Appendix B

Acoustic Parameters of Common Materials

Tables of fundamental parameters of selected isotropic solids, single crystals, liquids, gases, piezoelectric materials, and acousto-optic materials are given in this appendix. The data have been taken from a large number of sources. More information is available for some materials than for others, so inevitably, there are blanks in the tables where the value of a parameter could not be found by the author.

A large number of parameters for isotropic solids, liquids, and gases have been tabulated recently by Selfridge [1]. In Tables B.1, B.2, and B.3 we give values for selected materials taken from Selfridge's work, supplementing his data from other sources [2–7].

Table B.4 tabulates the parameters of a number of common piezoelectric ceramics. Most of these data are taken from an article by Berlincourt et al. [8]. It has also been supplemented with data on Japanese piezoelectric ceramics, kindly supplied to the author by Fukumoto of the Matsushita Company [9].

Recently, Selfridge has kindly supplied the author with data on his measurements of certain new piezoelectric ceramics [10]. Some of the more important experimental data for these ceramics, together with data for certain piezoelectric single-crystal materials and one plastic piezoelectric material, polyvinylidene fluoride (PVF_2), are given in Table B.5.

Figure B.1 illustrates the parameters used in Tables B.4 and B.5.

Data on selected acousto-optic materials is given in Tables B.6 and B.7. These data are taken from the work of Dixon [11], the *CRC Handbook of Lasers* [12], and from tables given by Yariv [13].

TABLE B.1 BULK MATERIAL CONSTANTS FOR SELECTED SOLIDS

All materials are isotropic or polycrystalline unless otherwise noted. The notation is that used in Chapters 1, 2, and 3.

Material	V_l (km/s)	V_s (km/s)	ρ_{m0} (kg/m^3 × 10^3)	Z_l (kg/m^2-s × 10^6)	Z_s (kg/m^2-s × 10^6)	σ	α (dB/cm or $A = \alpha/f^2$ neper-s^2/m × 10^{-15})
Aluminum	6.42	3.04	2.70	17.33	8.21	0.355	A = 0.86
Araldite 506/956	2.62		1.16	3.55			
Bakelite	1.59		1.40	3.63			
Beryllium	12.89		1.87	24.10	16.60	0.046	
Bismuth	2.20	1.10	9.80	21.5	10.75	0.33	
Boroncarbide	11.0		2.40	26.40			
Brass, yellow, 70%Cu, 30%Zn	4.70	2.10	8.64	40.6	18.14	0.38	
Butyl rubber	1.80		1.11	2.0			
Cadmium	2.80	1.50	8.60	24.0			
Carbon,							
Pyrolitic, variable properties	3.3		2.2	7.3			
Vitreous	4.26	2.68	1.47	6.26	3.82	0.17	
Chromium	6.65	4.03	7.0	46.6	28.21	0.21	
Copper, rolled	5.01	2.27	8.93	44.6	20.2	0.37	
Epoxy							
DER332, MPDA 15 parts per hundred by weight of resin, 60°C cure	2.68	1.15	1.21	3.25	1.39	0.37	6.7 at 2 MHz
Silver	1.9	0.98	2.71	5.14	2.65	0.32	16 at 2 MHz
Fused quartz	5.96	3.76	2.20	13.1	8.26	0.17	A = 0.13
Glass							
Corning sheet	5.66		2.49	14.1			
Crown	5.1	2.8	2.24	11.4	6.26	0.28	
Schott FK3	4.91	2.85	2.26	11.1	6.44	0.245	
Pyrex	5.64	3.28	2.24	13.1	7.62	0.24	
Gold, hard drawn	3.24	1.20	19.7	63.8	23.6	0.42	A = 2.3
Granite	6.5		4.1	26.8			
Hydrogen, solid at 4.2°K	2.19		.089	0.19			
Inconel	5.7	3.0	8.28	47.2	24.8	0.31	

TABLE B.1 (Continued)

Material	V_l (km/s)	V_s (km/s)	ρ_{m0} (kg/m^3 × 10^3)	Z_l (kg/m^2-s × 10^6)	Z_s (kg/m^2-s × 10^6)	σ	α (dB/cm or $A = \alpha/f^2$ neper-s^2/m × 10^{-15})
Indium	2.56		7.3	18.7			
Iron	5.9	3.2	7.69	46.4	25.2	0.29	
Lead 2.2	0.7	11.2	24.6	17.2	0.44		
Lithium niobate $LiNbO_3$, crystal-type trigonal 3m, propagation along Z axis	7.33		4.70	34.0			A = 0.0047
Lucite or Plexiglas	2.7	1.1	1.15	3.1	1.26	0.40	3.2 at 5 MHz
Magnesium, drawn annealed	5.77	3.05	10.0	5.3	1.74	0.32	
Molybdenum	6.3	3.4	10.0	63.1	34.1	0.29	
Monel	5.4	2.7	8.82	47.6	23.8	0.33	
Mylar	2.54		1.18	3.0			A = 92
Nickel	5.6	3.0	8.84	49.5	26.5	0.30	
Niobium	4.92	2.10	8.57	42.2	18.0	0.39	
Nylon	2.6	1.1	1.12	2.9	1.23	0.39	2.9 at 5 MHz
Paraffin wax	1.5		1.5	2.3			
Platinum	3.26	1.73	21.4	69.8	37.0	0.32	
Polyethylene, low density	1.95	0.54	0.92	1.79	0.50	0.487	
Polypropylene	2.74		0.88	2.40			5.1 at 5 MHz
Polystyrene	2.40	1.15	1.05	2.52	1.21	0.35	1.8 at 5 MHz
Porcelain	5.9		2.3	13.5			
PVC, gray rod stock	2.38		1.38	3.27			11.2 at 5 MHz
Quartz, SiO_2							
Propagation along Z axis	6.32		2.53	16.7			
Propagation along BZ axis		5.00	2.53			13.4	
RTV rubber							
RTV-11	1.05		1.18	1.24			2.5 at 0.8 MHz
RTV-577	1.08		1.35	1.46			3.8 at 0.8 MHz
Rubidium	1.26		1.53	1.93			
Rutile, TiO_2, crystal-type tetragonal 4/mmm, propagation along Z axis	7.90		4.26	33.6			

TABLE B.1 (continued)

Material	V_l (km/s)	V_s (km/s)	ρ_{m0} (kg/m^3 × 10^3)	Z_l (kg/m^2-s × 10^6)	Z_s (kg/m^2-s × 10^6)	σ	α (dB/cm or $A = \alpha/f^2$ neper-s^2/m × 10^{-15})
Sapphire, Al_2O_3, crystal-type trigonal 3m, propagation along Z axis	11.1	6.04	3.99	44.3	25.2	long. wave	$A = 0.0021$
Scotchtape	1.9		1.16	2.08			
Silicon nitride ceramic	11.0	6.25	3.27	36.0	20.5	0.26	
Silicone rubber (Sylgard 182)	1.027		1.05	1.07			
Silly putty	1.0		1.0	1.0			Very lossy
Silver	3.6	1.6	10.6	38.0	16.9	0.38	
Steel, mild	5.9	3.2	7.90	46.0	24.9	0.29	
Stycast 1267	2.57		1.16	3.00			4.6 at 3 MHz
Tantalum	4.10	2.90	16.6	54.8	38.8		
Teflon	1.39		2.14	2.97			3.9 at 5 MHz
Thorium	2.40	1.56	11.3	33.2	21.6	0.134	
Tin	3.3	1.7	7.3	24.2	12.5	0.31	
Titanium	6.1	3.1	4.48	27.3	13.9	0.32	
Tungsten	5.2	2.9	19.4	101.0	56.3	0.27	
Uranium	3.4	2.0	18.5	63.0	37.1	0.24	
Vanadium	6.0	2.78	6.03	36.2	16.8	0.36	
Vinyl, rigid	2.23		1.33	2.96			12.8 at 5 MHz
YAG[4], $Y_3Al_{15}O_{12}$, crystal-type cubic m3m, propagation along [001] direction	8.43		4.55	38.34			$A = 0.0034$
Zinc	4.2	2.4	7.0	29.6	16.9	0.26	
Zirconium	4.65	2.25	6.48	30.1	14.6	0.35	

TABLE B.2 MATERIAL CONSTANTS FOR LIQUIDS

The notation is that used in Chapters 1, 2, and 3. The parameter M is a quality factor of importance for microscopy [4]. It is defined by the relation $M = [V(H_2O)/V]\{[\alpha/f^2(H_2O)]/[\alpha/f^2]\}^{1/2}$, where the parameters for water correspond to a temperature of 30°C.

Material	V (km/s)	dV/dT (m/s-°C)	ρ_{m0} (10^3 kg/m^3)	Z (10^6 kg/m^2-s)	$A = \alpha/f^2$ (nepers-s^2/m × 10^{-15})	M
Acetone, CH_3OH at 25°C	1.174	−4.5	0.791	1.07	54	0.77
Alcohol C_2H_5OH at 25°C	1.207	−4.0	0.79	0.95	48.5	0.84
Alcohol, methanol CH_3OH at 25°C	1.103	−3.2	0.791	0.872	30.2	1.10
Argon, liquid at 87°K	0.840		1.43	1.20	15.2	2.01
Benzene C_6H_6 at 25°C	1.295	−4.65	0.87	1.12	873	
Fluorinert FC-40	0.640		1.86	1.19		
Gallium at 30°C	2.87		6.09	17.5	1.58	1.82
Glycol, ethylene at 25°C	1.658	−2.1	1.113	1.845	120	
Helium-4,						
Liquid at 0.4°K	0.238		0.147	0.035	1.73	
Liquid at 2°K	0.227		0.145	0.033	77	
Liquid at 4.2°K	0.183		0.126	0.023	226	
Honey, Sue Bee Orange	2.03		1.42	2.89		
Hydrogen, liquid at 20°K	1.19		0.07	0.08	5.6	2.34
Mercury at 23°C	1.45		13.53	19.6	5.8	1.89
Nitrogen, liquid at 77°K	0.860		0.85	0.68	120	2.2
Oil						
Castor, at 20.2°C	1.507	−3.6	0.942	1.420	10100	
Silicone Dow 710 at 20°C	1.352		1.11	1.50	8200	
Oxygen, liquid at 90°K	0.900		1.14	1.0	9.9	2.5
Sea water at 25°C	1.531	2.4	1.025	1.569		
Sonotrack couplant, Echo	1.62		1.04	1.68		
Water						
Liquid at 20°C	1.48		1.00	1.483		
Liquid at 25°C	1.497	2.4	1.00	1.494	22	0.94
Liquid at 30°C	1.509		1.00	1.509	19.1	1.00
Liquid at 60°C	1.55		1.00	1.55	10.2	1.29
Xenon, liquid at 166°K	0.630		2.86	1.80	22.0	

The reader is referred to Selfridge [1] for further information on solids, liquids, and gases. Auld [14] gives extensive tables of the parameters for crystalline solids, and the CRC handbook [12] has extensive tables on the parameters for acousto-optic diffraction. Some of the other references used in this appendix also give information on materials not tabulated here.

TABLE B.3 ACOUSTIC CONSTANTS FOR GASES

The notation is that used in Chapters 1, 2, and 3. The parameter M is a quality factor of importance for microscopy. It is defined by the relation $M = [V(H_2O)/V]\{[\alpha/f^2(H_2O)]/[\alpha/f_2]\}^{1/2}$, where the parameters for water are for a temperature of 30°C.

Material	V (m/s)	ρ_{m0} (kg/m³)	Z (× 10² kg/m²-s)	$\alpha = A/f^2$ (nepers - s²/m × 10⁻¹³)	M
Air, dry					
At 0°C	331	1.293	4.29		
At 20°C	344	1.24	4.27	190	
At 100°C	386	1.11	4.27		
At 500°C	553	0.77	4.28		
Ammonia, NH_3 at 0°C	415	0.771	3.20		
Argon					
At 0°C	319	1.78	5.67		
At 20°C, 40 bar	323	≈70.4	≈227	4.12	1.03
At 20°C, 250 bar	323	≈440	≈1437	0.83	2.28
Carbon dioxide, CO_2					
at 0°C	259	1.977	5.12		
Carbon monoxide, CO					
at 0°C	338	1.25	4.22		
Nitrogen, N_2 at 0°C	334		1.251		
Oxygen, O_2					
At 0°C	316	1.429	4.51		
At 20°C	328		1.32		
Xenon at 20°C, 40 bar	178			9.53	1.23

TABLE B.4 PROPERTIES OF COMMONLY USED PIEZOELECTRIC CERAMICS

The parameters and elastic boundary conditions appropriate to this table are illustrated in Fig. B.1. Most of the elastic and piezoelectric parameters are defined in Sec. 1.5. The attenuation per unit length α of the material can be stated in terms of its Q as follows: $\alpha = \pi f/VQ$, where f is the frequency and V the acoustic velocity.

Some additional parameters not defined in Sec. 1.5 or the additional tables and diagrams are:

Q_M The mechanical Q of the material.

Q_E The electrical Q of the material.

N_1 Frequency constant of a thin resonant rod of length l. $N_1 = fl$.

N_{3t} Frequency constant of a resonant plate of thickness l. $N_{3t} = fl$.

The parameters given below are small signal values taken at 25°C.

Material	s_{33}^E	s_{11}^E	Q_M	s_{44}^E	s_{66}^E	s_{33}^D	s_{11}^D	s_{44}^D	c_{33}^E	c_{11}^E	c_{33}^D	c_{11}^D	N_1	N_{3t}	V_l^D	V_s^D	Density (10^3 kg/m^3)
	pm^2/N								10^{10} N/m^2				Hz-m		m/s		
PZT-4[a]	15.5	12.3	500	39.0	32.7	7.90	10.9	19.3	11.5	13.9	15.9	14.5	1650	2000	4600	2630	7.5
PZT-5A[a]	18.8	16.4	75	47.5	44.3	9.46	14.4	25.2	11.1	12.1	14.7	12.6	1400	1890	4350	2260	7.75
PZT-6H[a]	20.7	16.5	65	43.5	42.6	8.99	14.1	23.7	11.7	12.6	15.7	13.0	1420	2000	4560	2375	7.5
PZT-6A[a]	13.0	10.7	450	—	27.8	9.2	10.1	—	13.1	—	15.5	—	1770	2140	4570	—	7.45
PZT-6B[a]	9.35	9.0	1300	28.2	24.0	8.05	8.8	24.2	16.3	16.8	17.7	16.9	1920	2225	4820	2340	7.55
PZT-7A[a]	13.9	10.7	600	39.5	27.8	7.85	9.7	21.8	13.1	14.8	17.5	15.7	1750	2100	4800	2490	7.6
PZT-8[a]	13.5	11.5	1000	31.9	29.8	8.0	10.4	22.6	12.3	13.7	16.1	14.0	1700	2070	4580	2420	7.6
PZT-2[a]	14.8	11.6	680	45.0	29.9	9.0	10.7	22.9	11.3	13.5	14.8	13.6	1680	2090	4410	2400	7.6
$BaTiO_3$[a]	9.5	9.1	600	22.8	23.6	7.1	8.7	17.5	14.6	15.0	17.1	15.0	2200	2520	5470	3160	5.7
$PbTiO_3$	8.0					6.3			13.2		16.8						
95 w% $BaTiO_3$, 5 w% $CaTiO_3$	9.1	8.6	400	22.2	22.4	7.0	8.3	17.1	15.0	15.8	17.7		2290	2740	5640	3240	5.55
NRE-4[b]	—	8.1	—	—	—	—	—	—	—	—	—		2310	2760	—	—	5.7
$PbNb_2O_6$	25.4	—	11	—	—	21.8	—	—	—	—	—		—	—	—	—	6.0
$Pb_{0.6}Ba_{0.4}Nb_2O_6$[c]	—	11.5	250	—	—	—	10.9	—	—	—	—		1915	—	—	—	5.9
$Na_{0.5}K_{0.5}NbO_3$	10.1	8.2	240	27.0	—	6.4	7.6	15.8	16.8	—	21.4	—	2570	—	6940	3760	4.46
PCMUS-1[d]	12.9					8.5			13.1		15.3						
PCMUS-2[d]	14.5					7.6			11.8		16.0						
PCM-5A[d]	17.6					8.7			11.6		14.9						
PCM-33[d]	19.3					8.7			11.5		15.5						

	k'_{z3}	k_p	k_{z1}	k_{z3}	k_{x5}	k_T	$\varepsilon^T_{zz}/\varepsilon_0$	Q_E	$\varepsilon^S_{zz}/\varepsilon_0$	$\varepsilon^T_{xx}/\varepsilon_0$	$\varepsilon^S_{xx}/\varepsilon_0$
PZT-4[a]		−0.58	−0.33	0.70	0.71	0.51	1300	250	635	1475	730
PZT-5A[a]	0.66	−0.60	−0.34	0.705	0.685	0.49	1700	50	830	1730	916
PZT-5H[a]	0.70	−0.65	−0.39	0.75	0.675	0.505	3400	50	1470	3130	1700
PZT-6A[a]		−0.42	−0.25	0.54	—	0.39	1050	50	730	—	—
PZT-6B[a]		−0.25	−0.145	0.375	0.377	0.30	460	110	386	475	407
PZT-7A[a]	0.62	−0.51	−0.30	0.66	0.67	0.50	425	60	235	840	460
PZT-8[a]		−0.51	−0.30	0.64	0.55	0.48	1000	250	580	1290	900
PZT-2[a]		−0.47	−0.28	0.63	0.70	0.51	450	200	260	990	504
$BaTiO_3$[a]	0.47	−0.36	−0.21	0.50	0.48	0.38	1700	100	1260	1450	1115
$PbTiO_3$	0.46			.46		.46					
95 w% $BaTiO_3$, 5 w% $CaTiO_3$		−0.33	−0.19	0.48	0.48	0.38	1200	170	910	1300	1000
NRE-4[b]		−0.31	−0.18	0.46	0.46	0.36	1420	200	1110	—	—
$PbNb_2O_6$		−0.07	−0.045	0.38	—	0.37	225	100	190	—	—
$Pb_{0.6}Ba_{0.4}Nb_2O_6$[c]		−0.38	−0.22	0.55	—	—	1500	100	—	—	—
$Na_{0.5}K_{0.5}NbO_3$		−0.46	−0.27	0.605	0.645	0.46	496	70	306	938	545
PCMUS-1[d]	0.66					0.54	785		484		
PCMUS-2[d]	0.64					0.55	734		369		
PCM-5A[d]	0.66					0.50	1710		784		
PCM-33[d]	0.69					0.50	3530		1518		

	d_{z3}	d_{z1}	d_{x5}	g_{z3}	g_{z1}	g_{x5}	e_{z3}	e_{z1}	e_{x5}
Material	10^{-12} C/N			10^{-3} V-m/N			C/m²		
PZT-4[a]	289	−123	496	25.1	−10.7	38.0	15.1	−5.2	12.7
PZT-5A[a]	374	−171	584	24.9	−11.4	38.0	15.8	−5.4	12.3
PZT-5H[a]	593	−274	741	1907	−9.1	26.8	23.3	−6.5	17.0
PZT-6A[a]	189	−80	—	20.4	−8.6	—	12.5	—	—
PZT-6B[a]	71	−27	130	1704	−6.6	31.0	7.1	−0.9	4.6
PZT-7A[a]	150	−60	362	3908	−15.9	48.8	9.5	−201	9.2
PZT-8[a]	225	−97	330	2504	−10.9	29.0	13.2	−4.0	10.4
PZT-2[a]	152	−60	440	3802	−15.1	50.1	9.0	−109	9.8
$BaTiO_3$[a]	190	−78	260	1206	−5.2	20.2	17.5	−4.3	11.4
95 w% $BaTiO_3$, 5 w% $CaTiO_3$	149	−58	242	14.0	−5.45	21.0	13.5	−3.1	10.9
NRE-4[b]	150	−59	—	1109	−4.7	—	—	—	—

TABLE B.4 (Continued)

Material	d_{z3}	d_{z1}	d_{x5}	g_{z3}	g_{z1}	g_{x5}	e_{z3}	e_{z1}	e_{x5}
	10^{-12} C/N			10^{-3} V-m/N			C/m^2		
$PbNb_2O_6$	85	~ −9	—	4205	~ −4.5	—	—	—	—
$Pb_{0.6}Ba_{0.4}Nb_2O_6$[c]	220	−90	—	1606	−6.8	—	—	—	—
$Na_{0.5}K_{0.5}NbO_3$	127	−51	306	29.0	−11.6	36.9	9.8	—	11.3
PCMUS-1[d]	176	−88							
PCMUS-2[d]	211	−93							
PCM-5A[d]	367	−186							
PCM-33[d]	575	−262							

[a]Trademark, Vernitron Piezoelectric Division.

[b]95 w% $BaTiO_3$, 5 w% $CaTiO_3$, plus 0.75 w% $CoCO_3$.

[c]General Electric Company.

[d]Trademark, Matsushita Electric Industrial Co. Ltd.

TABLE B.5 PROPERTIES OF SELECTED TRANSDUCER MATERIALS

The parameters in this table are defined in Fig. B.1 and in Chapters 1 and 2. The mechanical Q of the material is Q_M. The attenuation is $\alpha = \pi\omega/QV$. The Curie temperature of the material is T_C.

A. Longitudinal Waves

Material	V_l^D (10^3 m/s)	Z_l^D (10^6 kg/ms)	Q_M	$\varepsilon^S/\varepsilon_0$	ρ_{m0} (10^3 kg/m^3)	k_T	k_p	tan δ	T_C (°C)
Aluminum nitride AIN thin film, hexagonal 6 mm, Z cut	10.4	34.0		8.5	3.27	0.17			
Cadmium sulfide CdS single crystal and thin film, hexagonal 6 mm, Z cut	4.46	36.0		9.5	5.68	0.15			
Lithium niobate $LiNbO_3$ single crystal, trigonal 3m, 36° Y cut	7.36	34.2		39.0	4.64	0.49		0.001	1150
Keramos K83 modified lead metaniobate	5.95	25.6	110	150	4.3	0.41			570
Murata P3 barium titanate	5.75	31.3	100	885	5.45	0.42		0.003	110
Murate P5 zirconate titanate	4.33	31.6	80	847	7.30	0.36		0.011	260
Murata P6 zirconate titanate	4.78	35.1	70	883	7.34	0.47		0.014	290
Murata P7 zirconate titanate	4.68	36.0	65	1000	7.69	0.51		0.019	320
Murata "surface wave material"	4.71	37.4	1000	240	7.95	0.48	0.25	0.0014	280
Pennwalt kynar polyvinylidene fluoride (PVF_2) plastic film	2.2	3.92	19	12	1.78	0.11		0.015 at 10^4 Hz	
$e_{z3} = -108 \times 10^{-3}$, $e_{z1} = 69 \times 10^{-3}$, $e_{z2} = 9 \times 10^{-3}$, $k_T = 0.11$, $k_{z1} = 0.072$, $k_{z2} = 9.4 \times 10^{-3}$									
$Q \sim$ constant to 1 GHz									
Quartz, SiO_2 single crystal, trigonal 32, X cut	5.00	13.3		4.5	2.65	0.093			
Zinc oxide, ZnO single crystral and thin film, hexagonal 6mm, Z cut	6.33	36.0		8.8	5.68	0.28			

TABLE B.5 (Continued)

B. Shear Waves

Material	V_D^S (10^3 m/s)	Z_D^S (10^6 kg/m²-s)	$\varepsilon^S/\varepsilon_0$	k_T
Cadmium sulfide, X cut	1.76	8.5	9.0	0.19
Lithium niobate, 163°				
Y cut	4.44	20.6	58.1	0.55
X cut	4.80	22.6	44.0	0.68
Murata "surface wave material"	2.78	22.1	360	0.50
Quartz, X cut	3.80	10.1	4.5	0.14
Zinc oxide, X cut	2.72	15.5	8.3	0.32

COUPLING COEFFICIENT	ELASTIC BOUNDARY CONDITIONS
(a) $k_T^2 = \dfrac{e_{z3}^2}{\epsilon_{zz} c_{33}^D}$	$T_1 = T_2 \neq 0 \quad T_3 \neq 0$ $S_1 = 0 \quad S_2 = 0 \quad S_3 \neq 0$
(b) $k_{33}'^2 = \dfrac{e_{z3}'^2}{\epsilon'_{zz} c_{33}'^D}$	$T_1 = 0 \quad T_2 = 0 \quad T_3 \neq 0$ $S_1 \neq 0 \quad S_2 = 0 \quad S_3 \neq 0$
(c) $k_{31}'''^2 = \dfrac{X}{\text{TAN } X} \quad X = \dfrac{\pi}{2}\sqrt{\dfrac{c_{11}^E}{c_{11}^D}}$	$T_1 \neq 0 \quad T_2 \neq 0 \quad T_3 \neq 0$ $S_1 \neq 0 \quad S_2 = 0 \quad S_3 = 0$
(d) $k_{31}^2 = \dfrac{d_{z1}}{s_{11}^E \epsilon_{zz}^T}$	$T_1 \neq 0 \quad T_2 = 0 \quad T_3 = 0$ $S_1 \neq 0 \quad S_2 \neq 0 \quad S_3 \neq 0$
(e) $k_{33}^2 = \dfrac{d_{z3}}{s_{11}^E \epsilon_{zz}^T}$	$T_i = 0 \quad T_2 = 0 \quad T_3 \neq 0$ $S_1 = S_2 \neq 0 \quad S_3 \neq 0$
(f) $k_p^2 = \dfrac{2k_{31}^2}{\left(1 + \dfrac{s_{12}}{s_{11}}\right)}$	$T_1 = T_2 \neq 0 \quad T_3 = 0$ $S_1 = S_2 \neq 0 \quad S_3 \neq 0$
(g) $k_{x5}^2 = \dfrac{e_{x5}^2}{c_{44}^D \epsilon_{zz}^S}$	$T_1 = T_2 = T_3 = T_4 = T_6 = 0$ $S_1 = S_2 = S_3 = S_4 = S_6 = 0$ $T_5 \neq 0 \quad S_5 \neq 0$

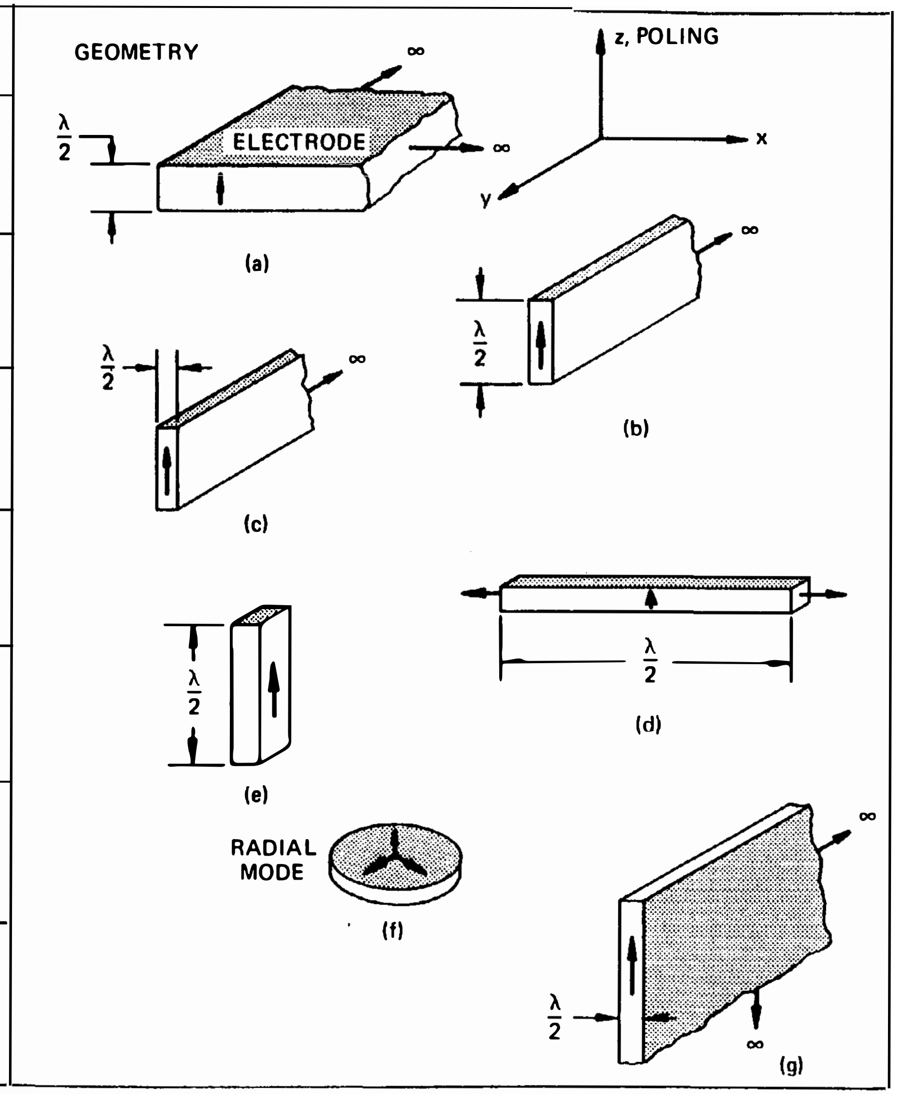

Figure B.1 Parameters used for defining piezoelectric ceramics in Tables B.4 and B.5.

TABLE B.6 PROPERTIES OF SOME COMMON ACOUSTO-OPTIC MATERIALS

The parameters used are defined in Sec. 4.9. The acousto-optic figure of merit $M = p^2 n_0^6/\rho_{m0} V_a^3$ is defined in Eq. (4.9.26) [11]. Other related figures of merit are often used in the literature [11, 12]. The parameters used in this table are given by Yariv [13].

Material	ρ_{m0} (10^3 kg/m^3)	V_a (10^3 m/s)	n_0	p	$M/M(H_2O)$
Water	1.0	1.5	1.33	0.31	1.0
Extra-dense flint glass	6.3	3.1	1.92	0.25	0.12
Fused quartz (SiO_2)	2.2	5.97	1.46	0.20	0.006
Polystyrene	1.06	2.35	1.59	0.31	0.8
KRS-5	7.4	2.11	2.60	0.21	1.6
Lithium niobate ($LiNbO_3$)	4.7	7.40	2.25	0.15	0.012
Lithium fluoride (LiF)	2.6	6.00	1.39	0.13	0.001
Rutile (TiO_2)	4.26	10.30	2.60	0.05	0.001
Sapphire (Al_2O_3)	4.0	11.00	1.76	0.17	0.001
Lead molybdate ($PbMO_4$)	6.95	3.75	2.30	0.28	0.22
Alpha iodic acid (HIO_3)	4.63	2.44	1.90	0.41	0.5
Tellurium dioxide (TeO_2) (slow shear wave)	5.99	0.617	2.35	0.09	5.0

TABLE B.7 MATERIAL CONSTANTS OF SOME COMMON ACOUSTO-OPTIC MATERIALS

The parameters in this table are those used in Sec. 4.9. The parameter $M = p^2 n_0^6/\rho_{m0} V_a^3$ is the acousto-optic figure of merit [11, 12]. The parameters used in this table are taken from Yariv [13].

Material	Optical wavelength (λ-μm)	n_0	ρ_{m0} (10^3 kg/m^3)	Acoustic wave polarization and direction	V_a (10^3 m/s)	Optical wave polarization and direction	M (10^{-15} s^3/kg)
Fused quartz	0.63	1.46	2.2	Long.	5.95	⊥	1.51
				Trans.	3.76	‖ or ⊥	0.467
GaP	0.63	3.31	4.13	Long. in [110]	6.32	‖	44.6
				Trans. in [100]	4.13	‖ or ⊥ in [010]	24.1
GaAs	1.15	3.37	5.34	Long. in [110]	5.15	‖	104
				Trans. in [100]	3.32	‖ or ⊥ in [010]	46.3
TiO_2	0.63	2.58	4.6	Long. in [11–20]	7.86	⊥ in [001]	3.93
$LiNbO_3$	0.63	2.20	4.7	Long. in [11–20]	6.57	[a]	6.99
YAG	0.63	1.83	4.2	Long. in [100]	8.53	‖	0.012
				Long. in [110]	8.60	⊥	0.073
YIG	1.15	2.22	5.17	Long. in [100]	7.21	⊥	0.33
$LiTaO_3$	0.63	2.18	7.45	Long. in [001]	6.19	‖	1.37
As_2S_3	0.63	2.61	3.20	Long.	2.6	⊥	433
	1.15	2.46		Long.		‖	347
SF-4	0.63	1.616	3.59	Long.	3.63	⊥	4.51
β-ZnS	0.63	2.35	4.10	Long. in [110]	5.51	‖ in [001]	3.41
				Trans. in [110]	2.165	‖ or ⊥ in [001]	0.57
α-Al_2O_3	0.63	1.76	4.0	Long. in [001]	11.15	‖ in [11–20]	0.34
CdS	0.63	2.44	4.82	Long. in [11–20]	4.17	‖	12.1
ADP	0.63	1.58	1.803	Long. in [100]	6.15	‖ in [010]	2.78
				Trans. in [100]	1.83	‖ or ⊥ in [001]	6.43

TABLE B.7 Continued

Material	Optical wavelength (λ-μm)	n_0	ρ_{mo} (10^3 kg/m^3)	Acoustic wave polarization and direction	V_a (10^3 m/s)	Optical wave polarization and direction	M (10^{-15} s^3/kg)
KDP	0.63	1.51	2.34	Long. in [100]	5.50	∥ in [010]	1.91
				Trans. in [100]		∥ or ⊥ in [001]	3.83
H_2O	0.63	1.33	1.0	Long.	1.5		160
Te	10.6	4.8	6.24	Long. in [11–20]	2.2	∥ in [0001]	4400
$PbMoO_4$	0.63	2.4		Long. ∥ c axis	3.75	∥ or ⊥	73

[a]The optical-beam direction actually differs from that indicated by the magnitude of the Bragg angle. The polarization is defined as parallel or perpendicular to the scattering plane formed by the acoustic and optical k vectors.

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