Appendix F

Bulk Waves

This appendix gives a brief account of the effects due to unwanted bulk-wave excitation in surface-wave devices, and of some devices that use bulk waves intentionally. It was seen in Chapter 2 that a variety of acoustic modes may propagate in a piezoelectric half-space, including several bulk waves and a variety of surface waves. For interdigital surface-wave devices the substrate material and orientaton are usually chosen such that the only surface wave that can be excited is the piezoelectric Rayleigh wave. However, some excitation of bulk waves is nearly always present. The analysis for the excitation of these waves by interdigital transducers is very complex, but for most practical purposes it is not necessary to consider this in detail; the degradation of device performance is not severe, and generally some simple design features are sufficient to ensure that adequate performance is obtained. Thus a descriptive account illustrating the main practical consequences is sufficient here, and this is given in Sections F.1 and F.2.

Some devices have made use of bulk waves deliberately, and these are described in Section F.3. This includes surface-skimming bulk wave devices, which use interdigital transducers on a substrate chosen such that there is negligible electrical coupling to surface waves. These devices can offer a higher operating frequency, or a better temperature coefficient, than surface-wave devices. We exclude here devices using parallel-plate transducers, such as the bulk wave delay line of Figure 1.1(a).

It is interesting to note that one of the earliest applications for interdigital transducers was in fact concerned with bulk waves rather than surface waves [504]. The device consisted of a block of crystalline quartz with two plane non-parallel surfaces, each bearing an interdigital transducer. The transducers were used to launch and detect bulk waves propagating in the body of the material, and gave a dispersive response owing to the fact that the acoustic path length varied with frequency. The device was proposed as a chirp filter for pulse-compression radar, but has been superseded by the surface-wave interdigital chirp filter (Chapter 9) which is easier to fabricate.

F.1. Bulk Wave Generation by Interdigital Transducers

In a surface-wave device, the general nature of the effects due to bulk-wave excitation can be understood quite readily from a simple phase-matching argument, similar to the delta-function model of Section 4.1 and to the analysis of end-fire antennas. We assume, as is usually the case, that the substrate material and orientation have been chosen such that the only surface-wave mode that can be excited is a piezoelectric Rayleigh wave; this applies, for example, if the substrate is *Y*, *Z* lithium niobate or *ST*, *X* quartz. Consider a uniform single-electrode launching transducer, illustrated in Figure F.1, and assume initially that the transducer is many periods long. To first order each electrode can be regarded as a source of bulk waves (as well as surface

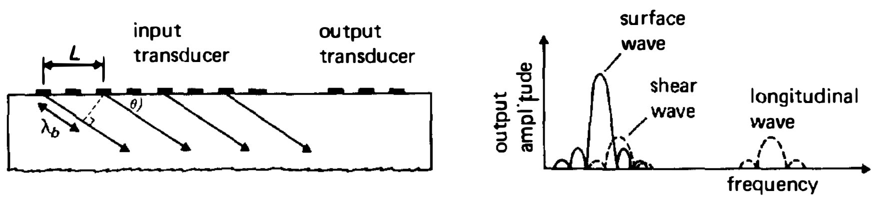

FIGURE F.1. Bulk wave generation by interdigital transducer.

waves), and the total bulk wave power will be relatively large if the waves due to individual electrodes can be added constructively. If L is the transducer period this condition is satisfied by a bulk wave travelling at an angle θ to the surface, such that the bulk-wave wavelength is $\lambda_b = L \cos \theta$, and hence

$$fL = v_b(\theta)/\cos \theta, \tag{F.1}$$

where f is the frequency and $v_b(\theta)$ is the bulk-wave velocity. Generally, $v_b(\theta)$ will vary somewhat with θ because of the substrate anisotropy, but this does not affect the argument. Equation (F.1) refers to the "fundamental" response; there will also be harmonic responses satisfying the relation $M\lambda_b = L \cos \theta$, where M is an odd integer, but for brevity these are ignored here. There will also be bulk waves generated to the left in Figure F.1.

Equation (F.1) shows that coherent bulk wave generation can only occur above a cut-off frequency $f_c = v_b(0)/L$, where $\theta = 0$ and the bulk wave travels parallel to the surface. At lower frequencies the equation has no real solution, but coherent bulk waves can be generated at *all* frequencies above f_c, with the angle θ increasing with frequency and approaching a limit of $\pi/2$ at infinite frequency. This is in contrast with surface-wave excitation, which is significant only over a narrow band if the transducer is many periods long. There will generally be several bulk waves involved, and for each of these the velocity $v_b(0)$ parallel to the surface will be greater than the surface-wave velocity v_s. The cut-off frequencies are therefore all greater than the centre-frequency of the surface-wave response, which is equal to v_s/L.

In practice the above account must be modified a little to allow for the fact that the transducer has finite length. A more detailed examination, treating the electrodes as independent sources, shows that at one frequency the bulk waves are in fact radiated over a range of angles; the polar diagram of the radiated power has a prominent main lobe whose maximum is directed at the angle θ satisfying equation (F.1), and whose width is inversely related to the transducer length. In addition there is no longer a sharp cut-off – for a long finite-length transducer there can in general be some bulk wave excitation below the "cut-off" frequency $f_c = v_b(0)/L$, though the power involved is usually very small.

The radiated bulk waves can be detected experimentally by shining a beam of light through the substrate, parallel to the surface [505–507]. In this way, Schmidt [505] has confirmed experimentally the frequency variation of θ given by equation (F.1), for the several bulk waves generated by a transducer on Y, Z lithium niobate.

In a two-transducer device, the main practical concern is that the bulk waves may cause some unwanted excitation of the output transducer. It is usual practice to roughen the rear surface of the substrate, as indicated in Figure F.1, so that bulk waves incident on it are scattered incoherently and therefore do not significantly excite the output transducer. The unwanted excitation therefore arises primarily from bulk waves travelling almost parallel to the surface, with small values of θ. Assuming that the two transducers have the same period L, it can be expected that the ouput due to a particular bulk wave will be maximised at the frequency for which the period is equal to the wavelength of bulk waves travelling parallel to the surface, that is, at the "cut-off" frequency $f_c = v_b(0)/L$. In fact, we can anticipate a response with a form similar to that of the surface-wave response, but shifted upwards in frequency owing to the higher velocity of the bulk wave. This is indicated on the right in Figure F.1, using broken lines to show responses due to a shear wave and a longitudinal wave, and a continuous line for the surface-wave response. The total response can be taken as the vectorial sum of these three. Note that the shear-wave response is maximised at a frequency quite close to the surface-wave centre frequency because the shear wave velocity is only a little higher than the surface-wave velocity. Thus the shear-wave response generally interferes with the surface-wave response, particularly at frequencies above the centre frequency. On the other hand, the longitudinal-wave velocity is typically twice the surface-wave velocity, giving a response centred at a much higher frequency. This is usually of little consequence because it is easily suppressed by external filtering, though it can interfere with the surface-wave response in very wide band devices.

Practical devices generally show behaviour consistent with the above description, except that the bulk-wave responses are rather distorted in comparison with the surface-wave response. The distortion arises because the bulk waves are not guided by the surface, and because the surface boundary conditions both inside and outside the transducers can considerably perturb the waves; in addition, there are generally two shear-wave components, overlapping in frequency because their velocities are similar. Some experimental results for Y, Z lithium niobate are given by Daniel and Emtage [508] and by Milsom *et al.* [93], showing that the longitudinal-wave response is typically 30 dB below the surface-wave response. The shear wave response, which overlaps the surface-wave response, is difficult to distinguish but appears to be at a similar level. In practice the rejection of the longitudinal-wave response is often rather better than this because the transducers are tuned, thus introducing some external frequency selectivity. The bulk wave contributions can usually be distinguished by applying absorbing material between the transducers, since this attenuates the surface waves much more than the bulk waves.

Another consequence of bulk-wave excitation is a distortion in the parallel conductance $G_a(\omega)$ of a transducer, since $G_a(\omega)$ is proportional to the total acoustic power generated. In addition to the surface-wave contribution, given by the analysis of Chapter 4, the conductance includes bulk-wave contributions extending over a wide frequency band, but mainly confined to frequencies above the surface-wave centre frequency [93, 508]. This affects the device frequency response via the circuit effect, though the consequent distortion is usually small. The presence of bulk-wave radiation in the surface-wave passband also implies an increase in the device insertion loss, but this is not usually significant unless the number of electrodes in the transducer is small. For example, for a transducer with $N_p = 5$ periods on Y, Z lithium niobate, the proportion of the total acoustic power generated in the form of bulk waves is 11%, at the surface-wave centre frequency [93]. For $N_p = 2$, the proportion of bulk wave power is about 25%.

Analysis of Bulk-Wave Effects. While the main features of bulk wave excitation are readily deduced from phase-matching arguments, as discussed above, it is necessary to resort to detailed analysis if quantitative results are required. The transducer analysis given in Chapter 4 neglects bulk waves because it is derived from the approximate Green's function of equation (3.48) in which the bulk-wave contribution $G_b(x_1, \omega)$ was neglected. However, Appendix B gives a reciprocity relation, equation (B.10), which is valid when bulk waves are excited.

Milsom *et al.* [92, 93] have given a well-developed analysis, based on the Green's function discussed in Section 3.4 with the bulk-wave term included. The Green's function is derived from the effective permittivity $\varepsilon_s(\beta)$ and therefore accounts for all of the acoustic modes that can be excited, including for example Bleustein–Gulyaev waves and leaky surface waves when appropriate. Further discussion is given in Section 3.3. The analysis allows for electrode interactions and for almost arbitrary transducer geometries. Apodisation can be allowed for by channelising the transducer, as in Section 4.7.2. This method is found to give results agreeing well with experiment, though its complexity makes it rather inconvenient to use.

Several other approaches have been developed, making simplifying approximations. In particular, it is usually assumed that electrode interactions are weak so that the waves generated by a launching transducer can be obtained from the electrostatic charge density, as was done for the surface-wave case in the quasi-static analysis of Section 4.3.1. Wagers [509] has considered transducers on a parallel-sided plate, and has obtained impressive agreement between the experimental and theoretical insertion losses of a two-transducer device. However, for most devices the rear surface is roughened and an analysis assuming propagation in a half-space [93, 510–513] is more appropriate. Some analysis for the generated fields of surface and bulk waves, derived from first principles, is given by Yashiro and Goto [510] and Lee [511]. Danicki [512] has introduced a useful approximation for the effective permittivity $\varepsilon_s(\beta)$ to simplify the analysis of bulk wave excitation, in a manner analogous to Ingebrigtsen's approximation for surface-wave excitation (Section 3.3), and this approach was developed further by Josse and Lee [513]. These methods are found to agree very well with experimental measurements of transducer admittances [511–513], even when substantial bulk wave excitation occurs, and they also predict well the measured responses of two-transducer devices [511, 513]. They have been applied in particular to excitation of surface-skimming bulk waves, described in Section F.3 below.

Reduction of Bulk-Wave Effects. Assuming that the rear surface of the substrate is roughened, bulk wave effects are not usually very consequential unless an exacting specification is to be met. The main exception to this occurs for Y, Z lithium niobate substrates, and for this case it is quite common to suppress bulk-wave effects by incorporating a multi-strip coupler, as in Section 5.3. Alternatively, it is sometimes possible to select a material and orientation giving relatively weak bulk-wave coupling, for example the 128°-rotated cut of lithium niobate mentioned in Section 6.5. Some criteria for selecting suitable orientations are discussed by Mitchell and Read [514] and by Milsom *et al.* [515]. It has also been shown that a metal pad on the surface can be beneficial: the pad reduces the surface-wave velocity but generally has little effect on bulk waves, and this feature can be exploited in a two-track device to partially cancel the bulk-wave excitation of the output transducers [516].

F.2. Mode Conversion in Arrays

In Section F.1 we have seen that unwanted bulk waves can be generated by the transducers of a surface-wave device. In some devices, bulk waves can also be generated by an array on the surface converting some of the surface-wave power into the form of bulk waves. This phenomenon can occur for arrays of either metal electrodes or grooves, and can seriously degrade the performance of a surface-wave chirp filter. As before, the main consequences can be appreciated from a simple phase-matching argument.

As shown in Figure F.2(a), we consider a surface wave incident on an array of identical electrodes, with uniform pitch p. The array may represent a transducer or a multi-strip coupler. Assuming that each electrode causes little perturbation of the surface wave, it is readily seen that coherent radiation of a bulk wave at an angle θ to the surface can occur if $fp(v_b(\theta) + v_s \cos\theta) = nv_s v_b(\theta)$, where v_s is the surface-

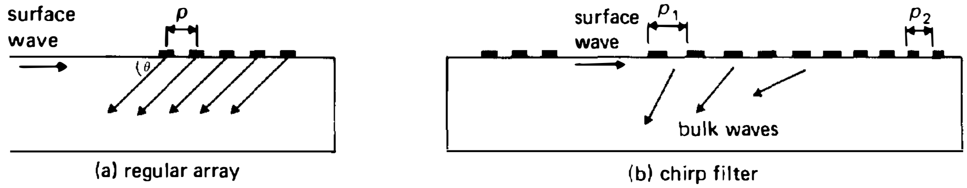

FIGURE F.2. Mode conversion in arrays.

wave velocity and n is an integer. Thus, coherent bulk waves can be produced only at frequencies above a cut-off point f_c for which $\theta = 0$ and $n = 1$, so that

$$pf_c[1 + v_s/v_b(0)] = v_s. \tag{F.2}$$

This equation applies for each of the three bulk waves; to avoid coherent radiation of bulk waves the frequency must be less than the cut-off for slow shear waves, since this is the lowest of the three cut-off frequencies. The same relationships apply if the array consists of grooves rather than electrodes.

Experimental work [517, 518] has shown that quite efficient conversion of surface waves to bulk waves, or vice-versa, can be obtained by using grooves above the cut-off frequency. Conversion coefficients of 1 or 2 dB can be obtained. Some quantitative analysis for the bulk wave excitation is given by Auld [32] and by Haus [519], assuming an isotropic material for simplicity.

In a multi-strip coupler, the first stop-band occurs at the frequency $f = v_s/(2p)$ where p is equal to half the surface-wave wavelength. The cut-off frequency for bulk shear wave generation is a little higher than this, because the shear-wave velocity is a little higher than v_s. Thus, coherent bulk-wave generation cannot occur for a coupler operated below the stop-band frequency, as is usually the case. A periodic array can also be used as a 180° reflector, as in the surface-wave resonator (Section 10.5). In this case the shear-wave cut-off point is a little above the centre frequency $f = v_s/(2p)$, and coherent bulk-wave excitation is of no consequence because the device bandwidth is small. In grooved resonators it has been found that the Q-factor can be reduced by *non-coherent* bulk-wave excitation, but this effect can be reduced substantially by grading the depths of the grooves nearest to the centre of the device [519].

Serious consequences can arise in wide-band chirp filters, as illustrated in Figure F.2(b). Here we consider an up-chirp interdigital device with a short uniform input transducer and a chirp output transducer, taking the latter to be the single-electrode type. If p_1 and p_2 are the electrode pitches at the two ends of the chirp transducer, the surface-wave band extends approximately from $f_1 = v_s/(2p_1)$ to $f_2 = v_s/(2p_2)$. From equation (F.2), coherent bulk-wave excitation can occur in this band if

$$\frac{f_2}{f_1} > \frac{2}{1 + v_s/v_b(0)}. \tag{F.3}$$

The main practical consequence of this is that the surface wave is attenuated. Since the surface wave is detected in a region beyond the region where bulk waves are generated, a corresponding attenuation is seen in the high-frequency part of the device frequency response. To avoid this condition, phase-matching considerations imply that f_2/f_1 should not exceed the right side of equation (F.3), but in practice it is found that significant attenuation occurs only for fractional bandwidths exceeding about 25%. The attenuation can be eliminated by using more than two electrodes per period, or by using the slanted geometry (Section 9.4). The problem does not occur in down-chirp devices, because for this case the bulk wave excitation occurs beyond the point at which the surface waves are detected, so that the attenuation does not significantly affect the device response. The same phenomenon can occur in an up-chirp in-line RAC (Section 9.6.3), which uses arrays of grooves parallel to the wavefronts. This is clearly shown by the frequency response of a device with 33% bandwidth [323].

For a conventional RAC, with angled grooves, the situation is more complicated. The phase-matching conditions for angled reflectors have been studied by Marshall and Paige [520] and by Islam *et al.* [521]. It is found that loss due to bulk wave excitation can be significant in up-chirp grooved RAC's [521]. Measurements using angled metal strips as reflectors on Y, Z lithium niobate showed strong surface-wave attenuation caused by coherent generation of a pseudo-surface wave [520].

F.3. Bulk Wave Devices

In the previous sections we considered the deleterious effects of bulk waves in surface-wave devices. Here we consider devices in which bulk waves are used as the primary acoustic mode, and surface-wave excitation is minimised.

Surface-Skimming Bulk Wave Devices. In the devices considered here, introduced by Lewis [522, 523], interdigital transducers are used to generate bulk waves deliberately. The device structure is essentially the same as that of a surface-wave device, with two interdigital transducers on a plane surface; the bulk wave travels close to the surface between the transducers, and is therefore called a "surface-skimming bulk wave", or SSBW. The configuration is as in Figure F.1 except that the angle θ is small. For practical devices, the substrate material and orientation are chosen such that there is no electrically-coupled surface-wave mode, so that no surface wave is excited. It is also necessary that the bulk wave should not be significantly disturbed by the boundary conditions at the surface. We have seen in Section 2.2.3 that, for an isotropic material, a shear-horizontal bulk wave propagating parallel to the surface is not affected by the surface boundary conditions. A similar solution can sometimes be found for anisotropic piezoelectric materials, and it is found that some orientations give this solution and also give no electrical coupling to surface waves, and are thus suitable for SSBW devices. For example, there are several suitable orientations of quartz [523].

SSBW devices have many features in common with surface-wave devices, including in particular the considerable flexibility obtainable by apodising the transducers. With a suitable choice of substrate the velocity can be 60% higher than that of surface waves, giving the advantage of a higher operating frequency for a given electrode periodicity. Alternatively, for other orientations a very good temperature stability can be obtained, much better than the stability for surface waves on ST, X quartz (Section 6.4). In addition, the SSBW is found to be less affected by surface contamination. Consequently, these waves are particularly suitable for oscillators and for narrow-band bandpass filters. However, the design of these devices is complicated by the fact that the bulk wave is not guided along the surface: thus, the wave diffracts into the bulk of the material, and the disturbance at the surface decays with distance. At large distances a wave generated at $x = 0$ can be expected to have an amplitude proportional to $x^{-1/2}$, as deduced from power conservation [523]. For a device using a short uniform transducer and a long apodised transducer, this attenuation is readily compensated by modifying the apodisation [524]. In practice, the form of the attenuation may be modified by the presence of an additional acoustic mode [513].

Experimental results are given in, for example, references [523–527]. Good temperature stability can be obtained by using -51° rotated Y-cut quartz, with propagation normal to the X-axis; this gives a delay constant within about ± 20 parts per million for a 0 to 100°C temperature range [523, 525]. For high-frequency devices a suitable substrate is $+36^\circ$ rotated Y-cut quartz, again with propagation normal to the X-axis. This gives a velocity of about 5100 m/sec [523], and has been used in delay lines for oscillators with frequencies up to 3.4 GHz [526]. Experimental bandpass filters using several substrate materials and orientations are described by Yen *et al.* [525].

Bloch *et al.* [527] have considered SSBW's in rotated Y-cut lithium niobate for application in television bandpass filters, centred at about 40 MHz. It was shown experimentally that the insensitivity to surface contamination implies that the device may be potted in an inert material instead of the usual hermetic encapsulation, thus reducing the cost. The same feature also implies that reflections from the ends of the substrate can be troublesome, since a lossy material on the surface is not an effective absorber. However, it was shown that the effects of reflections could be suppressed by angling the ends of the substrate, giving a device response almost as good as a surface-wave device.

Other Bulk-Wave Devices. Quite recently, Lewis [528] has introduced another interdigital bulk-wave device, shown in Figure F.3. Here the input transducer generates a bulk wave radiating at an angle to the upper surface. The wave is reflected at the lower surface, which must be flat and parallel to the upper surface, and thus reaches the output transducer. There may be several reflections at the lower surface, and Figure F.3 illustrates the case of two reflections. As in SSBW devices it is usual to choose the substrate material such that no surface-wave excitation occurs, and rotated Y-cut orientations of quartz are found to be suitable.

The main attraction of this device is that, for a given transducer periodicity, it enables the operating frequency to be much higher than that of a surface-wave device. This follows directly from equation (F.1), since $\cos\theta$ is less than unity here. Experimental devices [528] have given responses at up to six times the frequencies given by surface-wave devices, showing that for present-day lithography there is the possibility of operating up to about 10 GHz, well beyond the capabilities of surface-wave or SSBW devices. At present the device is insufficiently developed to enable firm conclusions to be drawn on its practicability. However, it has been found

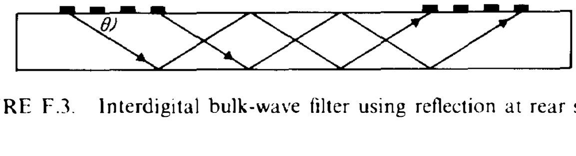

FIGURE F.3. Interdigital bulk-wave filter using reflection at rear surface.

that the frequency response can be predicted quite well [529]. The response is very different from that of a surface-wave device using similar transducers, implying that quite different design techniques are needed. It has also been shown that a temperature stability comparable with the best SSBW devices can be obtained [529].

Another proposed device using bulk waves exploits the coupling of surface waves to bulk waves in a periodic array of grooves [518]. As already noted in Section F.2, this process can be very efficient. Using a parallel-sided plate of lithium niobate, the transmission of surface waves through a groove array on one surface was found to exhibit a series of sharp minima due to coupling to the bulk modes of the plate, for frequencies such that the surface-wave wavelength is approximately equal to the groove pitch (about half the resonance frequency of a surface-wave resonator). It was also shown that the bulk modes generated can be efficiently converted to another surface wave by means of a second groove array, located either on the second surface or on the same surface as the first array. This use of two arrays gives a frequency response with a series of sharp peaks. These methods are therefore potentially applicable to narrow-band bandpass or band-stop filtering.