# *Section 5: Liquids*

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# Section 5

# LIQUIDS

## 5.1 Introduction

Liquids in this section include water ($H_2O$), heavy water ($D_2O$), and the following selected organic materials (CAS – Chemical Abstract Service Registry Number):

| CAS no. | Liquid | CAS no. | Liquid |
|---|---|---|---|
| 100 | acetic acid, $C_2H_4O_2$ | 5672 | ethanol, $C_2H_6O$ |
| 10411 | acetone, $C_3H_6O$ | 5569 | ethylene glycol, $C_2H_6O_2$ |
| 867 | benzene, $C_6H_6$ | 10186 | glycerine (glycerol), $C_3H_8O_3$ |
| 998 | bromobenzene, $C_6H_5Br$ | 6355 | heptane, $C_7H_{16}$ |
| 3993 | carbon disulfide, $CS_2$ | 6632 | hexadecane, $C_{16}H_{34}$ |
| 7540 | carbon tetrachloride, $CCl_4$ | 6731 | hexane, $C_6H_{14}$ |
| 7554 | chloroform, $CHCl_3$ | 7581 | methanol, $CH_4O$ |
| 4305 | cyclohexane, $C_6H_{12}$ | 4426 | methylcyclohexane, $C_7H_{14}$ |
| 5529 | 1,2-dichloroethane, $C_2H_4Cl_2$ | 7915 | 1-methylnaphthalene, $C_{11}H_{10}$ |
| 7499 | dichloromethane, $CH_2Cl_2$ | 2049 | nitrobenzene, $C_6H_5NO_2$ |
| 7529 | dimethylsulfoxide, $C_2H_6OS$ | 1947 | toluene, $C_7H_8$ |
| 5187 | 1,4-dioxane, $C_4H_8O_2$ | 8848 | 2,2,4-trimethylpentane, $C_8H_{18}$ |

## 5.2 Water

### 5.2.1 Physical Properties

Density, specific heat capacity at constant pressure ($C_p$), viscosity, vapor pressure, thermal conductivity, dielectric constant, and surface tension of water. All values (except vapor pressure) at for a pressure of 100 kPa (1 bar)**.** Temperature scale is IPTS-68.

| Temp. (°C) | Density (g/cm$^3$) | $C_p$ (J/g K) | Visc. (μPa s) | Vapor press. (kPa) | Therm. cond. (mW/m K) | Diel. const. | Surf. tens. (mN/m) |
|---|---|---|---|---|---|---|---|
| 0 | 0.99984 | 4.2176 | 0.6113 | 1793 | 561.0 | 87.90 | 75.64 |
| 10 | 0.99970 | 4.1921 | 1.2281 | 1307 | 580.0 | 83.96 | 74.23 |
| 20 | 0.99821 | 4.1818 | 2.3388 | 1002 | 598.4 | 80.20 | 72.75 |
| 30 | 0.99565 | 4.1784 | 4.2455 | 797.7 | 615.4 | 76.60 | 71.20 |
| 40 | 0.99222 | 4.1785 | 7.3814 | 653.2 | 630.5 | 73.17 | 69.60 |
| 50 | 0.98803 | 4.1806 | 12.344 | 547.0 | 643.5 | 69.88 | 67.94 |
| 60 | 0.98320 | 4.1843 | 19.932 | 466.5 | 654.3 | 66.73 | 66.24 |
| 70 | 0.97778 | 4.1895 | 31.176 | 404.0 | 663.1 | 63.73 | 64.47 |
| 80 | 0.97182 | 4.1963 | 47.373 | 354.4 | 670.0 | 60.86 | 62.67 |
| 90 | 0.96535 | 4.2050 | 70.117 | 314.5 | 675.3 | 587.12 | 60.82 |
| 100 | 0.95840 | 4.2159 | 101.325 | 281.8 | 679.1 | 55.51 | 58.91 |

From the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 2001), p. 6-3.

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### 5.2.2 Absorption

**Linear Absorption Coefficient α of Water***

| λ (nm) | α ($10^{-4}$ $cm^{-1}$) | Ref. | λ (nm) | α ($10^{-4}$ $cm^{-1}$) | Ref. |
|---|---|---|---|---|---|
| 185 | 14600 | 1 | 660 | 40.7 | 2 |
| 186 | 9700 | 1 | 665 | 41.9 | 2 |
| 187 | 6000 | 1 | 670 | 42.5 | 2 |
| 188 | 3800 | 1 | 675 | 43.8 | 2 |
| 189 | 2300 | 1 | 680 | 44.7 | 2 |
| 190 | 1400 | 1 | 685 | 46.7 | 2 |
| 400 | 5.8 | 2 | 690 | 49 | 4 |
| 410 | 4.7 | 2 | 690 | 51.5 | 2 |
| 420 | 3.8 | 2 | 694.2 | 52.6 | 3 |
| 430 | 4.0 | 2 | 695 | 56.9 | 2 |
| 440 | 3.2 | 2 | 700 | 64.8 | 2 |
| 450 | 3.3 | 2 | 702 | 69 | 4 |
| 460.7 | 2.11 | 3 | 705 | 75.0 | 2 |
| 469.4 | 2.05 | 3 | 710 | 90.4 | 2 |
| 480.7 | 1.86 | 3 | 714 | 98 | 4 |
| 490.1 | 1.89 | 3 | 715 | 111.4 | 2 |
| 499.9 | 2.33 | 3 | 720 | 137.5 | 2 |
| 510.1 | 3.13 | 3 | 725 | 134 | 4 |
| 520.7 | 3.80 | 3 | 725 | 175.6 | 2 |
| 529.0 | 4.09 | 3 | 730 | 230.9 | 2 |
| 540.4 | 4.80 | 3 | 735 | 238 | 4 |
| 546.3 | 5.28 | 3 | 735 | 260.8 | 2 |
| 574.5 | 8.05 | 3 | 740 | 269.8 | 2 |
| 580 | 10.9 | 2 | 745 | 271.2 | 2 |
| 585 | 11.9 | 2 | 746 | 275 | 4 |
| 590 | 17.2 | 2 | 750 | 268.3 | 2 |
| 595 | 21.4 | 2 | 752 | 281 | 4 |
| 598.6 | 19.25 | 3 | 755 | 269.6 | 2 |
| 600 | 27.2 | 2 | 758 | 272 | 4 |
| 602.2 | 23.2 | 3 | 760 | 268.5 | 2 |
| 605 | 29.3 | 2 | 769 | 251 | 4 |
| 610 | 29.3 | 2 | 770 | 251.9 | 2 |
| 615 | 30.0 | 2 | 780 | 234.6 | 2 |
| 620 | 30.9 | 2 | 781 | 230 | 4 |
| 625 | 30.5 | 2 | 790 | 205.2 | 2 |
| 630 | 32.0 | 2 | 794 | 210 | 4 |
| 635 | 32.5 | 2 | 806 | 195 | 4 |
| 640 | 33.4 | 2 | 813 | 191 | 4 |
| 645 | 33.9 | 2 | 820 | 199 | 4 |
| 649.2 | 32.3 | 3 | 833 | 308 | 4 |
| 650 | 35.1 | 2 | 847 | 387 | 4 |
| 655 | 38.7 | 2 | 862 | 428 | 4 |

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**Linear Absorption Coefficient α of Water*—*continued***

| λ (nm) | α ($10^{-4}$ $cm^{-1}$) | Ref. | λ (nm) | α ($10^{-4}$ $cm^{-1}$) | Ref. |
|---|---|---|---|---|---|
| 877 | 506 | 4 | 1370 | 54500 | 4 |
| 893 | 609 | 4 | 1389 | 91300 | 4 |
| 909 | 750 | 4 | 1408 | 215000 | 4 |
| 926 | 1190 | 4 | 1429 | 310000 | 4 |
| 935 | 1580 | 4 | 1443 | 317000 | 4 |
| 943 | 2140 | 4 | 1471 | 285000 | 4 |
| 952 | 3220 | 4 | 1493 | 217000 | 4 |
| 962 | 4710 | 4 | 1515 | 156000 | 4 |
| 973 | 5140 | 4 | 1538 | 121000 | 4 |
| 980 | 5020 | 4 | 1563 | 96800 | 4 |
| 990 | 4690 | 4 | 1587 | 80700 | 4 |
| 1000 | 4160 | 4 | 1613 | 68000 | 4 |
| 1010 | 3510 | 4 | 1639 | 60700 | 4 |
| 1020 | 2850 | 4 | 1667 | 56500 | 4 |
| 1031 | 2310 | 4 | 1695 | 56500 | 4 |
| 1042 | 1900 | 4 | 1724 | 62300 | 4 |
| 1053 | 1640 | 4 | 1754 | 76000 | 4 |
| 1070 | 1480 | 4 | 1786 | 91800 | 4 |
| 1087 | 1660 | 4 | 1802 | 94800 | 4 |
| 1099 | 1920 | 4 | 1818 | 94400 | 4 |
| 1111 | 2320 | 4 | 1852 | 108000 | 4 |
| 1124 | 3230 | 4 | 1887 | 575000 | 4 |
| 1136 | 5480 | 4 | 1927 | 1240000 | 4 |
| 1149 | 9700 | 4 | 1961 | 1090000 | 4 |
| 1163 | 11800 | 4 | 2000 | 692000 | 4 |
| 1176 | 12300 | 4 | 2041 | 450000 | 4 |
| 1190 | 12500 | 4 | 2083 | 310000 | 4 |
| 1205 | 12500 | 4 | 2128 | 236000 | 4 |
| 1220 | 12200 | 4 | 2198 | 193000 | 4 |
| 1235 | 11700 | 4 | 2273 | 230000 | 4 |
| 1250 | 11100 | 4 | 2326 | 293000 | 4 |
| 1266 | 10700 | 4 | 2381 | 418000 | 4 |
| 1282 | 11300 | 4 | 2439 | 635000 | 4 |
| 1299 | 13400 | 4 | 2500 | 957000 | 4 |
| 1316 | 16700 | 4 | 2564 | 1110000 | 4 |
| 1333 | 22500 | 4 | 2632 | 1930000 | 4 |
| 1351 | 38700 | 4 | | | |

* Measurements made at room temperature (Ref. 1 – 298 K; Ref. 2 – 296 ± 1.5 K; Ref. 4 – 300 K).

**References:**


1. Barrett, J. and Mansell, A. L., Ultra-violet absorption spectra of the molecules $H_2O$, HDO and $D_2$, *Nature* 187, 138 (1960).


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2. Sullivan, S. A., Experimental study of the absorption in distilled water, artificial sea water, and heavy water in the visible region of the spectrum, *J. Opt. Soc. Am*. 53, 962 (1963). This reference contains additional values of α at wavelengths intermediate to those given above.
3. Tam, A. C. and Patel, C. K. N., Optical absorption of light and heavy water by laser optoacoustic spectroscopy, *Appl. Opt.* 18, 3348 (1979).
4. Palmer, K. F. and Williams, D., Optical properties of water in the near infrared, *J. Opt. Soc. Am.* 64, 1107 (1974).

**Absorption Coefficient α for Water in the Infrared (T = 298 K)**

| λ (nm) | α ($cm^{-1}$) | λ (nm) | α ($cm^{-1}$) | λ (nm) | α ($cm^{-1}$) |
|---|---|---|---|---|---|
| 0.700 | 0.00602 | 3.45 | 481 | 7.1 | 566 |
| 0.725 | 0.0159 | 3.50 | 338 | 7.2 | 560 |
| 0.750 | 0.0261 | 3.6 | 180 | 7.3 | 554 |
| 0.775 | 0.0240 | 3.7 | 122 | 7.4 | 550 |
| 0.800 | 0.0196 | 3.8 | 112 | 7.5 | 546 |
| 0.825 | 0.0277 | 3.9 | 122 | 7.6 | 542 |
| 0.850 | 0.0433 | 4.0 | 145 | 7.7 | 540 |
| 0.875 | 0.0562 | 4.1 | 172 | 7.8 | 540 |
| 0.900 | 0.0678 | 4.2 | 206 | 7.9 | 539 |
| 0.925 | 0.144 | 4.3 | 247 | 8.0 | 539 |
| 0.950 | 0.374 | 4.4 | 294 | 8.2 | 538 |
| 0.975 | 0.449 | 4.5 | 374 | 8.4 | 540 |
| 1.00 | 0.363 | 4.6 | 402 | 8.6 | 544 |
| 1.20 | 1.04 | 4.7 | 420 | 8.8 | 550 |
| 1.40 | 12.4 | 4.8 | 393 | 9.0 | 557 |
| 1.60 | 67.2 | 4.9 | 351 | 9.2 | 567 |
| 1.80 | 80.3 | 5.0 | 312 | 9.4 | 579 |
| 2.00 | 69.1 | 5.1 | 274 | 9.6 | 594 |
| 2.20 | 16.5 | 5.2 | 244 | 9.8 | 614 |
| 2.40 | 50.1 | 5.3 | 232 | 10.0 | 639 |
| 2.60 | 153 | 5.4 | 240 | 10.5 | 793 |
| 2.65 | 318 | 5.5 | 265 | 11.0 | 1110 |
| 2.70 | 845 | 5.6 | 319 | 11.5 | 1550 |
| 2.75 | 2700 | 5.7 | 448 | 12.0 | 2080 |
| 2.80 | 5120 | 5.8 | 715 | 12.5 | 2600 |
| 2.85 | 8160 | 5.9 | 1330 | 13.0 | 2950 |
| 2.90 | 11600 | 6.0 | 2240 | 13.5 | 3190 |
| 2.95 | 12700 | 6.1 | 2700 | 14.0 | 3320 |
| 3.00 | 11400 | 6.2 | 1800 | 14.5 | 3360 |
| 3.05 | 9890 | 6.3 | 1140 | 15.0 | 3370 |
| 3.10 | 7780 | 6.4 | 882 | 15.5 | 3360 |
| 3.15 | 5390 | 6.5 | 758 | 16.0 | 3320 |
| 3.20 | 3630 | 6.6 | 678 | 16.5 | 3260 |
| 3.25 | 2360 | 6.7 | 632 | 17.0 | 3170 |
| 3.30 | 1400 | 6.8 | 604 | 17.5 | 3060 |
| 3.35 | 979 | 6.9 | 579 | 18.0 | 2970 |
| 3.40 | 720 | 7.0 | 575 | 18.5 | 2860 |

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**Absorption Coefficient α for Water in the Infrared (T = 298 K)—*continued***

| λ (nm) | α ($cm^{-1}$) | λ (nm) | α ($cm^{-1}$) | λ (nm) | α ($cm^{-1}$) |
|---|---|---|---|---|---|
| 19.0 | 2740 | 32 | 1270 | 90 | 749 |
| 19.5 | 2600 | 34 | 1220 | 100 | 669 |
| 20.0 | 2470 | 36 | 1200 | 110 | 607 |
| 21.0 | 2290 | 38 | 1190 | 120 | 551 |
| 22 | 2130 | 40 | 1210 | 130 | 497 |
| 23 | 2010 | 42 | 1220 | 140 | 449 |
| 24 | 1890 | 44 | 1250 | 150 | 415 |
| 25 | 1780 | 46 | 1260 | 160 | 390 |
| 26 | 1690 | 48 | 1280 | 170 | 367 |
| 27 | 1600 | 50 | 1290 | 180 | 348 |
| 28 | 1520 | 60 | 1230 | 190 | 331 |
| 29 | 1440 | 70 | 1030 | 200 | 317 |
| 30 | 1370 | 80 | 859 | | |

**Reference:**

Hale, G M. and Querry, M. R., Optical constants of water in the 200-nm to 200-_m wavelength region, *Appl. Opt.* 12, 555 (1973).

**Heavy Water**

**Absorption Coefficient α for Heavy water***

| λ (nm) | α ($10^{-4}$ $cm^{-1}$) | λ (nm) | α ($10^{-4}$ $cm^{-1}$) | λ (nm) | α ($10^{-4}$ $cm^{-1}$) |
|---|---|---|---|---|---|
| 400 | 31.8 | 540 | 6.3 | 680 | 3.2 |
| 410 | 28.5 | 550 | 5.8 | 690 | 3.3 |
| 420 | 26.3 | 560 | 5.3 | 700 | 4.5 |
| 430 | 23.4 | 570 | 5.4 | 710 | 5.1 |
| 440 | 20.8 | 580 | 4.9 | 720 | 5.4 |
| 450 | 18.2 | 590 | 4.4 | 730 | 5.9 |
| 460 | 15.6 | 600 | 4.2 | 740 | 6.7 |
| 470 | 14.1 | 610 | 4.0 | 750 | 6.9 |
| 480 | 13.1 | 620 | 4.0 | 760 | 6.9 |
| 490 | 11.6 | 630 | 3.3 | 770 | 6.5 |
| 500 | 10.1 | 640 | 3.2 | 780 | 6.7 |
| 510 | 8.9 | 650 | 3.4 | 790 | 7.4 |
| 520 | 8.6 | 660 | 2.9 | | |
| 530 | 7.4 | 670 | 3.5 | | |

Temperature: 296 ± 1.5 K
* 99.7% $D_2O$

**Reference:**

Sullivan, S. A., Experimental study of the absorption in distilled water, artificial sea water, and heavy water in the visible region of the spectrum, *J. Opt. Soc. Am*. 53, 962 (1963). This reference contains additional values of α at wavelengths intermediate to those given above.

### 5.2.3 Index of Refraction

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**Index of Refraction n of Water (298 K)**

| λ (μm) | n(λ) | λ (μm) | n(λ) | λ (μm) | n(λ) |
|---|---|---|---|---|---|
| 0.200 | 1.396 | 2.70 | 1.188 | 6.0 | 1.265 |
| 0.225 | 1.373 | 2.75 | 1.157 | 6.1 | 1.319 |
| 0.250 | 1.362 | 2.80 | 1.142 | 6.2 | 1.363 |
| 0.275 | 1.354 | 2.85 | 1.149 | 6.3 | 1.357 |
| 0.300 | 1.349 | 2.90 | 1.201 | 6.4 | 1.347 |
| 0.325 | 1.346 | 2.95 | 1.292 | 6.5 | 1.339 |
| 0.350 | 1.343 | 3.00 | 1.371 | 6.6 | 1.334 |
| 0.375 | 1.341 | 3.05 | 1.426 | 6.7 | 1.329 |
| 0.400 | 1.339 | 3.10 | 1.467 | 6.8 | 1.324 |
| 0.425 | 1.338 | 3.15 | 1.483 | 6.9 | 1.321 |
| 0.450 | 1.337 | 3.20 | 1.478 | 7.0 | 1.371 |
| 0.475 | 1.336 | 3.25 | 1.467 | 7.1 | 1.314 |
| 0.500 | 1.335 | 3.30 | 1.1450 | 7.2 | 1.312 |
| 0.525 | 1.334 | 3.35 | 1.432 | 7.3 | 1.309 |
| 0.550 | 1.333 | 3.40 | 1.420 | 7.4 | 1.307 |
| 0.575 | 1.333 | 3.45 | 1.410 | 7.5 | 1.304 |
| 0.600 | 1.332 | 3.50 | 1.400 | 7.6 | 1.302 |
| 0.625 | 1.332 | 3.6 | 1.385 | 7.7 | 1.299 |
| 0.650 | 1.331 | 3.7 | 1.374 | 7.8 | 1.297 |
| 0.675 | 1.331 | 3.8 | 1.364 | 7.9 | 1.294 |
| 0.700 | 1.331 | 3.9 | 1.357 | 8.0 | 1.291 |
| 0.725 | 1.330 | 4.0 | 1.351 | 8.2 | 1.286 |
| 0.750 | 1.330 | 4.1 | 1.346 | 8.4 | 1.281 |
| 0.775 | 1.330 | 4.2 | 1.342 | 8.6 | 1.275 |
| 0.800 | 1.329 | 4.3 | 1.338 | 8.8 | 1.269 |
| 0.825 | 1.329 | 4.4 | 1.334 | 9.0 | 1.262 |
| 0.850 | 1.329 | 4.5 | 1.332 | 9.2 | 1.255 |
| 0.875 | 1.328 | 4.6 | 1.330 | 9.4 | 1.247 |
| 0.900 | 1.328 | 4.7 | 1.330 | 9.6 | 1.239 |
| 0.925 | 1.328 | 4.8 | 1.330 | 9.8 | 1.229 |
| 0.950 | 1.327 | 4.9 | 1.328 | 10.0 | 1.218 |
| 0.975 | 1.327 | 5.0 | 1.325 | 10.5 | 1.185 |
| 1.00 | 1.327 | 5.1 | 1.322 | 11.0 | 1.153 |
| 1.20 | 1.324 | 5.2 | 1.317 | 11.5 | 1.126 |
| 1.40 | 1.321 | 5.3 | 1.312 | 12.0 | 1.111 |
| 1.60 | 1.317 | 5.4 | 1.305 | 12.5 | 1.123 |
| 1.80 | 1.312 | 5.5 | 1.298 | 13.0 | 1.146 |
| 2.00 | 1.306 | 5.6 | 1.289 | 13.5 | 1.177 |
| 2.20 | 1.296 | 5.7 | 1.277 | 14.0 | 1.210 |
| 2.40 | 1.279 | 5.8 | 1.262 | 14.5 | 1.241 |
| 2.60 | 1.242 | 5.9 | 1.248 | 15.0 | 1.270 |
| 2.65 | 1.219 | 6.0 | 1.265 | 15.5 | 1.197 |

**Index of Refraction n of Water (298 K)—***continued*

| λ (μm) | n(λ) | λ (μm) | n(λ) | λ (μm) | n(λ) |
|---|---|---|---|---|---|

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| | | | | | |
|---|---|---|---|---|---|
| 15.5 | 1.197 | 26 | 1.539 | 60 | 1.703 |
| 16.0 | 1.325 | 27 | 1.545 | 70 | 1.821 |
| 16.5 | 1.351 | 28 | 1.549 | 80 | 1.886 |
| 17.0 | 1.376 | 29 | 1.551 | 90 | 1.924 |
| 17.5 | 1.401 | 30 | 1.551 | 100 | 1.957 |
| 18.0 | 1.423 | 32 | 1.546 | 110 | 1.966 |
| 18.5 | 1.443 | 34 | 1.536 | 120 | 2.004 |
| 19.0 | 1.461 | 36 | 1.527 | 130 | 2.036 |
| 19.5 | 1.476 | 38 | 1.522 | 140 | 2.056 |
| 20.0 | 1.480 | 40 | 1.519 | 150 | 2.069 |
| 21.0 | 1.487 | 42 | 1.522 | 160 | 2.081 |
| 22 | 1.500 | 44 | 1.530 | 170 | 2.094 |
| 23 | 1.511 | 46 | 1.541 | 180 | 2.107 |
| 24 | 1.521 | 48 | 1.555 | 190 | 2.119 |
| 25 | 1.531 | 50 | 10587 | 200 | 2.130 |

**Reference:**

Hale, G M. and Querry, M. R., Optical constants of water in the 200-nm to 200-μm wavelength region, *Appl. Opt.* 12, 555 (1973).

**Index of refraction n of water (300 K)**

| λ (nm) | n | Ref. | λ (nm) | n | Ref. |
|---|---|---|---|---|---|
| 214.44 | 1.4032 | 1 | 746 | 1.332 | 3 |
| 303.4 | 1.3581 | 1 | 752 | 1.332 | 3 |
| 360 | 1.353 | 3 | 758 | 1.332 | 3 |
| 404.66 | 1.342742 | 2 | 769 | 1.331 | 3 |
| 408 | 1.344 | 3 | 781 | 1.331 | 3 |
| 435.84 | 1.340210 | 2 | 794 | 1.331 | 3 |
| 449 | 1.337 | 3 | 806 | 1.331 | 3 |
| 486.13 | 1.337123 | 2 | 813 | 1.331 | 3 |
| 508.6 | 1.3360 | 1 | 820 | 1.330 | 3 |
| 546.07 | 1.334466 | 2 | 833 | 1.330 | 3 |
| 556 | 1.333 | 3 | 847 | 1.330 | 3 |
| 587.56 | 1.333041 | 2 | 862 | 1.330 | 3 |
| 589.3 | 1.332988 | 2 | 877 | 1.330 | 3 |
| 632.8 | 1.331745 | 2 | 893 | 1.329 | 3 |
| 656.28 | 1.331151 | 2 | 909 | 1.329 | 3 |
| 670.8 | 1.3308 | 1 | 926 | 1.329 | 3 |
| 690 | 1.332 | 3 | 935 | 1.329 | 3 |

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**Index of Refraction n of Water (300 K)—*continued***

| λ (nm) | n | Ref. | λ (nm) | n | Ref. |
|---|---|---|---|---|---|
| 990 | 1.328 | 3 | 1471 | 1.321 | 3 |
| 1000 | 1.328 | 3 | 1493 | 1.320 | 3 |
| 1010 | 1.328 | 3 | 1515 | 1.320 | 3 |
| 1020 | 1.328 | 3 | 1538 | 1.319 | 3 |
| 1031 | 1.328 | 3 | 1563 | 1.319 | 3 |
| 1042 | 1.328 | 3 | 1587 | 1.318 | 3 |
| 1053 | 1.328 | 3 | 1613 | 1.318 | 3 |
| 1070 | 1.328 | 3 | 1639 | 1.317 | 3 |
| 1087 | 1.327 | 3 | 1667 | 1.316 | 3 |
| 1099 | 1.327 | 3 | 1695 | 1.315 | 3 |
| 1111 | 1.327 | 3 | 1724 | 1.314 | 3 |
| 1124 | 1.327 | 3 | 1754 | 1.314 | 3 |
| 1136 | 1.326 | 3 | 1786 | 1.313 | 3 |
| 1149 | 1.326 | 3 | 1802 | 1.312 | 3 |
| 1163 | 1.326 | 3 | 1818 | 1.312 | 3 |
| 1176 | 1.326 | 3 | 1852 | 1.311 | 3 |
| 1190 | 1.325 | 3 | 1887 | 1.310 | 3 |
| 1205 | 1.325 | 3 | 1927 | 1.309 | 3 |
| 1220 | 1.325 | 3 | 1961 | 1.307 | 3 |
| 1235 | 1.325 | 3 | 2000 | 1.306 | 3 |
| 1250 | 1.324 | 3 | 2041 | 1.305 | 3 |
| 1266 | 1.324 | 3 | 2083 | 1.303 | 3 |
| 1282 | 1.324 | 3 | 2128 | 1.301 | 3 |
| 1299 | 1.324 | 3 | 2198 | 1.296 | 3 |
| 1316 | 1.324 | 3 | 2273 | 1.291 | 3 |
| 1333 | 1.323 | 3 | 2326 | 1.285 | 3 |
| 1351 | 1.323 | 3 | 2381 | 1.281 | 3 |
| 1370 | 1.323 | 3 | 2439 | 1.276 | 3 |
| 1389 | 1.322 | 3 | 2500 | 1.268 | 3 |
| 1408 | 1.322 | 3 | 2564 | 1.257 | 3 |
| 1429 | 1.321 | 3 | 2632 | 1.239 | 3 |
| 1443 | 1.321 | 3 | | | |

**References:**


1. Kaye, G. W. and Laby, T. H., *Tables of Physical and Chemical Constants* (Longmans, Green & Co., London, 1959).
2. James, A. M. and Lord, M. P., *Macmillan's Chemical and Physical Data* (Macmillan, London, 1992).
3. Palmer, K. F. and Williams, D., *J. Opt. Soc. Am.* 64, 1107 (1974).


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## Index of Refraction of Water at Different Temperatures and Wavelengths

| | Wavelength (nm) | | | | | |
|---|---|---|---|---|---|---|
| **T (°C)** | **226.50** | **361.05** | **404.41** | **589.00** | **632.80** | **1013.98** |
| 0 | 1.39450 | 1.34896 | 1.34415 | 1.33432 | 1.33306 | 1.32612 |
| 10 | 1.39422 | 1.34870 | 1.34389 | 1.33408 | 1.33282 | 1.32591 |
| 20 | 1.39336 | 1.34795 | 1.34315 | 1.33336 | 1.33211 | 1.32524 |
| 30 | 1.39208 | 1.34682 | 1.34205 | 1.33230 | 1.33105 | 1.32424 |
| 40 | 1.39046 | 1.34540 | 1.34065 | 1.33095 | 1.32972 | 1.32296 |
| 50 | 1.38854 | 1.34373 | 1.33901 | 1.32937 | 1.32814 | 1.32145 |
| 60 | 1.38636 | 1.34184 | 1.33714 | 1.32757 | 1.32636 | 1.31974 |
| 70 | 1.38395 | 1.33974 | 1.33508 | 1.32559 | 1.32438 | 1.31784 |
| 80 | 1.38132 | 1.33746 | 1.33284 | 1.32342 | 1.32223 | 1.31576 |
| 90 | 1.37849 | 1.33501 | 1.33042 | 1.32109 | 1.31991 | 1.31353 |
| 100 | 1.37547 | 1.33239 | 1.32784 | 1.31861 | 1.31744 | 1.31114 |

**Reference:**

From Schiebener, P., Straub, J. Levelt Sengers, J. M. H., and Gallagher, J. S., *J. Phys. Chem. Ref. Data* 19, 677 (1990) and the *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994).

## Temperature Derivative of the Index of Refraction n of Water

| **λ (nm)** | **dn/dT × $10^6$ ($K^{-1}$)** | **Ref.** | **λ (nm)** | **dn/dT × $10^6$ ($K^{-1}$)** | **Ref.** |
|---|---|---|---|---|---|
| 226.50 | –128 (293–303 K) | 1 | 589.3 | –80 (293 K) | 4 |
| 361.05 | –113 (293–303 K) | 1 | | –97 (293–298 K) | 2 |
| 404.41 | –110 (293–303 K) | 1 | 632.8 | –96 (293–298 K) | 2 |
| 404.66 | –101 (293–298 K) | 2 | | –98.5 (298 K) | 3 |
| 435.84 | –100 (293–303 K) | 1 | | –106 (293–303 K) | 1 |
| 486.13 | –99 (293–298 K) | 2 | 656.28 | –96 (293–298 K) | 2 |
| 546.07 | –98 (293–298 K) | 2 | 706.52 | –95 (293–298 K) | 2 |
| | –100 (298 K) | 3 | 1013.98 | –100 (293–303 K) | 1 |
| 587.56 | –97 (293–298 K) | 2 | | | |

**References:**


1. Schiebener, P., Straub, J., Levelt Sengers, J. M. H., and Gallagher, J. S., *J. Phys. Chem. Ref. Data* 19, 677 (1990).
2. Kaye, G. W. and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).
3. Hauf, W. and Grigull, U., *Optical Methods in Heat Transfer* (Academic Press, New York, 1970).
4. Kaye, G. W. and Laby, T. H., *Tables of Physical and Chemical Constants* (Longmans, Green & Co., London, 1959).


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## 5.3 Physical Properties of Selected Liquids

Data in the following tables are in large part from the *CRC Handbook of Chemistry and Physics*, 82nd edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL). Physical and chemical property data for many additional organic and inorganic liquids are given in this reference.

| Liquid | Molecular weight | Density ($g/cm^3$) | Dielectric constant ε | Electric dipole moment (D) |
|---|---|---|---|---|
| acetic acid, $C_2H_4O_2$ | 60.05 | 1.0492 | 6.20 | 1.74 |
| acetone, $C_3H_6O$ | 58.08 | 0.7856 | 21.01 | 2.88 |
| benzene, $C_6H_6$ | 78.11 | 0.8765 | 2.2825 | 0 |
| bromobenzene, $C_6H_5Br$ | 157.01 | 1.4950 | 5.45 | — |
| carbon disulfide, $CS_2$ | 76.14 | 1.2556 | 2.6320 | 0 |
| carbon tetrachloride, $CCl_4$ | 153.82 | 1.5833 | 2.2379 | 0 |
| chloroform, $CHCl_3$ | 119.38 | 1.4800 | 4.8069 | 1.01 |
| cyclohexane, $C_6H_{12}$ | 84.16 | 0.7731 | 2.0243 | 0 |
| 1,2–dichloroethane, $C_2H_4Cl_2$ | 98.96 | 1.2457 | 10.10 | — |
| dichloromethane, $CH_2Cl_2$ | 84.93 | 1.3266 | 8.93 | 1.6 |
| dimethylsulfoxide, $C_2H_6OS$ | 78.14 | 1.0955 | 47.24 | 3.96 |
| 1,4–dioxane, $C_4H_8O_2$ | 88.11 | 1.0286 | 2.2189 | — |
| ethanol, $C_2H_6O$ | 46.07 | 0.7873 | 25.3 | 1.69 |
| ethylene glycol, $C_2H_6O_2$ | 76.10 | 0.9598 | 41.4 | 2.28 |
| glycerine (glycerol), $C_3H_8O_3$ | 92.10 | 1.2567 | 46.53 | — |
| heptane, $C_7H_{16}$ | 100.20 | 0.6837 | 1.9209 | ≈ 0 |
| hexadecane, $C_{16}H_{34}$ | 226.45 | 0.7733 | 2.0460 | — |
| hexane, $C_6H_{14}$ | 86.18 | 0.6563 | 1.8865 | — |
| methanol, $CH_4O$ | 32.04 | 0.7872 | 33.0 | 1.70 |
| methylcyclohexane, $C_7H_{14}$ | 98.19 | 0.7694 | 2.024 | ≈ 0 |
| 1–methylnaphthalene, $C_{11}H_{10}$ | 142.20 | 1.0202 | 2.915 | — |
| nitrobenzene, $C_6H_5NO_2$ | 123.11 | 1.1985 | 35.6 | — |
| toluene, $C_7H_8$ | 92.14 | 0.8647 | 2.379 | — |
| 2,2,4–trimethylpentane, $C_8H_{18}$ | 114.23 | 0.6877 | 1.943 | — |
| water, $H_2O$ | 18.01528 | 0.99705 | 80.100 | — |
| heavy water, $D_2O$ | 20.02748 | 1.1044 | 79.754 | — |

Density at 298 K.
1 D = $3.33564 \times 10^{-30}$ C m

**Dielectric Strength of Liquids***

| Liquid | Dielectric strength (kV/mm) | Ref. |
|---|---|---|
| carbon tetrachloride, $CCl_4$ | 5.5 | 1 |
| chlorobenzenze, $C_6H_5Cl$ | 7.1 | 1 |
| helium, He, liquid, 4.2 K | 10 | 2 |
| carbon tetrachloride, $CCl_4$ | 16.0 | 3 |

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**Dielectric Strength of Liquids*—*continued***

| Liquid | Dielectric strength (kV/mm) | Ref. |
|---|---|---|
| chlorobenzenze, $C_6H_5Cl$ | 18.8 | 3 |
| nitrogen, $N_2$, liquid, 77 K: | | |
| coaxial cylinder electrodes | 20 | 4 |
| sphere to plane electrodes | 60 | 4 |
| cyclohexane, $C_6H_{12}$ | 42–48 | 5 |
| hexane, $C_6H_{14}$ | 42.0 | 5 |
| water, $H_2O$ | 65–70 | 6 |
| 2,2,4–trimethylpentane, $C_8H_{18}$ | 140 | 7,8 |
| benzene, $C_6H_6$ | 163 | 7,8 |
| heptane, $C_7H_{16}$ | 166 | 7,8 |
| toluene, $C_6H_5C\,H_3$: | 199 | 7,8 |
| | 46 | 5 |
| | 20.4 | 3 |
| | 12.0 | 1 |

* The dielectric strength (or breakdown voltage) of a material depends on the specimen thickness, the electrode shape, and the rate of the applied voltage increase.

**References:**


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**Physical Properties**

| Liquid | Melting point (°C) | Boiling point (°C) | Specific heat capacity (J/g K) | Volume thermal expan. coeff. $B_t$ ($10^3$ $K^{-1}$) |
|---|---|---|---|---|
| acetic acid, $C_2H_4O_2$ | 16.6 | 117.9 | 2.05 | 1.1 |
| acetone, $C_3H_6O$ | –94.8 | 56.05 | 2.17 | 1.43 |
| benzene, $C_6H_6$ | 5.53 | 80.09 | 1.74 | 1.23 |
| bromobenzene, $C_6H_5Br$ | –30.6 | 156 | — | — |
| carbon disulfide, $CS_2$ | –111.5 | 46 | 1.00 | 1.19 |
| carbon tetrachloride, $CCl_4$ | –23 | 76.8 | 0.85 | 1.22 |
| chloroform, $CHCl_3$ | –63.6 | 61.17 | 0.96 | 1.28 |
| cyclohexane, $C_6H_{12}$ | 6.6 | 80.73 | 1.84 | 1.1[a] |
| 1,2–dichloroethane, $C_2H_4Cl_2$ | –35.5 | 83.5 | 1.30 | 1.16[a] |

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**Physical Properties**—*continued*

| Liquid | Melting point (°C) | Boiling point (°C) | Specific heat capacity (J/g K) | Volume thermal expan. coeff. $\beta_t$ ($10^3$ $K^{-1}$) |
|---|---|---|---|---|
| dichloromethane, $CH_2Cl_2$ | –95.1 | 40 | 1.19 | — |
| dimethylsulfoxide, $C_2H_6OS$ | — | — | 1.96 | — |
| 1,4–dioxane, $C_4H_8O_2$ | 11.8 | 101.5 | 4.9 | 1.03[a] |
| ethanol, $C_2H_6O$ | –114.1 | 78.29 | 2.44 | 1.10 |
| ethylene glycol, $C_2H_6O_2$ | –13 | | 2.39 | 0.566 |
| glycerine (glycerol), $C_3H_8O_3$ | 18.2 | | 2.38 | 0.53 |
| heptane, $C_7H_{16}$ | –90.6 | 98.5 | 2.24 | — |
| hexadecane, $C_{16}H_{34}$ | 18.1 | 286.8 | — | — |
| hexane, $C_6H_{14}$ | –95.3 | 68.73 | 2.26 | 1.35 |
| methanol, $CH_4O$ | –97.68 | 64.6 | 2.53 | 1.19 |
| methylcyclohexane, $C_7H_{14}$ | –126.6 | 100.9 | 1.88 | — |
| 1–methylnaphthalene, $C_{11}H_{10}$ | –30.4 | 244.7 | — | — |
| nitrobenzene, $C_6H_5NO_2$ | 5.7 | 210.8 | 1.51 | 0.83 |
| toluene, $C_7H_8$ | –94.99 | 110.63 | 1.71 | 1.06 |
| 2,2,4–trimethylpentane, $C_8H_{18}$ | –107.3 | 99.2 | — | — |
| water, $H_2O$ | 0.00 | 100.00 | 4.1818 | 0.256 |
| heavy water, $D_2O$ | 3.82 | 101.42 | — | — |

Specific heat capacity and volume thermal expansion coefficients measured at 298 K except for [a] measured at 293 K.

### 5.3.1 Thermal conductivity

Thermal conductivity values correspond to a nominal pressure of 1 atmosphere. The values for water, benzene, and toluene are particularly well determined and can be used for calibration purposes.

| | Thermal conductivity (W/m K) | | | | | |
|---|---|---|---|---|---|---|
| Liquid | –25°C | 0°C | 25°C | 50°C | 75°C | 100°C |
| acetic acid, $C_2H_4O_2$ | | | 0.158 | 0.153 | 0.149 | 0.144 |
| acetone, $C_3H_6O$ | | 0.169 | 0.161 | | | |
| benzene, $C_6H_6$ | | | 0.1411 | 0.1329 | 0.1247 | |
| carbon disulfide, $CS_2$ | | 0.154 | 0.149 | | | |
| carbon tetrachloride, $CCl_4$ | | 0.104 | 0.099 | 0.093 | 0.088 | |
| chlorobenzene, $C_6H_5Cl$ | 0.136 | 0.131 | 0.127 | 0.122 | 0.117 | 0.112 |
| chloroform, $CHCl_3$ | 0.127 | 0.122 | 0.117 | 0.112 | 0.107 | 0.102 |
| cyclohexane, $C_6H_{12}$ | 0.137 | 0.129 | 0.121 | 0.113 | | |
| dibromomethane, $CH_2Br_2$ | 0.120 | 0.114 | 0.108 | 0.103 | 0.097 | |
| 1,4–dioxane, $C_4H_8O_2$ | | | 0.159 | 0.147 | 0.135 | 0.123 |
| ethanol, $C_2H_6O$ | | 0.176 | 0.169 | 0.162 | | |
| ethylene glycol, $C_2H_6O_2$ | | 0.256 | 0.256 | 0.256 | 0.256 | 0.256 |

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| Thermal conductivity (W/m K)—*continued* | | | | | | |
|---|---|---|---|---|---|---|
| **Liquid** | **–25ºC** | **0ºC** | **25ºC** | **50ºC** | **75ºC** | **100ºC** |
| glycerine (glycerol), $C_3H_8O_3$ | | | 0.292 | 0.295 | 0.297 | 0.300 |
| heavy water, $D_2O$ | | | | 0.618 | | 0.636 |
| heptane, $C_7H_{16}$ | 0.1378 | 0.1303 | 0.1228 | 0.1152 | 0.1077 | |
| hexadecane, $C_{16}H_{34}$ | 0.144 | 0.140 | 0.136 | 0.133 | 0.129 | 0.125 |
| hexane, $C_6H_{14}$ | 0.137 | 0.128 | 0.120 | 0.111 | 0.102 | 0.093 |
| methanol, $CH_4O$ | 0.214 | 0.207 | 0.200 | 0.193 | | |
| nitrobenzene, $C_6H_5NO_2$ | | | | | | |
| toluene, $C_7H_8$ | 0.1461 | 0.1386 | 0.1311 | 0.1236 | 0.1161 | |
| water, $H_2O$ | | 0.5610 | 0.6071 | 0.6435 | 0.6668 | 0.6791 |

From the table in *CRC Handbook of Chemistry and Physics*, 75th edition, Lide, D. R., Ed. (CRC Press, Boca Raton, FL, 1994), p. 6–249. Thermal conductivity data for additional organic and inorganic liquids are given in this reference.

### 5.3.2 Viscosity

| | Viscosity (mPa s) | | | | | |
|---|---|---|---|---|---|---|
| **Liquid** | **–25ºC** | **0ºC** | **25ºC** | **50ºC** | **75ºC** | **100ºC** |
| acetic acid, $C_2H_4O_2$ | | | 1.056 | 0.786 | 0.599 | 0.464 |
| acetone, $C_3H_6O$ | 0.540 | 0.395 | 0.306 | 0.247 | | |
| benzene, $C_6H_6$ | | 0.604 | 0.436 | 0.335 | | |
| bromobenzene, $C_6H_5Br$ | | | 10.74 | 0.798 | 0.627 | 0.512 |
| carbon disulfide, $CS_2$ | | 0.429 | 0.352 | | | |
| carbon tetrachloride, $CCl_4$ | | 1.0321 | 0.908 | 0.656 | 0.494 | |
| chloroform, $CHCl_3$ | 0.988 | 0.706 | 0.537 | 0.427 | | |
| cyclohexane, $C_6H_{12}$ | | | 0.894 | 0.615 | 0.447 | |
| 1,2–dichloroethane, $C_2H_4Cl_2$ | | | 0.464 | 0.362 | | |
| dichloromethane, $CH_2Cl_2$ | 0.727 | 0.533 | 0.413 | | | |
| dimethylsulfoxide, $C_2H_6OS$ | | | 1.987 | 1.290 | | |
| 1,4–dioxane, $C_4H_8O_2$ | | | 1.177 | 0.787 | 0.569 | |
| ethanol, $C_2H_6O$ | 3.262 | 1.786 | 1.074 | 0.694 | 0.476 | |
| ethylene glycol, $C_2H_6O_2$ | | | 16.1 | 6.554 | 3.340 | 1.975 |
| glycerine (glycerol), $C_3H_8O_3$ | | | 934 | 152 | 39.8 | 14.8 |
| heptane, $C_7H_{16}$ | 0.757 | 0.523 | 0.378 | 0.301 | 0.243 | |
| hexadecane, $C_{16}H_{34}$ | | | | 2.487 | 1.609 | 1.132 |
| hexane, $C_6H_{14}$ | | 0.405 | 0.300 | 0.240 | | |
| methanol, $CH_4O$ | 1.258 | 0.793 | 0.544 | | | |
| methylcyclohexane, $C_7H_{14}$ | | 0.991 | 0.679 | 0.501 | 0.390 | 0.316 |
| nitrobenzene, $C_6H_5NO_2$ | | 3.036 | 1.863 | 1.262 | 0.918 | 0.704 |
| toluene, $C_7H_8$ | 1.165 | 0.778 | 0.560 | 0.424 | 0.333 | 0.270 |
| water, $H_2O$ | | 1.793 | 0.890 | 0.547 | 0.378 | 0.282 |

Viscosity values correspond to a nominal pressure of 1 atmosphere.

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### 5.3.3 Surface Tension

| Liquid | Surface tension σ (mN/m) | | | | |
|---|---|---|---|---|---|
| | 10°C | 25°C | 50°C | 75°C | 100°C |
| acetic acid, $C_2H_4O_2$ | | 27.10 | 24.61 | 22.13 | |
| acetone, $C_3H_6O$ | | 23.46 | 20.66 | | |
| benzene, $C_6H_6$ | | 28.22 | 25.00 | 21.77 | |
| bromobenzene, $C_6H_5Br$ | 36.98 | 35.24 | 32.34 | 29.44 | 26.54 |
| carbon disulfide, $CS_2$ | 33.81 | 31.58 | 27.87 | | |
| carbon tetrachloride, $CCl_4$ | | 26.43 | 23.37 | 20.31 | 17.25 |
| chloroform, $CHCl_3$ | | 26.67 | 23.44 | 20.20 | |
| cyclohexane, $C_6H_{12}$ | 26.43 | 24.65 | 21.68 | | |
| 1,2–dichloroethane, $C_2H_4Cl_2$ | | 31.86 | 28.29 | 24.72 | |
| dichloromethane, $CH_2Cl_2$ | | 27.20 | | | |
| dimethylsulfoxide, $C_2H_6OS$ | | 42.92 | 40.06 | | |
| 1,4–dioxane, $C_4H_8O_2$ | | 32.75 | 29.28 | 25.80 | 22.32 |
| ethanol, $C_2H_6O$ | 23.22 | 21.97 | 19.89 | | |
| ethylene glycol, $C_2H_6O_2$ | | 47.99 | 45.76 | 43.54 | 41.31 |
| heptane, $C_7H_{16}$ | 21.12 | 19.65 | 17.20 | 14.75 | |
| hexadecane, $C_{16}H_{34}$ | | 27.05 | 24.91 | 22.78 | 20.64 |
| hexane, $C_6H_{14}$ | 19.42 | 17.89 | 15.33 | | |
| methanol, $CH_4O$ | 23.23 | 22.07 | 20.14 | | |
| methylcyclohexane, $C_7H_{14}$ | 24.989 | 23.29 | 20.46 | | |
| nitrobenzene, $C_6H_5NO_2$ | | | 40.56 | 37.66 | 34.77 |
| toluene, $C_7H_8$ | 29.71 | 27.93 | 24.96 | 21.98 | 19.01 |
| water, $H_2O$ | 74.23 | 71.99 | 67.94 | 63.57 | 58.91 |

### 5.3.4 Absorption

**Ultraviolet Absorption of Pure Liquids:**

The following tables present data on the UV absorption edge of several common liquids. The data were obtained using a 1.00–cm pathlength cell and a water reference. From Bruno, T. J. and Svoronos, P. D. N., *CRC Handbook of Basic Tables for Chemical Analysis* (CRC Press, Boca Raton, FL, 1989), p. 213.

| Acetone | |
|---|---|
| Wavelength (nm) | Maximum absorbance |
| 330 | 1.000 |
| 340 | 0.060 |
| 350 | 0.010 |
| 375 | 0.005 |
| 400 | 0.005 |

| Benzene | |
|---|---|
| Wavelength (nm) | Maximum absorbance |
| 278 | 1.000 |
| 300 | 0.020 |
| 325 | 0.010 |
| 350 | 0.005 |
| 400 | 0.005 |

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**Carbon tetrachloride**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 263 | 1.000 |
| 275 | 0.100 |
| 300 | 0.005 |
| 350 | 0.005 |
| 400 | 0.005 |

**Chloroform**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 245 | 1.000 |
| 250 | 0.300 |
| 275 | 0.005 |
| 300 | 0.005 |
| 400 | 0.005 |

**Cyclohexane**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 200 | 1.000 |
| 225 | 0.170 |
| 250 | 0.020 |
| 300 | 0.005 |
| 400 | 0.005 |

**Dimethyl sulfoxide**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 268 | 1.000 |
| 275 | 0.500 |
| 300 | 0.200 |
| 350 | 0.020 |
| 400 | 0.005 |

**1,4–Dioxane**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 215 | 1.000 |
| 250 | 0.300 |
| 300 | 0.020 |
| 350 | 0.005 |
| 400 | 0.005 |

**Hexadecane**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 190 | 1.000 |
| 200 | 0.500 |
| 250 | 0.020 |
| 300 | 0.005 |
| 400 | 0.005 |

**Hexane**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 195 | 1.000 |
| 225 | 0.050 |
| 250 | 0.010 |
| 275 | 0.005 |
| 300 | 0.005 |

**Methanol**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 205 | 1.000 |
| 225 | 0.160 |
| 250 | 0.020 |
| 300 | 0.005 |
| 400 | 0.005 |

**Toluene**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 284 | 1.000 |
| 300 | 0.120 |
| 325 | 0.020 |
| 350 | 0.005 |
| 400 | 0.005 |

**Water**

| Wavelength (nm) | Maximum absorbance |
|---|---|
| 190 | 0.010 |
| 200 | 0.010 |
| 250 | 0.005 |
| 300 | 0.005 |
| 400 | 0.005 |

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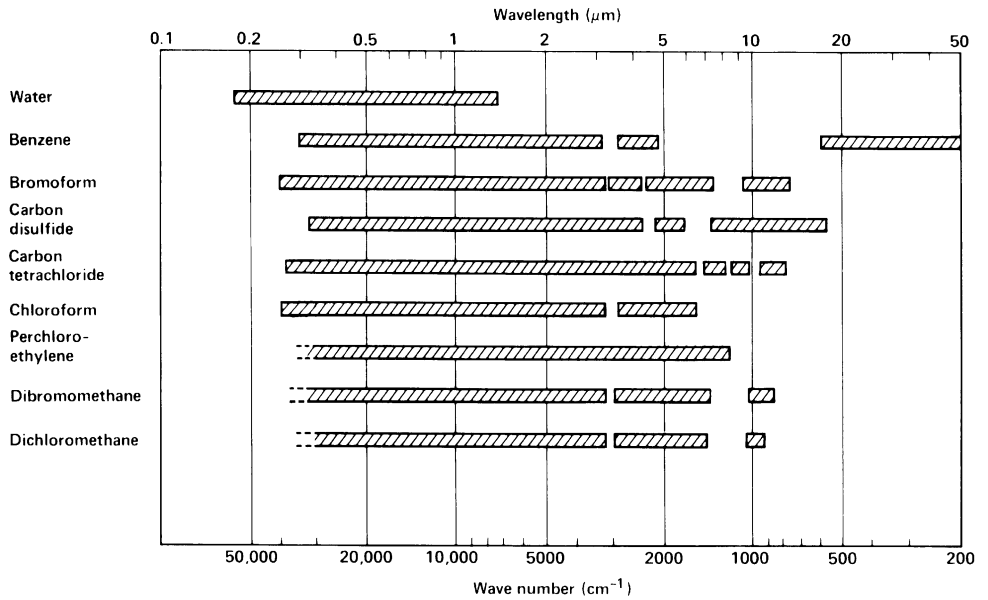
**Transmission Limits***

| Liquid | Limit (nm) | Liquid | Limit (nm) |
|---|---|---|---|
| acetone, $C_3H_6O$ | 200 | heptane, $C_7H_{16}$ | 196 |
| benzene, $C_6H_6$ | 270 | *n*–hexane, $C_6H_{14}$ | 202 |
| carbon tetrachloride, $CCl_4$ | 2250 | methanol, $CH_4O$ | 183 |
| chloroform, $CHCl_3$ | 220 | methylcyclohexane, $C_7H_{14}$ | 206 |
| cyclohexane, $C_6H_{12}$ | 211 | 1–octene, $C_6H_{16}$ | 210 |
| *n*–decane, $C_{10}H_{22}$ | 173 | *n*–pentane, $C_5H_{12}$ | 205 |
| *p*–dioxane, $C_4H_8O_2$ | 203 | toluene, $C_7H_8$ | 274 |
| ethanol, $C_2H_6O$ | 189 | water, $H_2O$ | 178 |

* Transmission limits are the wavelengths of the last visible blackening on a spectrogram for reasonable exposure and development time. From Klevens, H. B. and Platt, J. R., Ultraviolet transmission limits of some liquids and solids, *J. Am. Chem. Soc.* 69, 3055 (1947).




Spectral transmission ranges of several fluids used for liquid filters. The end points are for 50% transmission through 1 mm of the liquid [from Cook, L. M. and Stokowski, S. E., Filter materials, in *Handbook of Laser Science and Technology, Volume IV: Optical Materials, Part 2* (CRC Press, Boca Raton, 1995), p. 151].

For other organic and inorganic filter solutions, see Pellicori, S. F., Transmittances of some optical materials for use between 1900 and 3400 A, *Appl. Opt.* 3, 361 (1964); Bass, A. M., Short wavelength cut–off filters for the ultraviolet, *J. Opt. Soc. Am.* 38, 977 (1948); Ingersoll, K. A., Liquid filters for the visible and near infrared, *Appl. Opt.* 10, 2473 (1971); Ingersoll, K. A., Liquid filters for the ultraviolet, visible, and near infrared, *Appl. Opt.* 11, 2781 (1972).

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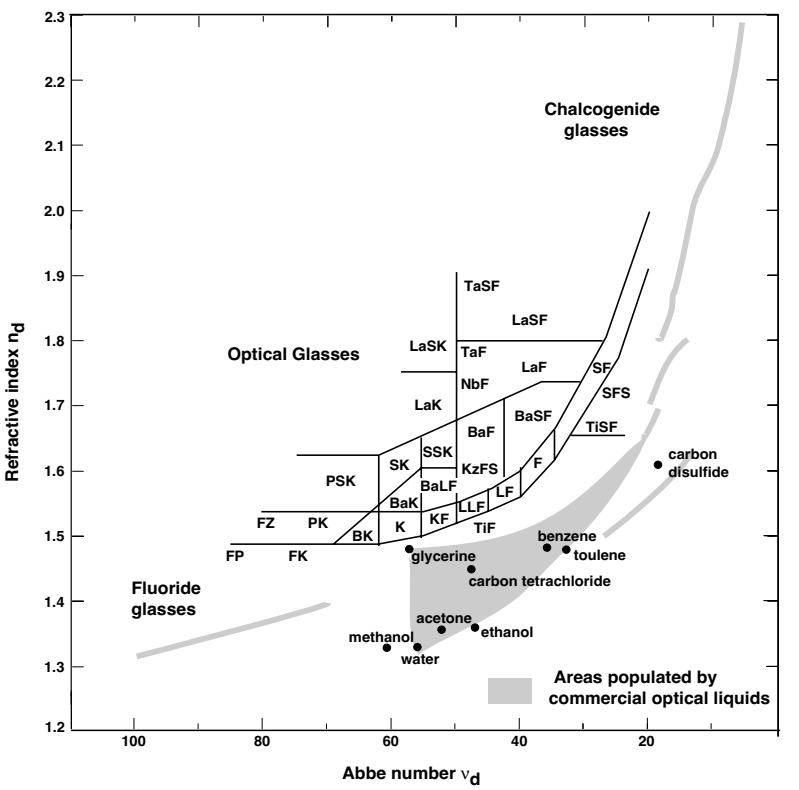
## 5.4 Index of Refraction

### 5.4.1 Organic Liquids

**Index of Refraction of Selected Liquids (293 K)**

| Liquid | $n_D$ | Liquid | $n_D$ |
|---|---|---|---|
| methanol, $CH_4O$ | 1.3288 | ethylene glycol, $C_2H_6O_2$ | 1.4318 |
| acetone, $C_3H_6O$ | 1.3588 | hexadecane, $C_{16}H_{34}$ | 1.4345 |
| ethanol, $C_2H_6O$ | 1.3611 | 1,2–dichloroethane, $C_2H_4Cl_2$ | 1.4448 |
| acetic acid, $C_2H_4O_2$ | 1.3720 | chloroform, $CHCl_3$ | 1.4459 |
| hexane, $C_6H_{14}$ | 1.3749 | carbon tetrachloride, $CCl_4$ | 1.4601 |
| heptane, $C_7H_{16}$ | 1.3878 | glycerine (glycerol), $C_3H_8O_3$ | 1.4746 |
| 2,2,4–trimethylpentane, $C_8H_{18}$ | 1.3915 | toluene, $C_7H_8$ | 1.4961 |
| dimethylsulfoxide, $C_2H_6OS$ | 1.4170 | benzene, $C_6H_6$ | 1.5011 |
| 1,4–dioxane, $C_4H_8O_2$ | 1.4224 | nitrobenzene, $C_6H_5NO_2$ | 1.5562 |
| methylcyclohexane, $C_7H_{14}$ | 1.4231 | bromobenzene, $C_6H_5Br$ | 1.5597 |
| dichloromethane, $CH_2Cl_2$ | 1.4242 | 1–methylnaphthalene, $C_{11}H_{10}$ | 1.6170 |
| cyclohexane, $C_6H_{12}$ | 1.4266 | carbon disulfide, $CS_2$ | 1.6319 |

Measured at a wavelength of 589 nm (sodium D line).




Comparison of selected liquids and optical glasses in an index of refraction Abbe number plot.

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## Index of Refraction n of Selected Liquids

**Acetic acid[1]**

| λ (nm) | n (296.05 K) |
|---|---|
| 434.05 | 1.38003 |
| 486.13 | 1.37610 |
| 589.3 | 1.37152 |
| 656.28 | 1.36944 |

**Acetone[1]**

| λ (nm) | n (292.55 K) |
|---|---|
| 434.05 | 1.36750 |
| 486.13 | 1.36366 |
| 589.3 | 1.35886 |
| 656.28 | 1.35672 |

**Carbon tetrachloride[1]**

| λ (nm) | n (285.45 K) |
|---|---|
| 434.05 | 1.4835 |
| 486.13 | 1.4726 |
| 589.3 | 1.4656 |
| 656.28 | 1.4599 |

**Benzene[1]**

| λ (nm) | n (293.15 K) |
|---|---|
| 276.3 | 1.625 |
| 298.1 | 1.598 |
| 313.3 | 1.582 |
| 361.0 | 1.548 |
| 434.05 | 1.52361 |
| 486.13 | 1.51327 |
| 508.6 | 1.509 |
| 589.3 | 1.50144 |
| 656.28 | 1.49663 |
| 0.8 | 1.489 |
| 1.0 | 1.485 |
| 1.5 | 1.480 |
| 1.85 | 1.478 |

**Carbon disulfide[1]**

| λ (nm) | n (291.15 K) |
|---|---|
| 361.0 | 1.740 |
| 394.4 | 1.704 |
| 434.05 | 1.67665 |
| 441.6 | 1.673 |
| 479.99 | 1.656 |
| 486.13 | 1.6539 |
| 508.6 | 1.647 |
| 533.8 | 1.640 |
| 589.3 | 1.6295 |
| 656.28 | 1.62011 |

**Toluene[2]**

| λ (nm) | n (293.15 K) |
|---|---|
| 404.66 | 1.526120 |
| 434.05 | 1.51970 |
| 435.84 | 1.517830 |
| 479.99 | 1.509285 |
| 486.13 | 1.508315 |
| 546.07 | 1.500715 |
| 589.3 | 1.49693 |
| 632.8 | 1.493680 |
| 656.28 | 1.49365 |
| 706.52 | 1.489795 |

**Chloroform[1]**

| λ (nm) | n (293.15 K) |
|---|---|
| 265.5 | 1.5051 |
| 289.4 | 1.4911 |
| 313.1 | 1.4806 |
| 486.13 | 1.45024 |
| 589.3 | 1.44432 |
| 656.28 | 1.44189 |

**Cyclohexane[1]**

| λ (nm) | n (293.15 K) |
|---|---|
| 265.5 | 1.4741 |
| 289.4 | 1.4631 |
| 313.1 | 1.4549 |
| 486.13 | 1.36662 |
| 589.3 | 1.36242 |
| 656.28 | 1.36062 |

**1,4–Dioxane[2]**

| λ (nm) | n (293.15 K) |
|---|---|
| 265.5 | 1.4699 |
| 289.4 | 1.4583 |
| 313.1 | 1.4500 |
| 546.07 | 1.4330 |
| 589.3 | 1.4311 |

**1,2-Dichloroethane[2]**

| λ (nm) | n (293.15 K) |
|---|---|
| 434.05 | 1.45528 |
| 486.13 | 1.45024 |
| 589.3 | 1.44432 |
| 656.28 | 1.44189 |

**Ethanol[1]**

| λ (nm) | n (291.5 K) |
|---|---|
| 434.05 | 1.37011 |
| 486.13 | 1.36662 |
| 589.3 | 1.36242 |
| 656.28 | 1.36062 |

**Ethylene glycol[2]**

| λ (nm) | n (293.15 K) |
|---|---|
| 435.83 | 1.4400 |
| 546.07 | 1.4330 |
| 589.3 | 1.4311 |

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## Index of Refraction n of Selected Liquids—*continued*

| Glycerine[1] | | Hexane[1] | | Methanol[1] | |
|---|---|---|---|---|---|
| λ (nm) | n (293.15 K) | λ (nm) | n (293.15 K) | λ (nm) | n (287.65 K) |
| 434.05 | 1.4839 | 434.05 | 1.38365 | 434.05 | 1.33801 |
| 486.13 | 1.4795 | 486.13 | 1.37988 | 486.13 | 1.33490 |
| 589.3 | 1.4740 | 589.3 | 1.37536 | 589.3 | 1.33118 |
| 656.28 | 1.4717 | 656.28 | 1.37337 | 656.28 | 1.32948 |

| Nitrobenzene[1] | |
|---|---|
| λ (nm) | n (293.15 K) |
| 486.13 | 1.57124 |
| 589.3 | 1.55291 |
| 656.28 | 1.54593 |

**References:**


1. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed. (McGraw–Hill, New York, 1930).
2. James, A. M. and Lord, M. P., *Macmillan's Chemical and Physical Data* (Macmillan, London, 1992).


## Temperature Derivative of the Index of Refraction

| Methanol | | | Ethanol | | |
|---|---|---|---|---|---|
| λ (nm) | $dn/dT \times 10^4$ ($K^{-1}$) | Ref. | λ (nm) | $dn/dT \times 10^4$ ($K^{-1}$) | Ref. |
| 434.05 | –3.90 (T = 288 K) | 1 | | | |
| 486.13 | –4.00 (T = 288 K) | 1 | | | |
| 546.07 | –4.05 (T = 298 K) | 2 | 546.07 | –4.05 (T = 298 K) | 2 |
| 600 | –4.68 (T = 278–298 K) | 3 | 600 | –4.38 (T = 278–298 K) | 3 |
| 632.8 | –4.00 (T = 288 K) | 2 | 632.8 | –4.00 (T = 298 K) | 2 |
| 656.28 | –4.00 (T = 298 K) | 1 | | | |

| Ethylene glycol | | | Glycerine | | |
|---|---|---|---|---|---|
| λ (nm) | $dn/dT \times 10^4$ ($K^{-1}$) | Ref. | λ (nm) | $dn/dT \times 10^4$ ($K^{-1}$) | Ref. |
| 486.13 | –2.70 (T = 288 K) | 1 | 486.13 | –2.30 (T = 288 K) | 1 |
| 600 | –3.06 (T = 278–298 K) | 3 | | | |
| 656.28 | –2.60 (T = 288 K) | 1 | 656.28 | –2.20 (T = 288 K) | 1 |

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## Temperature Derivative of the Index of Refraction—*continued*

### Hexane

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 434.05 | –5.60 (T = 298 K) | 1 |
| 486.13 | –5.50 (T = 298 K) | 1 |
| 546.07 | –5.43 (T = 298 K) | 2 |
| 632.8 | –5.40 (T = 298 K) | 2 |
| 656.28 | –5.30 (T = 298 K) | 1 |

### Cyclohexane

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 434.05 | –5.60 (T = 298 K) | 1 |
| 486.13 | –5.50 (T = 298 K) | 1 |
| 546.07 | –5.46 (T = 298 K) | 2 |
| 589.3 | –5.40 (T = 298 K) | 3 |
| 632.8 | –5.43 (T = 298 K) | 2 |
| 656.28 | –5.40 (T = 298 K) | 1 |

### Benzene

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 434.05 | –6.70 (T = 293 K) | 4 |
| 486.13 | –6.60 (T = 293 K) | 4 |
| 546.07 | –6.42 (T = 298 K) | 2 |
| 589.3 | –6.50 (T = 293 K) | 4 |
| 632.8 | –6.40 (T = 298 K) | 2 |
| 656.28 | –6.40 (T = 293 K) | 4 |

### Carbon tetrachloride

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 434.05 | –5.60 (T = 288 K) | 1 |
| 486.13 | –5.60 (T = 288 K) | 1 |
| 546.07 | –5.99 (T = 298 K) | 2 |
| 589.3 | –5.50 (T = 288 K) | 1 |
| 632.8 | –5.98 (T = 298 K) | 2 |
| 656.28 | –5.40 (T = 288 K) | 1 |

### Carbon disulfide

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 267.7 | –17.50 (T = 291 K) | 4 |
| 274.9 | –15.00 (T = 291 K) | 4 |
| 361.0 | –9.60 (T = 291 K) | 4 |
| 394.4 | –9.00 (T = 291 K) | 4 |
| 434.1 | –8.70 (T = 291 K) | 4 |
| 441.6 | –8.60 (T = 291 K) | 4 |
| 467.8 | –8.40 (T = 291 K) | 4 |
| 479.99 | –8.30 (T = 291 K) | 4 |
| 508.6 | –8.20 (T = 291 K) | 4 |
| 533.8 | –8.10 (T = 291 K) | 4 |
| 546.07 | –7.96 (T = 298 K) | 2 |
| 589.3 | –8.00 (T = 291 K) | 4 |
| 632.8 | –7.96 (T = 298 K) | 2 |
| 656.28 | –7.80 (T = 291 K) | 4 |

### Toluene

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 404.66 | –5.97 (T = 293 K) | 5 |
| 435.84 | –5.88 (T = 293 K) | 5 |
| 479.99 | –5.77 (T = 293 K) | 5 |
| 486.13 | –5.76 (T = 293 K) | 5 |
| 546.07 | –5.65 (T = 293 K) | 5 |
| 587.56 | –5.60 (T = 293 K) | 5 |
| 589.00 | –5.60 (T = 293 K) | 5 |
| 589.59 | –5.60 (T = 293 K) | 5 |
| 632.8 | –5.56 (T = 293 K) | 5 |
| | –5.55 (T = 298 K) | 2 |
| 643.85 | –5.55 (T = 293 K) | 5 |
| 656.28 | –5.54 (T = 293 K) | 5 |
| 706.52 | –5.51 (T = 293 K) | 5 |

### Acetic acid

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 486.13 | –3.80 (T = 288 K) | 1 |
| 656.28 | –3.70 (T = 288 K) | 1 |

### Chloroform

| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
|---|---|---|
| 546.07 | –5.98 (T = 298 K) | 2 |
| 632.8 | –5.98 (T = 298 K) | 2 |
| 656.28 | –5.30 (T = 298 K) | 1 |

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| Acetone | | | Nitrobenzene | | |
|---|---|---|---|---|---|
| λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. | λ (nm) | dn/dT × $10^4$ ($K^{-1}$) | Ref. |
| 486.13 | –5.00 (T = 288 K) | 1 | 486.13 | –4.80 (T = 288 K) | 1 |
| 546.07 | –5.31 (T = 298 K) | 2 | 546.07 | –4.68 (T = 298 K) | 2 |
| 589.3 | –5.00 (T = 288 K) | 1 | | | |
| 632.8 | –5.31 (T = 298 K) | 2 | 632.8 | –4.68 (T = 298 K) | 2 |
| 656.28 | –4.90 (T = 288 K) | 1 | 656.28 | –4.60 (T = 288 K) | 1 |

**References:**


1. Timmermans, J., *Physico-Chemical Constants of Pure Organic Compounds* (Elsevier, New York, 1950).
2. Hauf, W. and Grigull, U., *Optical Methods in Heat Transfer* (Academic Press, New York, 1970).
3. Lusty, M. E. and Dunn, M. H., *Appl. Phys.* B 44, 193 (1987).
4. *International Critical Tables of Numerical Data, Physics and Chemistry and Technology*, Vol. VII, Washburn, E. W., Ed., (McGraw-Hill, New York, 1930).
5. Kaye, G. W. and Laby, T. H., *Tables of Physical and Chemical Constants* (Longman Group, London, 1986).


### 5.4.2 Inorganic Liquids

| Name | Formula | Temperature (°C) | $n_D$ (589 nm) |
|---|---|---|---|
| ammonium | $NH_3$ | –77 | 1.3944 (578 nm) |
| antimony pentachloride | $SbCl_5$ | 22 | 1.5925 |
| argon | Ar | –188 | 1.2312 |
| arsenic trichloride | $AsCl_3$ | 16 | 1.604 |
| bromine tribromide | $BrF_3$ | 16 | 1.312 |
| carbon disulfide | $CS_2$ | 20 | 1.62774 |
| germanium tetrabromide | $GeBr_4$ | 26 | 1.6269 |
| germanium tetrachloride | $GeCl_4$ | 25 | 1.4614 |
| helium | He | –269 | 1.02451 (546 nm) |
| hydrogen peroxide | $H_2O_2$ | 28 | 1.4061 |
| oxygen | $O_2$ | –183 | 1.2243 (578 nm) |
| phosphorus tribromide | $PBr_3$ | 25 | 1.687 |
| phosphorus trichloride | $PCl_3$ | 21 | 1.5122 |
| sulfur dichloride | $SCl_2$ | 14 | 1.557 |
| sulfur trioxide | $SO_3$ | 20 | 1.40965 |
| tetrabromosilane | $SiBr_4$ | 31 | 1.5685 |
| tetrachlorosilane | $SiCl_4$ | 25 | 1.41156 |
| tin tetrabromide | $SnBr_4$ | 31 | 1.6628 |
| tin tetrachloride | $SnCl_4$ | 25 | 1.5086 |
| xenon | Xe | –112 | 1.3918 (578 nm) |

**Reference:**


Wohlfarth, C. and Wohlfarth, B., *Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, New Series*, III/38A, Martienssen, W., Ed. (Springer-Verlag, Heidelberg, 1996). The index of refraction at other temperatures and wavelengths may be found in this reference.


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### 5.4.3 Calibration Liquids

The six liquids below are available in highly pure form and their index of refraction has been accurately measured as a function of wavelength and temperature. They are therefore useful for calibration of refractometers. The estimated uncertainties in the values are:

| | |
|---|---|
| 2,2,4-Trimethylpentane | ±0.00003 |
| Hexadecane | ±0.00008 |
| *trans*-Bicyclo[4.0.0]decane | ±0.00008 |
| 1-Methylnaphthalene | ±0.00008 |
| Toluene | ±0.00003 |
| Methylcyclohexane | ±0.00003 |

Further details are given in the references below. This table is reprinted from Reference 1 by permission of the Intemational Union of Pure and Applied Chemistry.

**References:**


1. Marsh, K. N., Ed., *Recommended Reference Materials for the Realization of Physicochemical Properties* (Blackwell Scientific Publications, Oxford, 1987).
2. Tilton, L. W., *J. Opt. Soc. Am.* 32, 71 (1941).


| | **2,2,4-Trimethylpentane** | | | **Hexadecane** | | |
|---|---|---|---|---|---|---|
| **λ (nm)** | **20°C** | **25°C** | **30°C** | **20°C** | **25°C** | **30°C** |
| 667.81 | 1.38916 | 1.38670 | 1.38424 | 1.43204 | 1.43001 | 1.42798 |
| 656.28 | 1.38945 | 1.38698 | 1.38452 | 1.43235 | 1.43032 | 1.42829 |
| 589.26 | 1.39145 | 1.38898 | 1.38650 | 1.43453 | 1.43250 | 1.43047 |
| 546.07 | 1.39316 | 1.39068 | 1.38820 | 1.43640 | 1.43436 | 1.43232 |
| 501.57 | 1.39544 | 1.39294 | 1.39044 | 1.43888 | 1.43684 | 1.43480 |
| 486.13 | 1.39639 | 1.39389 | 1.39138 | 1.43993 | 1.43788 | 1.43583 |
| 435.83 | 1.40029 | 1.39776 | 1.39523 | 1.44419 | 1.44213 | 1.44007 |

| | ***trans*-Bicyclo[4.0.0]decane** | | | **1-Methylnaphthalene** | | |
|---|---|---|---|---|---|---|
| **λ (nm)** | **20°C** | **25°C** | **30°C** | **20°C** | **25°C** | **30°C** |
| 667.81 | 1.46654 | 1.46438 | 1.46222 | 1.60828 | 1.60592 | 1.60360 |
| 656.28 | 1.46688 | 1.46472 | 1.46256 | 1.60940 | 1.60703 | 1.60471 |
| 589.26 | 1.46932 | 1.46715 | 1.46498 | 1.61755 | 1.61512 | 1.61278 |
| 546.07 | 1.47141 | 1.46923 | 1.46705 | 1.62488 | 1.62240 | 1.62005 |
| 501.57 | 1.47420 | 1.47200 | 1.46980 | 1.63513 | 1.63259 | 1.63022 |
| 486.13 | 1.47535 | 1.47315 | 1.47095 | 1.63958 | 1.63701 | 1.63463 |
| 435.83 | 1.48011 | 1.47789 | 1.47567 | | 1.65627 | 1.65386 |

| | **Toluene** | | | **Methylcyclohexane** | | |
|---|---|---|---|---|---|---|
| **λ (nm)** | **20°C** | **25°C** | **30°C** | **20°C** | **25°C** | **30°C** |
| 667.81 | 1.49180 | 1.48903 | 1.48619 | 1.42064 | 1.41812 | 1.41560 |
| 656.28 | 1.49243 | 1.48966 | 1.48682 | 1.42094 | 1.41#42 | 1.41591 |
| 589.26 | 1.49693 | 1.49413 | 1.49126 | 1.42312 | 1.42058 | 1.41806 |
| 546.07 | 1.50086 | 1.49803 | 1.49514 | 1.42497 | 1.42243 | 1.41989 |
| 501.57 | 1.50620 | 1.50334 | 1.50041 | 1.42744 | 1.42488 | 1.42233 |
| 486.13 | 1.50847 | 1.50559 | 1.50265 | 1.42847 | 1.42590 | 1.42334 |
| 435.83 | 1.51800 | 1.51506 | 1.51206 | 1.43269 | 1.43010 | 1.42752 |

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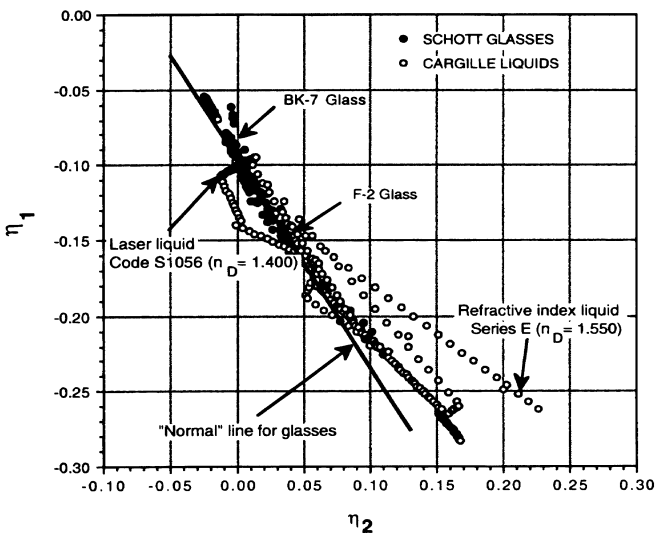
### 5.4.4 Abnormal Dispersion Liquids

Chromatic aberrations in complex lens systems can be corrected by combining lenses made of materials having different refractive indices and dispersions. When the partial dispersion of a material (refractive index for a pair of wavelengths) is plotted versus its Abbe number, most materials lie along a straight line, the so-called "normal" line. (Plots of relative dispersions showing the deviation of various glass types from the normal curve are included in most optical glass catalogs.) To correct for the secondary spectrum in apochromatic lens system (one corrected for three wavelengths), at least one of the materials must have an abnormal dispersion, that is, one lying off the normal line.

The wavelength dependence of the refractive index of a material can be described by the Buchdahl equation $N(\omega) = N_0 + \nu_1\omega + \nu_2\omega^2 + \ldots \nu_j\omega^j$, where $N_0$ is the refractive index at the wavelengths $\lambda$, $\nu_1$, $\nu_2$, . . . characterize the dispersion, and $\omega$ is the chromatic coordinate $\omega = (\lambda - \lambda_0/[1 + 5/2(\lambda - \lambda_0)]$. The dispersive power of a material in this model is given by

$$D(\lambda) = \delta N(\lambda) /(N_0 - 1) = \sum_{i=1}^{n} \eta_i\omega,$$

where n is the order of the Buchdahl dispersion equation. The dispersion coefficients $\eta$ are defined by $\eta_i = \nu_i/(N_0 - 1)$. Below is a plot of the primary and secondary dispersion properties of 178 Schott optical glasses and 300 Cargille optical liquids (courtesy of R. D. Sigler).




**References:**


1. Sigler, R. D., Apochromatic color correction using liquid lenses, *Appl. Opt*. 29, 2451 (1990).
2. Petrova, M. V., Petrovskii, G. T., Tolstoi, M. N., and Volynkin, V. M., Abnormal dispersion liquids, *Opt. Eng.* 31, 664 (1992).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## 5.5 Nonlinear Optical Properties

**Abbreviations for Materials**

| Abbreviations | Material |
|---|---|
| 4-BCMUy | Yellow form of poly-4-BCMU |
| 4ABP | 4-Aminobiphenyl |
| 123TB | 1,2,3-Trimethyl benzene |
| 124TB | 1,2,4-Trimethyl benzene |
| 1234TB | 1,2,3,4-Tetramethyl benzene |
| 1235TB | 1,2,3,5-Tetramethyl benzene |
| α-NPA | a-NPO (2-(1-naphthyl)-5-phenyloxazole) |
| BBPEN | Bis[*n*-butyl, 2-phenyl-1,2-ethenedithiolato(2-)-*S*,*S*′] nickel |
| BEEDT | Bis(1,2-diethyl-1,2-ethenedithiolato(2-)-*S*,*S*') nickel |
| bis-MSB | *p*-Bis(*o*-methylstyryl)benzene |
| BP4B | Benzopurpurin 4B |
| BPDDT | *trans*-(Bis-(1-decyl-2-phenylethenedithiolato-*S*,*S*') nickel |
| BRD | Bacteriorhodopsin |
| BSQ | 1,3-Bis(4'-*N*,*N*-dibutylamino-2'-hydroxyphenyl)-cyclobutene-2,4-dione |
| BTMSF | Bis (trimethylsilyl) ferocene |
| DCV | 4-*N*,*N*-Diethylamino-4'-*b,b*-dicyanovinyl (azobenzene) |
| DEANS | 4-Diethylamino-4'-nitrostilbene |
| DMF | Dimethylformamide |
| DMSM | 4'-Dimethylamino-*N*-methyl-4-stilbazolium methylsulfate |
| DNTA | 4-Nitrothenylidenyl (4'-*N*,*N*-dimethylaminoanilide) |
| DPA | Diphenyl amine |
| DQCI | 1,3'-Diethyl 1-2,2-quinolythiacarbocyanice iodide |
| DR1 | Disperse red 1 |
| ISQ | 1,3-Bis(3',3'-dimethyl-2'-indoleninylidenyl)-cyclobutene-2,4-dione |
| MDCB | *m*-Dicyanobenzene |
| MDNB | *m*-Dinitrobenzene |
| Mg:OPTAP | Magnesium octaphenyl tetraazaporphyrin |
| MNA | 2-Methyl-4-nitroaniline |
| MNTPM | Zinc meso-tetra-(*p*-methoxphenyl) tetrabenzporphyrin |
| MNTPMP | Zinc meso-tetra-(*p*-methylphenyl) tetrabenzporphyrin |
| MOMT | Magnesium octamethyltetrabenzporphyrin |
| NFAI | 5-Nitro(2-furanacroleindenyl (4'-*N*,*N*-dimethylaminoanilide) |
| NPCV | 4-*N*,*N* -Dibutylamino-4'-(b-cyano-b-(4'-nitrophenyl) vinyl) (azobenzene) |
| P(4ABP) | Poly(4-amino biphenyl) with 1.5% tetrafluoroborate doping |
| P(DPA) | Poly(diphenyl amine) with 1.5% tetrafluoroborate doping |
| PBPC | Pb-phthalocyanine |
| PMTBQ | Nonconjugated derivative of a polythiophene |
| PPV | Poly (*p*-phenylene vinylene) |
| PTPC | Pt-phthalocyanine |
| R6G | Rhodamine 6G |
| RB | Rhodamine B |
| rB | Rhodamine B |

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**Abbreviations for Materials**—*continued*

| Abbreviations | Material |
|---|---|
| Retinal | 6-*s*-*cis* and completelty *trans* retinal |
| retinal | *trans*-Retinal, malononitrile Knoevenagel adduct |
| Retinyl acetate | 6-*s*-*cis* and completety *trans* retinyl 1,2- |
| SiNc | Silicon naphthalocyanine |
| SiPc | Silicon phthalocyanine |
| TBPP | Tetrabenzporphyrin |
| TCV | 4-*N*,*N*-Diethylamino-4'-tricyanovinyl (azobenzene) |
| TKCPPC | Tetrakis(cumylphenoxy)phthalocyanines |
| TNF | 2,4,7-Trinitrofluorenone |
| ZHDFT | Zinc hexadecafluorotetrabenzporphyrin |
| ZMTM | Zinc meso-tetramethyltetrabenzporphyrin |
| ZMTMF | Zinc meso-tetra-(*m*-fluorophenyl) tetrabenzporphyrin |
| ZMTP | Zinc meso-tetraphenyltetrabenzporphyrin |
| ZMTPDMAP | Zinc meso-tetra-(*p*-dimethylaminohenyl) tetrabenzporphyrin |

**Experimental Methods**

| Abbreviation | Method | Ref. |
|---|---|---|
| AFRS | anharmonic forced Rayleigh scattering | 1 |
| AI1 | attenuation vs. irradiance for a single beam | 2,3 |
| DFWM | degenerate four-wave mixing | 4 |
| ID | ionization decay | 5 |
| KE | DC Kerr effect | 6 |
| L | luminescence or fluorescence | 7,8 |
| MSI | modified Sagnac interferometry | 9 |
| OKE | optical Kerr effect | 10 |
| OL | optical limiting | 11 |
| PS | polarization spectroscopy | 12 |
| PST | power for self-trapping | 13 |
| SA | saturated absorption | 14 |
| SFL | self-focal length | 15 |
| TBC | two-beam coupling | 14 |
| TL | thermal lensing | 16 |
| TPDR | two-photon double resonance spectroscopy | 17 |
| TPIF | two-photon induced fluorescence | 18 |
| TRI | time-resolved interferometry | 19 |

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### 5.5.1 Two-Photon Absorption Cross Sections

The two-photon absorption cross section $\sigma_2$ is related to the two-photon absorption coefficient $\beta$ by $\sigma_2 = (h\nu/N)\beta$, where N is the number density of molecules.

**Two-Photon Absorption Coefficient $\beta$**

| Liquid | Wavelength (nm) | Pulse length (ns) | $\beta \times 10^{11}$ (m/W) | Ref. |
|---|---|---|---|---|
| benzene, $C_6H_6$ | 354.7 | 5 | 1.5 | 1 |
| | 532.1 | 5 | $4.5 \times 10^{-5}$ | 1 |
| cyclohexane, $C_6H_{12}$ | 694.3 | 14 | 1.9 | 2 |
| toluene, $C_7H_8$ | 354.7 | 5 | 1.2 | 1 |
| | 532.1 | 5 | $6.3 \times 10^{-4}$ | 1 |

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## Two-Photon Absorption Cross Sections

| Material | Method | Excitation duration (ns) | Applied two–photon energy (eV) | Two–Photon cross section $\sigma_2$ $10^{-50}$cm$^4$ s/ phot. mol. | Ref. |
|---|---|---|---|---|---|
| 123TB | TPIF | 5 | 4.66 | 0.0021 | 1 |
| 124TB | TPIF | 5 | 4.66 | 0.075 | 1 |
| 1234TB | TPIF | 5 | 4.66 | 0.076 | 1 |
| 1235TB | TPIF | 5 | 4.66 | 0.18 | 1 |
| α-NPA | L | 0.002–0.003 | 3.57–4.62 | Relative spectrum | 2 |
| Aniline | TL | | 3.96–5.69 | Relative spectrum (8.8 × benzene @ 4.10 eV) | 3 |
| Anthracene | L | 40 | 3.57 | 14 | 4 |
| Azulene | AFRS | 42–67 | 4.66 | 1070 | 5 |
| Benzene | TL | | 4.46–5.69 | Relative spectrum (49.0 × benzene @ 4.98 eV) | 3 |
| | TPIF | 5 | 4.66 | 0.00025 | 1 |
| Bis-MSB | L | 0.002–0.003 | 3.57–4.62 | Relative spectrum (690 @ 4.24 eV) | 2 |
| BRD | TPDR | 6 | 2.07 | 169 | 6 |
| | TPDR | 6 | 2.12 | 207 | 6 |
| | TPDR | 6 | 2.16 | 247 | 6 |
| | TPDR | 6 | 2.21 | 289 | 6 |
| | TPDR | 6 | 2.30 | 288 | 6 |
| | TPDR | 6 | 2.36 | 244 | 6 |
| | TPDR | 6 | 2.56 | 201 | 6 |
| | TPDR | 6 | 2.70 | 167 | 6 |
| | TPDR | 6 | 2.78 | 127 | 6 |
| | TPDR | 6 | 2.92 | 174 | 6 |
| | TPDR | 6 | 3.02 | 199 | 6 |
| Fluorobenzene | TL | | 4.46–5.69 | Relative spectrum (1.5 × benzene @ 4.65 eV and 5.5 × benzene @ 5.69 eV) | 3 |
| Mesitylene | TPIF | 5 | 4.66 | 0.096 | 1 |
| *m*-Xylene | TPIF | 5 | 4.66 | 0.028 | 1 |
| *o*-Xylene | TPIF | 5 | 4.66 | 0.035 | 1 |
| *p*-Xylene | TPIF | 5 | 4.66 | 0.052 | 1 |

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**Two-Photon Absorption Cross Sections—***continued*

| Material | Method | Excitation duration (ns) | Applied two–photon energy (eV) | Two–Photon cross section $\sigma_2$ $10^{-50}$cm$^4$ s/ phot. mol. | Ref. |
|---|---|---|---|---|---|
| Phenol | TL | | 4.21–5.69 | Relative spectrum (0.8 x benzene @ 4.39 eV and 8.6 × @ 5.45 eV) | 3 |
| Pyridine | TL | | 4–6.2 | Relative spectrum (0.27 @ 4.5 eV) | 7 |
| R6G | AI1 | 0.015 | 3.57 | 180 | 8 |
| RB | AI1 | 0.015 | 3.57 | 120 | 8 |
| Retinal | L | 40 | 3.57 | 27 (in ethanol) | 4 |
| Retinyl acetate | L | 40 | 3.57 | 26 (in n-hexane) | 4 |
| | L | 40 | 3.57 | 29 (in EPIP | 4 |
| Toluene | TL | | 4.46–5.69 | Relative spectrum (2.1 × benzene @ 4.59 eV and 3.3 × @ 5.62 eV) | 3 |
| | TPIF | 5 | 4.66 | 0.0036 | 1 |

Table from Garito, A. F. and Kuzyk, M G., Two-photon absorption, organic materials, in *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 329.

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### 5.5.2 Nonlinear Refraction

**Nonlinear Refractive Index γ**

| Liquid | Wavelength (μm) | $\gamma \times 10^{20}$ ($m^2$/W) | Ref. |
|---|---|---|---|
| acetic acid, $C_2H_4O_2$ | 0.6943 | 22.6 | 1 |
| acetone, $C_3H_6O$ | 0.6943 | 13.3 | 1 |
| benzene,* $C_6H_6$ | 0.57 | 38 | 4,7 |
| | 0.6943 | 35 | 1 |
| carbon disulfide,* $CS_2$ | 0.53 | 310 ± 30 | 3 |
| | 0.6943 | 390 ± 50 | 4 |
| | 1.0642 | 290 ± 30 | 5 |
| | 1.32 | 330 | 4 |
| | 10.6 | 390 ± 150 | 6 |
| carbon tetrachloride, $CCl_4$ | 0.53 | 10.2 | 4,7 |
| | 0.56-0.59 | 8.0 | 8 |
| | 0.6943 | 5.8 | 1 |
| chloroform, $CHCl_3$ | 0.53 | 20 | 4,7 |
| | 0.6943 | 17 | 1 |
| cyclohexane, $C_6H_{12}$ | 0.53 | 7.6 | 4,7 |
| | 0.55-0.58 | 12.3 ± 0.9 | 9 |
| 1,2-dichloroethane, $C_2H_4Cl_2$ | 0.53 | 24 | 4,7 |
| ethanol, $C_2H_6O$ | 0.53 | 5.2 | 4,7 |
| glycerine (glycerol), $C_3H_8O_3$ | 0.53 | 4.7 | 4,7 |
| heavy water, $D_2O$ | 1.06 | 6.4 | 10 |
| methanol, $CH_4O$ | 0.53 | 4.7 | 4,7 |
| nitrobenzene, $C_6H_5NO_2$ | 0.53 | 450 | 4,7 |
| | 0.6943 | 240 | 1 |
| toluene, $C_7H_8$ | 0.53 | 113 | 4,7 |
| | 0.6943 | 85 | 1 |
| water, $H_2O$ | 0.53 | 2.7 | 4,7 |
| | 0.6943 | 2.8 | 1 |
| | 1.0642 | 5.4(?) | 10 |

Measurements made at room temperature.

* Materials used for liquid optics based on nonlinear self-focusing [Ramanthan, D. and Molian, P. A., Laser micromachining using liquid optics, *Appl. Phys. Lett.* 78, 1484 (2001)].

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**Nonlinear Refraction Data for Solutions**

| Material | Solvent | Dye weight fract.(%) | Method | Pulse length (ns) | Wave-length (nm) | Linear refract. index | $\chi^{(3)}_{1111}$ ,$\chi^{(3)}_{1212}$ ( $10^{-12}$cm$^3$/erg) | Ref. |
|---|---|---|---|---|---|---|---|---|
| 4-BCMUy | DMF | 14 | DFWM | 0.033 | 1064 | 1.43 | 1.4 | 7 |
| DEANS | DMF | 3 | OKE | 6 | 700, 830 | | [a]0.2 | 8 |
| DMSM | Ethanol | 5 | OKE | 6 | 700, 830 | | 0.46 | 8 |
| DMSM | Formamide | 20 | OKE | 6 | 700, 830 | | 3 | 8 |
| MNA | Ethanol | 5 | OKE | 6 | 700, 830 | | [a]0.2 | 8 |
| P(4ABP) | DMF | $10^{-2}$–$10^{-3}$ M/l | DFWM | 0.040 | 1064 | 1.43 | 0.31, 0.17 | 9 |
| P(DPA) | DMF | $10^{-2}$–$10^{-3}$ M/l | DFWM | 0.040 | 1064 | 1.43 | 0.48, 0.22 | 9 |
| PBPC[a] | $CHCl_3$ | 0.73 M/l | DFWM | 0.035 | 1064 | | 200 | 10 |
| PMTBQ[a] | DCM | 100 | DFWM | 0.030 | 532 | | 4600 | 11 |
| PTPC[a] | $CHCl_3$ | 0.73 M/l | DFWM | 0.035 | 1064 | | 20 | 10 |
| Retinal | DMSO | $10^{-3}$ M/l | DFWM | 6 | 532 | | 4.3 | 12 |
| TKCPPC[a] | $CHCl_3$ | 0.73 M/l | DFWM | 0.035 | 1064 | | 4.0 | 10 |

[a]Extrapolated from solution measurement.

**Nonlinear Refraction Data for Dye Solutions**

| Dye | Solvent | Dye conc. ($10^{22}$cm$^{-3}$) | Method | Pulse length (ns) | Wave-length (nm) | Linear refract. index | $\chi^{(3)}_{1111}$ ($10^{-20}$m$^2$/V$^2$) | Ref. |
|---|---|---|---|---|---|---|---|---|
| A9860 | 1,2-dichl-oroethane | 0.58 | DFWM | 0.16 | 532 | 1.45 | 1.8 | 2,3 |
| b-Carotene | EtOH | 20 | DFWM | 0.16 | 532 | 1.3 | 0.2 | 1,3 |
| BDN | Toluene | 1.6 | DFWM | 0.16 | 532 | 1.49 | 1.7 | 2,3 |
| BEEDT | Dichl-oromethane | 0.0001 | DFWM | 0.1 | 1064 | | 0.36 | 4 |
| BPDDT | Dichl-oromethane | 0.0001 | DFWM | 0.1 | 1064 | | 1.36 | 4 |
| DNTPC | MtOH | 4.3 | DFWM | 0.16 | 532 | 1.3 | 1.0 | 2,3 |
| DTTC | MtOH | 25 | DFWM | 0.16 | 532 | 1.3 | 0.8 | 2,3 |
| IR5 | 1,2-Dichl-oroethane | 1 | DFWM | 0.16 | 532 | 1.45 | 2.1 | 2,3 |
| Nigrosine | $H_2O$ | 42 | DFWM | 0.16 | 532 | 1.33 | 2.6 | 2,3 |
| S501 | *o*-Dichl-orobenzene | 0.5 | DFWM | 0.16 | 532 | 1.55 | 1.25 | 2,3 |

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**Nonlinear Refraction Data for Dye Solutions—*continued***

| Dye | Solvent | Absorption coeff. $\alpha(cm^{-1})$ | Method | Pulse length (ns) | Wave-length (nm) | $\chi^{(3)}_{1111}$ ($10^{-20}$ $m^2/V^2$) | $\chi^{(3)}_{1212}$,$\chi^{(3)}_{1221}$ ($10^{-12}$$cm^3$/erg) | Ref. |
|---|---|---|---|---|---|---|---|---|
| BP4B | Acetone | 0.39 | DFWM | 20 | 532 | 89 | | 5 |
| BP4B | Ethanol | 0.67 | DFWM | 20 | 532 | 151 | | 5 |
| BP4B | Glycerol | 2.28 | DFWM | 20 | 532 | 130 | | 5 |
| BP4B | Methanol | 0.74 | DFWM | 20 | 532 | 146 | | 5 |
| Chrysoidin[a] | Acetone | 0.21 | DFWM | 20 | 532 | 83.1 | | 5 |
| Chrysoidin | Ethonal | 0.67 | DFWM | 20 | 532 | 113 | | 5 |
| Chrysoidin | Methonal | 0.66 | DFWM | 20 | 532 | 146 | | 5 |
| DQCI | Acetone | 92 | PS | 6 | 590 | | 8000 | 6 |
| DQCI | Acetone | 16.1 | PS | 6 | 590 | | 1600 | 6 |
| DQCI | Acetone | 267 | PS | 6 | 590 | | 20000 | 6 |
| Malachite green | Acetone | 27.6 | PS | 6 | 610 | | 8800 | 6 |
| Malachite green | Acetone | 82.8 | PS | 6 | 610 | | 4000 | 6 |
| Malachite green | Acetone | 175 | PS | 6 | 610 | | 7000 | 6 |

[a]Linear refractive index = 1.33.

| Dye | Solvent | Dye conc. ($10^{-4}$ M/l) | Method | Pulse length (ns) | Wave-length (nm) | Linear refract. index | $\chi^{(3)}_{1111}$ ($10^{-20}$ $m^2/V^2$) | Ref. |
|---|---|---|---|---|---|---|---|---|
| BDN | Toluene | * | DFWM | 0.18 | 1064 | 1.5 | 91 | 2 |
| *Co*TPP | Toluene | 0.727 | DFWM | 0.08–0.2 | 532 | | 10 | 2 |
| $H_2$TPP | Toluene | 3.86 | DFWM | 0.08–0.2 | 532 | | 40 | 2 |
| IR5 | 1,2–Dich-loroethane | * | DFWM | 0.18 | 1064 | 1.45 | 62 | 2 |
| S501 | 1,2–Dich-loroethane | * | DFWM | 0.18 | 1064 | 1.45 | 59 | 2 |
| $Z_n$TPP | Toluene | 2.29 | DFWM | 0.08–0.2 | 532 | | 20 | 2 |

*Dye concentration adjusted for 50% transmission in a 2-mm cell.

| Dye | Solvent | Dye conc. ($10^{-4}$ g/ml) | Method | Pulse length (ns) | Wave-length (nm) | Linear refract. index | $\chi^{(3)}_{1111}$ ($10^{-12}$ $cm^3$/erg) | Ref. |
|---|---|---|---|---|---|---|---|---|
| MNTPM | THF | 0.1–1.0 | DFWM | 17 | 532 | | 14000 | 1 |
| MNTPMP | THF | 0.1–1.0 | DFWM | 17 | 532 | | 12000 | 1 |
| MOMT | THF | 0.1–1.0 | DFWM | 17 | 532 | | 8000 | 1 |
| TBPP | THF | 0.1–1.0 | DFWM | 17 | 532 | | 3000 | 1 |
| ZHDFT | THF | 0.1–1.0 | DFWM | 17 | 532 | | 2000 | 1 |
| ZMTM | THF | 0.1–1.0 | DFWM | 17 | 532 | | 15000 | 1 |
| ZMTMF | THF | 0.1–1.0 | DFWM | 17 | 532 | | 13000 | 1 |
| ZMTP | THF | 0.1–1.0 | DFWM | 17 | 532 | | 3000 | 1 |
| ZMTPDMAP | THF | 0.1–1.0 | DFWM | 17 | 532 | | 28000 | 1 |

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**Nonlinear Refraction Data for Liquids**

| Liquid | Method | Pulse length (ns) | Wave-length (nm) | Linear refract. index | $\chi^{(3)}_{1111}$ ·$\chi^{(3)}_{1212}$ ($10^{-12}$ cm$^3$/erg) | $\chi^{(3)}_{1111}$ ($10^{-12}$ cm$^3$/erg) | Ref. |
|---|---|---|---|---|---|---|---|
| 4ABP | DFWM | 0.040 | 1064 | | $<\chi^{(3)}> = 3$ | | 9 |
| α-Picoline | TRI | 0.025 | 532 | | 0.045 | 0.05 | 13 |
| Benzene | OKE | 0.03 | 1064, 459 | 1.52[a] | 0.057 | | 14 |
| Benzene | OKE | 0.03 | 1064, 472 | 1.52[a] | 0.057 | | 14 |
| Benzene | OKE | 0.03 | 1064, 496 | 1.51[a] | 0.068 | | 14 |
| Benzene | OKE | 0.03 | 1064, 517 | 1.51[a] | 0.059 | | 14 |
| Benzene | OKE | 0.03 | 1064, 590 | 1.50[a] | 0.070 | | 14 |
| Benzene | TRI | 0.025 | 532 | 1.51 | 0.036 | 0.049 | 13 |
| Benzene chloride | DFWM | 0.033 | 1064 | | $\chi^{(3)}_{1212} = 0.11$ | | 7 |
| BTMSF | OL | 10 | 1060 | 1.55 | | 0.20 | 15 |
| $CCl_4$ | TRI | 0.025 | 532 | 1.45 | 0.008 | 0.009 | 16 |
| $CH_3COCH_3$ | TRI | 0.025 | 532 | | 0.009 | 0.010 | 16 |
| Chloroform | TRI | 0.025 | 532 | 1.45 | 0.015 | 0.019 | 16 |
| $CS_2$ | DFWM | 0.033 | 1064 | | $\chi^{(3)}_{1212} = 0.32$ | | 7 |
| $CS_2$ | PST | 130 | 10600 | 1.63 | | 8.75 | 16 |
| $CS_2$ | TRI | 0.025 | 532 | 1.63 | 0.60 | 0.68 | 13 |
| $CS_2$ | SFL | 3 | 10600 | 1.63 | | 0.83 | 17 |
| Cyclohexane | RTI | 0.025 | 532 | 1.43 | 0.007 | 0.009 | 13 |
| DMF | DFWM | 0.033 | 1064 | | $\chi^{(3)}_{1212} = 0.033$ | | 7 |
| DPA | DFWM | 0.040 | 1064 | | $<c^{(3)}> = 3$ | | 9 |
| Molten ferrocene | OL | 10 | 1060 | 1.55 | | 0.17 | 15 |
| Nitrobenzene | OKE | 0.03 | 1064, 459 | 1.58[a] | 0.13 | | 14 |
| Nitrobenzene | OKE | 0.03 | 1064, 472 | 1.58[a] | 0.168 | | 14 |
| Nitrobenzene | OKE | 0.03 | 1064, 496 | 1.57[a] | 0.146 | | 14 |
| Nitrobenzene | OKE | 0.03 | 1064, 517 | 1.56[a] | 0.132 | | 14 |
| Nitrobenzene | OKE | 0.03 | 1064, 590 | 1.55[a] | 0.084 | | 14 |
| Nitrobenzene | OL | 10 | 1060 | 1.56 | | 0.20 | 15 |
| Nitrobenzene | TRI | 0.025 | 532 | 1.55 | 0.11 | 0.13 | 13 |
| P(4ABP) | DFWM | 0.040 | 1064 | | $<c^{(3)}> = 100$ | | 9 |
| P(DPA) | DFWM | 0.040 | 1064 | | $<c^{(3)}> = 100$ | | 9 |
| PPV | DFWM | 0.0004 | 602,580 | | 400 | | 18 |
| Toluene | RTI | 0.025 | 532 | 1.49 | 0.018 | 0.038 | 13 |

[a] Refractive index of probe beam.

The tables above are from Garito, A. F. and Kuzyk, M G., Two-photon absorption, organic materials, *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995) , p. 289.

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### 5.5.3 Kerr Constants

**DC Kerr Constants of Pure Liquids**

| Liquid | DC Kerr constant $B_0$ ($10^{-16}$ (m/V$^2$)) | Liquid | DC Kerr constant $B_0$ ($10^{-16}$ (m/V$^2$)) |
|---|---|---|---|
| acetone, $C_3H_6O$ | 1814 | cyclohexane, $C_6H_{12}$ | 8.2 |
| benzene, $C_6H_6$ | 66 | ethanol, $C_2H_6O$ | 85.5 |
| carbon disulfide, $CS_2$ | 358.9 | hexane, $C_6H_{14}$ | 5.0 |
| carbon tetrachloride, $CCl_4$ | 8.2 | methanol, $CH_4O$ | 107.9 |
| bronobenzene, $C_6H_5Br$ | 1012 | nitrobenzene, $C_6H_5NO_2$ | 28500 |
| cyclohexane, $C_6H_{12}$ | 8.2 | toluene, $C_7H_8$ | 83.3 |

Measurements made at a wavelength of 589.3 nm and 293 K.

**Reference:**

1. Shen, Y. R., Electrostriction, optical Kerr effect and self-focusing of laser beams, *Phys. Lett*. 20, 378–380 (1966).

**DC Kerr Response of Binary Liquids**

| Material A | Material B | Molar fraction A | Wave-length (nm) | Linear refract. index | Temp. (°C) | $n^{(2)}_{1111} - n^{(2)}_{1122}$ ($10^{-20}$ m$^2$/V$^2$) |
|---|---|---|---|---|---|---|
| Benzene | Chlorobenzene | 0 | 632.8 | 1.524 | 25 | 9.15 |
| Benzene | Chlorobenzene | 0.3 | 632.8 | | 25 | 6.21 |
| Benzene | Chlorobenzene | 0.6 | 632.8 | | 25 | 3.28 |
| Benzene | Chlorobenzene | 1.0 | 632.8 | 1.501 | 25 | 0 |
| Cyclohexane | Nitrobenzene | 0 | 632.8 | 1.556 | 25 | 28.2 |
| Cyclohexane | Nitrobenzene | 0.2 | 632.8 | | 25 | 16.4 |
| Cyclohexane | Nitrobenzene | 0.4 | 632.8 | | 25 | 9.32 |
| Cyclohexane | Nitrobenzene | 0.8 | 632.8 | | 25 | 1.41 |
| Cyclohexane | Nitrobenzene | 1.0 | 632.8 | 1.427 | 25 | 0 |
| Nitromethane | Chlorobenzene | 0 | 632.8 | 1.524 | 25 | 9.15 |
| Nitromethane | Chlorobenzene | 0.4 | 632.8 | | 25 | 10.7 |
| Nitromethane | Chlorobenzene | 0.7 | 632.8 | | 25 | 12.3 |
| Nitromethane | Chlorobenzene | 1.0 | 632.8 | 1.382 | 25 | 8.28 |
| Pyridine | 2,6-Lutidine | 0 | 632.8 | 1.495 | 25 | 8.28 |
| Pyridine | 2,6-Lutidine | 0.6 | 632.8 | | 25 | 11.9 |
| Pyridine | 2,6-Lutidine | 1.0 | 632.8 | 1.509 | 25 | 14.5 |

**Reference:**

Piazza, R., Degiorgio, V., and Bellini, T., Kerr effect in binary liquids, *J. Opt. Soc. Am.* B 3, 1642 (1986).

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**DC Kerr Response of Binary Liquids**

| Material A | Material B | Weight Percent of A (%) | Wavelength (nm) | Linear refractive Index | Temp. (°C) | $n^{(2)}_{1111} - n^{(2)}_{1122}$ ($10^{-20}$ $m^2/V^2$) |
|---|---|---|---|---|---|---|
| Lutidine | $H_2O$ | 0 | 632.8 | 1.33 | 23–32.8 | 24.0 |
| Lutidine | $H_2O$ | 35 | 632.8 | | 23 | 10.2 |
| Lutidine | $H_2O$ | 35 | 632.8 | | 32 | 21.9 |
| Lutidine | $H_2O$ | 35 | 632.8 | | 32.8 | 38.0 |
| Lutidine | $H_2O$ | 100 | 632.8 | | 32 | 8.76 |
| Lutidine | $H_2O$ | 100 | 632.8 | | 32.8 | 8.76 |
| Lutidine | $H_2O$ | 100 | 632.8 | 1.495 | 23 | 8.76 |

**Reference:**

Piazza, R., Degiorgio, V., and Bellini, T., Kerr effect in binary liquids, *J. Opt. Soc. Am.* B 3, 1642 (1986).

The tables above are from Garito, A. F. and Kuzyk, M. G., Two-photon absorption, organic materials, *Handbook of Laser Science and Technology, Supplement 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 289.

## Optical Kerr Constant

The laser-induced Kerr constant is given by $B_0 = (2\pi/n\lambda_p)(\chi^{(3)}_{1212} + \chi^{(3)}_{1221})$, where $\lambda_p$ is the linearly polarized probe beam wavelength.

**Optical Kerr Constants of Pure Liquids**

| Liquid | Wavelength (nm) | Optical Kerr constant $B_0$ ($10^{-16}$ m/$V^2$) |
|---|---|---|
| acetic acid | 532 | 33.0 |
| | 694 | 22.9 |
| | 1064 | 21.5 |
| acetone, $C_3H_6O$ | 694 | 8.2 |
| benzene, $C_6H_6$ | 532 | 79 |
| | 694 | 70 |
| | 1064 | 51 |
| carbon disulfide, $CS_2$ | 694 | 470 |
| | 1064 | 360 |
| carbon tetrachloride, $CCl_4$ | 694 | 8.9 |
| | 1064 | 3.3 |
| chlorobenzene, $C_6H_5Cl$ | 1064 | 89.9 |
| chloroform, $CHCl_3$ | 694 | 23 |
| | 1064 | 18 |

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**Optical Kerr Constants of Pure Liquids—***continued*

| Liquid | Wavelength (nm) | Optical Kerr constant $B_0$ ($10^{-16}$ m/V$^2$) |
|---|---|---|
| cyclohexane, $C_6H_{12}$ | 694 | 6.8 |
| *m*-dichlorobenzene, $C_6H_4Cl_2$ | 694 | 170 |
| *o*-dichlorobenzene, $C_6H_4Cl_2$ | 694 | 179 |
| ethanol, $C_2H_6O$ | 694 | 5.22 |
| | 1064 | 5.1 |
| heavy water, $D_2O$ | 1064 | 2.9 |
| heptane, $C_7H_{16}$ | 694 | 11.3 |
| | 1064 | 7.6 |
| hexadecane, $C_{16}H_{34}$ | 694 | 20.2 |
| hexane, $C_6H_{14}$ | 694 | 9.9 |
| | 1064 | 6.9 |
| methanol, $CH_4O$ | 694 | 4.76 |
| | 1064 | 3.3 |
| methylcyclohexane, $C_7H_{14}$ | 694 | 7.7 |
| nitrobenzene, $C_6H_5NO_2$ | 694 | 420 |
| | 1064 | 260 |
| tetrachloroethylene, $C_2Cl_4$ | 694 | 148 |
| toluene, $C_7H_8$ | 694 | 120 |
| | 1064 | 99 |
| water, $H_2O$ | 694 | 4.6 |
| | 1064 | 2 |
| *o*-xylene, $C_8H_{10}$ | 694 | 130 |
| *m*-xylene, $C_8H_{10}$ | 694 | 125 |
| *po*-xylene, $C_8H_{10}$ | 694 | 120 |

Measurements at room temperature.

## Reference:

1. Harrison, N. J. and Jennings, B. R., Laser-induced Kerr constants for pure liquids, *J. Phys. Chem. Ref. Data* 21, 157–163 (1992).

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### 5.5.4 Third-Order Nonlinear Optical Coefficients

| Liquid | Nonlinear optical process | Coefficient $C_{jn} \times 10^{20}$ m$^2$ V$^{-2}$ | Wavelength ($\mu$m) |
|---|---|---|---|
| acetone, $C_3H_6O$ | $(-\omega; \omega, \omega, -\omega)$ | $C_{11} = 0.252 \pm 0.056$ | 0.6943 |
| benzene, $C_6H_6$ | $(-\omega; \omega, \omega, -\omega)$ | $C_{11} = 0.518 \pm 0.07$ | 0.6943 |
| | | $C_{18} = 0.098$ | 0.5000 |
| | | $C_{18} = 0.0782$ | 0.6943 |
| | | $C_{18} = 0.091$ | 0.694 |
| | $(-\omega_1; \omega_1, \omega_2, -\omega_2)$ | $C_{18} = 0.028$ | 0.4880 |
| | $(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$ | $C_{11} = 0.56$ | 0.694 |
| | | $C_{11} = 0.242 \pm 0.024$ | 0.5250 |
| | | $C_{11} = 0.00859 \pm 0.00037$ | 0.545 |
| | | $C_{18} = 0.252 \pm 0.00014$ | 0.545 |
| | $(3\omega; \omega, \omega, \omega)$ | $C_{11} = 0.0184 \pm 0.056$ | 1.89 |
| | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.02215 \pm 15\%$ | 1.06 |
| | | $C_{11} = 0.02215 \pm 15\%$ | 1.318 |
| bromobenzene, $C_6H_5Br$ | $(-2\omega_1+ \omega_2; \omega_1, \omega_1, -\omega_2)$ | $C_{11} = 0.084$ | 0.6943 |
| | | $C_{11} = 0.0196 \pm 15\%$ | 1.06 |
| carbon disulfide, $CS_2$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{18} = 0.476$ | 0.694 |
| | | $C_{18} = 0.560$ | 0.500 |
| | $(-\omega_1; \omega_1, \omega_2, -\omega_2)$ | $C_{18} = 0.266$ | 0.4880 |
| | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.06233 \pm 15\%$ | 1.06 |
| carbon tetrachloride, $CCl_4$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{18} = 0.0168 \pm 30\%$ | 0.694 |
| | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.0182 \pm 15\%$ | 1.06 |
| chloroform, $CHCl_3$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{18} = 0.07 \pm 30\%$ | 1.06 |
| 1,2-dichloroethane, $C_2H_4Cl_2$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.042 \pm 15\%$ | 1.06 |
| 1,4-dioxane, $C_4H_8O_2$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.01351 \pm 15\%$ | 1.06 |
| ethanol, $C_2H_6O$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{18} = 0.0315$ | 0.694 |
| | | $C_{11} = 0.196 \pm 0.042$ | 0.6943 |
| glycerine (glycerol), $C_3H_8O_3$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{11} = 0.196 \pm 0.07$ | 0.6943 |
| heptane, $C_7H_{16}$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.84 \pm 15\%$ | 1.06 |
| hexane, $C_6H_{14}$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.7105 \pm 15\%$ | 1.06 |
| methanol, $CH_4O$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.301 \pm 15\%$ | 1.06 |
| methylbenzene, $C_6H_8$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.056$ | 0.6943 |
| nitrobenzene, $C_6H_5NO_2$ | $(-\omega; \omega, \omega,-\omega)$ | $C_{18} = 0.42$ | 0.500 |
| | | $C_{18} = 0.322$ | 0.6943 |
| | | $C_{11} = 1.148 \pm 0.140$ | 0.6943 |
| | $(-\omega_1; \omega_1, \omega_2, -\omega_2)$ | $C_{18} = 0.182$ | 0.4880 |
| | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.585 \pm 15\%$ | 1.318 |
| | | $C_{11} = 0.360 \pm 15$ | 1.06 |
| nitromethane, $CH_3NO_2$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.042 \pm 0.093$ | 0.6943 |
| toluene, $C_7H_8$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.0238 \pm 15\%$ | 1.06 |
| water, $H_2O$ | $(-2\omega; \omega, \omega, 0)$ | $C_{11} = 0.0616 \pm 15\%$ | 1.06 |

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Data in the preceding table are from S. Singh, Nonlinear optical materials, *Handbook of Laser Science and Technology, Vol. III: Optical Materials, Part 1* (CRC Press, Boca Raton, FL, 1986), p. 54 ff. Data for additional liquids are included in this reference.

## 5.5.5 Stimulated Raman Scattering

**Observed SRS Lineshifts ω of Liquids**

| Substance | ω ($cm^{-1}$) | Ref. |
|---|---|---|
| bromoforrn | 222 | 1 |
| tetrachloroethylene | 448 | 2 |
| carbon tetrachloride[a] | 460 | 3 |
| ethyl iodide | 497 | 4 |
| hexafluorobenzene[a] | 515 | 3 |
| bromoform | 539 | 1 |
| chlorine | 552 | 5 |
| methylene bromide | 580 | 3 |
| trichloroethylene | 640 | 1 |
| carbon disulfide | 655 | 6 |
| ethylene bromide | 660 | 7 |
| chloroform | 667 | 1 |
| α-xylene | 730 | 8 |
| FC104[b] | 757 | 9 |
| sulfur hexafluoride | 775 | 10 |
| α-dimethylphenethylamine | 836 | 11 |
| dioxane | 836 | 1 |
| morpholine[a] | 841 | 3 |
| thiophenol[a] | 916 | 3 |
| nitromethane[a] | 927 | 3 |
| deuterated benzene | 944 | 12 |
| potassium dihydrogen phosphate | 980 | 13 |
| cumene[a] | 990 | 3 |
| pyridine | 991 | 12 |
| 1,3-dibromobenzene | 992 | 2 |
| benzene | 992 | 12 |
| aniline | 997 | 14 |
| styrene | 998 | 15 |
| *m*-toluidine[a] | 999 | 3 |
| acetophenone | 999 | 16 |
| bromobenzene | 1000 | 14 |
| chlorobenzene[a] | 1001 | 3 |
| *tert*-butylbenzene | 1000 | 2 |
| benzaldehyde[a] | 1001 | 2 |
| ethylbenzoate | 1001 | 16 |
| benzonitrile | 1002 | 14 |
| ethylbenzene | 1002 | 8 |
| toluene | 1004 | 12 |

**Observed SRS Lineshifts ω of Liquids**—*continued*

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| Substance | ω ($cm^{-1}$) | Ref. |
|---|---|---|
| fluorobenzene | 1012 | 17 |
| γ-picoline | 1016 | 3 |
| *m*-cresol[a] | 1029 | 3 |
| *m*-dichlorobenzene[a] | 1034 | 3 |
| 1-fluoro-2-chlorobenzene[d] | 1034 | 2 |
| 1-fluoro-2-chlorobenzene[d] | 1034 | 2 |
| iodo-benzene[a] | 1070 | 3 |
| benzoyl chloride[a] | 1086 | 3 |
| benzaldehyde[a] | 1086 | 3 |
| anisole[a] | 1097 | 3 |
| pyrrole[a] | 1178 | 3 |
| furan[a] | 1180 | 3 |
| nitrous oxide | 1289 | 10 |
| styrene | 1315 | 15 |
| nitrobenzene | 1344 | 12 |
| 1-bromonaphthalene | 1363 | 12 |
| 1-chloronaphthalene | 1374 | 18 |
| 2-ethylnaphthalene | 1382 | 2 |
| *m*-nitrotoluene[a] | 1389 | 3 |
| carbon dioxide | 1392 | 10 |
| quinoline[a] | 1427 | 3 |
| homocyclohexane | 1438 | 4 |
| furan[a] | 1522 | 3 |
| methyl salicylate[a] | 1612 | 3 |
| cinnamaldehyde | 1624 | 18 |
| styrene | 1631 | 15 |
| 3-methylbutadiene | 1638 | 19 |
| pentadiene | 1655 | 19 |
| isoprene | 1792 | 11 |
| 1-hexyne | 2116 | 2 |
| dimethyl sulfoxide[c] | 2128 | 20 |
| α-dichlorobenzene[a] | 2202 | 3 |
| benzonitrile | 2229 | 18 |
| acetonitrile | 2250 | 4 |
| 1,2-dimethylaniline | 2292 | 3 |
| nitrogen | 2327 | 21 |
| hydrobromic acid | 2493 | 9 |
| hydrochloric acid | 2814 | 9 |
| methylcyclohexane | 2817 | 3 |
| methanol | 2831 | 1 |
| *cis trans,* 1,3-dimethylcyclohexane | 2844 | 2 |
| tetrahydrofuran | 2849 | 18 |
| cyclohexane | 2852 | 12 |
| *cis*- l,2-dimelhylcyclohexane | 2853 | 2 |

**Observed SRS Lineshifts ω of Liquids**—*continued*

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| Substance | ω ($cm^{-1}$) | Ref. |
|---|---|---|
| α-dimethylphenethylamine | 2856 | 11 |
| dioxane | 2856 | 1 |
| decahydronaphthalene | 2860 | 9 |
| cyclohexane | 2863 | 1 |
| cyclohexanone | 2863 | 8 |
| *cis. trans*-1,3-dimethylcyclohexane | 2866 | 2 |
| cyclohexane | 2884 | 1 |
| dichloromethane[a] | 2902 | 3 |
| dimethyl sulfoxide | 2916 | 20 |
| morpholine | 2902 | 3 |
| cargille 5610[f] | 2908 | 9 |
| 2,3-dimethyl-1,5-hexadiene | 2910 | 2 |
| limonene | 2910 | 11 |
| *o*-xylene | 2913 | 8 |
| 1-hexyne | 2916 | 2 |
| *cis*-2-heptene | 2916 | 2 |
| 2-octene | 2918 | 2 |
| acetonitrile | 2920 | 9 |
| mesitylene | 2920 | 11 |
| 2-bromopropane | 2920 | 2 |
| acetone | 2921 | 8 |
| ethanol | 2921 | 1 |
| *cis*-1,2-dimethylcyclohexane | 2921 | 2 |
| carvone | 2922 | 11 |
| *cis, trans*-1,3-dimethylcyclohexane | 2926 | 2 |
| 2-chloro-2-methylbutane | 2927 | 2 |
| dimethylformamide | 2930 | 1 |
| *m*-xylene | 2933 | 8 |
| 1,2-diethyl tartrate | 2933 | 11 |
| *o*-xylene | 2933 | 8 |
| piperidine | 2933 | 8 |
| 1,2-diethylbenzene | 2934 | 2 |
| 1-bromopropane | 2935 | 2 |
| piperidine | 2936 | 8 |
| tetrahydrofuran | 2939 | 18 |
| decahydronaphthalene | 2940 | 9 |
| piperidine | 2940 | 8 |
| cyclohexanone | 2945 | 8 |
| 2-nitropropane | 2945 | 2 |
| 1,2 diethyl carbonate[a] | 2955 | 3 |
| 1,2 dichloroethane[a] | 2956 | 3 |
| *trans*-dichloroethylene | 2956 | 1 |
| methyl fluoride | 2960 | 10 |
| 1-bromopropane | 2962 | 2 |

**Observed SRS Lineshifts ω of Liquids**—*continued*

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| Substance | ω ($cm^{-1}$) | Ref. |
|---|---|---|
| 2-chloro-2-methylbutane | 2962 | 2 |
| α-dimethylphenethylamine | 2967 | 11 |
| dioxane | 2967 | 1 |
| methyl chloride | 2970 | 10 |
| cyclohexanol[a] | 2982 | 3 |
| cyclopentane[a] | 2982 | 3 |
| cyclopentanol[a] | 2982 | 3 |
| bromocyclopentane[a] | 2982 | 3 |
| *o*-dichlorobenzene | 2982 | 3 |
| *p*-chlorotoluene | 2982 | 3 |
| *a*-picoline[a] | 2982 | 3 |
| *p*-xylene | 2988 | 8 |
| *o*-xylene | 2992 | 8 |
| dibutyl-phthalate[a] | 2992 | 3 |
| 1, 1, 1-trichloroethane | 3018 | 1 |
| ethylene chlorohydrin[a] | 3022 | 3 |
| isophorone[a] | 3022 | 3 |
| nitrosodimethylamine[a] | 3022 | 3 |
| propylene glycol[a] | 3022 | 3 |
| cyclohexane[a] | 3038 | 3 |
| styrene | 3056 | 15 |
| pyridine | 3058 | 2 |
| benzene | 3064 | 12 |
| *tert*-butylbenzene | 3065 | 2 |
| 1-fluoro-2-chlorobenzene | 3082 | 2 |
| turpentine[a] | 3090 | 3 |
| pseudocumene[a] | 3093 | 3 |
| acetic acid[a] | 3162 | 3 |
| acetonylacetone[a] | 3162 | 3 |
| methyl methacrylate[a] | 3162 | 3 |
| γ-picoline[a] | 3182 | 3 |
| aniline | 3300 | 14 |
| water[a] | 3651 | 3 |

a Observed at low resolution
b Product of 3M Co., St. Paul, MN
c 1:1 mixture with tetrachloroethylene
d Very weak and diffuse
e Deuterated
f Product of Cargille Laboratories, Cedar Falls, NJ

Table from Milanovich, F. P., Stimulated Raman scattering, *Handbook of Laser Science and Technology, Vol. III: Optical Materials* (CRC Press, Boca Raton, FL, 1986), p. 283.

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### 5.5.6 Stimulated Brillouin Scattering

**Brillouin Gain Parameters for Selected Liquids**

| Material | Pump wavelength (nm) | Frequency shift (GHz) | Δν (MHz) | $\tau_B$ (ns) | $g_B$ (cm/GW) | $n$ | Density (g/cm$^3$) | Ref. |
|---|---|---|---|---|---|---|---|---|
| Acetone | 1059 | 2.987 | 119 ± 5 | 1.34 | 15.8 | 1.355 | 0.791 | 1 |
| | 532 | 5.93 | 361 | 0.44 | 12.9 | 1.359 ($Na_D$) | | 2 |
| | 532 | 6.0 | 320 | 0.497 | 20 | | | 3 |
| Benzene | 1059 | 4.124 | 228 | 0.7 | 9.6 | 1.4837 | 0.879 | 1 |
| | 532 | 8.33 | 515 | 0.31 | 12.3 | 1.501 ($Na_D$) | 0.874 | 2 |
| Benzyl alcohol | 532 | 9.38 | 2120 | 0.08 | 5.75 | 1.54 (Na-D) | 1.045 | 2 |
| Butyl acetate | 532 | 6.23 | 575 | 0.28 | 9.13 | 1.394 ($Na_D$) | 0.882 | 2 |
| $CS_2$ | 1060 | 3.761 | 50 | 3.2 | 68 | 1.595 | 1.262 | 1 |
| | 532 | 7.7 | 120 | 1.9 | 130 | | | 3 |
| $CCl_4$ | 1060 | 2.772 | 528 | 0.3 | 3.8 | 1.452 | 1.595 | 1 |
| | 532 | 5.72 | 890 | 0.18 | 8.77 | 1.4595 | 1.594 | 2 |
| Chloroform | 532 | 5.75 | 635 | 0.25 | 11.7 | 1.446 ($Na_D$) | 1.492 | 2 |
| Cyclohexane | 532 | 7.19 | 1440 | 0.11 | 5.8 | 1.426 ($Na_D$) | 0.779 | 2 |
| *N*,*N*-Dimethyl formamide | 532 | 7.93 | 615 | 0.26 | 7.8 | 1.431 ($Na_D$) | 0.944 | 2 |
| Dichloromethane | 532 | 5.92 | 255 | 0.62 | 16.8 | 1.424 | 1.325 | 2 |
| *o*-Dichlorobenzene | 532 | 8.03 | 1340 | 0.12 | 4.7 | 1.551 | 1.306 | 2 |
| Ethanol | 532 | 5.91 | 546 | 0.29 | | 1.36 | 0.785 | 2 |
| Ethylene glycol | 532 | 10.2 | 3630 | 0.04 | 0.85 | 1.431 | 1.113 | 2 |
| Freon 113 | 532 | 3.72 | 81 | 0.18 | 5.5 | 1.3578 | 1.575 | 2 |
| *n*-Hexane | 532 | 5.64 | 580 | 0.27 | 8.8 | 1.379 | 0.67 | 2 |
| Nitrobenzene | 1060 | 4.255 | 396 | 0.4 | 7.2 | 1.5297 | 1.206 | 1 |
| Methanol | 532 | 5.47 | 325 | 0.49 | 10.6 | 1.329 | .791 | 2 |
| | 530 | 5.6 | 210 | 0.334 | 13 | | | 3 |
| Pyridine | 532 | 8.92 | 746 | 0.21 | 14 | 1.51 | 0.978 | 2 |
| Tin tetrachloride | 1064 | 2.21 ± 0.02 | 182 ± 12 | 0.874 | 11.2 ± 0.5 | 1.36 | 2.226 | 4 |
| | 532 | 4.71 | 357 | 0.45 | | | | 2 |
| Titanium tetrachloride | 1060 | 3.070 | 216 | 0.735 | 14.2 | 1.577 | 1.73 | 1 |
| Toluene | 532 | 7.72 | 1314 | 0.12 | 8.4 | 1.496 | 0.867 | 2 |
| Trichloroethylene | 532 | 5.94 | 765 | 0.21 | 12 | 1.4755 | 1.464 | 2 |
| Water | 1060 | 3.703 | 170 | 0.935 | 3.8 | 1.324 | 1 | 1 |
| | 532 | 7.4 | 607 | 0.26 | 2.94 | 1.333 | 1 | 2 |
| Xylenes | 532 | 7.74 | 1211 | 0.13 | 9.3 | 1.497 | 0.86 | 2 |

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## Brillouin Materials Used for Phase Conjugation

| Liquids | Temp. (K) | Wave-length λ (nm) | Refract. index | Sound speed $v_s$ (km/s) | Brillouin shift at λ (GHz) | Phonon lifetime $\tau_p$ (ns) | Line width $\Delta\nu_b$ (MHz) | Gain $g$ (cm/GW) | Density ρ (g/cm$^3$) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Acetic acid | | | | | 5.05 | | | | | 1 |
| | 295 | 633 | | | 5.64 | | 400 | | | 2 |
| Acetone | | 694 | | 1.40 | 4.61 | | 235 | | | 3 |
| | | 1064 | | | 3.1 | | | | | 4 |
| | | 1064 | 1.36 | 1.19 | | 4 | 40 | 18 | | 5 |
| | | 1064 | | | 2.97 | 1.8 | 90 | 12.9 | | 6 |
| | | 1064 | | | 5.93 | 0.44 | 361 | 12.9 | | 7 |
| | | 532 | | | 5.00 | | | 12.9 | | 7 |
| | 295 | 633 | | | 5.05 | | 260 | | | 2 |
| | 293 | 1064 | 1.355 | 1.168 | 2.987 | 2.67 | 119[a] | 15.8 | 0.791 | 8 |
| | | 694 | | | | | 180 | 20 | | 9 |
| | | 694 | | 1.19 | 4.600 | | 175 | 18 | | 11 |
| Acetonitrile | | 633 | | | 5.52 | | 300 | | | 2 |
| $BCl_3$ | | 1064 | | | | | | | | 6 |
| Benzene | | 694 | | 1.5 | | | 245 | 18 | | 11 |
| | | 632 | | 1.50 | 7.10 | | 340 | | | 3 |
| | | 532 | | | 8.33 | 0.31 | 515 | 12.3 | | 7 |
| | | | | | 7.03 | | 520 | | | 2 |
| | | | | | 7.08 | | | | | 1 |
| | | 1064 | 1.5 | 1.5 | | 3 | | 18 | | 5 |
| | 293 | 1060 | 1.4837 | 1.473 | 4.124 | 1.40 | 228[a] | 9.6 | 0.879 | 8 |
| | 323 | 1060 | 1.4648 | 1.359 | 3.757 | 1.07 | 297 | | | 8 |

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| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Benzene | | 694 | | | 6.470 | | 289[a] | 18 | | 9 |
| Benzyl alcohol | | 532 | | | 9.38 | 0.08 | 2120 | 5.75 | | 7 |
| Butanol | | 633 | | | 5.63 | | 720 | | | 2 |
| Butyl acetate | | 532 | | | 6.23 | 0.28 | 575 | 9.13 | | 7 |
| $C_2Cl_3F_3$ | | 532 | | | 3.72 | 0.18 | 865–880 | 5.50 | | 7 |
| (Freon 113) | | 1064 | 1.36 | 0.728 | 1.86 | 0.72 | 220 | 5.5 | | 6 |
| Carbon disulfide, | | 694 | | 1.25 | | | 55 | 45 | | 11 |
| $CS_2$ | | 694 | | 1.142 | 5.85 | | 80 | | 1.263 | 3 |
| | | 1064 | 1.62 | | 3.8 | 7 | 23 | 50 | 1.263 | 5 |
| | 293 | 1060 | 1.593 | 1.250 | 3.76 | 6.4 | | 68 | | 8 |
| | 300 | 1060 | | | | 4.9 | | | | 8 |
| | | 1064 | | | | 6.7 | | | | 4 |
| | | 694 | | | | 2.1 | | 130 | | 10 |
| | | 633 | | | 6.45 | | 140 | | | 2 |
| | 301 | 633 | | | 6.24 | | 132 | | | 11 |
| | 162 | 633 | | | 9.05 | | 396 | | | 11 |
| Carbon tetra- | | 694 | | 0.92 | 4.41 | | 630 | | 1.595 | 3 |
| chloride, $CCl_4$ | | 694 | 1.46 | 1.05 | | | 430 | 8 | | 11 |
| | | | 1.46 | 1.05 | | 1.3 | | 6 | | 5 |
| | | 1064 | | 1.04? | 2.9 | | 122 | 3.8 | 1.591 | 6 |
| | | 532 | | | 5.72 | 0.18 | 890 | 8.77 | | 7 |
| | | 633 | | | 4.82 | | 1260 | | | 2 |

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**Brillouin Materials Used for Phase Conjugation—*continued***

| Liquids | Temp. (K) | Wave-length λ (nm) | Refract. index | Sound speed $v_s$ (km/s) | Brillouin shift at λ (GHz) | Phonon lifetime $\tau_p$ (ns) | Line width $\Delta\nu_b$ (MHz) | Gain $g$ (cm/GW) | Density ρ ($g/cm^3$) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Carbon tetra-chloride, $CCl_4$ | 293 | | 1.452 | 1.012 | 2.772 | 0.60 | 528[a] | 3.8 | 1.595 | 8 |
| | | 1060 | | | | | | | | 12 |
| | | | | | 4.390 | | 650 | 6 | | 9 |
| | | | | | | | | 8 | | 9 |
| Chloroform | | 532 | | | 5.75 | 0.25 | 635 | 11.7 | | 7 |
| | | 633 | | | 4.88 | | 840 | | | 2 |
| Cyclohexane | | 532 | | | 7.19 | 0.11 | 1440 | 5.8 | | 7 |
| | | 1064 | 1.43 | 1.35 | | 1 | | 7 | | 5 |
| | | 694 | | | 5.550 | | 774[b] | 6.8 | | 9 |
| | | 694 | | 1.35 | | | 670 | 6.8 | | 11 |
| Dichloromethane, $CCl_2H_2$ | | 532 | | | 5.92 | 0.62 | 255 | 16.8 | | 7 |
| | | | | | 2.96 | 2.5 | 64 | 16.9 | | 4 |
| Ethanol | | 532 | | | 5.91 | 0.29 | 546 | | | 7 |
| | | 633 | | | 5.04 | | 600 | | | 2 |
| | | 694 | | | 4.550 | | 353[b] | 12[c] | | 9 |
| Ethylene glycol | | 532 | | | 10.2 | 0.04 | 3630 | 0.85 | | 7 |
| Germanium tetrachloride, $GeCl_4$ | | | 1.46 | | | | | 12 | 1.87 | 6 |
| Glycerol | 298 | | | | 2.8 | | | | | 11 |
| | 245 | | | | 3.3 | | 382 | | | 11 |

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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 166 | | | | 3.7 | | 42 | | 11 |
| Methanol | | 1064 | 1.33 | 1.12 | | 3.7 | | 13 | 5 |
| | | 532 | | | 5.47 | 0.49 | 325 | 10.6 | 7 |
| | | 633 | | | 4.68 | | 260 | | 2 |
| | | 694 | | | 4.250 | | 250[b] | 13 | 9 |
| | | 694 | 1.33 | 1.118 | | | 200 | 13.2 | 11 |
| *N*,*N*-Dimethyl formamide | | 532 | | | 7.93 | 0.26 | 615 | 7.8 | 7 |
| *n*-Hexanes | | 532 | | | 5.64 | 0.27 | 580 | 8.80 | 7 |
| | | 1064 | 1.37 | 1.11 | | 3.5 | | 19 | 5 |
| | | 694 | | | | | 220 | 26 | 9 |
| | | 694 | 1.37 | 1.113 | | | 212 | 19 | 11 |
| | | 694 | | | | | 212 | 10 | 9 |
| Nitrobenzene | | 694 | | 1.56 | | | 900 | 4.5 | 11 |
| | | 1064 | 1.56 | 1.56 | | 0.8 | | 4.5 | 5 |
| | 293 | 1060 | 1.530 | 1.474 | 4.255 | 0.80 | 396[a] | 7.2 | 1.206 | 8 |
| | 313 | 1060 | 1.521 | 1.414 | 4.057 | 0.77 | 416 | | | 8 |
| *o*-Dichlorobenzene | | 532 | | | 8.03 | 0.12 | 1340 | 4.70 | | 7 |
| $PCl_3$ | | | | | | | | | 8.6 | 6 |
| Pyridine | | 532 | | | 8.92 | 0.21 | 746 | 14.00 | | 7 |
| | | 633 | | | 7.38 | | | | | 13 |
| | | 633 | | | 7.36 | | 780 | | | 2 |

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**Brillouin Materials Used for Phase Conjugation—*continued***

| Liquids | Temp. (K) | Wavelength λ (nm) | Refract. index | Sound speed $v_s$ (km/s) | Brillouin shift at λ (GHz) | Phonon lifetime $\tau_p$ (ns) | Line width $\Delta\nu_b$ (MHz) | Gain $g$ (cm/GW) | Density ρ ($g/cm^3$) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Silicon tetrachloride, $SiCl_4$ | | | 1.41 | | | | | 10 | 1.48 | 6 |
| Tin tetrachloride, $SnCl_4$ | | | 1.51 | 0.830 | | | | | 11 | |
| | 308 | 1064 | | | 2.21 | 1.7 | 182 | 11.2 | | 14 |
| | | 532 | | | 4.71 | 0.45 | 357 | | | 7 |
| | | 1064 | | | 2.36 | 1.8 | 89 | | | 7 |
| | | 1064 | | | | | | | | 6 |
| Titanium tetrachloride, $TiCl_4$ | | 1064 | 1.62 | 1.05 | 3.2 | 2 | 80 | 14 | 1.73 | 5 |
| | | 532 | | | 4.71 | 0.45 | 357 | | | 7 |
| | | 1064 | | | | | | | | 15 |
| | | 1064 | | | | | 2.0 | | 20 ± 4 | 6 |
| | 293 | 1060 | 1.577 | 1.032 | 3.070 | 1.47 | 216[a] | 14.2 | 1.73 | 8 |
| Toluene | | 694 | 1.38 | | | 480 | | 13 | | 11 |
| | | 532 | | | 7.72 | 0.12 | 1314 | 8.4 | | 7 |
| | | 633 | | | 6.41 | 1000 | | | | 2 |
| | | 1064 | 1.5 | 1.4 | | 1.5 | | 10 | | 5 |
| Trichloroethylene | | 532 | | | 5.94 | .21 | 765 | 12.00 | | 7 |
| Water, $H_2O$ | | 1064 | 1.33 | 1.48 | 3.7 | | | | | |
| | | 1064 | | | 3.7 | 1.1 | 152 | 2.94 | | 7 |
| | | 532 | | | 7.4 | 0.26 | 607 | 2.94 | | 7 |
| | | 633 | | | 6.23 | | 440 | | | 2 |

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| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1064 | 1.33 | 1.49 | | 3.4 | | 4.8 | | 5 |
| | 293 | 1060 | 1.324 | | 3.703 | 1.87[a] | 170[a] | 3.8 | 0.997 | 8 |
| | | | | 1.482 | | | | | | 16 |
| | | 694 | 1.33 | 1.488 | | | 220 | 4.8 | | 11 |
| | | 694 | | | 5.69 | | 317[b] | 4.8 | | 9 |
| Water, $D_2O$ | | | 1.33 | 1.38 | 3.46 | 3.4 | 47 | 3.1 | 1.1 | |
| Xylenes | | 532 | | | 7.74 | 0.13 | 1211 | 9.30 | | |
| 26 Organic liquids | | XeCl laser | | | | | | | | 17 |
| 30 Organic liquids | | 532 | | | | | | | | 18 |

[a]These authors assume that lifetime = $1/(\pi \times$ linewidth); [b]This is the spontaneous scattering linewidth; these authors report different values for the spontaneous and stimulated scattering linewidth; [c]This is a theoretically calculated, not an experimental, number; [d]Density in amagats rather than pressure in atmospheres.

Table from Pepper, D. M., Minden, M. L., Bruesselbach, H. W. and Klein, M. B., Nonlinear optical phase conjugation materials, in *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 467.

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## 5.6 Magnetooptic Properties

The following tables and figure are from Munin, E., Magnetooptic materials: organic and inorganic liquids, *Handbook of Laser Science and Technology, Suppl. 2: Optical Materials* (CRC Press, Boca Raton, 1995), p. 403.

### 5.6.1 Verdet Constants of Inorganic Liquids

**Verdet Constants V of Inorganic Liquids**

| Liquid | λ(nm) | T(°C) | n | V(rad/T·m) | Ref. |
|---|---|---|---|---|---|
| $AsCl_3$ | 589 | | 1.60 | 12.4 | 1 |
| $COCl_2$ | 589 | 3 | | 3.93 | 1 |
| $D_2O$ | 578 | 19.7 | | 3.819 | 1 |
| | 589 | 19.7 | | 3.656 | 1 |
| $H_2O$ | 578 | 11.5 | | 3.971 | 1 |
| | 589 | 10 | | 3.811 | 1 |
| $N_2$ | 589 | –195.5 | | 1.21 | 2 |
| $NH_3$ | 578 | –40 | 1.35 | 5.47 | 3 |
| $O_2$ | 589 | –182.5 | | 2.27 | 2 |
| P[a] | 589 | 33 | 2.07 | 38.7 | 1 |
| $PBr_3$ | 578 | 20 | 1.70 | 17.6 | 1 |
| $PCl_3$ | 578 | 26 | 1.511 | 8.78 | 1 |
| $P_4S$ | 589 | 16 | | 32.0 | 2 |
| S[a] | 589 | 114 | 1.93 | 23.5 | 1 |
| $SO_2$ | 589 | –10 | 1.39 | 5.23 | 2 |
| $SbCl_5$ | 589 | 16 | | 20.5 | 2 |
| $S_2Cl_2$ | 589 | 16 | | 12.2 | 2 |
| $SiCl_4$ | 589 | 16 | | 5.50 | 2 |
| $SnCl_4$ | 578 | 28 | 1.516 | 13.0 | 1 |
| $TiBr_4$ | 578 | 46 | | –15.4 | 5 |
| $TiCl_4$ | 578 | 17 | 1.612 | –4.80 | 6 |

[a]Fused.

### 5.6.2 Verdet Constants of OrganicLiquids

**Verdet Constants V of Organic Liquids (from Ref. 7)**

| Formula | Name | λ (nm) | T(°C) | V (rad/T m) |
|---|---|---|---|---|
| $CCl_4$ | tetrachloromethane | 589 | 25.1 | 4.65 |
| $CHCl_3$ | trichloromethane | 589 | 20.0 | 4.72 |
| $CH_2Br_3$ | tribromomethane | 589 | 17.9 | 9.10 |
| $CH_2O_2$ | formic acid | 589 | 20.8 | 3.04 |
| $CH_2Cl_2$ | dichloromethane | 589 | 11.9 | 4.65 |
| $CH_2Br_2$ | dibromomethane | 589 | 15.9 | 7.97 |
| $CH_2I_2$ | diiodomethane | 589 | 15.0 | 4.39 |
| $CH_3Cl$ | monochloromethane | 589 | 23 | 3.99 |
| $CH_3Br$ | monobromomethane | 589 | 1.5 | 5.93 |
| $CH_3I$ | monoiodomethane | 589 | 19.5 | 9.74 |
| $CH_4O$ | methyl alcohol | 589 | 18.7 | 2.79 |
| $CH_3O_2N$ | mononitromethane | 589 | 9.9 | 2.40 |

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**Verdet Constants V of Organic Liquids (from Ref. 7)**—*continued*

| Formula | Name | λ (nm) | T(°C) | V (rad/T m) |
|---|---|---|---|---|
| $C_2H_3Br$ | vinylbromide | 589 | 7.8 | 6.11 |
| $C_2H_4O$ | ethyleneoxide (1,2-epoxiethane) | 589 | 8.0 | 2.68 |
| $C_2H_4O$ | acetaldehyde (ethanal) | 589 | 16.3 | 2.91 |
| $C_2H_4O_2$ | acetic acid | 589 | 21.0 | 3.04 |
| $C_2H_4O_2$ | methylformate | 589 | 16.5 | 2.79 |
| $C_2H_4Cl_2$ | 1,1-dichloroethane | 589 | 14.4 | 4.39 |
| $C_2H_4Cl_2$ | 1,2-dichloroethane | 589 | 14.4 | 4.80 |
| $C_2H_4Br_2$ | 1,2-dibromoethane | 589 | 15.2 | 7.74 |
| $C_2H_5Cl$ | monochloroethane | 589 | 5.0 | 3.96 |
| $C_2H_5Br$ | monobromoethane | 589 | 19.7 | 5.29 |
| $C_2H_5I$ | monoiodoethane | 589 | 18.1 | 8.58 |
| $C_2H_6O$ | ethyl alcohol | 589 | 16.8 | 3.29 |
| $C_2H_6O_2$ | glycol (1,2-ethanediol) | 589 | 15.1 | 3.64 |
| $C_2H_6S$ | ethylmercaptan | 578 | 16.0 | 5.38 |
| $C_2H_2O_2Cl_2$ | dichloroacetic acid | 589 | 13.5 | 4.42 |
| $C_2H_3O_2Cl$ | chloroacetic acid (cloroethanoic acid) | 589 | 64.5 | 3.87 |
| $C_2H_3O_2Cl_3$ | chloralhydrate | 589 | 54.6 | 4.80 |
| $C_2H_5O_2N$ | mononitroethane | 589 | 10.2 | 2.75 |
| $C_3H_4O$ | acrolein (propenal) | 578 | 20.0 | 5.12 |
| $C_3H_4O_3$ | pyruvic acid (2-oxopropanoic acid) | 589 | 14.5 | 3.52 |
| $C_3H_6O$ | allyl alcohol | 589 | 18.3 | 4.65 |
| $C_3H_6O$ | propyl alcohol (1-propanol) | 589 | 13.6 | 3.17 |
| $C_3H_6O$ | acetone (2-propanone) | 589 | 20 | 3.24 |
| $C_3H_6O_2$ | propionic acid (propanoic acid) | 589 | 20.3 | 3.20 |
| $C_3H_6O_2$ | formic acid ethyl ester (ethylmethanoate) | 589 | 18.8 | 3.05 |
| $C_3H_6O_2$ | acetic acid methyl ester (methyl acetate) | 589 | 20.0 | 3.00 |
| $C_3H_7Cl$ | propylchloride (1-chloropropane) | 589 | 16.1 | 3.90 |
| $C_3H_7Cl$ | isopropylchloride (2-chloropropane) | 589 | 17.2 | 3.90 |
| $C_3H_7Br$ | propylbromide (1-bromopropane) | 589 | 19.2 | 5.21 |
| $C_3H_7Br$ | isopropylbromide (2-bromopropane) | 589 | 17.1 | 5.15 |
| $C_3H_7I$ | propyliodide (1-iodopropane) | 589 | 18.1 | 7.82 |
| $C_3H_7I$ | isopropyliodide (2-iodopropane) | 589 | 26.3 | 7.65 |
| $C_3H_8O$ | *n*-propyl alcohol (1-propanol) | 589 | 15.6 | 3.49 |
| $C_3H_8O$ | isopropyl alcohol (2-propanol) | 589 | 20.0 | 3.58 |
| $C_3H_8O_3$ | glycerine (1,2,3-propanetriol) | 589 | 16.0 | 3.87 |
| $C_3H_9N$ | *n*-propylamine | 589 | 9.6 | 3.87 |
| $C_3H_5O_9N_3$ | nitroglycerine | 589 | 13.5 | 2.62 |
| $C_3H_7O_2N$ | 1-nitropropane | 589 | 18.9 | 2.96 |
| $C_4H_6$ | 1,3-butadiene (erythrene) | 589 | 15.0 | 6.28 |
| $C_4H_8$ | 1-butene (a-butylene) | 589 | 15.0 | 4.04 |
| $C_4H_8$ | *cis*-2-butene (b-butylene) | 589 | 15.0 | 4.01 |
| $C_4H_8$ | *trans*-2-butene | 589 | 15.0 | 3.75 |
| $C_4H_{10}$ | butane | 589 | 15.0 | 3.17 |
| $C_4H_{10}$ | isobutane (2-methylpropane) | 589 | 15.0 | 3.23 |
| $C_4H_4O$ | furan (furfuran) | 589 | 20.0 | 5.18 |
| $C_4H_4S$ | thiophene (thiofuran) | 589 | 20.0 | 8.23 |
| $C_4H_6O_3$ | acetic anhydride (ethanoic anhydride) | 589 | 20.0 | 3.24 |

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**Verdet Constants V of Organic Liquids (from Ref. 7)**—*continued*

| Formula | Name | λ (nm) | T(°C) | V (rad/T m) |
|---|---|---|---|---|
| $C_4H_8O_2$ | *n*-butyric acid (butanoic acid) | 589 | 18.8 | 3.35 |
| $C_4H_8O_2$ | ethyl acetate (ethyl ethanoate) | 589 | 20.0 | 3.14 |
| $C_4H_8O_2$ | propionic acid methyl ester | 589 | 20.0 | 3.11 |
| $C_4H_{10}O$ | ethyl ether (ethoxyethane) | 589 | 20.0 | 3.17 |
| $C_4H_{10}O$ | *n*-butyl alcohol (1-butanol) | 589 | 20.0 | 3.58 |
| $C_4H_{10}O$ | isobutyl alcohol (2-methyl-1-propanol) | 589 | 17.7 | 3.69 |
| $C_4H_{10}O$ | *sec*-butyl alcohol (methylethylcarbinol) | 589 | 20.0 | 3.69 |
| $C_5H_6$ | cyclopentadiene | 589 | 15.0 | 5.88 |
| $C_5H_8$ | 1,3-pentadiene | 589 | 15.0 | 6.05 |
| $C_5H_8$ | isoprene (2-methyl-1,3-butadiene) | 589 | 15.0 | 6.05 |
| $C_5H_8$ | cyclopentene | 589 | 15.0 | 4.42 |
| $C_5H_{10}$ | 1-pentene | 589 | 15.0 | 4.04 |
| $C_5H_{10}$ | isopentane (2-methyl-1-butane) | 589 | 15.0 | 4.04 |
| $C_5H_{10}$ | cyclopentane | 589 | 20.0 | 3.58 |
| $C_5H_{12}$ | pentane | 589 | 15.0 | 3.35 |
| $C_5H_{12}$ | isopentane (2-methylbutane) | 589 | 15.0 | 3.40 |
| $C_5H_4O_2$ | furfural (2-furancarbonal) | 578 | 20.0 | 5.99 |
| $C_5H_5N$ | pyridine | 589 | 11.9 | 7.50 |
| $C_5H_{10}O_2$ | propionic acid ethyl ester | 589 | 20.0 | 3.29 |
| $C_5H_{10}O_2$ | acetic acid propylester | 589 | 15.7 | 3.29 |
| $C_5H_{14}N_2$ | cadaverine (1,5-pentanediamine) | 589 | 14.7 | 4.45 |
| $C_6H_6$ | benzene | 589 | 15.0 | 8.73 |
| $C_6H_{12}$ | cyclohexane | 589 | 20.0 | 3.61 |
| $C_6H_{14}$ | hexane | 589 | 15.0 | 3.49 |
| $C_6H_4Cl_2$ | 1,4-dichlorobenzene (*p*-dichlorobenzene) | 589 | 64.5 | 7.82 |
| $C_6H_5F$ | fluorobenzene (phenylfluoride) | 589 | 19.0 | 7.30 |
| $C_6H_5Cl$ | chlorobenzene (phenylchloride) | 589 | 15.0 | 8.49 |
| $C_6H_5Br$ | bromobenzene (phenylbromide) | 589 | 15.0 | 9.48 |
| $C_6H_5I$ | iodobenzene (phenyliodide) | 589 | 15.0 | 11.8 |
| $C_6H_6O$ | phenol (hydroxibenzene) | 589 | 39.0 | 9.34 |
| $C_6H_7N$ | aniline (aminobenzene) | 589 | 15.0 | 12.2 |
| $C_6H_{11}Cl$ | chlorocyclohexane (cyclohexylchloride) | 589 | 13.0 | 4.25 |
| $C_6H_{12}O_3$ | paraldehyde (paraacetaldehyde) | 589 | 17.3 | 3.46 |
| $C_6H_{14}O$ | 2-hexanol (butylmethylcarbinol) | 589 | 20.0 | 3.81 |
| $C_6H_{14}O$ | 3-hexanol (ethylpropylcarbinol) | 589 | 20.0 | 3.78 |
| $C_6H_{14}O$ | 2-methyl-3-pentanol | 589 | 20.0 | 3.84 |
| $C_6H_4O_4N_2$ | 1,3-dinitrobenzene (*m*-dinitrobenzene) | 589 | 17.1 | 6.31 |
| $C_6H_5O_2N$ | nitrobenzene | 589 | 15.0 | 6.31 |
| $C_7H_8$ | toluene (methylbenzene) | 589 | 15.0 | 7.88 |
| $C_7H_{14}$ | 1-heptene (a-heptylene) | 589 | 18.0 | 4.16 |
| $C_7H_{16}$ | heptane | 589 | 15.0 | 3.58 |
| $C_7H_5N$ | benzonitrile (benzenecarbonitrile) | 589 | 15.7 | 7.97 |
| $C_7H_7Cl$ | *o*-chlorotoluene (2-chloro-1-methylbenzene) | 589 | 15.4 | 8.58 |
| $C_7H_7Cl$ | *p*-chlorotoluene (4-chloro-1-methylbenzene) | 589 | 15.2 | 7.71 |
| $C_7H_7Br$ | *o*-bromotoluene (2-bromo-1-methylbenzene) | 589 | 16.7 | 8.96 |
| $C_7H_7Br$ | *p*-bromotoluene(4-bromo-1-methylbenzene) | 589 | 39.0 | 8.38 |
| $C_7H_8O$ | *o*-cresol (*o*-methylphenol) | 589 | 16.0 | 8.93 |

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**Verdet Constants V of Organic Liquids (from Ref. 7)**—*continued*

| Formula | Name | λ (nm) | T(°C) | V (rad/T m) |
|---|---|---|---|---|
| $C_7H_8O$ | *m*-cresol (*m*-methylphenol) | 589 | 17.9 | 8.41 |
| $C_7H_8O$ | *p*-cresol (*p*-methylphenol) | 589 | 17.0 | 8.46 |
| $C_7H_9N$ | *o*-toluidine (*o*-methylaniline) | 589 | 17.3 | 11.0 |
| $C_7H_9N$ | *m*-toluidine (*m*-methylaniline) | 589 | 15.0 | 10.4 |
| $C_7H_9N$ | *p*-toluidine (*p*-methylaniline) | 589 | 50.0 | 9.80 |
| $C_7H_{14}O$ | enanthaldehyde (heptanal) | 589 | 16.2 | 3.67 |
| $C_7H_{16}O$ | 1-heptanol (*n*-heptylalcohol) | 589 | 12.6 | 3.87 |
| $C_7H_{16}O$ | 2-heptanol (amylmethylcarbinol) | 589 | 20.0 | 3.84 |
| $C_7H_{16}O$ | 3-heptanol (butylethylcarbinol) | 589 | 20.0 | 3.99 |
| $C_7H_7O_2N$ | *o*-nitrotoluene | 589 | 18.0 | 6.28 |
| $C_7H_7O_2N$ | *p*-nitrotoluene | 589 | 54.3 | 5.73 |
| $C_8H_{10}$ | ethylbenzene (phenylethane) | 589 | 15.0 | 8.14 |
| $C_8H_{10}$ | *o*-xilene (1,2-dimethylbenzene) | 589 | 15.0 | 7.62 |
| $C_8H_{10}$ | *m*-xilene (1,3-dimethylbenzene) | 589 | 15.0 | 7.18 |
| $C_8H_{10}$ | *p*-xilene (1,4-dimethylbenzene) | 589 | 15.0 | 7.16 |
| $C_8H_{16}$ | 1-octene (a-octylene) | 589 | 15.0 | 4.19 |
| $C_8H_{16}$ | 2-octene (b-octylene) | 589 | 15.0 | 4.16 |
| $C_8H_{18}$ | octane | 589 | 15.0 | 3.67 |
| $C_8H_{18}O$ | 1-octanol (*n*-octyl alcohol) | 589 | 20.0 | 3.87 |
| $C_8H_{18}O$ | 2-octanol (methylhexylcarbinol) | 589 | 20.0 | 3.90 |
| $C_8H_{18}O$ | 3-octanol (ethylamylcarbinol) | 589 | 20.0 | 3.87 |
| $C_9H_{12}$ | *o*-ethyltoluene (1-ethyl-2-ethylbenzene) | 589 | 15.0 | 6.75 |
| $C_9H_{12}$ | *m*-ethyltoluene (1-ethyl-3-ethylbenzene) | 589 | 15.0 | 8.46 |
| $C_9H_{12}$ | *p*-ethylbenzene (1-ethyl-4-ethylbenzene) | 589 | 15.0 | 6.89 |
| $C_9H_{12}$ | mesitylene (1-3-5-trimethylbenzene) | 589 | 15.0 | 6.63 |
| $C_9H_{20}$ | nonane | 589 | 15.0 | 3.72 |
| $C_{10}H_8$ | naphthalene | 589 | 89.5 | 13.0 |
| $C_{10}H_{20}$ | 1-decene (*n*-decylene) | 589 | 21.0 | 4.22 |
| $C_{10}H_{22}$ | decane | 589 | 15.0 | 3.78 |
| $C_{10}H_7Cl$ | 1-chloronaphthalene (*a*-chloronaphthalene) | 578 | 18.0 | 14.3 |
| $C_{10}H_7Br$ | 1-bromonaphthalene (*a*-bromonaphthalene) | 578 | 20.0 | 15.1 |
| $C_{10}H_8O$ | *b*-naphthol (2-hydroxinaphthalene) | 578 | 13.6 | 14.0 |
| $C_{10}H_9N$ | 1-naphthylamine (*a*-naphthylamine) | 589 | 32.6 | 19.9 |
| $C_{10}H_{12}O_2$ | isoeugenol (4-propenylguaiacol) | 589 | 19.3 | 10.33 |
| $C_{10}H_{12}O_2$ | eugenol (4-allylguaiacol) | 589 | 15.4 | 8.38 |
| $C_{10}H_{12}O_2$ | benzoic acid propylester (*n*-propylbenzoate) | 589 | 15.4 | 6.40 |
| $C_{10}H_{12}O_2$ | *o*-toluic acid ethyl ester | 589 | 15.2 | 6.54 |
| $C_{10}H_{12}O_2$ | *p*-toluic acid ethyl ester | 589 | 15.0 | 6.34 |
| $C_{10}H_{12}O_2$ | *a*-toluic acid ethyl ester (ethylphenylacetate) | 589 | 14.0 | 6.54 |
| $C_{10}H_{12}O_2$ | methylsaliciclic acid ethylester | 589 | 18.6 | 7.27 |
| $C_{10}H_{18}O$ | *a*-terpineol | 589 | 16.0 | 4.54 |
| $C_{10}H_{18}O$ | Citronellal | 589 | 14.5 | 4.39 |
| $C_{10}H_{18}O_4$ | dipropylsuccinate | 589 | 11.4 | 3.55 |
| $C_{10}H_{10}O_6$ | tartaric acid dipropyl ester (propyltartrate) | 589 | 15.4 | 3.61 |
| $C_{10}H_{20}O$ | menthol | 589 | 45.2 | 4.07 |
| $C_{11}H_{24}$ | undecane | 589 | 20.5 | 3.81 |
| $C_{12}H_{26}$ | dodecane | 589 | 21.5 | 3.84 |

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**Verdet Constants V of Organic Liquids (from Ref. 7)**—*continued*

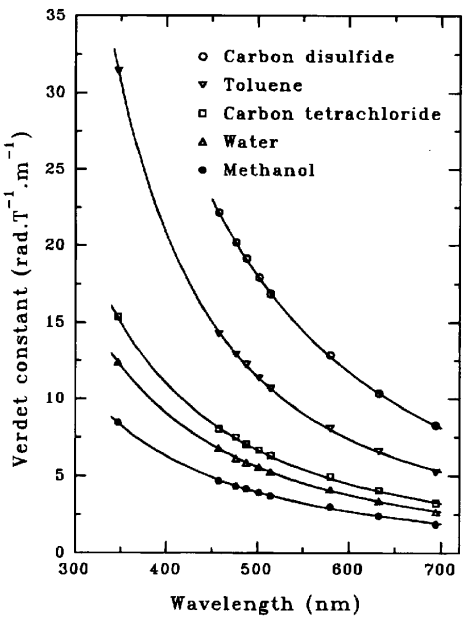
| Formula | Name | λ (nm) | T(°C) | V (rad/T m) |
|---|---|---|---|---|
| $C_{14}H_{10}$ | phenanthrene | 578 | 100.0 | 17.0 |
| $C_{16}H_{34}$ | hexadecane | 589 | 15.0 | 3.93 |
| $C_{18}H_{14}$ | 1,2-diphenylbenzene | 589 | 15.0 | 13.7 |
| $C_{18}H_{22}$ | 1,6-diphenylhexane | 589 | 20.0 | 8.00 |

### 5.6.3 Dispersion of the Verdet Constants

**Dispersion of the Verdet Constant V in the Near Ultraviolet and Visible**

| | | V(λ)(rad/T·m), λ(nm) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Formula** | **Name** | **347.1** | **457.9** | **488.0** | **514.5** | **580.0** | **632.8** | **694.3** |
| $CH_3NO_2$ | nitromethane | | 4.07 | 3.58 | 3.26 | 2.60 | 2.15 | 1.67 |
| $CH_4O$ | methanol | 8.46 | 4.68 | 4.16 | 3.69 | 3.00 | 2.40 | 1.88 |
| $C_2H_4O_2$ | acetic acid | 9.75 | 5.29 | 4.65 | 4.13 | 3.29 | 2.71 | 2.09 |
| $C_2H_6O$ | ethanol | 10.5 | 5.61 | 4.95 | 4.45 | 3.49 | 2.90 | 2.30 |
| $C_3H_6O$ | acetone | 10.5 | 5.64 | 4.95 | 4.45 | 3.46 | 2.84 | 2.79 |
| $H_2O$ | water | 12.4 | 6.78 | 5.85 | 5.24 | 4.10 | 3.35 | 2.66 |
| $CCl_4$ | carbon tetrachloride | 15.4 | 8.03 | 7.04 | 6.31 | 4.95 | 4.04 | 3.23 |
| $C_6H_5NO_2$ | nitrobenzene | | 10.7 | 9.60 | 8.41 | 6.66 | 5.41 | 4.33 |
| $C_7H_8$ | toluene | 31.4 | 14.3 | 12.2 | 10.7 | 8.09 | 6.60 | 5.24 |
| $C_6H_6$ | benzene | | 16.0 | 13.6 | 12.1 | 9.13 | 7.39 | 5.93 |
| $CS_2$ | carbon disulfide | | 22.2 | 19.2 | 16.8 | 12.9 | 10.4 | 8.26 |

Liquids are listed in increasing order of the Verdet constant.[8]




Dispersion of the Verdet constant for several liquids listed in the table above

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## Dispersion of the Verdet Constant V in the Near Infrared[2]

| | | Vλ) (rad/T·m), λ(μm) | | | | |
|---|---|---|---|---|---|---|
| **Formula** | **Name** | **0.6** | **0.8** | **1.0** | **1.5** | **2.0** |
| $H_2O$ | water | 3.67 | 2.04 | 1.28 | (0.844 at 1.25 _m) | |
| $SnCl_4$ | tin tetrachloride | 11.9 | 6.31 | 3.93 | 1.75 | 0.902 |
| $TiCl_4$ | titanium tetrachloride | –3.81 | –1.45 | –0.756 | –0.291 | –0.145 |
| $CCl_4$ | carbon tetrachloride | 4.68 | 2.59 | 1.66 | 0.727 | 0.378 |
| $CS_2$ | carbon disulfide | 11.5 | 6.23 | 3.93 | 1.69 | 0.902 |
| $CHCl_3$ | chloroform | 4.51 | 2.50 | 1.63 | 0.698 | 0.378 |
| $CH_3I$ | methyl iodide | 9.25 | 5.18 | 3.26 | 1.40 | 0.785 |
| $CH_2I_2$ | methylene iodide | 13.8 | 7.80 | 4.92 | 2.12 | 1.16 |
| $CH_4O$ | methyl alcohol | 2.71 | 1.48 | 0.931 | 0.553 | 0.378 |
| $C_2H_5I$ | ethyl iodide | 8.12 | 4.39 | 2.82 | 1.19 | 0.698 |
| $C_2H_6O$ | ethyl alcohol | 3.23 | 1.75 | 1.11 | 0.553 | 0.291 |
| $C_3H_6O$ | acetone | 3.00 | 1.77 | 1.16 | 0.495 | 0.262 |
| $C_4H_{10}O$ | ethyl ether | 2.97 | 1.69 | 1.05 | 0.465 | 0.233 |
| $C_4H_{10}O$ | *n*-butyl alcohol | 3.49 | 1.95 | 1.25 | 0.524 | 0.407 |
| $C_6H_6$ | benzene | 8.17 | 4.45 | 2.76 | 1.13 | 0.640 |
| $C_6H_5NO_2$ | nitrobenzene | 6.08 | 3.32 | 2.12 | 0.902 | 0.524 |
| $C_7H_8$ | toluene | 7.50 | 3.99 | 2.53 | 1.02 | 0.582 |
| $C_7H_{16}$ | *n*-heptane | 3.46 | 1.92 | 1.25 | 0.524 | 0.262 |
| $C_8H_{10}$ | xilene | 6.75 | 3.72 | 2.33 | 1.02 | 0.553 |
| $C_{10}H_7Br$ | α-bromonaphthalene | 13.4 | 7.13 | 4.42 | 1.83 | 1.02 |

Temperature = 23°C.

### References:


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## 5.7 Commercial Optical Liquids

Cargille Refractive Index Liquids are examples of commercially available liquids having a wide range of known property values for optical applications. Specific refractive index and dispersion values are maintained by exacting quality control. These liquids are sold individually or in sets covering certain refractive index ranges at 25ºC and 589.3 nm:

| | |
|---|---|
| Series AAA | 1.300–1.395 |
| Series AA | 1.400–1.458 |
| Series A | 1.460–1.640 |
| Series B | 1.642–1.700 |
| Series M | 1.705–1.800 |
| Series H | 1.81–2.00 |
| Series EH | 2.01–2.11 |
| Series FH | 2.12–2.21 |
| Series GH | 2.22–2.31 |

Other Cargille liquids are available with special properties of dispersion, transmittance, compatibility, fluorescence, stability, toxicity, etc. for special applications.

Whereas evaporation of a pure substance will not change the index of refraction, liquids that are mixtures of substances with different indices of refraction and different volatilities change refractive index through evaporation.

Typical optical liquids transmit well in the visible, begin to absorb in the near-UV and are characterized by a series of absorption bands from 800 to 1600 nm. Exceptions to this pattern are Cargille Laser Liquids Code 433 and Code 3421 which do not reach a UV cutoff until below 240 nm and which are highly transparent, without peaks and valleys in the IR out to 2500 nm.

The best optical liquids with refractive index above 1.810 are arsenic based, highly toxic, and corrosive (Cargille Refractive Index Liquids Series H, EH, FH, and GH).

Properties of representative Cargille optical immersion and laser liquids are given in the following three tables. For a discussion of the optical, physical, and chemical properties of liquids, see R. Sacher and W. Sacher, Optical liquids, *Handbook of Laser Science and Technology*, *Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995).

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## Properties of representative Cargille immersion liquids

| Representative liquid | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Formula code | | | | S1050 | | | | 5040 | | | 40BN | | BNDN | |
| Refractive index range for code ($n_D$ 25°C) | | | | 1.400–1.458 | | | | 1.459–1.570 | | | 1.571–1.656 | | 1.657–1.698 | |
| Refractive | 290 | | 1.433 | 1.461 | 1.499 | – | – | – | – | – | – | – | – – | |
| index @25°C | | | 67% | 73% | 82% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0%0% | |
| and percent | 365 | l | 1.418 | 1.444 | 1.478 | 1.500 | 1.531 | – | – | – | 1.711 | 1.750 | 1.776 | – |
| transmittance through | | | 98% | 98% | 99% | 17% | 1% | 0% | 0% | 0% | 1% | 50% | 12% | 0% |
| 1 cm at representative | 404.7 | h | 1.4127 | 1.4382 | 1.4719 | 1.4920 | 1.5214 | 1.5625 | 1.6036 | 1.6437 | 1.6832 | 1.7174 | 1.7408 | 1.7690 |
| wavelengths | | | 99% | 99% | 99% | 85% | 67% | 49% | 35% | 45% | 58% | 72% | 17% | 2% |
| (nm) | 486.1 | F | 1.4054 | 1.4306 | 1.4637 | 1.4819 | 1.5086 | 1.5460 | 1.5833 | 1.6170 | 1.6504 | 1.6794 | 1.7001 | 1.7250 |
| | | | 100% | 100% | 100% | 98% | 96% | 92% | 89% | 90% | 90% | 90% | 64% | 40% |
| Calibrated | 589.3 | D | 1.4000 | 1.4250 | 1.4580 | 1.4750 | 1.5000 | 1.5350 | 1.5700 | 1.6000 | 1.6300 | 1.6560 | 1.6750 | 1.6980 |
| at $n_D$ 25°C | | | 100% | 100% | 100% | 100% | 99% | 99% | 99% | 99% | 99% | 99% | 98% | 96% |
| ±0.0005 | 656.3 | C | 1.3977 | 1.4227 | 1.4557 | 1.4722 | 1.4966 | 1.5307 | 1.5648 | 1.5936 | 1.6224 | 1.6473 | 1.6657 | 1.6881 |
| | | | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 99% | 99% |
| | 1064.8 | | 1.392 | 1.417 | 1.450 | 1.465 | 1.488 | 1.520 | 1.552 | 1.578 | 1.605 | 1.628 | 1.645 | 1.666 |
| | | | 96% | 96% | 95% | 96% | 96% | 97% | 97% | 98% | 99% | 99% | 99% | 99 |
| | 1300 | | 1.390 | 1.415 | 1.449 | 1.464 | 1.487 | 1.518 | 1.550 | 1.576 | 1.602 | 1.624 | 1.641 | 1.662 |
| | | | 97% | 94% | 90% | 90% | 90% | 91% | 91% | 93% | 94% | 96% | 96% | 97% |
| | 1550 | | 1.390 | 1.415 | 1.448 | 1.463 | 1.486 | 1.517 | 1.549 | 1.574 | 1.600 | 1.622 | 1.639 | 1.659 |
| | | | 75% | 79% | 84% | 84% | 85% | 86% | 86% | 89% | 92% | 94% | 94% | 94% |
| Abbe ν, $(n_D - 1)/(n_F - n_C)$ | | | 52 | 54 | 57 | 49 | 42 | 35 | 31 | 26 | 22 | 20 | 2019 | |
| Temp. Coeff., $dn_D/dt$ (°C) | | | –.000412 | –.000402 | –.000388 | –.000393 | –.000401 | –.000411 | –.000421 | –.000438 | –.000454 | –.000468 | –.000473 | –.000479 |
| Viscosity, cSt, @25°C | | | 10 | 13 | 17 | 22 | 31 | 50 | 82 | 29 | 10 | 4 | 4 4 | |
| Density g/cm$^3$ @25°C | | | 0.930 | 0.887 | 0.831 | 0.855 | 0.894 | 0.948 | 1.003 | 1.184 | 1.359 | 1.511 | 1.608 | 1.722 |
| Thermal exp. cm$^3$/cm$^3$/°C | | | 0.0010 | 0.0009 | 0.0008 | 0.0008 | 0.0008 | 0.0007 | 0.0007 | 0.0006 | 0.0006 | 0.0006 | 0.0006 | |
| Flash point, °C | | | | >138 | | | | >138 | | | >113 | | >93 | |
| Pour point, °C | | | | <–7 | | | | <–7 | | | <6 | | <6 | |
| Boiling point, °C | | | | >200 | | | | >262 | | | >279 | | >279 | |
| Toxicity (request MSDS) | | | | Low | | | | Low | | | Moderate | | Moderate | |

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| **Representative liquid** *(cont.)* **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Compatible (c) and incompatible (i) | | | | | | | | | | | |
| Acrylic | c | | | c | | | c | | | c | |
| Polycarbonate | na | | | c | | | i | | | na | |
| Polyethylene | c | | | c | | | c | | | c | |
| Polypropylene | c | | | c | | | c | | | c | |
| Polystyrene | c | | | i | | | i | | | i | |
| Latex rubber | i | | | i | | | i | | | i | |
| Neoprene rubber | c | | | i | | | i | | | i | |
| Silicone rubber | i | | | i (some) | | | c | | | c | |
| Aluminum | c | | | c | | | c | | | c | |
| Copper | c | | | c | | | i | | | i | |
| Steel | c | | | c | | | c | | | i | |
| Color stability in sun | Very high | | | Moderate | | | Low to moderate | | | Low | |
| Best solvents | ethyl ether, naphtha, xylene, toluene, heptane, methylene chloride, turpentine | | | | | | Acetone, ethyl ether, naphtha, xylene, methylene chloride, toluene, heptane, turpentine | | | | |

na = not available; MSDS=materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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## Properties of representative special Cargille optical immersion liquids

| Representative liquid | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Formula code | | | 4550* | 4501 | 50350* | | 1160 | | 50BN* | | 5095 | | OHGL* | OHZB |
| Refractive index range for code ($n_D$ 25°C) | | | 1.452–1.457 | 1.452–1.470 | 1.458–1.475 | | 1.482–1.538 | | 1.459–1.656 | | 1.458–1.580 | | 1.333–1.470 | 1.333–1.556 |
| Refractive | 290 | | 1.489 | – | 1.518 | – | – | – | – | – | – | – | 1.503 | – |
| index @25°C | | | 56% | 0% | 72% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 59% | 0% |
| and percent | 365 | l | 1.471 | 1.500 | 1.496 | 1.512 | 1.535 | 1.584 | 1.673 | 1.715 | 1.536 | 1.647 | 1.488 | 1.598 |
| transmittance through | | | 100% | 53% | 99% | 90% | 90% | 90% | 75% | 71% | 94% | 85% | 97% | 78% |
| 1 cm at representative | 404.7 | h | 1.4655 | 1.4902 | 1.4894 | 1.5024 | 1.5237 | 1.5686 | 1.6481 | 1.6853 | 1.5244 | 1.6243 | 1.4832 | 1.5847 |
| wavelengths | | | 100% | 96% | 100% | 95% | 95% | 95% | 80% | 76% | 98% | 95% | 98% | 91% |
| (nm) | 486.1 | F | 1.4577 | 1.4779 | 1.4809 | 1.4902 | 1.5094 | 1.5501 | 1.6185 | 1.6511 | 1.5097 | 1.5972 | 1.4757 | 1.5679 |
| | | | 100% | 100% | 100% | 99% | 99% | 99% | 93% | 92% | 100% | 100% | 100% | 97% |
| Calibrated | 589.3 | D | 1.4520 | 1.4700 | 1.4750 | 1.4820 | 1.5000 | 1.5380 | 1.6000 | 1.6300 | 1.5000 | 1.5800 | 1.4700 | 1.5560 |
| at $n_D$ 25°C | | | 100% | 100% | 100% | 100% | 100% | 100% | 99% | 99% | 100% | 100% | 100% | 99% |
| ±0.0005 | 656.3 | C | 1.4497 | 1.4670 | 1.4726 | 1.4788 | 1.4963 | 1.5333 | 1.5931 | 1.6221 | 1.4962 | 1.5735 | 1.4676 | 1.5512 |
| | | | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| | 1064.8 | | 1.444 | 1.460 | 1.467 | 1.471 | 1.487 | 1.522 | 1.577 | 1.604 | 1.487 | 1.558 | 1.461 | 1.539 |
| | | | 94% | 95% | 93% | 97% | 97% | 97% | 98% | 99% | 96% | 98% | 80% | 93% |
| | 1300 | | 1.442 | 1.459 | 1.466 | 1.469 | 1.486 | 1.520 | 1.574 | 1.601 | 1.485 | 1.555 | 1.460 | 1.537 |
| | | | 88% | 85% | 87% | 92% | 93% | 94% | 94% | 95% | 92% | 95% | 58% | 60% |
| | 1550 | | 1.442 | 1.458 | 1.465 | 1.468 | 1.485 | 1.519 | 1.573 | 1.599 | 1.484 | 1.554 | – | – |
| | | | 81% | 84% | 81% | 87% | 88% | 90% | 91% | 93% | 86% | 90% | 0% | 0% |
| Abbe ν, $(n_D - 1)/(n_F - n_C)$ | | 57 | 43 | 58 | 42 | 38 | 32 | 24 | 22 | 37 | 25 | 58 | 33 | |
| Temp. Coeff., $dn_D/d_t$ (°C) | | | –.000394 | –.000488 | –.000360 | –.000348 | –.000349 | –.000350 | –.000446 | –.000458 | –.000398 | –.000416 | –.000377 | –.000330 |
| Viscosity, cSt @25°C | | | 11 | 0.4 | 112 | 41 | 41 | 41 | 6 | 5 | 14 | 10 | 679 | 9 |
| Density, g/cm$^3$ @25°C | | | 0.816 | 0.840 | 0.867 | 0.969 | 1.016 | 1.115 | 1.322 | 1.426 | 0.881 | 0.981 | 1.254 | 2.498 |
| Thermal Exp., cm$^3$/cm$^3$/°C | | | 0.00080.0010 | 0.0007 | 0.0007 | 0.0007 | 0.0006 | 0.0007 | 0.0007 | 0.0008 | 0.0007 | 0.0008 | 0.0006 | |
| Flash point, °C | | | >135 | >47 | >138 | | >199 | | >113 | | >138 | | >165 | None |
| Pour point, °C | | | <2 | <2 | <–7 | | <–45 | | <6 | | <–7 | | <18 | <1 |
| Boiling point, °C | | | >244 | >178 | >262 | | >370 | | >262 | | >262 | | >212 | >212 |
| Toxicity (request MSDS) | | | None | Moderate | None | | Low | | ModerateModerate | | | Low | Moderate | |

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| **Representative liquid** *(cont.)* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compatible (c) and incompatible (i) | | | | | | | | | | | | |
| Acrylic | c | na | c | | c | | c | | c | | c | c |
| Polycarbonate | c | na | c | | c | | i | | c | | c | na |
| Polyethylene | c | na | c | | c | | c | | c | | c | c |
| Polypropylene | c | na | c | | c | | c | | c | | c | c |
| Polystyrene | c | na | c | | i | | i | | i | | c | c |
| Latex rubber | i | na | i | | c | | i | | i | | c | c |
| Neoprene rubber | c | na | c | | i | | i | | i | | c | c |
| Silicone rubber | i (some) | na | i (some) | | c | | c | | i (some) | | c | c |
| Aluminum | c | na | c | | c | | c | | c | | i | i |
| Copper | c | na | c | | c | | c | | c | | i | i |
| Steel | c | na | c | | c | | c | | c | | i | c |
| Color stability in sun | Very high | Moderate | Very high | | High | | Low to moderate | | Moderate | | na | Moderate |
| Best solvents | Ethyl ether, naphtha, xylene, methylene chloride toluene, heptane, turpentine | | | | Ethanol, acetone, ethyl, ether, naphtha, xylene methylene chloride, toluene | | | Ethyl ether, naphtha xylene, methylene chloride toluene, heptane, turpentine | | | Water, ethanol | Water, ethanol, acetone |

*=very low fluorescence 356 nm excitation; na = not available; MSDS = materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, in *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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## Properties of representative Cargille laser liquids

| Representative liquid | | | 1 | 2 | 3 | 4 | 5 | 6 | | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Formula code | | | 433 | 3421 | | S1056 | | 5610 | | 5610 | | 1074 | 1057 | 5763 | |
| Refractive index range for code ($n_D$ 25°C) | | | 1.295–1.319 | 1.320–1.400 | | 1.398–1.459 | | 1.460–1.535 | | 1.460–1.535 | | 1.535–1.557 | 1.558–1.578 | 1.579–1.630 | |
| Refractive | 240 | | 1.31 | 1.33 | 1.44 | 1.45 | – | – | 290 | 1.579 | 1.633 | – | – | – | – |
| index @25°C | | | 34% | 11% | 22% | 8% | 0% | 0% | | 42% | 34% | 0% | 0% | 0% | 0% |
| and percent | 365 | l | 1.301 | 1.327 | 1.414 | 1.418 | 1.483 | 1.507 | 365 l | 1.537 | 1.579 | 1.608 | 1.631 | 1.663 | 1.705 |
| transmittance through | | | 100% | 100% | 100% | 98% | 95% | 95% | | 93% | 92% | 80% | 80% | 15% | 2% |
| 1cm at representative | 486.1 | F | 1.2970 | 1.3222 | 1.4041 | 1.4055 | 1.4631 | 1.4840 | 404.7 h | 1.5252 | 1.5639 | 1.5909 | 1.6139 | 1.6416 | 1.6795 |
| wavelengths | | | 100% | 100% | 100% | 100% | 100% | 100% | | 96% | 95% | 97% | 92% | 82% | 70% |
| (nm) | 589.3 | D | 1.2950 | 1.3200 | 1.4000 | 1.4000 | 1.4550 | 1.4750 | 486.1 F | 1.5102 | 1.5457 | 1.5704 | 1.5923 | 1.6163 | 1.6491 |
| | | | 100% | 100% | 100% | 100% | 100% | 100% | | 99% | 99% | 99% | 97% | 96% | 96% |
| Calibrated | 656.3 | C | 1.2941 | 1.3190 | 1.3983 | 1.3977 | 1.4518 | 1.4713 | 589.3 D | 1.5000 | 1.5340 | 1.5570 | 1.5780 | 1.6000 | 1.6300 |
| at $n_D$ 25°C | | | 100% | 100% | 100% | 100% | 100% | 100% | | 100% | 100% | 100% | 99% | 99% | 99% |
| ±0.0002 | 1064.8 | | 1.292 | 1.316 | 1.394 | 1.392 | 1.444 | 1.462 | 656.3 C | 1.4960 | 1.5295 | 1.5518 | 1.5724 | 1.5937 | 1.6229 |
| | | | 100% | 100% | 100% | 96% | 96% | 96% | | 100% | 100% | 100% | 100% | 100% | 100% |
| | 1300 | | 1.291 | 1.316 | 1.393 | 1.390 | 1.442 | 1.460 | 1064.8 | 1.486 | 1.519 | 1.539 | 1.559 | 1.579 | 1.606 |
| | | | 100% | 100% | 100% | 97% | 95% | 95% | | 96% | 97% | 99% | 100% | 99% | 99% |
| | 1550 | | 1.291 | 1.315 | 1.392 | 1.390 | 1.441 | 1.459 | 1300 | 1.484 | 1.517 | 1.537 | 1.556 | 1.576 | 1.603 |
| | | | 100% | 100% | 100% | 75% | 74% | 75% | | 95% | 95% | 95% | 97% | 96% | 95% |
| | 2500 | | 1.29 | 1.31 | 1.39 | – | – | – | 1550 | 1.483 | 1.516 | 1.535 | 1.555 | 1.574 | 1.602 |
| | | | 89% | 90% | 95% | 0% | 0% | 0% | | 77% | 80% | 84% | 83% | 87% | 92% |
| Abbe ν: $(n_D - 1)/(n_F - n_C)$ | | 101 | 100 | 69 | 51 | 40 | 38 | | 35 | 33 | 30 | 29 | 27 | 24 | |
| Temp. Coeff., $dn_D/dt$ (°C) | | | –.000351 | –.000326 | –.000346 | –.000412 | –.000414 | –.000407 | | –.000397 | –.000383 | –.000414 | –.000426 | –.000425 | –.000423 |
| Viscosity, cSt @25°C | | | 3 | 30 | 18 | 10 | 22 | 46 | | 125 | 484 | 40 | 177 | 454 | 1734 |
| Density, g/cm$^3$ @25°C | | | 1.896 | 1.982 | 1.903 | 0.933 | 0.981 | 1.011 | | 1.049 | 1.101 | 1.062 | 1.092 | 1.135 | 1.196 |
| Thermal Exp., cm$^3$/cm$^3$/°C | | 0.0012 | 0.0010 | 0.0009 | 0.0010 | 0.0009 | 0.0008 | | 0.0008 | 0.0007 | 0.0007 | 0.0007 | 0.0006 | 0.0006 | |
| Flash point, °C | | | None | None | | >121 | | >121 | | >121 | | >221 | >243 | >243 | |
| Pour point, °C | | | <–20 | <–20 | | <–70 | | <–22 | | <–22 | | <–20 | <–6 | <5 | |
| Boiling point, °C | | | >174 | >215 | | >149 | | >149 | | >149 | | >288 | >288 | >476 | |
| Toxicity (request MSDS) | | | Low | None | | Low | | None | | None | | None | None | Low | |

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| **Representative liquid** *(cont.)* | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compatible (c) and incompatible (i) | | | | | | | | | | | | |
| Acrylic | c | | c | c | | c | c | | c | c | | c |
| Polycarbonate | na | | na | c | | c | c | | c | c | | c |
| Polyethylene | c | | c | c | | c | c | | c | c | | c |
| Polypropylene | c | | c | c | | c | c | | c | c | | c |
| Polystyrene | c | | c | c | | c | c | | c | c | | c |
| Latex Rubber | c | | c | c | | c | c | | c | c | | c |
| Neoprene Rubber | c | | c | c | | c | c | | c | c | | c |
| Silicone Rubber | c | | i (some) | i (some) | | i (some) | i (some) | | c | c | | i (some) |
| Aluminum | c | | i | c | | c | c | | c | c | | c |
| Copper | c | | c | c | | c | c | | c | c | | c |
| Steel | c | | c | c | | c | c | | c | c | | c |
| Color stability in sun | Very high | | Very high | Very high | | Very high | Very high | | Very high | Very high | | Low |
| Best solvents chloride, | Freon TF and other chlorofluorocarbons; also remove with soap and water | | | Ethyl ether, naphtha, xylene, methylene Chloride | | Acetone, ethyl, ether, naphtha, xylene, methylene chloride | | | Acetone, ethyl, ether, xylene, methylene toluene, turpentine | | | |

na = not available; MSDS=materials specification data sheet.

Table from Sacher, R. and Sacher, W., Optical Liquids, in *Handbook of Laser Science and Technology, Supplement 2:Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 97.

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