Droplet Ejection and Liquid Jetting by Visible Laser Irradiation in Pyro-Photovoltaic Fe-Doped LiNbO₃ Platforms

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Controlling liquid dispensing and jetting from a reservoir drop or a liquid film require strong electric fields. One efficient method proposed some years ago is based on the high pyroelectric-electrohydrodynamic (EHD) effect presented by lithium niobate when it undergoes a high temperature change. Additionally, first experiments generating droplets using the photovoltaic effect of Fe-doped lithium niobate crystal (LiNbO₃:Fe) have been recently reported. Here, it is shown how the excitation of the photovoltaic and pyroelectric effects of LiNbO₃:Fe by visible light irradiation allows droplet dispensing and jetting. A basic characterization of the process, including the important role of the excitation light intensity, is reported. The experimental investigation demonstrates that efficient droplet ejection and liquid jetting can be easily achieved in different optical configurations and with various liquid solutions (water, alcohol, aqueous suspension of particles or polymers). This new explored method is analyzed by discussing some of its intrinsic and attractive advantages, namely the flexible and versatile control offered by light excitation and the activation of the photovoltaic and pyroelectric effects. The results let us to foresee that this strategy will have very good chances to become a viable inkjet printing method for addressing new challenges in directed liquid dispensing and patterning.

1. Introduction

The development of innovative strategies for liquid dispensing and droplet motion control represents a key enabling technology for the construction of miniaturized and low-cost microfluidic devices very common in our daily life. In the last decade, the interest in investigating and controlling liquids raised continuously, opening toward powerful potential applications both for the industrial and for the academic point of view. Manipulating buffers and organic solvents on surfaces is fundamental for many biological, medical, and/or chemical operations.[1–9] Point of care applications for a prompt on-site diagnosis and treatment, clinical diagnostics, cell-based applications, and detection or sensing are few examples of case of use.[10] A lot of effort has been focused on miniaturization and automatization, also because they could be considered as possible routes for telemedicine application, increasing efficiency and reducing the total amount of the materials involved. In case of diagnostic tests, for example, the reduction in terms of biological material and chemical reagents involved in a microfluidic chip could contrast the cost of chemicals, increasing the number of total processing tests, speeding up the time, and, in case of automation, could also reduce the risk of cross-contamination and the one of maintenance.

Different solutions based on smart surface have been proposed for controlling droplet motion and opening to two-phase oil–water separation, biotechnology, self-cleaning, and anticing application, just to cite few.[11–14] On planar surfaces, the motion of droplets can be controlled using diverse developed approaches such as surface acoustic wave, magnetic-controlled surfaces, thermocapillary forces, dielectrophoresis, and electrowetting-on-dielectric chips.[15–21] In the latter case the pixelated size of the electrodes limits the minimum droplet size that can be manipulated, to overcome this issue light-patterned electrowetting has been proposed for droplet manipulation on an open, featureless, and photoconductive surface.[22] Alternative ways to create surface gradients for liquid manipulation include the alteration of the surface charge density and texture in response to an external stimulus (e.g., magnetic/electric field) and the enrichment of the surface with chemical functional groups controlling surface wettability dynamically.[23,24] Overcoming the need to create a topographical pattern both on flat, flexible, or vertical substrates,[25,26] that challenge.

In this context, platforms based on ferroelectric crystals have been proposed as a useful innovative tool for liquid manipulation. Consolidated advances in 3D droplets manipulation have been achieved in case of liquid and polymer solution based on the activation of temperature gradient on pyro-electric
materials. Droplets can be moved in two dimensions along designed paths, dispensed onto functionalized target, and printed with high resolution for 2D and 3D applications. Another interesting alternative based in undoped lithium niobate reports 2D droplet manipulation by photo-activated pyro-electric fields in the near infrared. On the other hand, several works report droplet manipulation by the so called photovoltaic optoelectronic tweezers. Among them, reference introduces a very efficient and versatile approach particularly suitable for water and aqueous droplets containing biological materials. The technique uses the light-induced electric fields (bulk photovoltaic effect) generated mainly in Fe-doped lithium niobate crystals. It enables efficient demand aqueous droplet migration, trapping, merging, and splitting. The droplets are separated and not in contact with the substrate avoiding electrowetting, trapping, and immobilization on it. In addition to the manipulation techniques, the implementation of digital microfluidic devices requires efficient and flexible droplet dispensing. For this purpose, electrical methods are also a very convenient option, specially, if they do not require electrodes. Particularly, the electrohydrodynamic method based in the photovoltaic effect, proposed by some of the authors, has been rapidly developed, optimized, and applied in different fields for a multipurpose platform guided by physical intelligence for handling liquid unit volumes. Another interesting approach, that takes advantage of the photovoltaic effect of Fe-doped lithium niobate, has been recently reported. This latter reference reports light-induced generation of pico- and femto-droplets of water and aqueous bio-solutions. However, the electric fields reached are lower than in the previous case and the experimental configuration should be still optimized in order to be more useful for functional applications.

A possible alternative that will be addressed in this work is combining the photovoltaic (PV) and pyro-electric (PY) effect in the same ferroelectric platform. Recently, some works have explored this combination for droplet manipulation or particle trapping. In the two first references, the PV effect is generated by light, independently from the PY effect that is excited by direct thermal heating or cooling. In turn, in the PY effect is unintentionally excited by a focused laser beam.

In this work, we propose a new strategy taking advantage of the flexibility of light excitation and the combination of the photovoltaic and pyroelectric effects. To this end, we have chosen a crystal presenting simultaneously a high PV and photoinduced PY effect, namely lithium niobate highly doped with iron. This crystal allows very efficient, simple, and flexible activation of droplet generation and liquid jetting in 3D only by visible light avoiding the direct heating of the reservoir drop. Indeed, in the present configuration the reservoir drop is placed on a glass surface not in contact with LN. We describe and characterize the liquid jetting behavior of micro reservoir drops using the far fields generated by Fe-doped LiNbO$_3$ substrate situated at a certain distance from the reservoir drop. The proposed strategy provides high resolution for the electric field distribution and high flexibility because the liquid manipulation is in air and not in oil as already demonstrated in a previous paper. The contact-free manipulation has been tested in case of water and polymer-based solutions simply placed on a commercial slide and without the need of functionalized surfaces. By simply switching on–off the light illumination on the LN substrate, we can start and stop the jetting process without delay. The jetting could be thigh localized in the area of interest by addressing temporary charges and the process is easily reconfigurable. Furthermore, by tuning the power and the direction of the emitted light source we show that we can control the jetting. The experiments described in this paper report an overview of the jetting properties in case of water solution opening to biological and lab on chip microfluidic application, overcoming the problem of cross-contamination and heating. Moreover, we proof the transport of latex microspheres mediated by jetted water drops. Overall, this new approach appears flexible and could be activated with moderate intensity. The multiplexing property for controlling jetting and blasting of two droplets contemporary is here proposed for the first time, giving an evidence of the great advantage of employing light to address the liquid manipulation.

2. Photovoltaic and Pyroelectric Effects in Lithium Niobate

Ferroelectric crystals present several effects able to generate internal electric fields. Among them, the bulk photovoltaic effect and the pyroelectric effect appear particularly relevant/suitable for the implementation of active ferroelectric platforms. The photovoltaic effect of ferroelectrics (also known as bulk photovoltaic effect) is a singular phenomenon discovered in 1974 which notably appears in a few crystalline ferroelectric materials (LiNbO$_3$ clearly standing out) when properly doped (mainly Fe). It allows the generation of remarkably high electric fields (1–3 x 10$^5$ V cm$^{-1}$) for moderate or low light excitation levels ($\approx$mW cm$^{-2}$). The active wavelengths depend on the material and doping. The PV effect is associated with optical transitions from localized states of impurities, such as Fe$^{2+}$/Fe$^{3+}$ or Cu$^+$/Cu$^{2+}$, and with a directional electron migration along the polar axis (photovoltaic current). Once displaced, the electrons are trapped in other defects and generate an electric field spatial distribution. The photovoltaic effect is the working basis of the PV optoelectronic tweezers technique already briefly described. On the other hand, the pyroelectric effect is related to the spontaneous polarization and screening charges existing at the surfaces of the ferroelectric material. After a sudden temperature change $\Delta T$, caused either by heating or cooling, the spontaneous polarization changes its magnitude, giving rise to an uncompensated surface charge density $\sigma_p$ at the crystal polar faces. As a consequence of this surface charge density, a pyroelectric field develops in the surroundings of the ferroelectric crystal. This field can also be used for micro- and nano-manipulation and applied to biomolecules. The main advantage of the PY effect is that it exists in any ferroelectric material without the need of doping. However, the all optical control of the PY effect is easy and versatile, and allows higher resolution due to the flexibility and focusing capabilities of light illumination.

The crystal used in this work, namely LiNbO$_3$:Fe presents both effects. When irradiated with low-light intensity, only the photovoltaic effect is activated. However, for relatively higher light intensities, due to the high absorption of the Fe impurity, the crystal heats up (see Section 4.1.3) and the pyroelectric effect is also excited. Thus, the light-induced electric field generated in the LiNbO$_3$ platform is the result of the interaction of both effects.
3. Experimental Methods and Materials

A schematic of the experimental setup is presented in Figure 1a. The light excitation is provided by a cw frequency doubled Nd:YAG operating at $\lambda = 532$ nm. As active material we are utilized 1 mm thick plates (surface size $\approx 7 \times 9$ mm$^2$), cut from a Z-cut 0.25% mol Fe-doped congruent LiNbO$_3$ wafer (integrated optics grade), purchased from Photonlines Ltd. The absorption spectrum of the LiNbO$_3$:Fe substrate is shown in Figure 1b. It indicates a value of about 27 cm$^{-1}$ for the absorption coefficient at the working wavelength (532 nm). As it is shown in the inset of Figure 1a, the reservoir drop is placed on a glass slide and the LiNbO$_3$:Fe sample is on top at a certain distance. The laser is focused on the bottom crystal surface that in all experiments is the $+c$ face. The Gaussian beam power has been changed along the study of the process. A LED light has been added to the system for bottom illumination and a CMOS camera to observe the process in real time from side point of view.

Reservoir drops of deionized water, silver (Ag) nanowires in alcohol solution (Silver nanowires 60 nm of diameter from Sigma Aldrich 739421), and phosphate-buffered saline solution (PBS) have been used for the jetting experiments. Water solution of latex polystyrene micro-spheres monodisperse (diameters: 1, 2, and 6 $\mu$m) from Sigma Aldrich (Fluka 80177-SML) have been used without further preparation. Poly lactic-co-glycolic acid (PLGA) Resomer RG 504H (38 000 to 54 000 Da; 50:50 lactide: glycolide, Boeringer Ingelheim) was dissolved in Resomer RG 504H (38 000 to 54 000 Da; 50:50 lactide: glycolide, Boeringer Ingelheim) was dissolved in dimethyl carbonate (DMC) (99%; Sigma Aldrich) at 25 wt%. Poly(dimethylsiloxane) (PDMS) solution was obtained by mixing ratio 10:1 base to curing agent. PLGA and PDMS have been used for the test of polymer jetting. Conventional microscope glass slides, cleaned with pure ethanol and dried at room temperature have been used without further functionalization as a base for the reservoir drop.

4. Results

4.1. Characterization of the Light-Induced Liquid Dispensing Process

4.1.1. Real-Time Observation of the Droplet Ejection Process

First, we have investigated the action of the light-induced electric fields on an aqueous drop and the possibility of generating small droplets. To this end, a water drop (reservoir drop) of 0.5 $\mu$L has been deposited on the glass slide (Figure 2a) and the crystal has been illuminated with the laser beam ($I = 170$ W cm$^{-2}$). An appropriate distance $d = 0.7$ mm from the bottom of the LiNbO$_3$ crystal surface to the top of the reservoir drop has been chosen. Larger distances reduce the induced electric field decreasing the droplet generation efficiency. On the
other hand, if \( d \) is too short, the activated reservoir drop could contact the crystal substrate and a stable liquid bridge is generated avoiding droplet ejection (see Figure 2e). During illumination, the drop deforms and for high enough intensities starts to eject tiny droplets. The process is illustrated in Figure 2b–d through the frames extracted from the binarized experimental movies. Each ejection event starts with non-distorted rounded drop (Figure 2b) that progressively deforms before ejecting one droplet (Figure 2c). After dispensing, the droplet recovers the initial shape (Figure 2d). The process repeats many times generating a liquid jetting. The droplets are accumulated on LiNbO₃:Fe, however, for water or aqueous liquids they can evaporate quickly depending on the environmental conditions. The whole process has been monitored and it can be seen in Movie S1, Supporting Information.

4.1.2. Role of Light Intensity

The light intensity plays a key role on the process that we have investigated in detail by several experiments. First, we have paid attention to the drop deformation during illumination. In all the experiments the drop had an initial height \( d_i = 0.3 \) mm before the crystal illumination that rises during droplet deformation to a final height \( d_f \) (see Figure 3a,b). We characterized the deformation by the height difference \( \Delta d = d_f - d_i \). The evolution of \( \Delta d \) with the incident light intensity (i.e., measured at the upper face of the crystal), is represented in Figure 3c. It has a fast initial increase that tends to saturate as the intensity grows. This behavior indicates that the active electric field that induces this deformation also grows with light intensity.

We have also investigated the influence of light intensity on the droplet generation rate measured through the drop deformation and cone ejection events. The results are presented in Figure 4a where the average number of events of cone jetting per minute \( N \) is plotted as a function of light intensity. The intensity region with no droplet ejection has been marked in red color. In this region (\( I \) lower of about 25 W cm\(^{-2}\)), the light-induced electric field could only produce a slight deformation of the reservoir drop that keeps in time because it could not evolve in the cone formation and consequently it is not large enough to eject droplets. For higher intensities the rate of cone jetting events increases progressively with a roughly linearly trend.

![Figure 3](image)

**Figure 3.** a) Water droplet on the slide with a height \( d_i \) (0.3 mm) before illumination. Dashed white lines represent the boundaries between the different media (air-LiNbO₃:Fe, and air/drop-slide). b) Water droplet under the action of the electric field generated by the LiNbO₃:Fe crystal reaching a height \( d_f \). Dashed black lines represent the boundaries between the different media. c) Deformation \( \Delta d \) as a function of the light intensity. The dashed red line is a fitting to the experimental points.

Obviously, during droplet ejection, the reservoir drop undergoes a volume decrease \( \Delta V_m \). Assuming the ejection of one droplet per ejection event, as it is often observed in the video frames, the average volume of the generated droplets \( V_d \) can be obtained as the ratio between the initial volume \( V_i \) and the number cone ejection events \( N_d \). In this case, \( N_d \) is obtained from the videos monitoring the experiments for 1 min, and \( \Delta V_m \) is calculated measuring the initial volume and final volume of the reservoir drop.

\[
V_d = \frac{\Delta V_m}{N_d}
\]

The dependence of the average volume of ejected droplets with the light intensity is plotted in Figure 4b. After the small intensity region with no generation (\( V_d = 0 \)) in red color, the curve shows a pronounced peak followed by a decreasing trend of \( V_d \) for higher intensities.

All these experiments indicate an important role of the light intensity. However, this role is not easy to understand in terms of the PV effect because the standard one center model (that refers to Fe\(^{2+}\) as photovoltaic center) predicts a constant steady photovoltaic field with no dependence with \( I \). An intensity dependence has been reported for an alternative model that includes a second center, namely the Nb antisite, but only active for high intensities.[49,50] However, for highly doped crystals and temperatures above room temperature, that center should be activated for higher light intensities than those used in this...
work. So, the observed light intensity dependences seem not to be directly related with the PV effect.

4.1.3. Light-Induced Thermal Heating and Activation of the Pyroelectric Effect

The moderate-large intensities used to illuminate the highly absorptive Fe-doped crystal could heat it up. This heating would contribute to generate electric fields by the PY effect and so, it could affect the droplet ejection process. Then, to complete the characterization of the method we have measured the crystal temperature increase as a function of the light intensity during droplet illumination (Figure 5). The temperature has been measured by an infrared camera and the values plotted correspond to the center of the light spot in the illuminated crystal surface. A linear light intensity dependence is observed with a slope of 0.1 °C per W cm$^{-2}$, reaching a temperature increase of $\Delta T \approx 25$ °C for the highest intensity $I = 250$ W cm$^{-2}$.

In addition, the photovoltaic effect is activated for any light intensity. In a recent paper on the synergies between PY and PV effects in LiNbO$_3$:Fe, it is reported that for very similar doping and absorption coefficient of those of our crystal, and for PV and PY effects acting independently, the PY field equals the PV field for $\Delta T \approx 20$ °C. According to this reference and for those conditions, one can estimate the PY field, proportional to $\Delta T$, as $E_{PY} = (\Delta T/20)E_{PV}$. Hence, in this LiNbO$_3$:Fe crystal, the PY field could reach values about a 10% of the PV field for the lowest intensity with droplet ejection ($I = 25$ W cm$^{-2}$, $\Delta T = 2.5$ °C), whereas it should be larger, about 100%, (at least transiently), for the highest intensity ($I = 250$ W cm$^{-2}$, $\Delta T = 25$ °C).

In other words, in the intensity range analyzed both components should interact and contribute to the active electric field. Moreover, the pyroelectric component presents a pronounced dependence with light intensity that is probably the origin of the intensity dependence. A detailed model for the interaction of the PY and PV effects will be addressed in the near future.

4.2. Potential of the Pyro-Photovoltaic Fe-Doped LiNbO$_3$ Platforms

To illustrate the flexible and versatile capabilities of the technique we show in this section a variety of applications and optical configurations.

4.2.1. Contact-Free Dispensing of Water/Alcohol-Based Solution of Particles

The reservoir drop can contain different micro/nanomaterials (micro- and nanoparticles, bio-objects, analytes just to cite few) what allows dispensing them by the jetting process. The analysis of the experimental movies acquired during the experiments shows that in some case, the jetting rate is faster than the frame rate of the camera used for the acquisition of the movie so that is not possible to detect the droplets ejection, even if at the end of the blasting process the material is dispensed on the target.
Hence, in this section we have characterized the jetting process through the material accumulated on the crystal surface. The jetting process has been made in a static condition, meaning that the ejected droplets have been accumulated one over the other in a fixed position. We also fixed the distance between the plate supporting the reservoir drop and the upper active crystal. The experimental conditions used in this subsection are a laser power of 150 mW with light intensity of about 75 W cm$^{-2}$, a starting volume of the reservoir of 0.5 $\mu$L and, a 20$\times$ objective to collimate the irradiating light. The laser is focused on the reservoir drop. For the first experiment, we selected the dispersion of latex spheres in water (diameter 2 $\mu$m) as a model solution and used it for the characterization of the liquid jetting process as described in the following. In the frames reported in Figure 6 it appears clear that the overwriting of the emitted droplets leaves a footprint that increase its diameter with time and, at the end, could be visible at the microscope (Movie S2, Supporting Information).

Future exploitation of the jetting process activated by visible laser irradiation will be conducted using a fast rate camera and a movable target, in order to detect the dispensing array, the corresponding single spots and the minimum size of features obtainable. In fact, the resolution of the liquid jetting activated by visible laser irradiation in pyro-photovoltaic platforms actually is in the range between 10 and 500 $\mu$m. Such results are comparable with the conventional pyro-EHD printing in static configuration, (i.e., when the distance and the volume of the reservoir drop remains fixed) in term of minimum size that could be obtained by conventional ink-jet printing. When one switches to a flexible configuration, that is, by tuning the working distance and the starting volume of the reservoir drop, the minimum size of the dispensed droplet could be reduced to hundreds of nanometers. We have investigated the jetting process for a variety of particles suspended in different liquids, namely, water-based solution of latex microspheres of different diameters and, alcohol-based suspension of Ag nanowires. We also tested the PBS solution usually used for cell culturing. In Figure 7 the material accumulation resulting from these jetting experiments is shown. Figure 7a–c corresponds to latex microspheres with diameters of 1.2 and 6 $\mu$m, respectively. Figure 7d displays the salts after evaporation of the liquid jetting from a reservoir drop containing cell culture medium. Finally, in Figure 7e we can see Ag nanowires left on the substrate after alcohol evaporation. For all the cases the material accumulated on the supporting target has a radial symmetry and the final amount of material dispensed is a function of the light intensity and the ejection time selected for the experiment. During the jetting the target remains in a fixed position and, as a consequence, the ejected droplets are accumulated one over the other. In this modality the materials is ejected even at same place thus causing the non-uniformity of the circular edge of the dispensed spot. Additional experiments of dispensing water solution, with latex microsphere having a diameter of 2 $\mu$m, were performed in the static configuration by keeping fixed the time of dispensing and the volume of the starting droplet while the light intensity was changed. In particular, the laser power was tuned from 150 to 240 mW with a step of 30 mW for activating the process. In general, by

Figure 6. Experimental frames of dispensing latex microspheres in water solution. a) The crystal appears clean before the jetting starts. b–d) Once activated the electric field the droplet deformed in a conical shape and few latex microspheres are accumulated in the central zone, corresponding to the apex of the jetting cone. During the jetting, the footprint leaved from the microsphere becomes more visible and bigger. The accumulation expands in time over the area till the jetting is on. Scale bar 50 $\mu$m.
increasing the power it is possible to increase the number of jets and the total amount of material delivered for unit time. Moreover, at higher power, some situations of instability could occur and an extended characterization in a dynamic configuration will furnish additional informations.

4.2.2. Manipulation of Polymeric Solutions

Dispensing of polymeric solutions is very useful for a variety of applications. Hence, we have checked the ability of our pyro-photovoltaic dispensing platform to polymeric liquid jetting generation. We selected two different materials for the polymer blasting experiment: PDMS and PLGA. PDMS is a commercial resin usually used by direct writing for micro-fluidic chips and optical components that could be cured with temperature, made of a base and a crosslinker. PLGA is a biopolymer biocompatible and biodegradable approved by the Food and Drug Administration for biomedical devices, that could solidify after the evaporation of the solvent selected for the solution. The results for the two solutions are shown in Figure 8. The deformation of the polymeric solution is similar to the pyro-EHD. The reservoir drop starts to deform and elongate under the light irradiation, and the elongated cone reaches the upper plate creating an unstable liquid bridge. We can observe a continuous flow of material from the bottom to the top and vice versa. Analogously with the manipulation driven by the pyro-EHD effect we could select the polymeric shape that we want to fix and cure it. The green color visible in the images is the light reflection through the polymeric structures.

4.2.3. Jetting Multiplexing

Multiplexing of jetting is important as the printed process can be speed-up. Here we demonstrate that by the proposed approach the spatial multiplexing for having multiple liquid jets through a single laser irradiation shot can be activated. The technique allows flexible configurations for laser illumination getting different dispensing schemes. For instance, jetting multiplexing in the platform can be achieved by illuminating through a diffraction grating. In the following experiments, a diffractive grating (Newport 80 lines/mm) has been used for creating multiple laser spots. The laser spots have been adopted for the simultaneous activation of multiple drops (or films in case of controlling the working distance), as shown in Figure 9. Such configuration makes possible to multiplexing spatially the dispensing process by using a single laser beam and a single lens. Laser light passes across the grating, the zero order and the first two orders diffracted by the grating are injected into a microscope objective (5× magnification). In Figure 9a the scheme of the adopted configuration is depicted. The two reservoir water drops containing latex microspheres, that can be seen at the bottom part of Figure 9b, were at a distance of 500 µm in correspondence of the focalization spots of the zero order and one of the two diffracted beams. The dispensed material can be seen in the upper part of this Figure 9b and in Figure 9c,d (magnification of one of the dispensed spots).

5. Conclusions and Future Perspectives

In summary, droplet dispensing activated and controlled by visible light illumination of highly Fe doped lithium niobate crystals has been proposed and demonstrated. The method is based on the photovoltaic and pyroelectric effects presented by these ferroelectric crystals. The key role of light intensity that activates the pyroelectric and photovoltaic effects has been experimentally characterized. This technique shows relevant advantages, with regard to purely pyroelectric or photovoltaic methods,
especially in case of processing water-based solutions and could open new routes for single cells patterning and other biological applications. A temperature change is needed in both cases (PY and PY + PV), however, in the second case only a few degrees are necessary, increasing the working time usually very short due to water evaporation. Moreover, this moderate temperature change can avoid possible crystal breaking and should not damage biomaterials contained inside the droplets. Moreover,

![Figure 8](image-url)  
**Figure 8.** Photographs of the dispensing process of two polymeric liquids a–c) PDMS: a) reservoir drop starts to elongate when the laser beam is turned on, b) the reservoir drop deforms and contacts the lithium niobate crystal, and c) an unstable bridge structure is formed; and d–f) PLGA: d) laser beam is turned on, e) light induces a conical deformation approaching the crystal, and f) the polymeric liquid contacts the crystal establishing a jetting cone.

![Figure 9](image-url)  
**Figure 9.** a) Outline of the set-up used for the activation of the jetting of multiple aqueous droplets of latex microspheres placed under the beams coming from the grating. b) Two reservoir drops are partially seen during the jetting. c) The accumulation of latex spheres on the crystal was observed through an optical microscope. d) Magnified view of the dispensed microspheres. Scale bars 100 micron.
the platform we proposed here keeps the unique advantage of the pyro-EHD effects and avoids the use of external electrodes, power supply, and micro-nano engineered nozzle, giving the possibility of extending the use of the same device to different inks from low to high viscous solutions. The main advantage in respect to pyro-EHD is that a visible light is used for excitation of the pyroelectric stimulus instead of the mid-IR laser source (i.e., CO2 laser emitting at wavelength of 10 mm). This has a key advantage as visible laser light is much more flexible and simple to use and integrate on such kind of platform based on lithium-niobate crystals. In fact, optical elements for visible light are much more simple and low cost and practical to be used. On other hand, for the configuration proposed in this paper droplet ejection do not operate at intensities with negligible sample heating and so, with no PY effect, as discussed in the Section 4.1.3. The capability of the dispensing process has been tested for different kind of materials, starting from water-based solutions to polymeric inks. The multiplexing properties of multiple reservoirs drops, based on the illuminating of the crystal through a diffraction grating, could be a very important task for simplifying the jetting activation in case of a matrix of droplets that could be made of different materials, or even when starting from a liquid or polymeric film. We are confident that droplet ejection and liquid jetting activated by visible laser irradiation could be comparable in term of resolution, or even better, with the pyro-EHD dispensing. Future perspectives will focus on dynamic configuration, introducing a moving collecting target for the detection of the single dispersed spots, tuning the dimension of the smallest droplet that could be dispensed. Moreover, the introduction of a functionalization of the support used for the reservoir drop and coatings for the target could be adopted for a better visualization of the pattern produced. The proposed configuration could be very useful as high sensitive sensor of low abundant biomolecules.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Research data are not shared.

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