Liquid Drop Lenses for Miniature Sensors

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Abstract: We introduce a lens fabrication method for computational imagers with on-contact dispensing of high-viscous UV curable epoxies on planar substrates. We further model and calibrate these lenses, and demonstrate applications in stereo and multi-aperture imaging.

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1. Introduction

Multiple aperture architectures are being developed for applications requiring miniature detectors such as three dimensional imagers [1]. This follows an overall trend in the slimming of electronic devices such as cell phones and tablets. The design space for such multiple aperture systems is quite large, and the optimal arrangement of lenses depends on constraints imposed by a given application [2]. While simulations provide insight into the merits of one configuration versus another, demonstrating the expected benefits remains a challenge due to the high cost involved in fabrication of customized optics. In this paper, we address the issue of the cost versus customization of prototyping lenses by introducing a low-cost method for fabricating lenses.

Miniature lenses have previously been fabricated with inkjet print-heads that dispense low-viscous epoxy drops on patterned substrates [3]. However, the need for patterned substrates makes the inkjet method both expensive and restrictive. The shape of liquid drops and the effect of gravity on them have been studied in the context of thermal reflow [4,5]. Unfortunately, the model for the lens shape in the form of an asphere up to 4th order requires knowledge of lens cross sectional area before and after melting.

In our method, we dispense a calibrated volume of high-viscous epoxy on a planar substrate. At equilibrium, the natural balancing of forces acting on the surface of the epoxy drop makes it acquire the shape of a lens. 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. We fabricate lenses with various diameters and focal lengths by controlling the volume of epoxy dispensed on the substrate. Further, we present a model describing the shape of a liquid drop where aspheric coefficients up to 8th order can be calculated knowing only the radius of the lens. We import our model into Zemax® [6] to simulate the lens properties, including the influence of gravity in reducing spherical aberration.

2. Liquid drop lenses

Liquid drop lenses (LDLs) are polymer lenses fabricated from drops of epoxy cured by UV radiation. In this method, a dispenser places a drop of epoxy onto a planar substrate (Fig. 1a). In order to reduce surface tension, the droplet takes a nearly spherical shape. Smaller drops are more spherical than larger drops. After exposure to UV radiation, the droplet becomes a solid lens. The lenses are fabricated by dispensing a fixed volume of epoxy onto a glass coverslip from a pipette held steady by a pana-vise. The glass coverslip rests on a microscope slide which is fixed to a 3D micrometer stage (Fig. 1b). The stage is raised up to be nearly in contact with the pipette tip and the drop is dispersed and then lowered in order to break the drop free from the pipette tip. Translating the stage laterally allows multiple lenses to be placed side by side for the production of stereo and multi-aperture imagers.

Fig. 1. (a) Method of liquid drop lens fabrication. A drop of epoxy is dispensed onto a planar substrate. A liquid lens forms and is cured by UV light. (b) LDLs fabricated with a pipette and micrometer stage. The stage is raised up to the pipette tip to dispense the LDL and then lowered to break contact between the LDL and pipette tip. (c) Miniature LDLs of various sizes after UV curing. (Inset) 3D profile of a LDL measured with a ZYGO profilometer.
Our lenses were cured for 10 minutes using a 6W UVP® UVL-56TM Ultra-Violet Lamp from Summers Optical at a distance of approximately 2 inches from the lamp source. Fig. 1c shows an example of miniature LDLs with different mm and sub-mm scale diameters and focal lengths produced with our method.

3. Modeling LDL surface profile

The surface of a LDL will have radial symmetry if the flow of the dispensed liquid is uniform in all directions and if the substrate roughness does not exhibit significant asymmetry. The shape of a drop of liquid that is assumed to have radial symmetry can be described by finding the curve that minimizes the free energy or by balancing the Young-Laplace equation with the change in pressure with respect to lens sag [4]. The former is the approach taken here. The second order ordinary differential equation describing the profile of a liquid drop lens is given by Eq. 1.

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

(1)

In Eq. 1, the term \( L_c = \sqrt{\gamma / \rho g} \), where \( \gamma \) is the surface tension between the liquid and the surrounding air or gas, \( \rho \) is the density of the liquid, and \( g \) is the gravitational acceleration. \( L_c \) is referred to as the characteristic length of a liquid. Shilling et al. have shown solutions to this equation using numerical methods [4]. A more designer-friendly solution would be to find the aspheric expansion of the lens surface (Eq. 2). This approach was taken in [5], but their model uses the cross-sectional areas of reflow photoresist pucks and lenses as parameters. We have found that the aspheric coefficients can be calculated knowing only the nominal radius of curvature of the lens. From the designer’s perspective, this model is simpler to work with, and can be implemented in macros for lens design software such as Zemax®.

\[
z(r) = -\frac{r^2}{1+1/2(r/L_c)^2} + \sum_{n=2}^{N} a_{n} r^{2n}
\]  

(2)

The Taylor series expansion of Eq. 1 results in recursive equations for derivatives of \( z(r) \). The first three terms of the aspheric expansion are given in Eq. 3.

\[
a_2 = -\frac{1}{32RL_c^2}, \quad a_3 = -\frac{40L_c^2 + R^2}{1152R^3L_c^4}, \quad \text{and} \quad a_4 = -\frac{2520L_c^4 + 32RL_c^2R^2 + R^4}{73728R^5L_c^6}
\]  

(3)

Using this model of the lens shape, one can find the radius of an inverted LDL for which there is no primary spherical aberration when imaging an object at a distance: \( 2nL_c\sqrt{n-T} \). This model can also be used to calculate the focal length of the lens if the volume and contact angle are known. Fig. 2. shows results from porting our model into Zemax®. Our model shows that inverted (curved lens surface facing down) curing of LDLs results in 3.6x times reduction in on-axis spherical aberration compared to normal (curved surface facing up) curing due to the effect of gravity.

![LDL Experiments](image-url)

4. LDL Experiments

Not all UV curable optical epoxies produced desirable LDLs in our experiments. Although most epoxies produced near-spherical lens shapes after dispensing, we observed that some epoxies do not retain their shape during curing.

Our experiments identified Norland Optical Adhesive 61 to be suitable for fabricating LDLs. We dispensed calibrated volumes of this adhesive on Fisherbrand 12-541-B cover glass using the setup described in section 2. Lenses with volumes of 0.2, 0.24, 0.3, 0.34, 0.4, 0.44, 0.5, 0.74, 1, 2, and 7 μL were fabricated in sets of 4 for...
volumes under 0.5 μL, a set of 2 for the 7 μL lens, and sets of 3 for the rest. The focal lengths of these lenses were calculated using the thin-lens equation by measuring the size of a focused image of a known object at a predetermined distance. Fig. 3a shows a plot of volume vs. focal length for our fabricated LDLs. We observe an increasing trend of focal lengths with increasing volume over a large volume range (0 to 7 μL). In this volume range, we obtain around 7mm of focal length variation. The inset in Fig. 3a shows a zoomed-in plot for a smaller volume range (0 to 1 μL). In this small range, we find the focal length trend to be non-monotonic. The exact reasons for this behavior are under current investigation. Using such calibration plots, lens makers can translate focal length specifications into material volume specifications.

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.

Fig. 3b shows a USB powered stereo imaging system using two LDLs positioned over a single monochrome image sensor. A stereo image acquired by this system is shown in Fig. 3c. The two LDLs used by the stereo system is shown in the top-right inset of Fig. 3c. Fig. 3d shows an example image from a multiaperture imager fabricated using LDLs. Only four of the 6 lenses (shown in inset of Fig. 3d) were used for image capture. While the stereo imager did not use a field stop, the multiple aperture imager needed a stop to avoid overlapping of different views.

5. Conclusions

We have introduced a low-cost method of fabricating lenses with high-viscous UV curable epoxy. The aspheric coefficients of the lens profile have been analytically determined and depend only on the lens radius and liquid characteristic length. Experimental results have shown that the precision within a group of lenses is high enough that computational imaging systems such as stereo and multi-aperture imagers can be fabricated.

6. References

[6]. Zemax is a trademark of Radiant Zemax, LLC.