Supplementary Material (ESI) for Lab on a Chip

Dynamically reconfigurable liquid-core liquid-cladding lens in a microfluidic channel

Supplementary Information

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Figure S1. Microscope images of 6–μm beads suspended in water flowing in expansion chambers with the following geometries: (a) square, (b) square with rounded corners, and at the following flow rates: (i) 1 mL hr^{-1}, (ii) 10 mL hr^{-1}, (iii) 20 mL hr^{-1}, and (iv) 50 mL hr^{-1}, respectively. The length and width of the expansion chamber are both 1 mm. Recirculation zones are prominent at 50 mL hr^{-1}.

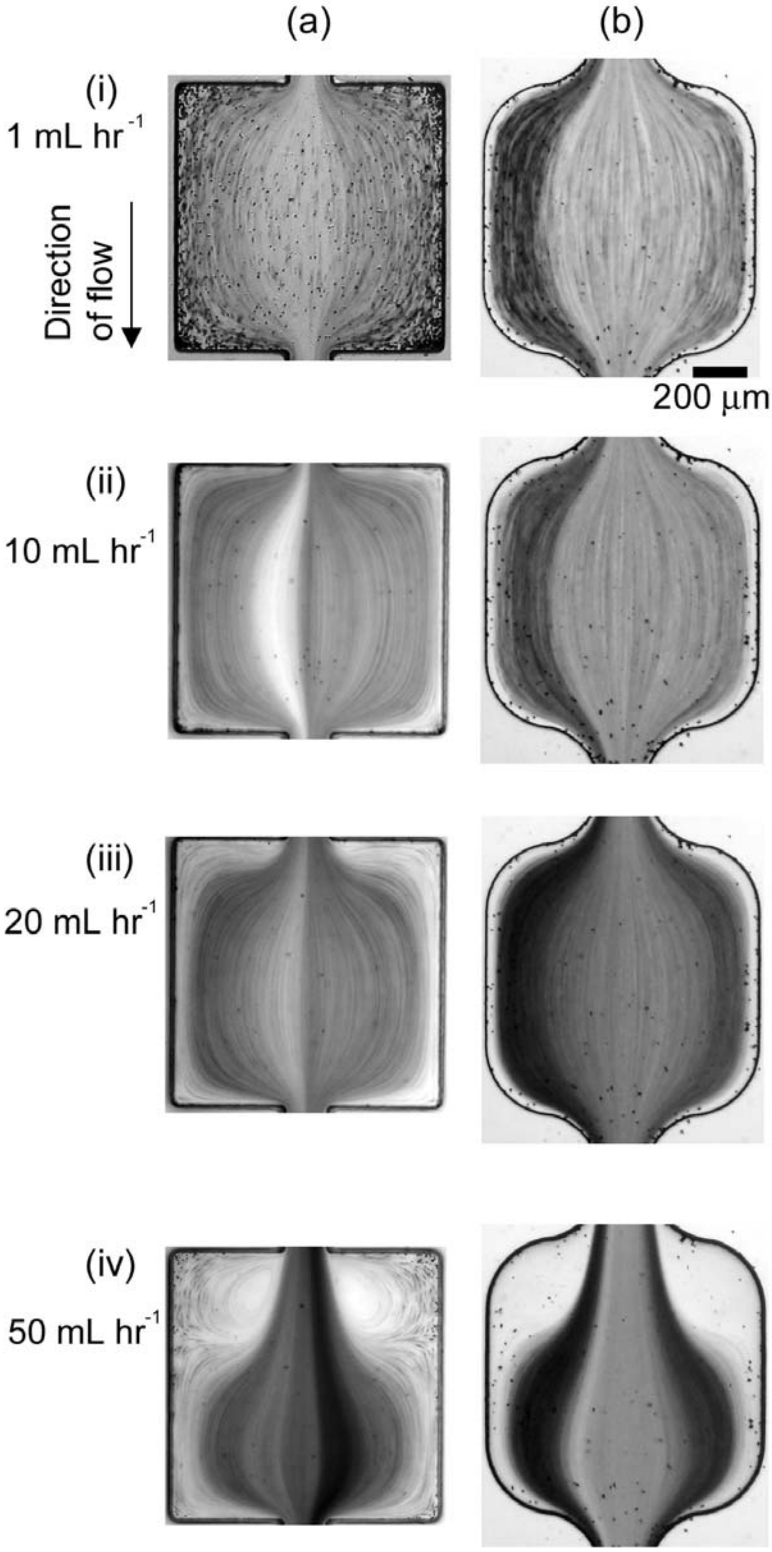
(a)
(b)
(i)
1 mL hr-1
Direction of flow
200 µm
(ii)
10 mL hr-1
(iii)
20 mL hr-1
(iv)
50 mL hr-1

Figure S2. Radius of curvature ($R_{curvature}$) of the core-cladding interface of the L^2 lens as a function of time (t) using (a) a 10 mL-plastic syringe (Becton Dickinson 'Luer-Lok' series), and (b) a 1 mL-glass syringe (Hamilton Gastight series), respectively, when the rate of flow of the core stream changed from 6 to 1.5 mL hr^{-1} at time $t = 0$. The total flow rate of the core and both cladding streams was fixed at 10 mL hr^{-1}. The core liquid was benzothiazole, and the cladding liquid was methanol. The data were extracted from movies of the L^2 lens recorded with a high-speed digital camera (Phantom v7, Vision Research) at (a) 10 and (b) 100 frames per second respectively. The lines are fits to the data using the following expression:

$$R_{curvature}(t) = R_{curvature}(t = \infty) + \Delta R_{curvature}\, e^{-\frac{t}{\tau}},$$

where $\Delta R_{curvature} = R_{curvature}(t = \infty) - R_{curvature}(t = 0)$

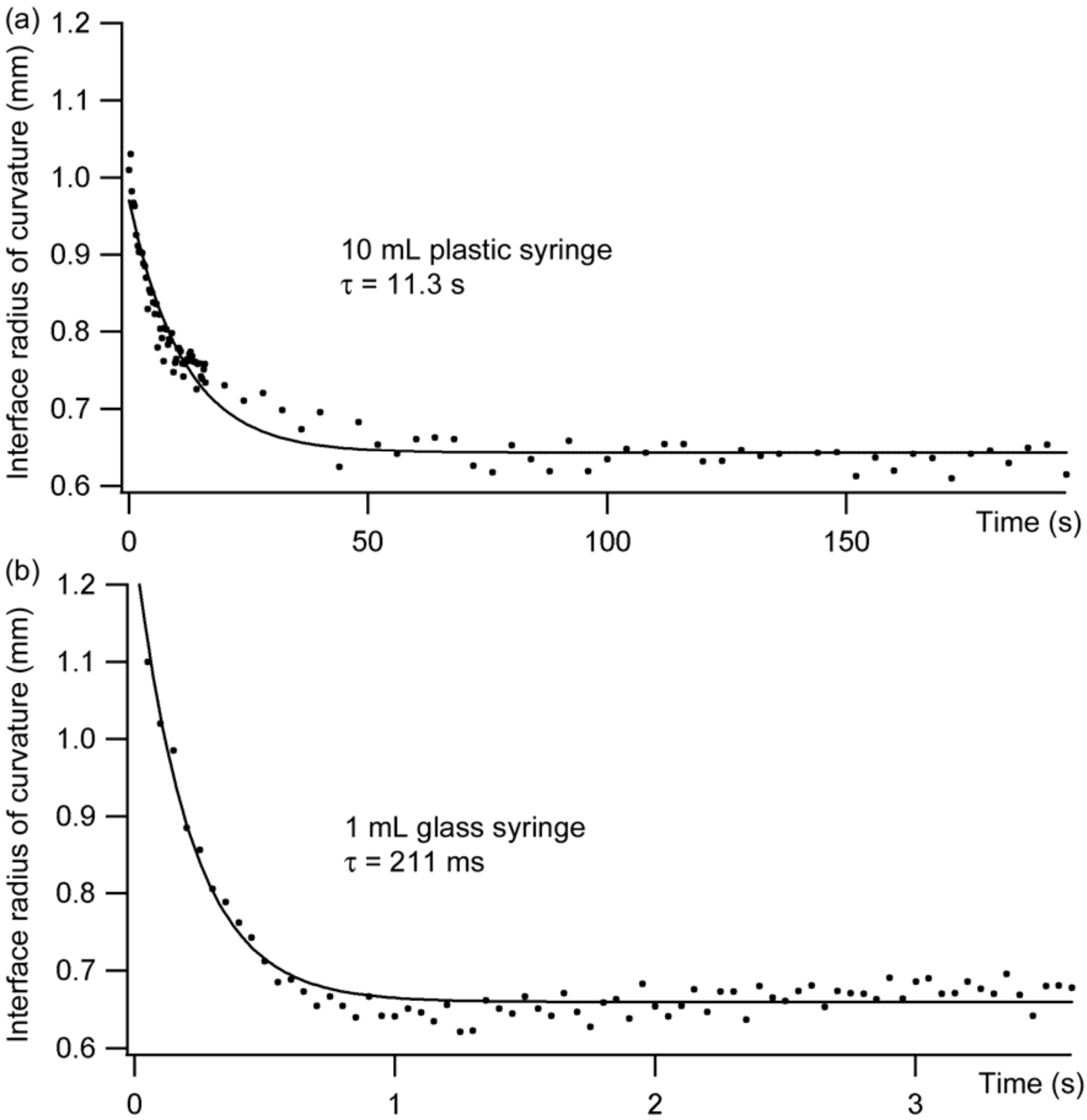
(a)
Interface radius of curvature (mm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
10 mL plastic syringe
τ = 11.3 s
0
50
100
150
Time (s)
(b)
Interface radius of curvature (mm)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
1 mL glass syringe
τ = 211 ms
0
1
2
3
Time (s)

Figure S3. Radius of curvature ($R_{curvature}$) of the core-cladding interface of the L^2 lens as a function of time (t) using (a) a 10 mL-plastic syringe (Becton Dickinson 'Luer-Lok' series), and (b) a 1 mL-glass syringe (Hamilton Gastight series), respectively. The rates of flow of the core and the cladding streams were kept constant at 6 mL hr^{-1} and 4 mL hr^{-1} respectively. The core liquid was benzothiazole, and the cladding liquid was methanol. The data were extracted from movies of the L^2 lens recorded with a high-speed digital camera (Phantom v7, Vision Research) at (a) 10 and (b) 100 frames per second respectively.

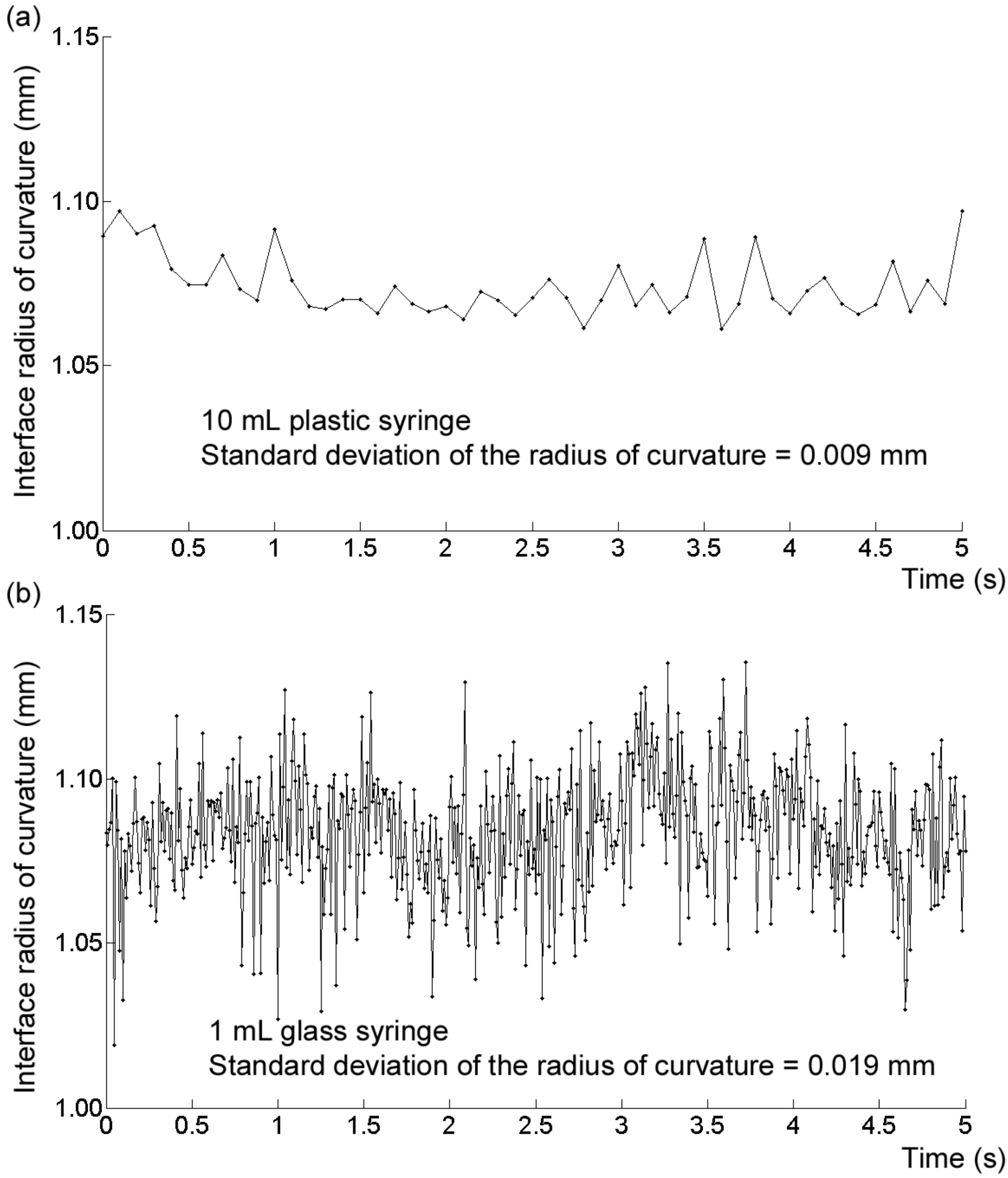
(a)
1.15
1.10
1.05
1.00
Interface radius of curvature (mm)
10 mL plastic syringe
Standard deviation of the radius of curvature = 0.009 mm
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)
(b)
1.15
1.10
1.05
1.00
Interface radius of curvature (mm)
1 mL glass syringe
Standard deviation of the radius of curvature = 0.019 mm
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (s)

Figure S4. The variation in beam width as a function of the distance from the center of the L^2 lens (x_1) in a device with a 334-µm aperture. The data were recorded using a CCD camera through a microscope objective with 5x magnification and a lens tube with a further 1.6x magnification. The line is a hyperbola fitted to the data. The core liquid was benzothiazole, and the cladding was a mixture of 53.6% trifluoroethanol, 31.5% benzothiazole and 14.9% ethanol with effective refractive index matched to that of PDMS (n_D^{22} = 1.412), and density matched to that of benzothiazole in the core stream (ρ = 1.24 g cm^{-3}). The flow rates of the core and cladding streams were at 5 mL hr^{-1}, and 5 mL hr^{-1} respectively. The minimum FWHM was approximately 16 µm.

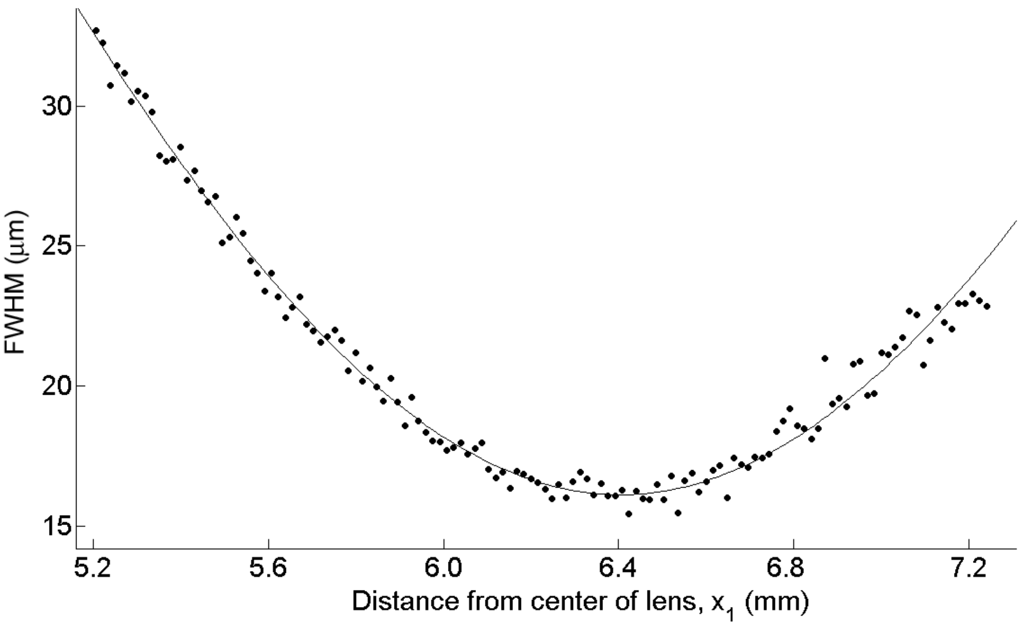

Figure S5. (a) Optical micrograph of the focused beam with no aperture in front of the expansion chamber for a L^2 lens formed using benzothiazole as the core liquid, and a mixture of 53.6% trifluoroethanol, 31.5% benzothiazole and 14.9% ethanol with effective refractive index matched to that of PDMS (n_D^{22} = 1.412), and density matched to that of benzothiazole in the core stream (ρ = 1.24 g cm^{-3}) as the cladding. The flow rates of the core and cladding streams were at 4.5 mL hr^{-1}, and 5.5 mL hr^{-1} respectively. The beam-tracing chamber was filled with rhodamine 640 perchlorate in ethylene glycol. (b) Intensity profile of fluorescence of the focused beam (blue dots) in (a) at x_1 (distance away from the center of the L^2 lens) = 8.6 mm. The FWHM was approximately 40 μm. We also plotted the intensity profile of an unfocused beam (black dots) at the same point in the beam-tracing chamber with no lens. The lines are Gaussian curves fitted to the data. The peak intensity of the focused beam was enhanced approximately 9 times.

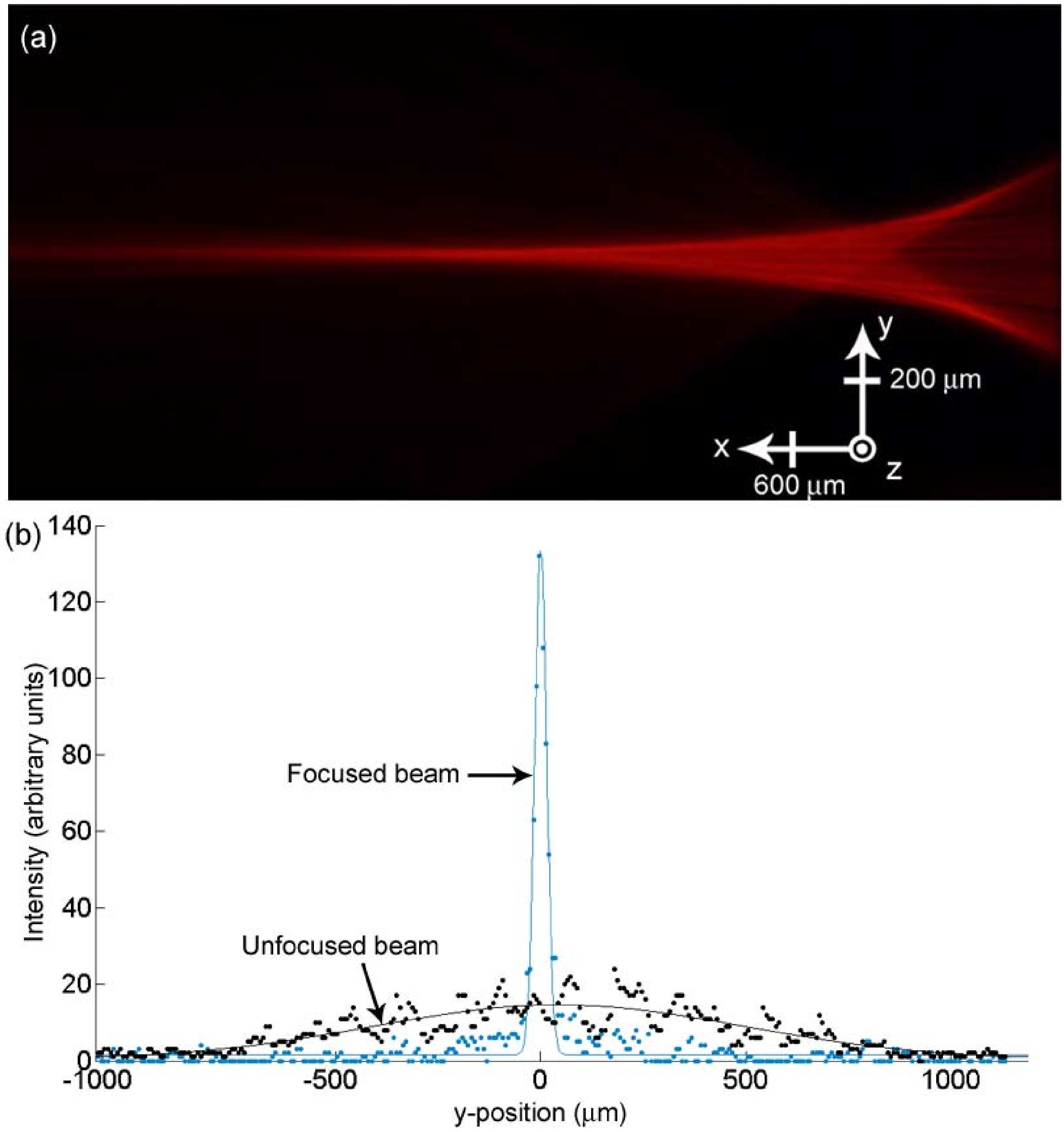
(a)
y
200 μm
x
z
600 μm
(b)
Focused beam
Unfocused beam
Intensity (arbitrary units)
y-position (μm)
140
120
100
80
60
40
20
0
-1000
-500
0
500
1000

Table S1. Refractive index and hazard codes of selected liquids.

Name	**CAS Number**	**Refractive index[1]**	**Sigma Aldrich Hazard Codes[2]**	**NFPA[3]**
methylene iodide	75-11-6	1.749	Xi	H3; F1; R0
1,2-diiodobenzene	615-42-9	1.718	Xi	[4] H1; F1; R1
1-iodonaphthalene	90-14-2	1.701	Xi	H2; F1; R0
benzothiazole	95-16-9	1.642	Xn	H2; F0; R0
1,1,2,2-tetrabromoethane	79-27-6	1.637	T+	H3; F0; R1
carbon disulfide	75-15-0	1.627	F, T	H3; F4; R0
1-methylnaphthalene	90-12-0	1.618	Xn, N	H1; F2; R1
bromoform	75-25-2	1.596	T, N	H3; F0; R0
3-bromobenzaldehyde	3132-99-8	1.593	Xn	H2; F0; R0
2-chloroaniline	95-51-2	1.589	T,N	H2; F0; R0
thiophenol	108-98-5	1.588	T+	H4; F2; R0
aniline	62-53-3	1.586	T,N	H3; F2; R0
2-iodoethanol	624-76-0	1.572	T	H2; F2; R0
benzyl benzoate	120-51-4	1.568	Xn	H1; F1; R0
2-thiophenemethanol	636-72-6	1.564	(not available)	H1; F0; R0
bromobenzene	108-86-1	1.557	Xi, N	H2; F2; R0
pyrrole-2-carbonitrile	4513-94-4	1.551	Xn, T	H3; F0; R0;
nitrobenzene	98-95-3	1.550	T, N	H3; F2; R1
styrene	100-42-5	1.545	Xn	H2; F3; R0
benzaldehyde	100-52-7	1.544	Xn	H2; F2; R0
m-cresol	108-39-4	1.542	T	H3; F2; R0
2-acetyl thiophene	88-15-3	1.540	T	H1; F2; R0
benzyl alcohol	100-51-6	1.538	Xn	H1; F1; R0
3-acetyl-2,5-dimethylthiophene	2530-10-1	1.532	Xi	[4] H1; F1; R1
thiophene	110-02-1	1.526	F, T	H2; F3; R0
pyrrole	109-97-7	1.508	T	H2; F2; R0
2,4-dimethyl thiazole	541-58-2	1.502	Xi	[4] H1; F2; R1
2-isobutyl thiazole	18640-74-9	1.491	Xi	[4] H1; F2; R1
dimethyl sulfoxide	67-68-5	1.479	(not available)	H1; F1; R0
formamide	75-12-7	1.447	T	H2; F1; R0

N,N-dimethylacetamide	127-19-5	1.438	T	H2; F2; R0
ethylene glycol	107-21-1	1.429	Xn	H1; F1; R0
propylene carbonate	108-32-7	1.422	Xi	H1; F1; R0
acetic acid	64-19-7	1.370	C	H2; F2; R2
ethanol	64-17-5	1.359	F	H0; F3; R0
acetonitrile	75-05-8	1.344	F, Xn	H2; F3; R0
water	7732-18-5	1.333	None	H0; F0; R0
methanol	67-56-1	1.328	F, T	H1; F3; R0
2,2,2-Trifluoroethanol	75-89-8	1.300	Xn	H2; F3; R0

[1] Source of refractive indices: Sigma-Aldrich catalog. http://www.sigmaaldrich.com

[2] Hazard codes from Sigma Aldrich:

C	Corrosive
F	Flammable
F+	Extremely flammable
Xn	Harmful
Xi	Irritant
N	Dangerous for the environment
T	Toxic
T+	Very toxic

http://www.sigmaaldrich.com/Help_Pages/Help_Welcome/Product_Search/Risk___Safety_Statements.html#Risk Phrases

[3] The National Fire Protection Agency (NFPA) hazard identification system: H, F, R represent Health, Flammability, and Reactivity here. The number ratings range from 0-4. A rating of 0 represents essentially no hazard; a rating of 4 indicates extreme danger. http://www-ssrl.slac.stanford.edu/safety/nfpa_hazard_class.html

[4] National Paint & Coatings Association (NPCA) Hazardous Materials Identification System (HMIS) ratings: H, F, R represent Health, Flammability, and Reactivity. The number ratings range from 0-4. A rating of 0 represents essentially no hazard; a rating of 4 indicates extreme danger.