

Microchannels Fabricated by Laser: From the Nanosecond to the Femtosecond Pulse Duration

María Aymerich¹, Javier R. Vázquez de Aldana², David Canteli³, Carlos Molpeceres³
and M. Teresa Flores-Arias¹ ^a

¹*Photonics4Life Research Group, Departamento de Física Aplicada, Facultad de Físicas,
Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Spain*

²*Aplicaciones del Láser y de la Fotónica Research Group, Departamento de Física Aplicada, Facultad de Ciencias,
Universidad de Salamanca, 37008, Salamanca, Spain*

³*Centro Láser UPM, Universidad Politécnica de Madrid, Crta. de Valencia km 3.7, 28031, Madrid, Spain
maite.flores@usc.es*

Keywords: Pulsed Laser, Laser Ablation, Laser Microstructuring, Microchannels, Laser-matter Interaction.

Abstract: Laser technologies are used to fabricate microchannels over glass substrates. A comparison among the results obtained when these microchannels are fabricated with pulsed lasers in the three more important regime in terms of pulse duration is made. A roadmap for obtaining a similar device when different pulsed lasers are used is presented. The control on the surface roughness, a very important parameter to be taken into account when biological applications are the possible ones, is also analysed.

1 INTRODUCTION

The last decades the fabrication of microchannels has presented a huge interest. There are several techniques used to fabricate these channels like embossing; injection moulding or other thermoforming techniques (Tsao, 2009); lithography techniques (Fu, 2006); electron beam lithography (Mali, 2006); photolithography (Stroock, 2002) and soft-lithography (Xia, 1998) among others. Each of these techniques is more suitable and it is chosen depending on the substrate where the microchannels want to be fabricated. Regarding the substrates, the more commonly materials used for channel fabrication are polymers (Xu, 2000), silicon (Dwivedi, 2000) and glasses. The last one presents numerous advantages such as their hardness, it is chemically robust and has good electrical and thermal properties. It has a low autofluorescence and is transparent in the range of optical inspections (Carlen, 2009).


Regarding the fabrication techniques, the laser has outstand when using glass substrates, due to the speediness of the process, the no contact nature, versatility, precision and so on (Liao, 2012). Although laser ablation is more common using

ultraviolet wavelengths when processing transparent material in the visible range, IR range has also been used for this aim (Nieto, 2014), (Nieto, 2010)

Physical phenomena involved in the ablation of dielectric materials are different depending on the laser pulse duration. (Liu, 1997), (Chichkov, 1996), (Weck, 2008)

There are a huge number of application fields of the glass microchannels, being one of them the microfluidic studies. This field aroused a big interest due to its numerous and promising biomedical applications (Whitesides, 2006), (Sackmann, 2014). Drug delivery (Metz, 2004), lab-on-a-chip analysis (Stone, 2004), cell trapping or imitation of vessels for in-vitro bioassays (Aymerich, 2017). The advantages of using microchannel is, mainly, the small volumes of liquid that are needed for the different analysis.

In this work, we present a roadmap for fabricating microchannels on glass substrates by laser ablation using pulsed laser in three pulse duration regimes (nanosecond, picosecond and femtosecond). All the lasers have their fundamental wavelength in the infrared spectral range. In particular, it will be analysed the different irradiances and parameters should be used when microchannels with a fixed ratio

^a  <https://orcid.org/0000-0002-8036-9654>

wants to be fabricated. These microchannels will be characterised and compared.

Section 2 presents materials and methods. Main results and discussions are presented in Section 3. Section 4 summarizes the conclusions.

2 MATERIALS AND METHODS

The lasers used in the development of this works are, a Rofin Nd:YVO₄ laser, a Lumera Super Rapid-HE (Nd:YVO₄) and one Spitfire from Spectra Physics. The Rofin laser operates in Q-switch regime with 20 ns pulse duration and 1064 nm fundamental wavelength. The laser setup was combined with a galvanometer system that addressed the output beam on the target. The lens used for focusing the laser over the substrate is a flat field lens with a 100mm focal length, that allows to operate with the same energy in an area of 80x80 mm². The Lumera Super Rapid-HE (Nd:YVO₄) has a fixed pulse duration of 12 ps and a fundamental wavelength of 1064 nm. The system had a motorized table and a processing head with a fix lens providing a beam radius in focus of 16 μm. The Spitfire of Spectra Physics emits pulses in the femtosecond regime, with a fixed pulse duration of 100 fs and it works at its central wavelength of 800 nm. In this case, the beam is focused with an achromatic lens of 200 mm. For fabricating microchannels with this laser a computer-controlled 3-axes motorized stage is used. Beam radii for this system was around 11 μm.

The substrate for fabricating the microchannels are chosen to be a cheap soda-lime glass obtained from a local supplier. The chemical composition of both surfaces of the material is shown in table 1.

Table 1: Chemical composition of the used glass in both sides of the piece.

Element	Weight (%)
O	50.25
Si	33.06
Na	9.08
Ca	4.87
Mg	2.19
Al	0.54

Element	Weight (%)
O	48.97
Si	32.34
Na	9.14
Ca	4.91
Mg	2.24
Al	0.49
Sn	1.90

Silicon dioxide (SiO₂) is the main component in both surfaces of soda-lime glass, followed by sodium oxide (Na₂O) and calcium oxide (CaO). However due to the process used in the fabrication of these glasses, in one side of the piece appears tin that play a key role in laser ablation of the material (Nieto, 2014), (Nieto, 2015).

3 RESULTS

As a first step, we proceed to determine the parameters for each laser system that assure the homogeneous ablation of the soda-lime substrate. This is a very important step in order to be sure that the microchannel fabricated will be homogeneous in its final form.

We found that in the case of working with the nanosecond laser we need a pulse energy of 700 μJ, a repetition rate of 10kHz, a scan speed of the galvanometer system of 50 mm/s and a pulse overlapping of 73%. In the case of the laser with pulses in the picosecond range, the pulse energy was 80 μJ pulse energy, the repetition rate 10 kHz, the scan speed 20 mm/s and the pulse overlapping 96%. Finally, for the laser with pulses in the femtosecond regime, the pulse energy needed is 40 μJ, the repetition rate is 1 kHz, the scan speed of the 3-axes motorized stage is 0.6 mm/s and the pulse overlapping 97%. Scanning speed and repetition rate were determined to assure the overlapping needed between two consecutive pulses for obtaining a homogeneous channel.

All these parameters allow us to determine the threshold mean fluences. As it is well known there is several ways to define the threshold mean fluences. Authors determine it experimentally as the minimum fluence value that generates ablation in the material with no overlapped pulses. For the nanosecond case, it was found to be 138 J/cm², 49 J/cm² for the picosecond regime and 5 J/cm² for the femtosecond one. In order to assure the quality and homogeneity of the final microchannels, we decide to use an energy per pulse equal to the double of the threshold energy. In this way we assure the quality of the final device. It can be observed that the value of the fluence needed for ablating the material decrease as the pulse duration decreases, as predicted in the literature. (Liu, 1997), (Chichkov, 1996), (Weck, 2008).

For comparing the channels obtained with the three different lasers we propose the fabrication of a channels with and aspect ratio 2:1 diameter:depth. We carried out a previous study of the number of laser scans we need to make, in order to achieve channels

with this ratio. As expected, it is different for each laser. In particular nine scans for the nanosecond laser, one laser scan for the picosecond laser and one laser scan for the femtosecond one are used. For these numbers of laser scans, we obtain a channel of 8.7 μm depth and 23.9 μm diameter fabricated with the nanosecond laser; a microchannel 8.4 μm depth x 17.8 μm diameter with the picosecond laser and a channel with 10.1 μm depth and 20.7 μm diameter in the femtosecond regime.

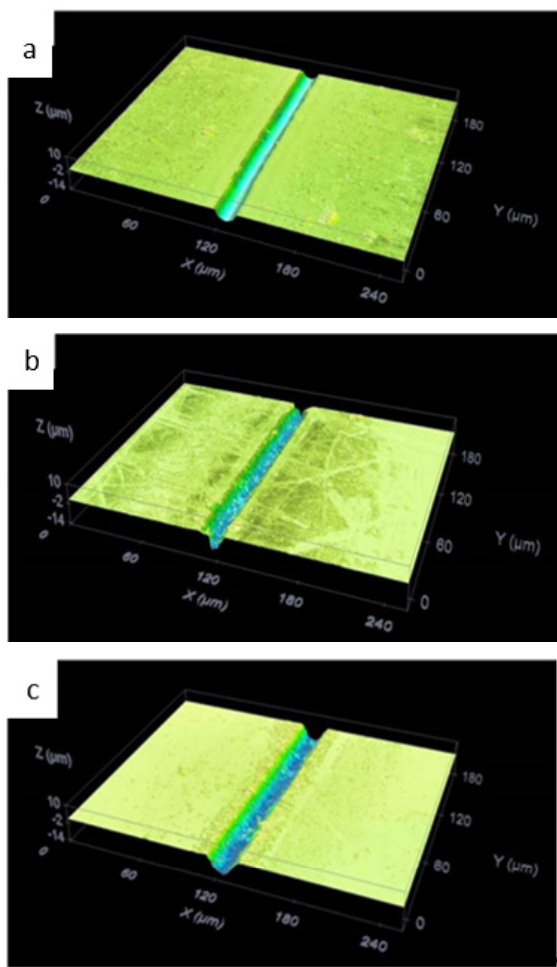


Figure 1: 3D confocal images of the microchannels fabricated with: a) nanosecond, b) picosecond and c) femtosecond pulse durations.

Figure 1 shows confocal images of channels fabricated with the different pulsed lasers. We can see that the channels fabricated with the three lasers have the same aspect ratio. However, the surface roughness of the channel was not equal at all. That is due to the difference in the processes involved in the ablation process when the three different temporal regimes are considered. For the nanosecond case, the material is

expelled by heat deposition, melted and vaporized. In the femtosecond pulse regime, the nature of the process is more explosive, inducing a direct vaporization of the material. In this case almost no thermal effect nor melting mechanics occur, so the final channel has a high roughness value in contrast with the smooth surface obtained in the channels fabricated with the nanosecond pulses. In the picosecond situation, a combination of both effects occurs, resulting in a process where part of the material is directly vaporized but also has a significant transfer of heat to the lattice and, therefore, melted material may appear.

Arithmetical mean roughness of the surface (S_a) was measured according to ISO 25178. Values for the channels fabricated with the nanosecond pulse duration were 178.7 nm, 1028.3 nm for the picosecond and 1016.3 nm for the femtosecond situation. As it can be observed, the surface roughness of the picosecond and femtosecond channels is higher than the ones manufactured with nanosecond pulse duration (see Figure 2). This is due to the more explosive nature of ablation with ultra-short pulses, where material is directly vaporised.

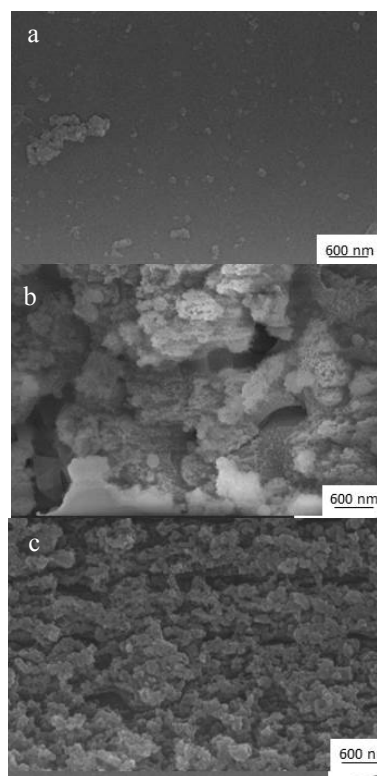


Figure 2: SEM images of the surface of the microchannels fabricated with a) nanosecond, b) picosecond and c) femtosecond pulse duration.

4 CONCLUSIONS

In this work, we presented a roadmap for fabricating microchannels with a same aspect ratio by direct laser writing techniques. In particular, there were used pulsed lasers working at the nanosecond, picosecond and femtosecond regime. The microchannels were fabricated on a soda-lime glass substrate. They were characterized in terms of height and width as well as in terms of their value of the surface roughness. Laser direct writing is shown as a fast, accurate, versatile and non-contact technique for the manufacturing of microchannels over soda-lime glass, advantageous material due to its robustness and competitive cost. It has been shown that channel with the same aspect ratio can be obtained with lasers working in the three temporal regimes. However, the roughness obtained are very different due to the physical mechanism involved in each ablative process. Depending on the application the roughness of the wall of the channel can be more appropriated. In particular a higher roughness is more suitable for applications in the biological area since the cell attachment is higher as the roughness increases.

ACKNOWLEDGEMENTS

This work has been supported under contracts RTI2018-097063-B-I00, AEI/FEDER, UE, FIS2017-87970-R Ministerio de Economía y Competitividad, ED431E 2018/08, Xunta de Galicia/FEDER, SA046U16, Junta de Castilla y León and FIS2015-71933-REDT Ministerio de Competitividad, Spain.

REFERENCES

- Moore, R., Lopes, J., 1999. Paper templates. In *TEMPLATE'06, 1st International Conference on Template Production*. SCITEPRESS.
- Smith, J., 1998. *The book*, The publishing company. London, 2nd edition.
- Tsao, C., Wand De Voe, D.L., 2009 Bonding of thermoplastic polymer microfluidics in *Microfluid. Nanofluid.*
- Fu, C., Hung, C., H. Huang, C., 2006. A novel and simple fabrication method of embedded SU-8 micro channels by direct UV lithography, *J. Phys. Conf. Ser*
- Mali, P., Sankar, A., Lal, R., 2006. Facile fabrication of microfluidic systems using electron beam lithography, *Lab Chip*.
- Stroock, A.D., Dertinger, S. K., Ajdari, A., Mezić, I., Stone, H.A., Whitesides, G.M., 2002. Chaotic mixer for microchannels, *Science*.
- Xia, Y., Whitesides, G.M., 1998 Soft lithography, *Annu. Rev. Mater. Sci.*
- Xu, J., Locascio, L., Gaitan, M., Lee, C.S., 2000. Room-temperature imprinting method for plastic microchannel fabrication. *Anal. Chem.*
- Dwivedi, V.K., Gopal, R., Ahmad, S., 2000. Fabrication of very smooth walls and bottoms of silicon microchannels for heat dissipation of semiconductor devices. *Microelectron. J.*
- Carlen, E.T., Bomer, J.G., van Nieuwkastele, J.W., van den Berg, A., 2009. *Silicon and Glass Micromachining, in Lab-on-a-Chip Technology for Biomedical and Biological Applications: Fabrication and Microfluidics*, Caister Academic Press, Norfolk.
- Liao, Y., Song, J., Li, E., Luo, Y., Shen, Y., Chen, D., Cheng, Y., Xu, Z., Sugioka, K., Midorikawa, K., 2012. Rapid prototyping of three-dimensional microfluidic mixers in glass by femtosecond laser direct writing, *Lab Chip*.
- Nieto, D., Delgado, T., Flores-Arias, M.T., 2014. Fabrication of microchannels on soda-lime glass substrates with a Nd: YVO 4 laser. *Opt. Lasers Eng.*
- Nieto, D., Delgado, T., Flores-Arias, M.T., 2014. Fabrication of microchannels on soda-lime glass substrates with a Nd: YVO 4 laser. *Opt. Lasers Eng.*
- Liu, X., Du, D., Mourou, G., 1997. Laser ablation and micromachining with ultrashort laser pulses in *IEEE J. Quantum Electron.*
- Chichkov, B.N., Momma, C., Nolte, S., Von Alvensleben, F., Tünnermann, A., 1996. Femtosecond, picosecond and nanosecond laser ablation of solids. *Appl. Phys. A*
- Weck, A., Crawford, T.H.R., Wilkinson, D.S., Haugen, H.K., Preston, J.S., 2008. Laser drilling of high aspect ratio holes in copper with femtosecond, picosecond and nanosecond pulses. *Appl. Phys. A*
- Whitesides, G.M., 2006. The origins and the future of microfluidics, *Nature*.
- Sackmann, E.K., Fulton, A.L., Beebe, D.J., 2014. The present and future role of microfluidics in biomedical research. *Nature*.
- Metz, S., Bertsch, A., Bertrand, D., Renaud, P., 2004. Flexible polyimide probes with microelectrodes and embedded microfluidic channels for simultaneous drug delivery and multi-channel monitoring of bioelectric activity. *Biosens. Bioelectron.*
- Stone, H.A., Stroock, A.D., Ajdari, A., 2004. Engineering flows in small devices: microfluidics toward a lab-on-a-chip. *Annu. Rev. Fluid Mech.*
- Aymerich, M., Álvarez, E., Bao-Varela, C., Moscoso, I., González-Juanatey, J.R., Flores-Arias, M.T., 2017. Laser technique for the fabrication of blood vessels-like models for preclinical studies of pathologies under flow conditions. *Biofabrication*.
- Nieto, D., Arines, J., Flores-Arias, M.T., 2014. Fluence ablation threshold dependence on tin impurities in commercial soda-lime glass. *Appl. Opt.*
- Nieto, D., Arines, J., O'Connor, G.M., Flores-Arias, M.T., 2015. Single-pulse laser ablation threshold of borosilicate, fused silica, sapphire, and soda-lime glass for pulse widths of 500 fs, 10 ps, 20 ns.