Liquid Drop Lenses for Miniature Sensors

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Introduction

- Multi-aperture imagers add depth and/or spectral information to 2-D dimensional camera images for multi-dimensional imaging in a slim form factor [1,2]
- Design space for multiple-aperture systems is large, and optimal arrangement of lenses depends on application-specific constraints
- Demonstrating the expected benefits of modern multiple-aperture systems remains a challenge due to the high cost involved in fabrication of customized optics
- Here, we introduce a low-cost method for fabricating lenses. Our lenses are called Liquid Drop Lenses (LDLs)
- Our fabrication method avoids costly masks and patterned substrates required by inkjet printed lenses [3]
- Surface of LDLs can be modeled using an aspheric polynomial knowing only the radius of curvature and characteristic length of the epoxy

Liquid Drop Lenses

- LDLs are lenses made of droplets of high-viscous liquid epoxy that cures upon exposure to ultra-violet light
- LDLs are formed by on-contact dispensing of calibrated volumes of epoxy onto a cover-slip from a pipette held immobilized in a vise
- A variety of lens shapes and sizes are obtained by tuning epoxy and substrate properties
- Dispensing multiple such drops at predetermined positions followed by ultra-violet (UV) curing allows us to inexpensively fabricate a variety of multiple aperture lens designs

a

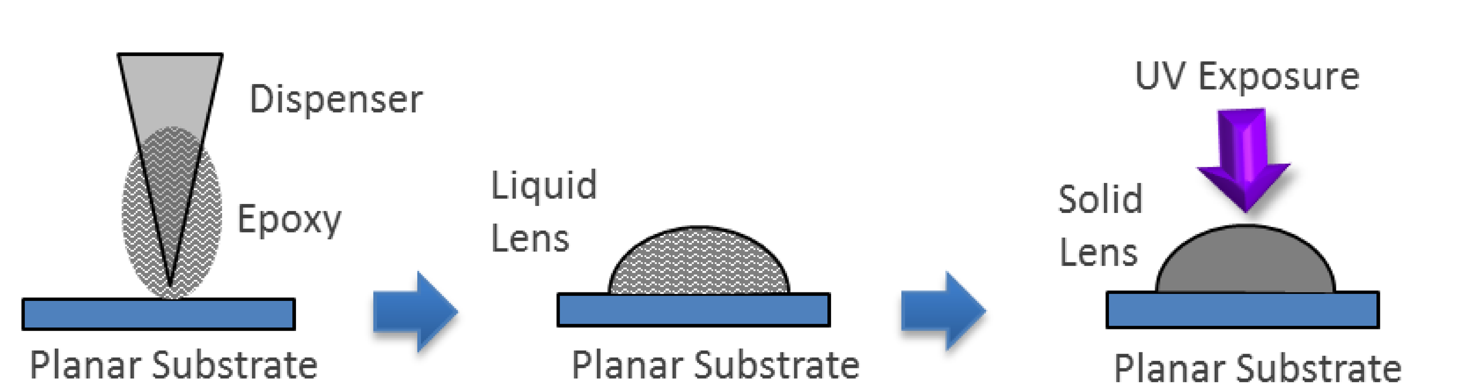
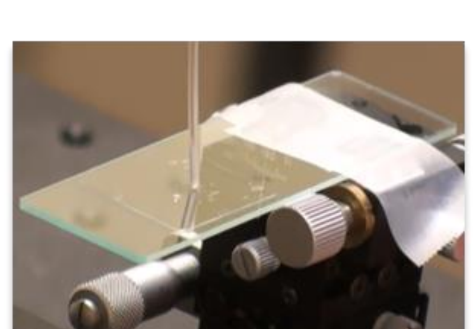


Fig. 1. (a) Method of liquid drop lens fabrication. (b) LDLs fabricated with a pipette and micrometer stage. (c) Miniature LDLs of various sizes after UV curing. (Inset) 3D profile of a LDL measured with a ZYGO profilometer.

b



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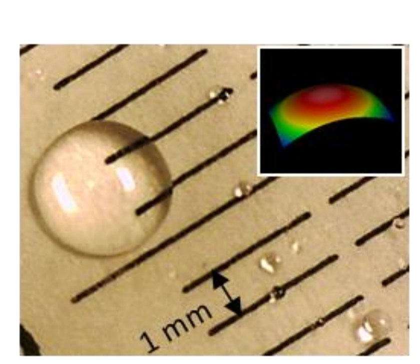

Modeling LDL Surface Profile

- Surface profile of an LDL is radially symmetric if:
  - Flow of liquid from dispenser is uniform
  - Roughness of substrate is uniform
- Radial profile of lens can be found by balancing the Young-Laplace equation with respect to hydrostatic pressure [4]

$$\frac{z''}{(1+(z')^2)^{3/2}} + \frac{z'}{r(1+(z')^2)^{1/2}} - \frac{z}{L_c^2} = const$$

$$L_c = \sqrt{\gamma/\rho g}$$

- L_c: characteristic length
- γ: surface tension
- ρ: density
- g: acceleration of gravity
- Coefficients for an aspheric expansion can be found that solves the Young-Laplace equation
- Aspheric expansion is more designer friendly than other solutions [4,5]
- Model predicts improved performance for upside-down curing over upright curing (Fig. 2)

$$z(r) = \frac{r^2/R}{1+\sqrt{1-\left(r/R\right)^2}} + \sum_{n=2}^{N} a_n r^{2n}$$

$$a_2 = -\frac{1}{32RL_c^2} \qquad a_3 = -\frac{40L_c^2 + R^2}{1152R^3L_c^4}$$

$$a_4 = -\frac{2520L_c^4 + 328L_c^2R^2 + R^4}{73728R^5L_c^6}$$

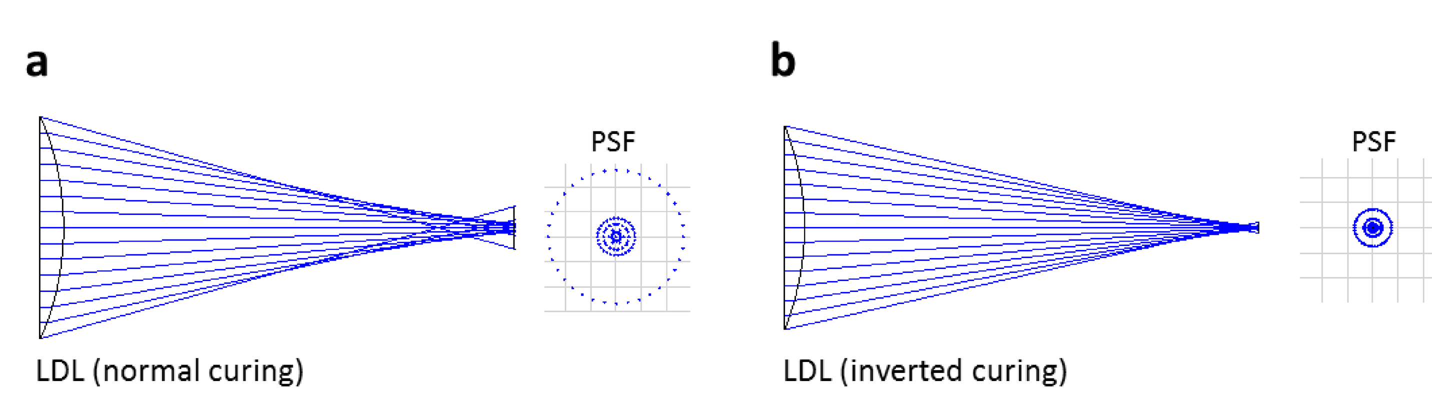

Fig. 2. Ray trace and spot diagram of a normal LDL (left) and inverted LDL (right) of Norland Optical Adhesive 61. The nominal radius of both lenses is 3.651 mm (f = 6.525). The diameter of both lenses is 2.8 mm. The spot size of the normal LDL is 0.271 mm. The spot size of the inverted LDL is 0.074mm, 3.6x smaller.

LDL Experiment

- Computational imaging devices, including stereo and multi-aperture systems, were prototyped using LDLs

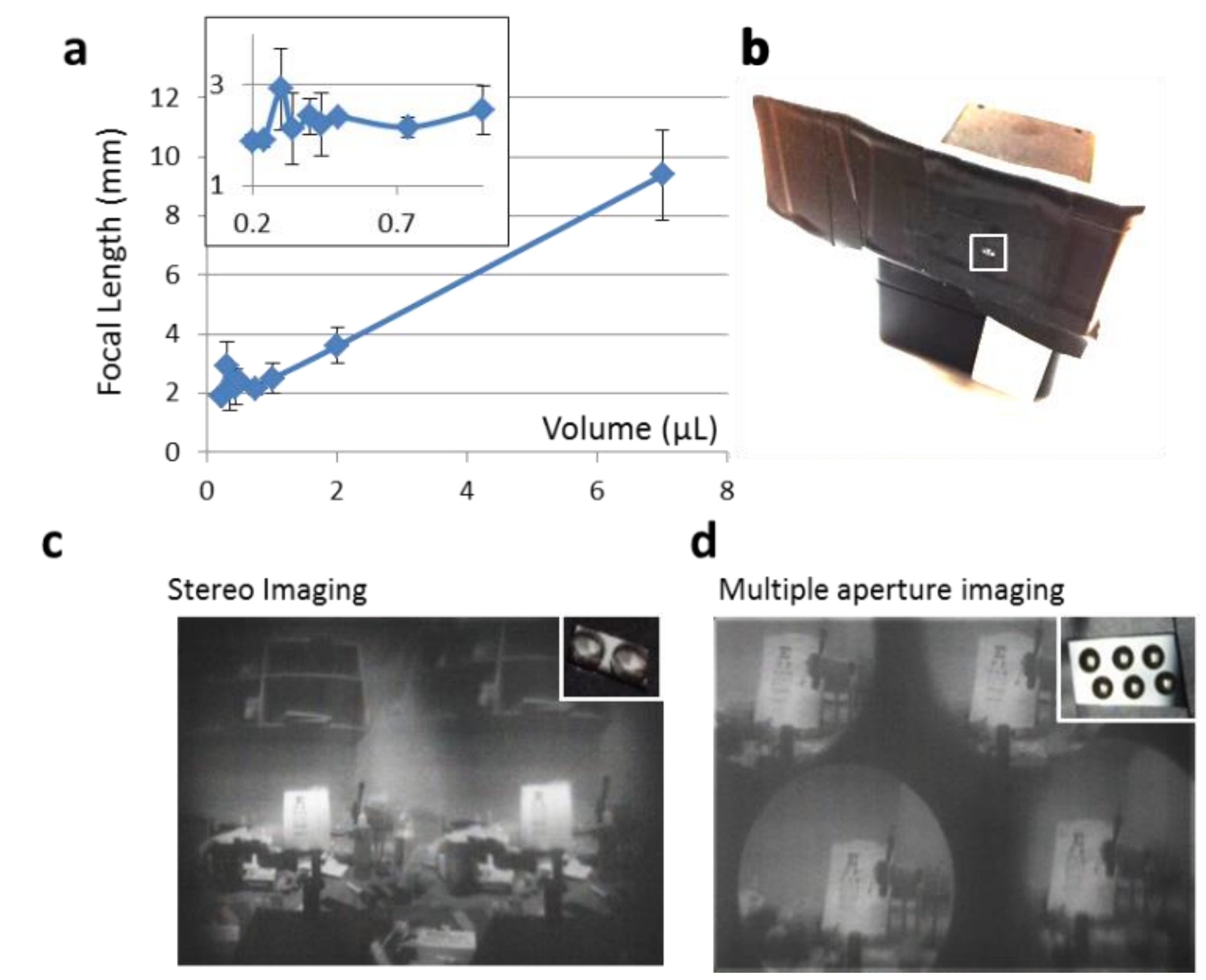

Fig. 3. (a) Plot of volume vs. focal length of fabricated LDLs. (Inset) Zoomed-in plot for a smaller volume range. (b) Stereo imager with two LDLs in front of a single image sensor. (c) Stereo image produced by the stereo imager in (b). (Inset) The two LDLs that formed the stereo image. (d) Multiple aperture image formed by LDLs. (Inset) LDLs fabricated for multiple aperture imaging.

Conclusions

- A low-cost method of fabricating lenses with high-viscosity UV curable epoxy has been introduced
- Aspheric coefficients of the profiles of these lenses have been analytically determined
- Dispensing method demonstrated for rapid prototyping of multi-aperture imagers

References

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