AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **99**, 213505 (2011); doi: 10.1063/1.3663633

View online: http://dx.doi.org/10.1063/1.3663633

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v99/i21

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Electrowetting based infrared lens using ionic liquids

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(Received 4 October 2011; accepted 31 October 2011; published online 22 November 2011)

We demonstrated an infrared variable focus ionic liquids lens using electrowetting, which could overcome the problems caused by use of water, e.g., evaporation and poor thermostability, while keeping good optical transparency in visible light and near-infrared region. Besides, the type of lens (convex or concave) could be tuned by applied voltage or refractive index of ILs used, and the transmittance was measured to exceed 90% over the spectrum of visible light and near-infrared. We believe this infrared variable focus ionic liquids lens has a great application prospect in both visible light and infrared image systems. © *2011 American Institute of Physics*.
[doi:10.1063/1.3663633]

Electrowetting-based variable-focus liquid lens (EVFLL), on account of miniaturization, celerity, low power consumption, and durability, has attracted considerable attention for various optical systems.[1,2] However, the most frequently used conductive liquid in EVFLL is limited to water, which inevitably caused problems such as evaporation, tedious addition of inorganic salts to enhance its electrical conductivity, unsuitability in extreme conditions such as high/low temperature, and poor transmittance in near-infrared even in most region of infrared. Therefore, development of robust media for EVFLL is highly desirable.

Recently, room temperature ionic liquids (RTILs or ILs) have emerged as a class of versatile solvent and soft material due to its negligible vapor pressure, liquid in wide temperature range, intrinsic ionic conductivity, acceptable electrochemistry stability, good optical transparency, etc.[3,4] These unique physicochemical properties render them potential candidates for electrowetting as well as EVFLL.[5–8]

Herein, we report the ILs-based EVFLL, which can overcome all the mentioned problems above while keeping good optical transparency in visible light and near-infrared region. As shown in Fig. 1, a custom-built ILs-based EVFLL was proposed according to the typical fabrication reported by Kuiper *et al*.[9]

The lens can be driven by a direct as well as an alternating voltage. In this paper, 1 kHz AC voltage instead of DC signal was applied since high frequency AC electric field facilitate stable and high efficiency electrowetting of ILs, as reported by us and others.[10–12] When applying voltage across the insulator, the electric field changes the wettability of ILs and lowers the interfacial tension between ILs and the insulator effectively,[13–15] which leads to the curvature of the meniscus changed from convex to flat and then to concave [Figs. S5(a)–S5(c) in supplemental material[17]] based on the principle of electrowetting; thus, variable focus was achieved. We use a direct voltage of typically 85 V to cover the full range required for commonly use. This only requires energy of 0.1 mJ to charge the equivalent capacitor formed by the steel wall electrode and the ILs.[16] A decrease in Parylene thickness and interfacial surface tension (e.g., by adding surfactants) could lower the voltage.

First, the relations between focal length and voltage with different ILs were tested [Fig. 2]. The application of an AC electric field as a function of the type of cation and anion exhibits a remarkable change in focusing behavior of ILs-based EVFLL. As for $[EMIm]^+$-based EVFLL, significant difference in optical property (f_0, f, and focusing curves) occurs upon changing the anions. $[EMIm][HSO_4]$-based EVFLL exhibits positive focal length ($f > 0$); however, $[EMIm][BF_4]$-based EVFLL showed a negative focal length, which is similar with H_2O-based EVFLL. The different focusing behavior could be explained as following. Because of higher surface tension than dodecane ($\sigma_{\mathrm{Ils}} - \sigma_{\mathrm{dodecane}} > 0$), the interface between ILs and dodecane presents a convex profile at first [Fig. S5(a) supplemental material[17]]. Consequently, the type of lens (convex or concave) is determined by the refractive index difference value ($\Delta n = n_{\mathrm{ILs}} - n_{\mathrm{dodecane}}$). If Δn is less than zero ($n_{\mathrm{ILs}} < n_{\mathrm{dodecane}}$), the lens exhibits a concave lens; on the contrary, if Δn is greater than zero ($n_{\mathrm{ILs}} > n_{\mathrm{dodecane}}$) the lens presents a convex lens.

For a given ILs-based EVFLL, where refractive index of dodecane (n_{Dod}), radius of the cylinder (r), dielectric constant (ε_r), and thickness (t) of insulating layers remain constant, considering initial contact angle (θ_0) is a function of

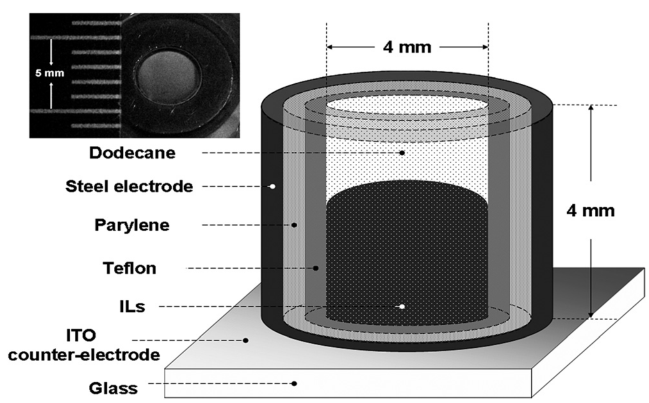

FIG. 1. Schematic of an ILs-based EVFLL.

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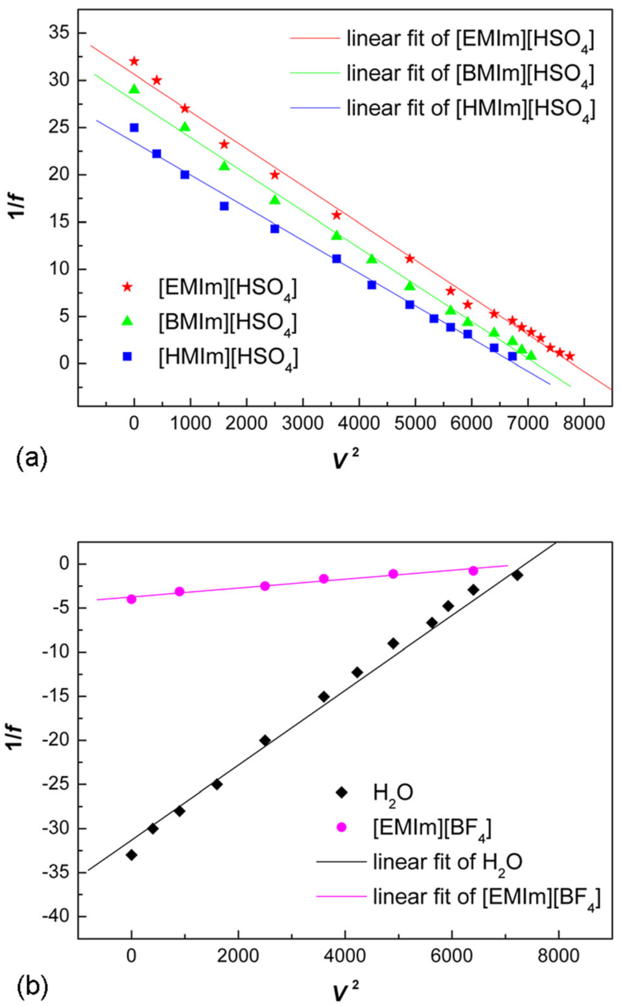

FIG. 2. (Color online) Change of reciprocal of focal length (f) with square of the applied voltage (V) at room temperature. The solid lines are linear fits of experimental data. (a) For [EMIm][HSO_4], [BMIm][HSO_4], and [HMIm][HSO_4]-based EVFLL. (b) For [EMIm][BF_4] and H_2O-based EVFLL.

interface tension between ILs and dodecane ($\sigma_{\text{ILs-Dod}}$), and $\sigma_{\text{ILs-Dod}}$ is directly proportional to surface tension of ILs (σ_{ILs}); the focal length (f) depends only on applied voltage (V), surface tension (σ_{ILs}), and refractive index (n_{ILs}) of ILs as in the following equation[16]:

$$\frac{1}{f} = \left(\frac{n_{\text{Dod}} - n_{ILs}}{r}\right)\left(\cos\theta_0 + \frac{\varepsilon_0\varepsilon_r}{2t\sigma_{\text{ILs}-Dod}}V^2\right) = a + bV^2. \tag{1}$$

According to Eq. (1), the reciprocal of focal length (f) is in proportional to the square of the applied voltage (V^2). The fitted values of the free parameters, a and b, nearly changed with the order of their surface tensions and refractive indices [Fig. 2 and Table I]. For H_2O and [EMIm][BF_4]-based EVFLL, which presents concave lenses ($f < 0$), a is positive while b is negative. In the contrary, For [HSO_4]-based EVFLL, which exhibits convex lenses ($f > 0$), a is negative and b is positive.

The applied voltage (V) to obtain the same focal length (f) presents $V_{[\text{EMIm}][\text{HSO4}]} > V_{[\text{BMIm}][\text{HSO4}]} > V_{[\text{HMIm}][\text{HSO4}]}$. It is because that the square applied voltage (V^2) is in proportion to interface tension ($\sigma_{\text{ILs-Dod}}$) between ILs and dodecane (thus the surface tension of ILs (σ_{ILs})) according to Eq. (1), and longer alkyl chain length of cation guarantees lower surface tension of ILs (σ_{ILs}) [Table SI in supplemental material[17]], so the longer alkyl chain length of cation the lower applied voltage was required to reach the same focal length (f). Thus, [HMIm][HSO_4]-based EVFLL, whose surface tension and refractive index are the least, required a lower voltage (V) to reach the same focal length (f). Hence, our experimental results demonstrate that long alkyl chain could be better choice to reduce the focusing voltage for imidazolium ILs-based EVFLL.

It is demonstrated that there was no obvious variation of the focal length when the drop volume were 20, 30, and 40 μL [Fig. S6 in supplemental material[17]]. As is well-known the contact angle is determined by the balance of interfacial tensions and does not depend on the volume unless the volume is a few orders of magnitude smaller than discussed here, when line tension effects begin to play a role. Consequently, the curvature of the meniscus kept constant with drop volume varying, and thus the focal length.

Considering the lens diameter (r) is one of the parameters of the system as described in Eq. (1), the effect of the lens diameter on the focal length was investigated. Three lenses tube were prepared with diameter 3, 4, and 5 mm. Each lens was injected with 30 μL [EMIm][ClO_4], respectively. Then the focal length (f) was recorded with driving voltage (V) varying. It is demonstrated that, for identical volume of ILs, increasing diameter (r) of the lens obviously increased the focal length (f) under the same driving voltage (V), and so did the initial focal length (f_0) [Fig. S7 in supplemental material[17]]. The theoretical derivation accord with the experiment results very well. Firstly, according to Eq. (1), larger diameter (r) of the lens guarantees larger initial focal length ($f_{0,\,5\,\text{mm}} > f_{0,\,4\,\text{mm}} > f_{0,\,3\,\text{mm}}$), and then $0 > \cos\theta_{0,\,5\,\text{mm}} > \cos\theta_{0,\,4\,\text{mm}} > \cos\theta_{0,\,3\,\text{mm}}$. Both larger diameter ($r$) of the lens and $\cos\theta_0$ guarantee larger focal length (f) under the same driving voltage (V), according to Eq. (S4) in supplemental material.[17] Thus, increasing the diameter of the lens increased the initial focal length (f_0) and the focal length (f) under the same driving voltage (V).

Change the thickness of insulating layer was also found to affect the focusing property of ILs-based EVFLL [Fig. S8 in supplemental material[17]]. It could be concluded that thinner thickness of insulating layer guarantees lower focusing voltage to obtain the same focal length. Considering reducing energy consumption, thinner insulating layer should be chosen preferentially in practical application. However, according to our experiment, the very thin (<1 μm) insulating layer turns unreliable and could be easily broken down;

TABLE I. Fitted values of the free parameters, a and b for H_2O and four ILs-based EVFLL investigated.

Compound	a	b
H_2O	−31.91	0.0045
[EMIm][BF_4]	−3.74	0.0005
[EMIm][HSO_4]	30.62	−0.0039
[BMIm][HSO_4]	27.86	−0.0038
[HMIm][HSO_4]	23.44	−0.0034

TABLE II. Measured characteristics of [EMIm][BF_4]-based EVFLL.

Applied voltage (V)	20	40	60	80	100	120	140
Focal length (mm)	−30	−45	−68	−190	160	60	41
Power (mW)	0.8	1.4	2	2.9	3.7	4.6	5.8
Transmittance (%)	93.7	94.2	94.4	94.8	95.3	95.6	96.8
Actuation time (S)	0.18	0.21	0.23	0.23	0.26	0.29	0.33
Relaxation time (S)	0.28	0.39	0.55	0.68	0.89	1.05	2.36

besides, the adhesion becomes poor. Consequently, 5 μm might be a nice choice, in consideration of both efficiency and reliability.

Another important aspect of ILs-based EVFLL is good transmittance in near-infrared (800–1100 nm). The transmittance of ILs and H_2O at normal incidence was characterized by Agilent 8453 UV-visible diode array spectrometer (Agilent, USA), as shown in Fig. S9(a) in supplemental material.[17] H_2O showed an obviously absorption peak at ~980 nm, which would greatly weaken the light intensity and limit the imaging performance of H_2O-based EVFLL in near-infrared area. However, ILs shows a good transmittance in the spectrum of both visible light and near-infrared. The transmittance of ILs was measured to exceed 90% between 400 and 1100 nm, and it could be further improved by using antireflection coatings on the glass. In addition, the transmittance of both ILs and H_2O-based EVFLL at 980 nm were tested too. The experimental results were shown in Fig. S9(b) in supplemental material.[17] It could be easily obtained that the transmittance of ILs-based EVFLL was measured to exceed 90% and independent of ILs volume. However, the transmittance of ILs-based EVFLL was demonstrated to be connected with volume of H_2O. That is because the transmittance of ILs and dodecane was greater than 90%, but that of H_2O is less than 65%. Thus, larger volume of H_2O guarantees less transmittance of H_2O-based EVFLL; the transmittance of ILs-based EVFLL keeps almost unchanged. Consequently, the ILs-based EVFLL could have a big potential in near-infrared image system since most ILs are optical transparent in this region.

The measured characteristics of [EMIm][HSO_4]-based EVFLL are listed in Table II. The maximum power consumption was measured to be 5.8 mW. The Actuation time (i.e., the time for the interface curve to reach its final shape after the voltage is applied) was less than 400 ms. The Relaxation time (i.e., the time for the interface curve to reach its initial shape after the voltage is removed) depends on the deformation ratio. Higher applied voltage guarantees larger deformation ratio, thus longer relaxation time. The maximum deformation recovery was achieved in about 1.5 s.

In the top of Fig. 3, three infrared images are presented. The gloomy one [Fig. 3(a)] was taken through H_2O-based EVFLL due to the poor transparency of H_2O in near-infrared. However, pictures taken through ILs-based EVFLL [Figs. 3(b) and 3(c)] presented good performance during the operating voltage range. Furthermore, the resolution of ILs-based EVFLL was measured by collimator [Fig. 3(d)]. It was 231 lines/mm, which might be further improved by using antireflection coatings on the glass.

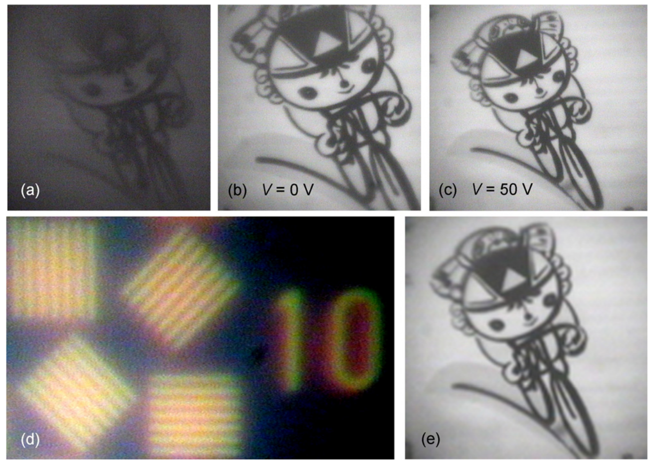

FIG. 3. (Color online) (a) Pictures taken by a CCD through a H_2O-based EVFLL at 980 nm. The captured infrared images of [EMIm][BF_4]-based EVFLL at the rest state (b) and at 50 volts (c). (d) Imaging of resolution chart through ILs-based EVFLL. (e) Movie of the focal length tuning of the [EMIm][BF_4]-based EVFLL in the infrared light irradiation (enhanced online) [URL: http://dx.doi.org/10.1063/1.3663633.1].

To conclude, an ILs-based EVFLL was introduced in this letter. The ILs-based EVFLL could continuously vary its focal length with voltage applied and demonstrated perfect transmittance over the spectrum of both visible light and near-infrared compared to H_2O-based EVFLL. Besides, the type of lens (convex or concave) could be tuned by applied voltage or refractive index of ILs used. We believe that the ILs-based EVFLL can be applied in both visible light and infrared image systems.

The authors acknowledge National Natural Science Foundation of China (Nos. 21103208, 21173240, and 20533080), Science and Technology support program of Gansu Province (No. 1011GKCA018) for financial support.

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[17] See supplementary material at http://dx.doi.org/10.1063/1.3663633 for details of the fabrication process, ionic liquid characterization, physical measurements, and other experiment results.