.~:... ~ Ultrasonic transducers for Sillllultaneous generation *pf* longitudinal and shear waves

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Dolh longiludinal and shear waves can be generaled simultaneollsly and efiicienlly using 10° rolated Y-eullithiumniobale disks and lilted C-axis zinc oxide thin fihm. Uy properly varying Ihe operatiug frequencies, Ihe ratio belween longitudinal and shear excitation strenglh can be adjusted.

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INTRODUCTION

Ultrasonic transducers arc llorl1 1L1Ily used 10 generate eilher longitudinal or shear waves in a medium. In order to oblain a high electromechanical coupling cfiiciency of Ihe desired modes, and 10 reduce spurious signals, Ihe crystal orientation ofpiezoeleclric I ransducer malerials, such as single crystal lithium niobate (LiNbO.,) or thin film zinc oxide (ZnO), musl be carefully selected. H II is well known that, along each sllch orientation. one longil udinal (pure or quasi) and two shear (pure or quasi) Il10des may be excited. Neglecting parameters such as the temperature eocfficients and nonlinear eO'ects of the piezoeleclric ultrasonic transducers. a few general criteria may be considered in the select ion of longit udinal and shear wave transducers, as outlined in Table l.

Ultrasonic material eharaeterizalion llnen requires the measurement of both longiludinal and shear wave velocities. In such cases, ultrasonic tr<l nsducers thai can gem~rale both of lhe above-mentioned waves would be of great use. Transducers that can genera Ie bolh longiludinal and shear waves are preferred. For example, in a previous study of fiber acoustic waveguides/,.7 it has been shown lhat both shear (FII) and longitudinal (Lm) modes can bc guided in weakly guiding acoustic fibers. Since small shear or longitudinal transducers must be bonded and aligncd to t he tiny.fiber ends (with a 500-/lm diameter in general) 10 excite shear or longitudinal waves, it is very inconvenient 10 change from onc t ransdllccr type to t hc ot her. The si 111 II It aneous generation orJongitlidilial and shear wavcs using a single Illtrasonic Iransducer Iherdorc has nlll1lerous advalilages. In this artick. Ihe design and experimentailise of Iwo sllch 'ullrasonic I r:lnsdueers, OJIC rabricaled from a 10. rotated Y - ell I LiNbO, single crystal and the olher from a I (1" I illed C-axis ZnO I hin film, will be given.

I. LITHIUM NIOBATE DISK ULTRASONIC TRANSDUCERS

Several LiNbO-, crystal oriental ions are used commercially for bulk ultrasonic longit udinal or shear wave transducers. For comparison purposcs, a few importanl ullrasoniC properties thai werc calculatcd using thc com pulcr programs in Ref. 5 arc listed in Table II for live different crystal orienlations, wherc *V*, *K* ,and *0"* refer to the velocity, electromechanical coupling cocfficicnt, and power flow angle, respectively. Also in the table, *U"* *U2*, LInd *U*-, (dcfined in Ref. 5) represenlthc dircction cosines of thc particle displaccment componcnts along the cut and two orthogonally Iransverse directions, respcctively.

.Iudgingby thc values for five different cryslal orientations listed in Table II, il can be concluded Ihal both 36°rolaled V-cut and Z-cul LiNbO-, crystals can be utilized as longitudinal wave transdllcers. Since the former has a much larger *K* factor, even though *0"* is slightly higher and the longitudinalmodc is less pure, it is used more onenthanthc laller in pract ice. For shear wavc excitalions both 163° rotated Y -cut and X-cui LiNbO, can be chosen, However, becalise of its zcro-power now angle and higher *K* for SI shear waves, the X-cul LiNbO, is produced commercially on a larger scale. Each of (he abovc four cuts is employed for eilhcr longitudinal or shcar wavc cxcit:1lions solely.

Our ohjective W:IS (0 find a particular cryslal cui that can excite bOll1longitlldinal and shcar waves cflicicntly. The selection crileri;l werc those lisled in Tablc 1, cxceptlhat *K* should be equal and high for the longitudinal wave and one oflhe shear waves, bllt very low for the second shear \yavc. Using Ihc compuler programs dcveloped in Ref. 5, and trying many piezoeleclric materials, it was concludcd that the *Z Y* plane of LiNbO, is onc of I he bcst choices. I n this particlilal' plane. I here is no piezoelect rical coupling 10 Iho S2 shcar wave whose polari;r.alion is parallel 10 thc erysl<Jlline X axis. Since lhe longitlldinal *(L)* and I he shear wavc (SI) veloc

TABLE I. Transducer selection crilcri;1.

(I) Iligh cleclmll1 (,ehallic,,1 cOllplillg eolsl,,"1 (f..:) for lhe desired llIOde hu,low (or *Lern)* for lhe olher lwo!\lotles.

(2) SM<lII powu now angle devialioll fro!\I I he desired prop<lgalion direc lioll.

(.1) Close 10 <I l'" re !\lode.

TABLE II. Ultrasonic properties of $LiNbO_3$ with five different crystal orientations.

Cut	Mode	V(m/s)	K	Q_p	U_1	U_2	U_3
36°	L	7340	0.485	4.7	0.998	0.065	0.000
rotated	S_1	4001	0.004	1.1	0.065	0.998	0.000
Y-cut	S_2	4084	0.000	3.2	0.000	0.000	1.000
	L	7316	0.162	0.0	1.000	0.000	0.000
Z-Cut	S_1	3573	0.000	8.5	0.000	0.924	0.382
	S_2	3573	0.000	8.5	0.000	0.382	0.924
163°	L	6707	0.002	2.3	0.999	0.029	0.000
rotated	S_1	4528	0.612	4.9	0.029	0.999	0.000
Y-cut	S_2	3823	0.000	9.6	0.000	0.000	1.000
	L	6572	0.000	0.0	1.000	0.000	0.000
X-cut	S_1	4795	0.684	0.0	0.000	0.754	0.656
	S_2	4079	0.098	0.0	0.000	0.656	0.754
10°	L	7063	0.427	10.0	0.991	0.137	0.000
rotated	S_1	4271	0.436	13.9	0.137	0.991	0.000
Y-cut	S_2	4064	0.000	4.3	0.000	0.000	1.000

ities are different, in order to excite both longitudinal and shear waves simultaneously and efficiently, a crystal orientation is to be selected. It should be noted that the polarization of the longitudinal and S_1 shear waves is parallel to the cut direction, and perpendicular to both L and S_2 polarizations respectively.

It is well known that if the top and bottom surfaces of a piezoelectric ultrasonic transducer are parallel and well polished, not only will the fundamental mode be excited, but also the higher-order odd harmonics. The longitudinal (f_l and shear wave (f_s) resonance frequencies are given as nf_L=$nV_l/d2$ and mf_s=$mV_s/2d$, where d is the thickness, and n and m are odd and positive integers. In order to excite both waves at the same frequency, nf_L must be equal to mf_s. The choice of the possible combination of the lowest n and m for $LiNbO_3$ is n = 3 and m = 5. Therefore, the ratio of V_L/V_S should preferably be close to 5/3 (1.667).

Figures 1 and 2 illustrate the electromechanical coupling constants *(K)* and velocities *(V)* as a function of direction in the ZY plane of $LiNbO_3$. A careful examination of these two figures determines that the 10° rotated Y-cut (whose properties are listed in Table II) meets the selection criteria reasonably well: The *K* factors are high (0.43) and approximately equal for thé longitudinal *(L)* and the shear waves *(S_1)*. Furthermore, both waves are close to pure modes, V_L/V_S is equal to 1.654, and the 0p's are only slightly higher than required. It is noted that piezoelectric disk transducers having a higher *Op* value perform better with a thinner disk thickness (i.e., a higher operating frequency) and larger electrodes.

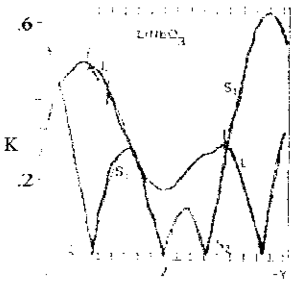

FIG. 1. Electromechanical coupling constants (K) along the ZY plane of $LiNbO_3$. Each increment of the abscissa is 10°.

FIG. 2. Bulk longitudinal and shear wave velocities along the ZY plane of LiNbO3. Each increment of the abscissa is 10°.

Ultrasonic transducers having this particular cut and different thicknesses were obtained from Valpey Fisher Corp., Hopkinton, MA. A disk thickness 0.118 mm (chosen arbitrarily) provides a fundamental 28-MHz resonance frequency, approximately, for the longitudinal *(f_l)* wave and 17 MHz for the shear *(f_s)* wave. The diameter of the coaxial type top electrode is 2 mm. Figure 3 shows the results of the reflection measurement using an HP 8754A network analyzer. The third harmonics of f_L coincide with the fifth harmonics of f_s, agreeing very well with the desired design. In this particular case, the transducer is bonded to the center of a fused silica block whose dimension is 10 X 25 X 25 mm. The coupling medium is a few micrometers thick phenyl salicylate layer. The pulse echoes measured using a MATEC (plug-in model 760) at frequencies 17, 28, and 84 MHz are given in Fig. 4(a)-(c), respectively. Based upon the material properties of fused quartz, it can be concluded that the echo trains shown in Fig. 4(a)-(c) are the shear, longitudinal, and both shear and longitudinal waves, respectively. Some small spurious signals appear in Fig. 4(b) but not in Fig. 4(a) and (c). In Fig. 4(c), the amplitude of the shear wave echoes are smaller than those of longitudinal waves due to the higher attenuation of the phenyl salicylate thin coupling layer for shear waves at the frequency employed. Figure 4 clearly indicates that this particular transducer made of 10° rotated Y-cut $LiNbO_3$ can generate longitudinal, shear, or both waves simultaneously by simple alteration of the operating frequency. It is noted that the same type of transducers, with different thicknesses (1.177 and 0.353 mm), perform similarly in the lower frequency range, and that their behavior also agrees well with theoretical expectations.

II. THIN ZINC OXIDE FILM ULTRASONIC TRANSDUCERS

For high-frequency ultrasonic applications, thin piezoelectric film transducers such as zinc oxide (ZnO) are the

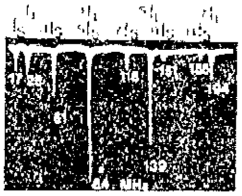

FIG. 3. Reflection measurement using an HP 8754A network analyzer for a 10° rotated Y-cut $LiNbO_3$ disk transducer.

FIG. 4. Pulse-echo trains at operating frequencies of: (a) 17 MHz, (b) 28 MHz, and (c) 84 MHz for a 10° rotated Y-cut $LiNbO_3$ disk transducers.

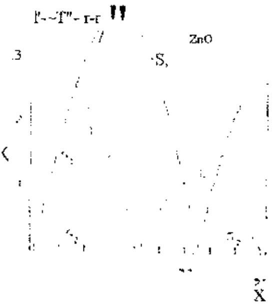

FIG. 5. Electromechanical coupling constants (K) along the ZX plane of ZnO. Each increment of the abscissa is 10°.

obvious choice. It is well known that ZnO thin film with C axis (crystalline Z axis) and 41° tilted C-axis crystalline orientations can excite longitudinal and shear waves, respectively.[4,5] Here, "tilted C-axis" means that the crystalline C axis of the ZnO film deviates from the direction normal to the substrate surface on which the thin ZnO film is grown. Figure 5 shows the variation of *K* as a function of direction in the ZX plane of ZnO. In this plane, there is no piezoelectric coupling to the S2 shear waves that are polarized parallel to the crystalline Y axis. Figure 5 also indicates that, at along a C axis tilted at approximately 16°, the K 's for the longitudinal *(L)* and the shear (S_1) waves are about equal to 0.25. At a 16° tilted angle, both modes are close to pure modes; however, the power flow angle (O_p) is somewhat high. For comparison purposes, the ultrasonic properties of ZnO thin films with their C axis tilted at 0°, 41°, and 16° are listed in Table III.

Figure 6 shows a ZnO thin film with 16° tilted C-axis crystalline orientations. This film (approximately 6 um thick) is sandwiched between two 200-nm-thick gold electrodes, all grown on a 3-mm-thick fused quartz substrate by reactive dc magnetron sputtering.[8] Because of the large attenuation and for reasons of electronic generator and receiver performance at high frequencies, experiments with higher-order harmonics were not performed. Figure 7(a)–(c) gives the experimental pulse echoes measured at 510, 450, and 350 MHz, respectively. They clearly indicate that, by varying the operating frequency, the ratio of the excitation strength between the longitudinal and shear waves can be adjusted. Experiments were also performed with a 6O° tilted C-axis ZnO thin film, and similar results to those in Fig. 7(a)-(c) were obtained. For this tilt angle, K^2 is smaller

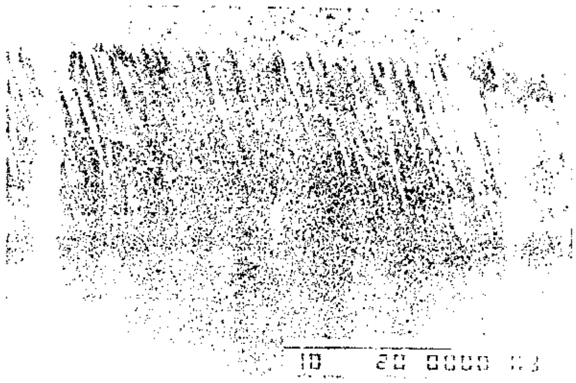

FIG. 6. Crystalline orientation of a 16° tilted C-axis ZnO thin film.

TABLE III. Ultrasonic properties of ZnO thin film with three different tilted C-axis angles.

Angle	Mode	V(m/s)	*K*	O_p	U_1	U_2	U_3
	L	6371	0.290	0.0	1.000	0.000	0.000
0°	*S1*	2733	0.000	0.0	0.000	0.710	0.705
	S2	2733	0.000	0.0	0.000	0.705	0.710
	L	5940	0.020	1.6	-0.999	0.017	0.000
41°	*S1*	3229	0.337	0.4	-0.017	-0.999	0.000
	S2	2764	0.000	1.5	0.000	0.000	1.000
	L	6247	0.248	5.8	-0.998	0.069	0.000
16°	*S1*	2921	0.250	19.5	-0.069	-0.998	0.000
	S2	2738	0.000	0.8	0.000	0.000	1.000

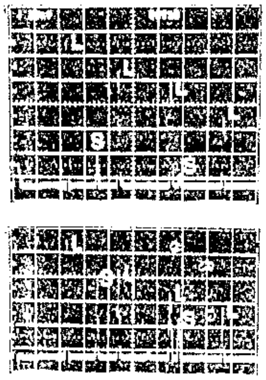

FIG. 7. Pulse-echo trains at operating frequencies of: (a) 510 MHz, (b) 450 MHz, and (c) 350 MHz for a transducer made from a 16° tilted C-axis ZnO thin film.

(0.1) as well as the power flow angles (2.9° for the L mode), 13.5° for the S_1 mode).

III.

CONCLUSIONS

Piezoelectric ultrasonic transducers can be used to generate both longitudinal and shear waves simultaneously and efficiently (high K). By properly varying the operating frequency, the ratio between the longitudinal and shear excitation can be varied. The experimental use of such transducers, made from 10° rotated Y-cut $LiNbO_3$, disk crystals and tilted C-axis ZnO thin films, was demonstrated.

ACKNOWLEDGMENTS

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