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MISCELLANEOUS DATA ON MATERIALS FOR MILLIMETRE AND SUBMILLIMETRE OPTICS

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Abstract

Several parameters of various materials, including solid and foam dielectrics, absorbers, and metals, are collected for use in optical design in the millimetre and submillimetre range. Although the list is not exhaustive it covers most of the important materials and parameters, and extensive references are given.

Key Words: Dielectrics, millimetrewaves, submilleterwaves, material properties

Introduction

In the design of optical systems for the millimetre and submillimetre wavelength range there are various materials available with suitable properties. Choice of materials depends on losses, dielectric constants, and frequently on low-temperature suitability for cryogenic applications. There have been many types of measurements of materials in the millimetre, sub-millimetre, and infrared wave bands which are of interest in optical design. No attempt has been made to be critical of the different measurement methods and it is left to the reader to judge the accuracy and appropriateness of the measurements from the original publications. The Tables give refractive index and absorption data for some of the dielectrics which are most important for optical design.

Many more materials have been measured but these are often more for the understanding of the materials than for applications. More extensive lists of references for dielectrics are given by Simonis [1] and Birch [2].

Data are also given for metal reflectivities. Other physical properties which are useful in cryogenic optical design, such as thermal contraction and conductivity, are also tabulated.

Dielectric Parameters

The data are presented in terms of the real part of the dielectric constant, ε', and the loss tangent, tanδ, which are commonly used by microwave engineers. The complex dielectric constant is

$$\hat{\epsilon} = \epsilon' - i\epsilon'' \tag{1}$$

where $i = \sqrt{-1}$, and

$$\tan\delta = \epsilon''/\epsilon \tag{2}$$

In millimetre optics it is perhaps more common to deal with the refractive index, n, (which is also tabulated here) and power absorption coefficient, α. These are related to the complex refractive index

$$\hat{n} = n - ik \tag{3}$$

with

$$\alpha = 4\pi\nu k/c \tag{4}$$

c the speed of light, and ν the frequency. For non-magnetic materials the two representations are related by

$$\epsilon' = n^2 - k^2 \qquad \epsilon'' = 2nk \tag{5}$$

or, for low loss materials,

$$\epsilon' = n^2 \qquad \tan\delta = 2k/n = \alpha c/2\pi n\nu \tag{6}$$

Note that α is often given in units of cm^{-1} or Np cm^{-1}. In the conventions of millimetrewave optics the neper (Np) is used as a measurement of power absorption (1 Np = 4.343 dB), in contrast to the normal electrical engineering definition in terms of amplitude.

Variability of Dielectric Properties

There are significant variations in the tabulated values for some of the materials. These arise from the measurement technique, the supplier, or the preparation of the material. Original references should be consulted for details. Generally there are larger discrepancies in the absorption coefficients than the refractive indices, since they are more difficult to determine and are relatively sensitive to material preparation (annealing, sintering, impurities, *etc.*). Several papers discuss the differences between measurement techniques [3][4][5], and a recent paper presents the measurements of the same samples by several different laboratories [6].

Temperature Dependence

Most of the measurements have been made at room temperature (~300 K), but there are fewer results at cryogenic temperatures. In some cases where measured data are not available the *Lorentz-Lorenz formula* [7]

$$\rho \propto \frac{\epsilon - 1}{\epsilon + 2} \tag{7}$$

relating the density, ρ, and dielectric constant may be used along with the known thermal contraction to estimate the dielectric constant at different temperatures. PTFE and HDPE lenses designed accordingly have shown correct focusing compared to lenses where the effect was not accounted for [8]. In that instance, computing the dielectric constant at 4.2 K using (7) corrected a 25 % beam broadening in a feed system with a PTFE lens, yet some published data show no change in refractive index [9][10]. In the design of a cryogenic lens both the change in dimensions and the change in refractive index need to be taken into account.

Absorption in some samples varies significantly with temperature and in other only slightly [11]. In the context of cryogenic low-noise optics probably the most significant benefit of cooling is the reduction of the thermal emission rather than the reduction of loss.

Metallic Reflection

There are few measurements on the resistivity of metallic reflectors at mm and sub-mm wavelengths. Cook *et al.* describe an apparatus at 337 GHz [12], but their measurements are preliminary and subject to comparison with an aluminum plate of unknown absolute reflectivity. In practice, losses at mm wavelengths are almost negligible. For sub-millimetre wavelengths it may be sufficient to assume that the surface resistivity is twice as high as calculated from the nominal DC conductivity. Surface resistivity, R_s, related to conductivity, σ, by

$$R_s = 10.88\times10^{-3}\sqrt{\left(\frac{10^7}{\sigma}\right)\frac{1}{\lambda_0}} \tag{8}$$

(λ_0 in m, σ in S m^{-1}). Surface roughness effects are discussed by Tischer [13] who indicates that when the roughness is greater than a skin depth the increase in effective surface resistivity is equal to the increase in area. The reflection loss is found (for normal incidence) from

$$f_L = \frac{R_s}{30\pi} \tag{9}$$

where f_L is the fraction of the power dissipated in the reflector.

Explanation of the Tables

It is difficult to ensure uniformity in the tabulations because of the different measurements and reporting of the various authors. Often the same material goes under different names (*e.g.*, PMMA, Perspex, Plexiglas, Lucite, *etc.*). A single name has been used and a cross-reference table provided. Where possible, manufacturers names have been included with the material designation or as a footnote. The nomenclature for SiO_2 materials is confusing as the names silica and quartz are both used. There are perhaps differences in naturally and synthetically produced SiO_2 so the original designations have been retained.

Table I: Dielectric constants for a number of homogeneous solids which have reasonably low losses.

Table II: Losses for foams and woven sheet materials. These are materials which are suitable for vacuum or environmental windows and infrared filters. Over the last few years there has been a change in the foaming gasses from ones which are harmful to ozone to more benign ones. This has corresponded to a significant increase in the absorption at millimetre wavelengths and the number of suitable foams has decreased dramatically. Materials which are known to be no longer available are not included in the table. Expanded polystyrene appears to be a transparent material, but there do not appear to be any definive infrared transparency figures.

Dielectric constants are not given here, but an empirically derived formula for expanded foams has been given by Sanford [14] as follows

$$\epsilon_r = \frac{2}{5}(\epsilon_{r0})^{\frac{d}{d_0}} + \frac{3}{5}\left[1 + \frac{d}{d_0}(\epsilon_{r0} - 1)\right] \tag{10}$$

where, for polystyrene, $\varepsilon_{r0} = 2.54$, $d_0 = 1.05$ g cm^{-3}, and for polyethylene, $\varepsilon_{r0} = 2.25$, $d_0 = 0.092$ g cm^{-3}.

Table III: Absorption properties of some solids suitable for optical loads at room and cryogenic temperatures.

Table IV: Reflection and transmission losses of some commercially available free-space absorbers of various types.

Table V: Thermal contraction of some dielectrics which can be used for lens design, *etc.*

Table VI: Thermal conductivity at cryogenic temperatures for some dielectrics.

Table VII: Material cross-reference for dielectrics. Some materials are known under various common, chemical, or trade names. The most common are given in the table.

Table VIII: Guide to reflectivities of metals at millimetre wavelengths. For a description of the material preparation or surface condition the original references should be consulted.

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Table I: Low-Loss Dielectric Materials

Material	f (GHz)	T (K)	n	ε'	tan δ × 10⁴	Ref.
Acrylic 31	100	300	1.611	2.595	8.1	[15]
	200		1.609	2.590	11.0	
	300		1.609	2.590	13.5	
AlN: (Generic)	146	300	2.81-2.88	7.90-8.29	6-38	[16]
(Tokuyama Soda)	140	300	2.883	8.312	6.0	
Alumina:	100	300	3.0983	9.599	6.0	[4],[17]
(WESGO)	250		3.0975	9.595	11.5	
	400		3.0980	9.598	16.0	
Alumina:	100	300	3.1451	9.892	14.5	[4],[17]
(COORS)	250		3.1440	9.885	21.5	
	400		3.1451	9.892	26.0	
Alumina: (BK-99)	140	300	3.244-3.252	10.523-10.576	2.7-3.2	[16]
(22XC)	150		3.05-3.06	9.30-9.36	2.7-3.5	
Alumina	245	300	3.093	9.5666		[18]
Beryllia	245	300	2.6126	6.8256	7.4	[19]
Beryllia	30-900	293	2.588	6.700		[6]
	300				12	
Beryllia, Hot pressed	150	300	2.6732	7.1462	9.5	[4]
	300		2.6725	7.1425	22.6	
Beryllia:	100	300	2.5842	6.6780	16	[4],[17]
(Ceradyne Ceralloy 418s)	250		2.5833	6.6735	22	
	450		2.5824	6.6690	25	
Beryllia: (B97-1)	140	300	2.6-2.62	6.76-6.86	6-8	[16]

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Beryllia	390	300	2.5871	6.693	11.5	[20]
BN	245	300	2.0727	4.2961	6.4	[19]
BN, Hot pressed[1]	141	300	1.783	3.179	14	[16]
	150	300	1.782	3.176	15	
BN, Pyrolitic	140	300	2.10-2.22	4.41-4.93	8-15	[16]
CaF_2	140	300	2.609	6.807	19	[16]
Diamond, chemical vapour deposition (CVD)	120	300			100	[54]
	200		2.381	5.669	5	
	400		2.373	5.631		
	600		2.375	5.641		
	800		2.373	5.631		
Eccofoam SIL[2]	22	300	1.71	2.91	260	[10]
		77	1.69	2.87	100	
Epoxy casting resin, 36DK[(2)]	94	300	2.3845	5.685	42	[21]
Epoxy casting resin, 36DA[(2)]	94	300	1.9950	3.980	14	[21]
Epoxy casting resin, 36D[(2)]	94	300	1.5770	2.487	11	[21]
Epoxy casting resin, 36DS[(2)]	94	300	1.3285	1.765	41	[21]

[1] Not Homogeneous

[2] Emerson and Cuming, Inc

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Epoxy casting resin, Eccosorb CR110(2)	100	4.8	1.87	3.50	315	[9]
	300	4.8	1.87	3.50	400	
	900	4.8	1.87	3.50	500	
	100	300	1.88	3.53	570	
	300	300	1.88	3.53	640	
	900	300	1.88	3.53	715	
Epoxy casting resin, Stycast 2850FT(2)	100	4.8	2.00	4.00	20.8	[9]
	300	4.8	2.00	4.00	88	
	900	4.8	2.00	4.00	330	
	100	300	2.28	5.20	65	
	300	300	2.28	5.20	275	
	900	300	2.28	5.20	1040	
Epoxy-Araldit CY 209, HY 951[3]	22	300	1.72	2.96	230	[10]
		77	1.69	2.87	41	
Epoxy-Araldit CY 220, HY 951(3)	22	300	1.72	2.97	250	[10]
		77	1.70	2.89	42	
Epoxy-Araldit D, HY 951(3)	22	300	1.73	2.99	240	[10]
		77	1.70	2.90	39	
Epoxy-Araldit F, HY 951(3)	22	300	1.76	3.08	340	[10]
		77	1.70	2.90	43	
Epoxy-LMB 1386, HY 951(3)	22	300	2.08	4.33		[10]

[3] Ciba-Geigy

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Epoxy-LMB 1386,						[10]
LMB 1387, Mixed by wgt.	22	300	2.09	4.38	110	
DY 067[3] Mixed by vol.	22	300	2.13	4.55	110	
		77	2.11	4.45	60	
Epoxy, Araldite	80-105	300	2.90	8.41	200	[22]
Epsilam-10	150	290	3.20	10.2	20	[23]
	600		3.25	10.2	50	
	900		3.25	10.2	130	
Ethyl cellulose	25	300	1.628	2.65	300	[24]
Ethyl cellulose	140	300	1.926	3.71	1000	[25]
Ferroflow	150	290	3.58	12.6	2700	[23]
	300		3.45	11.3	2800	
	600		3.30	10.6	3000	
Ferroflow	30-900	293	3.6	13.0		[6]
	300				3200	
Fluorogold: Parallel to grain	150	293	1.625	2.641	77	[26]
"	300		1.625	2.641	77	
"	600		1.630	2.657	125	
"	900		1.632	2.663	265	
Perpendicular to grain	150		1.602	2.566	40	
"	300		1.602	2.566	59	
"	600		1.606	2.579	110	
"	900		1.610	2.592	210	
Fluorogold	300-900	300	-	-	-[4]	[27]

[4] Strong dichroism

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Fluorogold, rod	100	4.8	1.68	2.82	0.6	[9]
	300	4.8	1.68	2.82	13	
	900	4.8	1.68	2.82	230	
	100	300	1.70	2.89	12	
	300	300	1.70	2.89	64	
	900	300	1.70	2.89	295	
Fluorosint	150	6	1.881	3.538	<8	[28]
	300	6	1.881	3.538	231	
	600	6	1.885	3.553	76	
	150	77	1.878	3.527	<8	
	300	77	1.879	3.531	21	
	600	77	1.884	3.549	87	
	150	295	1.872	3.504	17	
	300	295	1.873	3.508	42	
	600	295	1.876	3.519	115	
Fused silica, 85% density, slip cast	94	300	1.814	3.29	26	[29]
Fused silica QU:			1.958	3.8338	14-15	[16]
QV:	150	300	1.953	3.8142	5.5-7.1	
QI:			1.952	3.8103	5-5.3	

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Fused silica, slip cast	50	300	1.81	3.28		[30]
	400				1.7	
	500				2.7	
	600				3.6	
	700				5.1	
	800				5.9	
	900				6.2	
	1000				6.4	
Fused silica, Titanium silicate with 7% TiO_2[5]	120	300	1.9992	3.9968	12	[4]
	250		1.9983	3.9932	22	
	360		1.9983	3.9932	22	
Fused silica: (Spectrosil)	10	300	1.944	3.78	1.7	[24]
Fused silica: (Spectrosil)	60-90	300	1.954	3.82		[31]
Fused silica: (Dynasil 4000)	245	300	1.955	3.822	18.0	[19]
Fused silica: (Spectrosil WF)	245	300	1.9516	3.8087	8.0	[19]
Fused silica	393	300	1.9469	3.801	12.87	[20]
Fused silica: (Spectrosil)	2-300	300	1.962	3.85	1	[32]
Germanium, Crystalline	890	300	3.9904	15.923	14.4	[33]
Germanium, Crystalline	900	300	4.006	16.048	1.3	[34]
	900	1.5	3.928	15.429	1.4	
	1200	300	4.006	16.048	2.0	
	1200	1.5	3.928	15.429	1.0	

[5] Corning

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Glass, Cover slip	100	4.8	2.42	5.86	6.0	[9]
	300	4.8	2.42	5.86	110	
	900	4.8	2.42	5.86	1500	
Glass, Pyrex(5)	100	4.8	2.08	4.33	4.2	[9]
	300	4.8	2.08	4.33	53	
	900	4.8	2.08	4.33	530	
	100	300	2.11	4.45	125	
	300	300	2.11	4.45	255	
	900	300	2.11	4.45	494	
Glass, Pyrex(5)	400	300			28	[30]
	600				40	
Glass, Schott	100	4.8		4.33	1.8	[9]
	300	4.8	2.08	4.33	36	
	900	4.8	2.08	4.33	560	
Glass(5) 7070	25	300	1.97	3.9	31	[24]
Glass(5) 7070	2-300	300	2.0	4.0	24	[32]
HDPE	156	300			2.5	[35]
HDPE	160	290	1.5246	2.3244	3.1	[36]
	300		1.5247	2.3247	3.9	
	450		1.5246	2.3245	4.1	
	600		1.5247	2.3247	4.0	
	970		1.5245	2.3242	6.3	
HDPE	300	300			2.1	[37]
	600				3.9	
	900				5.2	
	1200				6.5	

Material	f (GHz)	T (K)	n	ε'	tan δ × 10⁴	Ref.
HDPE	890	300	1.4711	2.1641	9.7	[33]
HDPE	1900-13000	293	1.5304-1.5320	2.3422-2.3472	8.6-30	[38]
HDPE	26-40	300	1.53	2.34		[39]
	26-40	77	1.51	2.29		
HDPE	300-900	4.2	1.567	2.455		[40], [41]
		20	1.566	2.452		
		60	1.565	2.449		
		120	1.560	2.434		
		200	1.549	2.399		
		295	1.525	2.326		
LDPE	156	300			2.7	[35]
LDPE	160	290	1.5141	2.2923	3.1	[36]
	300		1.5141	2.2924	2.8	
	450		1.5139	2.2918	3.9	
	600		1.5137	2.2913	4.5	
	1000		1.5136	2.2911	6.8	
LDPE	1875-13700	293	1.5131-1.5139	2.2894-2.2920	5.5-13	[38]
LDPE	300-900	4.2	1.556	2.421		[40],[41]
		20	1.555	2.418		
		60	1.554	2.415		
		120	1.548	2.396		
		200	1.537	2.362		
		295	1.514	2.292		
Macor	100	300	2.382	5.673	15.0	[4]
	200		2.377	5.648	20.0	
	300		2.377	5.648	25.0	

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Macor	150	290	2.37	5.62	135	[23]
	450		2.37	5.61	313	
	750		2.38	5.66	340	
	900		2.38	5.65	900	
Macor	30-900	293	2.38	5.66		[6]
	300				23	
Macor	390	300	2.3799	5.664	269	[20]
$MgAl_2O_4$ Spinel	100	300	2.89420	8.3764	5.0	[4],[17]
	200		2.89454	8.3784	9.0	
	300		2.89430	8.3770	11.5	
Neoprene, Sheet	100	4.8	2.4	5.76	500	[9]
	300	4.8	2.4	5.76	630	
	900	4.8	2.4	5.76	790	
Nickel ferrite	245	300	3.7298	13.911	17.4	[19]
Nylon	50	300	1.791	3.21		[30]
	400				16	
	450		1.778	3.16		
	500				22	
	600				26	
Nylon	100	4.8	1.72	2.99	-	[9]
	300	4.8	1.72	2.99	-	
	900	4.8	1.72	2.99	-	
Nylon	100	300	1.730	2.993	8.8	[15]
	200		1.729	2.993	12.5	
	300		1.729	2.995	16	

Material	f (GHz)	T (K)	n	ε'	tan δ × 10⁴	Ref.
Nylon	150	290	1.7267	2.9814	101	[36]
	300		1.7266	2.9812	170	
	450		1.7268	2.9814	250	
Paraffin	22	300	1.51	2.27	3	[10]
Paraffin	25	300	1.48	2.2	<3	[24]
Paraffin	120	300	1.480	2.19	27	[42]
	168	300	1.48	2.2	13.5	
Paraffin	2-300	300	1.52	2.3	10	[32]
Parylene N	6000-15000	300	1.44[6]	2.07	300-700	[43]
PE	25	300	1.497	2.24	2.1	[24]
PE	71	300	1.510	2.28		[30]
	400				1.7	
	450		1.506	2.27		
	500				1.9	
	600				1.5	
	700				1.4	
	800				1.3	
	900				1.3	
	1000				1.3	
PE	100	300	1.5185	2.3058	3.7	[15]
	200		1.5183	2.3053	4.2	
	300		1.5182	2.3048	4.2	

[6] Difference compared to manufacturesrs optical data of 1.62 possibly due to impurities.

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
PE	143	300	1.520	2.31		[44]
	343		1.520	2.31		
PE	393	300	1.531	2.343	3.72	[20]
PE	850	300	1.526	2.33	4	[29]
PE	1000	298	1.5200	2.3104	14	[45]
	3000		1.5200	2.3104	14	
	5000		1.5200	2.3104	6	
PE	30-900	293	1.512-1.526	2.286-2.329	0-7	[6][7]
PETP	55	300	1.733	3.145	44	[46]
PETP	140	300	1.830	3.35	100	[25]
PETP	890	300	1.83	3.35	264	[47]
PMMA	25	300	1.603	2.57	32	[24]
PMMA	25	300	1.609	2.59	67	[24]
PMMA	71	300	1.615	2.61		[30]
	400				20	
	450		1.619	2.62		
	500				20	
	600				36	
PMMA	100	300	1.608	2.585	8.1	[15]
	200		1.607	2.582	11.0	
	300		1.607	2.582	13.5	

[7] Inter-laboratory comparison measurements

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
PMMA	100	4.8	1.57	2.46	27	[9]
	300	4.8	1.57	2.46	90	
	900	4.8	1.57	2.46	270	
	100	300	1.60	2.56	6.0	
	300	300	1.60	2.56	15.7	
	900	300	1.60	2.56	38	
PMMA	120	300	1.609	2.59	75	[42]
	168	300			89	
PMMA	140	300	1.600	2.56		[25]
	210		1.606	2.58		
PMMA	143	300	1.613	2.60		[44]
	343		1.615	2.61		
PMMA	150	290	1.6090	2.5887	89	[36]
	300		1.6081	2.5861	146	
	450		1.6061	2.5791	214	
PMMA	245	300	1.616	2.612		[18]
PP	35	300	1.50	2.25		[31]
PP	100	300	1.5017	2.2550	7.3	[15]
	200		1.5016	2.2549	6.2	
	300		1.5015	2.0545	5.2	
PP	120	300			5.3	[48]
PP	156	300			6.5	[35]
PP	1500-12000	290	1.4970-1.4983	2.241-2.245	57-110[8]	[49]

[8] Several absorption peaks

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
PP, Sintered	890	300	1.4875	2.2127	30.1	[33]
PS	25	300	1.594	2.54	12	[24]
PS	71	300	1.54	2.37		[30]
	400				3	
	450		1.57	2.48		
	600				5	
	1000				7	
PS	120	300			13	[42]
	168	300			25	
PS	143	300	1.600	2.56		[44]
	343		1.603	2.57		
PS	150	290	1.5925	2.5361	18	[36]
	300		1.5920	2.5345	27	
	450		1.5916	2.5331	36	
	600		1.5910	2.5312	44	
	900		1.5897	2.5277	48	
PS	850	300	1.587	2.52	9	[29]
PS	1640-13000	290	1.583-1.593	2.505-2.537	8.8-53	[49]
PS	300-900	4.2	1.620	2.624	[9]	[40],[41]
		20	1.619	2.621		
		60	1.617	2.615		
		120	1.616	2.611		
		200	1.603	2.570		
		295	1.591	2.531		

[9] Small change in absorption with temperature

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
PTFE[10]	22	300	1.40	1.96	5	[10]
		77	1.40	1.96	3	
PTFE	25	300	1.442	2.08	6	[24]
PTFE	35	300	2.058	1.73	3	[50]
PTFE	71	300	1.45	2.10		[30]
	400				4	
	450		1.41	1.99		
	600				2	
	1000				2	
PTFE	94	300	1.4370	2.065	2.1	[21]
PTFE	100	4.8	1.44	2.07	-	[9]
	300	4.8	1.44	2.07	-	
	900	4.8	1.44	2.07	-	
PTFE	100	300	1.4389	2.0701	5.3	[15]
	200		1.4386	2.0797	6.2	
	300		1.4385	2.0794	6.8	
PTFE	140	300	1.432	2.05	30	[25]
	210		1.442	2.08		
PTFE	143	300	1.439	2.07		[44]
	343		1.439	2.07		

[10] Dupont, Inc.

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
PTFE	150	290	1.4330	2.0535	2.9	[36]
	300		1.4330	2.0535	2.8	
	450		1.4330	2.0535	6.1	
	1000		1.4330	2.0535	15	
PTFE	156	300			3.6	[35]
PTFE	850	300	1.429	2.042	7	[29]
PTFE	890	300	1.4333	2.0543	13.1	[33]
PTFE	1600-5700	290	1.440-1.478	2.074-2.187	24-160[11]	[49]
PTFE, Sintered	300	300			4.4	[37]
	600				11	
	900				20	
	1200				22	
PTFE, Unsintered	35	300	1.396	1.950		[51]
PTFE, Unsintered	35	300	1.397	1.952	0.5	[52]
PTFE, Unsintered	300	300			<1	[37]
	600				5	
	900				13	
	1200				15	
Quartz, Crystalline	245	300	2.107	4.439		[18]
Quartz, Crystalline	390	300	2.1059	4.435		[20]
Quartz, Crystalline	890	300	2.1133	4.4660	2.5	[33]
Quartz, Fused (Herasil)	94	300	1.8738	3.511	10	[21]
Quartz, Fused	245	300	1.951	3.806		[18]

[11] Strong absorption band above 6000 GHz

Material		f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Quartz:	O	245	300	2.1059	4.4348	1.0	[19]
	E			2.1533	4.6367	1.4	
Quartz:	E	30-900	293	2.154	4.640		[6]
		300				2	
Quartz:	O	35	300	2.105	4.43	0.31	[51]
Quartz:	O	140	300	2.1076	4.4420	5.1	[16]
	E			2.1550	4.6440	2.4	
Quartz:	O	900	300	2.113	4.465	8	[34]
		900	1.5	2.110	4.452	8	
		1200	300	2.115	4.473	7.5	
		1200	1.5	2.111	4.456	7.5	
	E	900	300	2.156	4.648	0.5	
		900	1.5	2.142	4.588	0.3	
		1200	300	2.157	4.653	0.7	
		1200	1.5	2.144	4.597	0.2	
Quartz:	O	30-900	293	2.106	4.435		[6]
		300				2	
Rexolite		10	300	1.594	2.54	5	[24]
Rexolite		71	300	1.61	2.58		[30]
		400				1	
		450		1.58	2.52		
		600				3	
		1000				5	
Rexolite		94	300	1.5987	2.556	2.6	[21]
Rexolite		140	300	1.572	2.47	20	[25]
		210		1.581	2.50		

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Rexolite	143	300	1.562	2.44		[44]
	343		1.594	2.54		
Rexolite	390	300	1.5912	2.532	27.4	[20]
Rexolite	850	300	1.589	2.525	30	[29]
Rexolite	30-900	293	1.586-1.64	2.515-2.69		[6]
	150				10	
	300				20	
	600				35	
	900				47	
Sapphire	36	300			0.2	[53]
		150			0.07	
		100			0.003	
		70			0.0007	
		10			0.00003	
		4			0.000002	
	72	300			0.4	
		150			0.2	
		100			0.01	
		70			0.002	
		10			0.00009	
		4			0.0001	
Sapphire (HEMLITE)	100	300	3.065	9.395	4.6	[54]
	200		3.065	9.393	6.5	
	350		3.065	9.393	9.4	

Material		f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Sapphire	(HEMLUX)	100	300	3.094	9.574	4.8	[54]
		200		3.094	9.572	6.9	
		350		3.094	9.571	9.0	
		90	6.5			1.4	
		90	35			0.7	
		90	77			1.9	
		90	300			1.5	
		180	6.5			4.2	
		180	35			5.0	
		180	77			4.85	
		180	300			5.75	
Sapphire, α:	O	140	300	3.066-3.071	9.400-9.431	2.1-2.5	[16]
	E	140		3.400-3.405	11.560-11.594	1.1-1.4	
Sapphire:	O	900	300	3.069	9.419	17	[34]
		900	1.5	3.052	9.315	1.7	
	E	900	300	3.415	11.662	30	
		900	1.5	3.372	11.370	1.6	
Sapphire, z-cut		100	300	3.06396	9.3879	4.5	[4],[17]
		200		3.06356	9.3854	6.0	
		300		3.06350	9.3850	8.0	
Scotchcast 830		22	300	1.74	3.03	210	[10]
			77	1.71	2.92	51	
Silicon		100	300	3.4464	11.878	19	[4]
		250		3.4471	11.883	7.5	
		400		3.4469	11.881	5.0	
Silicon		245	300	3.4182	11.684	7.6	[19]

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Silicon	900	300	3.4155	11.666	6	[34]
	900	1.5	3.3818	11.437	1.6	
Silicon: (ICHPS RAN.)	150	300	3.424	11.72	0.24	[16]
(Wacker Ch.)			3.421-3.424	11.70-11.72	0.7-1.1	
Silicon	30-300	290	3.416-3.423	11.669-11.717		
Silicon (HR-Si)	50	290			2.0	[55]
	100				1.4	
	150				0.8	
	200				0.6	
	250				0.5	
	300				0.4	
Silicon (eHR-Si)	150	290			0.35	[55]
	200				0.25	
	250				0.20	
	300				0.20	
Silicon (HP-Si;dLR-Si)	70	290			0.50	[55]
	100				0.36	
	150				0.25	
	200				0.20	
	250				0.15	
	300				0.10	
Silicon (HR-Si)	145	330			0.7	[55]
		290			0.7	
		150			1.3	
		100			1.1	

Material		f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Silicon	(HP-Si)	145	290			0.28	[55]
			150			0.72	
			100			0.80	
			70			0.5	
Silicon	(eHR-Si)	145	330			0.40	[55]
			290			0.23	
			150			0.13	
			100			0.15	
			70			0.15	
Silicon	(dLR-Si)	145	330			0.05	[55]
			290			0.20	
			150			0.08	
			100			0.09	
			70			0.08	
Silicon	1 500 Ω cm	100	298	11.697	3.420	17	[56]
		200		11.687	3.419	10	
		300		11.685	3.418	8	
		400		11.686	3.418	9	
Silicon	2 000 Ω cm	100	298	11.678	3.417	17	[56]
		200		11.678	3.417	11	
		300		11.678	3.417	8	
		400		11.678	3.417	9	
Silicon	11 000 Ω cm	200	298	11.655	3.414	1	[56]
		300		11.655	3.414	2	
		400		11.655	3.414	3	

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
Teflon-Vergussmasse	22	300	1.73	3.00	190	[10]
		77	1.71	2.92	48	
TPX	35	300	1.470	2.126	4.8	[51]
TPX	94	300	1.4659	2.149	9	[21]
TPX	100	300	1.4587	2.1276	6.4	[15]
	200		1.4583	2.1266	8.1	
	300		1.4581	2.1262	8.4	
TPX	120	300			7.6	[48]
TPX	156	300			6.1	[35]
TPX	245	300	1.459	2.129		[18]
TPX	300	290	1.4600	2.1316	6.0	[36]
	450		1.4600	2.1316	6.8	
	1000		1.4600	2.1316	11	
TPX	890	300	1.4583-1.4585	2.1266-2.1272	10.7-10.6	[33]
TPX	900-12600	293	1.4555-1.4568	2.1182-2.1222	6.5-(>20)[12]	[57]
TPX	1000	298	1.4563	2.1208	13	[45]
	3000		1.4557	2.1191	13	
	5000		1.4559	2.1196	5	
TPX	300-900	4.7	1.475	2.176		[58],[41]
		77	1.475	2.176		
		100	1.474	2.173		
		210	1.466	2.149		
		290	1.458	2.162		

[12] Several absorption bands. Strongest absorption at 12300 GHz

Material	f (GHz)	T (K)	n	ε'	tan δ × 10^4	Ref.
TPX, Sheet.	100	4.8	1.42	2.02	11.2	[9]
	300	4.8	1.42	2.02	11.2	
	900	4.8	1.42	2.02	11.2	
	100	300	1.43	2.04	-	
	300	300	1.43	2.04	-	
	900	300	1.43	2.04	-	
YAG	72	300			0.4	53
		150			0.2	
		100			0.03	
		70			0.007	
		10			0.001	
		4			0.001	
ZnSe	100	300	3.0158	9.087	19	[4]
	250		3.0155	9.092	27	
	350		3.0166	9.100	28	
ZnSe	890	300	3.1246	9.7631	33.1	[33]

Table II: Foam and Fabric Dielectrics

Material	Characteristics		f (GHz)	Loss[13]	Ref.
Gore-Tex, cloth	Expanded PTFE, 2×2 basket weave, with laminated film		120	1	[59]
			300	4	
			600	10	
			900	18	
			1200	33	
Dylite[14]	Expanded PS foam:	0.92 lb ft^{-3} (17.8 kg m^{-3})	200	0.0018	[60]
			230	0.0045	
			260	0.0045	
		1.26 lb ft^{-3} (20.2 kg m^{-3})	200	0.0035	
			230	0.0055	
			260	0.0075	
		1.33 lb ft^{-3} (21.3 kg m^{-3})	200	0.0035	
			230	0.0055	
			260	0.0075	
		1.84 lb ft^{-3} (29.5 kg m^{-3})	200	0.0091	
			230	0.011	
			260	0.013	
Styrodure[15], Green		38 kg m^{-3}	320	0.030	[61]
Wallmate S1-E, Blue		34 kg m^{-3}	320	0.020	[61]

Table III: Solid Absorbers

Material	f (GHz)	T (K)	n	α (Np cm^{-1})	Ref.
CR110[16]	36	300		1.2	[62]
	94			2.0	
	250			7.1	
	670			9.7	
	2550			>15	
CR110[(16)]	36	80		0.83	[62]
	94			1.3	
	250			4.7	
	2550			11.5	

[13] Losses given in % for cloths, Np cm^{-1} for foams.
[14] Radva Corporation, Radford, VA.
[15] BASF
[16] Emerson and Cuming, Inc.

Material	f (GHz)	T (K)	n	α (Np cm^{-1})	Ref.
CR112[16]	36	300		6.0	[62]
	94			6.5	
	250			>15	
	670			>13	
CR112[16]	36	80		4.4	[62]
	94			5.5	
CR114[16]	36	300		7.7	[62]
	94			9.0	
	250			>15	
	670			>13	
CR117[16]	36	300		10.5	[62]
	94			11	
	250			>15	
	670			>13	
CR110[16]	100-300	1.2	1.93		[63]

Table IV: Foam Absorbers

Material	Geometry	f (GHz)	T (dB)	R (dB)	Ref.
Eccosorb ANP-73[17] Gold side	flat	85	22	11	[64]
White side		85	23	5.5	
Eccosorb AN-72[17] Gold side	flat	85	24	17.5	[64]
White side		85	24	18.5	
Eccosorb VHP-94-1[17]	pyramid	80	>40	>20	[65]
		115	>40	>15	
Eccosorb VHP-94-2[17]	pyramid	80	>50	>25	[65]
		115	>50	>15	
Eccosorb AN-72[17] White side	flat	80	>15	>12	[65]
		115	>20	>6	
Eccosorb CV-3[17]	egg box	80	>50		[65]
		115	>50		
APM3[18], unpainted	pyramid	80			[65]
		115			
APM3[18], painted	pyramid	80		>20	[65]
		115		>17	
APM5[18], unpainted	pyramid	80	>25	>30	[65]
		115	>30	>30	

[17] Emerson and Cuming, Inc.
[18] Hyfral

APM5[18], painted	pyramid	80 115	>27 >33	>25 >20	[65]
Thomas Keating Absorber	pyramid	80 115		>20 >25	[65]
LAO5[19]	flat	80 115		>20 >20	[66]
LAO12[19]	flat	80 115		>15 >20	[66]
AF40[19]	flat	80 115		>27 >30	[66]

Table V: Thermal Expansion

Total contraction in % from 300 K to temperature T as $(\ell_{300\,\mathrm{K}} - \ell_T)/\ell_{300\,\mathrm{K}}$

Material	**4.2 K**	**20 K**	**80 K**	**200 K**	**Ref.**
Epoxy, CY221/HY979[3]	1.14	1.14	1.03	0.57	[67]
HDPE	2.02	2.01	1.89	1.05	[67]
Nylon	1.32	1.30	1.07	0.93	[68]
PETP	1.24	1.24	1.09	0.53	[67]
PMMA	1.07	1.05	0.93	0.50	[67]
PP	1.25	1.25	1.15	0.62	[67]
PS	1.44	1.43	1.27	1.07	[67]
PTFE	1.86	1.86	1.76	0.91	[67]
Pyrex	0.04	0.04	0.04	0.01	[68]
Quartz, fused	-0.015	-0.015	0.000	0.003	[68]

Table VI: Thermal Conductivity

Material	**T (K)**	**k ($\mathrm{W\ cm^{-1}\ K^{-1}}$)**	**Ref.**
Epoxy Resin, MF110	15	1.4	[69]
Epoxy Resin, MF114	15	1.9	[69]
Glass, Pyrex	85 200 300	5.3 8.4 10	[70]
Nylon	4 20 100	0.13 1.0 2.5	[70]

[19] GEC Marconi

Material	T (K)	k (W cm^{-1} K^{-1})	Ref.
PE	4	0.11-0.26	[70]
	20	1.1-4.6	
	100	3.6	
	300	3.1-3.3	
PETP	30	0.6	[70]
	100	1.1	
	300	1.2	
PMMA	4	0.56	[70]
	20	0.72	
	80	1.5	
	300	2.0	
PS	4	0.35	[70]
PTFE	5	0.56	[70]
	20	1.4	
	80	2.0-2.3	
	300	2.2	
Quartz, fused	4	0.95-1.3	[70]
	20	1.3-1.5	
	80	4.7-6.0	

Table VII: Material Cross-Reference

Material	Comments
Acrylic	Polymethacralate
Alumina	Al_2O_3
Beryllia	Beryllium oxide, BeO
BN	Boron nitride
CFRP	Carbon-fibre reinforced plastic
Epsilam-10	Ceramic powder filled TFE resin: 3M Company
Ferroflow	Castable microwave absorber: Microwave Filter Company Inc.
Fluorogold	PTFE filled with glass grains. Reg. trademark of Fluorocarbon Inc.
Fluorosint	PTFE alloyed with mica: Polymer Corporation USA & Polypenco Companies
Fused silica	Silica glass, SiO_2
HDPE	High density polyethylene
LDPE	Low density polyethylene
Macor	Machinable glass ceramic (code 9658), Corning
Nylon	Polyamide
Parylene N	Poly para-xylene, Union Carbide
PE	Polyethylene
PETP	Polyethylene tetephthalate; Mylar (US), Melinex (UK)
PMMA	Polymethyl methacrylate: Perspex (US), Plexiglas (UK), Lucite

Material	Comments
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
Quartz:O E	Ordinary ray Extraordinary ray
Rexolite	Cross linked polystyrene
Sapphire	Al_2O_3
Fused silica	QU - For ultraviolet; QV - For visible; QI - For infrared
Spectrosil	Fused silica: Thermal American Fused Quartz Co; WF: Water-free
TPX	A poly 4-methyl 1-pentene
Teflon	Treated PTFE
YAG	Yttrium Aluminium Garnet

Table VIII: Metallic Reflector Conductivities

Material	f (GHz)	T (K)	σ_{eff} (10^7 S m^{-1})	Ref.
Aluminium	9	300	1.7	[71]
Aluminium, pure	24	300	1.97	[72]
Aluminium, pure	0	300	3.25	[72]
Aluminium 6061-T6, polished	260	300	1.2	[73]
Aluminium on glass[20]	260	300	1.7-2.3	[73]
Aluminium on CFRP[(20)]	260	300	0.3-1.6	[73]
Aluminium, bulk	377	300	1.6	[74]
Aluminium, film	377	300	2.7-4.6	[74]
Aluminium, pure	790	200	3.0	[75]
Aluminium, Alloy A5052	790	200	2.0	[75]
Bismuth, 500 nm on aluminium	260	300	0.37	[73]
Brass, free machining	0	300	1.48	[72]
Brass, free machining	24	300	1.11	[72]
Brass, yellow (80-20)	0	300	1.57	[72]
Brass, yellow (80-20)	24	300	1.45	[72]
Brass	260	300	0.96	[73]
Copper[21]	337	300	7.8	[12]
Copper	35	300	4.5	[12]
Copper, electroformed	0	300	5.92	[72]
Copper, electroformed	24	300	3.15	[72]
Copper, plate	24	300	2.28-1.81	[72]
Copper, plate	0	300	5.92	[72]

[20] Variation over several samples

[21] Measured relative to an Al plate.

Material	f (GHz)	T (K)	σ_{eff} (10^7 S m^{-1})	Ref.
Copper, bulk	337	300	1.8-4.6	[74]
Gold, 0.5 μm on quartz(21)	337	300	2.06	[12]
Gold, evaporated	890	300	0.83	[76]
Gold, plate	24	300	1.87	[72]
Gold on glass	260	300	2.5	[73]
Phosphor-bronze	790	200	1.0	[75]
Gold, plate	0	300	4.10	[72]
Gold, film	337	300	1.3-2.7	[74]
Molybdenum	337	300	0.8-1.3	[74]
Silver; coin, drawn	24	300	2.92	[72]
Silver; coin, drawn	0	300	4.79	[72]
Silver; Fine, machined	24	300	2.92	[72]
Silver; Fine, machined	0	300	6.14	[72]
Silver; Plate	24	300	3.98-2.05	[72]
Silver; Plate	0	300	6.14	[72]
Stainless Steel, 304(21)	337	300	0.09	[12]
Stainless Steel	890	200	0.17	[75]
Tantalum(21)	337	300	0.58	[12]

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