# Acoustic Surface Waves

Edited by A. A. Oliner

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# Preface

Acoustic surface waves form the basis of an exciting new field of applied physics and engineering, extending to several disciplines as diverse as nondestructive evaluation (NDE), seismology, and signal processing in electronic systems. This field, often referred to as the SAW (Surface Acoustic Wave) field, has developed enormously during the last decade, particulary within the past half-dozen years, with its principal impact on signal processing, with important applications to radar, communications and electronic warfare.

The extremely low velocity, and therefore extremely small wavelength, of these (ultrasonic) acoustic waves permits them to perform functions in a very simple fashion that would be very difficult or cumbersome to accomplish using any other technology. Devices from the VHF to the low microwave frequency range employing these waves are therefore very practical, in addition to offering dramatically small size and weight, combined with ruggedness and reliability. The vitality and strength of this field derive from its interdisciplinary nature, combining the talents of solid mechanicians, solid-state physicists, and microwave engineers. Great strides were therefore made quickly in both the understanding of these acoustic wave types and in the ingenious engineering developments that have followed from this understanding.

This book is concerned with the *fundamentals* of the acoustic surface wave field, with stress on implications for signal processing. The book includes in one place the following four most important basic aspects of this field: the properties of the basic wave types, the principles of operation of the most important devices and structures, the properties of materials which affect device performance, and the ways by which the devices are fabricated. The attempt throughout has been to stress the the fundamentals so that this book is not likely to be outdated soon. Although a variety of books and journal publications have appeared which present certain basic material or contain broad reviews, there is no single published source, to our knowledge, that duplicates the intent or the contents of this book.

I wish to thank my contributors, each an acknowledged expert in his own specialty in this field, for their fine cooperation in the preparation of the manuscript. I am also very grateful to Mrs. Jean B. Maher for her superb typing skill, her perceptiveness in suggesting improvements, and her creative assistance in the preparation of the index.

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*A. A. Oliner*

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# Contents

# 1. Introduction

A. A. Oliner

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The field of acoustic surface waves is concerned primarily with the understanding and exploitation of the properties of elastic waves of very high frequency that can be guided along the interface between two media, at least one of them being a solid. The solid medium is usually piezoelectric, so that interactions with electromagnetic fields become possible, and the second medium is usually air or vacuum.

Although much had been known for many years about some of the fundamental properties of acoustic surface waves, this field has developed enormously during the last decade, particularly within the past half-dozen years. Current concerns with this field extend to several disciplines, as diverse as nondestructive evaluation (NDE), seismology, and signal processing in electronic systems. Although the early interest in acoustic surface waves related almost solely to seismological applications, and although such waves are becoming increasingly important for NDE considerations, the principal impact of the acoustic surface wave field today and over the past few years has been on *signal processing*, with important applications to radar, communications, and electronic warfare. It was the recognition that acoustic surface waves could furnish a new approach to signal processing that gave the acoustic wave field its enormous impetus during the past decade.

The acoustic surface wave field is an interdisciplinary one, and it has derived its great drive and strength from the combination of talents which contributed to its recent development. In addition to the solid mechanics people who furnished the foundations for the field and who continue to contribute to it, the recent rapid development was made possible by the influx of solid state physicists and microwave engineers, who interwove their backgrounds and capabilities with those of the solid mechanicians. As a result, great strides have been made in both the understanding of these wave types and in the ingenious engineering developments that have followed from this understanding.

This book is concerned with the *fundamentals* of the acoustic surface wave field. The chapters which follow present these fundamentals in a way that highlights their relation to signal processing applications. The applications themselves are not treated, but the basic principles underlying the most important devices which are essential to those applications are presented in some detail. In addition to these device principles, the fundamental aspects considered in this book include the wave types themselves, basic guiding structures, the

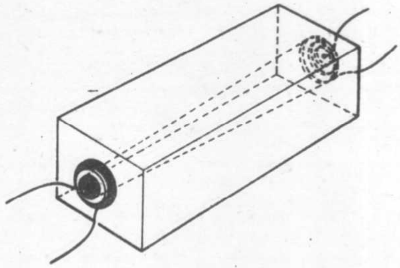

Fig. 1.1. A typical simple bulk-wave delay line. A bulk wave beam propagates within the solid medium between the transducers

properties of materials, and methods for fabricating the required surface wave structures.

The field of acoustic surface waves often uses the designation SAW, standing for "surface acoustic waves". This designation is employed frequently in the remainder of the book.

To tie together the various independent fundamental aspects of the acoustic surface wave field, and to place them in a suitable perspective, this introductory chapter presents first an overview of some features of this field, and then outlines the specific topics treated in each of the following chapters.

## 1.1 An Overview of the Field

Let us first review why surface acoustic waves (SAW) are of such great interest for signal processing applications. What properties of these waves permit them to be exploited in such a novel (and practical) fashion?

The first, and most important, property is their *extremely low velocity*, about $10^{-5}$ times that of electromagnetic waves. This property makes acoustic wave structures ideal for long delay lines, a feature which has been recognized for many years in connection with bulk acoustic waves. Because of the low velocity, acoustic waves also possess *extremely small wavelengths*, when compared with electromagnetic waves of the same frequency. The reduction in size is again of the order of $10^{-5}$, the precise value depending on the materials used. Acoustic wave devices, when compared with electromagnetic devices, therefore offer *dramatic reductions in size and weight*. In addition, acoustic surface wave devices are fabricated on the surface of a crystal, so that they are also generally more *rugged* and *reliable*.

Early acoustic wave devices employed bulk acoustic waves, as sketched in Fig. 1.1, which represents a typical simple delay line. An incoming electromagnetic wave is first converted into a bulk acoustic wave by a transducer, the acoustic wave traverses the length of the crystal (and the signal is delayed), and the acoustic wave is then transduced back into an outgoing electromagnetic wave. Because the acoustic wave is present in the interior of the crystal, it is difficult to obtain access to the wave in order to modify it or tap into it. This difficulty is overcome by the use of the surface wave structure shown in Fig. 1.2,

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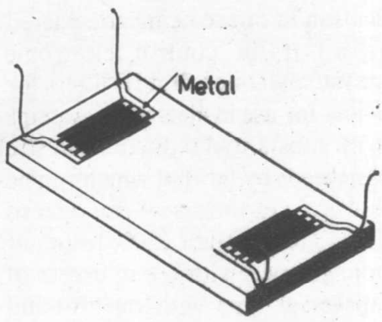


Fig. 1.2. A simple surface wave delay line, which employs interdigital transducers on the surface of a piezoelectric crystal. A Rayleigh surface wave propagates between the transducers

which employs interdigital transducers to excite a Rayleigh surface wave that travels along the surface of the solid and is confined to its vicinity. The clearly *accessible* nature of the surface wave now permits a new order of flexibility which has encouraged the creation of a large variety of novel and effective devices.

The use of surface waves also permits these acoustic wave devices to be compatible with integrated circuit technology and to allow their fabrication by lithographic techniques. Devices using these waves can therefore be mass produced at relatively low cost with precise and reproducible characteristics.

The extremely slow nature of these acoustic surface waves therefore permits a time-varying signal to be completely displayed in space on a crystal surface at a given instant of time. In addition, the lithographic fabrication capability easily permits a complex circuit to be present on the crystal surface. Thus, while the signal progresses from the input end to the output end, one can readily sample the wave or modify it in various ways. As a result, one can perform functions in a very simple fashion that would be very difficult or cumbersome to accomplish using any other technology.

Acoustic surface wave devices can be designed with a center frequency of operation which may lie from the low MHz values up to approximately a GHz, that is, in the VHF or UHF range. Since the size of a circuit element is proportional to the wavelength, the lower frequency limit is governed by the size of available substrates, and the upper limit occurs because of fabrication difficulties.

Despite the short development period, certain aspects of the acoustic surface wave field already correspond to a mature technology. Devices exhibiting exceptional performance have been used to retrofit existing systems (such as pulse compression filters for FM signals used in radar systems), and they are being incorporated into new systems (such as matched filters for phase-coded applications in spread spectrum communications systems). These and other devices such as delay lines, bandpass filters, UHF oscillator control elements, programmable devices for frequency and time domain filtering, frequency synthesizers, correlators, etc., are finding application in or are being considered for radar, spread spectrum communications, air traffic control, electronic warfare, microwave radio relays, data handling systems, sonar, and IF filters for TV use, just to name the major areas. These devices for use in electronic systems not only offer improved reliability, combined with substantial reductions in size and weight, but in many cases their *performance* exceeds by far that which can be achieved by their best electromagnetic counterparts. As examples we can refer to pulse compressors with time-bandwidth products greater than 5000, resonant cavities in the UHF range comprised of periodic grooves with $Q$'s in excess of 50000, and UHF bandpass filters of the transversal type with out-of-band suppression of about 70 dB over the frequency range from DC to 1 GHz.

Despite these impressive accomplishments, many feel that the systematic exploitation of acoustic surface waves is still in its infancy. For one thing, the devices developed so far are not customarily integrated with one another, or with electronic integrated circuit components, on the same substrate surface. Many writers have proposed schemes which could readily benefit from such integration, but the systems needs are not yet apparent. A more widespread utilization of these devices would also occur if the costs of materials and fabrication technology would be significantly reduced. The range of applications for acoustic surface wave devices has so far been limited largely to high-technology needs, where price is secondary to performance; the IF filters for TV use is a notable exception. If mundane commercial applications like the latter become more widespread, costs for substrates should go down, and the popularity of such devices should increase.

In addition, there are other areas of application or potential application which are only embryonic. Examples of such areas, which could well become important, are imaging and nondestructive evaluation (NDE). With respect to imaging, it has been shown that acoustic surface waves can be used to scan an optical image, and to scan and focus an acoustic image. Much more needs to be done before these techniques become practical or competitive with other imaging techniques, but there are implications for medical electronics and for the nondestructive evaluation of materials. With respect to NDE, until relatively recently, simple techniques of testing and interpretation were deemed adequate for most requirements. The recent demands for more quantitative characterizations, which have resulted in the change in terminology from NDT (nondestructive testing) to NDE, have imposed the need for more sophisticated approaches, which the acoustic surface wave field can contribute in the form of better transducers, better theoretical descriptions of wave scattering from defects, novel imaging approaches, and new adaptations of signal processing techniques.

The discussion above has indicated that the acoustic surface wave field has already achieved significant, even spectacular, success in the area of signal processing devices, particularly in connection with high-technology applications, and that there is still much more room for growth, both for application to electronic systems and to new areas of application.

## 1.2 The Organization of This Book

Underlying all of the applicational developments discussed above are a number of *fundamental* features, ranging from the theoretical understanding of the basic wave types to the essential materials and fabrication technology. This book attempts to include in one place the most significant of these fundamental features, together with the principles of operation of the most important devices and structures in the surface acoustic wave signal-processing field.

Basic to the understanding and design of devices is a knowledge of the properties of the *basic waves* which can propagate in solid volumes and be guided along surfaces and by plates. The fundamental features of such waves are presented in Chapter 2, entitled "Types and Properties of Surface Waves". Although the emphasis is on surface waves, the bulk waves which can propagate in solid media are treated first, before the surface boundary conditions are introduced. These bulk waves are important in their own right, and they come under consideration in later chapters with respect to surface wave device performance, usually because they introduce undesired second-order effects.

Even though most devices employ anisotropic substrates, the properties of the wave types on isotropic substrates are considered in some detail in Chapter 2 to describe the principal behavioral features. Anisotropic substrates, with their added complexity, are treated next, because only with anisotropic substrates can the device designer obtain high piezoelectric coupling and low attenuation at the higher frequencies. The complications relating to the choice of crystal cut and the direction of the propagation of the wave are considered in detail. Power flow in anisotropic media, where the energy-flow and phase-progression directions are usually different, is also examined; this effect leads to beam steering, a property which is also considered in Chapter 6 in connection with specific materials.

Piezoelectric effects are also analyzed in Chapter 2, since the electric fields accompanying the waves represent the way in which the mechanical circuits couple to external electrical circuits or to semiconducting materials. The presence of piezoelectricity leads to stiffened Rayleigh waves, and to an interesting surface wave type, the Bleustein-Gulyaev wave, which can be viewed as a modification of an SH bulk shear wave and which could not exist as a surface wave in the absence of piezoelectricity.

Many devices employ a thin layer of one material placed on a substrate of another material. The presence of the added thin layer not only modifies the properties of the Rayleigh wave which can exist in its absence, but also permits the propagation of another wave type, the Love wave, with polarization different from that of the Rayleigh wave (where polarization is defined by the direction of particle displacement produced by the wave). Chapter 2 also contains discussions on reflections from discontinuities such as corners and steps, and on diffraction effects for a beam of finite width, which results in beam spreading.

The most fundamental component in acoustic surface wave technology is the *interdigital* (ID) *transducer*. Its key importance lies in its dual role as the most common method for transducing electrical input signals into elastic surface waves and as a building block for many surface wave devices in view of its inherent versatility. The first portion of Chapter 3 treats the ID transducer in substantial detail. The discussion there indicates how the ID transducer works, and presents an equivalent circuit model which yields physical insight and which has been found very useful for design purposes. The approach takes into account the three independent elements of the transducer and the interactions among them: the metal electrodes, the properties of the substrate, and the electromagnetic tuning circuits. Later in Chapter 3 it is shown that certain important second-order effects can degrade the performance of devices employing ID transducers, and that modifications in the transducer geometry, such as double electrodes (sometimes called split fingers) and dummy electrodes associated with apodization, can overcome these deleterious second-order effects.

The major objective of Chapter 3 is announced in its title: "Principles of Surface Wave Filter Design". Early in the chapter it is pointed out that the *surface wave filter* is basically an idealized $\delta$-function implementation of a transversal filter. It is shown clearly, however, that the actual filter, which uses the ID transducer as a basic element, is far more complicated, involving elastic, piezoelectric, and electromagnetic variables, since it is incorporated into an electronic system. The chapter reviews the basic principles of transversal filter theory, which are implemented by the repeated delaying and sampling of an input signal. In this context, the discussion explains the importance of amplitude weighting and phase weighting of the required taps, and presents ways of achieving these weightings when ID transducers are employed.

Surface wave filters constitute one of the most important classes of surface wave devices. The technology of surface wave filters has become practical, indeed outstanding, because it has been possible to characterize and control the various second-order effects which cause the actual device to deviate from the ideal one. In practice, however, it is not possible to compensate for all second-order effects simultaneously and, as a result, trade-offs relating to various performance characteristics become necessary. The discussion in Chapter 3 not only presents the principles of operation of these surface wave filters and describes the most important effects which cause deviations from the ideal, but it also shows the engineering steps required to overcome the main difficulties and indicates in some detail what trade-offs must be involved and how they influence the various parameters in filter performance. At the end of the chapter, the process of designing a surface wave filter is reviewed, two examples of filter performance are presented, and two mathematical appendices are included which elaborate on the basic filter principles.

As mentioned earlier, this book is designed to present the fundamentals of surface acoustic waves in a way that highlights their relation to *signal processing* applications, even though much of the material is also of interest to other aspects of the acoustic wave field. Chapter 4, entitled "Fundamentals of Signal Processing Devices", is concerned directly with signal processing, of course, but it stresses the *principles* underlying the most important devices, rather than signal-processing technology or device design details. The basic ID transducer and the surface wave filter analyzed in Chapter 3 are also devices used in signal processing, but the treatment of those devices is presented in a special way to illustrate the engineering designs and trade-offs which arise there. Chapter 4 considers various additional, but also basic, devices and, although the treatment is more descriptive, it nevertheless exposes the key considerations which affect the design and range of applicability of the devices.

The first class of devices considered in Chapter 4 is that of *delay lines*, possibly performing the simplest function and the one recognized earliest as one for which acoustic waves are eminently qualified. The discussion examines the major problems involving the performance of such delay lines, including insertion loss, the suppression of spurious signals (such as "triple transit echo"), bandwidth, and temperature stability. In addition, some special structures are described for use as long delay lines. The next device class explored is that of surface wave *resonators*, which form the surface wave counterpart of the well-known bulk wave resonators (the "quartz crystals") which are used as frequency control elements and as circuit elements for narrow band filters. The surface wave resonators employ periodic arrays of grooves or strips, operated in their stop bands, as reflecting elements, and are found to yield extremely high values of $Q$, in excess of 50000, with careful design. These grating resonators can also be used as the frequency control element to form a stable signal source. If we arrange a recirculating path for the acoustic energy (or effect the feedback electrically), and include an amplifier in the feedback path to overcome the loop loss, we obtain a surface wave *oscillator*, which is the device treated next in Chapter 4. Such a stable signal source for the UHF range offers much promise; the discussion covers such considerations as stability, mode control, tuning, etc.

The next group of devices described in Chapter 4 is classified as coded "time domain" structures, and they include such highly important devices as the *pulse compression filter* for chirp radar (perhaps the most important single application so far) and *phase-coded* devices for spread-spectrum communications. These devices are composed largely of appropriate modifications in the basic ID transducer, as is the frequency filter treated in Chapter 3. Indeed, much of the discussion there, and the synthesis procedures, are also applicable to these devices. However, in contrast to the use of transfer functions, which express behavior in the frequency domain, these devices are more naturally described in terms of the impulse response, i.e., in the time domain, and this feature forms the basis for the name "time domain" filters chosen in Chaper 4. Considerations relating to pulse compression filters, such as time-bandwidth product, are explored in detail, and alternative geometries, such as the RAC and the RDA, are discussed. Of phase-coded transducers, the binary phase shift keyed (PSK) modulation is stressed; its advantages, and various problems relating to optimal design, are considered, including possibilities for programmable devices, which would permit rapid changing of the code used. In addition, generalizations of linear chirp filters are explored, with the Fourier transformer and variable time delay elements as examples.

*Nonlinear* signal processing devices are considered next in Chapter 4; nonlinear interactions have led to the development of new classes of device because the nonlinearity of the acoustic medium permits analog signals to be multiplied together instead of only added, as in the linear devices considered up to now. The important convolver and correlator devices, and their implementations using either piezoelectric nonlinearity or the nonlinearity in contiguous semiconductors, are examined in detail. The correlator can be a highly valuable device in a radar system since it permits the radar system to use as a reference the return received from a nearby large target instead of a perfect sample of the transmitted pulse. This return signal can then be correlated with that from the target of interest, much further away; as a result, the performance of the radar is no longer degraded by distortions introduced in the transmitter. A new and exciting development, the storage correlator, which uses an array of discrete diodes on a silicon layer, is also described at some length. The last section in Chapter 4 treats multiport acoustic devices, and considers primarily the *multistrip coupler* (MSC) and its various modifications. The MSC is a versatile device whose incorporation in Chapter 3 in a band-pass filter permits the use of two apodized transducers. Other functions performed by the MSC include bulk wave suppression, track changing, power division, beam compression, multiplexing, etc. The discussion in Chapter 4 indicates why the MSC works and how these functions are accomplished.

Almost all of the acoustic surface wave devices described in Chapters 3 and 4 utilize wide-beam surface waves, despite certain limitations possessed by these beams: beam spreading, inefficient use of the substrate area, and awkwardness in bending their paths. These limitations are all overcome by the use of *waveguides* for surface waves, where the term "waveguide" implies a geometrical structure which confines the lateral extent of the surface wave and binds the wave to itself. The types and the properties of such waveguides are described in Chapter 5, entitled "Waveguides for Surface Waves".

Waveguides are being considered seriously for certain applications, such as long delay lines, as described in Section 4.2; for most other device needs, waveguides are not essential but, with ingenuity, they could be useful in improving device performance. The most intriguing potential application for waveguides is that of a highly-compact sophisticated circuit technology, sometimes referred to as "microsound". So far, the acoustic wave device field has not moved in the direction of circuitry which performs several functions simultaneously; instead, SAW devices generally (but not always) perform a single function, and consist of a simple circuit placed between input and output transducers. When the philosophy changes, and when the performance of multiple functions on the same substrate using wide surface-wave beams is seen to result in cross talk between neighboring beams and to require excessive substrate area, waveguides will be logically called upon. Thus, although the applications for waveguides at present are few, the potential for future use could be very great.

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