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No Moving Parts, Liquid Lens Capability Realization Soon for Mass Production

Refraction Control using Voltage Change

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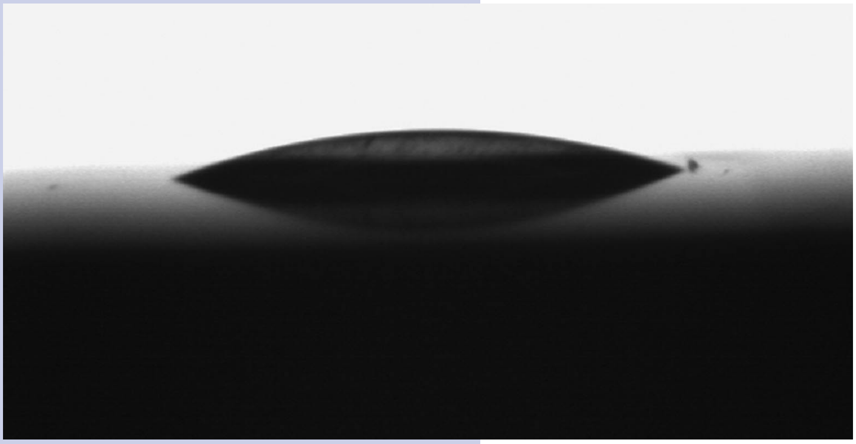


Height of droplet controlled
The height of the oil placed atop a metal plate which is surrounded by non-conductive material can be altered with the input of voltage. The liquid lens makes use of this phenomena. The plate and the oil are within a solution

Contributed Paper

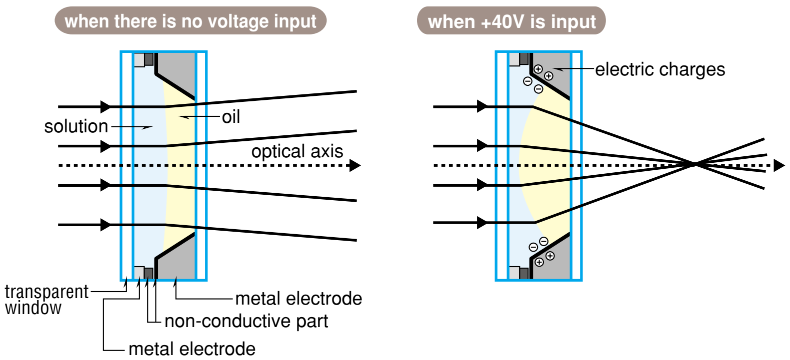
Introduction by T. OTSUKI

One of the problems facing manufacturers of mobile telephones is realization of auto-focus and optical zoom for the phones' camera portion. The problem arises due to the large mounting space required by the camera module. The large space becomes necessary since the lens position must be adjusted mechanically, for movement along the optical axis. This being the case, a bold and befitting solution would be to eliminate the need to move the lens to and fro. Such a solution is being offered by Varioptic of France. This company has developed optical parts called the liquid lens, with mass-production shipment preparations being completed by the end of calendar year 2005. It is expected that Samsung Electro-Mechanics Co., Ltd. of South Korea will produce the liquid lens through use of Varioptic technology. Should the liquid lens be used, Varioptic claims that both production costs and power consumption will be kept down. The person in charge of development at the company describes such advantages and lens performance, while outlining the reliability testing as well as the operational principles of the product. (Tomohiro OTSUKI = Nikkei Electronics)

Otsuki note 1) Varioptic does not disclose the composition of the solution and the oil. In order for both liquids to fulfill the temperature and the optical characteristics desired, it is said that this composition was devised. As for the solution, anti-freeze, etc. is mixed in. The refractive indices of the solution and the oil differ.

We have developed the "liquid lens" which can drastically miniaturize the optical module equipped with the auto-focus or the optical zoom. There is no need to move the lens itself along the optical axis so as to attain the desired refraction power, unlike the conventional solid lens.

(a) Basic structure



(b) Imaging results

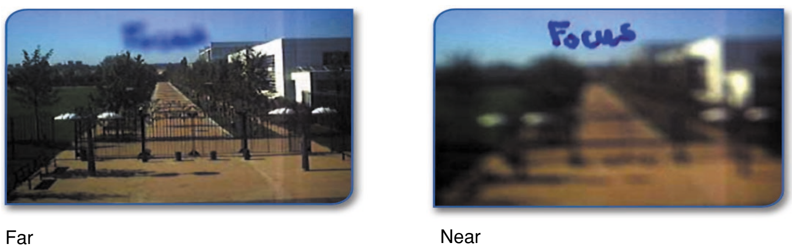


Fig. 1. Light emitted, focused by changing shape of interface
Liquid lens comprises mainly the solution and the oil. The material ingredient of the solution and the oil have not been disclosed. The container for the solution and the oil has been partially coated on the inside with a water-repellant coating. Because of this, when there is not voltage input at the electrode, the repelled solution and oil form a nearly flat interface. This equals the case when the focal point is at infinity. When voltage is input, the electric charge gathers around the non-conductive portion, and the repellency becomes weakened in comparison to the overall repellency due to the surrounding power balance. This results in the interface of the solution and the oil taking the shape of a lens that focuses the light (a); (b) shows the imaging results using the experimental product, at 5cm in front with a focus on the letters there and at infinity.

With this liquid lens, the encapsulated solution/oil interface offers the lens function of convergence and emission. The liquid lens attains the desired refraction power by altering, through input of voltage, the shape of this interface. (**Fig. 1**)[NE Notes 1 and 2]

We will complete preparations as to mass-production shipment of the liquid lens for auto-focus use by the end of calendar year 2005. The sample shipment for mass production will be the "AMS1000" type available at present. (**Fig. 2**) By using one liquid lens attached to the object side and one conventional solid lens attached to the image sensor side, the auto-focus is realized. In addition, it is necessary to mount a driver IC [VIC-040] for the liquid lens integrated into the DC-DC converter.

Upon start-up of mass production, our company's factory — which has a production capacity at present of 100 units per day — will increase its capacity to 1000 units per day. The manufacturing technology of our liquid lens is a very general one, as is the case with press processing of a thin metal plate, and is not so complicated. For this reason, most likely all the manufacturing processes involved can be automated with ease. Already, some processes such as the filling of the liquid, have been automated.

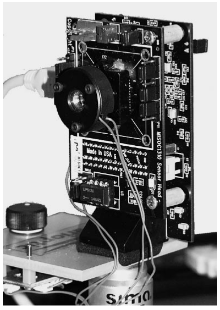
We want to perfect the development of the optical module which realizes 2.5 times the optical zoom by the end of calendar year 2005. (**Table 1**) Three types of lens, the liquid lens for the zoom, the liquid lens for auto-focus and a solid lens, will comprise the optical zoom, in that order from the object side. The distance with the photographic subject that a focus matches (focusing range) is 10cm to infinity. The optical size of the planned image sensor use is the 1/4-in. to 1/3-in. one. The total number of pixels will range from 2 million to 3 million.

The application foreseen for any of the liquid lens is for the mobile phone with an embedded camera. Yet, the small optical module is required in a variety of fields. We are going to develop the liquid lens for use with thin digital camera, endoscope, car-mounted camera, surveillance camera, bar-code reader, etc. in the near future.

Our main business is the provision of technology licenses. For example, a (non-exclusive) license has already been granted to Samsung Electro-Mechanics Co., Ltd. of South Korea. We are making preparations so that a licensee firm can also begin mass production, right after our mass production starts up. (NE Note 3)

(a) External view

(c) Evaluation board



(b) Specifications

External dimensions	diameter 10.5mm x width 2.46mm
Aperture diameter	3.6mm
Focal distance	–200mm ~ +75mm
Coverage distance	5cm ~ ∞
Distortion	rms figure 1µm
Optical transparency at wavelength of 350nm to 700nm	88% ~ 92%
Time needed to change shape of solution/oil interface	Max. 100ms
Guaranteed cycle time	1 million times
Operating temperature range	–25 deg C ~ +60 deg C
Storage temperature range	–40 deg C ~ +85 deg C
Operating voltage	Typically +40Vrms (Max. +60Vrms)
Operating frequency	1kHz
Power consumption	Below 1mW

rms: root mean square

(d) Main parts to be used in combination with liquid lens

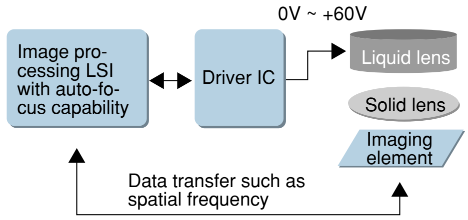


Fig. 2. Outline of AMS1000
(a) Liquid lens AMS1000 with auto-focus whose sample is now being shipped. (b) External view is 10.5mm diameter x 2.46mm width. Operational temperature is between -25 deg C to +60 deg C, meeting the ordinary standards that mobile electronics manufacturers require. (c) We have readied an evaluation board for AMS1000. (d) This board has covered peripheral parts like the VIC-040 Driver IC for liquid lens.

Realizing miniaturization, lower costs and low power consumption

Our liquid lens does not produce the image by itself.[1)] Due to this reason, it is used in combination with a solid lens. The role of the liquid lens is to adjust the distance at which the focus is attained. It may be referred to as fulfilling the role of the "actuator" in an optical system using the solid lens.

In comparison to the solid lens-conventional actuator combination, an optical system using the liquid lens features miniaturization, lower costs and low power consumption (**Table 2**). Rough speaking in terms of miniaturization, the space taken up by the mounting compared with the auto-focus mechanism found in today's mobile telephone may be halved. This is because the space as well as the mechanical parts used to move the lens can be dispensed with.

As for lower costs, this is realized due to the fewer part items required and the easier assembly work involved. We will henceforth push forward plans to lower the price of the

Otsuki note 2) Royal Philips Electronics of the Netherlands is developing a liquid lens. Mr. Etienne Paillard, CEO of Varioptic, said about this in April, 2005 as follows. "The Philips' technology is very similar to our company's. However, unlike that of Philips, our company can use two important patents. They are the WIPO patents No. 99018456 and No. 00058763. We have acquired concessions to both patents from the University of Grenoble in France. Since Philips applied for a patent six years after the patent our company is using, I think the establishment of their patent will be difficult."

Otsuki note 3) Mr. Etienne Paillard, CEO of Varioptic, stated the following. "I want to make the combined mass production scale of our licensee companies and our company into approximately 1 million pieces per month in toto for the future, in not so many years."

Table 1. Target specifications for optical zoom products development is to be completed at end of 2006

Optical zoom ratio	x2.5
Focal distance	4.26mm~10.64mm (35mm film camera equivalent: 42mm~105mm)
Lens components	Liquid lens x 2, Solid lens x 1
Distortion	rms figure: 0.1µm (max 0.5µm)
Image angle when focal distance at 4.26mm	56 deg
F figure	2.8~4 or 5
MTF at 100 cycles/mm	Center 60% Four-fifth overall 40% Overall 20%

MTF: modulation transfer function

liquid lens. The AMS1000 price at mass-production shipment is about 3 Euros per piece, though this will fluctuate depending upon purchase conditions and other factors. We want to place the liquid lens costing 1 Euro per piece on the market around the middle of calendar year 2006. As regards the driver IC, although it will be priced at about 0.8 Euro per piece during the early stages of mass production of the liquid lens, we wish to price it at below 0.5 Euro as of mid-2006.

The optical module using the liquid lens will also have a low power consumption level. Although high voltage — at a maximum of +60 V — is being used, the consumption current is at a mere 120μA. Upon considering phase difference between the voltage and current, the power consumption of the liquid lens is below 1mW. The driver IC we developed also consumes a miniscule amount of power. Overall, it is only about 10mW to 15mW. Our product will output 0V to +60V with an input of about +3V, which is similar to the CMOS sensor in popular use for mobile telephones. [Note 1]

Additionally, enabling an optical zoom for the liquid lens as mentioned above offers an advantage over both the voice coil motor and the piezoelectric element. It seems the manufacturers using the piezoelectric element or the voice coil motor cannot, as to the moving distance of a lens, easily realize an optical zoom with a length of several millimeters (having a large change of refraction power). We have announced already a demonstration of the optical zoom at the “CeBIT 2005” show held in March, 2005 in Germany.

A resolution of 3 million pixels

The liquid lens features a quick response speed as well. It only takes a maximum of 100ms for the focus that matches the distance to the photographic subject to go from 5cm to infinity. This speed changes according to the temperature of the surrounding environment. Liquid in general increases viscosity within a low-temperature environment. Even the liquid we use for the liquid lens is not an exception to the above rule so it takes more time for the interface shape to be altered. Yet, it is usually not a problem upon practical use. The AMS1000 samples being shipped now can change the focus to match the distance in under 100ms within a –25 deg C environment. Among the materials we have found, there are some that take only 30ms to alter the shape within a –20 deg C environment.

Acceptable results have been obtained concerning liquid lens resolution. If a person uses a camera under conventional temperature conditions, the optical size can in combination with a regular quality solid lens handle the 1/4-in. 3-million pixel image sensor. The distortion value to which the image is projected through the lens distortion due to slackness in shape is 0.1μm for AMS1000 in the rms (root-mean-square) value. [Note 2][NE Note 4] Since the interface tension between the liquids is in operation, the lens side of the liquid lens has a very high level of smoothness. The sur-

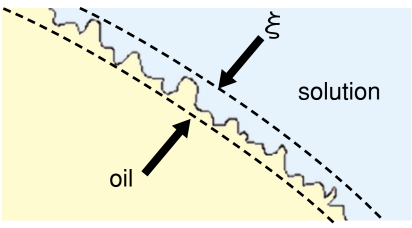
Note 1) The technical requirements for which the driver IC of the liquid lens are similar to the piezoelectric device and the voice coil motor. Regarding VIC-040, it was manufactured using the standard CMOS process by UMC (United Microelectronics Corp.) in Taiwan.

Note 2) The distortion here shows the difference between the wave face of the light passed along the liquid lens and its ideal form. Since the measurement method of the distortion of the solid lens was inapplicable to the liquid lens, it has been measured using our original system.

Otsuki note 4) Technically speaking, if the number of electrodes inside the liquid lens is increased and the arrangement location is devised, the interface of the non-surface of a sphere can be formed between the solution and the oil. Control of distortion represented by the surface-of-a-sphere distortion becomes easier. The distortion is a general term for the gap between the ideal images and images made through a lens.

Table 2. Liquid lens, better than other methods
Based on our study results, a comparison in general of the merit loss as to power source for auto focus is offered.

Power source for auto focus	Stepping motor	Voice coil motor	Peizoelectric element	Liquid lens
Ease of miniaturization	△ (Many parts)	○	○	○
Response time	△ (over 0.1 sec.)	○	○	○
Impact resistance	△	△	△	○ (No mechanical parts)
Power consumption for Driver IC	△ (50mW)	n/a	n/a	○ (10-20mW)
Ease of lens module assembly	×	△	△	○ (No mechanical parts)
Lowness of manufacture costs	△	○	△	○



Change in interface by heat addition

$$\xi \fallingdotseq \sqrt{K_B T/\gamma_{OW}}$$

K_B : Boltzmann constant
T : Absolute temperature
γ_{OW} : Surface tension of liquids

Fig. 3. Fairly smooth lens surface
The surface fineness of the interface between the liquids are at a practically useful level. The formula indicating the interface change ξ due to heat addition is shown here.

face coarseness is approximately only 0.3nm (**Fig. 3**).[2)]

We consider the liquid lens reliability to be at a level that meets the one required by mobile telephone manufacturers and others. There are not a few engineers who fear that the container which holds the liquid will break due to the shock from a fall. We need to withhold public disclosure since we are yet to begin mass-production shipment, but test results should show that such fears can be allayed. We are conducting tests repeatedly as to operation within the +85 deg C and the –40 deg C environment, respectively, under continuous voltage input over a 20-day period or upon 1.5m falls repeated 20 times at differing angles, and obtaining good results.

Reason why an interface can be controlled with voltage change

There are three major factors that made the realization of the liquid lens possible. Namely, these are (A) the technology that controls the interface of a liquid through voltage change, (B) the maintenance of equal density for the two liquids, and (C) keeping stable the shape of the "droplet." The high-speed response and low power consumption for the liquid lens are realized by (A), (B) and (C) are of importance upon realizing the quality of a practical lens.

We refer to the interface control technology through use of voltage change as "electrowetting."[3)-6)] The liquid lens has the structure comprising two transparent windows and containing two liquids, these being a solution and an oil, that are kept separate. There are three interfaces to be found insider, and the interface shape used as the lens is determined by the balance of the tension produced at each interface (**Fig. 4**). Electrowetting alters the power balance between the three by inputting the voltage, in order to control the shape of the interface.

Prior to voltage input, the state is such that the interface between the solution and the oil — being used as the lens — and the angle θ formed with the electrode is comparatively small. If the interface tension produced in each interface between the solid electrode and the solution (SW), between the oil and the solution (OW) and between the solid electrode and the oil, are named γ_{SW}, γ_{OW} and γ_{SO}, respectively, θ is determined by the Young-Laplace equation:[7)]

$$\cos\theta = \frac{(\gamma_{SW} - \gamma_{SO})}{\gamma_{OW}}$$

If this angle is chosen appropriately, when the voltage in not input, the position where the focus matches will be at infinity. We provided water-repellent coating on a portion of the container, in order to adjust the angle of θ.

Next, if a high voltage of +40V is applied to the electrode of the liquid lens, another power will arise due to static electricity. Between the liquid lens electrodes, one is in contact with the conductive solution, while the other is covered with a thin insulator and in contact with both the solution and the insulating oil. Consequently, an electric charge

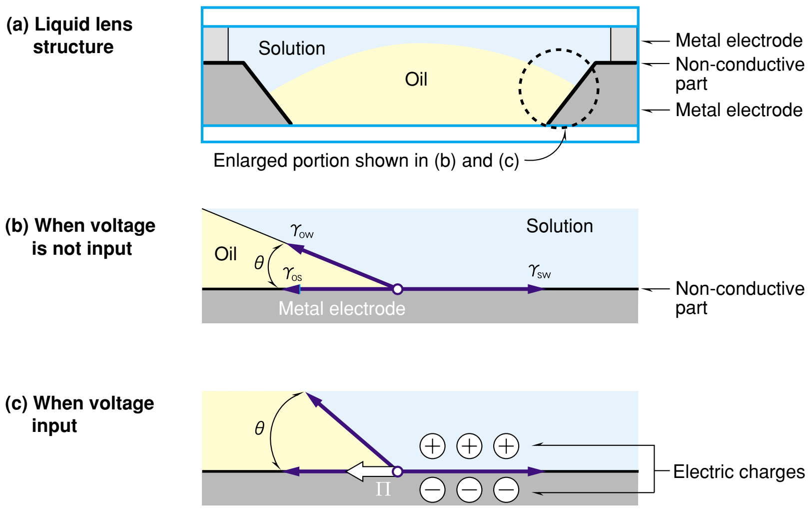


Fig. 4. Interface tension (power) changes
Within the liquid lens, 3 types of power (surface tension) occur (a). Power that acts between electrode and solution (SW), oil and solution (OW) and electrode and oil (SO), respectively shown by γ_{SW}, γ_{OW} and γ_{SO}. When no voltage is input the three surface tensions and the angle (θ) at the metal electrode and oil convergence portion can be indicated using the Young-Laplace $\cos\theta = (\gamma_{SW} - \gamma_{SO})/\gamma_{OW}$ (b). When voltage is input, the power resulting from electric charge (Π) is born (c). <Π> is indicatged by the formula $1/2 \cdot (\varepsilon\varepsilon_0)/e \cdot V^2$ Here, ε is the electroconductive rate at the non-conductive part, ε_0 is the vacuum electroconductive rate, *e* is the width of the non-conductive part, and *V* is the input voltage. At time of voltage input, the relationship between θ and the respective surface tension is indicated by the formula $\cos\theta = (\gamma_{SW} - \gamma_{SO})/\gamma_{OW} - 1/2 \cdot (\varepsilon\varepsilon_0)/e \cdot V^2$.

arises at the interface between the insulated electrode and solution. The electric charge gives rise to the power (Π) shown in **Fig. 4**, and the angle of θ changes. Π and θ respectively are described by:

$$\Pi = \frac{1}{2}\cdot\frac{\varepsilon\varepsilon_0}{e}\cdot V^2$$

$$\cos\theta = \frac{(\gamma_{SW} - \gamma_{SO})}{\gamma_{OW}} - \frac{1}{2}\cdot\frac{\varepsilon\varepsilon_0}{e}\cdot V^2$$

Here, ε stands for the dielectric constant of the insulated part; ε0, for a vacuum dielectric constant; e, for the thickness of an insulated part; and V, for voltage. The formula shows that θ increases before voltage input, and the shape of the interface comes into focus at a specified distance.

By modifying the interface with electrowetting, there is little energy which must be added from the outside. We assume there are other methods where the structure differs completely from our product, i.e., in terms of the container, inside which the liquid is placed, being separated into two using a thin film and liquid being sent in using an external pump, and thus moving the film. Much pressure must be applied in order to make the thin film move when using such a structure. At least ten times the energy that we use with our system is needed in order to alter the shape of the interface. Thus, much electric power and time become necessary for such methods.

In fact, though there is not much influence exerted by interface tension over electrowetting power, another power also become involved simultaneously (**Fig. 5**). One also has to consider such influence, upon designing the liquid lens.

Note 3) The influence of lineic forces increases in proportion to $K\varepsilon\varepsilon_0 V^2 L$ Log L. K is for the absolute temperature, ε is for the dielectric constant of an insulated part, ε0 is for the vacuum dielectric constant and L is for the length of the contact line of the solution, the oil and a solid.

One power acts upon the entire volume of the liquid (volumic force). Wang *et al.* recently found that there was an interaction between the power resulting form the water molecule attracted by the strong electric charge. Another is the power acting as a line at the location which the three electrodes touch the solution and the oil (lineic force). This lineic force leads to instability of the interface when the electric charge intensity for the liquid lens is raised.(Note 3)

The material and the container form the key

Upon raising the quality of the liquid lens, the respective density of the two liquids must be equalized as much as possible within the usage temperature range. Should there be much difference between the two densities, a coma aberration will arise. The coma aberration refers to the asymmetrical dotage, with a "tail" extended like that of a comet, which is formed on the image sensor by the light entering the optical axis of the lens from an askew angle thereto.

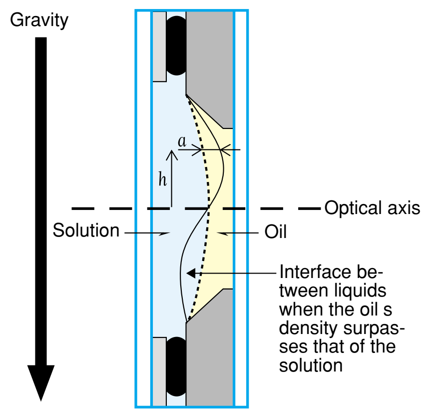


Fig. 6. Coma aberration may occur due to gravitational pull
The oil and the solution used in the liquid lens needs to maintain equilibrium in density (weight according to each unit volume) over a wide range of temperatures. There is a possibility that coma aberration will occur when the density balance is altered. Coma aberration means the occurrence of blurring which looks like a tail has been stretched across the image surface. Fig. shows case of the interface between liquids when the oil's density surpasses that of the solution, as shown by the thin reverse S line. a stands for the surface position that has strayed away from the desired position at a distance h from the optical axis. It has been found for AMS1000, h is 0-1.5millimeter range and coma aberration occurs at a of 0.5μm.

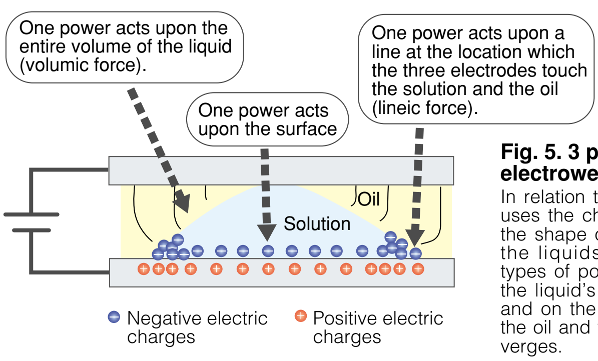


Fig. 5. 3 powers that relate to electrowetting
In relation to "electrowetting" which uses the change in voltage to alter the shape of the interface between the liquids, there are actually 3 types of power. Power that acts on the liquid's volume, on the surface and on the line where the solution, the oil and the metal electrode converges.

An example of an interface where the densities differ is shown in **Fig. 6**. Because the density of the oil exceeds that of the solution, a "reverse S" curve appears at the interface of the two liquids. Should the interface be in such a state, the coma aberration will arise.

Such a situation occurs when the surrounding temperature changes and if the gap in the densities of the solution and the oil should widen. To prevent such a problem, the $\Delta\rho/\rho$ must be kept below 10^{-2}, $\Delta\rho$ being the two liquids' density gap and ρ being the density average of both liquids. Since the heat expansion rate for water is quite small compared with oil, etc., it is not easy to find a material that realizes this (10^{-2}) condition. The reason why we can soon start mass-production shipment is that we have been able to meet said required condition over a wide range of temperatures with our solution and oil. (Note 4)

One crucial matter to be kept in mind upon making the liquid lens on a commercial basis is the need to prevent the appearance of the optical axis differential. A solid lens can adjust the optical axis location using a conventional lens holder and a body tube. In comparison, the liquid lens cannot use the same items only in order to adjust the optical axis. For example, hysteresis may arise due to the friction between the liquid and the container upon modification of the interface, and the interface shape may become asymmetrical. It is necessary to devise a method, enabling the liquid itself to return to the original shape on a spontaneous basis, to prevent such a problem from occurring.

This can be realized if the shape of the container for storing the liquid can be devised.(**Fig. 7**) The container shape is designed to fully minimize the potential energy when the interface attains the wanted state. By doing so, even if the interface is altered the power works toward the return to the original shape. This power can be increased to a maximum of 0.1N/m. By deftly utilizing this method, the interface can be controlled at an order of several micrometers.

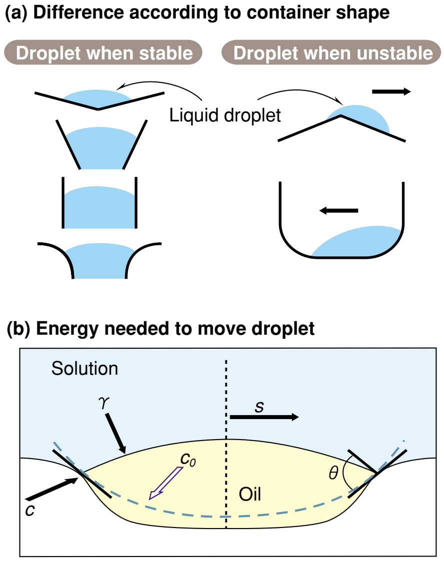


Fig. 7. Centering the droplet
Comparison of examples of container shape (a).
In the actual liquid lens, the container designed so that the center of the liquid is set to make it difficult for the drop to move. The required energy (ΔE) to move the liquid sideways a distance of S is indicated by the formula $\Delta E = (c_0 - c)\,\gamma\, r \sin\theta\, s^2$.
s: movement amount of the oil indicated in Fig.
c and c0: respective instance (reverse of radius to instance)
γ: surface tension of interface between solution and oil
r: radius of oil droplet
θ: angle to each interface angle indicated

Note 4) Considering the environment in which an end-user actually makes use of our product, the solution and the oil are prepared in order for the coma aberration, one type of image-quality degradation, to be minimized to +25 deg C.

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