

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

Supplementary Information

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Figure 1. 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.

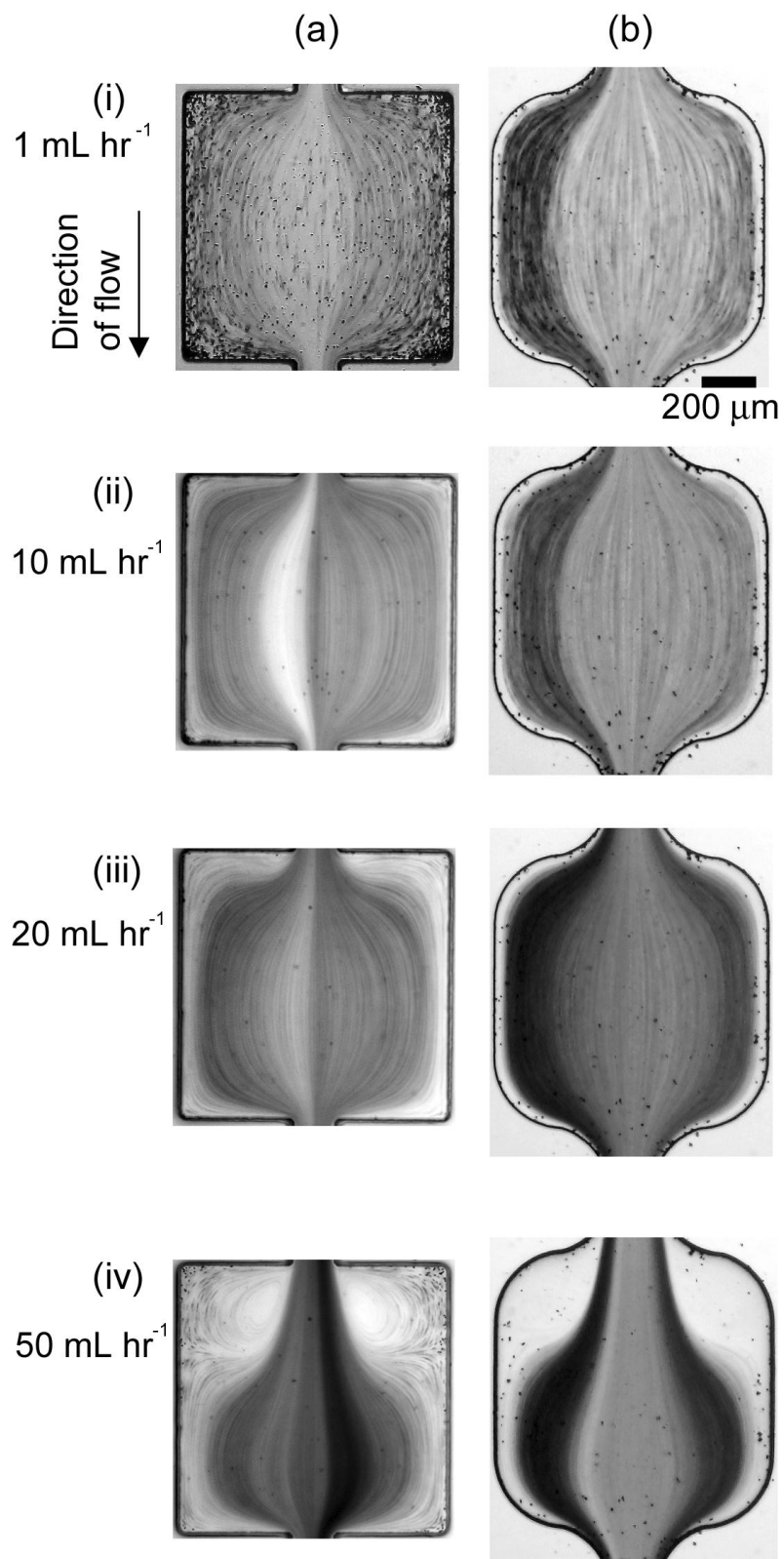


Figure 2. Radius of curvature ($R_{curvature}$) of the core-cladding interface of the L^2 lens as a function of time (t) using (a) a 10 mL-plastic syringe (Becton Dickinson ‘Luer-Lok’ series), and (b) a 1 mL-glass syringe (Hamilton Gastight series), respectively, when the rate of flow of the core stream 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 $\Delta R_{curvature} = R_{curvature}(t = \infty) - R_{curvature}(t = 0)$

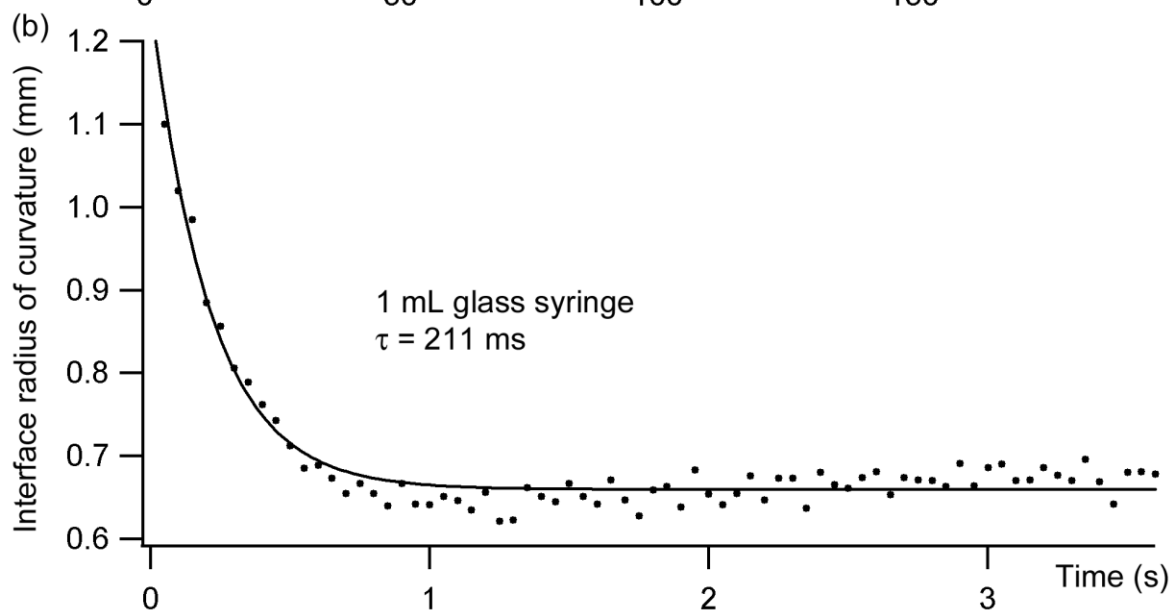
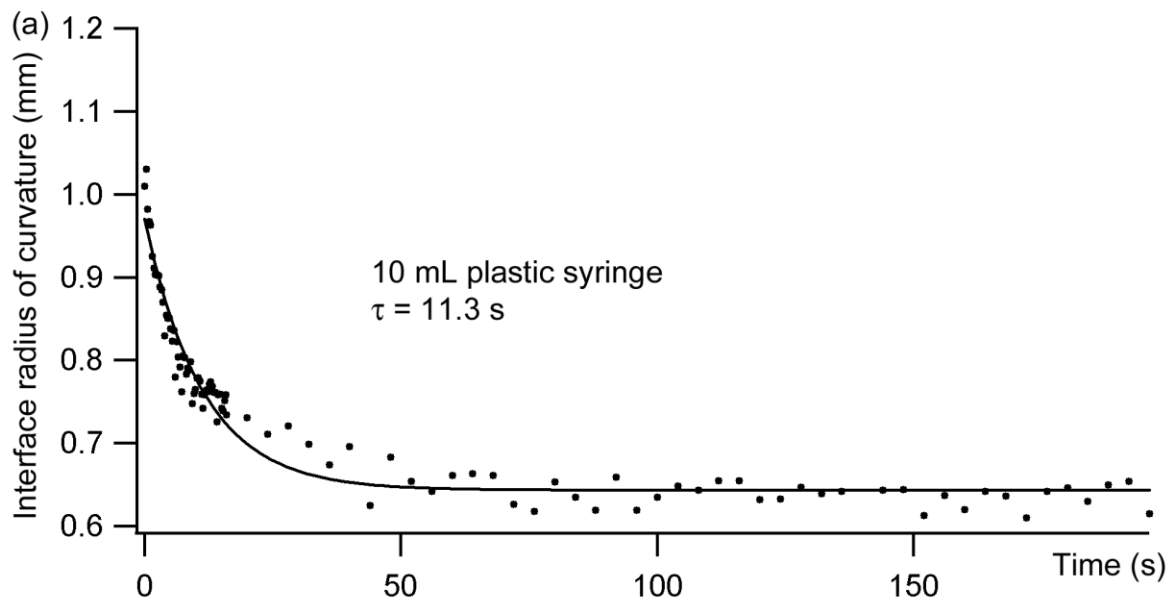


Figure 3. Radius of curvature ($R_{curvature}$) of the core-cladding interface of the L^2 lens as a function of time (t) using (a) a 10 mL-plastic syringe (Becton Dickinson ‘Luer-Lok’ series), and (b) a 1 mL-glass syringe (Hamilton Gastight series), respectively. The rates of flow of the core and the 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.

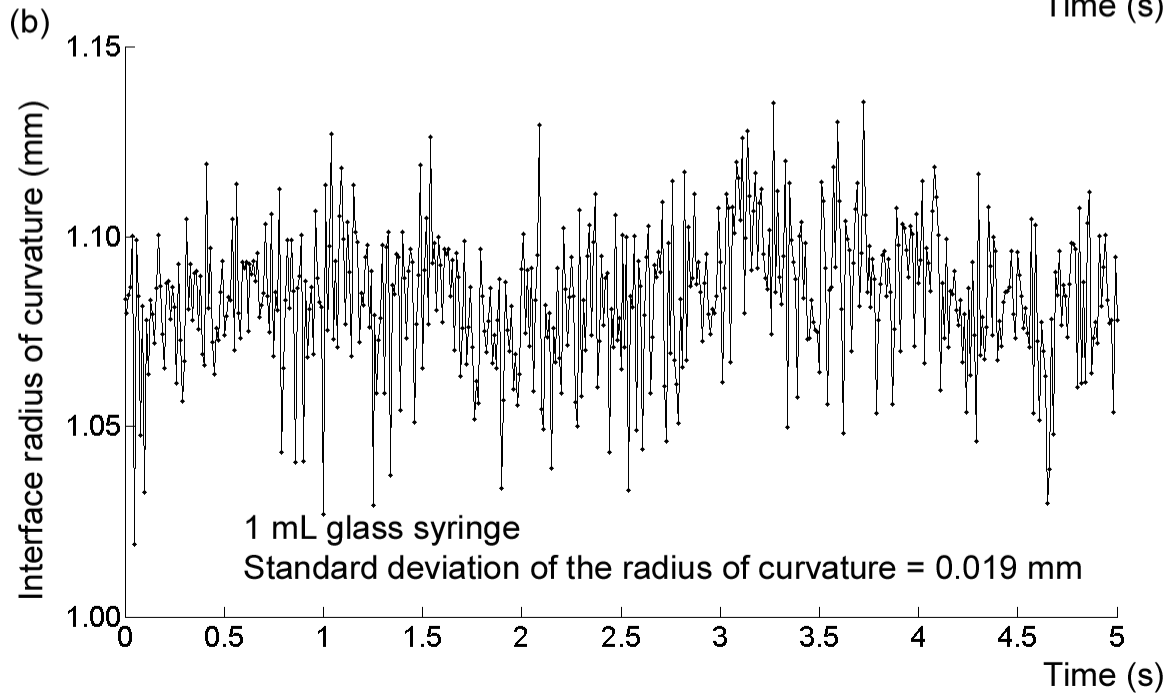
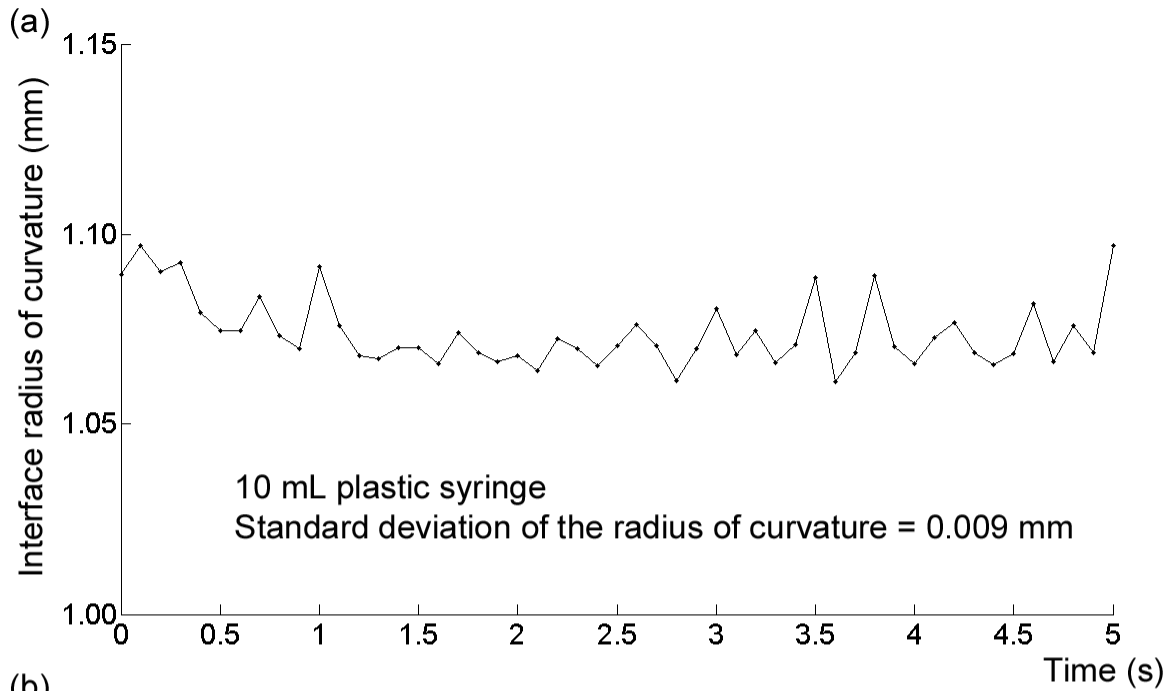


Figure 4. The variation in beam width as a function of the distance from the center of the L^2 lens (x_1) in a device with a 334- μm aperture. The data were recorded using a CCD camera through a microscope objective with 5x magnification and a lens tube with a further 1.6x magnification. The line is 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 ($\rho = 1.24 \text{ g cm}^{-3}$). 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 $16 \mu\text{m}$.

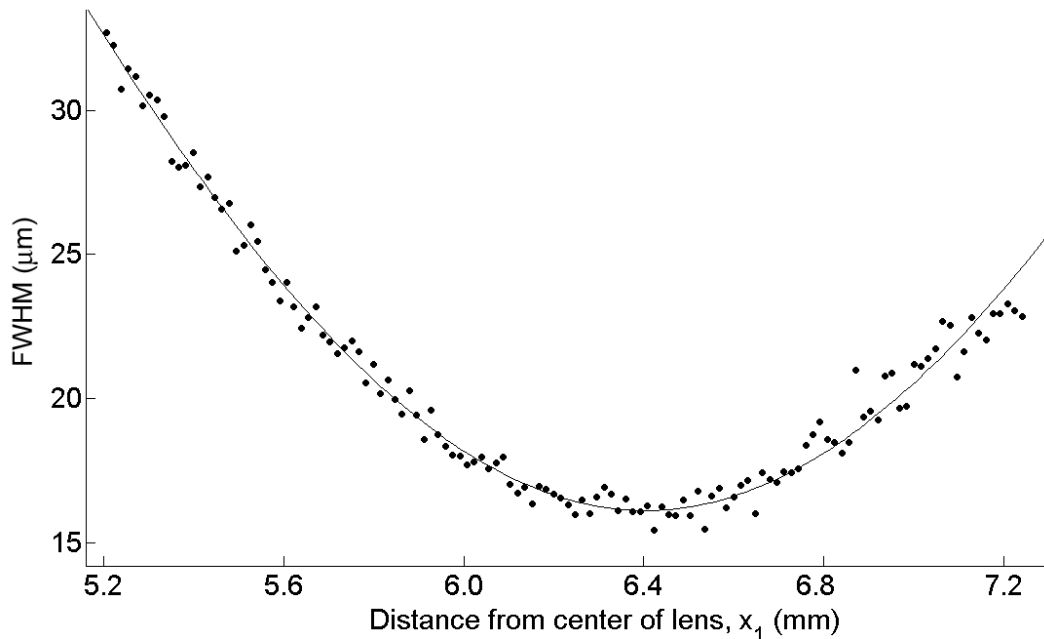


Figure 5. (a) Optical micrograph of the focused beam with no aperture in front of the expansion chamber for a L^2 lens formed using benzothiazole as the core liquid, and a mixture of 53.6% trifluoroethanol, 31.5% benzothiazole and 14.9% ethanol with effective refractive index matched to that of PDMS ($n_D^{22} = 1.412$), and density matched to that of benzothiazole in the core stream ($\rho = 1.24 \text{ g cm}^{-3}$) 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 $40 \text{ }\mu\text{m}$. 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.

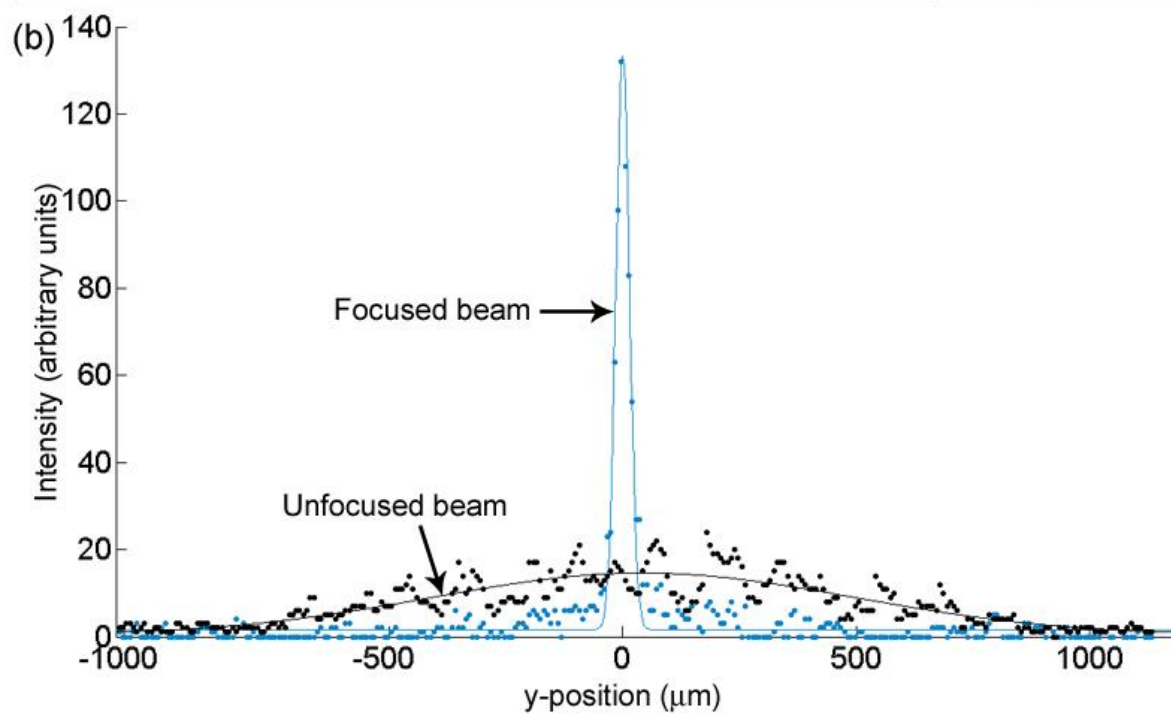
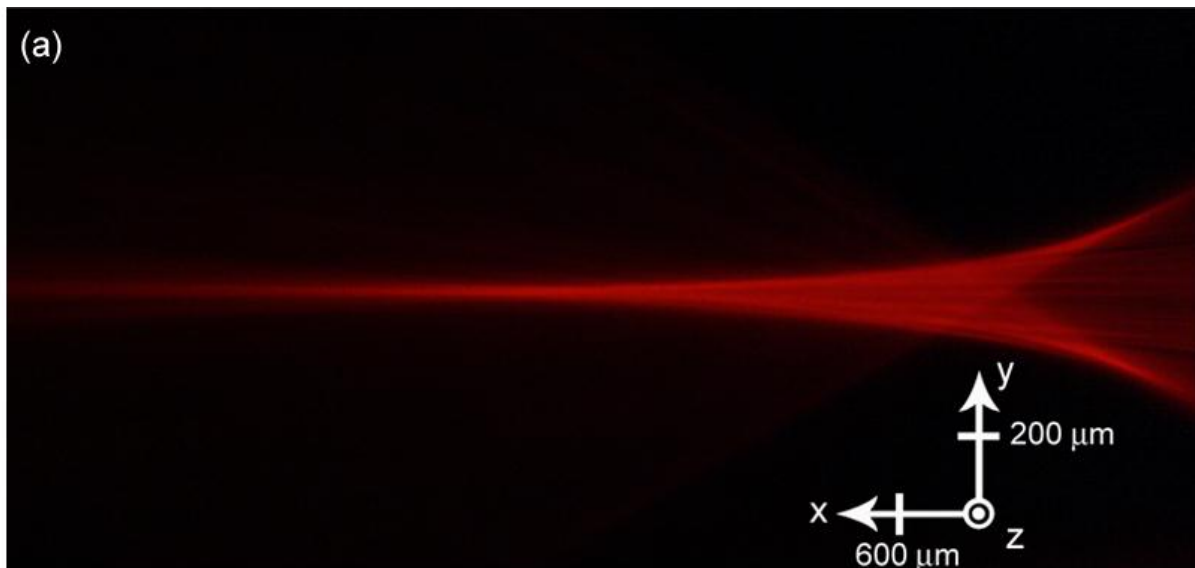


Table 1. Refractive index and hazard codes of selected liquids.

| 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_State_ments.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.