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Full Length Article

Laser-induced forward transfer: Propelling liquids with light

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ABSTRACT

Laser-induced forward transfer (LIFT) constitutes an interesting alternative to conventional printing techniques in microfabrication applications. Originally developed to print inorganic materials from solid films, it was later proved that LIFT was feasible for printing liquids as well, which substantially broadened the range of printable materials. Any material which can be suspended or dissolved in an ink can be in principle printed through LIFT.

The principle of operation of LIFT relies on the localized absorption of a focused laser pulse in a thin film of the ink containing the material to print (donor). This results in the generation of a cavitation bubble which expansion displaces a fraction of the liquid around it, leading to the formation of a jet which propagates away the donor and towards the receiving substrate, placed at a short distance from the liquid free surface. The contact of the jet with this receiving substrate results in the deposition of a sessile droplet. Thus, each droplet results from a single laser pulse, and the generation of micropatterns is achieved through the printing of successive droplets. A similar ejection and deposition process is produced by generating a cavitation bubble below the surface of a liquid contained in a reservoir in the film-free laser printing configuration.

In this work we review our main achievements on the laser printing of inks, paying special attention to the analysis of the liquid transfer dynamics and its correlation with the printing outcomes.

1. Introduction

Engraving and printing symbols or text gave rise to perdurable memory of human history. For many centuries printing techniques were devised for writing and graphic arts purposes with the goal to spread culture and knowledge. By now, the printing of materials has been extended to other industrial areas for marking, labeling and as a new approach for the fabrication of devices, like in the ever growing field of printed electronics, for example. This extension required the invention of new methods to transfer materials and the design of new inks adapted to these methods. Traditional techniques such as screen-printing, photolithography or stamp based methods require the use of masks or moulds. However, these traditional methods, with good performance in mass production, lack the flexibility required for rapid-prototyping and for the manufacture of customized products on demand, and are not well suited to satisfy the needs of rapidly changing markets. On the contrary, direct-write techniques, being maskless and allowing printing sequentially, make possible the fast transfer from design to production, which makes them perfectly suited for digital manufacturing. Hence, inkjet, dip-pen, or laser-based printing techniques can easily transfer patterns that can be different in every printing process, and therefore facilitate the transition from the digital file to the end product [1].

Many direct-write techniques rely on the transfer of droplets with resolutions in the micrometers range in order to create patterns of metals, semiconductors, polymers, and even biological materials such as DNA, protein or cells [1]. Thus, these techniques can be applied in a quite straightforward way to the production of electronic devices, sensors, biomedical devices, and even for tissue engineering in regenerative medicine applications. Among the direct-write techniques inkjet printing is probably the best-known. It is based on thermoelectric or piezoelectric actuators that promote the expulsion of a tiny amount of liquid through a nozzle [2–4] whose dimensions limit the minimum size of the droplets that can be dispensed and the maximum size of the suspended particles permissible in the ink. Hence, the decrease of the droplet size requires smaller nozzles which are in turn more prone to clogging. Dip-pen microspotting is also a well-established technique based on the actuation of capillary forces to transfer inks from a sharp tip onto a substrate, being mostly used for the printing of biological materials and the production of microarrays. With its resolution

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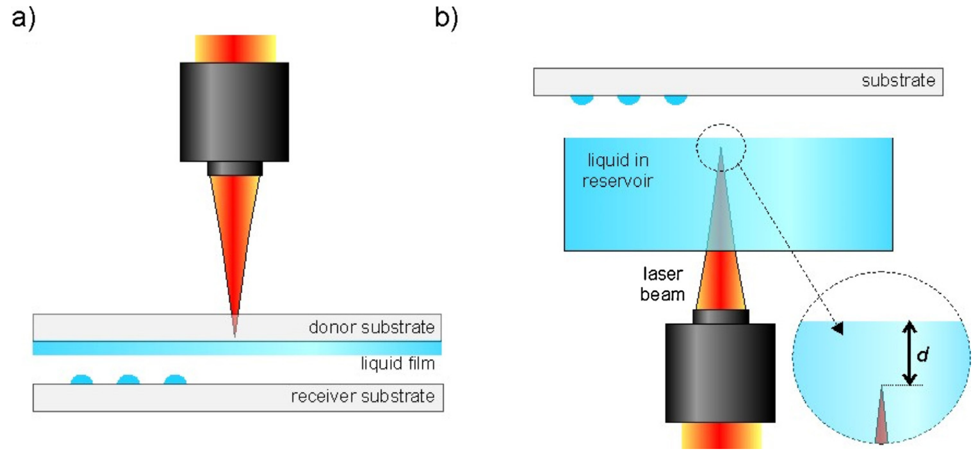

Fig. 1. Principle of operation of a) the LIFT technique and b) the film-free laser printing technique. *d* in the insert is the distance below the free surface where the focal point is located.

determined by the tip size, sub-micron resolutions can be reached through especially adapted AFM-tips, but at highly punishing processing speeds [5].

More recently, laser-induced forward transfer (LIFT) was suggested as an interesting alternative for the printing of materials from liquid suspensions or pastes [6]. The principle of operation is the same as the one for the LIFT from solid donor films [7,8], a process that was first described in the late sixties [9,10]. The material is transferred from a donor thin film previously deposited on a substrate which is transparent to the laser radiation. The action of a laser pulse focused through the donor substrate in the interface between this substrate and the thin donor film promotes the ejection of material towards the receiver substrate. One of the main advantages of LIFT is that it does not require a nozzle, avoiding the characteristic clogging problems of inkjet printing. Additionally, it is not too restrictive with the rheological properties and viscosities of the inks that can be printed, thus enlarging the list of printable materials and simplifying the formulation of new specific inks. When the ink is transparent to the laser radiation printing can also be carried out from the liquid directly contained in a reservoir through the use of ultrashort laser pulses, hence skipping the step of producing the donor film [11]. This technique, based in the same principle as LIFT, is known as film-free laser printing [12].

In this brief review we present an overview of the different laser printing techniques outlined above, with special emphasis on the mechanisms which make possible to use laser light to propel liquids with the aim of depositing inks for the fabrication of miniaturized devices.

2. Experimental setup

A sketch of the principle of operation of LIFT is presented in Fig. 1a. The most common is to use a laser source delivering short (ns) or ultrashort (ps or fs) pulses, with its wavelength in accordance with the donor substrate and ink properties. In general, glass is used as donor substrate with near-infrared and visible laser wavelengths, while quartz or fused silica substrates are typically used for UV wavelengths. However, other materials are possible as well (like flexible organic substrates in roll-to-roll production), as long as they are transparent to the laser radiation. On the contrary, the ink must absorb the laser radiation to be transferred. However, this requirement can be skipped by using an absorbing layer between the donor substrate and the liquid [13,14]. This layer is usually a metallic thin film of some tens of nanometers or a thicker polymeric layer (up to a few microns), that in some cases decomposes during transfer. Typically, few microjoules per pulse are needed for printing micron-sized droplets of water-based solutions with metallic absorbing layers or common inkjet printing conductive inks [13,15–21]. However, the pulse energies required for printing depend in general on the size of the laser beam on the donor film, the specific properties of the donor system and the characteristics of the droplets that have to be printed. The laser repetition rate, in turn, is related with the speed at which the printing process is performed.

The laser beam in a laser printing setup is usually guided through mirrors and beam-splitters up to a converging lens that focuses the radiation onto the interface between the donor substrate and the ink or at the absorbing layer, if present. The donor system consists of a solid substrate transparent to the laser radiation and the liquid layer of ink that has been spread on its surface, with a thickness commonly ranging from a few microns up to around 100 μm. If required, the absorbing layer must be previously deposited. The receiving substrate is placed in front and parallel to the donor liquid surface, and the gap between them is not usually a restrictive parameter: it can range from a few tens of micrometers up to few millimeters, depending on the operating conditions, a degree of tolerance which constitutes a real advantage in terms of further industrial implementation.

A motion stage system able to translate the donor/receiving substrates with respect to the laser beam is needed to generate patterns. Alternatively, the laser beam can be scanned along the donor layer by means of galvanometric mirrors or other beam deflection devices. The patterns are generated by sequentially printing droplets, in a very similar way to most digital printing techniques. The printing process can be usually performed at ambient conditions (vacuum is not a requirement), though if necessary for the production of extremely delicate devices it is also compatible with clean-room facilities.

In the case of film-free laser printing the deposition setup is not essentially different from that of LIFT, except that the ink is contained in a reservoir and it must be transparent to the laser radiation (Fig. 1b). Additionally, ultrashort laser pulses (fs or ps) are required in order to promote absorption of the laser pulse energy in the liquid through non-linear mechanisms [22]. With the focal point conveniently located a few microns below the free surface of the liquid transfer is possible and it leads to an identical outcome to that of LIFT [23,24].

3. Mechanisms of liquid ejection and deposition

Time-resolved imaging studies of the printing process helped to understand the underlying mechanisms of LIFT [25–34]. The pro-