are actuated by four LC pistons. All the dimensions are the same as that of the lens cell shown in Fig. 2(a). As the voltage increases, the optical power of the two lenses is tuned from negative to positive, since the initial diminished images become magnified at 80 V_{rms} as shown in Figs. 3(c)-(d). For easy observation, the aperture holes are circled by red curves. A dynamic switch between the two states is shown in Fig. 3(d) (Media 4). The image changed continuously and uniformly in the transition and no obvious aberration was observed.

Figure 4(a) indicates that there is a threshold of ~40 V_{rms} in the lens actuation. Since the actuation power can be enhanced by increasing the number of LC pistons rather than the operating voltage, it is critically important to reduce the threshold for low-voltage operation. For a single LC piston, the threshold depends on the exerted dielectric force and the interfacial tension along the three-phase contact line (Teflon-LC-L_S), which can be reduced by using narrower-gap stripe electrodes, surrounding liquid with smaller dielectric constant, smaller LC droplet and thinner Teflon layer. If the voltage is too high, crosstalk between two stretched LC droplets (e.g. LC_1 and LC_2, or LC_3 and LC_4 in Fig. 2(a)) will appear and the actuation power will be severally degraded. In practical applications, the LC droplets should be separated by a black matrix in the chamber. The switching time is affected by the liquid interfacial tension and flow viscosity, and it can be improved by using a surrounding liquid with lower viscosity. Overall speaking, to optimize the device performance, parameters of the lens cell, e.g. the hole size, layout of the holes, cell gap, top slab thickness and electrodes pattern, need to be further studied. To achieve good mechanical stability, a third liquid which is immiscible and has good density match with both ZLI-4389 and silicone oil could be adopted in the lens cell. Its refractive index and surface tension should also be different from that of the silicone oil. Such a liquid helps to minimize the gravity effect and strengthen the liquid-liquid interface confinement at the aperture hole [24]. In our experiments, we use a liquid-air interface as the refractive surface, because it is difficult to find a third liquid which satisfies the above-mentioned criteria in our lab. Since the droplets in the demonstrated lens cell are in millimeter-scale, the lens works well in horizontal placement but gravity effect appears in vertical placement. For the micron-sized droplets, the surface tension dominates over the gravity, thus the microlens should be free from gravity effect even without the third liquid [25]. Meanwhile, lower operating voltage and faster response time are also expected [21]. Microlens array based on this actuation method is promising for parallel processing and sample analysis in lab-on-chip systems.

4. Conclusion

We demonstrate an adaptive liquid lens actuated by LC pistons. The LC droplet with a reciprocating movement functions like a piston, which can effectively tune the lens surface and corresponding optical power. For a 2-mm-aperture lens actuated by four LC pistons, BFD is changed from −5.5 mm to infinity to ~66.5 mm as the voltage increases from zero to 80V_{rms}. The competitive features are compact size, simple fabrication, good optical performance, lower power consumption (~mW) and reasonably fast switching time (~17 ms). Surface treatment and fine processing will help to improve the lens performance and widen the dynamic range. Since the actuation power can be enhanced by increasing the number of LC pistons rather than the operating voltages, it is possible to significantly actuate a large-aperture lens or lens array at a relatively low operating voltage.

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