control system using a micro-heater is developed to maintain the deformable mirror module at a constant temperature. Numerical results are used to determine the relationship between displacement and the temperature of the deformable mirrors. Experimental results are used to elucidate the relationship between the source image data and the temperature of the deformable mirror module. A micro-beam projector with a temperature control system is used to produce high quality images under various ambient temperatures.**

***Index Terms*—Deformable mirror arrays, micro-beam projector, temperature control.**

NOMENCLATURE

L	Ribbon length (nm).
L_p	PZT length (nm).
h_p	PZT thickness (nm).
E_P	PZT Young's modulus (Pa).
V	Voltage (V).
d_{31}	Transverse piezoelectric constant (N/mV).
H	SiN thickness (nm).

GREEK SYMBOL

σ	Mirror tensile stress (N/m^2).

SUBSCRIPT

P	Lead-zirconate-titanate (PZT).

I. INTRODUCTION

MICRO-BEAM projector systems for handheld devices are very sensitive to their environments. Variation in the ambient temperature of the deformable mirror module package can result in significant problems. In particular, the performance of a piezo-actuated display package (PADP) [1]–[4] is very sensitive to its thermal environment. Hence, it is essential to investigate the causes of package malfunctions and eliminate them.

To maintain a constant temperature for the PADP regardless of ambient temperature changes, a micro-heater and its control circuit have been developed [5]. However, studies of the causes of the malfunctions and of PADP performance improvements have been insufficient. Malfunctions have been attributed to electrical, mechanical, and thermal problems.

We introduce the structure and operation of a PADP, and the causes of malfunctions due to variations in temperature are identified. The displacements of deformable mirrors were calculated using an analytical method. The thermal characteristics of the PADP were visualized using an infrared camera. A temperature management system was designed, and a PADP with the proposed system showed high quality images under variations in ambient temperature.

II. STRUCTURE AND OPERATING PRINCIPLE OF A PADP

The schematic structure of a PADP is shown in Fig. 1(a) and (b). The deformable mirror module is a flip chip bonded to the center of a glass substrate. Two driver integrated circuits (ICs) are bonded at both sides of the deformable mirror module. These driver ICs control the input signal of the deformable mirror module. The deformable mirror module and two driver ICs can be seen through the transparent glass substrate. Red, green, and blue incident light sources pass through the glass substrate and are reflected or diffracted at the deformable mirror arrays. The reflected or diffracted light then goes through the glass substrate again. The three light sources are combined and illuminated during the reflection or diffraction process. They are then projected to the image plane through projection optics.

The deformable mirror module is the most important component in the reflection/diffraction process of the PADP. The schematic structure of the deformable mirror module is shown in Fig. 1(c). The deformable mirrors are actuated by lead–zirconate–titanate (PZT). When voltage is applied to PZT, horizontal shrinkage of the PZT material produces vertical

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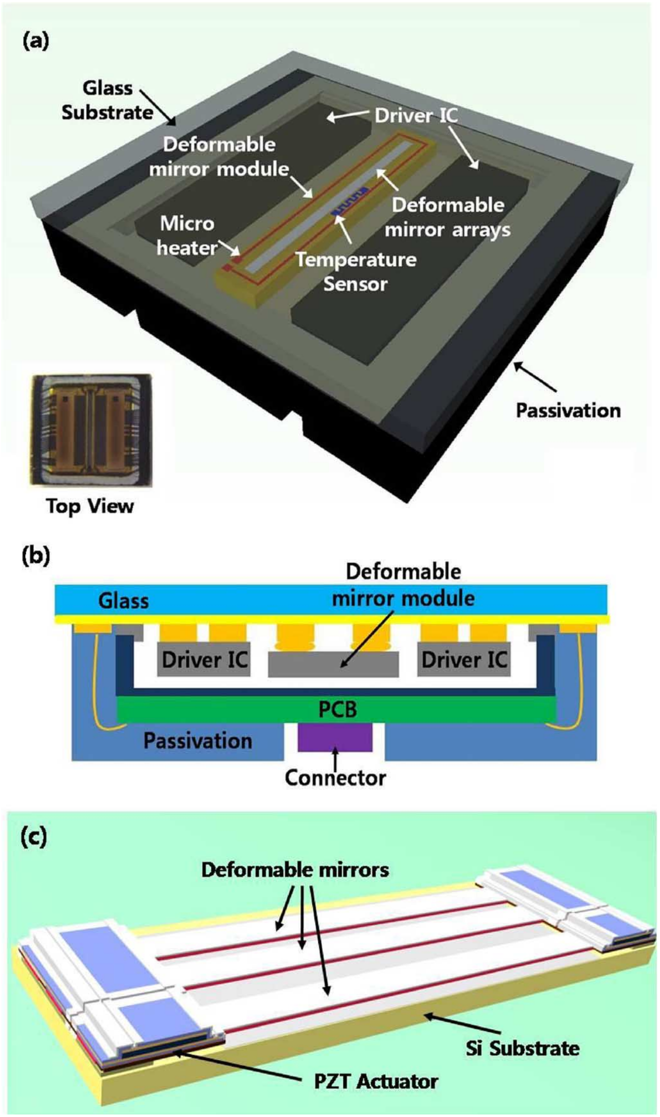

Fig. 1. (a) Schematic of a PADP. Inserted photograph shows the top view of the PADP. (b) Cross-sectional view of the PADP. (c) Schematic structure of the deformable mirror module (for one and one-half pixels). The deformable mirror suspended part can be moved up and down to form dynamic diffraction gratings by piezoelectric actuation.

motion of the mirrors. Piezoelectric actuation of individual grating micro-mirrors controls the displacement between the deformable mirrors to achieve variable phase shift, thereby providing diffractive light modulation of irradiated light sources onto the mirrors.

The module was fabricated by a well-established surface micro-machining technique. It consists of a 1-D linear array of 480 identical piezoelectric-actuated mirrors. Since the deformable mirror is controlled with 8-bits of information, each pixel made by the deformable mirror has a brightness value ranging from 0 (black) to 255 (white) with 256 gray levels in between.

III. ANALYSIS OF THE CAUSE OF MALFUNCTION

A. Analysis of the Displacement of the Deformable Mirror

Fig. 2(a) shows a scanning electron microscope (SEM) image of the fabricated deformable mirror arrays. The PZT actuators were arrayed with a 16 μm pitch, 100 μm mirror length, and 200 μm ribbon length. The gap height is a basic controlling parameter for diffraction intensity [see Fig. 2(b)], and is determined by the stresses of all layers such as the PZT and the deformable mirror. Dimensional uniformity of the deformable mirror arrays is necessary for the desired brightness value of the projected images. Therefore, precisely controlled fabrication is required for good optical performance of the deformable mirror module.

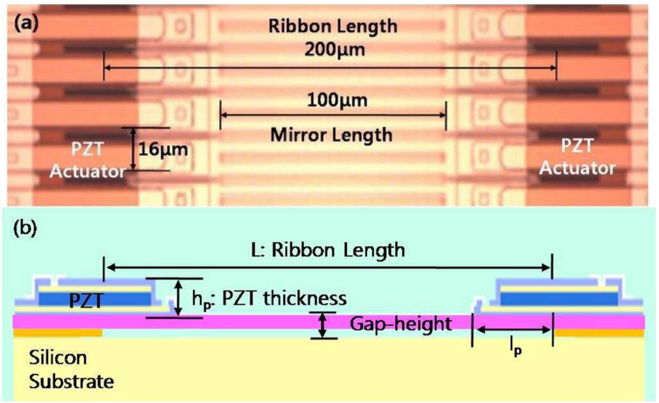

Fig. 2. (a) SEM image of deformable mirror arrays. (b) Cross-sectional view of deformable mirror module.

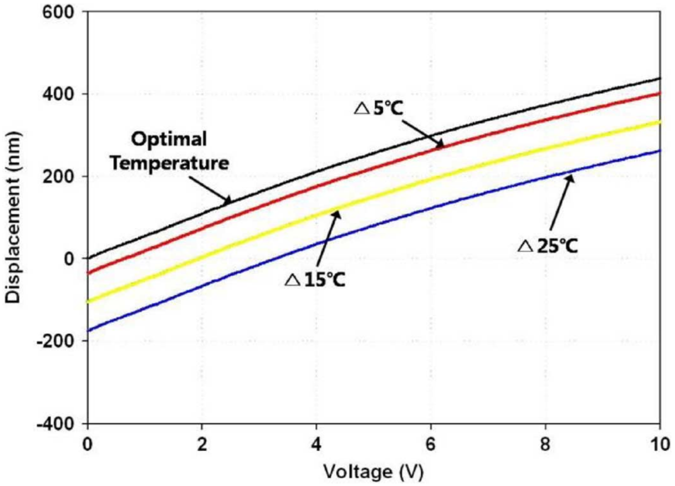

Fig. 3. Displacement of the deformable mirror at a gap height of 1368 nm.

The deformable mirror arrays are thermo-mechanical structures. Hence, the displacement of the deformable mirrors is affected by temperature change. It is necessary to calculate displacements at various temperatures to determine the value at which displacement is affected by temperature. A simplified deformable mirror structure showing the variables needed for calculating the displacement through analytical modeling is shown in Fig. 2(b). Based on Hooke's law and the structure described in Fig. 2(b), an analytical model for the displacement of the mirror can be expressed as follows [1]:

$$\mathrm{Disp}_{\mathrm{Max}} = \frac{\left[\frac{128 l_o}{L^3}\left(\frac{3L}{2} - 2l_o\right) h_o E_p d_{31} V\right]}{\left[\frac{8\sigma H}{L} + 2E_p\left(\frac{h_o}{l_o}\right)\right]}. \tag{1}$$

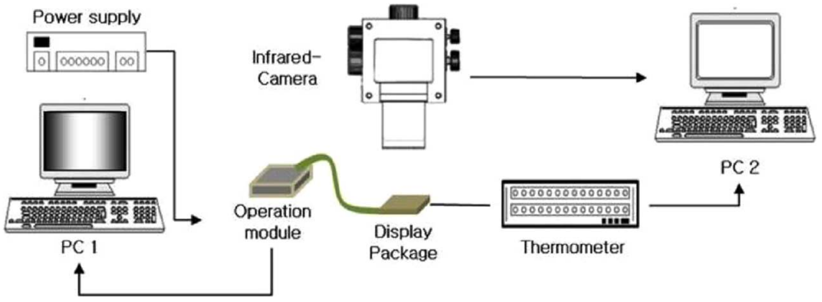

Fig. 4. Schematic of the experimental setup used to study thermal characteristics of the display package for various source image data.

Fig. 3 shows the results obtained from the analytic modeling of the deformable mirror's displacement at different temperatures as the input voltage was increased. The displacement increased gradually from 0 nm to about 440 nm as the voltage increased at the optimal temperature. However, the displacement decreased as the temperature of the deformable mirror was changed. From our analytical calculation, the temperature dependence is −7 nm/°C. The displacement of the deformable mirror should be precisely controlled regardless of temperature change: a 1 nm change in the displacement produces about 2 gray shifts using 8-bit brightness control [4]. Hence, as the temperature of the deformable mirror changes, the quality of the projected image can deteriorate.

The temperature change of the module can be attributed to two causes. The first cause is a change in ambient temperature due to the atmospheric temperature; e.g., a high temperature during summer may cause a temperature increase in the module. The temperature change of the module is directly proportional to the atmospheric temperature. The second cause is the change in temperature of IC chips by the voltage corresponding to the source image data. As the IC chips are bonded on both sides of the module, the heat from the IC chips can directly affect the displacement of the mirrors. However, the relationship between the temperature change in the module and the source image data has not been defined. Therefore, an investigation of the temperature characteristics of the module with respect to the various source image data is needed.

B. Analysis of Thermal Characteristics of Package

Fig. 4 shows a schematic diagram of the experimental setup used to measure the thermal characteristics of the display package for various source image data. The test setup consisted of an infrared (IR) camera, thermometer, display package, operation module, power supply, and computers. To examine the temperature of the module, the temperature distribution was measured with an IR camera and the temperature was calibrated using a thermocouple.

The IR camera was positioned to obtain a top view [Fig. 1(a)] of the PADP to record its thermal characteristics during operation. The brightness values of the camera ranged from 0 (black) to 255 (white) with 256 gray levels. The black color and the white color represent the lowest position and highest position of the deformable mirrors, respectively. The black color source image had a 0 V input voltage to the deformable mirror module, and the white color source image had a 10 V input voltage. The experiment was performed at an ambient temperature of 25 °C. The thermal sensitivity of the camera was 0.08 °C and the sample rate was 60 Hz. Emissivity equalization was used to produce an accurate temperature image [5]. The relationship between temperatures of the glass substrate and the deformable mirror module was acquired through experimental and numerical analyses [6] that showed a temperature difference of 0.1 °C between the glass substrate and deformable mirror module.

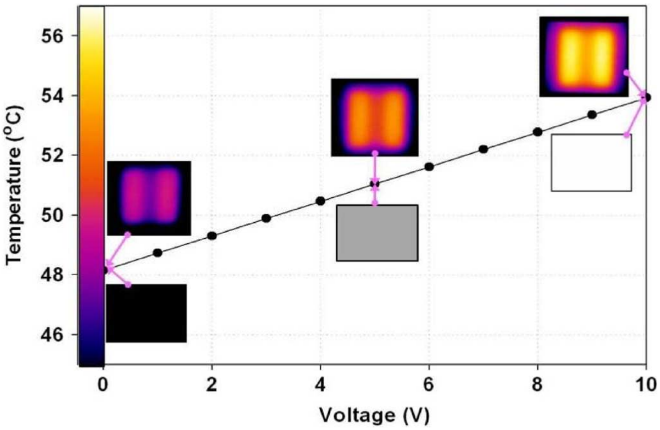

Fig. 5. Average temperature of the module versus input voltage.

Fig. 5 shows the average temperature of the module versus input voltage. The thermal images are arranged with their source image equivalents. In the PADP, the two ICs work as a dominant heat source, and heat generation increased with the input voltage of the module as the source image changed from black to white. As a result, the maximum temperature difference of the module along the source image is 6 °C. Fig. 6 shows the temperature profiles on the surface of the package. From the temperature profile of line A, two hot spots occurred because the two driver ICs are bonded to both sides of the deformable mirror module. The temperature difference between where the ICs are bonded and where the module is bonded is around 3 °C.

The temperature profile is almost symmetrical with respect to the deformable mirror module. From the temperature profile of line B, we note that the temperature of the location where the module is bonded to the glass (position from −4 to 4 mm) was uniform within a 1 °C difference. The heat of the ICs was transferred to the module in real time mainly by conduction through the glass substrate because the two ICs and the module are bonded closely at the glass substrate, as shown in Fig. 1(b). As the source image changed, the temperature of the ICs also

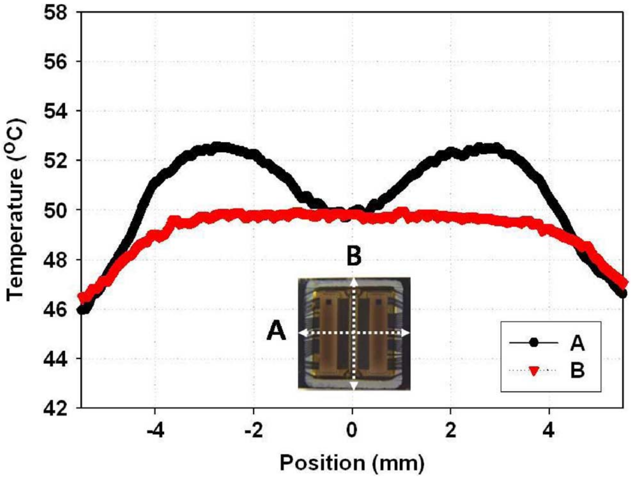

Fig. 6. Temperature profiles along lines A and B.

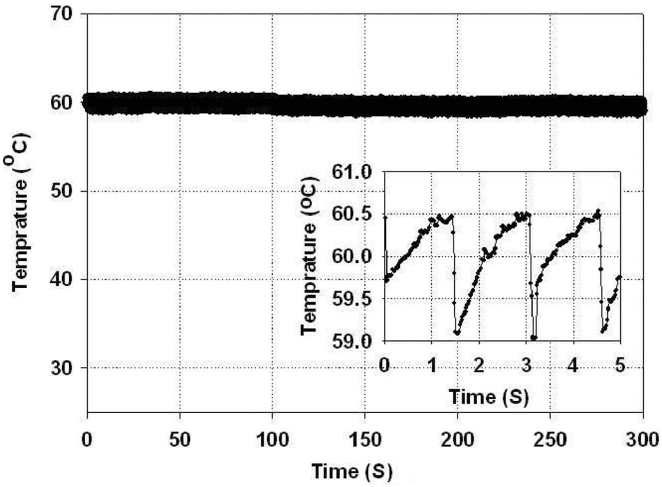

Fig. 7. Variation of temperature versus time of the deformable mirror module.

changed, and these changes affected the temperature of the module. The temperature changes of the module caused a malfunction in the displacement of the deformable mirror. Therefore, a temperature management system is needed to prevent such a malfunction.

IV. Performance Evaluation

A. *Feedback Temperature Control System*

To maintain the temperature of the module at the optimal temperature, a gold thin film micro-heater and platinum thin film temperature sensor were deposited on the module as shown in Fig. 1(a). A feedback control was used for the micro-heater. Feedback control for temperature maintenance was achieved by turning off the micro-heater when it became overheated, and turning on the micro-heater when it became overcooled. In this study, the ambient temperature was assumed to vary from 0 °C to 40 °C. The optimal temperature was determined to be 60 °C by considering the surrounding temperature. The temperature of the module was gradually increased from the ambient temperature to 60 °C when the display package and micro-heater were powered. After the module temperature reached an operating temperature of 60 °C, the temperature of the module fluctuated in a $\pm 0.5\,^{\circ}$C range. Fig. 7 shows the temperature of the deformable mirror module when temperature feedback was applied. As a result, the optimal temperature automatically adapted to the surrounding temperature changes. Despite the source image data changes, an optimal temperature was maintained.

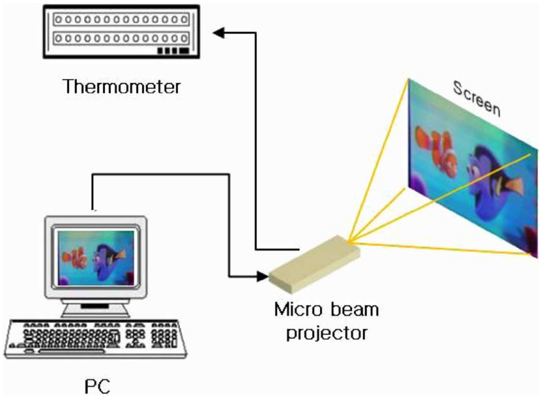

Fig. 8. Time variation of temperature of the deformable mirror module.

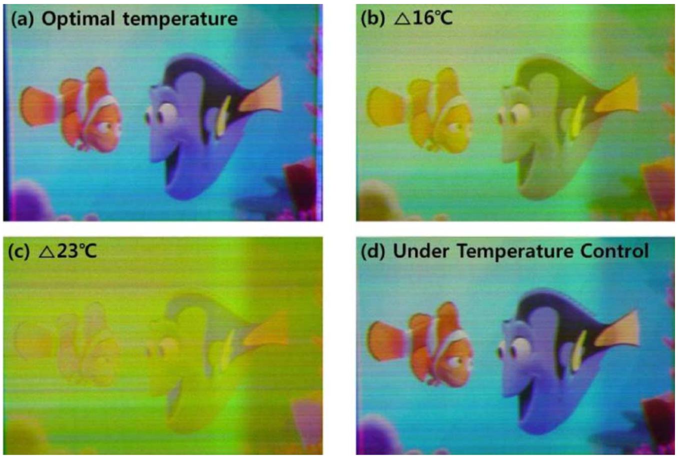

Fig. 9. Projected images under (a) optimal temperature, (b) △ 16 °C, (c) △ 23 °C, and (d) temperature control.

B. *Micro-Beam Projector*

Fig. 8 shows a schematic diagram of the experimental setup used to evaluate the qualification of the projected images from the micro-beam projector as the temperature of the module was managed by the temperature feedback control system for various ambient temperatures. The test setup consisted of the micro-beam projector and a thermometer.

The performance of projected images was evaluated at various temperatures as shown in Fig. 9. The optimal image of the micro-projector is shown in Fig. 9(a). Fig. 9(b) and (c) shows the images when the difference between the actual temperature

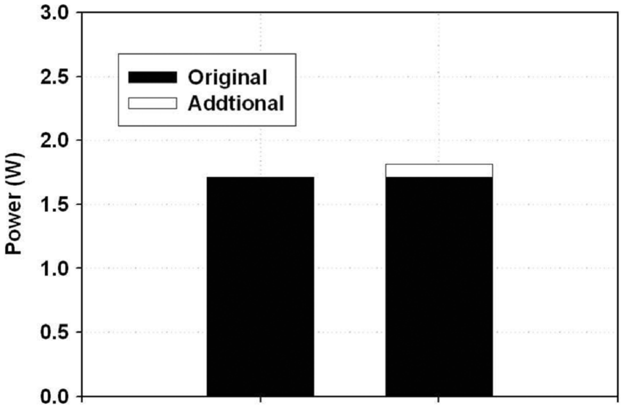

Fig. 10. Comparison of the required power of the display package.

and the optimal temperature, $\triangle T$, was 16 °C and 23 °C, respectively. We note that the image quality decreased as temperature difference increased. The image, however, returned to its optimal state when the temperature of the module was controlled by the feedback temperature control, as shown Fig. 9(d).

Fig. 10 shows the average power required to operate the display package. The left bar shows the required power of the display package when the temperature control system turns off, and the right bar shows the required power under temperature control. Although the power required when the temperature control system is in use is around 100 mW (5.8% power consumption increasing), which is higher than the required power without the control, the display package's performance can be enhanced dramatically.

V. CONCLUSION

The causes and their solutions of the display packages due to temperature variation are analyzed and investigated. The displacement of the mirror was calculated for different temperatures. The temperature characteristics of the module in the range of 256 gray levels were investigated. A micro-beam projector with a temperature management system produced high quality images under a controlled temperature. These results could be helpful in the performance enhancement of micro-beam projector systems with embedded PADPs. Our approach could also be useful in the implementation of devices that have temperature dependency.

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