Lasersonic® LIFT Process for Large Area Digital Printing

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The currently used digital printing methods e.g. Inkjet or Xerography are very costly on an industrial scale, because they use expensive consumables, specific inks and specially-coated substrates for the printing process. The laser-induced forward transfer of inks from a donor ribbon or roller to substrates allows for the use of inexpensive inks and paper as they are commonly used in today's industrial rotogravure or offset printing. The challenge of this approach is to develop a fast direct laser writing unit which can cover an area of more than 1 m^2/min with a screen resolution of 300 dpi to 600 dpi and which allows for laser spot pointing accuracy of less than 4 µm and for a fine (8 bit) reproduction of each grey tone value of the printed image pixels. Due to the large area and the desired high printing speed, the laser power (mean) needs to be within a range of a few hundred Watts. At 20 to 25 MHz modulation rate of the high power laser beam and at a laser spot scanning speed of 800 to 2116 m/s over a scan field length of 530 mm, we demonstrated reproducible printing of commonly used, water-based environment-friendly and inexpensive inks.

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1. Digital printing methods

The requirements of today's printing markets are changing more and more from uniform high volume mass production to personalized printing or print on demand applications which allow for a very high flexibility of printed content, but can only be performed by digital direct computer to press printing methods.

To be competitive with other mass media as i.e. the internet, especially in the illustration printing industry old production schemes have to be improved regarding the processing of changes of the printed image data set with respect to up-to-dateness or to individual attributes, preferences and interests of the consuming user.

Moreover, functional properties of printed devices like packages with intelligent etiquettes, RFID's or sensors are targeted by digital printing.

According to PIRA International [1], the market share of digital printing applications in the total global printing output will grow from about 10% in 2010 to 18 % in 2016 representing a total revenue of about 160 Billion Dollar.

Currently, the most commonly used digital printing methods are Inkjet and Xerography. In Inkjet, the droplets have to pass through the small apertures of the tiny nozzles of the print head array. This requires special ink pigments which must be smaller than the nozzles' diameter and have typically diameters in the range of 1 µm to 5 µm. This makes the production costs of such inks a lot more expensive than the production of commonly used solvent or water based pigmented inks for rotogravure, flexography or offset printing.

Table 1 shows a comparison of the costs per square meter for printing with different methods. Digital printing, which doesn't require any printing form fabrication, functions with the same prices/m^2 from small to high number of runs. Traditional flexography, rotogravure and offset printing are becoming economical only at high number of runs due to the high costs of the printing form and the low costs of the consumables ink and paper. Functional properties of the printed ink layer, i.e. conductivity which can be achieved better with larger ink particles are difficult to print with Inkjet. Also special features like mother-of-pearl effect or metallic glamour effects require large ink particles with diameters of up to 100 µm.

Table 1 Costs per square meter in €

# runs	gravure	inkjet	Xerography	LIFT
1	1200.00	0.6	1.6	0.3
10^3	1.35	0.6	1.6	0.3
10^4	0.24	0.6	1.6	0.3

Inkjet is not suited for the printing of these materials. Xerography needs fine toner powders and shows similar restrictions as inkjet for such applications. The toner does have a high level of processing in production and is comparatively more expensive. Furthermore, the paper has to be specially coated.

The printformless digital Lasersonic® printing by laser induced forward transfer of ink, as described below, functions with the lowest costs because it allows for the use of inexpensive inks and substrates from rotogravure, flexography or screen printing [2]. The diameter of the pigments, which can be transferred, may be chosen from nanosize to 100 µm.

The Lasersonic® printing technique addresses mainly those parts of the digital printing markets which are not covered by today's digital printing methods and which have also a too small number of runs to be competitively performed by the traditional printform based printing methods.

This includes for example customized short run jobs for decor printing with large ink particles for special effects or functional printing for added value in packaging, as printed RFID, or other applications such as proof printing jobs which require original inks from rotogravure, flexography or screen printing. An interesting market for Lasersonic® is also food packaging which performs the printing of heat resistant inks which have to be stable in the sterilization process. The name Lasersonic® is a registered trademark of Aurentum GmbH, Germany.

2. The Lasersonic® LIFT printing method

Fundamental studies of the LIFT laser induced forward transfer process of liquid films are reported in [3],[4],[5],[6],[7],[8],[9]. Research on diverse other LIFT applications, i.e. in micro manufacturing and bioscience is described in [10] and [11].

The basic schemes how the Lasersonic® LIFT process can be used for industrial large area printing applications are explained separately for the transfer of black, laser absorptive ink in Fig. 1 and for color inks whose pigments are transparent at the laser wavelength of 1070 nm in Fig. 2. In both cases, a cw laser beam is pulse-modulated and gray scale matched by direct power modulation according to the digital prepress data.

In case of absorptive ink (Fig.1) the laser beam passes through a transparent donor substrate (film) and is focused with a spot size $2w_o$ of about 40 µm to 60 µm exactly at the interface between the donor substrate and the absorptive black ink layer. The laser beam energy is absorbed by the black ink and converted into thermal energy. This induces a small vapor bubble with high pressure at this spot. The explosive expansion of the bubble pushes the ink in front of it to move forward to the acceptor substrate. This setup is in essence similar to a lot of other LIFT applications. However, the difference is that for large area printing with a web size of, in our case, 530 mm the laser beam is scanned ultrafast with 800 m/s up to 2116 m/s (depending on the operation mode) across the donor substrate in order to achieve an acceptable area throughput for the application. Currently our maximum area feed rate is 2.6 m^2/min with 300 dpi and 1.3 m^2/min with 600 dpi resolution. Additionally, the substrate is moving with up to 5 m/min in cross-scan direction to perform a roll to roll process. Moreover, the donor film must be continuously moved forward in order to provide a fresh ink layer for each printed spot.

The distance d between the donor and the acceptor substrates must be large enough to avoid mechanical contact between donor and acceptor, especially, when both are feeding, and as small as possible to avoid spreading of the ink during the transfer. Typical values for d in R2R (roll to roll) printing are in the range of 0.5 mm < d < 1 mm.

A full color print requires - apart from black - at least the basic inks cyan, magenta and yellow. Those colors are mostly not absorptive at the laser wavelength of 1070 nm. This means that a different approach for the Lasersonic® printing of transparent colors is required.

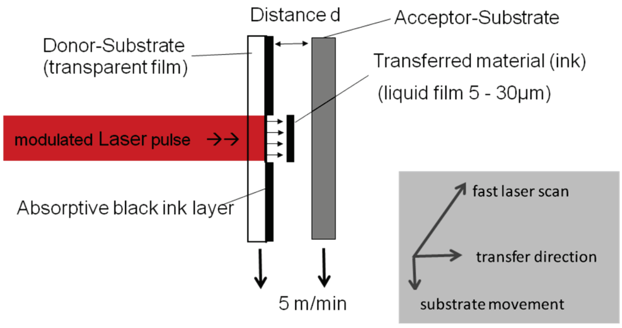


Fig. 1. Scheme of Lasersonic® printing of black (absorptive)ink

The solution is shown in Fig. 2. First, the donor substrate is coated by an additional absorption layer and then, the ink is applied on top. The laser beam propagates through the transparent ink layer and is focused on the surface of the absorption layer. The energy is absorbed on that side of the absorption layer which faces the ink and generates explosively expanding high pressure vapor bubbles at this interface zone. This induces the forward transfer of the ink. The absorption layer is pressed by the bubble against the donor substrate and not transferred, apart from negligible traces. Scanning of the laser beam and the substrate movement is analog to Fig. 1.

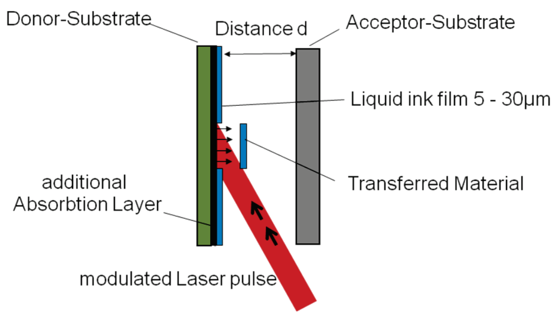


Fig. 2. Lasersonic® LIFT printing of transparent inks

The donor substrate must not be transparent for the printing of non-absorptive inks. Instead of the transparent film an ink roller can be used which is pre-coated with an absorbing layer. Fig. 3 shows a printing unit for continuous R2R printing of color pigmented transparent inks.

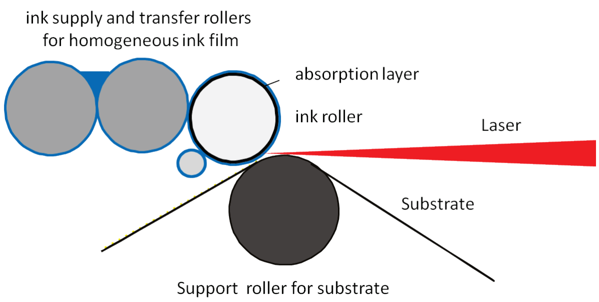


Fig. 3. Printing unit for transparent inks; the ink roller is pre-coated with an absorbing material

The ink roller is coated with ink by a common inking system. The laser beam scans a line on the surface of the ink roller parallel to the roller axis with up to 2 kHz line frequency and the substrate is moving in cross-scan direction similar to the substrate in Fig. 1.

3. The high throughput Lasersonic® printing machine

The key components of the Lasersonic® LIFT printing machine are

- a fast data calculation and transfer rate,
- a high power laser modulation rate of 20 to 25 MHz
- a high speed laser scanning polygon wheel
- a synchronized and aligned feed rate of the paper
- a stable control of the pigment density and of the rheological parameters of the ink, i.e. viscosity.

For printing all those components must be controlled and coordinated.

The optical beam path of the laser scan unit is shown in Fig. 4. A high power cw fiber laser beam with 300 W is modulated by an acousto-optical modulator (AOM). The modulated beam is scanned by a fast rotating polygon mirror and focused by an f-theta lens system onto the scan line at the ink roller surface, respectively at the absorption layer.

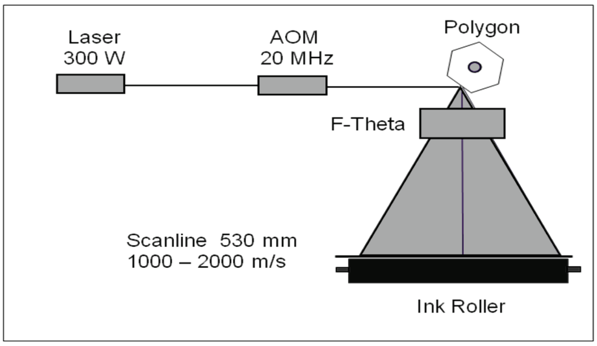
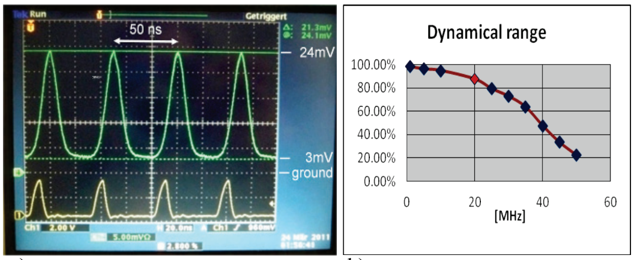


Fig. 4. Optical laser beam path of the printing unit (one-color)

3.1 Ultrafast high power laser modulation

For the above described printing applications a fast writing speed of at least 1 square meter per minute with 600 dpi pixel resolution is desired. For a one-color printing unit this requires 1.2 Gigapixel per minute and a high modulation rate of more than 20 MHz, which is very challenging at this high power regime.

With 300 W cw power from the laser, we achieved an efficiency of more than 56% in the first diffracted order. The dynamical contrast ratio of the AOM is the ratio of the minimum to the maximum power signal of the 1st diffracted order when an on/off modulated input signal is applied. It was measured with a fast photodiode. The dynamical contrast ratio depends strongly on the modulation rate, if - in the high frequency regime - the modulation rate is as fast as the minimum rise- and fall-times of the AOM sound field permit. At 20 MHz the measured contrast ratio has been 1:8 and enables for a dynamical modulation range of 87.5% of the laser peak power. The example in Fig. 5a shows that the photodiode signal of the power in the 1st AOM order can be varied from 12.5% to 100% of the full signal (3 mV to 24 mV) by changing the input signal from 0% to 100%. This power modulation hub of 87.5 % enables for an on/off pulse control of the LIFT process at each single pixel of the printed image. The residual power of 12.5% in the



a) b)

Fig. 5. a) Laser power signal of 1st diffracted order at 20 MHz (AOM input signal is displayed at screen bottom)
b) Frequency response of the dynamical range for on/off

first diffracted order doesn't have any impact on the transfer because the value is below the process threshold of the LIFT process if the laser is scanned as fast as described in section 3.2.

At 25 MHz the contrast ratio drops down to 1:5. This is equivalent to a modulation range of only 80%. Even this is sufficient to modulate the LIFT process. The increased residual power of now 20% is again below the process threshold because the threshold power increases as well due to a shorter time of impact of the laser at higher frequency and higher scan speed. At lower frequencies, i.e. at 5 MHz, the contrast ratio exceeds 1:25 according to a dynamical modulation range of 96% (Fig. 5b) with a residual power of only 4%. Therefore, the process steering by modulation functions over a large frequency range.

If the power level of the first diffracted order is switched just from one value to the next value without intermediate off mode, a doubling of the pixel rate up to 50 MHz is possible.

3.2 Fast scanning of the laser beam

As described in section 3.1 the market accepts only a productive printing speed of at least several m^2/min, even at a screen resolution of 600 dpi. This can be satisfied only with a beam scanning strategy which allows for a scan speed of more than 1000 m/s over the whole scanline.

Therefore, the scanning unit was designed based on a fast spinning polygon wheel and an f-theta lens unit. We achieved a scan speed of more than 2000 m/s over a scan line length of 530 mm and with a pixel to pixel distance of 42 μm (600 dpi) using power level switching modulation.

The duty cycle of a polygon is the percentage of the revolution time which can be used effectively for the scan of the beam. During transit time when the extended diameter of the laser beam crosses one of the edges of the polygon, the laser beam must be interrupted. Normally, the laser energy is wasted during this time. To use nearly continuously the whole power delivered by one laser source we switch the laser beam between two different printing units on opposite sides of a two-color double print unit. This works as follows (see Fig. 6):

The duty cycle of the polygon was chosen closely below 50%. As long as the beam from the right side hits on top of a facet of the rotating polygon, the right printing unit is scanned by this beam. However, just before the beam starts to run over the edge from one facet to the other, the beam path is switched to hit the polygon from its other side (again on a facet) in order to serve the left printing unit.

By this method only one laser source and one polygon are needed to generate two timely alternating scan lines each with a line frequency of up to 2 kHz and a scan length of 530 mm.

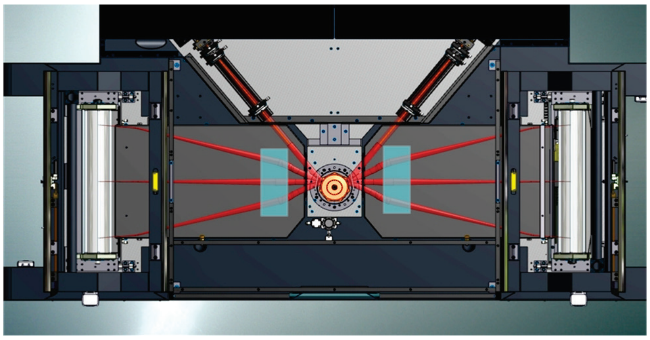


Fig. 6. Two-color double printing unit for transparent inks. The laser beam alternates between left and right scanline.

3.3 The four-color Lasersonic® printing machine

In Fig. 7 the scheme of a four-color machine is shown. The substrate passes the four printing units one after another with intermediate ink drying devices and automated corrections of path tolerances (webguide control). Multicolor printing with several printing units requires a precise synchronization between the time-dependent local position of the fast scanned laser beams on each scan line, the x,y - feed position of the substrate at each printing unit and the exact timing of each AOM signal for the laser modulation based on the data flow.

For this purpose, at each double print unit the angular position of the fast rotating polygon - which represents the laser spot position - is detected by a rotary encoder. The clock signal of the encoder is used as a master trigger. Steering signals which are synchronized to this master regulate the feed forward of the substrate and control the image data output processing for the laser power modulation with the AOM. The laser beam position, the transversal and longitudinal control of the correct substrate movement and the start position of the scan line are essential „to be matched“- parameters. Multiple control systems and more than 50 motor-driven axis are used for this. Moreover, the mixture and viscosity of the ink can be actively adjusted to optimize the conditions for the LIFT process.

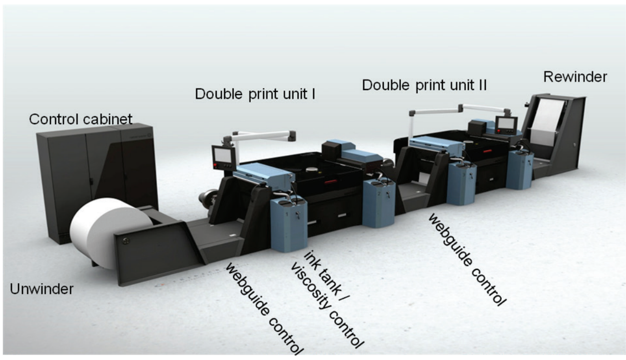


Fig. 7. Four color Lasersonic® printing machine with unwinder and rewinder unit of the substrate, ink mixing and supply tanks, printing units and human interfaces

Fig. 8. Lasersonic® printing machine in the lab. The first printing unit is for absorbing ink, like black, the other three for non-absorbing inks like magenta, cyan and yellow. Printing units can be exchanged within a few minutes to vary between different inks or ink sequences.

4. First printing results

At first, we started to study and optimize the LIFT printing process with one printing unit. The results show that the LIFT process with modulated cw laser beam is suited to transfer inks with different sizes, attributes and features of the pigments. We tested highly scattering white ink as well as ink with large pigments for mother-of-pearl-effect (Fig. 9a,b) and colored inks with standard pigments (Fig. 9c). Most of the tested inks have been water-based, environment-friendly and inexpensive inks. Optical densities of the printouts have been achieved as required for the printing industry (i.e. OD > 1.95 for magenta, OD > 2.5 for cyan).

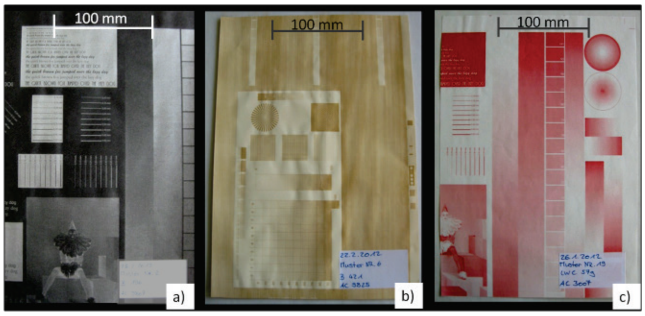


Fig. 9. Print samples produced on the Lasersonic® machine
a) Silver ink with large pigments on black decor paper
b) Gold ink with mother-of-pearl-effect
c) Red standard ink on LWC (light weight coated) paper

There is still a lot to do, i.e. to improve the optical beam path and to optimize the transfer process in order to eliminate satellite drops which arise during the collapse of the bubble or if the ink layer is boiling too much.

5. LIFT with fast cw-laser scanning and modulation

For fast LIFT printing we have to consider some fundamental details such as the timescales of the laser interaction and of the ink transfer in order to control the print process and to match the desired screen resolution (screen pitch) and quality of the image.

For the “laser exposure part” of the LIFT process the modulation screen pitch is defined as the minimum spatial distance along the scan line which can be achieved between two consecutive laser pulses when the laser beam is scanned with the fastest rate of the laser power modulation. For example, at a scan speed of 1000 m/s and with an on/off modulation rate of 23.8 MHz consecutive laser pulses have a distance of 42 µm on the scan line. This is equivalent to a pixel size of 42 µm and a screen resolution of 600 dpi of the image data. The spot size of the laser beam (60 µm) and the diameters of the printed dots may be larger than 42 µm because in printing an overlap of the dots is allowed and for full color applications even necessary to avoid white, uncovered areas. The diameter of a printed dot mainly depends on the volume of the transferred ink (Fig. 12, 14) and not directly on the screen resolution. The ink layer thickness on the ink roller has a direct influence on the dot diameter.

Due to the fast scan velocity of the laser beam within the range of 1000 m/s to 2000 m/s even a cw-laser beam has locally (at one point of the scan line) only a short timely impact resulting in a "single quasi laser pulse" at this point. The transient field of the fast-passing laser gives a pulsed energy input to the absorption layer where the pulse duration τ is approximately given by the speed and the diameter of the laser spot (i.e. $\tau = 60$ ns at 1000 m/s for a 60 µm spot size).

The time scale for the energy impact (ink excitation) is in the ns-regime whereas the transfer process itself i.e. the bubble and jet formation lasts 1 µs to 200 µs ([3]-[9]). On the time scale of the jet formation and transfer process the energy impact to successive, closely spaced pixels along the scan line is been effected quasi simultaneously by the fast scanning laser beam. At a scan velocity of 1000 m/s and with a screen resolution of 600 dpi (42µm screen pitch) a line section of about 24 pixels can be activated per 1µs.

In order to write dot lines in scan direction we tried to do this by line writing with a "continuous laser on" mode by setting the laser modulation gray level permanently on a value above the threshold for the LIFT process.

However, the resulting bubble formation and the ink transfer are not as continuous as the excitation by the laser beam, but show droplets and interruptions which lead to an irregular pattern of separated dots along this line (Fig.11).

This separation into droplets should be investigated by numerical modeling of the interaction between shock wave forces during bubble expansion and tension forces of the ink. As a first approach of an explanation, we assume that the different time scales of the fast excitation by the laser (60 ns) and the slow transfer process (1µs to 100 µs) result in a quasi simultaneous start of the bubble formation over many pixels along the scanned line. Over a line section of a few mm the ink is transferred quasi simultaneously. Tension forces inside of the ink lead to a separation into single droplets of various sizes during bubble formation and during the transfer process between ink roller and substrate. The separations don't occur periodically along the scan direction, but rather randomly with a large spatial jitter (Fig. 10 left side). Important parameters for this effect are the viscosity of the ink, the scanning speed, the laser beam intensity and the distance d between donor and acceptor. During this process it may happen that not only the ink area which is directly excited by the laser is pushed away, but

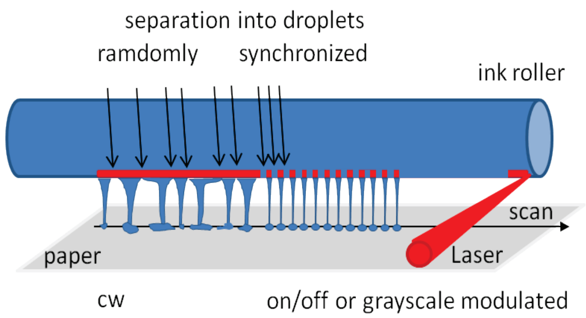


Fig. 10. Line writing in scan direction with "cw-laser-on"-mode compared to an on/off-modulated laser; at cw mode an ink-layer-stripe of a few mm length is quasi simultaneously transferred and separates due to tension forces of the ink randomly into droplets of various sizes. On/off-modulation of the laser synchronizes the droplet separation with the pixel screen along the scan line.

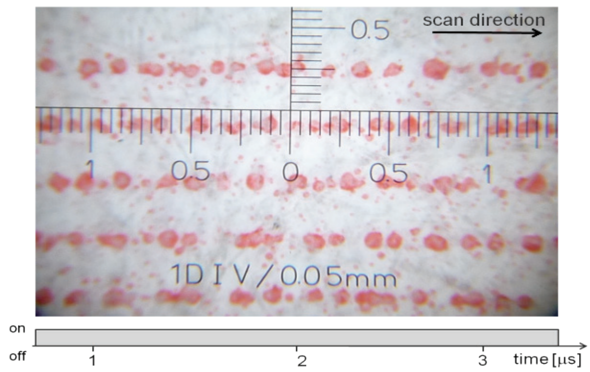


Fig. 11. Line writing in scan direction with "continuous laser on" and v=1000 m/s shows irregular patterns of dots along the scan line; also a lot of small satellite drops are seen between the lines.

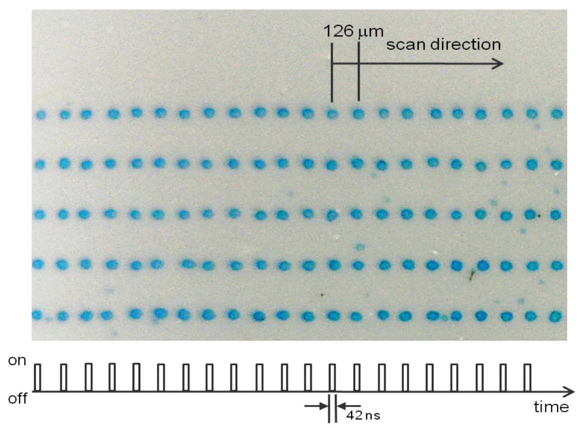


Fig. 12. Line writing with 1000 m/s in scan direction e.g. with an 1-pixel on/ 2-pixel off modulation shows regular patterns of dots; due to the off-time less overall ink volume is transferred and dot diameters (~ 50 µm) are smaller than in Fig. 11; also less satellite drops are between the lines.

due to tension forces also ink from the surrounding area is taken off and contributes to a droplet.

To eliminate this random behavior of the droplet formation, an active on/off switching as well as power level grayscale modulation of the laser beam has been investigated. The modulation signal was synchronized to the local position of the laser spot along the scan line (Fig. 10 right side).

First results show evidence that it is possible to realign the starting point of the droplet evolution by switching the laser beam off and on again in order to introduce controlled separations for the droplet formation while moving along the scan direction. For example, scanning with a "1-pixel on / 2-pixel off "- pattern (instead of the cw–signal) leads to the periodical dot patterns of Fig. 12 instead of the randomly droplet separation and irregular pattern of Fig. 11.

The distance d between ink roller and substrate should be as small as possible in order to get optimized transfer results. For the tests in Fig. 11-14 it was fixed at 0.5 mm to avoid any contact of the ink roller with the moving substrate. The feed rate of the substrate was 2.33 m/min, the scan speed 1000 m/s and the modulation rate 23.8 MHz. In Fig. 11–14 the on-level of the AOM input signal was in each case equal for all pulse-lengths and "laser-on" periods.

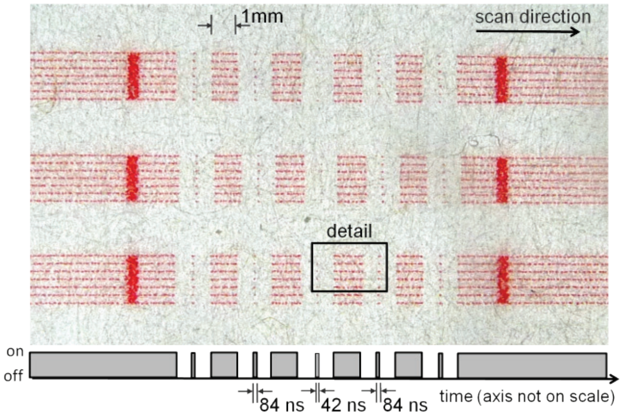


Fig. 13. Line writing with 1000 m/s in scan direction with different lengths of laser on/off-modulation signals: large "on" intervals and single shots; The vertical full color bars are for marking the region of interest between the bars.

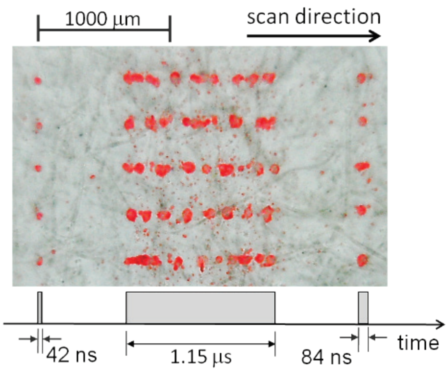


Fig. 14. Detail of Fig.13.: Effects of "laser on"-periods with different durations: long "laser-on" periods show separation of droplets; for single shots in the ns range the dot size increases with the pulse length.

Fig. 13 and Fig. 14 show several scan lines, one below the other. Dots printed by short modulated single pulses (t = 42 ns and t = 84 ns) occur for each scan at the same position of the scan line. This means their position is controllable.

The length of the single pulse defines the amount of ink which is transferred by the droplet. The 84 ns long pulses generate dots with a larger diameter (dot size < 100 µm) than the 42 ns long pulses (dot size < 50 µm). Fine structures must be printed with short pulses.

For long "laser-on periods" the dots are randomly distributed along the scan line with the exception of the first dots of the long periods which are also aligned. This behavior along the scan lines shows that the alignment and positioning of the transferred LIFT dots and the correct reproduction of the gray values of an image depends on the modulation scheme. The development of suited modulation algorithms and time schemes for the laser beam must be adapted to the physics of the transfer process.

6. Summary

The Lasersonic® LIFT process is suited to be used for commercial digital printing applications which are difficult to be performed by Inkjet or Xerography.

The required high area throughput can be achieved by using a high power cw-laser which is scanned at high speed (> 1000m/s) over the substrate. A fast modulation of the high power beam with a data rate of 20 - 25 MHz allows even at this speed for screen resolutions of 600 dpi.

We demonstrated the large area printing on different common substrates and with common inks from the printing industry. Inks with small (< 1 µm) and large (100 µm) sized pigments could be transferred by the LIFT process. The maximum area feed rate was about 2.6 m^2 per minute.

Next steps will be to tune the parameters of the modulation, of the optical beam path and the ink properties to optimize the transfer process. Theoretical modeling of the process could be helpful to enforce the optimization.

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