Quasioptical Systems

Paul F. Goldsmith

TABLE 5.1 (*Continued*)

Material	Index of Refraction	Loss Tangent ($\times 10^{-4}$)	Frequency (GHz)	Reference
Macor	2.38	275	380–390[37]	[STUM89]
Magnesium oxide[38]	3.132	0.46	92.8	[KOMI91]
Mica	2.54–2.58	13–24	120–1000	[IGOS74]
Mylar	1.73–1.76	360–680	120–1000	[IGOS74]
Mylar	1.83	100 + 100/–50	140	[SOBE61]
Mylar	1.73	380	654	[KOOI94]
Mylar	1.83 ± 0.05	264 ± 7	890	[ADE71]
Mylar[39]	1.717; 1.752 ± 0.002	237 ± 7	1500	[SMIT75]
Nylon	1.729–1.735	85–158	60–300	[AFSA87]
Nylon	3.066	145	70–110	[GOY94]
Nylon[40]	1.7267 ± 0.0002	96–269	130–180	[BIRC81]
Paraffin[41]	1.50	34	289	[STOC93]
Paraffin[42]	1.51	80	289	[STOC93]
Plexiglas	1.599 ± 0.008	32.7 ± 2.6	50	[CULS62]
Plexiglas 36	1.6065–1.6115	78–135	60–300	[AFSA87a]
Plexiglas	1.60 ± 0.05	—	140	[SOBE61]
Plexiglas	1.61 ± 0.016	—	143	[DEGE66]
Plexiglas[43]	1.6067 ± 0.0002	87–264	150–600	[BIRC81]
Plexiglas	1.61 ± 0.05	—	210	[SOBE61]
Plexiglas	1.616 ± 0.0007	—	245	[SIMO83a]
Plexiglas	1.589–1.562	250–690	300–1800	[CHAM71a]
Plexiglas	1.62 ± 0.016	—	343	[DEGE66]
Plexiglas	1.593 ± 0.012	—	890	[CHAM71b]
Polyethylene[44]	1.5172 ± 0.0015	3.8 ± 0.2	26–38	[SHIM88]
Polyethylene[45]	1.536 ± 0.0007	1.73 ± 0.02	35	[COOK74]
Polyethylene	1.461	0.85 + 0.15 (f/30 GHz)	60–1500	[CHAN71a]
Polyethylene	1.51865–1.51875	3.6–4.4	90–270	[AFSA87a]
Polyethylene	1.52 ± 0.014	—	143; 343	[DEGE66]
Polyethylene[46]	1.5246 ± 0.0002	3–6	150–960	[BIRC81]
Polyethylene[47]	1.5138 ± 0.0002	3–8	150–1110	[BIRC81a]
Polyethylene	1.53	3.7	380–390[37]	[STUM89]
Polyethylene	1.461 ± 0.023	—	890	[CHAM65]
Polyethylene	1.508 ± 0.001	10 ± 2	890	[TSUJ82]
Polyethylene[48]	1.4711 ± 0.0003	9.7 ± 0.3	891	[QIU92]
Polyethylene[49]	1.519–1.520	—	1300–6000	[AFSA76]
Polyethylene	1.518 ± 0.0015	29.4 ± 3	1500[50]	[SMIT75]
Polypropylene[44]	1.5037 ± 0.0005	5.0 ± 0.3	26–38	[SHIM88]
Polypropylene	1.501–1.507		29–36	[LYNC82]
Polypropylene	1.5014 ± 0.002	1.54 ± 0.08	35	[AFSA84]
Polypropylene	1.4971 ± 0.00003	13.6 ± 1.4	60	[AFSA90]
Polypropylene	1.50155–1.50175	5.6–8.5	90–270	[AFSA87a]
Polypropylene	1.488 ± 0.001	25 ± 3	890	[TSUJ82]
Polypropylene	1.499 ± 0.003	—	890	[CHAM71b]
Polypropylene[51]	1.4875 ± 0.0003	30.1 ± 0.9	891	[QIU92]
Polystyrene[44]	1. 5944 ± 0.0005	8.7 ± 0.7	26–38	[SHIM88]
Polystyrene	1. 590 ± 0.008	7.2 ± 0.6	50	[CULS62]
Polystyrene[52]	1.5912 ± 0.0002	19–48	120–960	[BIRC81a]
Polystyrene	1.59 ± 0.005	20 + 20/–10	140	[SOBE61]
Polystyrene	1.60 ± 0.016	—	143	[DEGE66]
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Polyethylene	1.53	3.7	380–390[37]	[STUM89]
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Polyethylene	1.508 ± 0.001	10 ± 2	890	[TSUJ82]
Polyethylene[48]	1.4711 ± 0.0003	9.7 ± 0.3	891	[QIU92]
Polyethylene[49]	1.519–1.520	—	1300–6000	[AFSA76]
Polyethylene	1.518 ± 0.0015	29.4 ± 3	1500[50]	[SMIT75]
Polypropylene[44]	1.5037 ± 0.0005	5.0 ± 0.3	26–38	[SHIM88]
Polypropylene	1.501–1.507		29–36	[LYNC82]
Polypropylene	1.5014 ± 0.002	1.54 ± 0.08	35	[AFSA84]
Polypropylene	1.4971 ± 0.00003	13.6 ± 1.4	60	[AFSA90]
Polypropylene	1.50155–1.50175	5.6–8.5	90–270	[AFSA87a]
Polypropylene	1.488 ± 0.001	25 ± 3	890	[TSUJ82]
Polypropylene	1.499 ± 0.003	—	890	[CHAM71b]
Polypropylene[51]	1.4875 ± 0.0003	30.1 ± 0.9	891	[QIU92]
Polystyrene[44]	1. 5944 ± 0.0005	8.7 ± 0.7	26–38	[SHIM88]
Polystyrene	1. 590 ± 0.008	7.2 ± 0.6	50	[CULS62]
Polystyrene[52]	1.5912 ± 0.0002	19–48	120–960	[BIRC81a]
Polystyrene	1.59 ± 0.005	20 + 20/−10	140	[SOBE61]
Polystyrene	1.60 ± 0.016	—	143	[DEGE66]
Polystyrene	1.59 ± 0.005	—	210	[SOBE61]

TABLE 5.1 *(Continued)*

Material	Index of Refraction	Loss Tangent $(\times 10^{-4})$	Frequency (GHz)	Reference
Polystyrene	1.60 ± 0.016	—	343	[DEGE66]
Pyrex[53]	2.11 ± 0.03	28–40	250–400	[BREE67]
Quartz[54]	2.108	0.13	9.03 (300 K)	[GEYE95]
Quartz[55]	2.142	0.07	9.06 (77 K)	[GEYE95]
Quartz[54]	2.103	—	7.75 (300 K)	[GEYE95]
Quartz[55]	2.140	—	7.77 (77 K)	[GEYE95]
Quartz—c	2.1063 ± 0.0004	0.60 ± 0.06	60	[AFSA90]
Quartz—o[56]	2.1059 ± 0.0002	1.0 ± 0.3	245	[DUTT86]
Quartz—e[56]	2.1533 ± 0.0002	1.4 ± 0.5	245	[DUTT86]
Quartz[57]	2.132 ± 0.026	—	890	[CHAM65]
Quartz[58]	2.114 ± 0.009	—	890	[CHAM71b]
Quartz[58]	2.1133 ± 0.0004	2.49 ± 0.08	891	[QIU92]
Quartz—o	2.1073–2.2072	[59]	600–6000	[RUSS67]
Quartz—e	2.1541–2.2502	[59]	600–6000	[RUSS67]
Quartz—o[60]	2.113–2.214	—	900–6000	[LOWE73]
Quartz—e[60]	2.156–2.162	—	900–6000	[LOWE73]
Rexolite	1.599	4	13 (300 K)	[GEYE95]
Rexolite	1.582	2.5	13 (77 K)	[GEYE95]
Rexolite[44, 61]	1.5962 ± 0.0005	8.9 ± 0.7	26–38	[SHIM88]
Rexolite[61]	1.59	15–40	120–550	[SIMO84]
Rexolite	1.57 ± 0.005	20 + 20/−10	140	[SOBE61]
Rexolite[61]	1.56 ± 0.016	—	143	[DEGE66]
Rexolite	1.58 ± 0.03	—	210	[SOBE61]
Rexolite	1.59 ± 0.016	—	343	[DEGE66]
Rexolite[61]	1.58 ± 0.02	—	300–10800	[GILE90a]
Rexolite	1.59	27	380–390[28]	[STUM89]
Sapphire[62]	3.064035–3.0640	4–8	90–350	[AFSA84]
Sapphire—perpendicular	3.066 ± 0.0003	2.9 ± 0.2	168	[DRYA92]
Sapphire—parallel	3.047 ± 0.0003	1.87 ± 0.09	168	[DRYA92]
Sapphire[63]	3.094	5.8	180	[AFSA94b]
Sapphire[64]	3.064	6.2	180	[AFSA94b]
Sapphire	—	8	469–479	[GOY94]
Sapphire—o[65]	3.0666–3.0649	4–9	90–400	[AFSA87b]
Sapphire—e[65]	3.4056–3.4039	4–8	90–400	[AFSA87b]
Sapphire—o[33]	3.069–3.260	—	900–6000	[LOWE73]
Sapphire—e[33]	3.415–3.708	—	900–6000	[LOWE73]
Silicon[66]	3.417–3.418	6–13	90–450	[AFSA84]
Silicon[67]	3.4182 ± 0.0008	7.6 ± 0.9	245	[DUTT86]
Silicon[68] 1500 Ω · cm	3.419	8	300	[AFSA94b]
Silicon[68] 2000 Ω · cm	3.417	9	300	[AFSA94b]
Silicon[68] 11000 Ω · cm	3.414	2.5	300	[AFSA94b]
Silicon[69]	3.416–3.419	2–12	600–4200	[RAND67]
Silicon[70]	3.4155–3.4200	—	900–10,500	[LOWE73]
Spectralon[71]	1.31	213	291	[STOC93]
Spinel[72]	2.8942–2.8945	5–14	90–350	[AFSA84]

TABLE 5.1 *(Continued)*

Material	Index of Refraction	Loss Tangent (× 10^{-4})	Frequency (GHz)	Reference
Styrofoam[73]	—	0.53–0.81	200–260	[KERR92]
Styrofoam	1.017 ± 0.001	—	245	[SIMO83]
Styrofoam[74]	1.05	3.2	654	[KOOI94]
Styrofoam[75]	1.05	1.2–2.4	654	[KOOI94]
Teflon	1.434	2.0	9.93 (300 K)	[GEYE95]
Teflon	1.431	0.08	9.95 (77 K)	[GEYE95]
Teflon	1.429 ± 0.0003	2.17 ± 0.06	26–38	[SHIM88]
Teflon[76]	—	0.48 ± 0.04	34.9	[AFSA84]
Teflon[76]	1.397 ± 0.004	0.48 ± 0.01	35	[COOK74]
Teflon[77]	1.433 ± 0.007	3.2 ± 0.3	50	[CULS62]
Teflon	1.43855–1.43885	5.3–6.9	90–270	[AFSA87a]
Teflon[78]	1.4330 ± 0.0002	2.5–17	120–1110	[BIRC81]
Teflon	1.43 ± 0.005	30 + 30/–15	140	[SOBE61]
Teflon	1.44 ± 0.014	—	143	[DEGE66]
Teflon	1.44 ± 0.015	—	210	[SOBE61]
Teflon	1.44	8.5	299	[STOC93]
Teflon	1.44 ± 0.014	—	343	[DEGE66]
Teflon	1.391 ± 0.017	—	890	[CHAM65]
Teflon	1.4333 ± 0.0003	13.1 ± 0.4	891	[QIU92]
Titanium dioxide[79]	9.54 ± 0.01	5 ± .5	10.125	[SEEL62]
TPX[80]	1.4589 ± 0.00013	—	34.5	[LYNC82]
TPX	1.458 ± 0.0003	4.77 ± 0.05	34.5	[JONE76a]
TPX	1.458 ± 0.002	4.27 ± 0.21	35.3	[AFSA84]
TPX	1.45815–1.4589	5.0–8.3	70–270	[AFSA87]
TPX	1.4576 ± 0.0003	6.3 ± 0.54	245	[JONE84]
TPX	1.46	14	289	[STOC93]
TPX[81]	1.4600 ± 0.0002	5.6–13	300–1200	[BIRC81]
TPX	1.456 ± 0.002	—	890	[CHAM71b]
TPX	1.453 ± 0.002	21 ± 2	890	[TSUJ82]
TPX	1.4584 ± 0.0002	10.7 ± 0.3	891	[QIU92]
TPX[82]	1.4556–1.4564	—	1000–6000	[AFSA76]
TPX	1.447 ± 0.0015	132 ± 7	1500[50]	[SMIT75]
Trans-Tech 2-111[83]	3.74–3.76	30–45	120–550	[SIMO84]
Trans-Tech 2-111[83]	3.7298 ± 0.0008	17.4 ± 1.4	245	[DUTT86]
Zinc selenide	3.00–3.05	8–50	18–40	[SHIM91]
Zinc selenide	3.1246 ± 0.002	33.1 ± 1.0	891	[QIU92]
Zinc sulfide	2.90–2.93	5–13	18–36	[SHIM91]

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[1] Some of the values included in this table were obtained from curves presented in various references, while for others, only representative or average values are given. In these latter cases the range of values given generally reflects the variation over the frequency range covered rather than measurement uncertainty. For measurements at a single frequency, limits given are the experimental uncertainties. Most materials, for example, have loss tangents that increase with increasing frequency, but an interesting exception is polypropylene [AFSA87a], while other materials (e.g., crystal quartz) have relatively sharp resonances in the submillimeter region. For most accurate and complete data, it is advisable to consult the references cited. All data obtained at room temperature unless otherwise noted. A cross-reference between common and chemical names of a number of materials is given in Table 5.2

[2] Type AL23, 99.5% pure Al_2O_3 produced by Friedrichsfeld, Mannheim, Germany. The range of data given includes 14 samples in the 30–40 GHz range, 6 samples at 380 GHz, but only 1 sample at 140 GHz, where the errors reflect the statistical uncertainties of the measurements.

TABLE 5.1 *(Continued)*

[3] 999 alumina containing less than 0.1% MgO manufactured by Coors Porcelain Company.

[4] 995 alumina containing less than 0.5% $CaOMgSiO_2$ manufactured by WESGO.

[5] 995 alumina produced by Ampex Corporation.

[6] 99.7% chemically pure sample from Sumitomo Electric Industry. Virtually identical results obtained at 96.5 GHz.

[7] Ceradyne Ceralloy type 418S 99.5% BeO containing about 0.5% magnesium trisilicate flux.

[8] Hot-pressed material containing 0.25% lithia flux, manufactured by the Union Carbide Corporation.

[9] Type K-150 hot-pressed 99.5% chemically pure material with density = 2.9723 g/cm^{-3}, obtained from National Beryllia Corporation, Haskell, NJ. The uncertainty in the index of refraction represents the average deviation for *n* over the frequency range studied,

[10] Isopressed material with density 2.9086 g/cm^{-3}, obtained from National Beryllia Corporation, Haskell, NJ. The uncertainty in the index of refraction represents the average deviation for *n* over the frequency range studied. See reference for dependence of index of refraction of beryllia on density of material.

[11] Type K-150; 99.5% chemically pure material obtained from National Beryllia Corporation, Haskell, NJ.

[12] Sample from Denka prepared by chemical vapor deposition method; impurity content $\leq$ 10 parts per million.

[13] Grade HP material obtained from the Carborundum Company, Niagara Falls, NY. The index of refraction shows considerably more variation with frequency. The absorption coefficient and thus the loss tangent are remarkably similar for the two crystal orientations.

[14] Grade A material obtained from the Carborundum Company, Niagara Falls, NY. The index of refraction of this material is relatively independent of frequency. The loss tangent has a large frequency variation, as well as a dependence on crystal orientation that becomes greater at higher frequencies.

[15] The measurements reported here cover the frequency range 1500 to 10,500 GHz.

[16] Synthetic diamond grown by chemical vapor deposition. Data cover 120 to 900 GHz for index of refraction and 75 to 200 GHz for loss tangent; the latter drops with increasing frequency over the range of the measurements.

[17] RT/Duroid is a glass-microfiber-reinforced polytetrafluoroethylene material produced by Rogers Corporation, Chandler, AZ.

[18] Fluorogold is a registered trademark of Fluorocarbon Inc. and is an aggregate of aligned grains of glass in a Teflon (PTFE) network often used as a low-pass filter in detector systems. The data in this line pertain to the electric field perpendicular to the direction of alignment of the glass grains in the material.

[19] As in note 18, but for electric field parallel to the direction of alignment of the glass grains in the material.

[20] Fluorosint consists of Teflon alloyed with mica and is manufactured by Polypenco Ltd., P.O. Box 56, Welwyn Garden City, Hertfordshire AL7 1LA, United Kingdom.

[21] Infrared-grade material from Nippon Silicon Glass Company; OH content approximately 8 parts per million.

[22] Corning type 7490 UV-grade SiO_2 material.

[23] Corning type 7971 titanium silicate (7% TiO_2 by weight) SiO_2.

[24] Type Spectracil WF water-free SiO_2 manufactured by Thermal American Fused Quartz Company, Montville, NJ.

[25] Type WF is a low-water-content material produced by Thermal American Fused Quartz Company, Montville, NJ.

[26] Type Dynasil 4000 is an infrared-grade window material produced by the Dynasil Corporation, Berlin, NJ.

[27] Infrasil low-water-content material.

[28] Combination of results obtained using different measurement techniques.

[29] The measurements cover the frequency range 600 to 3600 GHz; the index of refraction is approximately 1.970 at the upper frequency limit.

[30] High-resistivity ($\geq 10^7$ $\Omega \cdot$ cm) GaAs with chromium doping concentration of 2×10^{16} cm^{-3}; sample #D3, manufactured by Hughes.

TABLE 5.1 *(Continued)*

[31] High resistivity ($\geq 10^7\ \Omega \cdot$ cm) GaAs with chromium doping concentration of 5×10^{15} cm^{-3}; sample #1089, manufactured by MA/COM.

[32] 10 to 20 $\Omega \cdot$ cm material from Exotic Materials, Costa Mesa, CA.

[33] At 300 K; measurements were also made at 1.5 K. There is considerable frequency structure in the absorption coefficient and thus the loss tangent, so that synoptic data are not very useful; consult the reference for details.

[34] Kapton made by Dupont. It is a birefringent material; the measurements reported here are made at 45 degrees to the optical axis, and cover the frequency range of 1500 to 10,500 GHz.

[35] Thallium bromide–iodide samples from Harshaw Chemical Company, Solon, OH. The first value of the index of refraction is that obtained from the waveguide Fabry–Perot measurement, while the second is the average value from the measurements made during the waveguide reflection measurement. The uncertainties in each are estimated by the authors ([BRID82]) to be about 0.25. The values of the loss tangent are from the Fabry–Perot method with uncertainties suggested by the authors.

[36] Thallium bromide–chloride samples from British Drug House, Poole, England; see note 35.

[37] Results obtained from three different samples and employing different measurement techniques.

[38] <100> face single crystal produced by Tateko Chemical Industry.

[39] The two different values for the index of refraction indicate a significant birefringence for Mylar. The measurements cover the range of 1500 to 10,200 GHz.

[40] Material obtained from G. H. Bloore Ltd, 480 Honeypot Lane, Stanmore, Middlesex HA7 1JD, United Kingdom. Loss tangent values from [BIRC81b].

[41] 48°C melting point material.

[42] 72°C melting point material.

[43] Sample obtained by casting material supplied as PMMA type 2 powder by RAPRA, Shawbury, Shrewsbury, Worcestershire SY4 4NR, United Kingdom. Loss tangent values from [BIRC81].

[44] Average values for n and $\tan \delta$ together with standard deviations over the frequency range of measurements.

[45] Ridgidex 2000 high density material.

[46] Sample from extruded rod supplied by Polypenco Ltd (P.O. Box 56, Welwyn Garden City, Hertfordshire AL7 1LA, United Kingdom) formed from UHMW-1900 manufactured by Hercules Ltd, 1 Great Cumberland Place, London W1 H8L, United Kingdom. Loss tangent values from [BIRC81].

[47] Sample obtained by casting material supplied as LDPE type 2 powder by RAPRA, Shawbury, Shrewsbury, Worcestershire SY4 4NR, United Kingdom. Loss tangent values from [BIRC81].

[48] High density material.

[49] The index of refraction of polyethylene is substantially invariant over the 1000 to 6000 GHz frequency range with the exception of two features at approximately 2200 and 4000 GHz. The loss tangent varies significantly with a particularly prominant resonance at 2200 GHz; see reference for details.

[50] The reference reports measurements from 1500 to 10,500 GHz.

[51] Sintered material.

[52] Sample obtained by casting material supplied as PS type 2 powder by RAPRA, Shawsbury, Shrewsbury, Worcestershire, SY4 4NR, United Kingdom. Loss tangent values from [BIRC81].

[53] Loss tangent of 280×10^{-4} at 400 GHz and 400×10^{-4} at 600 GHz; the index of refraction pertains to the entire frequency range given.

[54] Normal to c axis.

[55] Parallel to c axis .

[56] Cross-cut material grown by Sawyer Research Products, Eastlake, OH.

[57] Crystal cut with the optical axis perpendicular to the plane faces of the sample.

[58] Orientation not specified.

[59] There is considerable structure in the absorption of crystal quartz, which is particularly evident in the data for the ordinary ray given in [RUSS67] and also in [LOWE73]. Additional information is presented in Chapter 8, Table 8.1.

Thanks for your understanding! Main Quasioptical Systems: Gaussian Beam Quasioptical Propogation and Applications (IEEE Press Series on.. Quasioptical Systems: Gaussian Beam Quasioptical Propogation and Applications (IEEE Press Series on RF and Microwave Technology). Paul F. Goldsmith. The resulting quasioptical system is diffraction-limited over the field of view (20 cm x 30 cm) at the design working distance of 4 m and has an adjustable focus optics for distances from 2 m up to 6 m. Â© (2009) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE). Downloading of the abstract is permitted for personal use only. Citation Download Citation. C. am Weg, W. von Spiegel, R. Henneberger, R. Zimmermann, T. Loeffler, and H. G. Roskos "Quasioptical system design", Proc.