Chapter 1

Introductory Survey

This book is concerned with a variety of surface acoustic wave devices and their applications in electronic systems. In subsequent chapters a number of theoretical topics are developed and are then, starting at Chapter 7, applied to the analysis of practical devices. However, in view of the breadth of the subject it is helpful to first survey the entire field briefly, thus clarifying the objectives of the later analysis. The survey, given in this chapter, also serves to introduce some of the terminology. Acoustic waves are described briefly, followed by a discussion of some bulk acoustic wave devices used in electronics. Some principles used in surface acoustic wave devices are then given, followed by an account of the devices most commonly found in electronic systems. Finally, the fabrication of the devices, and their applications, are discussed. The coverage given is necessarily very selective.

(a) Acoustic Waves in Solids. In a solid, an acoustic wave is a form of disturbance involving deformations of the material. Deformation occurs when the motions of individual atoms are such that the distances between them change, and this is accompanied by internal restoring forces which tend to return the material to its equilibrium state. If the deformation is time-variant, the motion of each atom is determined by these restoring forces and by inertial effects, and this can give rise to propagating wave motion with each atom oscillating about its equilibrium position. In most materials the restoring forces are proportional to the amount of deformation, provided the latter is small, and this can be assumed for most practical purposes. The material is then described as "elastic", and the waves are often called "elastic waves", though the term "acoustic waves" is used here. In an ideal elastic material, acoustic waves can propagate with no attenuation.

The simplest types of wave are the plane waves that can propagate in an infinite homogeneous medium. The deformation is harmonic in space and time, and all the atoms on a particular plane, normal to the propagation direction, have the same motion. There are two types of plane waves: longitudinal waves, in which the atoms vibrate in the propagation direction, and shear waves, in which the atoms vibrate in the plane normal to the propagation direction. These are directly analogous to the longitudinal and transverse waves that can propagate on an elastic string. The waves are non-dispersive at the frequencies of interest here, with velocities usually between 1000 and 10,000 m/s.

If the propagation medium is bounded, the boundary conditions can substantially alter the character of the waves. The case of primary interest here is the *surface acoustic wave*, whose existence was first shown by Lord Rayleigh. This type of wave can exist in a homogeneous material with a plane surface. It is guided along the surface, with its amplitude decaying exponentially with depth. The wave is strongly confined, with typically 90% of the energy propagating within one wavelength of the surface. It is non-dispersive, with a velocity of typically 3000 m/s. A bounded medium also supports many other types of acoustic waves, and the boundary conditions can substantially affect the nature of the waves. For example, in a plate with two plane parallel boundaries, a series of dispersive modes with different velocities can propagate. On the other hand, a medium with dimensions much larger than the wavelength can support waves with characteristics similar to those of waves in an infinite medium. The term *bulk waves* is often used to describe waves which are not bound to a surface.

Acoustic waves have a practical significance in many different contexts. A particular example is seismology. The motion of earthquakes involves both bulk and surface acoustic waves, and surface waves often contribute a major part of the motion because they are guided along the surface, spreading in two dimensions rather than three. The substantial seismological literature, extending back into the 19th century, established many of the important properties of acoustic waves, and has had an impact on many later developments. There are also many industrial uses of acoustic waves, in particular nondestructive testing, in which invisible defects such as cracks are detected without damaging the material.

(b) Bulk Wave Devices. Electronic applications are of prime concern here. Bulk waves have been used in several ways, taking advantage of two particular features. Firstly, acoustic velocities are very much less than electromagnetic velocities. Secondly, the attenuation can be low, though this depends on the choice of propagation medium, particularly at high frequencies. A device taking advantage of these features is the bulk-wave delay line [1, 2], which can take the form illustrated in Figure 1.1(a). This device consists of a solid propagation medium with a transducer at each end. The transducer at one end generates an acoustic wave when an oscillatory voltage is applied to it, and the transducer at the other end generates a voltage in response to the incident wave. The output voltage waveform is thus a delayed replica of the input waveform, with the delay determined by the acoustic path length and velocity. The low velocity enables large delays to be obtained compactly, typically a few microseconds for each cm of the propagation path.

For frequencies below about 50 MHz the propagation medium is usually fused quartz or glass, and the transducers are usually parallel-sided plates of a ceramic material. Sometimes the device is made more compact by using plane facets on the propagation medium to reflect the waves, thus folding the propagation path. In this

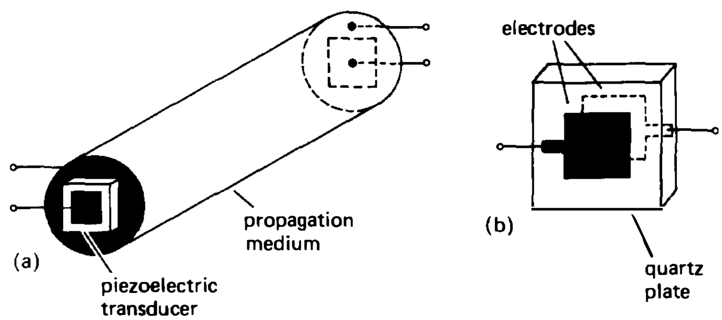

FIGURE 1.1. Devices using bulk acoustic waves. (a) delay line, (b) resonator.

way, delays up to 1 ms are achievable. Applications include radar systems requiring delay lines for moving target indication, and television receivers which require a delay corresponding to one line scan, about 60 μs. The acoustic wave can also be used to diffract a beam of light in a manner similar to a diffraction grating, and this phenomenon may be used to detect the acoustic wave and to measure its frequency.

At higher frequencies a crystalline propagation medium is used in order to obtain acceptably low attenuation. For example, at 1 GHz sapphire (Al_2O_3) gives about 0.3 dB attenuation per microsecond of delay, at room temperature. The transducers are usually plates of zinc oxide or lithium niobate. Such devices can operate at frequencies up to about 5 GHz, with delays up to about 10 μs.

The transducers in these devices make use of the piezoelectric effect [3]. This phenomenon is a property of many materials, and couples acoustic deformations of the material to electric fields. A transducer consists of a parallel-sided plate of piezoelectric material, firmly bonded on to the propagation medium. An oscillatory voltage is applied to the plate by means of electrodes (shown solid in Figure 1.1(a)), causing the plate to vibrate and thus generate acoustic waves. The piezoelectric effect is used in a wide variety of acoustic devices.

Another common acoustic device is the crystal resonator [4] shown in Figure 1.1(b). This consists of a parallel-sided plate of crystalline quartz with electrodes on both sides. If the major dimensions are much larger than the thickness, the plate resonates at a frequency such that its thickness equals half the acoustic wavelength, and at harmonics of this frequency. Quartz is piezoelectric, so the acoustic resonances can be excited electrically. In the familiar crystal-controlled oscillator the resonator is incorporated in an electrical oscillator circuit to control its frequency. The quartz resonator gives a very high Q-factor, up to 10^6, and excellent temperature stability. It is very widely used in electronic systems, particularly for communications. Frequencies up to about 50 MHz are obtainable, the limitation being that higher frequencies require thinner, more fragile, crystals.

The crystal resonator is also used in bandpass filters, designed to pass signals in some specified band of frequencies and reject signals at other frequencies. These may take the form of ladder circuits, incorporating a number of resonators coupled electrically. Alternatively, acoustic coupling may be obtained by fabricating the electrodes for several resonators on a single plate of quartz. With an appropriate spacing between the electrodes, a controlled amount of coupling is obtained by means of the evanescent acoustic fields which surround each resonator. These devices are known as "monolithic crystal filters". They are practicable up to about 50 MHz, giving bandwidths of typically a few kHz [5], and are used in telecommunications systems.

(c) Surface Wave Technology. In this book we are concerned with applications of surface acoustic waves in electronics. The use of surface waves in electronic devices was first considered in the early 1960's, and since then there has been a substantial growth of research into methods of generating and manipulating the waves, and in developing practical devices for use in a wide range of electronic applications. Some general literature on the subject is listed in Refs [6–22]. These include books, special issues of journals, and conference proceedings. A considerable amount of literature appears in the Proceedings of the annual IEEE Ultrasonics Symposium, and papers from the 1970–1977 Proceedings are published in a collected edition [14].

As for bulk waves, surface waves are attractive for electronics applications since they offer low velocity non-dispersive propagation, with low attenuation up to microwave frequencies. There is however a significant additional advantage since the propagation path, at the surface of the material, is accessible. This implies, at least in principle, a considerable degree of versatility. Because two dimensions are available rather than one, there is much more scope to exploit methods of generating and detecting the waves, or of modifying them as they propagate, and considerable structural complexity is feasible. A similar argument applies in the field of semiconductor devices, where the use of planar technology for integrated circuits has led to a remarkable growth in sophistication and complexity. In fact, the technology of integrated circuits has had a very direct bearing on the development of surface-wave devices, because of the range of fabrication techniques that it has made available. Established techniques of particular relevance include the deposition of thin films of various materials, etching of the propagation medium itself, and lithography for defining complex geometries with high precision. These techniques enable structures of considerable complexity to be made quite conveniently; moreover, in many cases they are also economically effective and suitable for large-scale production.

In the past twenty years a wide variety of techniques has been developed for use in surface-wave devices. Methods have been developed for electrically generating and detecting the waves (that is, for transduction), for reflecting, guiding, focussing and amplifying the waves, and for introducing controlled dispersion. These methods employ a variety of physical principles. As in bulk wave devices an important factor is the use of piezoelectric materials, though for surface waves the usage is somewhat different in that the propagation medium itself is piezoelectric. Some of the uses of piezoelectricity in surface-wave devices are illustrated in Figure 1.2. For a piezoelectric material, a propagating surface wave is accompanied by an electric field localised at

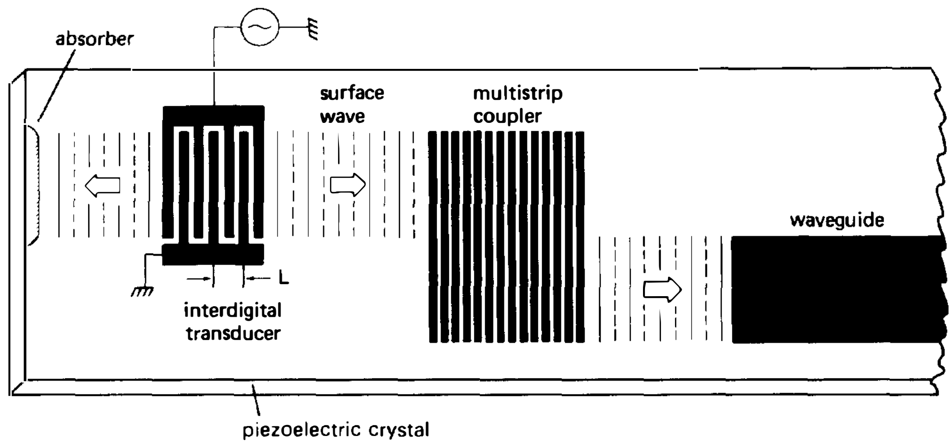

FIGURE 1.2. Metal film components using the piezoelectric effect.

the surface, and this enables the wave to be generated by applying a voltage to an array of metal electrodes on the surface. The electrode array is known as an *interdigital transducer*, and will be considered later in more detail. The transducer can also be used to detect surface waves, producing an electrical output waveform, and is used in all the devices under consideration here. In another application of piezoelectricity, a set of metal strips in the path of a surface wave can be used to generate a secondary surface wave, which may be displaced laterally with respect to the input wave (Figure 1.2), or may propagate in a different direction. This principle is used in the *multi-strip coupler*, which has a variety of forms with many different applications. An array of metal strips may also be used to reflect surface waves, and with two such arrays a resonant cavity can be formed. Another consequence of piezoelectricity is that a metal strip on the surface may be used as a *waveguide* for surface waves, enabling a narrow beam to propagate long distances without diffraction spreading. However, this method of controlling diffraction is necessary only for beam widths less than about five wavelengths, and in most practical cases larger widths are used.

In all the above examples the structure is simply a piezoelectric medium with a metal film on the surface, etched to give an appropriate geometry. Owing to the simplicity of the structure, and the availability of convenient fabrication methods, nearly all surface-wave devices use piezoelectric materials. Crystalline materials are usually chosen in order to obtain low attenuation of the waves, and the commonest choices are quartz and lithium niobate.

In addition to the direct use of piezoelectricity, there are several other principles that can be employed. Some devices make use of grooves etched in the surface of the substrate, in order to reflect surface waves, or to guide them. Dielectric films can be deposited, and can be used to introduce dispersion or to guide the wave. It is also possible to deposit a piezoelectric film, such as zinc oxide (ZnO), and then deposit metal electrodes on top. This enables an interdigital transducer to be fabricated on a non-piezoelectric substrate. Some devices make use of non-linear effects associated with the propagating surface wave. The non-linearity is weak, but in some materials, notably lithium niobate, is strong enough for useful interactions to be obtained. The prime example is the surface-wave convolver in which two surface waves are mixed, giving an output at the sum frequency; this device is used to correlate coded waveforms.

Interaction of surface waves with light has received much attention. The waves scatter light in a manner similar to a diffraction grating. This effect can be used to measure the distribution of surface waves over the surface, a procedure known as probing. Since the light is diffracted through an angle dependent on the frequency of the surface wave, the frequency can be measured. This principle may be used for electronic frequency measurement, in a device known as a Bragg cell; the electrical signal, whose frequency is required, is converted into a surface wave by an interdigital transducer.

The techniques described above have been used in a wide variety of surface-wave devices with applications in many electronic systems, notably in radar, communications and broadcasting. In many cases the function of a device is that of linear *signal processing*, that is, an electrical input waveform is applied to the device, which then produces an electrical output waveform linearly related to the input in a prescribed manner. In the terminology of systems analysis, such a device is called a linear filter. Examples are delay lines, bandpass filters and filters for correlating complex waveforms. To appreciate the operation of these devices, we first need to consider the interdigital transducer in more detail.

(d) Transducers and Delay Lines. A key feature of all the devices for electronics applications is the interdigital transducer for generating and receiving surface waves, illustrated in Figure 1.2. This transducer was first used for surface wave excitation by White and Voltmer [23] in 1965, though it is also referred to in earlier patents [24]. There are in fact many other types of transducer for surface waves [9], but these will not be considered here; most of them are not compatible with planar technology, and are not used in devices for electronics applications.

The interdigital transducer generates surface waves by exploiting the piezoelectric effect. As shown in Figure 1.2, the transducer has a set of identical electrodes connected alternately to two metal bus-bars. When an oscillatory voltage is applied, the transducer generates an electric field which is spatially periodic, with its period, L, equal to the spacing of the electrodes connected to one of the bus-bars. Owing to the piezoelectric effect, a corresponding pattern of mechanical displacements is also produced. Efficient coupling to surface waves occurs if the transducer period L is equal to or close to the surface-wave wavelength, and this requires an appropriate frequency for the applied voltage. Typically, the transducer will be designed for operation at, say, 100 MHz, where the wavelength is about 32 μm. The width of each electrode, equal to one quarter of the wavelength, is then about 8 μm. Owing to the symmetry, the transducer generates surface waves equally in two opposite directions,

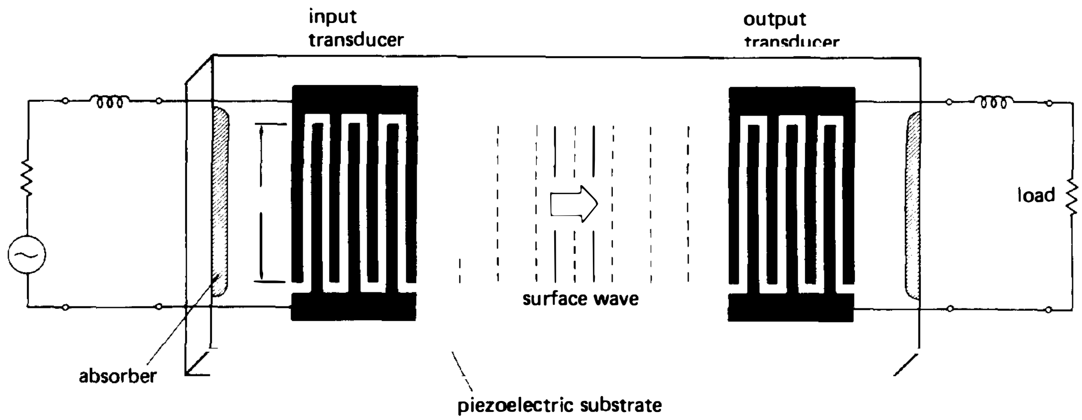

FIGURE 1.3. Interdigital delay line.

so that it is *bidirectional*. Usually, the waves in one direction are not required, and are eliminated by an absorber comprising a lossy material applied to the surface.

The simplest type of surface-wave device is a delay line employing two such transducers, one to generate the waves and one to receive them, as shown in Figure 1.3. The propagation medium, often called the *substrate*, is a piezoelectric crystal typically 1 mm thick. An electrical signal applied to the input transducer is converted to a corresponding surface wave, which causes a voltage to appear on the output transducer after a delay determined by the transducer separation and the surface wave velocity. Provided the input signal is confined to a frequency band in which the transducers are effective, there is little distortion because the wave is non-dispersive. Typical delays are from 1 to 50 μs.

Practical transducers can be quite efficient, converting most of the available electrical power into surface wave power. However, half of the power is radiated in an unwanted direction, giving a loss of 3 dB, and in a delay line with two transducers this factor contributes 6 dB to the total insertion loss. Losses due to other causes can be small. The surface wave propagates with little attenuation, and diffraction spreading can be minimised by using a sufficiently wide aperture (W in Figure 1.3), so that the output transducer is in the near field of the input transducer. For low loss one or more lumped components are usually added to match the transducer electrically to the source or load. The transducer impedance is largely capacitive, and often it is sufficient to tune it using a series inductor, as in Figure 1.3. The aperture W influences the transducer impedance and the diffraction spreading, but can often be chosen such that minimal diffraction spreading and an impedance convenient for matching are both obtained. Typical apertures are 20 to 100 wavelengths, or a few mm, and are convenient for fabrication.

With appropriate design, practical delay lines can give insertion losses of 10 dB or less. However, the devices are usually designed to give larger losses in order to reduce reflections. It is a consequence of the bidirectional nature of the transducer that, when it is well matched to an electrical source or load, it reflects incident surface waves quite strongly. This gives rise to an unwanted additional output signal known as the *triple–transit* signal, due to surface waves traversing the device three times. The triple-transit signal is often suppressed by deliberately avoiding a good electrical match to the source and load, and in consequence the insertion loss usually exceeds 15 dB. However, some more complex types of transducer are unidirectional, generating surface waves in only one direction, and these enable low losses to be obtained while still suppressing the unwanted reflections.

(e) Main Surface-Wave Devices. So far, we have considered only the simplest form of interdigital transducer. The transducer design can however be modified in a variety of ways, enabling the device to process an applied electrical signal in a prescribed manner, for example, to reject unwanted frequency components. Signal processing is one of the commonest uses of surface wave devices, and the versatility of the interdigital transducer is a crucial factor in this context. The two commonest modifications are to vary the electrode lengths and to vary the pitch. Transducers which do not use these modifications, such as the transducers in Figure 1.3, are described as *uniform*.

The technique of varying the electrode lengths is known as *apodisation* and is illustrated in Figure 1.4, which shows a device with one apodised and one uniform transducer. For convenience, it is assumed here that the uniform transducer is much shorter than the apodised transducer; for this case, the response of the device as a whole is essentially determined by the apodised transducer. The effect of apodisation can be appreciated by supposing that a short electrical pulse is applied to the uniform transducer. A short packet of surface-wave energy is produced, and this travels along the surface of the substrate, scanning the apodised transducer. At any instant, the output voltage produced by the apodised transducer depends on the amount by which its electrodes overlap at the location of the scanning surface wave packet. Thus the

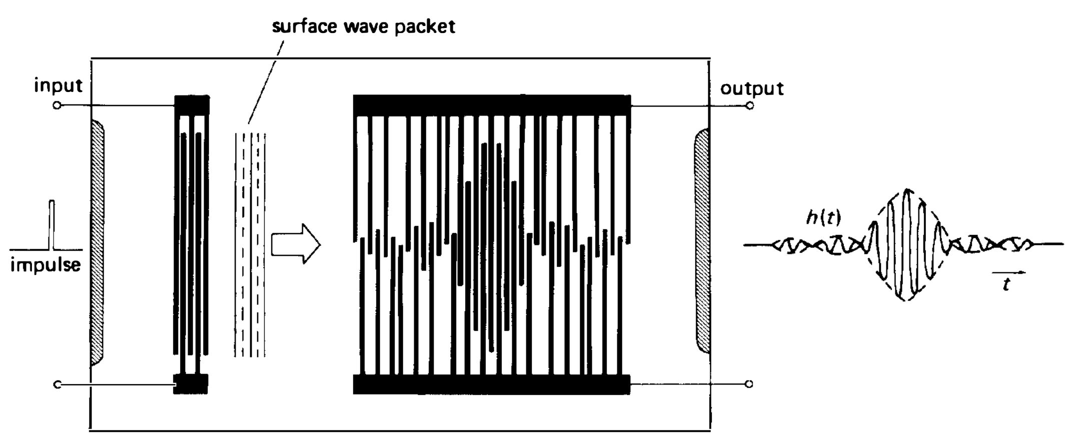

FIGURE 1.4. Bandpass filter using apodised transducer.

output waveform has an amplitude, as a function of time, directly related to the overlap of the electrodes as a function of position, with the time-scale related to the position-scale by the surface wave velocity. The output amplitude is approximately proportional to the electrode overlaps.

The output waveform produced in response to a short pulse is known as the *impulse response*, designated $h(t)$. The Fourier transform of $h(t)$ is the frequency response of the device, giving the output amplitude and phase when a c.w. signal is applied to the device, as functions of frequency. The frequency response can therefore be calculated quite straightforwardly from the electrode overlaps. More significantly, this procedure can be reversed in order to design a transducer to give some specified frequency response: Fourier transformation gives the required impulse response $h(t)$, and the amplitude of this function then gives the required apodisation for the electrodes. This demonstrates a very high degree of versatility, since the method may be used for *any* specified frequency response, provided it is consistent with the limitations of the technology.

This principle is commonly used in surface-wave *bandpass filters*, where the usual requirement is that the device should pass c.w. signals with frequencies within a specified band and reject signals with other frequencies. For this case the required impulse response has an amplitude of the form $(\sin \alpha t)/(\alpha t)$, with the constant α determined by the bandwidth, and the geometry is typified by Figure 1.4. In practice there are many complications affecting the performance and different approaches to the design may be adopted, depending on the requirements.

The direct relationship between the transducer geometry and the impulse response also applies to transducers whose electrode pitch varies. Figure 1.5 shows a device using a transducer of this type and a short uniform transducer. When the uniform transducer is impulsed a short surface wave packet is produced, and this scans along the output transducer. At any one time, the frequency of the output voltage depends on the pitch of the electrodes at the location of the scanning pulse, so that a frequency-swept output pulse is produced. If the periodicities at the two ends of the transducer are L_1 and L_2, the frequency sweeps from $f_1 = v/L_1$ to $f_2 = v/L_2$, where v is the surface wave velocity. The duration of the output pulse, T, corresponds to the length of the transducer, vT. A frequency-swept pulse of this type is often called a *chirp* pulse, and the surface-wave device is called a *chirp filter*. It is also described as a dispersive delay line, because the group delay of the device varies with frequency; the delays at frequencies f_1 and f_2 differ by an amount T.

The main application of the chirp filter occurs in radar systems, where the device is used to perform *pulse compression*. This process is illustrated in the lower part of Figure 1.5. A chirp waveform is applied to the device, the waveform being similar to the device impulse response but reversed in time, so that the frequency starts at f_2 and ends at f_1. The short uniform transducer generates a surface wave pulse with a corresponding form, and this propagates along the surface. At a particular instant, the peaks and troughs of the surface wave pulse match the electrode positions of the long transducer, and the output voltage peaks, producing a narrow pulse. The width of the output pulse is approximately $1/B$, where $B = f_1 - f_2$ is the bandwidth. The ratio of the input and output pulse widths is called the compression ratio, and is equal

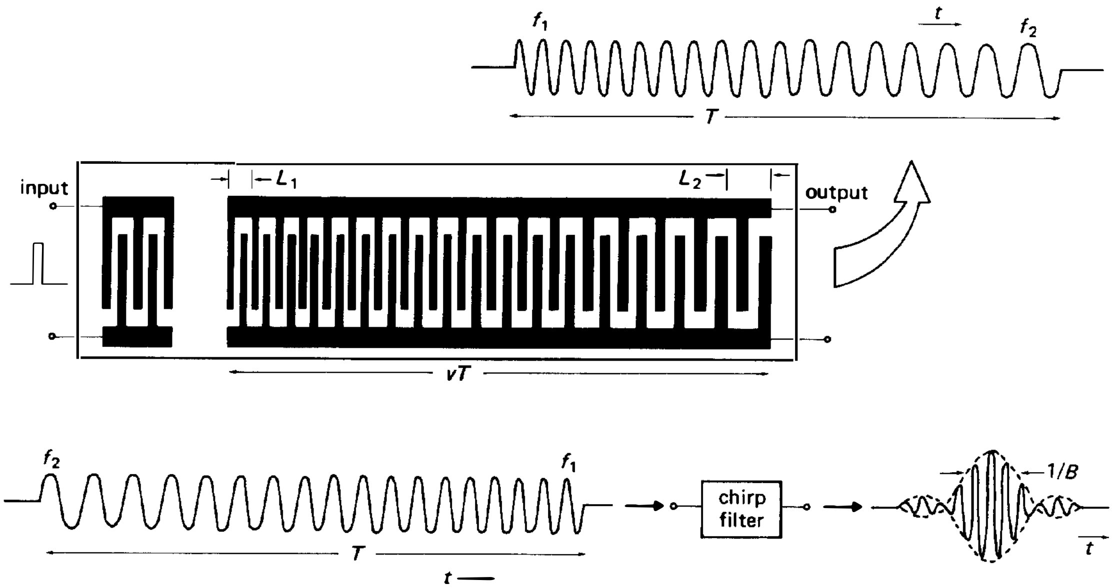

FIGURE 1.5. Upper: interdigital chirp filter and its impulse response. Lower: pulse compression.

to the time-bandwidth product of the device, *TB*. Typical time-bandwidth products are in the range 50 to 500.

The chirp filter is one example of a device designed to have its impulse response corresponding to the time-reverse of a specified waveform. Such a device is called a *matched filter*, and the process of compressing the waveform in the filter is also called "correlation". The filter responds most strongly to the waveform that it is matched to, discriminating against other waveforms and, in particular, against noise. This feature can be used to improve the sensitivity of a radar system. In a pulse-compression radar, the transmitter emits a frequency-swept chirp pulse. The echo received from a target has the same form, and is compressed by a chirp filter in the receiver. As in all electronic systems, noise is also present, but the filter discriminates against it. Thus a weak echo, initially obscured by noise, is processed to produce a pulse exceeding the noise level, and can therefore be detected. This principle is frequently used in present-day radar systems.

An alternative type of chirp filter is the *Reflective Array Compressor*, or RAC, shown in Figure 1.6. This device has two arrays of inclined shallow grooves, with graded periodicity, arranged to reflect surface waves through 90°. The surface waves are generated by a uniform interdigital transducer at one end of the device, and are then reflected twice by the grooves so that they reach the interdigital output transducer, located at the same end as the input transducer. Because the grooves are shallow, with a depth typically 1% of the wavelength, the reflection coefficient of any one groove is small. However, at any one frequency the reflected waves from many grooves add coherently, producing a much larger reflected wave amplitude. This

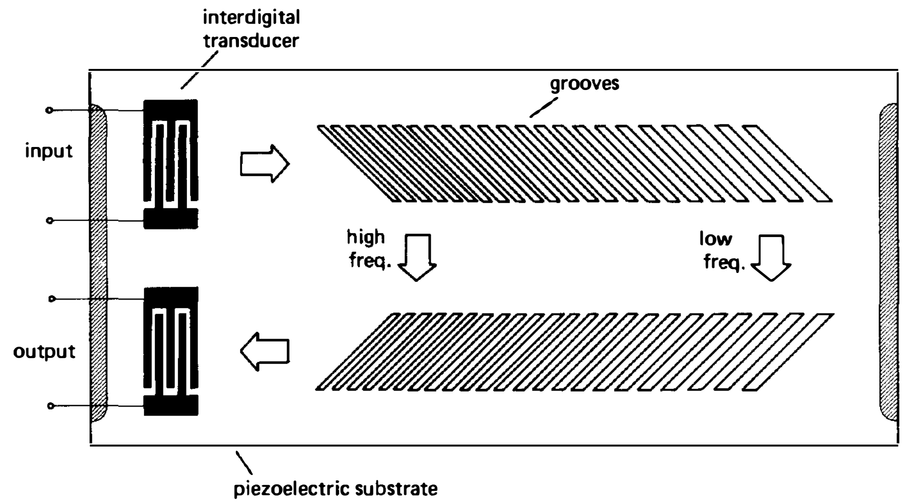

FIGURE 1.6. Reflective Array Compressor (RAC).

requires the pitch of the grooves to correspond with the surface-wave wavelength. Because the pitch varies along the length of the device, different frequencies are reflected at different locations, giving different path lengths. The delay therefore depends on frequency, and the device is a type of dispersive delay line. The RAC can be used for pulse compression of chirp waveforms, and enables very large compression ratios, up to 10,000, to be obtained. In contrast, the interdigital chirp filter described above is, for technical reasons, limited to compression ratios below 1,000.

Matched filtering is also applicable to other types of waveform, notably to phase-shift-keyed, or PSK, waveforms. For such waveforms, an appropriate matched filter is the surface-wave *PSK filter*, which is essentially a form of tapped delay line using interdigital transducers. This device is applicable to spread-spectrum communication systems, and to some radar systems.

Surface wave techniques can also be used to produce several types of stable *oscillator*, generally using quartz as the propagation medium because of its good temperature stability. One method is to use an interdigital delay line with an amplifier connected between the output and the input, forming a loop. The amplifier small-signal gain exceeds the loss of the delay line, so that the loop oscillates at a frequency related to the surface wave velocity. Alternatively a surface-wave resonator may be used. The resonator is basically two reflectors forming a surface wave cavity, the reflectors being periodic arrays of either metal strips or grooves. The resonator can give very high Q-factors, up to 10,000, giving good stability. The delay-line oscillator gives lower Q-factors, but has the advantage that the frequency can be made adjustable by incorporating a phase shifter in the loop external to the delay line. These techniques give highly stable c.w. sources with frequencies up to about 2 GHz, in contrast to the parallel plate resonator using bulk waves, which is limited to about 50 MHz.

(f) Fabrication. The manufacturing methods used for surface-wave devices have a strong bearing on device performance. In particular, the minimum line width obtainable determines the maximum frequency of operation, and for long delays the ability to process long substrates is required. A brief outline of the method is given here, and the reader is referred elsewhere [25] for further details.

Most devices consist essentially of metal patterns, such as transducers, deposited on crystalline piezoelectric substrates. These devices are made by photolithography, using a procedure exemplified by Figure 1.7. The substrate is carefully polished and cleaned to give a flat smooth surface of optical quality, free of extraneous particles or grease. A metal film is then deposited, usually by vacuum evaporation (Figure 1.7(a)). The film is usually of aluminium and is typically 0.1 to 0.3 μm thick. A thin underlay of chromium is often used to improve the adhesion. The sample is then coated with photo-resist, a solution of a photo-sensitive polymer, and is spun at high speed so that the resist becomes a thin uniform layer. Subsequent baking solidifies the resist, which is then exposed to ultraviolet light through a mask, as in Figure 1.7(b). The mask has opaque areas, usually of photographic emulsion or chromium film, corresponding to the areas to be metallised on the final device. The exposed areas of resist undergo a chemical change, and can then be removed by a developing solution, as in Figure 1.7(c). This exposes areas of metal which are removed chemically, and finally the remaining resist is dissolved away, leaving a metal pattern on the substrate corresponding to the pattern on the mask, as in Figure 1.7(d). With this process, line widths down to 0.5μm can be replicated with care, giving interdigital transducers operating at about 1.5 GHz. The most critical stage is the optical exposure, where the mask must be in contact with the sample, and a commercial mask aligner is normally used here. Owing to anisotropy, the angular alignment of the mask relative to the substrate is important, and an accuracy of 1° or better is often necessary. There are many variants to this basic process, and for very fine lines there are techniques using X-rays or electron beams instead of optical exposure, though these are not generally in commercial usage.

For the smaller devices, up to a few cm long, the process is very similar to standard techniques used in the semiconductor industry and is well suited to large-scale

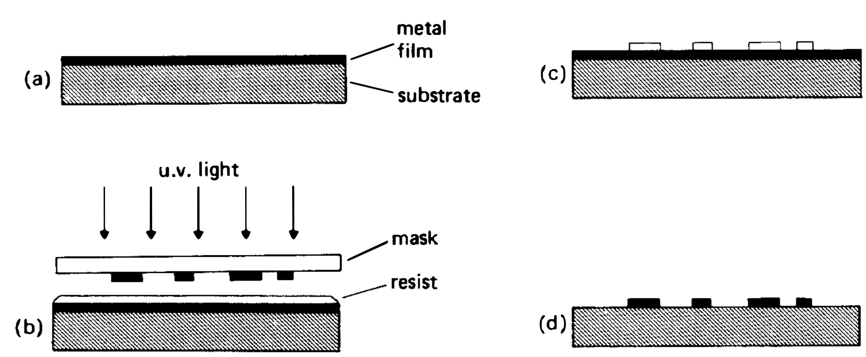

FIGURE 1.7. Fabrication using optical lithography.

production. The crystal substrate is often in the form of a disc of diameter 7.5 cm, with a straight edge cut as a reference for orientation. The required pattern is repeated many times on the mask so that many devices are fabricated simultaneously, and the disc is subsequently sawn to separate the individual devices. For larger devices, which are usually chirp filters or delay lines, the process is more specialised. Crystal substrates are available commercially with lengths up to about 25 cm, and present-day pattern generation machines can produce masks of this length with sub-micron accuracy. This enables interdigital devices to have delays up to about 50 μs. The devices are usually made individually, using specially adapted equipment for resist coating and mask alignment.

Devices using grooves, such as RAC's, require an additional fabrication stage. The grooves are usually cut by exposing the substrate to an ion beam, using a metal masking pattern on the surface to define the geometry.

The final stage of fabrication is packaging. Production devices are hermetically sealed in an inert atmosphere or vacuum, to exclude moisture (which may cause erosion of the metal) and surface contaminants (which cause attenuation of the surface waves). Standard packages, such as the circular TO-series or the dual-in-line types, are often used for the smaller devices, but for longer devices custom-designed packages are necessary. The substrates are mounted using adhesives, often of the elastomer type to minimise mechanical stress, since stress can affect the performance somewhat. Electrical connections are made by means of thin wires, typically of gold and with 25 μm diameter, attached to the substrate metallisation by thermo-compression or ultrasonic bonding. In some cases temperature regulation is necessary, so the package is mounted within a thermally insulating enclosure.

(g) Performance and Applications. The applicability of surface-wave devices to practical electronic systems is basically determined by the centre frequencies, bandwidths and delays obtainable, together with the performance and cost effectiveness. The upper limit for the centre frequency is determined by fabrication techniques, and for current photolithography is about 1.5 GHz. At low frequencies surface-wave devices become more bulky and expensive and other technologies become more suitable, for example bulk acoustic wave resonators for bandpass filters or digital techniques for signal processing. Consequently, surface-wave devices are not normally used below a few MHz. In most applications, this frequency range implies that the devices are used in the I.F. section of the system, and this has the important consequence that low insertion loss is not generally a priority. For example, bandpass filters have typically 15 to 30 dB loss, and this is acceptable for many applications. Bandwidths generally range from a minimum of about 100 kHz to a maximum of about 50% of the centre frequency. The delay obtainable ranges from about 0.1 to 50 μs, with the upper limit determined by the lengths of available crystal substrates. For the RAC, in which the surface-wave traverses the length of the substrate twice, the maximum delay becomes 100 μs.

These figures are well suited to a wide range of system requirements, particularly in radar and communication systems. In terms of quantity, the most widely used surface-wave device is the bandpass filter used in the I.F. section of colour television receivers. Bandpass filters are also used extensively in radar and communication systems, and in television broadcasting equipment. Chirp filters (interdigital and RAC) are widely used in radar systems. They can also serve a number of other functions, notably in the compressive receiver, a sub-system for frequency measurement with applications in electronic surveillance. Some radar systems make use of delay lines or PSK filters. In spread-spectrum communication systems PSK filters are used as matched filters, and surface-wave non-linear convolvers are also beginning to impact this area. It is emphasised that this description is selective, and more details are given elsewhere [19–22]. For example, Williamson [21] lists 45 separate types of surface-wave device, and gives an extensive list of systems using them. Some of the applications are discussed further in later chapters of this book.

The success of surface-wave devices in meeting these requirements can be ascribed to a number of factors. Foremost among these is the substantial degree of versatility due to the accessibility of the propagation path, a feature well illustrated by the variety of types of interdigital transducer. Accurate reproducibility is another key feature. The device characteristics are mainly determined by the geometry of the pattern on the mask, and by the acoustic properties of the substrate. Modern pattern generation machines produce masks of very high accuracy, and good reproducibility of the substrate properties is obtained by the use of single-crystal materials. This is particularly true for quartz substrates, which can also give excellent temperature stability. For this material the surface wave velocity, for example, can be controlled to within 50 parts per million or better. In addition, design techniques are sophisticated enough to exploit this accuracy, so that the design procedure does not limit the device accuracy obtainable. The accuracy is an important factor in the success of matched filters and oscillators. Other contributing factors are the simplicity of the fabrication procedure, using equipment already developed for semiconductor fabrication, and the low surface wave velocity, which enables long delays to be obtained in relatively short devices.