공학석사학위논문

경로 선스캐닝 기법을 이용한 곡면상 액체금속 패터닝 시스템

Direct Writing of Liquid Metal Patterns on Curved Surface with Path Pre-scanning

2019년 2월

서울대학교 대학원

기계항공공학부

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이 논문을 공학석사 학위논문으로 제출함

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김신명의 공학석사 학위논문을 인준함

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Abstract

In this paper, a direct writing of eutectic gallium indium on curved surfaces by applying an improved distance maintaining algorithm is presented. Path pre-scanning method is postponing the patterning process until the path scanning process is complete. Scanning process is measuring thickness and gradient of a substrate with a laser sensor and a motorized Z stage and enqueuing the substrate thickness data. The data is used for maintaining the distance between a dispenser tip and a substrate during patterning process. Because the laser sensor and the dispenser do not affect each other, fabricating diverse shape of patterns and patterning on steep surfaces are possible. With the help of this idea, curvy, cuspal, crossing, and overlapped patterns are acquired, and it is verified that patterning on curved surfaces is possible.

Keyword : direct writing, liquid metal, EGaIn, scanning

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Table of Contents

List of Figures

List of Variables

d_{total}: the distance between the laser sensor and the floor

$d_l(n)$: the readout of the laser sensor at n^{th} point

$d_s(n)$: the thickness of the substrate at n^{th} point

$d_{z,s}(n)$: the readout of the Z stage at n^{th} point

d_n: the distance from the laser sensor to the dispenser tip

d_t: target value of the dispenser tip-substrate distance

$d_{z,p}(n)$: the target height of the Z stage control at n^{th} point

$d_s(n-k)$: the thickness of substrate at n-k^{th} point

θ: the dispenser tip-substrate angle

h: the horizontal distance between n^{th} point and n-k^{th} point

$d'_{z,p}(n)$: the modified height of the Z stage control at n^{th} point

OD: the outer diameter of the needle

Chapter 1. Introduction

Recently wearable electronics and soft robotics attract much attention and many researchers are investigating flexible electronic materials, as foldable devices are commercialized. Liquid metal is one of the most widely used materials for that purpose because it has relatively high conductivity and it is hardly broken under large strain. Among many kind of liquid metals, most of researchers are using Ga-In alloy because it is stabler and less toxic than other liquid metals.[1]

Patterning methods, fabricating sensors or circuits with liquid metals and flexible substrates, have already been reported for many years.[2-11] Lithography,[2,3] injection,[4,5] subtractive,[6,7] and additive[8-11] are the most common approaches. Direct writing, one of the additive way, has simple processes and can be implemented in a general laboratory environment.

It was reported several years ago that the distance between liquid metal dispenser tip and substrate affects quality or width of patterns.[9,10] Recently, a dispenser tip-substrate distance maintaining algorithm, which is called preceding algorithm, using a laser sensor and a rotation stage has been introduced and patterning straight lines on curved surfaces has been enabled.[11]

In this paper, we propose an improved dispenser tip-substrate distance feedback algorithm. With a motorized XYZ stage, a 45 ° bent 30 gauge needle, a laser sensor, and two pressure regulators, we built a basic eutectic gallium indium (EGaIn) direct writing system. By separating the scanning process and the patterning process, we fabricated various type of liquid metal patterns on Ecoflex substrates to verify the algorithm. Chapter 2 shows hardware setup and detail of feedback algorithm.

Chapter 3 to 5 is the results of patterning experiment. In Chapter 6, conclusion follows.

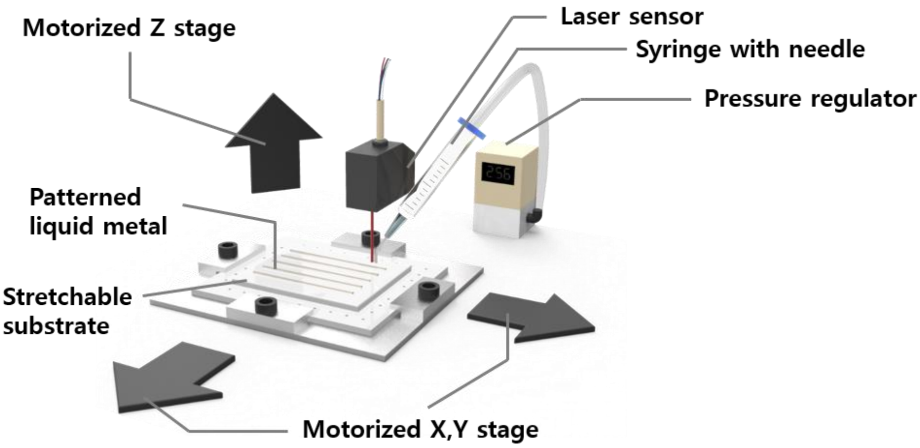

Figure 1. Concept design of the liquid metal direct writing system.

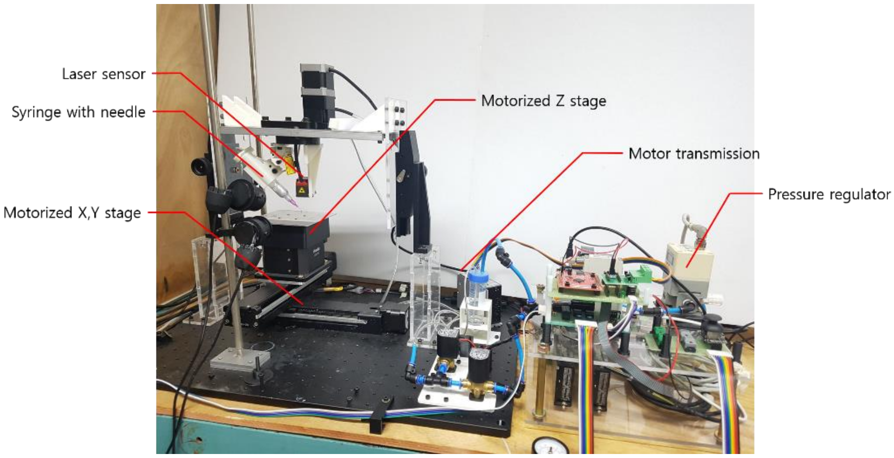

Figure 2. Liquid metal direct writing system.

Chapter 2. Experiment setup

2.1. Hardware

Figure 1 shows the schematic design of the liquid metal direct writing system and **Figure 2** shows the system we built in actual. The system is composed of a motorized XYZ stage for transporting substrates, a 45 degree bent 30 gauge needle for dispensing liquid metal, a laser sensor for measuring the distance and two pressure regulators for discharging the liquid metal. The motorized XY stage (JAEWON) is controlled by its own controller. The motorized Z stage (8MVT100-25-1, Standa) and the laser sensor (optoNCDT-1420, Micro-Epsilon) are controlled by a micro controller unit (STM32F767ZI, STMicroelectronics). The pressure regulators (ITV2050-312BL2, ITV0010-2BL, SMC) are controlled by another micro controller unit (Arduino Uno R3, Arduino). All controllers are connected to a computer and controlled by a LabVIEW program. And two micro controller units are synchronized by GPIO pins of the XY stage controller.

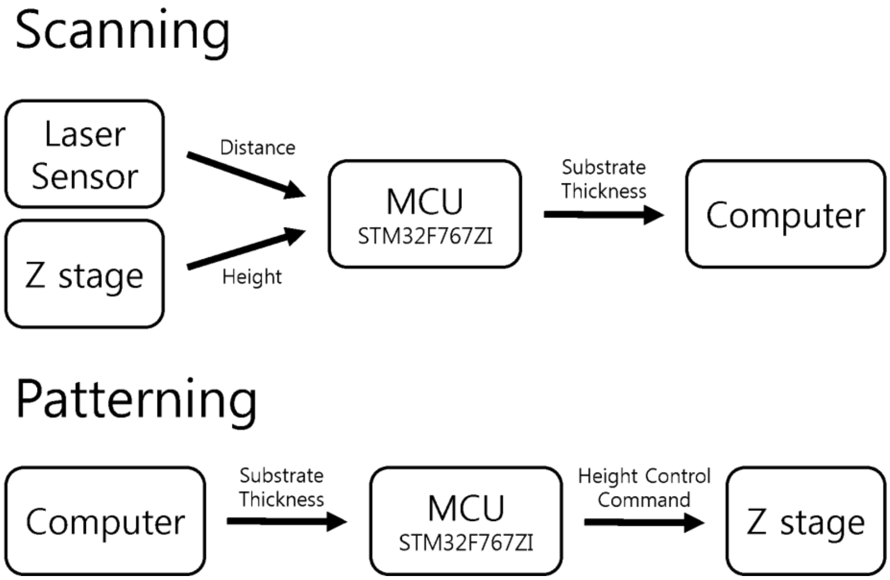

Figure 3. Data flow of path pre-scanning.

2.2. Path pre-scanning

Path pre-scanning is a method of maintaining the distance between the dispenser tip and the substrate. First, we decide the shape of the liquid metal pattern and set the path according to the shape. Next, the laser sensor is moved to the starting point of the path. Along the path, the XY stage moves at a speed of 1 mm/s. Simultaneously, the laser sensor and the Z stage measure the distance. And the distance data is transformed and modified at the MCU before it is transmitted to the computer by TCP/IP. At the computer, the LabVIEW program enqueues the data in a time sequence. When the path ends, the laser sensor is removed and the dispenser is located at the starting point. The pressure regulators are operated before the XY stage moves. And the XY stage is also controlled at a speed of 1 mm/s along the path. At the same time, the LabVIEW program dequeues the distance data and transmit it to the MCU. Based on the data, the MCU controls the height of the Z stage to maintain the distance between the dispenser tip and the substrate.

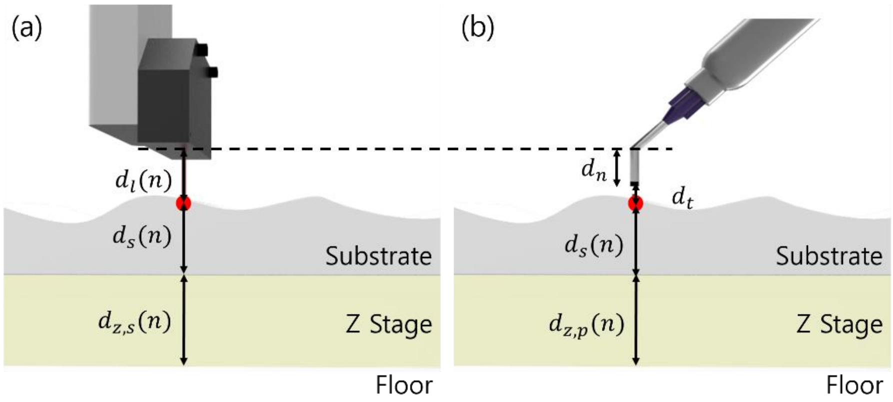

Figure 4. Main parameters of the dispenser tip-substrate distance feedback.

2.3. Feedback algorithm

2.3.1. Dispenser tip-substrate distance

Figure 4 (a) shows the scanning process at a point on a substrate. During the process, the distance between the laser sensor and the floor(d_{total}) does not change. So, the readout of the laser sensor($d_l(n)$), the thickness of the substrate($d_s(n)$), and the height of the Z stage readout($d_{z,s}(n)$) have the following relationship.

$$d_l(n) + d_s(n) + d_{z,s}(n) = d_{total} \tag{1}$$

This scanning process is enqueuing $d_l(n)$ and $d_{z,s}(n)$ in a time sequence, while the laser sensor moves along the path.

Figure 4 (b) shows the patterning process at the point on the substrate. Patterning process starts at the very point that scanning started at. Similarly, d_{total} does not change during this process. Therefore, the distance from the laser sensor to the dispenser tip(d_n), target value of the dispenser tip-substrate distance(d_t), and the target height of the Z stage control($d_{z,p}(n)$) have the following relationship.

$$d_n + d_t + d_s(n) + d_{z,p}(n) = d_{total} \qquad (2)$$

Following equation (3) can be derived from equation (1) and (2).

$$d_{z,p}(n) = d_l(n) + d_{z,s}(n) - d_n - d_t \qquad (3)$$

Equation (3) shows that $d_{z,p}(n)$ can be derived from $d_l(n)$ and $d_{z,s}(n)$ because both d_n and d_t are defined value. In this way, the dispenser tip-substrate distance can be maintained at a single point. Plus, setting the Z stage controlling rate equal to the data sample rate and maintaining speed of the XY stage constant enable that the distance can be controlled at every point on the path only by dequeuing the data in a time sequence. By this process, setting more diverse paths and overlapping the patterns are possible.

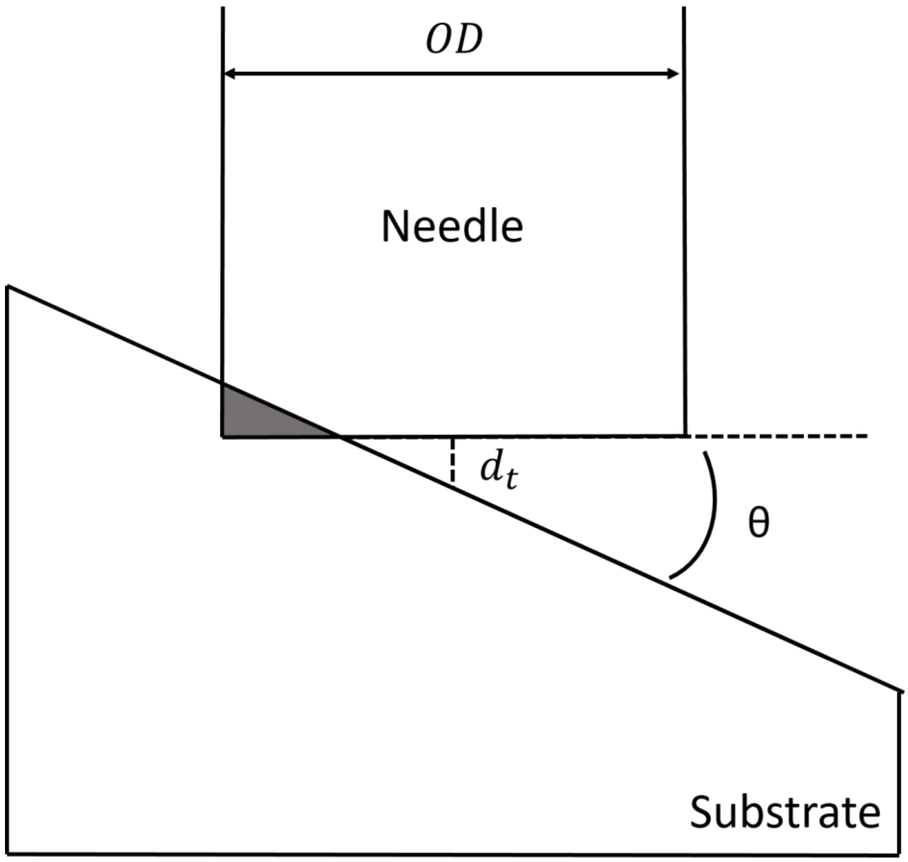

Figure 5. Limitation of the dispenser tip-substrate distance feedback.

2.3.2. Dispenser tip-substrate angle

Figure 5 shows a problem case that the dispenser needle partly collides with the substrate though the dispenser tip-substrate distance is being controlled. When the dispenser goes upward, this collision would not be a big deal. However, when the dispenser goes downward, this collision can cause huge damage on the pattern because the needle scratches the pattern. This problem affects width of patterns and, if serious, liquid metal may not be discharged. That's why the dispenser tip-substrate angle feedback is needed.

The thickness of substrate at n^{th} point($d_s(n)$) and n-k^{th} point($d_s(n-k)$), the dispenser tip-substrate angle(θ) and, the horizontal distance(h) between n^{th} point and n-k^{th} point have the following relationship.

$$\tan\theta = \frac{d_s(n) - d_s(n-k)}{h} \tag{4}$$

$$\tan\theta = \frac{d_l(n-k) + d_{z,s}(n-k) - d_l(n) - d_{z,s}(n)}{h} \tag{5}$$

Also, modified target height of the Z stage can be described as follows.

$$d'_{z,p}(n) = d_{z,p}(n) + \frac{OD\{d_l(n-k) + d_{z,s}(n-k) - d_l(n) - d_{z,s}(n)\}}{2h} \tag{6}$$

Where $d'_{z,p}(n)$ is the modified height of the Z stage, OD is the outer diameter of the needle.

Because the laser sensor has ±10 μm error, we have set h to 240 μm to make sure that $(d_s(n) - d_s(n-k))$ is greater than 20 μm when patterning on 5 ° inclined surface. With the help of this compensation, stabler patterning on inclined surfaces can be possible.

2.4. Preparation

2.4.1. Measurement

The distance from the laser sensor to the dispenser tip(d_n) is defined by the system design. However, because of tolerances, the distance must be measured accurately. To measure the distance, a load cell was used. After the load cell was mounted on the XY stage, the height of the Z stage was raised by 6 ㎛ until the readout of the load cell changed. When the readout changed, laser sensor was located at the point and measured the distance. By this method, the distance from the laser sensor to the dispenser tip can be measured with ± 6 ㎛ error.

2.4.2. Materials

The substrates used in this study is Ecoflex (0030, Smooth-on). The same amount of the base and the curing agent were mixed. And 2 % of white dye (Silc Pig, Smooth-on) was added to make the laser diffused better on the substrates. After mixed uniformly, the mixture was poured on a flat mold and cured in a heat chamber at 40 ℃ for at least 2 hours. After the curing, the Ecoflex was moved onto a 3D printed plate and used in direct writing of liquid metal.

Figure 6. Spiral liquid metal pattern.

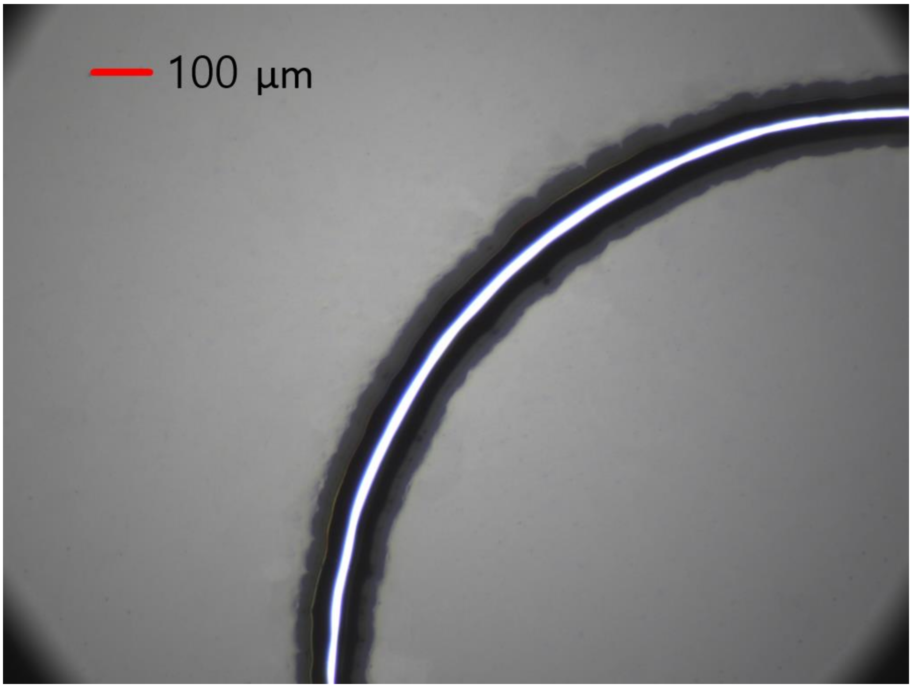

Figure 7. Optical microscope image of spiral liquid metal pattern.

Chapter 3. Liquid metal patterns on flat surface

3.1. Curvy pattern

Figure 6 and **Figure 7** shows curvy patterns on flat surface. The maximum radius is 15 ㎜ and the minimum radius is 1 ㎜. Both clockwise and counterclockwise are patterned without defects.

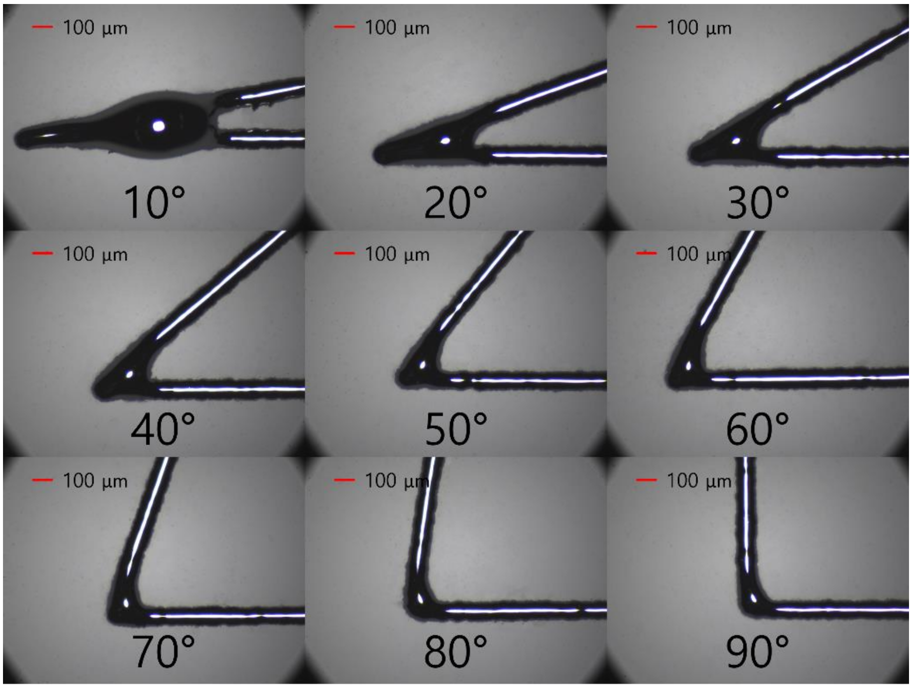

Figure 8. Optical microscope images of cuspal liquid metal patterns.

3.2. Cuspal pattern

Figure 8 illustrates cuspal liquid metal patterns and shows that the smaller the angle is, the bigger the pattern width of cuspal edge. Particularly, the drop on the 10 ° cuspal pattern is visible to the naked eye, but it does not flow or move.

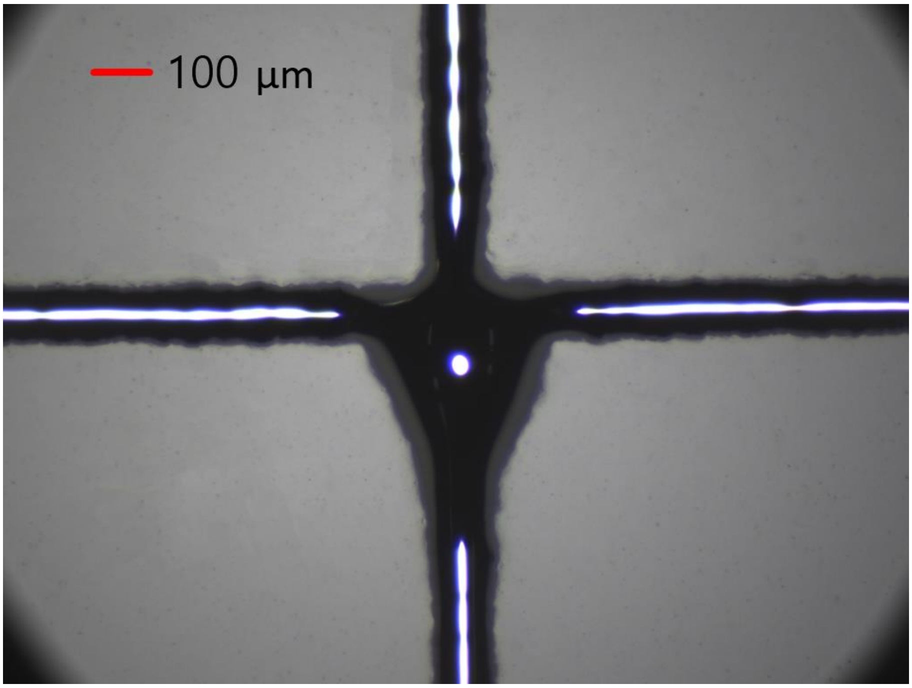

Figure 9. Optical microscope image of a crossing liquid metal pattern.

3.3. Crossing pattern

Figure 9 shows crossing pattern. Vertical pattern passed from top to bottom after horizontal one patterned. A small amount of liquid metal appears to have been dragged downward and part of the horizontal pattern seems to have thinned out. However, connection is well maintained and this kind of pattern can be used for fabricating multi-node circuits.

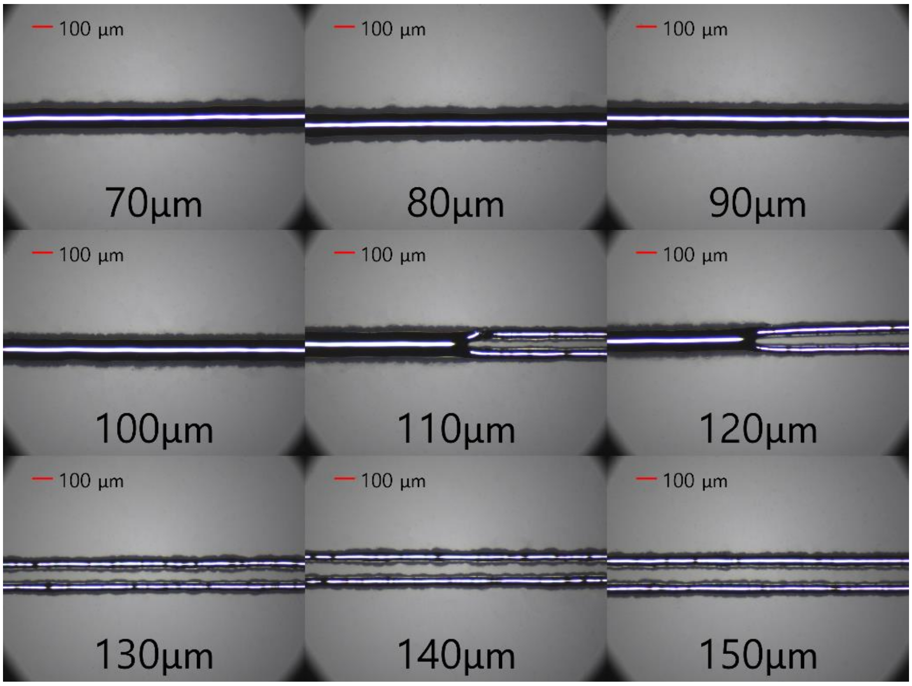

Figure 10. Optical microscope images of overlapped liquid metal patterns.

3.4. Overlapped pattern

Figure 10 shows overlapped liquid metal patterns on a flat surface. When the distance between patterns are less than or equal to 100 ㎛, overlapped patterns can be fabricated reliably. This can be an efficient method to make thicker patterns without resetting the dispenser tip-substrate distance or changing the needle for bigger one. And the minimum distance to make parallel patterns is about 130 ㎛.

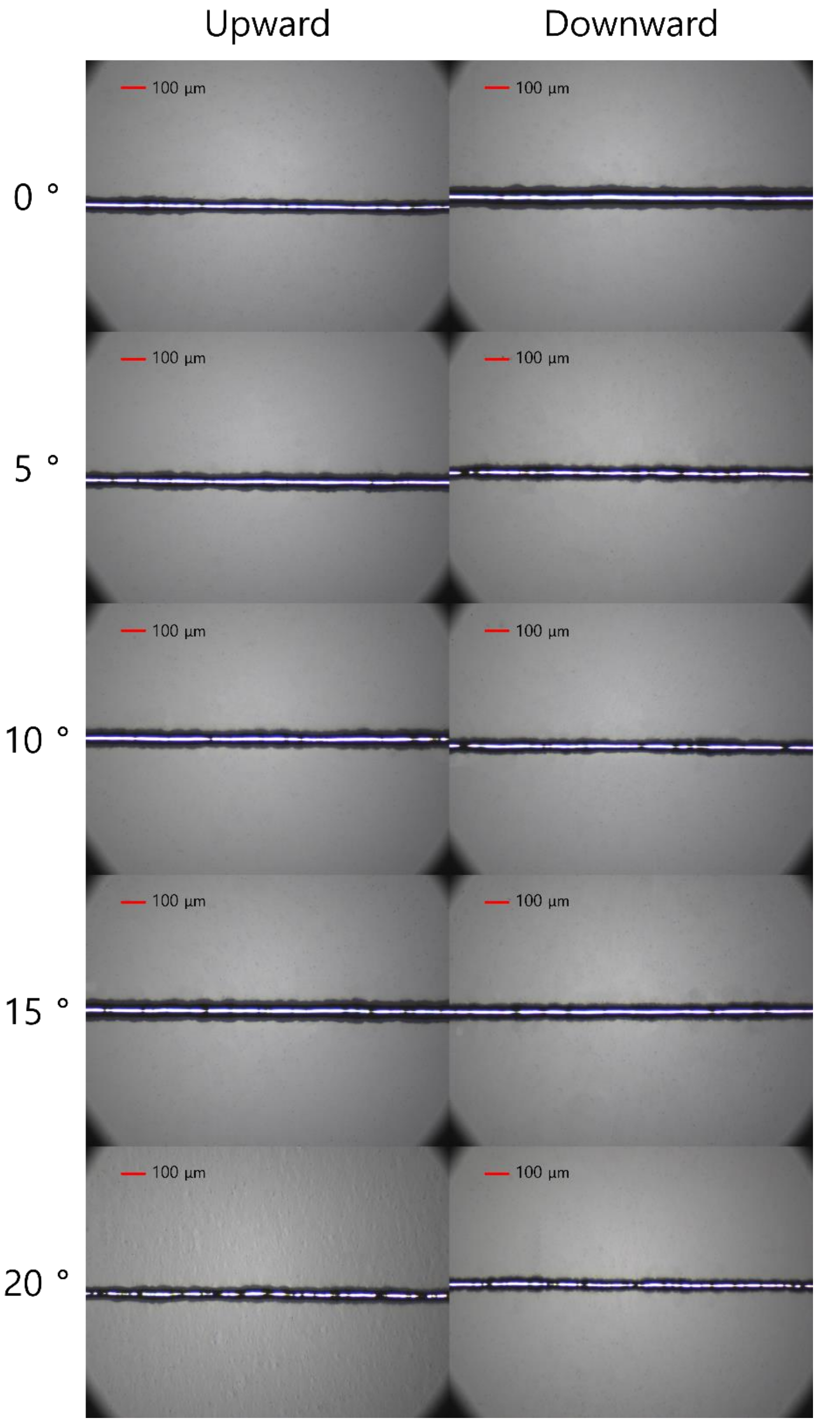

Figure 11. Optical microscope images of liquid metal patterns on 0 ~ 20 ° inclined substrates.

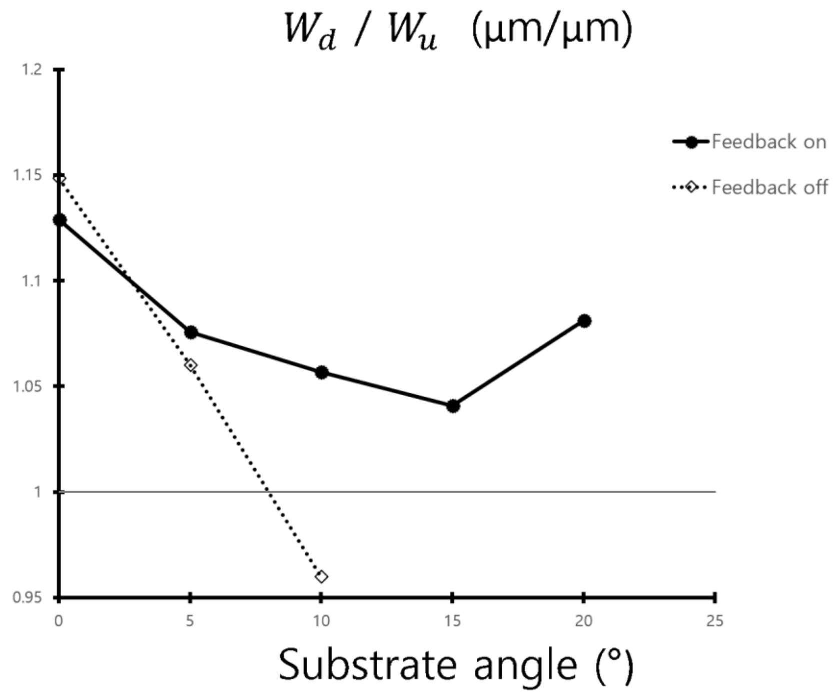

Figure 12. The ratio of pattern widths patterned downward to upward.

Chapter 4. Liquid metal patterns on inclined surface

Figure 11 illustrates straight liquid metal patterns on inclined surfaces. They are also patterned well. **Figure 12** shows the ratio of pattern widths as substrate angle changes. The ratio was calculated by dividing the pattern width of downward patterning by that of upward patterning. And mean width of the pattern was calculated by averaging widths of 10 random points. When the dispenser tip-substrate angle feedback was not working, patterning failed from 15 °. It is assumed that the needle was bent to upward about 5 ~ 10 ° because the ratio value when feedback was not working is smaller than 1 from 10 °. The feedback seems to have an effect because the change of the ratio when feedback was working is much smaller.

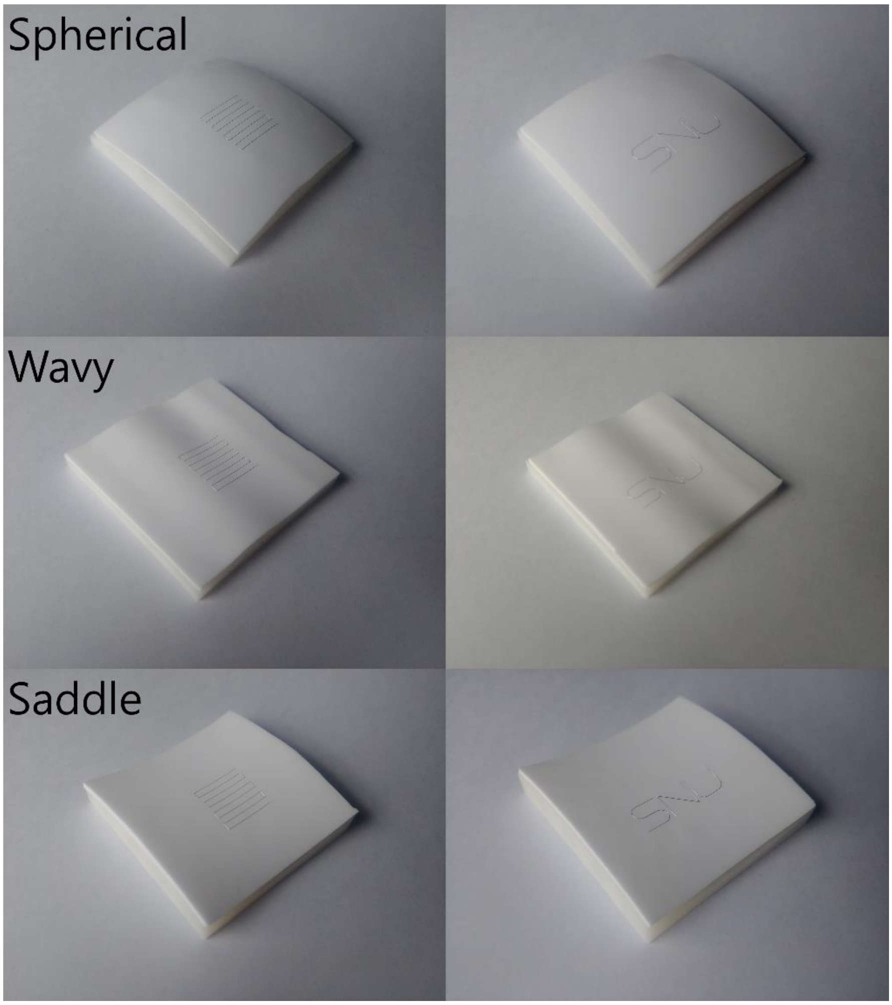

Figure 13. Meander and letter-shaped liquid metal patterns on various curved substrates.

Figure 14. Spiral liquid metal pattern on a spherical substrate.

Chapter 5. Liquid metal patterns on curved surface

Figure 13 shows meander patterns and letter-shaped patterns on spherical, wavy, and saddle surface. Feedback algorithm seems to be working well. **Figure 14** shows spiral liquid metal patterns on spherical substrate. A small defect was found in the center of the spiral. Only traces of the dispenser are left. It is assumed that long path and low speed precision of the XY stage can cause the defect.

Chapter 6. Conclusion

In this paper, a typical EGaIn direct writing system was constructed. Path pre-scanning was applied to maintain the distance between the dispenser tip and the substrate. This is a method that completely separates the scanning process from the patterning process. With the help of the method, diverse shape of patterns, such as cuspal and overlapped patterns, can be fabricated. Plus, the dispenser tip-substrate angle feedback was applied to increase stability of patterning. Because of this feedback, patterning up to 20 ° inclined surface was possible. Although fabricating long and curvy patterns did not show good quality, it was possible to fabricate meander patterns or letter-shaped patterns on curved surfaces.

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Abstract in Korean

본 연구는 액체금속 토출부와 기판 사이의 거리 유지 알고리즘을 개선하여 액체금속을 직접 인쇄 방식으로 곡면상에 다양한 형태의 패턴을 제작할 수 있는 방법을 제시하고 있다. 경로 선스캐닝 기법은 스캐닝 과정이 모두 완료된 후에 패터닝 과정을 진행하는 것으로 스캐닝 과정에서는 레이저 센서와 Z 축 자동 스테이지를 이용하여 기판의 두께와 기울기를 측정하며, 이 값들을 바탕으로 패터닝 과정에서 Z 축 자동 스테이지를 제어하여 액체금속 토출부와 기판 사이의 거리를 일정하게 조절한다. 두 과정을 분리함으로써, 곡선이나 첨점 등의 다양한 형태의 패턴을 제작할 수 있으며, 경사면이나 곡면 위에 패턴을 제작하는 것도 가능하다. 실험은 Ecoflex 로 제작된 기판 위에 갈륨-인듐 공융합금(EGaIn)을 이용하여 패턴을 제작했으며, 평면상에 곡선, 첨점, 교차선, 겹쳐진 선 형태의 패턴과 곡면상에 글자 형태의 패턴을 제작할 수 있다는 것을 보이고 있다.

주요어 : 직접 인쇄, 액체금속, 갈륨-인듐 공융합금(EGaIn), 스캐닝

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