Laser printing of mircolenses

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Abstract: Laser-Induced Forward Transfer (LIFT) is a printing method that uses a pulsed laser beam as the driving mechanism to transfer material deposited on a donor film onto a substrate. It offers the possibility to print with a high spatial resolution. In this study, we examine how the energy of the laser pulse affects the geometrical properties of the printed droplets of an optical glue that can be used as microlenses. By varying the laser pulse energy, we identify a threshold at which the droplets undergo a sudden increase in diameter while the contact angle between the material and the substrate decreases. Despite this abrupt change in diameter, a linear increase in the deposited volume is observed. Also a study of the microlenses focusing capacity has been carried out, where it is observed that with the use of a microlense we can increase the light recollection by a almost a 178%.
Keywords: Microlenses; Laser printing; Contact angle; Focal length.
SDGs: This work is related with the ninth sustainable-development goal: Industry, innovation and infrastructure.

I. INTRODUCTION

The advancement of modern technology increasingly depends on devices that include optical, mechanical and electrical components. Micro-optics plays an important role in this evolution by enabling the miniaturization of photonic systems.

Among other micro-optical elements, microlenses have become fundamental pieces in next-generation optoelectronic systems, with applications in different fields such as imaging and optical interconnection. Their ability to enhance photon collection efficiency gives them important applications in astronomy, while also contributing to improved emission efficiency in OLEDs [1]. Additionally, microlenses can help increase scanning speeds of confocal microscopy and improve the collection efficiency of photodetectors.

Different fabrication techniques have been developed for producing microlenses, each offering benefits and limitations. Among these, we find optical methods such as photolithography and thermal reflow of photoresists, chemical methods like wet etching or ion exchange and mechanical methods such as micro droplet jetting or hot embossing [1]. Another possible method of printing microlenses is Laser-induced forward transfer (LIFT). LIFT is a printing technique that enables high spatial resolution using relatively simple setups [2]. In this process, a liquid donor film of a certain thickness is deposited onto the surface of a transparent donor substrate. This material film is what is going to be transferred to the receiving substrate. Both the donor and the receiver are positioned facing each other at a short distance.

A laser pulse is then focused at the interface between the donor film and the donor substrate. The film absorbs the light and when the energy is high enough, a small volume of liquid is transferred to the receiving substrate forming a droplet. This process is similar to inkjet printing but offers an advantage due to the fact that LIFT is a nozzle-free technique. Because of that, it is not influenced by the nozzle diameter and can handle high-viscosity inks [2].

The transfer mechanism starts with the formation of a vapour bubble caused by the energy absorbed from the pulse. This bubble expands, pushing the donor film in all horizontal directions and generating a pressure gradient that drives liquid toward the top of the bubble. The convergence of liquid at the tip coming from all directions rises the pressure on the bubble pole, producing a jet responsible of the droplet generation. The size of the transferred droplets can be controlled by adjusting process parameters such as laser fluence, beam diameter, and donor film thickness [2][3].

The primary goal of this work is to study droplets produced using the LIFT technique by varying one of its parameters, the energy of the laser pulse, and prove that the droplets can act as microlenses and focus light.

II. EXPERIMENTAL SETUP

The LIFT setup consisted of a Flare NX pulsed laser with a pulse duration of 1.15 ns, a wavelength of 343 nm, a maximum repetition rate of 2 kHz and a power of 200 mW. The laser beam was directed through a half-wave retarder and a polariser to control its energy. After this, a 10:90 beam splitter mirror divided the beam into two paths: 10% was directed to a photodiode for real-time energy monitoring, while the remaining 90% was sent toward a 15x objective lens. The objective focused the beam onto the donor film. With the help of a camera, we were able to focus the substrate and to control where the minimum laser spot diameter was in respect of the donor surface. Then, the objective was always placed in a specific position in respect of the focused donor to grant that the laser spot was always of the same diameter when printing, approximatly of 40 μm. That way, the only variable at play was the energy of the pulse. The camera helped in the positioning of the microlenses too. Due to the ink's transparency at the laser wavelength, the donor had to be a microscope slide coated with titanium because of its capability to absorb ultraviolet light. The ink was Norland Optical Adhesive 61 with a viscosity of 0.3 Pa·s and a refractive index of 1.56. This optical adhesive cures under exposure to UV light. The donor thickness was of approximately 80 μm.

With this setup and donor conditions, two experiments were performed. In them, the receiver conditions were a little different. For the first one, the receiving substrate was a piece of 3M VHB Tape 4910 on a crystal microscope slide. The refractive index of this VHB Tape is 1.47 and the thickness of the tape is approximately 550 μm. The gap between the donor film and the substrate was of approximately 90 μm. For the second one we also used VHB tape and the exact same gap, but this time the tape was placed on a titanium coated slide with a previous treatment. Using this same system, a matrix of holes was fabricated in the titanium coating using ablation. These holes had a diameter of approximately 9 μm. The hole diameter and separation was chosen this way to simulate the area of the sensible regions of a Single-photon Avalanche Diode (SPAD) detector. In order to produce holes of this characteristics, a study was carried out varying the energy of the laser beam and the focusing distance. With this second parameter we control the area of the spot of the laser on the titanium. Once the matrix of holes was fabricated, the VHB was placed on them, on the titanium face of the slide.

Both the donor and the receiver were positioned face-to-face on a motorized two-axis stage with micrometric resolution.

The optical microscope Carl Zeiss model AXIO Imager.A1 was used to inspect and measure the microlenses. In order to capture the their topography, the Sensofar PLμ 2300 interferometer was used.

III. RESULTS AND DISCUSSION

As said before, two different procedures were conducted. The first one studies how the geometry of the droplets, the contact angle and the focal length varies with the energy of the laser pulse. The second one studies the effects in light intensities that go through a matrix of holes when a microlens matrix is placed on it.

A. Analysis of the droplet dependency on the energy of the pulse

To analyse the dependency of the droplet geometry with the energy, an interval is chosen in which the lower limit is the minimum energy required to produce the printing of droplets, and the upper limit is the maximum energy before LIFT produces splashing. This interval goes from approximately 11.5 μJ to 26.7 μJ. Inside this interval, the printing of microlenses has been carried out with 19 different values of energy and in each of them, 20 microlenses have been printed. Once fully cured, the microlenses shown in FIG.1 are obtained.

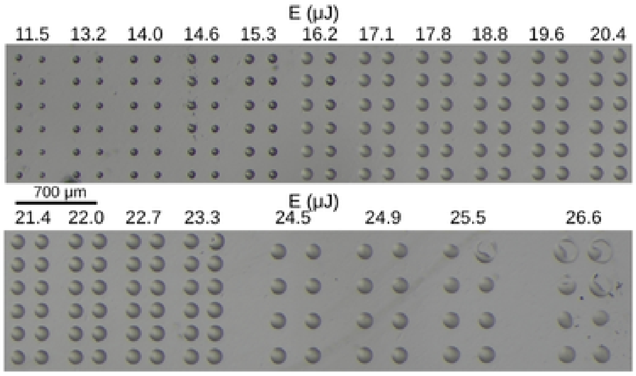

FIG. 1: Image of some of the microlenses obtained varying the energy of the laser pulse.

As it is observed, at high energies, with the fluctuation of the energy of the laser, the splashing threshold is sometimes crossed. Also, a sudden increase of the droplet diameter is visible in the image when a certain energy threshold is reached. FIG. 2 shows the diameter as a function of the energy of the laser pulse. Although they are not visible, the error bars are included but are too small to be seen.

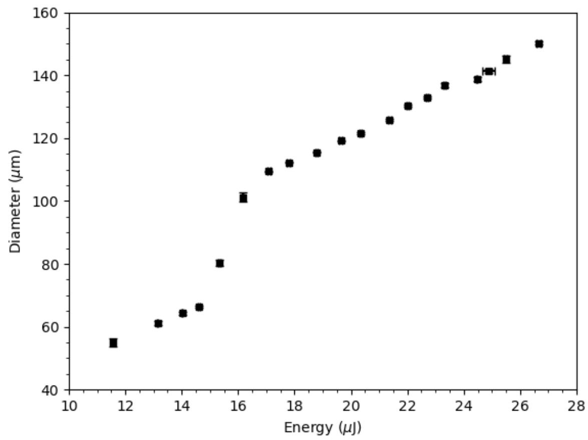

FIG. 2: Diameter of the microlenses as a function of the laser pulse energy.

As it can be seen in FIG.2, an abrupt increase in diameter occurs between laser energies of 15 to 17 μJ. Before that, the mean diameter of the microlenses grows quite linearly and, after this abrupt change, it maintains the tendency.

In order study the geometry of the microlenses it is interesting to compute the radius of curvature of their surface. To do so, we can use the contact angle. With the following expression we can calculate the radius of curvature.

$$R = \frac{r}{\cos(90 - \alpha)} \tag{1}$$

Where R is the radius of curvature, r the measured radius of the lens and α the contact angle. If the contact angle of the lenses stayed constant in every deposition, and if we knew its value, the R parameter would be easy to compute as it would solely depend on the radius of the lens. But with a look at FIG. 1, it seems that this is not the case. Because of this, it is needed to clarify if the contact angle stays constant during the experiment or not. To do so, a confocal microscope is used. With this instrument, it is possible to extract a surface profile of a sample. FIG.3 shows an example.

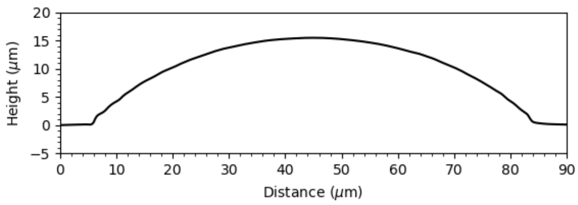

FIG. 3: Surface profile of a microlens printed at 15.3 μJ. Both axis have the same scale to show the real shape of the lens.

To compute the contact angle of the deposited droplet the profile is divided into two sections, the curve corresponding to the microlens and the horizontal line corresponding to the receiving surface. By fitting the curve to a circumference function and the surface to a line it is possible to find their intersection points, compute the slope, and therefore, the contact angle.

FIG.4 shows the contact angle as a function of the laser pulse energy. From the figure, it is clear that the contact angle is not constant. Between approximately 15 and 17 μJ, it suffers a sudden drop, decreasing from around 50° at lower energies to about 20° at higher ones. Usually, when the gap between the donor and the substrate is larger and the laser beam energy is lower, the LIFT technique produces droplets with a relatively constant contact angle, which depends solely on the properties of the donor and substrate materials as shown by M. Colina et al. (2006) [4]. The conditions of our experiment are far from this, and the results obtained do not quite follow the expected behaviour. What explains this abrupt growth in diameter and decrease in contact angle is related to the transfer mechanism at work during microlens printing. As shown by Duocastella et al. (2011) [5], due to the small gap between the donor film and the receiver and the action of a high-energy laser pulse, a big enough bubble is generated. This bubble makes contact with the substrate before it can start propelling the jet

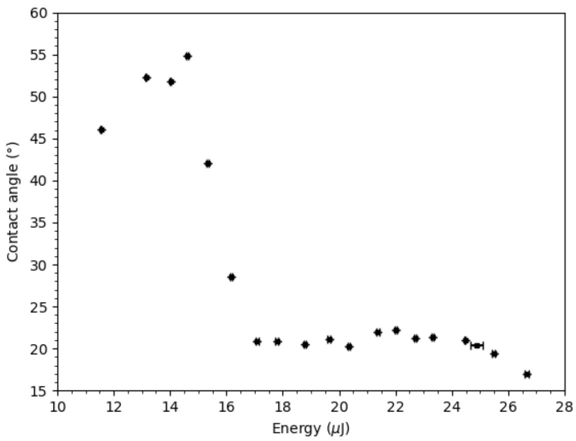

FIG. 4: Contact angle between the microlens and the substrate as a function of the laser pulse energy.

that is usually responsible for ink deposition. So, what is seen in these plots is that, before the 15 to 17 μJ range, the usual LIFT mechanism is active, whereas for energies above this range, the mechanism changes generating a bubble that touches the substrate and produces larger and flatter droplets.

It is also interesting to compute the volume of the deposited lens and observe if it has any kind of dependency with the parameters at play in this experiment. To do so we can also use the parameters of the fitted circumference, know its radius and then, by using the following expression, it is possible to compute the volume of the deposited lens.

$$V = \frac{1}{3}\pi h^2(3R - h) \tag{2}$$

Where h is the height of the lens and R is the radius of the curve. FIG.5 shows the deposited volume as a function of the energy.

As illustrated, a linear relationship between the deposited volume and the energy of the laser pulse is found. As it can be seen, this dependency is not affected by the aforementioned change in the transfer mechanism and is a result that matches previous findings [4][5].

In order to compute the focal length of the microlenses, the paraxial approximation is assumed. We will consider the equations for the two spherical surfaces of the lens.

$$\frac{n_1}{s} + \frac{n_2}{s'_1} = \frac{n_2 - n_1}{R_1} \tag{3}$$

$$\frac{n_2}{s_2} + \frac{n_3}{s'} = \frac{n_3 - n_2}{R_2} \tag{4}$$

Where n_1 corresponds to the air refractive index, n_2 to the Norland 61 index and n_3 corresponds to the VHB index. s_i corresponds to the position of the object in

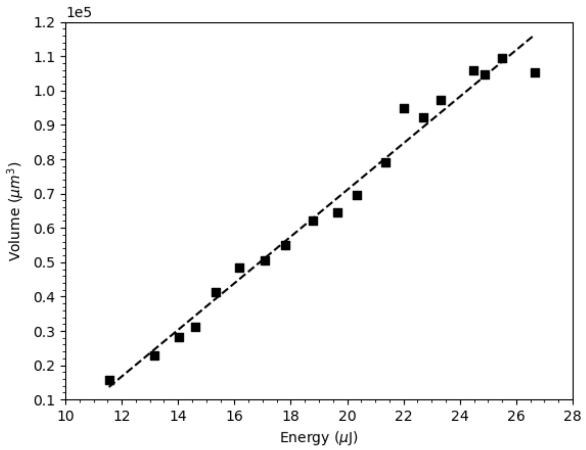

FIG. 5: Volume of the deposited microlens as a function of the laser pulse energy.

respect of the different surfaces and s_i' corresponds to the position of the image in respect of the surfaces. Finally, R_i corresponds to the radius of the spherical surface. In the case of the transition between the microlens and the VHB substrate, the radius is assumed to tend to infinity. With this in mind, and knowing that $s_2 = -s_1'$ we reach the following expression:

$$\frac{n_3}{s'} - \frac{n_1}{s} = \frac{n_2 - n_1}{R_1} \tag{5}$$

Thus, by taking the object distance s to infinity, we derive the following expression for the focal length:

$$f = \frac{n_3 R_1}{n_2 - n_1} \tag{6}$$

The computed focal length for the printed microlenses is shown at FIG. 6.

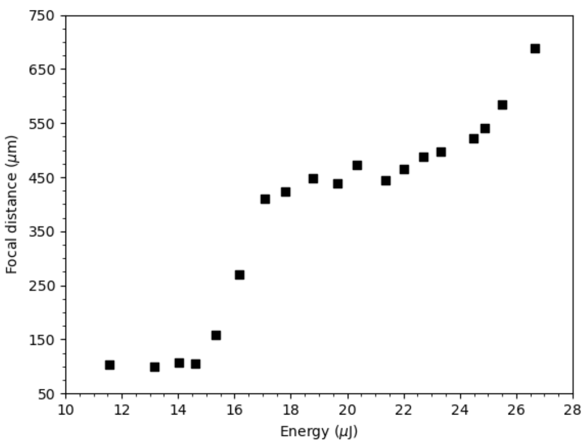

FIG. 6: Focal length as a function of the laser pulse energy.

As we can see, in contrast to the volume behaviour, the focal length does get affected by the change in the transfer mechanism. We observe that, when the energy grows, due to the decrease in contact angle, the focal length grows with it.

B. Increase of pixel intensity of the hole matrix due to the microlens effects

The aim of this experiment is to show that the printed microlenses can focus light and improve the collection of it for detectors like SPAD.

To do so, we first need to produce a substrate that can act as a mask that simulates the sensitive area of the sensor. For this purpose, we use a microscope slide coated with titanium. On the titanium layer, using the same laser system and through ablation, a matrix of holes with a diameter of approximately 9 μm is created. To achieve this, a laser pulse of 2.4 μJ and a spot diameter of 10 μm is used.

After this process, the VHB is placed on top of the titanium coating where the holes have been made. The objective is to print microlenses on the VHB with the appropriate focal length. Since the VHB thickness is approximately 550 μm, the microlenses must be printed using the same donor conditions as before, but with a laser pulse energy of around 25 μJ (as seen in FIG. 6). After careful alignment, it is possible to print the microlenses exactly on top of the already fabricated holes. In order to view the effects of the microlens application, and after curing them, the substrate is placed upside down in a microscope in light transmission mode. After carefully focusing on the titanium surface and configuring the camera to work with a capture time of 2 ms the following results are obtained.

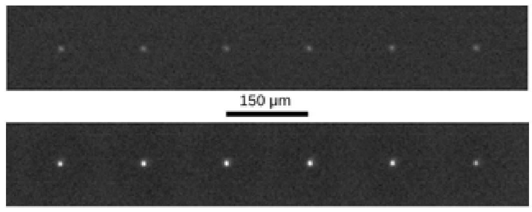

FIG. 7: Photos taken by the microscope in transmission mode. The upper picture is an array of holes without the microlens printed on them. The bottom image is the resulting hole array with microlenses on them.

As it can be observed, the bottom line has brighter pixel intensity that the upper one. With the use of the program ImageJ we can extract the pixel intensity profile. What is shown in FIG. 8 is the pixel intensity profile of a bigger array of holes than the one shown in FIG. 7. This profiles have been obtained after filtering and subtracting the background noise.

As it can be seen, the pixel intensity profile is significantly higher when a microlens is placed in front of the

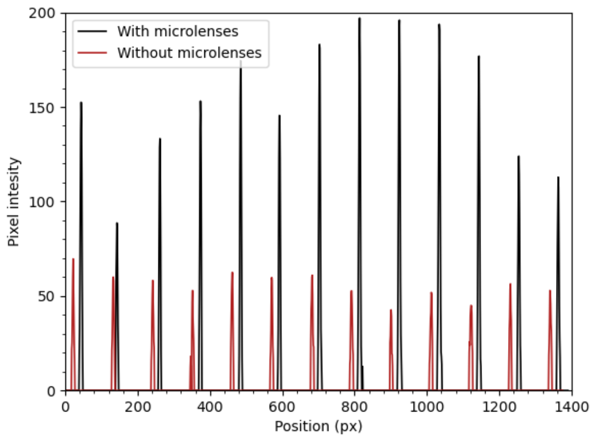

FIG. 8: In black, the pixel intensity profile corresponding to the holes with printed microlenses. In red the pixel intensity profile corresponding to the holes without printed microlenses.

hole. Averaging the maximum pixel intensities, we find that with the microlens, it reaches 156±9, whereas without it, it only reaches 56±2. This represents an increase of approximately a 179%.

IV. CONCLUSIONS

This work demonstrated how it is possible, with the LIFT technique, to successfully fabricate microlenses and change their geometrical characteristics with the energy of the laser pulse. The results show a clear transition in the transfer mechanism between 15-17 μJ where lower energies produce droplets through the usual jet method while higher energies lead to bubble-contact deposition. This transition leads to pronounced changes in droplet morphology, with the contact angle decreasing suddenly from around 50° to 20°, and the droplet diameter increasing accordingly.

The deposited volume shows a linear relationship with laser energy regardless of the transfer mechanism, while the focal length increases with energy due to the reduced contact angles. The printed microlenses demonstrate their capacity to focus light by enhancing the pixel intensity that crosses the titanium holes by approximately 179%.

Acknowledgments

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Impressió de microlents amb làser

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Resum: La tècnica d'impressió anomenada transferència directa induïda per làser (LIFT per les seves sigles en anglès) és un mètode que mitjançant un làser polsat com a mecanisme motor, permet transferir material dipositat sobre un substrat donador cap a un receptor. Aquesta tècnica permet imprimir amb una alta resolució espacial. En aquest estudi examinem com l'energia del pols làser afecta les gotes impreses d'una tinta òptica que es poden utilitzar com a microlents. Variant l'energia del pols làser, s'ha identificat un llindar per al qual les gotes pateixen un ràpid creixement en diàmetre mentre que els angles de contacte entre la tinta i el substrat disminueixen. Alhora s'ha estudiat l'evolució del volum dipositat en funció de l'energia del pols i s'ha observat que aquest canvi abrupte no afecta el creixement lineal d'aquest. També s'ha estudiat la capacitat de les lents de focalitzar la llum, on s'ha observat que mitjançant una microlent podem incrementar la recol·lecció de llum en un 178%.
Paraules clau: Microlents; Impressió en làser; Angle de contacte; Longitud focal
ODSs: Aquest TFG està relacionat amb els Objectius de Desenvolupament Sostenible (SDGs)

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar		12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climàtica	
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures	X		

El contingut d'aquest treball es podria relacionar amb l'ODS 9, i en concret amb la fita 9.5, gràcies a les grans aplicacions de les microlents en sectors com la biologia o l'astronimia, així com en dispositius i sistemes àmpliament utilitzats en la recerca, com per exemple la microscopia confocal o en fotodetectors.