A retrospect on laser micromachining for the fabrication of microfluidic components

R. INDHU[a,*], S. RADHA[a], E. MANIKANDAN[b], B. S. SREEJA[a]
[a]*Department of ECE, SSN College of Engineering, Chennai– 603110, India*
[b]*School of Electronics Engineering, Vellore Institute of Technology, Chennai campus, Tamil Nadu 600127, India*

Lab-on-chip technology plays a major role in developing the world. Lab-on-chip is preferred for their user-friendly approach, miniature in size and less time-consuming. One such device developed using lab-on-chip technology is the Microfluidic device used for various applications. Many conventional manufacturing techniques are involved in the fabrication of such devices. Different materials like metal, polymer are used based on the type of application. In recent days, the laser micromachining has evolved in the fabrication of microfluidic devices. A review on the fabrication of Microfluidic devices using laser processing techniques like nanosecond laser, femtosecond laser, and picoseconds laser are discussed in this paper. A detailed description is given on laser usage for rapid modeling of the lab-on-chip devices using various materials for different applications.

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1. Introduction

A new distinct method in the field of the lab-on-chip is the microfluidics, which involves the flow of fluidic through microchannels and structures in a device with a dimension less than 1mm. This springing up technology is used major research areas of biomedical research, diagnostic and advanced analytical chemistry. The importance of using Microfluidic devices is due to the step-down size, batch production, reliable, user-friendly, portable, uses less amount of sample under test. The first Microfluidic device was made using silicon material since, ease of metal deposition, resistance to organic solvents and high thermal conductivity. The creation of micropump and microvalve in silicon material for Microfluidic application is achievable. Silicon device fabrication uses some chemicals for etching the surface as they require more safety precautions. It is an opaque material and elastic modulus is 130-180 GPa[1]. The devices developed using silicon uses dry or wet etching or chemical vapor deposition. Glass is electrically insulating and optically transparent, so it overcomes the drawbacks of silicon and used for developing fluidic chips. The glass fabrication also uses dry or wet etching and photolithography[2]. The glass is simpatico to biological testing as it does not allow gas to pass through. Glass is also used for on-chip reaction and solvent extraction. The microchannels are made of glass since its surface has stable electroosmotic mobility and high thermal conductivity. The limits to the usage of glass occurred due to its safety facility, the high pressure involved during fabrication, hardness and high cost of fabrication.

Many years later to the development of silicon and glass Microfluidic devices, Polymer-based lab-on-chip evolved. Polymers are preferred for their flexibility compared to inorganic materials. The most widely used polymer in research is the polydimethylsiloxane(PDMS) due to its ease of fabrication, cost-effective, good optical transparency[3]. The fabrication of PDMS based Microfluidic devices is carried out using conventional techniques like photolithography where different designs are imprinted on it. Multiple layers can also be formed using PDMS for creating complex designs. Over silicon material, PDMS is preferred for developing micropumps, microchannels, and microvalves due to its low elastic modulus 300-500 kPa[4]. Researchers also use some other polymers like thermoset polyester(TPE), polystyrene(PS), polycarbonate(PC), poly-methyl methacrylate(PMMA), polyethylene glycol diacrylate(PEDGA), Teflon, Polyurethane(PU) for developing microfluidic devices. Thermoset polyester is optically transparent, high resistance, cost-effective, insoluble. The mechanical and physical strength is high for TPE as its structure is highly cross-linked but when heated they get harden. Thermoset polyester is not preferred for the development of valves due to high stiffness. Thermoplastic polymers are highly cross-linked polymers which are capable of reshaping by changing the glass temperature and can retain the shape when cooled. Thermo-molding is the fabrication method used for developing thermoplastic-based Microfluidic devices[5]. This provides the production of devices in large quantities at a high rate and low cost for commercial production. PDMS is used as intermediate for transferring patterns over thermoplastics for rapid prototyping. This process can be carried out till transition temperature 150’C above which release of gas by PDMS takes place. Conformal contacts cannot be created for thermoplastic with other surfaces but can be done only with PDMS. To form the contacts with other surfaces, the dynamic coating can be done to modify the surface and this provides integration of flexible electric circuits[6].

Polystyrene is also the most widely used polymer for Microfluidic application due to its properties like easy functionalization, inert, biocompatible, optically transparent and most important credit is, it can be converted from hydrophobic to hydrophilic some chemical methods[7]. Injection molding and hot embossing are the expensive techniques used to prepare polystyrene chips which could be an encumbrance for its usage[8]. Thus it adapts microscale system mass manufacturing for its rapid production and building multilayer is also carried out easily. Due to its commercial availability, researchers use this material in the cell-culture[9]. Another polymer that fits the DNA thermal cyclic application is polycarbonate, which is durable and prepared by polymerization of bisphenol A and phosgene with its transition temperature 145’C.use of polycarbonate provides some advantages like the ease of cost, low moisture absorption, and high impact resistance. This serves as an alternative to the protocol like lithography and molding of PDMS multilayer. Albeit a few researchers effectively created Polycarbonate chips using thermal bonding procedures that do not server good bonds even at low temperatures[10].

The fabrication is done using a hot embossing technique and can be used to develop micropumps. The major applications of polycarbonate usage are enzymatic amplification, sample lysis, amplicon labeling, nucleic acid isolation and detection of pathogens. Also, the polycarbonates are made into sheets and used for the electrochemical glucose sensor chip[11]. The most reliable and commonly used material in Microfluidic chip development is polymethylmethacrylate. This material is cheap, optically transparent, compatibility to electrophoresis with the rigid mechanical property. The fabrication of PMMA chips are developed using hot embossing, thermal bonding, inject printing, laser ablation, and solvent imprinting[12]. The fine microstructures are fabricated using a CO_2 laser which controls the dimensions. Researchers have reported microvalve and pump developed using PMMA[13]. The material poly-ethylene glycol diacrylate(PEDGA) divvy some properties with PDMS like optical clarity, water stability, low background fluorescence. This material is referred to as convenient since polymerization occurs at room temperature without the usage of much energy[14]. PEDGA fluidic devices also follow the same fabrication methodology as PDMS[15]. In recent years, Teflon has evolved in making Microfluidic chips due to its excellent solvent resistance. The use of Teflon provides vantage of optical transparency, non-stick, soft enough to make valves and can create complex structures at high thermal molding with nanometer resolution[16]. For an artificial heart, heart valves, pacemaker lead, intra-sortic balloons, water repellent material like polyurethane is widely used[17]. A study on Cellular and tissue response of polyurethane have been analyzed in vitro and in vivo to know the biocompatible nature. From the analysis, it is essential to considerate its biocompatibility[18]. The fabrication technique for polyurethane follows the traditional method like rotating mandrel, vertical dipping rotating plate for developing sheets, membrane. For the replication of complex microstructures, the above fabrication methods are not preferred. So, microfabrication techniques like injection moulding plasma, etching, reaction polymerization, imprinting are preferred. These techniques are also not suitable for rapid prototyping as they are expensive techniques that involve costly equipment. Thus PU uses a photolithography method to fabricate Microfluidic devices[19]. In recent trends, paper-based Microfluidic devices play a major role as it is biocompatible, cheap, eco-friendly, can also be readily modified through a chemical process based on the application[20]. Paper-based Microfluidic chip can be used in the detection of analytes using methods like electrochemical, chemiluminescence, colorimetric, electrochemiluminescence.

Still, paper-based Microfluidic chips can be used for limited applications because of weak mechanical properties. Solid waxing and Inkjet printing is the method used for drawing patterns on paper to fabricate a fluidic device[21]. Researchers are currently working on composite materials for Microfluidic devices. One such composite material is a cyclic-olefin copolymer which has interesting properties likened to existing polymers like PMMA, PU[22]. It is easy to fabricate and available at ease of cost. It includes some groundbreaking properties like biocompatibility, low moisture absorption, optical transmission, high water barrier, high chemical resistance, and heat resistance. It is limited to use in some applications due to low heat diffusivity[23].

Conventionally, fabrication techniques like micro-milling, 3D printing, hot embossing, injection moulding, photolithography, wet/dry etching are used for developing the microfluidic device on a large scale[24]. Xiaoyong Ku discusses the development of glass Microfluidic device using the convention micro-milling technique. Here the glass substrate is dipped in cool water to remove the dirt. An analysis is made with the parameters like feed rate, spindle speed, cutting depth and damage along the channel[25]. Zhizhi Zhou also discussed the fabrication of microchannel on the PDMS membrane using the micro-milling technique. The microchannel is fabricated by creating a positive mask on the acrylic block and pre-curing the PDMS on it. This is a low-cost effective method and it avoids the breakage at the ends of the channel. The fabricated device is shown in Fig.1[26]. Most of the above techniques used some toxic chemicals, repeated steps, the hierarchical procedure which is difficult to execute for rapid production. So a method called laser surface texturing is used to develop Microfluidic devices in the current trend. Laser texturing process includes laser patterning, laser texturing, laser structuring which is a direct treatment method. Laser processing can modify the surface of the substrate to micro and nanoscale with high spatial and temporal resolution[27]. The major advantage of using laser processing is high speed, direct writing, and easy automation. This paper discusses the different types of laser used in the development of the device of Microfluidic device chips.

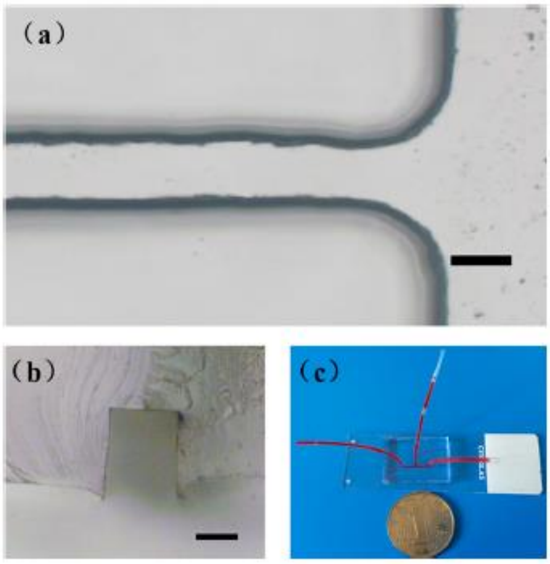


Fig. 1. (a) Microchannel fabricated using micro-milling technique (b) cross sectional view (c) prototype of the complete device combined with glass slide (color online)

2. Different laser micromachining

2.1. CO_2 laser

Many researchers work on CO_2 laser processing for the development of the Microfluidic device since it is cost-effective, and provide a precise method of fabrication. The general schematic diagram of CO_2 laser micromachining is given in Fig.2. Xueye Chen et.al, discuss the fabrication of polymer-based Microfluidic chip using CO_2 laser. Some of the polymer discussed here are Polymethylmethacrylate (PMMA), Polycarbonate (PC), Polystyrene (PS) and Polyethylene Terephthalate (PET). They compared the influence of the above-given polymers covers plates on aspect ratio. From the analysis, it is clear that the polystyrene has the smallest aspect ratio compared to other polymers. The aspect ratio of the microstructure created on the polymer with high laser power produces huge change when compared to lower laser power[28]. Zengliang Hu et.al, also consider the above-given polymers and calculate the roughness for them. The analysis shows that material polystyrene has less roughness when compared to other polymers under consideration. The roughness is reduced by increasing the laser power[29]. Researchers also concentrate on raster scanning of the CO_2 the laser beam which plays an essential part in the development of microstructures. Shashi Prakash and Subrata Kumar discussed the exploration of microstructures with different dimensions created using the CO_2 laser-based raster scanning process. They also discuss the determination of raster speed on a single laser pulse and the pulse smearing phenomenon damages the laser beam intensity[30]. Mohamed O Helmy et.al talks about the thermal damage that occurs during the development of polymethyl methacrylate microchannel using CO_2 laser. Surface roughness, aspect ratio, heat affected zone are analyzed for the developed device using laser and the experiment was conducted in dry air and underwater medium.

From the analysis, the thermal damage is reduced by applying low laser power with high scanning speed in both dry and underwater medium. Increasing the laser power and reducing the scanning speed, the aspect ratio is increased[31]. Zengliang Hu et.al, discuss the creation of microchannel on polycarbonate(PC) using two-pass of the CO_2 laser. Three sheets of polycarbonate(PC) are considered with different substrates for analyzing the cleanliness after CO_2 laser processing. The PC sheet with the transparent substrate is tended to be clear but it has large width and depth in microchannel created. This analysis is done to know the effect of creating microchannel on a different substrate with PC sheet fabricated using CO_2 laser. Then a microchannel is created using a CO_2 laser and the transparent substrate is attached to the PC sheet to process the edges. Taguchi method is applied to optimize the dimension of the channel[32]. Carlos and Armando discuss the fabrication of Microfluidic devices on PMMA substrate using laser micromachining. Rapid prototyping of thermoplastic Microfluidic device with a low entry barrier is proposed and developed that overcomes the conventional equipment in laboratories[33]. The proposed design is shown in Fig. 3.

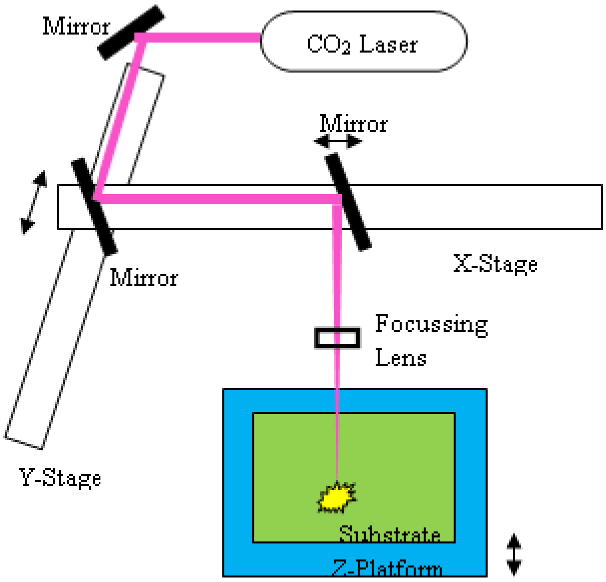


Fig. 2. Schematic diagram of CO_2 laser micromachining process (color online)

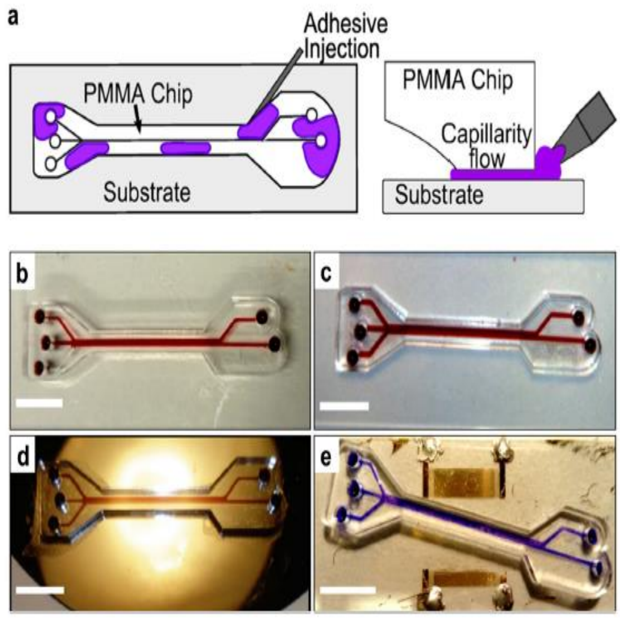


Fig. 3. (a) Adhesive bonding method is used throughout the channel to avoid the flooding and it is injected in the spaces between the chip and substrate, b-e) Microfluidic device developed using PMMA with adhesive bonding via capillary adhesive delivery on PMMA where (b)-glass (c)- silicon (d)LiNbO3 (e) substrate (color online)

2.2. Nanosecond laser

The high instantaneous power and less heat affected area lead to the use of laser processing for microstructure fabrication. Among any laser processing techniques, nanosecond laser is used due to the capability of creating satisfactory quality at a minimal cost. The schematic diagram for the nanosecond laser is shown in Fig.4. Many engineering applications and researchers are interested in modifying the device surface to superhydrophobic. One such way to modify the surface of the device to superhydrophobic is the use of nanosecond laser. Juanjuan Song et.al, work on surface modification of carbon steel material to superhydrophobic nature using nanosecond laser. This modification leads to a change in the roughness of the substrate. Perhydropolysilazane were used as precursors to material surface since it has low surface energy and high barrier property. The hierarchical design fabricated extends the use of mechanical durability of the superhydrophobic surface which is long-acting and stable in applications. The combination of nanosecond laser and the precursor perhydropolysilazane can be used in the application of surface wettability materials, corrosion-resistance, self-cleaning and anti-fouling[34]. Yu Deng et.al states that surface morphology plays a vital role in the development of polymer-based microfluidic devices. Microcracks are formed on PDMS polymer surfaces using nanosecond laser. Many characterizations like scanning electron microscopy, atomic force microscope, and 2D Raman are used to investigate the surface morphology of the device with micro-cracks. The outcomes disclose that the micro-cracks are the overwhelmed morphology along the laser examining routes. Laser scanning speed and laser power determine the length and orientation of the micro-cracks[35]. Guanbao Yang et.al discussed the mechanism of geometric phase analysis and nanosecond laser processing with important factors (laser fluence, ablation threshold of material, laser energy) associated with it. Experimental analysis is carried out with the fabricated microscale grating. To obtain high-quality grating, Al material is deposited on the substrate before the laser processing[36]. Nanosecond laser is also used in scribing on thin-film solar cells. Seungkuk Kuk et.al talks about the photovoltaic architecture of Cu(In, Ga)Se2 (CIGS) thin films with bottom contact as ITO. Laser scribing is performed on ITO to make it interconnect. Essential scribing conditions were incurred from parametric tuning for both numerical and experimental investigations[37]. A development of microchannel on PMMA material using nanosecond laser was discussed by Daniel teixidor et.al. The near-infrared wavelengths are used in the experiment where the depth and width of the microchannel are varied and analyzed[38].

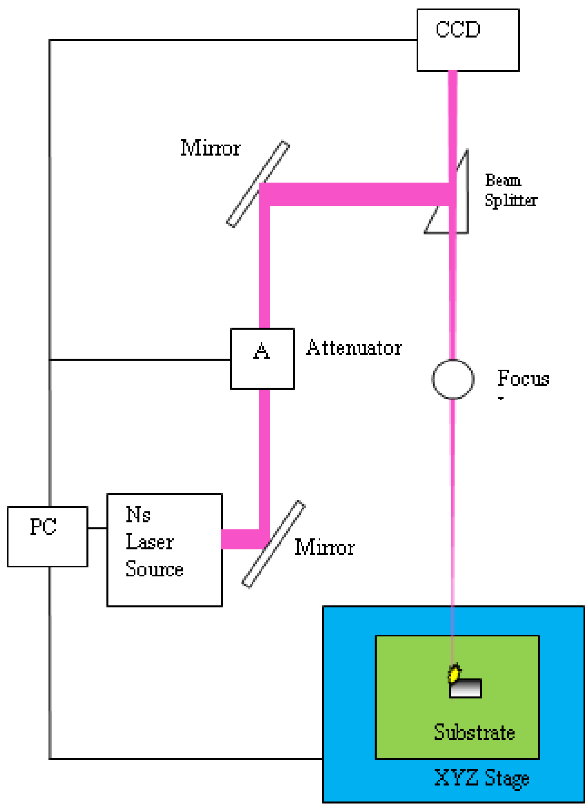
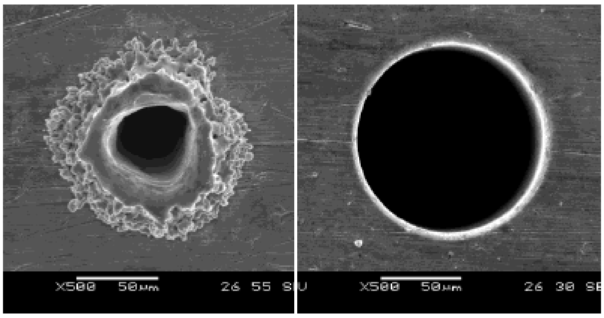


Fig. 4. Schematic diagram of Nanosecond laser micromachining process (color online)

Sanha Kim et.al discussed the fabrication of micro-hole and micro-groove using pulsed nanosecond laser ablation and micro-electrical discharge machining (EDM). The major drawback of the EDM process is the high tool wear and slow machining speed. But the nanosecond laser ablation has a fast and non-wear machine with low quality. So sanha kim et.al integrated these two process and discovered a novel hybrid micromachining system which overcomes the disadvantage of both the process. The hybrid process results are compared with laser ablation and EDM process results. Scanning electron microscopic images of micro-holes fabricated using laser ablation and EDM is shown in Fig.5 and the micro grooves created using hybrid process with 0.1and 1mJ/pulse is shown in Fig. 6[39].



(a) (b)

Fig. 5. Scanning Electron Microscopic image of micro-holes fabricated using (a) laser ablation (b)EDM

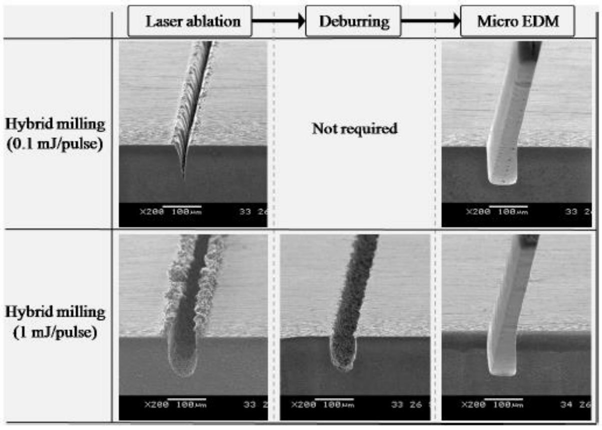


Fig. 6. Micro-grooves fabricated using hybrid process at 0.1 and 1 mJ/Pulse energy of the laser

2.3. Picosecond laser

The use of the Picosecond laser plays an important role in current research since it is used in the precise fabrication of microstructures. Picoseconds laser heats the material precisely at interference maximum position with a reduction in heat affected region. This can also be used for the fabrication of sub-micron range patterns. The general schematic diagram of picoseconds laser is shown in Fig.7. Ronán McCann et.al, discuss the fabrication of an array of microchannel on cyclic olefin polymer using picoseconds laser. To analyze the depth and width of the microchannel, Taguchi orthogonal array experimental is carried out for Zeonor polymer Films ZF14 and ZF16 using laser ablation. Laser fluence, number of passes and substrate thickness are the factors affecting the width and depth[40]. Alfredo I. Aguilar-Morales et.al, also discussed the fabrication of micro line and micropillars on stainless steel using picoseconds laser with high aspect ratio. During fabrication, depth and homogeneity of the microstructures can be controlled by increasing the laser fluence. Also using laser beam polarization, the orientation of the microstructures can be controlled[41]. Ronán McCann et.al, discussed the fabrication of microchannel using picoseconds second laser and analyzed the surface chemistry of polymer before and after laser ablation. The group also discusses the variation in depth and width for single and multiple passes. Also, verified the change in morphology of the material due to the effect of laser fluence using a Scanning electron microscope and infrared spectroscopy[42]. X C Wang et.al discuss the superhydrophobic surface texturing of nickel substrate using picoseconds laser. Microstructures like micro bumps and nanoscale ripples are created on a nickel substrate. The process of surface texturing uses a laser-induced NiO catalyst for surface chemistry modification by reducing energy. This process improves the function of nickel mold in Microfluidic chips[43]. Tianyang Yan discusses the formation of microstructure and groves on yttria-stabilized tetragonal zirconia polycrystal using picoseconds laser. The structures are formed to control the wettability of liquid on the bioceramic surface [44].

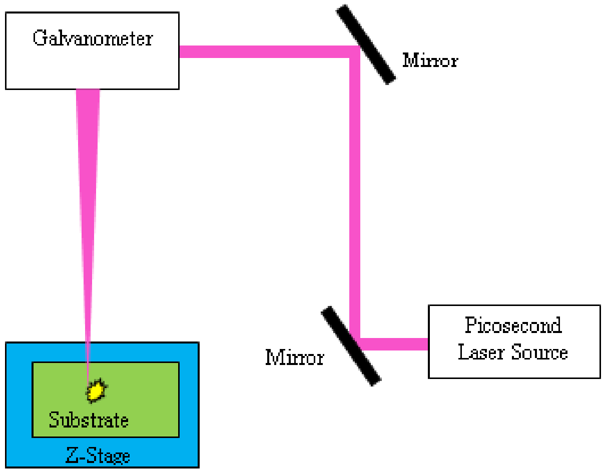
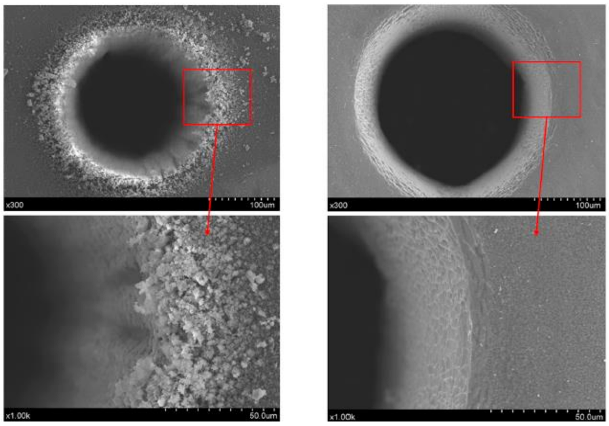


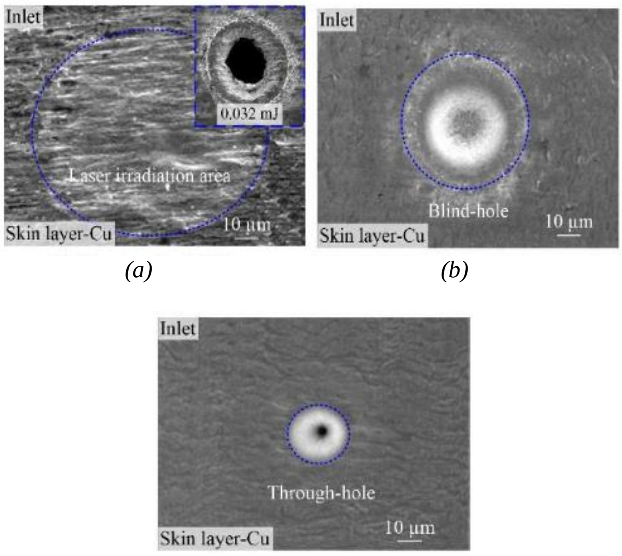
Fig. 7. Schematic Diagram of Picosecond laser micromachining process (color online)

Hao Zhu et.al investigated the direct and chemical assisted picosecond laser fabrication of micro-holes on a single silicon wafer. The results found that the thermally affected regions are high using direct picoseconds laser and negligible while using chemical assisted picoseconds laser. The chemical assisted picoseconds laser uses NaOH 1 mol/L concentrated solution for material removal. The use of this solution improves the removal rate and provides a wider hole when compared to the direct method. The direct and chemical assisted method is compared and shown in Fig.8[45]. Miniaturized and lightweight products require high density and high quality interconnects. Printed circuit boards need to be designed with small diameter and high-quality through-hole. Wanqin Zhao and Lingzhi Wang discuss the picoseconds ultrafast pulsed laser method for the development of through-holes on a printed circuit board. The investigation was carried out by varying parameters like pulse, wavelength and energy are shown in Fig.9 and Fig.10[46].



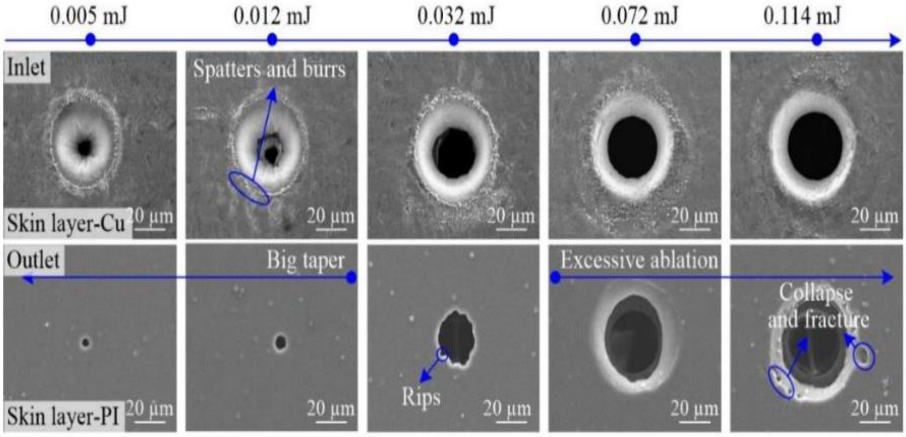
(a) *(b)*

Fig. 8. Fabrication of micro-hole using a) direct b) chemical assisted picoseconds laser (color online)

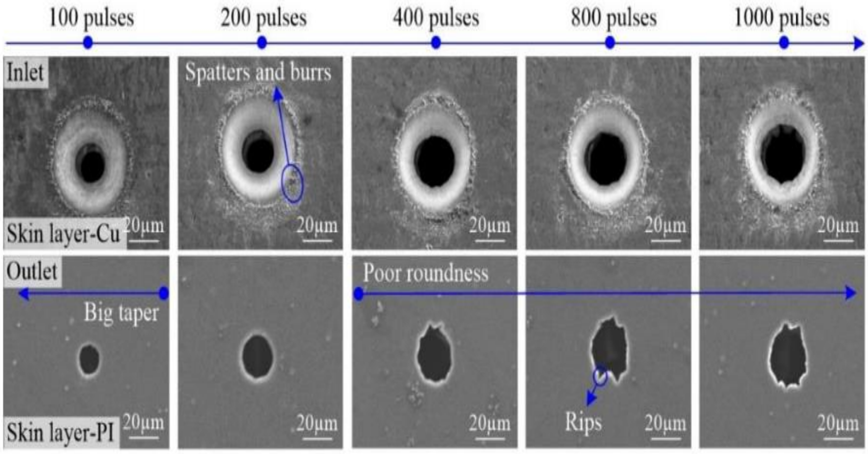


(a) *(b)* *(c)*

Fig. 9. Effect of laser on holes by varying the wavelength (a)1064nm (b)532nm (c)355nm (color online)



(a)



(b)

Fig. 10. Effect of laser on holes by varying (a) laser energy (b) laser pulses (color online)

2.4. Femtosecond laser

Even though many ultra-short pulses lasers exist, researchers and industry focus on femtosecond laser processing. In comparison with a nanosecond laser, femtosecond laser provides a more precise structure with less heat affect area. The general schematic diagram of a femtosecond laser is shown in Fig.11. Mitsuhiro terakawa discusses the fundamentals and booming of the femtosecond laser in industries and research field. He also explains about the laser ablation where removal of material takes place during laser sintering, laser-irradiated area, and photopolymerization. He states that femtosecond is used for precise manufacturing of various kinds of materials[47]. Felix Sima et.al describes a review on principles of the femtosecond laser for 3D micro/nanofabrication that is carried out for various lab-on-chip applications. Two processing methods like subtractive(direct fabrication), additive (two-photon polymerization) are discussed and introduced a hybrid technique which is functionally enhanced for lab-on-chip device[48]. Kenneth Aycock discusses the fabrication of Microfluidic devices using femtosecond laser with high resolution at the wavelength near-visible, infrared, ultraviolet spectra. Analysis of laser ablation on various substrates with a resolution higher than 80µm was carried out. The major limitation is the soot deposition which many create hindrance during the development of microchannel for biological assay[49]. Clemens Kunz et.al talks about the development of hierarchical surface structures on silica using a femtosecond laser. Silanization process was carried out on micro and nanostructures to make surface superhydrophobic. These testing were done on glass samples which have high optical transparency. Thus concerning application like Microfluidic, bio fluidics and optics use materials with high optical transparency and wettability[50]. Koji sugioka discussed the fabrication of 3D glass Microfluidic chip using femtosecond laser. Here femtosecond laser is used for fabricating Microfluidic, electrofluidic, optofluidic devices. The hybrid femtosecond laser is used by combining FLAE with two-photon femtosecond laser polymerization to invent new biochip[51] and it is shown in Fig.12. H.Y.Zeng et.al discuss the fabrication of microchannel for bubble switch on a polycarbonate substrate using femtosecond laser micromachining[52]. Very few researchers have explored the studies on plastic material using femtosecond laser ablation. The major drawback is the controllability in the fabrication of plastic materials. Using the conventional laser ablation techniques, the depth profile of micro-holes cannot be precisely fabricated. Caizhi Liao discusses the rapid fabrication of micro-holes on plastic materials using femtosecond laser. This method provides arbitrarily shaped structures on plastic with single pulsed laser ablation. Fig.13 shows the formation of a cylindrical hole by varying the parameters like laser fluence(energy) and scanning speed[53]. Moez Haque and Peter R.Herman discuss the design and development of an array of micro-optical resonator used for refractive index sensing application. These optical resonators explore with benefits of having open dielectric stack which is not present in the existing resonators. The resonator is fabricated precisely on fused silica using femtosecond laser along with selective chemical etching which is shown in Fig.14[54]. Kitty Kumar and et.al, discuss the interaction of laser inside the transparent material for the formation of the nanofluidic channel. Channels are fabricated using short pulse non-linear interaction and optical focussing and can be carried for science and technology applications[55]. Alexandros Mouskeftaras and Yves Bellouard discuss the micromachining of channels inside the fused silica using laser assist wet etching. Their results discuss the speeding-up of the etching rate by using polarization perpendicular to the writing direction of the beam. The energy of the pulse is divided into two polarized pulses by 100fs delay to improve the efficiency of the etching rate when compared to a single pulse[56]. Saood Ibni Nazir and Yves Bellouard designed and fabricated a tunable gimbal mirror using femtosecond laser micromachining direct-write method. The mirror is designed using CAD software and the equivalent kinematics is shown and explained in Fig.15[57]. Petra Paie et.al discussed the integration of optical and Microfluidic components to form a multifunctional lab-on-chip device from literature. The fluidic components are fabricated using femtosecond laser. The microscope is used for the detection, counting and imaging of cells. They believed that a simple, portable microscopic lab-on-chip can be developed once the microscope is integrated on-chip which consumes low power also combining various components for the detection of cells[58]. Developing and integrating multifunctional lab-on-chips devices may provide an effective platform for real-time testing.

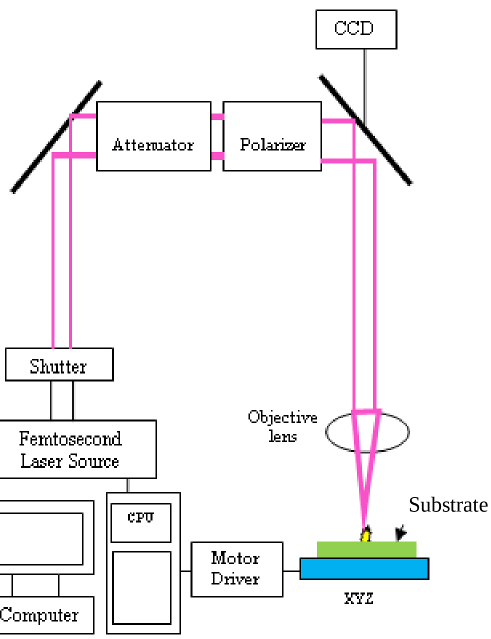


Fig. 11. Schematic diagram of Femtosecond Laser micromachining process (color online)

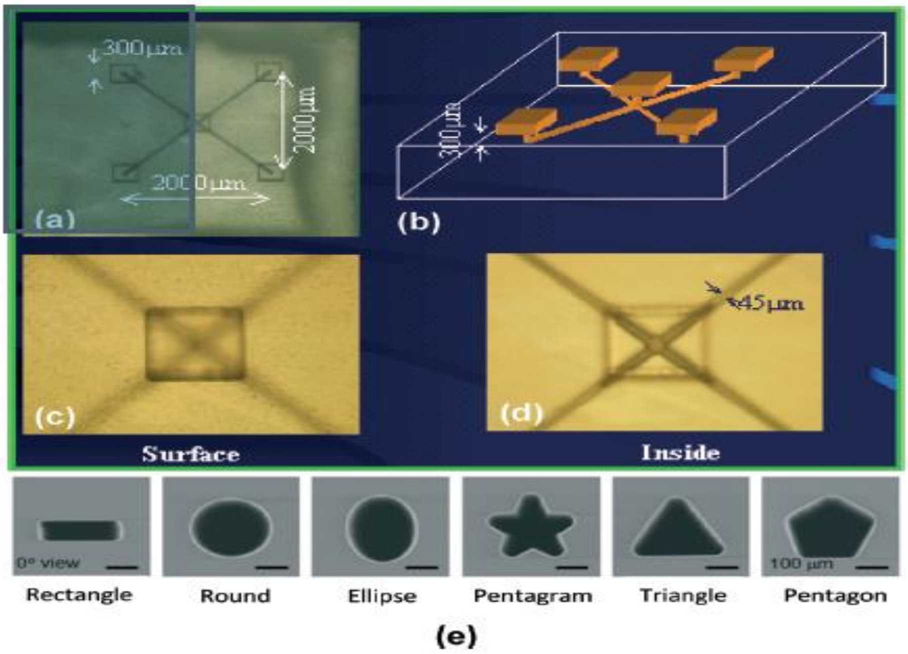


Fig. 12. Fabrication of Microfluidic X shape channel on 300µm glass substrate (a) overall dimension of the microchannel design (b) schematic diagram of the design to be fabricated (c)the base substrate (d) fabricated microchannel on the substrate (e) SEM images of various shaped microchannel formation (color online)

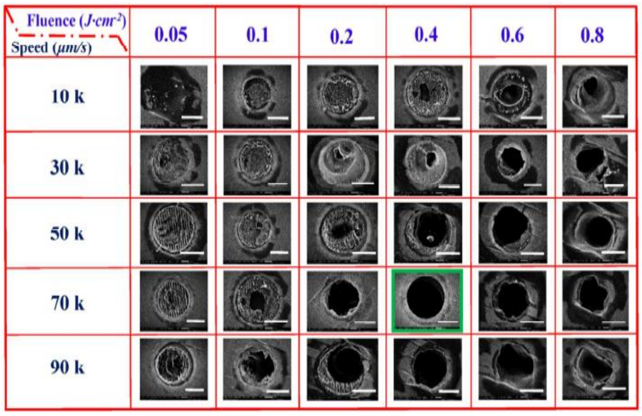


Fig. 13. Fabrication of the cylindrical hole using femtosecond laser by varying the laser fluence and scanning speed (color online)

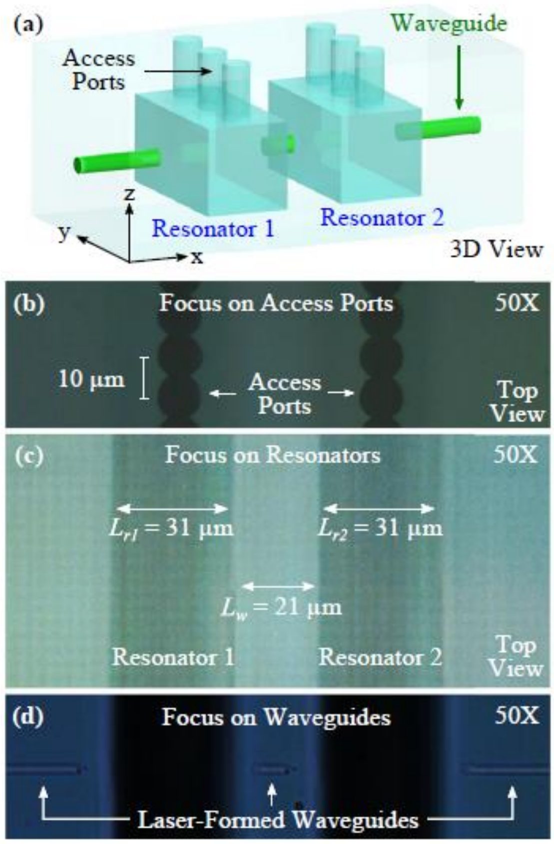


Fig. 14. (a) 3D view of resonator array with waveguide and access point (b) Access port (c) Side walls of the resonator (d) Waveguides formed using laser (color online)

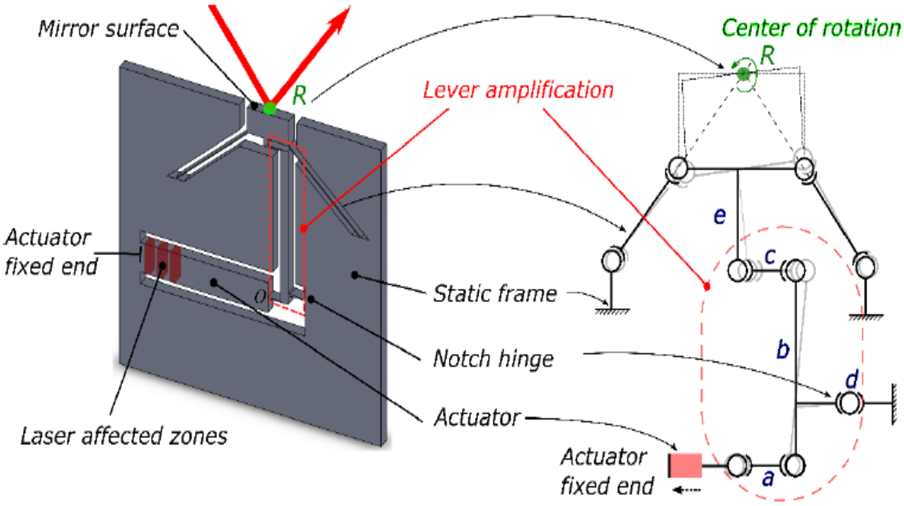


Fig. 15. Design and Mirror kinematics of tunable gimbal mirror. The actuator is coupled to a (a) lever arm through a thin beam. At the top, the second thin beam (b) pulls the mirror to (c) induce rotation. A circular notch is used for the execution of lever mechanism. During the exposure of the actuator, the total displacement is towards left and rotation of mirror occurs. Gray shade in the kinematics shows the deformation of mirror (color online)

In the recent development, an array of micropores is created on a cyclic olefin polymer substrate using femtosecond laser which was discussed by indhu et.al. A diameter of 12µm is achieved with 1µm depth with the laser fluence varying from 1-12J/cm^2. The developed device is subjected to cell viability to check the bio compactable nature and can be used for isolating tumor cells. The developed device with varying fluence level and optimized design is shown in Fig.16(a-b)[59]. Later, they also worked on silicon(100) material by developing an array of microholes for cancel cell separation application. Multiple pulses are given and analyzed to obtain an optimized diameter and depth. The developed device can be carried out for real-time analysis for which a 3D printing module is used as an outer case. The 3D printed module was developed using flexible polyurethane material. The developed device is placed inside the developed case and top and bottom layers are closed in order to avoid leakage. The developed silicon device with diameter and depth is shown in Fig.17(a-c). Fig.18 explains the 3D printing module used for real-time testing. Fig.19 explains about the complete setup carrying out real-time testing[60]

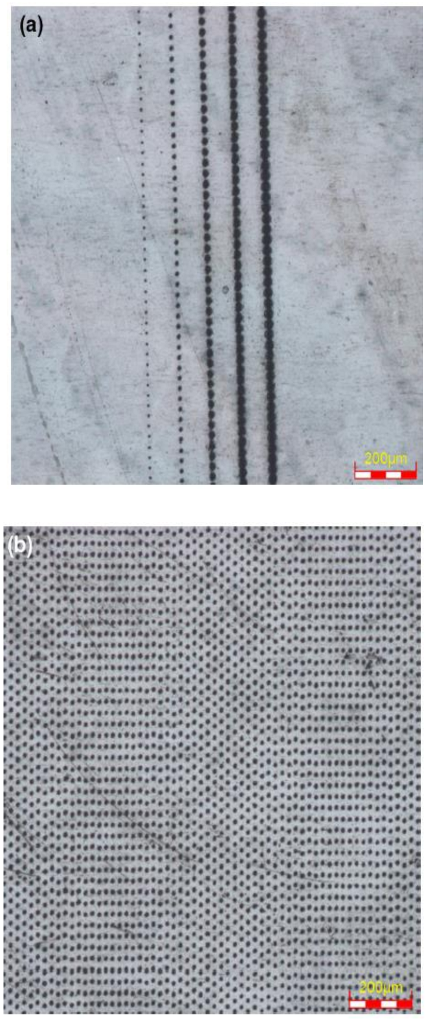
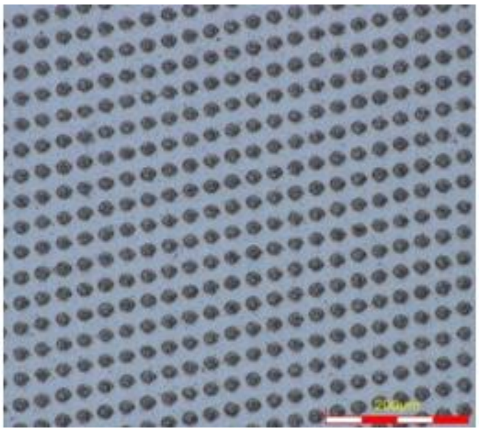
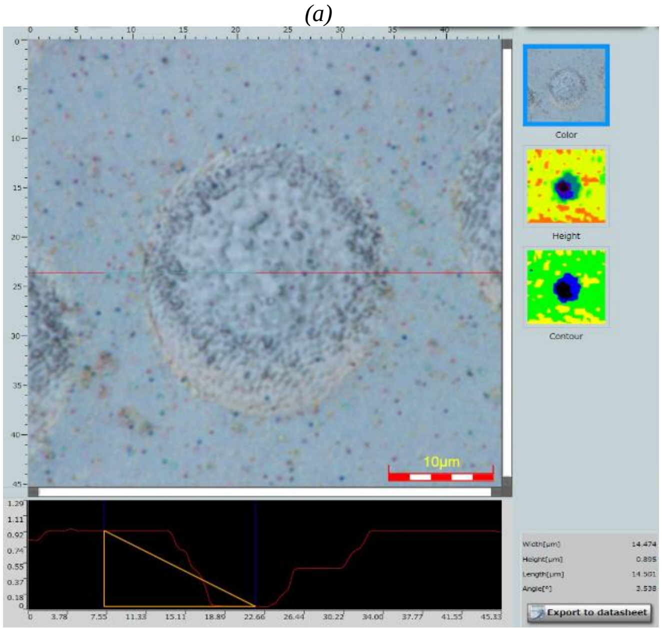


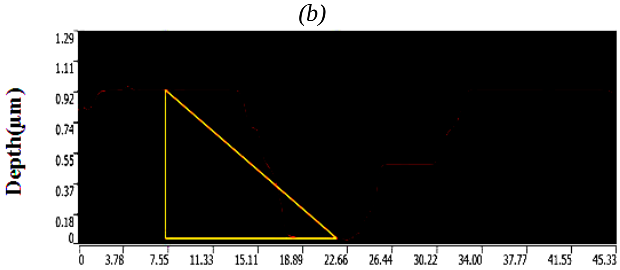
Fig. 16. Optical Microscopic image of micropores a) varying the fluence level b) optimized micropore device (color online)



(a)



(b)



(c)

Fig. 17. Optical microscopic image of silicon microholes (a) array of microholes (b) diameter of microhole (c) depth of microhole (color online)

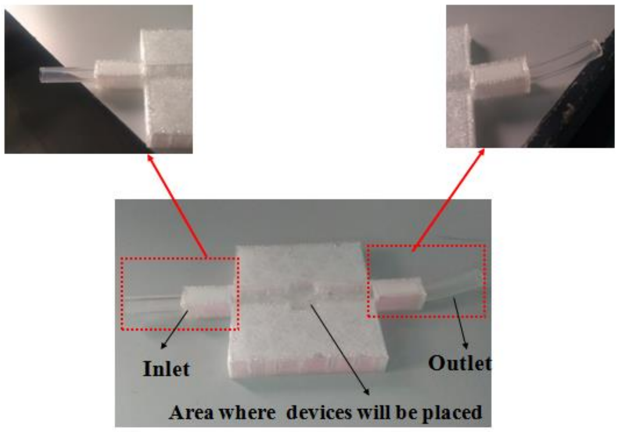


Fig. 18. 3D printing case to hold the device for real time testing (color online)

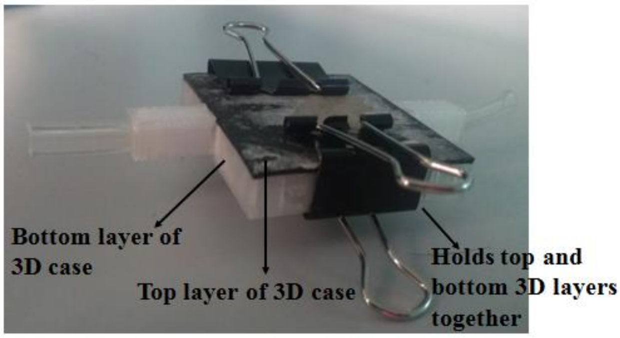


Fig. 19. Complete setup for real time testing (color online)

3. Conclusions

As discussed above, the development of Microfluidic device has become easy using laser micromachining as direct-write method. Also, different types of laser methods used for various applications were discussed. Different materials were used based on the type of application. From the above review, the use of laser micromachining helps in direct-write method providing rapid prototyping, less power consumption and less time compared to the conventional method of fabrication of Microfluidic devices.

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*Corresponding author: indhur@ssn.edu.in