

Precision Generation of Optical Elements Using Drop-on-Demand Technology

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1 Overview

Optical methods and elements are playing a large and ever more increasing role in communications and computing applications. At MicroFab Technologies, Inc., we have developed drop-on-demand technology capable of handling a large variety of materials, including polymers suitable for optical elements. This permits the direct, data-driven construction of, e.g., lenses and fiber sections at the location of use, unlike photolithographic and other machining techniques which shape elements through removal of material. These process advantages provide an opportunity for significant cost reductions that will help the expansion of the use of high-speed communications technologies. We are working with a number of companies and research institutions on specific applications.

The most common use of drop-on-demand technology is found in ink-jet printers. While that application is highly specialized for specific inks, with precision requirements characterized by a few tens of microns, the optics field demands a variety of fluids to be dispensed (Figure 1) with precisions down to 1-3 μm (3 std. dev.). To date, we have accomplished a relative placement accuracy of less than 2 μm (1 std. dev.) in arrays of microlenses (Figure 2). It appears that this result is still dominated by the properties of the motion system and the currently used software corrections. Thus, there is room for improvement by using better motion equipment and control procedures. Applications include microlenses on pixel arrays for collimating laser beams, lenslets on fiber ends for increased efficiency in couplings, and lenses with an axial gradient index of refraction (AGRIN) for creating small focal spots. On arrays, solder balls for electrical connections may be needed alongside the lenses. Ink-jet technology can provide these, too, and optical polymers are available that will allow the solder process to be performed without damage to the optical elements nearby.

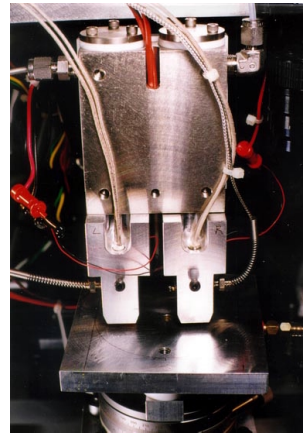


Fig. 1: Heated dual drop-on-demand print head.

Beyond placement accuracy, requirements arise on focal length, focal spot size and lens speed, which translate into performance requirements for the dispensing system, i.e., control of drop sizes and spreading behavior on the target substrate. Required microlens diameters range from tens of microns to millimeters, depending on the specific application. For lenses of diameters in the order of 300-330 μm , we have achieved errors on diameter of less than 0.6%, and on focal length (also around 300-330 μm) of less than 1.1% (both 1 std.dev.). We have produced microlenses with speeds as fast as $f/1.2$ which is very hard to do with any other manufacturing technology.

2 Technical Implementation

Our core technology is the development of drop-on-demand fluid dispensing technology for applications ranging from printing of biomedical arrays to optical elements to solder balls to controlled creation of aromatic odors. The fundamental element consists of a piezoceramic cylinder fitted around a small glass tube with a narrow orifice (as is the case for the applications discussed here) or a piezoceramic block with a number of fluid channels directly machined into it. The underlying principle of operation is the

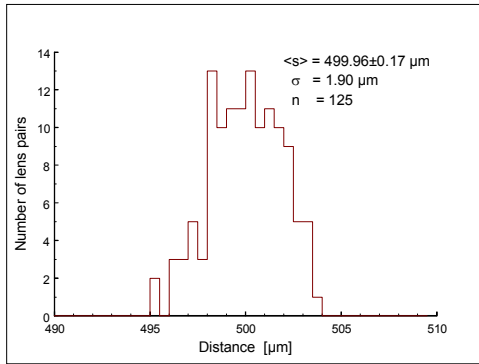


Fig. 2: Distribution of spacings in a lens array.

creation of acoustic waves in the fluid column by the piezo actuator which then, under proper shaping of the stimulating pulse to the piezo element, leads to controlled ejection of single droplets (Figure 3)[3].

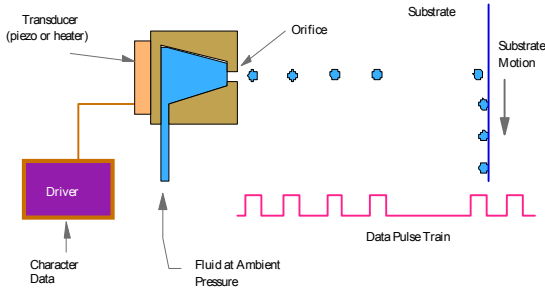


Fig. 3: Principle of drop-on-demand dispensing.

We build print stations in which the dispensing head is held in a fixed position and the substrate is moved to produce the desired pattern. By convention, the substrate (glass for experiments, glass, silicon and other substrates for custom applications), moves horizontally in the x-y plane. The print station on which the patterns and results of the present paper were created uses Parker Daedal 806000CT type motorized stages (150 mm travel) for the x and y motion. The stages are driven by with Parker Compumotor LN57-83 stepper motors and drives which are operated in microstepping mode at 20000 steps per turn of the 1 mm pitch lead screw. Position feedback is obtained through optical linear encoders made by RSF Elektronik, of their MSA670 class with $0.25 \mu\text{m}$ resolution. A Parker Compumotor AT6400 motion controller is set to employ position maintenance with a deadband parameter of 7 encoder counts or $1.75 \mu\text{m}$. A third stage parallel to the x stage al-

lows to position either of the two print heads show in Figure 1 as well as a downward looking camera over the center of the x-y region of motion. Its accuracy characteristics are very similar to those of the x and y stages; however, we need only the reproducibility of a few positions. Manual motion capabilities allow vertical adjustment of the print heads and camera, and rotational adjustment of the substrate. (The latter can also be accommodated in software.) The print station is controlled from an elderly PC (Intel 486DX 66 MHz processor, Windows 95 operating system) using a custom program written in-house.

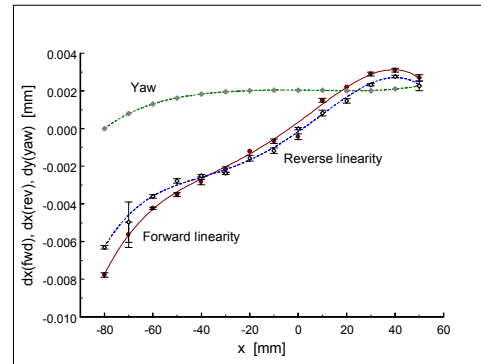


Fig. 4: Linearity and yaw for x axis.

The x and y stages have been surveyed by an outside contractor with a laser interferometer for linearity and yaw. Given that the carriages and their supports are longer than the total travel, we have assumed that the yaw can be translated into a transverse displacement of the center of the carriage by integrating it along the path of travel. The surveys have recorded data every 10 mm for each axis and quantity, with three runs forth and back for the linearities. The three runs are averaged and the resulting data approximated by polynomials up to 5th degree (Figure 4). The yaw angle is then used again to translate from the center of the carriage to the fixed location of the active print head. These corrections are employed in the control software on the host PC which feeds corrected position information to the motion controller. Our a priori expectation was to shrink the positioning errors from about $\pm 10 \mu\text{m}$ (the typical range of linearity errors reported by the manufacturer for the type of stages used) to the order of $\pm 2 \mu\text{m}$, i.e., close to the position maintenance bandwidth we are demanding from our motion

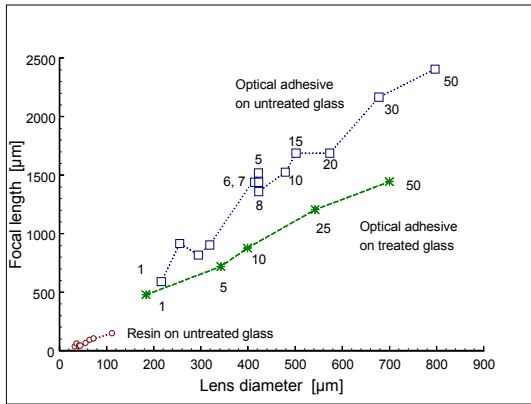


Fig. 5: Control of lens diameter and focal length. Numbers are numbers of droplets per lens.

system.

As described, the surveys give us good accuracy for reaching any point on the substrate once we have picked a starting point. The absolute placement of droplets then still depends on some additional effects: the accuracy of finding a starting point, i.e., the home position for the x and y stages, the positioning and orientation of the print head, and the directionality of the dispensed droplets with respect to the center axis of the print head. We circumvent any inaccuracies induced by these sources by using a CCD camera looking down on the substrate, tied to a monitor outfitted with a Boeckeler VIA-100 screen calibration system. This allows us to pick up a suitable first position for a printing project, e.g., from survey marks, and by performing test prints and inspecting those with the camera, to summarily compensate for all error sources related to the fluid dispensing. Experience has shown that dispensing of optical polymers at elevated temperatures (needed foremost to make and keep them liquid) is quite stable and reproducible over long periods of time.

3 Printing Optical Elements

Our custom projects in the optics sector are centered around creating small lenses on flat substrates like glass plates or on the ends of fibers. The former are useful for building massively parallel optical switches while the latter include, e.g., efficient and stable couplings for single fibers. The basic lens is spherical, coming about quite naturally when one or

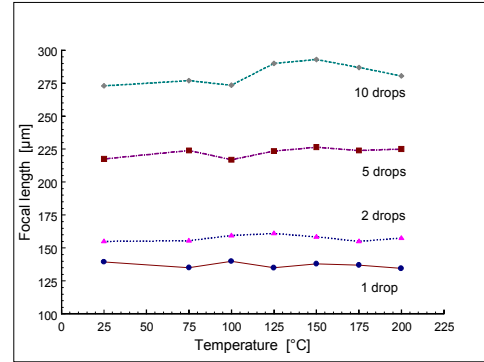


Fig. 6: Focal lengths vs baking temperature for different lens size (numbers of drops).

a few droplets are dispensed at a fixed location. The drop-on-demand technology does allow us to also make quite odd-shaped lenses, e.g., hemielliptical or even nearly-square based ones. Tools to influence diameter and focal length include the choice of material and treatment of the substrate surface. Data from an early study in Figure 5 show both options at work.

Once printed, the optical material is cured by exposure to ample heat or UV light. The curing process is quite uncritical in terms of maintaining a specified focal length; e.g., a wide variation of the baking temperature will affect the focal length only to within a very few percent (Figure 6). This also implies that the lenses remain unaffected by large temperature variations in their operating environment.

A good example for the requirements set by applications is demonstrated by the coupling of light from an edge emitting diode laser (Figure 7) into fibers. Using an air gap is the most stable choice available. Its backdraw is that exiting light is diverging, leading to loss of signal intensity if the capturing element does not cover the full cross section of the light cone. In turn, increasing the capturing element increases the amount of background noise, so there may be a balance between two evils to be made. Placing a focussing lens onto the laser and the end of the fiber can narrow the cone significantly, improving the quality of the signal transfer. In figures 8 and 9, the estimated effect of the lens radius (and with it, the focal length), and of the displacement between the fiber and lens axes is shown. Without lenses, efficiencies of order of 10-15% are obtained. Thus

even a lens of $40\ \mu\text{m}$ diameter, which we have produced successfully already some time ago, will yield an improvement by a factor of two. In general, with drop-on-demand technology a wide range of focal lengths from tens to hundreds of microns is available to accomplish the task at hand. We also note the significant loss in efficiency for lenses on fibers misaligned by more than about $2\ \mu\text{m}$.

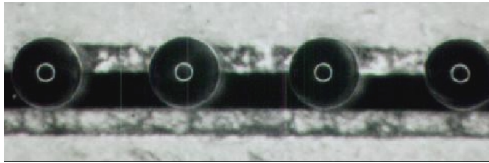


Fig. 7: Edge emitting laser with $200\ \mu\text{m}$ lenses.

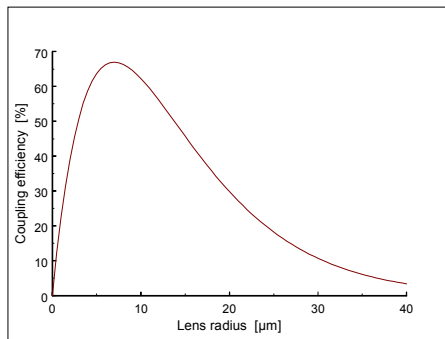


Fig. 8: Coupling efficiency vs. lens radius.

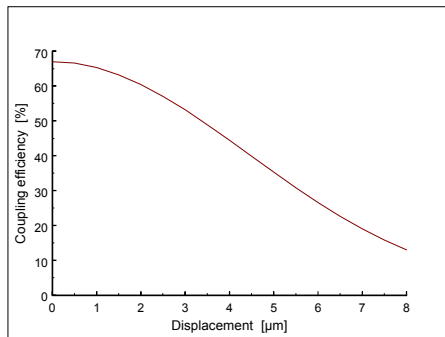


Fig. 9: Efficiency vs. lens-fiber displacement.

The curve in Figure 8 shows that the radius of curvature of the lens has to be maintained to a few microns in order to accomplish a well-defined coupling efficiency. We have inspected random subsets of lenses in a planar array of 2700 lenses for their

diameters and back focal lengths (measured on the flat side of the lenses) and find both quantities to behave satisfactorily (Figures 10, 11). To maximize the efficiency for the case shown in Figure 8, we will have to reduce the diameters of the droplets which form the lenses. We are developing and tuning our technology to do this reliably.

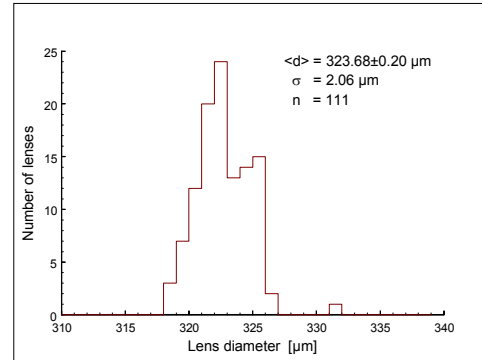


Fig. 10: Distribution of lens diameters in an array.

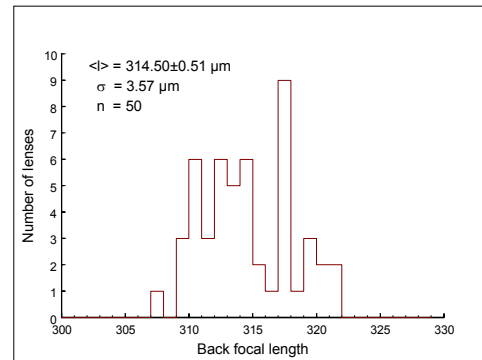


Fig. 11: Distribution of focal lengths in an array.

In summary, drop-on-demand technology offers new avenues in the development and production of optical devices, and combines challenges for control of fluid dispensing with those of more mechanical machining techniques.

- [1] W.R. Cox et al., SPIE Proceedings 2382 (1995) 110-115.
- [2] W.R. Cox et al., IMAPS International Journal of Microcircuits & Electronics Packaging 20 (1997) 89-95.
- [3] D.B. Wallace, ASME Pub. 89-WA/FE-4 (1989).