Design and fabrication of an electrothermal MEMS micro-actuator with 3D printing technology

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Abstract
This study presents the design and fabrication results of an electrothermal micro-electro-mechanical system (MEMS) actuator. Unlike traditional one-directional U-shaped actuators, this bi-directional electrothermal (BET) micro-actuator can produce displacements in two directions as a single device. The BET micro-actuator was fabricated using two-photon polymerization (2PP) and digital light processing (DLP) methods, which are 3D printing techniques. These methods have been compared to see the success of BET micro-actuator fabrication. The compound of these methods and the essential coefficients through the 3D printing operation were applied. Evaluation experiments have demonstrated that in both methods, the 3D printer can print materials smaller than 95.7 μm size features. Though the same design was used for the 2PP and DLP methods, the supporting structures were not produced with the 2PP. The BET micro-actuator was manufactured by removing the supports from the original design in the 2PP. The number of supports, the diameter, and height on the arms of the micro-actuator is 18, 4 μm, and 6 μm, respectively. Although 4 μm diameter supports could be produced with the DLP, it was not possible to produce them with 3D printing device based on 2PP. Besides, the DLP was found to be better than the 2PP for the manufacturing of asymmetrical support structures. The fabrication process has been carried out successfully by two methods. When the fabrication success is compared, the surface quality and fabrication speed of the micro-actuator fabricated with DLP is better than the 2PP. Presented results show the efficiency of the 3D printing technology and the simplicity of fabrication of the micro-actuator via 2PP and DLP. An experimental study was carried out to characterize the relationship between displacement and input voltage for the micro-actuator. Experimental results show that the displacement range of the micro-actuator is 8 μm with DLP, while 6 μm with 2PP.

1. Introduction

Micro-electro-mechanical system (MEMS) is a process technology comprising of miniaturized mechanic and electronic parts, that includes the transformation of a measured mechanic signal into a readable signal. This signal may be force, press, heat, or chemical. MEMS has created serious innovations in the field of micro and nano study field since the early 1980s [1]. Primarily, MEMS was improved for different implementations for example force, navigation, optical transmitting, radiofrequency, biological & medical, microfluidics, and gyroscopes applications [2–6]. These days, MEMS has become an essential part of various study fields such as material, mechanical, and electrical engineering studies [7–10]. MEMS device is usually formed four components, such as micro-structures, micro-sensors, micro-actuators, and micro-electronics for data utilization [11, 12].

MEMS-based micro-actuators are significant devices for producing motion at the micro scales. These actuators are generally used by a wide variety of applications requiring large displacement range, high operating frequencies, miniaturization, packaging, and integration facilities [13–15]. Actuation mechanisms such as
piezoelectric, electrostatic, electrothermal, and electromagnetic are used to implement each application [16, 17]. Among these mechanisms, electrothermal actuation stands out in terms of high force output, real-time diagnosis, and robust structure. Considering these advantages, electrothermal driven micro-actuators are restricted in response time. As the response of an electrothermal micro-actuator depends on heat-transfer rates, it executes slower operating characteristics than other types of actuators. These actuators can be driven at frequencies up to 2 kHz [18, 19]. Hence, electrothermal micro-actuators are generally utilized in high-force, low-frequency applications. These features make micro-actuators usable in applications such as biomedical, micro-assembly, and micro-optics, etc [20–22].

Electrothermal actuation depends on thermal expansion caused by asymmetrical Joule heating of hot and cold arms [23]. To achieve movement, micro-actuator components must thermally expand to a different extent, causing the device to displacement or deform. The electric current resulting from the application of voltage passes from one anchor to another in the micro-actuator. The high current density in the thin (hot arm) heats the micro-actuator and leads to expansion. Therefore, a planar operation occurs for the wide (cold arm). When current flows through the micro-actuator, the high resistance in the longer or thinner hot arm causes, the shorter or thicker cold arm to become warmer and wider [24, 25]. As a result, the resulting differential expansion forces the end of the micro-actuator to move. Thus, displacement occurs in the end region of the micro-actuator.

The electrothermal micro-actuators have been widely studied for MEMS applications. The basic application is in the field of micro and nano manipulation. The potential applications of electrothermal micro-actuators includes optical switching [26, 27], micro-positioners [28], micro-maneuipulation [29], micro-grippers [30], and micro-robotic applications [31]. These tools are used for micro assembly, biological cell manipulation, and material characterization [32–34].

MEMS devices are manufactured by traditional methods such as lithography, galvanoformung, and photolithography, etc. These conventional methods are extremely precise and appropriate for the fabrication of planar geometries [35, 36]. Although the precision, these operations associate with some drawbacks such as many processing steps, the requirement of cleanroom, advanced work environment, long-time fabrication, and costly fabrication process [37]. With the improvement of 3D printing technology, the fabrication costs and processing steps of MEMS devices have been gradually reduced. According to these improvements, it is possible to fabricate MEMS devices in atmospheric air without the need for many operations and cleanrooms [38, 39].

3D printing, i.e., additive manufacturing, is one of the most significant technology in the last decades because it can be used to produce complicated matters clearly from digital files, for instance, computer-assisted design drawings [40]. This technology helps to improve the design and fabrication and especially facilitated the fabrication and repair of complex parts using its printing through the layer-by-layer deposition of the constituent materials [41–43]. 3D printing technology for building MEMS systems have grown remarkably in the areas of biomedical, electronics, wearable device, soft robots, and automotive applications [44–49]. Unlike traditional manufacturing processes such as machining and punching, 3D printing does not entail on-site process control, cutting tools, coolers, or other additional resources. One of the important factors of 3D printing methods is its capability to make miniaturized complex structural geometries using easy steps that are not reachable by traditional manufacturing methods [50, 51]. Besides that, 3D printing methods submit many other characteristics for example, flexibility in geometrical designs, excellent feature size and shapes, and the ability to print functionally classified materials [52, 53].

Fabrication methods are very important to design and research the electrothermal micro-actuator. Until now, conventional MEMS fabricating methods have been used, such as photolithography and surface micromachining, etc [54–56]. These methods are usually time-consuming, fabrication costs, and multi-step fabrication processing. Alternatively, the 3D printing method solves these problems by manufacturing the structure directly. In recent years, various 3D printing methods have been employed, for instance, frontal polymerization (FP), projection micro-stereolithography (PμSL), laser micro sintering (LMS), selective laser melting (SLM), etc [57, 58].

The fabrication of the designed electrothermal micro-actuator was carried out by the two-photon polymerization (2PP) and digital light processing (DLP) methods, which are 3D printing fabrication techniques. 2PP is the 3D printing process that achieves the highest resolution and has been utilized to create many complex structures for photonic and nanoscale applications [59]. 2PP fabrication can be achieved with a femtosecond laser in combination with a pair of laser scanners. Along the 2PP process, the laser is focused on a highly confined region within a photosensitive resin, which induces nonlinear absorption, i.e., two or more photons are absorbed by the polymers and later polymerizes the local resin as nanoscale building blocks. The 2PP process has been used to fabricate many microstructures and nanostructures for a wide range of applications, e.g., micro-sensors or micro-fluidics devices [60, 61].

The DLP method using photocurable resins is appealing since it can be used to manufacture a single layer of the 3D object through spatially-controlled solidification using a projector light [62]. This light causes benefits
such as fast fabrication, high sensitivity, and surface quality. Besides, it is feasible to adapt the last features of the printed object by only altering the photocurable resin formulations [63]. In this way, it is feasible to reach a large diversity of systems for the fabrication of structures with excellent features and functions [64]. Studies that have been performed with the DLP method include optical networks, biomedical devices, and mobile phones [65, 66].

In this study, the 2PP and DLP methods, which are 3D printing fabrication techniques, were investigated in detail, and an electrothermal micro-actuator was manufactured using these techniques. These methods were compared on account of the fabrication results. The micro-actuator is designed to move in two directions. An experimental study was carried out to observe the displacement of the fabricated micro-actuator. Experimental results show that the displacement range of the BET micro-actuator is 8 µm (4 µm in both directions) with the DLP method, while 6 µm (3 µm in both directions) with 2PP method. With this study, a bi-directional electrothermal micro-actuator was manufactured for the first time utilizing the 3D printing method. It is expected that this paper will contribute to the literature in terms of manufacturing a micro device through the use and comparison of different techniques.

This study is arranged as follows. Section 2 describes the working principle and design of the micro-actuator. Besides, the 2PP and DLP methods are explained in detail. Section 3 defines the fabrication process, results, and discussion. Section 4 explains the experimental results. Section 5 shows the general result of the studies.

2. Materials and methods

2.1. Working principle of the micro-actuator

In this study, a modified U-type actuator was taken as a reference when performing the design of the micro-actuator. This type of actuator is a typical MEMS device, which has been employed to design several micro devices described in the literature [67]. Such actuators generally comprise of two line-shaped beams. One of them is thin (hot arm), and the other one is wide (cold arm). These arms are limited by two anchors. The flexure arm is found between the cold beam and its coincident anchor (figure 1).

The activation of the micro-actuator results from the differential thermal expansion between a pair of arms of different widths. Once the voltage is applied to actuator, high current density because of the reduced dimensions of the actuator causes the distribution of heat. After that, the thermal expansion of the hot arm decreases the gap between both arms, owing to the cross-sectional motion that is produced via a mechanical arching action of the hot arm towards the cold arm. The movement of the micro-actuator occurs for these reasons.

Traditional U-shaped micro-actuators are just capable of displacement throughout one direction. When voltage is applied to the micro-actuator with serial wiring, it produces high temperatures in the hot arm because of resistive Joule heating, which procures micro-actuator’s length to increase. This length replaces a net right direction motion (figure 2(a)). Concerning [68], demonstrated that left direction motion could be achieved if a traditional U-shaped actuator is electrically connected in parallel instead of in series (figure 2(b)). In this form, the wide arm will draw more current than the higher resistance hot arm, and so will achieve a higher temperature because of the Joule heating [68]. Therefore, the wide arm is the ‘hot arm’, and the displacement is left direction. This still only symbolizes one-direction motion as the parallel wiring does not let for right direction motion. Theoretically, a micro-actuator with both parallel and serial wiring would be able to perform the bi-directional movement. Nevertheless, the real-time application is the inclusion of an electrical connection at the end of the micro-actuator, thus making it difficult to parallel wiring.
This study shows the improvement of electrothermal micro-actuators with bi-directional functionality as a single integrated device capable of producing a movement range comparable to traditional U-shaped actuators. When we look at the literature, electrothermal micro-actuators that can produce bi-directional motion as a single integrated device have not yet been developed.

2.2. Design conditions of the micro-actuator

As shown in Figure 3, unlike previous designed micro-actuator studies [69, 70] the bi-directional electrothermal (BET) micro-actuator is symmetrically designed, allowing displacements throughout two directions (left, and right). In these studies, the displacement of the micro-actuator ensured in one direction using 2 pads. To make the whole structure move right direction, DC-1 is supplied with a voltage, while DC-2 and DC are grounded. In this form, the 'hot arm-1' has a higher current density, while the 'cold arm' and the 'hot arm-2' have a lower current density. Due to its lower resistivity, the majority of electrical current passes the 'cold arm' entirely to the anchors. Accordingly, the 'hot arm-2' executes a low current density, which outcomes in low Joule heating. Hence, the device moves the right direction. Similarly, because of symmetry, when the connections for DC-1 and DC-2 are changed, the micro-actuator moves left direction. As the designed BET micro-actuator is symmetrical and cannot move in both directions at the same time, input voltages DC-1 and DC-2 are not applied at the same time. The BET micro-actuator will displacement to the right or left direction according to the user request. Figure 4 demonstrates the BET micro-actuator’s motion through two directions, as achieved from finite element simulation utilizing COMSOL software. As a result of simulated displacement under an applied input voltage of 5 V, a maximum of 2.85 μm movement was observed in both directions.

The length of the flexure arm is of great significance for the micro-actuator movement. The design of BET micro-actuator was made according to the following criteria:

- The flexure arm should be as thin as possible. The thinness of this arm creates low resistance for the micro-actuator and allows higher current to pass.
The flexure arm should not be thinner than the hot and cold arms since the flexure arm can overheat and produce deformation.

The flexure arm should be long enough to allow the micro-actuator to change directions because the length of this arm will increase the movement capability of the micro-actuator.

The flexure arm should be long enough not to deform the micro-actuator. When the length of the actuator is more or less, it may cause deformation.

As the BET micro-actuator has a symmetrical structure, dimensioning and designing were applied for a single-arm as demonstrated in figure 5.

All the dimensions of the designed BET micro-actuator are given in table 1. These values were obtained by considering the design criteria of the micro-actuator. The same design was used for 2PP and DLP methods during the fabrication process. Nevertheless, as the supporting structures cannot be manufactured by the DLP method, the measurements related to the support are shown in section 3. Photopolymer materials were used for the fabrication of the BET micro-actuator. These materials are frequently employed in the field of MEMS owing to their essential physical and electrical properties.

Figure 4. Simulated displacement under an applied input voltage of 4 V. (a) Left direction movement. (b) Right direction movement.

Figure 5. Dimensions of the BET micro-actuator.

Table 1. Descriptions of BET micro-actuator.

| Parameter                  | Symbol | Value (μm) |
|----------------------------|--------|------------|
| Length of the hot arm      | $L_h$  | 300        |
| Length of the cold arm     | $L_c$  | 250        |
| Length of the flexure arm  | $L_f$  | 150        |
| Gap of the actuator        | $L_g$  | 9.5        |
| Width of the hot arm       | $w_h$  | 5          |
| Width of the cold arm      | $w_c$  | 8          |
| Width of the flexure arm   | $w_f$  | 5          |
| Thickness of the air-gap   | $t_a$  | 6          |
| Thickness of the actuator  | $t$    | 5          |
2.3. Electrothermal model

Considering previous research \([71, 72]\), it has been found that heat lost through convection and radiation to the atmospheric can be neglected in comparison with heat dissipated thanks to conduction. This is because the thermal conductivity of IP-S resin is much larger than atmospheric air. For this reason, the heat dissipated owing to convection and radiation to the atmospheric is neglected for the next temperature distribution analysis.

Because the length of each arm is larger than its width and height, a two-dimensional model has been developed to simplify analysis (figure 5). According to the basis of heat transfer, heat conduction is dedicated as follows:

\[
Q = -K_p A \frac{dT}{dx}
\]  

(1)

Here \(K_p\) is the thermal conductivity of IP-S resin, \(A\) is the conductive cross-sectional area, \(T\) is the temperature and \(x\) is the length of the micro-actuator. When heat is transferred into the structure and then out of the structure, the heat conduction into the structure is as bellows:

\[
Q_I = -K_p w h \frac{dT}{dx}
\]  

(2)

The heat conduction out of the structure is as follows:

\[
Q_O = -K_p w h \frac{dT}{dx} x + dx
\]  

(3)

Here \(w\) is the width and \(h\) is the height of the micro-actuator. When voltage is applied between the two terminals of this electrothermal micro-actuator, current is passed through the whole system and travels from one anchor to the other. This results in joule heat and is expressed as follows:

\[
Q_I = j^2 \rho w h dx
\]  

(4)

\[
\rho = \rho_0 [1 + \zeta (T - T_0)]
\]  

(5)

\[
J = \frac{V}{\rho L}
\]  

(6)

Here \(j\) is the current density, \(\rho\) is the resistivity of the structure, \(\rho_0\) is the resistivity of the micro-actuator at temperature \(T_0\), \(\zeta\) is the temperature coefficient of resistance, \(V\) is the voltage across the arm and \(L\) is the length of the arm. According the first law of thermodynamics (equation (5)), this yields:

\[
Q_I + Q_I = Q_O
\]  

(7)

Substituting equations (2) to (4) into equation (7), taking the limit as \(dx \rightarrow 0\), produces the second order differential equation. As the micro-actuator has the same conductor cross-sectional area, some variables are neglected and the following equation is obtained:

\[
\left( \frac{d^2T}{dx^2} \right) = -\frac{j^2 \rho}{K_p}
\]  

(8)

The boundary conditions assumed are that the anchor pads have the same temperature as the substrate, \(T_s\). Solving equation (8) gives the temperature distribution during the arm is:

\[
T(x) = \frac{V^2}{2L^2 \rho K_p} (Lx - x^2) + T_i
\]  

(9)

The thermal and electrical features of the resin are given in table 2. From equation (9), it is shown that the temperature is parabolic and symmetric about the center point of the length with a maximum temperature, \(T_M\) at \(x = L/2\). By substituting \(x = L/2\), the maximum temperature is calculated as follows:

\[
T_m = \frac{V^2}{8\rho K_p} + T_i
\]  

(10)

2.4. Digital light processing method

Digital light processing (DLP) is an additive fabrication technology with fast and high sensitivity. The working basis of DLP technology has been explained in \([74, 75]\) and is shortly abstracted as follows.

As demonstrated in figure 6, the 3D pattern of a matter is first sliced into layers horizontally (in the x-axis). Thin layers are then transformed into 2D mask images. A light projection device is utilized to harden the photopolymer resin. This device employs a digital masking method to reflect a dynamically described mask image on the resin plane. Concerning \([74]\), a bottom-up projection system has many benefits compared to a top-
bottom system. In this system, the mask image is reflected on the bottom of the resin tank and cured resin to the tank bottom and the curved part at the same time. When one layer hardened, the platform is firstly lifted to allocate the cured layer from the tank bottom. After that, it has driven down to form a gap with the tank to cure the next layer. The operation is recapped up to all matter is manufactured.

We established a bottom-up DLP system to fabricate the BET micro-actuator. The DLP projector is equipped to ensure a 400 nm full HD ultraviolet light source. The contrast ratio of the projector is 900:1. The XY resolution of the 3D printing device is 65 μm and the maximum building size 125 × 70 × 120 mm.

Concerning [74], the masking method primarily occurs of three types: liquid crystal display (LCD), digital micro-mirror device (DMD), and liquid crystal on silicon (LcoS). In our improvement, the projector uses the DMD method. An optical reflector is employed to set the direction of the UV light. A position adjusting device is employed to set the position and behavior of the reflector. The adjustable angle range is ±20°, and the accuracy is 0.004°. A flexible compressing device is used to press the resin vat. This device lets the vat to be lifted at a specific height. The pressing force that the device enforces to the vat rises as the lifting height increases to refrain effect forces. A linear stage is used to operate the platform. The positioning accuracy of the stage is 4 μm.

For the DLP method, IP-S resin was used as the material, which is a photopolymer. This resin is designed to tend the double function of index-matching dip fluid for final focusing object and photo-polymerizable, thus enabling the highest resolution at a given magnification. IP-S resin is viscous and designed for 3D printing devices. The elemental composition and fundamental features of the resin are given in table 2 [73]. The composition was decided using the procedure discussed in [77] and is significant for this study since it decided the x-ray absorption characteristics of the foam [78]. The foam structure extracted from the glass substrate was qualified using optical microscopy and scanning electron microscope (SEM). SEM sample preparation included a sputter coating of 30 nm thick gold to allow electrical charge conductivity while imaging.

Table 2. The elemental composition and fundamental features of the IP-S resin [73].

| Elemental analysis of resin | Physical and mechanical features | Thermal and electric features |
|---------------------------|---------------------------------|------------------------------|
| Carbon (at.%) | Hydrogen (at.%) | Nitrogen (at.%) | Oxygen (at.%) | Empirical formula |
| 31.45 | 54.07 | 5.75 | 11.7 | CH1.77N0.085O0.35 |
| Density (liq) g/cm³ | Density (s) g/cm³ | Youngs modulus (GPa) | Hardness (MPa) | Refractive index |
| 1.5 | 1.5 | 3.8 | 150 | 1.51 |
| Thermal conductivity (Kp) | Thermal expansion (α) | Temperature coefficient (ζ) | Resistivity of resin (ρ) | Resistivity of air (ρ₀) |
| 45 | 4.5 × 10⁻⁶ | 1.5 × 10⁻³ | 4 × 10⁻³ | Variable |

Figure 6. Schematic of the DLP system. Reprinted from [76], Copyright (2018), with permission from Elsevier.
2.5. Two-photon polymerization method

The two-photon polymerization (2PP) is one of the most precise 3D printing technology that has been utilized to create 3D complex structures for advanced photonic and nanoscale applications. However, to date, the 2PP technology remains a laboratory tool because of its high operation cost and limited fabrication rate. Despite these disadvantages, the 2PP method is a technology widely used in the fabrication of 3D micro-structures such as grippers, optics, biomedical devices, fluidics, etc [79, 80]. Photopolymer materials are generally used with this technology in the fabrication of 3D structures.

To manufacture a BET micro-actuator with the 2PP method, a femtosecond (fs) pulse width laser light source is required. Figure 7 demonstrates a schematic image of the working principle of 3D micro-fabrication for the 2PP method. Near-infrared (NIR) fs pulses produced with titanium (Ti) sapphire laser (wavelength: 550 nm, pulse width: < 120 fs, repetition rate: 70 MHz) are transformed into visible ones with an optical parametric oscillator. The laser power is precisely set by a combination of λ/2 wave-plate and polarizing beam splitter cube. The photo-polymerized structure is created layer-by-layer with a combination of an x–y galvanometric mirror scanner and a high-resolution linear stage in the z-axis. The laser beam is focused on the sample with a microscope objective to begin polymerization. The movement of the scanning layer is pre-programmed with a computer to produce different microstructures. A charge-coupled device (CCD) camera is assembled behind the mirror for monitoring of the 2PP process. For the 2PP method, IP-S resin was used as the material, which is a photopolymer. The properties of photopolymer resin, which were utilized in the fabrication of the BET micro-actuator, are given in table 2.

3. Fabrication

3.1. Fabrication with the DLP method

The BET micro-actuator, whose design is demonstrated in figure 8, was manufactured by a digital light processing (DLP) method based on 3D printing device. 3D printing technology entails an input CAD model of the part that may be designed in software or obtained from reverse engineering such as 3D scanners. When the CAD model of the BET micro-actuator is completed, it is transformed into the standard STL format, which is most commonly used to represent 3D CAD models in 3D printing. In an STL file, the CAD model is symbolized using triangular facets, which is described by the x-, y-, and z-coordinates of the three vertices. The step-by-step diagram of the 3D printing operation is displayed in figure 9. After the STL format of the BET micro-actuator is sliced and transformed into mask images, the 3D printer is turned on, and the images are importer into the control system of the printer. The slicer first divides the object as a stack of flat layers, followed by describing these layers as linear movements of the 3D printer extruder, fixation laser, or equivalent. All these movements, together with some specific printer commands like the ones to control the extruder temperature or bed temperature, are finally written in the g-code file, that can after be transferred to the printer.

The 3D printer begins operating after the photopolymer is poured into the resin vat. Before the printing of the first layer, the platform is driven down to create a gap between the bottom of the resin tank and micro-actuator. After curing the first layer, the printing operation is paused, and the current position is recorded. The platform is then lifted to assign whether the cured layer can be separated from the bottom of the resin tank. Then the zero position of the platform is recalibrated after it is located upper than the last trial to create a larger gap for...
reducing the separation force. The platform is driven near the tank bottom, and the first layer is reprinted. Once the first layer is appropriately printed, the platform is driven down to the recorded position.

During the manufacturing of the BET micro-actuator, printing parameters for example, the layer thickness (LT), the light intensity (LI), and the curing time (CT) of all layers significantly affect the print quality. In this
Each parameter is selected for the printing material and set $TL = 40 \mu m$, and $CT = 4$ s. When the first layer is printed, LI is set to 50% of the brightness to provide the layer bond to the platform. LI is set as 15% of the brightness for the rest layers.

An image of the BET micro-actuator fabricated with the DLP method is given in figure 10. This image was taken from the microscope of the 3D printing device. There are supports to the arms and pads of this micro-actuator design. The number of supports, the diameter, and height on the arms of the micro-actuator is 18, 4 $\mu m$, and 6 $\mu m$, respectively while the number of supports, the diameter, and height on the pads is 3, 35 $\mu m$, and 5 $\mu m$, respectively.

Some unsuccessful experiments have been carried out to achieve the optimum design. Collapses, and breakings were formed during the fabrication when the number of supports to the arm, and pad was low. As a result, the BET micro-actuator’s fabrication was achieved with the support numbers specified above. Since the number of supports to the flexure arm is related to the cold arm, collapses occurred in experimental studies. The optimum support number for the flexure arm was determined to be 8. Considering the experimental studies, the maximum value of the 3D printer resolution should be 1 $\mu m$, and the average distance between supports 30. Otherwise, the supports cannot be fully fabricated, and they cause fractures and collapse of the BET micro-actuator.

### 3.2. Fabrication with the 2PP method

The BET micro-actuator, whose 3D design is shown in figure 11, was fabricated by a two-photon polymerization (2PP) method based on 3D printing device. As the supported structures represent the system as a 3D design, it was not possible to produce with 3D printing device based on 2PP technology. Many different support structures have been used, but the fabrication of BET micro-actuator has not been possible with this method. For this reason, supports from 3D design were removed in fabrication with the 2PP method (figure 11).

The flow chart of manufacturing with this method is the same as DLP (figure 9). During the 2PP operation, the sealed microscope is dipped into a tray filled with a liquid IP-S resin material. The depth of the material pool
utilized in this contribution is 20 mm. 2PP can fabricate structures with a height far beyond the working distance of the microscope employed for laser beam focusing. In the fabrication process, the laser beam at 30 mW power is scanned at 2 mm s$^{-1}$ speed. The scanning size for laser in the x-y layer is 0.3 $\mu$m. The z-axis is acted stepwise by 0.6 $\mu$m to make 3D structures layer by layer. The polymerized structure is created via an assembling of an x–y galvanometric mirror scanner and z-axis controlled with 3D design data. After the polymerization process, non-irradiated IP-S resin is removed and dried with a crucial point dryer.

In the fabrication process of the BET micro-actuator, a high-repetition-rate Ti: Sapphire fs laser system is utilized. This system has some parameters such as repetition rate (RT), Wavelength ($\lambda$), pulse width (fs) of all layers significantly affect the print quality. In this study, these parameters are selected for the material and set $RT = 70$ MHz, $\lambda = 750$ nm, and $fs < 120$.

When the support structures are removed, as shown in figure 11, it is possible to perform the fabrication as the BET micro-actuator design can be introduced to the device (a 2PP technology- 3D printer device). An image of the BET micro-actuator manufactured with the 2PP is given in figure 12. This image was taken with the microscope of the 3D printer device. The fabrication of a 3D designed BET micro-actuator without support structure has been carried out successfully with the 2PP method.

4. Experimental results

Fabricated microscope images of the BET micro-actuator are shown in figures 10 and 12, respectively. The BET micro-actuator was manufactured using the DLP and 2PP methods with a structural layer 3.0 $\mu$m thick and 3.0 $\mu$m above the substrate. An experimental study was carried out to characterize the relationship between displacement and input voltage for BET micro-actuator. The micro-actuator placed in the probe station is connected to the circuit board with cables attached to the electrical pads. A setup with an optical microscope at 120x magnification and the digital camera was used to characterize the displacement of micro-actuator at the probe station. Moreover, the power supply was used to apply the input voltage. The input voltages were applied in 0.5 V increments starting from 0 V, and images of the resulting displacement were recorded by a camera. The experiments continued until breakings, and permanent deformation occurred in the BET micro-actuator.

The displacement response of the BET micro-actuator fabricated by the DLP method as a function of input voltage is shown in figure 13. The magnitude of displacement is symbolized in this way for simplicity, but it must be noted that negative voltages performed displacement opposite to that of positive voltage. It has been determined that the BET micro-actuator has a maximum displacement of approximately 4 $\mu$m in both directions and provides a total displacement range of 8 $\mu$m, which can be compared with the U-shaped micro-actuators fabricated.

The displacement response of the BET micro-actuator manufactured by the 2PP method as a function of input voltage is given in figure 14. It has been determined that the BET micro-actuator has maximum displacement of approximately 3 $\mu$m in both directions and provides a total displacement range of 6 $\mu$m.

Following the finite element simulation (FES), the experimental results reveal that the BET micro-actuator demonstrates an exponential correlation between displacement and applied input voltage. Figures 13 and 14 shows that the ability of FES to forecast the experimental response of BET micro-actuator. The value of the difference between the numerical estimate and the experimental result is found to be stable ($\sim 0.2$) for the voltage range above 1 V. The reason for this difference is that it is a hysteresis due to contact between the beam and the micro-actuator substrate.

When the characterization results of the BET micro-actuator fabricated by the two methods are compared, the displacement of the DLP method is higher. The reason for this is the number of supporting structures used in the DLP. The supported structure increased the motion capability of the BET micro-actuator. After 6 V voltage,
breakings and permanent deformation occurred in the BET micro-actuator due to the temperature increase above the working limit of the IP-S resin.

5. Conclusion

This paper submitted the design and fabrication results of an electrothermal driven MEMS actuator that can produce displacements along with two directions as a single device. The BET micro-actuator was manufactured using the 2PP and DLP methods, which are 3D printing techniques. These methods were used for the first time in the fabrication of an electrothermal micro-actuator. The compound of these methods and the essential coefficients through the 3D printing operation were applied. Evaluation experiments have demonstrated that in both methods, the 3D printer can print materials smaller than 95.7 μm size features.

The optimal CAD design of the BET micro-actuator was obtained by design criteria and finite element simulation. Although the same design was used for the 2PP and DLP methods, the supporting structures were not produced with the 2PP. After these support structures were removed, the micro-actuator was fabricated with 2PP. The experimental studies showed that 3 μm diameter supports were fabricated with the DLP method. However, they could not be fabricated with the 2PP method even when the diameters of the supports were 4 μm. The fabrication process has been carried out successfully by two methods. When the fabrication success is compared, the surface quality and fabrication speed of the micro-actuator fabricated with DLP is better than the 2PP method. Besides, the DLP was found to be better than the 2PP for the fabrication of complex, unsymmetrical supporting structures. Presented results in this study show the efficiency of the 3D printing technology and the simplicity of fabrication of the BET micro-actuator via 2PP and DLP methods.

An experimental study was carried out to characterize the relationship between displacement and input voltage for the BET micro-actuator. Following the FES, the results reveal that the BET micro-actuator demonstrates an exponential correlation between displacement and applied input voltage. The experimental
results show that the displacement range of the BET micro-actuator is 8 μm (4 μm in both directions) with DLP method, while 6 μm (3 μm in both directions) with 2PP method. The reason for the high displacement of the micro-actuator with DLP is the support structure used. The supported structure increased the motion capability of the BET micro-actuator. After 6V voltage, breakings and permanent deformation occurred in the BET micro-actuator.

As a result of this study, it was found that the DLP is more appropriate since it allows the fabrication of complex 3D structures with smaller dimensions. It is expected that this paper will contribute to the literature in terms of manufacturing a micro device through the use and comparison of different techniques.

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