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MISCELLANEOUS DATA ON MATERIALS FOR MILLIMETRE AND SUBMILLIMETRE OPTICS

James W. Lamb

*Institut de Radio Astronomie Millimétrique
300, Rue de la Piscine, Domaine Universitaire de Grenoble
F-38406 St-Martin-D'Hères Cedex, France*

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, submillimeterwaves, 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, submillimetre, 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, $\tan\delta$, which are commonly used by microwave engineers. The complex dielectric constant is

$$\hat{\epsilon} = \epsilon' - i\epsilon'' \quad (1)$$

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

$$\tan\delta = \epsilon''/\epsilon' \quad (2)$$

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

$$\hat{n} = n - ik \quad (3)$$

with

$$\alpha = 4\pi\nu k/c \quad (4)$$

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

$$\epsilon' = n^2 - k^2 \quad \epsilon'' = 2nk \quad (5)$$

or, for low loss materials,

$$\epsilon' = n^2 \quad \tan\delta = 2k/n = \alpha c/2\pi n \nu \quad (6)$$

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 ($1 \text{ Np} = 4.343 \text{ dB}$), 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]

$$\rho \propto \frac{\epsilon - 1}{\epsilon + 2} \quad (7)$$

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

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

(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

$$f_L = \frac{R_s}{30\pi} \quad (9)$$

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 SiO₂ materials is confusing as the names silica and quartz are both used. There are perhaps differences in naturally and synthetically produced SiO₂ 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 definitive 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

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

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

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.

Acknowledgements

I wish to thank the many people have contributed information in this compilation. In particular, I wish to mention Paul Goldsmith who made available a table due to be published in a quasi-optics text, and also Nigel Keen who supplied a number of references.

Table I: Low-Loss Dielectric Materials

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	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) (Tokuyama Soda)	146	300	2.81-2.88	7.90-8.29	6-38	[16]
	140	300	2.883	8.312	6.0	
Alumina: (WESGO)	100	300	3.0983	9.599	6.0	[4],[17]
	250		3.0975	9.595	11.5	
	400		3.0980	9.598	16.0	
Alumina: (COORS)	100	300	3.1451	9.892	14.5	[4],[17]
	250		3.1440	9.885	21.5	
	400		3.1451	9.892	26.0	
Alumina: (BK-99) (22XC)	140	300	3.244-3.252	10.523-10.576	2.7-3.2	[16]
	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: (Ceradyne Ceralloy 418s)	100	300	2.5842	6.6780	16	[4],[17]
	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]
Beryllia	390	300	2.5871	6.693	11.5	[20]

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
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, Pyrolytic	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]
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	

¹ Not Homogeneous

² Emerson and Cuming, Inc

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
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]
Epoxy-LMB 1386, LMB 1387, Mixed by wgt. DY 067 ⁽³⁾ Mixed by vol.	22	300	2.09	4.38	110	[10]
	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	

³ Ciba-Geigy

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
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	30-900 300	293	3.6	13.0	3200	[6]
Fluorogold: Parallel to grain " " " " Perpendicular 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	
	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]
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	

⁴ Strong dichroism

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
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: QV: QI:	150	300	1.958	3.8338	14-15	[16]
			1.953	3.8142	5.5-7.1	
			1.952	3.8103	5-5.3	
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	

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
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	
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	

⁵ Corning

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
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	
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]

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
HDPE	26-40 26-40	300 77	1.53 1.51	2.34 2.29		[39]
HDPE	300-900	4.2 20 60 120 200 295	1.567 1.566 1.565 1.560 1.549 1.525	2.455 2.452 2.449 2.434 2.399 2.326		[40],[41]
LDPE	156	300			2.7	[35]
LDPE	160 300 450 600 1000	290	1.5141 1.5141 1.5139 1.5137 1.5136	2.2923 2.2924 2.2918 2.2913 2.2911	3.1 2.8 3.9 4.5 6.8	[36]
LDPE	1875-13700	293	1.5131-1.5139	2.2894-2.2920	5.5-13	[38]
LDPE	300-900	4.2 20 60 120 200 295	1.556 1.555 1.554 1.548 1.537 1.514	2.421 2.418 2.415 2.396 2.362 2.292		[40],[41]
Macor	100 200 300	300	2.382 2.377 2.377	5.673 5.648 5.648	15.0 20.0 25.0	[4]

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	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 ₂ O 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	κ	$\tan \alpha \times 10^4$	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 manufactures optical data of 1.62 possibly due to impurities.

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	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		
PMMA	600			36		
	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	κ	$\tan \alpha \times 10^4$	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]

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
PP	1500-12000	290	1.4970-1.4983	2.241-2.245	57-110 ⁸	[49]
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]

⁸ Several absorption peaks

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
PS	300-900	4.2 20 60 120 200 295	1.620 1.619 1.617 1.616 1.603 1.591	2.624 2.621 2.615 2.611 2.570 2.531	⁹	[40],[41]
PTFE ¹⁰	22	300 77	1.40 1.40	1.96 1.96	5 3	[10]
PTFE	25	300	1.442	2.08	6	[24]
PTFE	35	300	2.058	1.73	3	[50]
PTFE	71 400 450 600 1000	300	1.45 1.41	2.10 1.99	 4 2 2	[30]
PTFE	94	300	1.4370	2.065	2.1	[21]
PTFE	100 300 900	4.8 4.8 4.8	1.44 1.44 1.44	2.07 2.07 2.07	- - -	[9]
PTFE	100 200 300	300	1.4389 1.4386 1.4385	2.0701 2.0797 2.0794	5.3 6.2 6.8	[15]

⁹ Small change in absorption with temperature

¹⁰ Dupont, Inc.

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
PTFE	140 210	300	1.432 1.442	2.05 2.08	30	[25]
PTFE	143 343	300	1.439 1.439	2.07 2.07		[44]
PTFE	150 300 450 1000	290	1.4330 1.4330 1.4330 1.4330	2.0535 2.0535 2.0535 2.0535	2.9 2.8 6.1 15	[36]
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	300 600 900 1200	300			4.4 11 20 22	[37]
PTFE, Unsintered	35	300	1.396	1.950		[51]
PTFE, Unsintered	35	300	1.397	1.952	0.5	[52]
PTFE, Unsintered	300 600 900 1200	300			<1 5 13 15	[37]
Quartz, Crystalline	245	300	2.107	4.439		[18]

¹¹ Strong absorption band above 6000 GHz

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
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]
Quartz: O	245	300	2.1059	4.4348	1.0	[19]
E			2.1533	4.6367	1.4	
Quartz: E	30-900 300	293	2.154	4.640		[6]
					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	30-900 300	293	2.106	4.435		[6]
					2	
Rexolite	10	300	1.594	2.54	5	[24]

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
Rexolite	71 400 450 600 1000	300	1.61 1.58	2.58 2.52	1 3 5	[30]
Rexolite	94	300	1.5987	2.556	2.6	[21]
Rexolite	140 210	300	1.572 1.581	2.47 2.50	20	[25]
Rexolite	143 343	300	1.562 1.594	2.44 2.54		[44]
Rexolite	390	300	1.5912	2.532	27.4	[20]
Rexolite	850	300	1.589	2.525	30	[29]
Rexolite	30-900 150 300 600 900	293	1.586-1.64	2.515-2.69	10 20 35 47	[6]

Material	f (GHz)	T (K)	n	κ	tan δ × 10 ⁴	Ref.			
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	
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				

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
Sapphire, ϵ	140	300	3.066-3.071	9.400-9.431	2.1-2.5	[16]
	140		3.400-3.405	11.560-11.594	1.1-1.4	
Sapphire:	900	300	3.069	9.419	17	[34]
	900	1.5	3.052	9.315	1.7	
	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]
Silicon	900	300	3.4155	11.666	6	[34]
	900	1.5	3.3818	11.437	1.6	
Silicon: (ICHPS RAN.) (Wacker Ch.)	150	300	3.424	11.72	0.24	[16]
			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	

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
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	
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	

Material	f (GHz)	T (K)	n	κ	$\tan \delta \cdot 10^4$	Ref.
Silicon (dLR-Si)	145	330 290 150 100 70			0.05 0.20 0.08 0.09 0.08	[55]
Silicon 1 500 μm	100 200 300 400	298	11.697 11.687 11.685 11.686	3.420 3.419 3.418 3.418	17 10 8 9	[56]
Silicon 2 000 μm	100 200 300 400	298	11.678 11.678 11.678 11.678	3.417 3.417 3.417 3.417	17 11 8 9	[56]
Silicon 11 000 μm	200 300 400	298	11.655 11.655 11.655	3.414 3.414 3.414	1 2 3	[56]
Teflon-Vergussmasse	22	300 77	1.73 1.71	3.00 2.92	190 48	[10]
TPX	35	300	1.470	2.126	4.8	[51]
TPX	94	300	1.4659	2.149	9	[21]
TPX	100 200 300	300	1.4587 1.4583 1.4581	2.1276 2.1266 2.1262	6.4 8.1 8.4	[15]
TPX	120	300			7.6	[48]
TPX	156	300			6.1	[35]
TPX	245	300	1.459	2.129		[18]

Material	f (GHz)	T (K)	n	κ	$\tan \alpha \times 10^4$	Ref.
TPX	300 450 1000	290	1.4600 1.4600 1.4600	2.1316 2.1316 2.1316	6.0 6.8 11	[36]
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 3000 5000	298	1.4563 1.4557 1.4559	2.1208 2.1191 2.1196	13 13 5	[45]
TPX	300-900	4.7 77 100 210 290	1.475 1.475 1.474 1.466 1.458	2.176 2.176 2.173 2.149 2.162		[58],[41]
TPX, Sheet.	100 300 900 100 300 900	4.8 4.8 4.8 300 300 300	1.42 1.42 1.42 1.43 1.43 1.43	2.02 2.02 2.02 2.04 2.04 2.04	11.2 11.2 11.2 - - -	[9]

¹² Several absorption bands. Strongest absorption at 12300 GHz

Material	f (GHz)	T (K)	n	κ	$\tan \delta \times 10^4$	Ref.
YAG	72	300 150 100 70 10 4			0.4 0.2 0.03 0.007 0.001 0.001	53
ZnSe	100 250 350	300	3.0158 3.0155 3.0166	9.087 9.092 9.100	19 27 28	[4]
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) 1.26 lb ft ⁻³ (20.2 kg m ⁻³) 1.33 lb ft ⁻³ (21.3 kg m ⁻³) 1.84 lb ft ⁻³ (29.5 kg m ⁻³)	200	0.0018	[60]
		230	0.0045	
		260	0.0045	
		200	0.0035	
		230	0.0055	
		260	0.0075	
		200	0.0035	
		230	0.0055	
		260	0.0075	
		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 BASF¹⁶ 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	85	22	11	[64]
	White side	85	23	5.5	
Eccosorb AN-72 ⁽¹⁷⁾	Gold side	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]
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 $(\ell_{300\text{ K}} - \ell_T)/\ell_{300\text{ K}}$

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 at Cryogenic Temperatures

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

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 ₂ O 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 terephthalate; Mylar (US), Melinex (UK)
PMMA	Polymethyl methacrylate; Perspex (US), Plexiglas (UK), Lucite
PP	Polypropylene

Material	Comments
PS	Polystyrene
PTFE	Polytetrafluoroethylene
Quartz: O E	Ordinary ray Extraordinary ray
Rexolite	Cross linked polystyrene
Sapphire	Al ₂ O 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]
Copper, bulk	337	300	1.8-4.6	[74]

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.
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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