Tunable liquid microlens with three-dimensional adjustment of the position of the focal spot

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A tunable liquid microlens that can be varied from a concave to a convex configuration and which provides three-dimensional adjustment of the position of the focal spot is demonstrated. The tuning is carried out with no reduction of the effective diameter and no surface distortion of the microlens. The focal length is varied by changing the volume of liquid in a microtube. As the focal length is adjusted, three-dimensional adjustment of the focal spot can be obtained by suitably tilting the removable transparent backing. The operating quality of such a microlens is brought out in the results of an experiment: It can be used in such applications as optical switching, optical memory devices with multiple high-density recording, etc. © *2005 Optical Society of America*

The trend to miniaturize optical and electrooptic elements has brought about a requirement for microoptical elements. There are several approaches to the fabrication of microoptical elements, and such elements are widely used in many applications, such as optical-beam switching, ray control, optical-image processing, signal processing, optical probing, three-dimensional images, etc.[1–5]

Optical microlenses are important microoptical elements and are used in numerous optical devices. The capability of dynamically tuning the focal length of a microlens, i.e., of altering its optical properties, opens up tempting possibilities in many new and existing applications.[6] There are several approaches that make it possible to create microlenses with definite tuning.[6–9] Thus, Ref. 9 presents a liquid-filled lens whose focal length can be varied by changing the volume of the liquid in the lens by means of a syringe. Because of the large aperture (diameter 27 mm), it cannot be called a microlens and can operate only as a convex lens. References 7 and 8 reported the creation of a microlens by changing the refractive index of a liquid crystal, and this resulted in a change of the focal length. The surface of these microlenses could be changed from concave to convex. However, none of these could provide a high degree of adjustability of the position of the focal spot in all three dimensions.[6,7] Krupenkin *et al.* demonstrated[6] a tunable liquid microlens whose focal length could be adjusted and whose focal spot could be displaced in a transverse direction. However, it can operate only as a convex lens, and an inhomogeneous electric field results in surface distortion of the microlens.

As far as we know, this paper constitutes the first demonstration of a tunable liquid microlens with tuning from a concave to a convex configuration and with three-dimensional adjustment of the position of the focal spot, but at the same time with no reduction of the aperture and with no distorting action on the surface of the microlens by comparison with the microlens fabricated in Ref. 6.

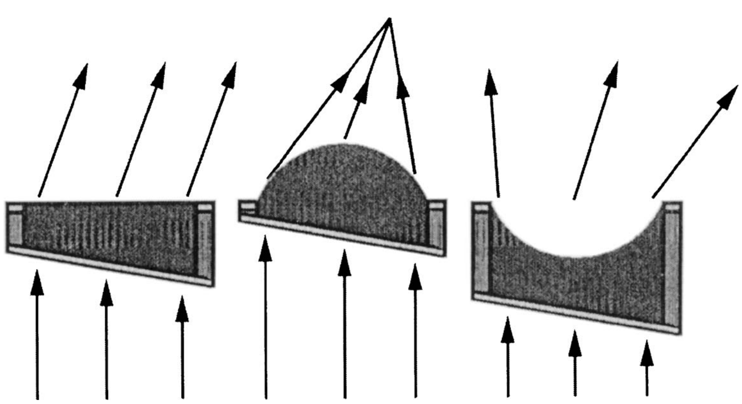

FIG. 1. Schematic diagram of tunable liquid microlens. *1*—rigid noncompressible tube, *2*—compressible tube, *3*—transparent removable backing, *4*—light beam, *5*—liquid. (a) Initial state (plane-parallel plate), (b) convex lens, (c) concave lens (see text for explanation).

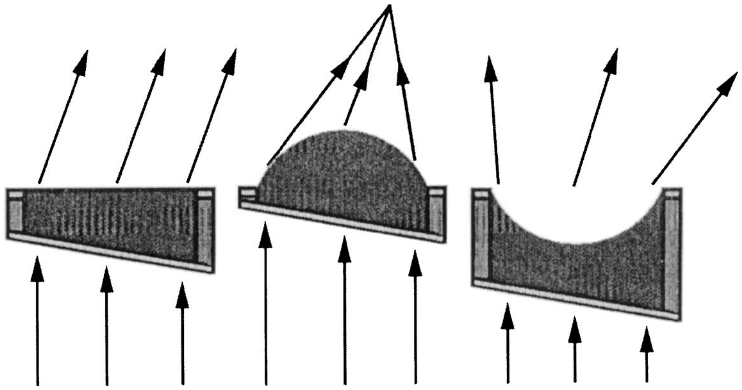

FIG. 2. Diagram showing three-dimensional tuning of focal spot (see text for explanation).

Liquids potentially provide an attractive possibility for creating strongly tunable optical elements. On the scale of microoptics (hundreds of micrometers), surface tension and the liquid-solid interaction are the dominant influence on the behavior of liquids.[6] The concept of our tunable microlens is shown in Fig. 1. A stationary rigid incompressible tube, a compressible tube, and a rigid transparent removable backing together constitute a container for a liquid. When no external force acts on the compressible tube or on the rigid transparent removable backing, the container will be in its natural state (Fig. 1a). We then introduce the necessary volume of liquid and ensure the correct flatness of the liquid's surface. Perfect flatness can be achieved by accurately adjusting the position of the backing in the axial direction. In such a state, the liquid will operate as a transparent glass plate. A light beam passes through the liquid without converging or diverging.

When the tube is compressed, the excess liquid forms a convex lens under the action of the force of surface tension (Fig. 1b). The surface of the lens will be perfect, since no external forces act on it except for gravitation. At the scales of a microlens, the action of gravitation can be neglected. On the other hand, when the tube is stretched, the volume of the liquid will be insufficient to fill the tube, and the surface of the liquid will form a perfect concave lens under the action of surface tension and the liquid-solid interaction (Fig. 1c). It should be pointed out that the inner surface of the tube must be fairly hydrophilic.

The layout for a three-dimensional tunable focal spot is shown in Fig. 2. When the suitably monitored rigid transparent removable backing is tilted while keeping the volume constant, the liquid in the tube will operate as a prism, and a ray will be directed by the corresponding slope of the backing. The ray can also be directed by tilting the entire assembly, but this cannot be done for a single element in a lens array. At the same time, if a concave or convex lens is present on the other side of the prism, the directed ray will converge or diverge. Thus, by adjusting the focal length by compressing or stretching the tube, three-dimensional tuning of the focal spot can be achieved as the backing is tilted. It should be noted here that the refractive indices of the liquid and the backing must be selected to coincide.

A model device consisting of a glass tube with inner diameter 1 mm and a compressible plastic tube for varying the volume of the liquid in the glass tube was used for the experiment. SHIPLY-1805 photoresist was adopted as a liquid, since its refractive index is close to that of the glass backing. Since the photoresist is volatile, a membrane was installed on top of the tube. The experimental results are shown in Fig. 3. Because of the microscope's limited depth of field, when the contour of the convex surface is in focus, the outer wall of the tube will not be in focus, and its image will be smeared, as seen in Figs. 3a and 3b. Figure 3a corresponds to a convex surface formed by excess liquid, and its radius of curvature equals 1.58 mm. Figure 3b corresponds to a less convex surface with radius of curvature 3.32 mm. Figure 3c corresponds to a concave surface having a radius of curvature of 1.25 mm. The effective diameter of this tunable microlens equals 1 mm. The focal length of the convex lens can be altered from 1.49 mm to $+\infty$, while the focal length of the concave lens can go from -3.27 mm to $-\infty$. If one takes a liquid with a larger refractive index, the limiting focal length will be less. It can also be detected, and this is

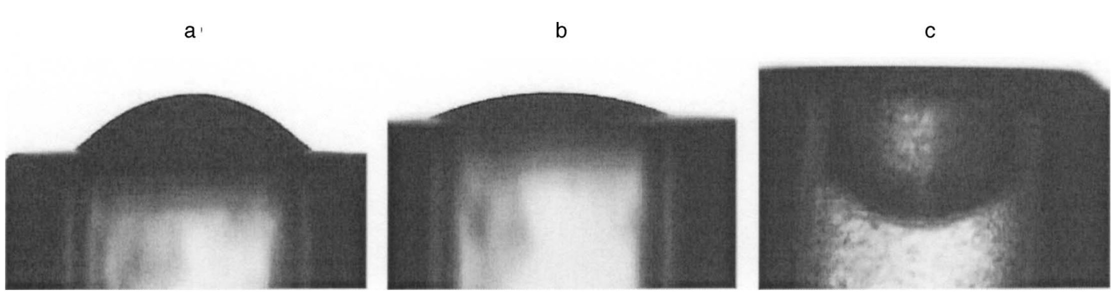

FIG. 3. Variation of the surface configuration of the liquid. (a) Convex surface, (b) slightly convex surface, (c) concave surface.

obvious, that the focal spot is displaced in the focal plane when the glass backing is tilted.

In conclusion, we should point out that, as far as we know, this paper represents the first demonstration of a tunable liquid microlens with tuning from a concave to a convex configuration and three-dimensional adjustment of the position of the focal spot, but at the same time with no reduction of the effective diameter and no surface distortion of the microlens. The focal length is made adjustable by varying the volume of the liquid in the microtube. The focal spot can be tuned in three dimensions by appropriately tilting the transparent removable backing while adjusting the focal length. Such a tunable microlens is suitable for incorporating into lens arrays, since the light diameter and the fill index are not reduced. Another advantage of this tunable microlens is that it is cheap and suitable for mass production. This work can be used in such applications as optical switching, optical memory devices with multiple high-density recording, etc. The compressible plastic tube should subsequently be replaced with an electrotension-compression tube, and then such a microlens will become an electrically controllable microoptical element.

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