STUDIES IN ELECTRICAL AND ELECTRONIC ENGINEERING 19

Surface-Wave Devices for Signal Processing

DAVID P. MORGAN

STUDIES IN ELECTRICAL AND ELECTRONIC ENGINEERING 19

Surface-Wave Devices for Signal Processing

DAVID P. MORGAN

Plessey Research (Caswell) Ltd., Allen Clark Research Centre, Towcester, U.K.

ELSEVIER
Amsterdam – Oxford – New York – Tokyo 1985

ELSEVIER SCIENCE PUBLISHERS B.V.
Molenwerf 1
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
52, Vanderbilt Avenue
New York, NY 10017

Library of Congress Cataloging in Publication Data

Morgan, David P.
Surface-wave devices for signal processing.

(Studies in electrical and electronic engineering ; vol. 19)
Bibliography: p.
Includes index.
1. Acoustic surface wave devices. 2. Signal processing. I. Title. II. Series: Studies in electrical and electronic engineering; 19.
TK5981.M63 1985 621.38'043 85-10330
ISBN 0-444-42511-X (U.S.)

ISBN 0-444-42511-X (Vol. 19)
ISBN 0-444-41713-3 (Series)

Printed in The Netherlands

Preface

Devices using acoustic waves have been employed in electronic systems for many years, notable examples being the quartz crystal oscillator and the acoustic delay line, both of which use acoustic wave propagation in the bulk of a material. In contrast, the use of *surface* acoustic waves, in which the wave motion is bound to a plane surface of a solid, has developed quite recently, though the existence of the wave itself was established by Lord Rayleigh in the 19th Century. The use of surface waves introduces several attractions, notably a considerable degree of versatility due to the accessibility of the wave in two dimensions, and the prior existence of a variety of suitable fabrication techniques. These attractions were first recognised in the 1960's, and since then there have been substantial developments in understanding the wave behaviour and a wide variety of electronic devices has emerged. Today, surface-wave devices are used in many practical systems, particularly in communications, radar and broadcasting.

In this book I have chosen to concentrate on the devices most commonly found in electronic systems, and the principles underlying them. Most of these devices perform signal processing operations – for example, a bandpass filter is used to select some required frequency band, while chirp filters and PSK filters perform correlation of complex waveforms. To appreciate the function of the devices some knowledge of signal processing is necessary, and this is included in the appropriate parts of the book.

Chapter 1 gives a descriptive survey, intended to introduce the subject to those unfamiliar with it, and Chapters 2 to 5 give the theoretical background needed to appreciate the operation of the devices considered later. The devices here use surface waves in piezoelectric materials, which enable the waves to be generated or detected by means of metal electrodes on the surface. Chapter 2 considers basic properties of acoustic waves and emphasises surface waves in piezoelectric materials, though some other relevant cases are also included. Chapter 3 covers electrical excitation of surface waves, introducing the effective permittivity and the Green's function, and these concepts are applied to the analysis of interdigital transducers in Chapter 4 and to multi-strip couplers in Chapter 5. Interdigital transducers are used in all of the devices considered in this book, and in many devices the response is determined mainly by the transducer behaviour, which is therefore treated in detail. The analysis for transducers and multi-strip couplers makes use of the quasi-state approximation, described in Section 4.3. This simplifies the results considerably since it neglects electrode interactions, which are not very significant in most practical devices; however, interaction effects are considered in Appendices D and E. Generation of bulk waves in surface-wave devices is another complication ignored in Chapters 4 and 5, but this is considered in Appendix F.

Chapter 6 describes several surface-wave propagation effects, particularly diffraction, and gives a comparative assessment of materials commonly used for practical devices. The remaining chapters are mainly concerned with the design and performance of devices. Chapter 7 describes delay lines, including some practical aspects of transducer performance, while bandpass filters are covered in Chapter 8. Chapter 9 describes chirp filters, commonly used in pulse-compression radar systems, including interdigital devices and reflective array compressors. This chapter also includes the characteristics and design of chirp waveforms. Finally, Chapter 10 is mainly concerned with devices for spread-spectrum communication systems, including the PSK filter and the non-linear convolver which are used to correlate phase-shift-keyed waveforms. The surface-wave oscillator and resonator are also considered briefly.

It should be noted that the coverage here is quite selective. The literature includes substantial material on topics hardly mentioned, for example interaction with light and with semiconductors, and the behaviour of surface-wave waveguides. There is also a very considerable variety of devices in addition to those mentioned above, and these are omitted apart from some brief comments.

The book is intended to appeal mainly to engineers developing surface-wave devices and to those developing systems using the devices, though it should also be helpful in connection with university course or research work. The reader will not need a prior knowledge of acoustics, as the concepts required are included in Chapter 2. However, an undergraduate-level knowledge of network analysis, and of some basic concepts of crystallography, are assumed. The extensive use of Fourier transforms arises quite naturally, since the time- and frequency-domain representations of a device response both correspond to common laboratory measurements, and both domains occur in device specifications. In addition, Fourier transforms are used in the analysis of transducers and other structures. The relationships needed are summarised in Appendix A, which also gives some basic relationships for analysis of linear filters. However, the reader unfamiliar with these topics will probably find that further reading, from the references quoted in Appendix A for example, will be helpful.

The material in this book arises from experience in several laboratories, and has benefited substantially from cooperation and discussion with many colleagues. It is a pleasure to acknowledge the past involvement with colleagues in University College London, the Central Research Laboratories of the Nippon Electric Company Ltd. (Kawasaki), and the University of Edinburgh. I am especially indebted to the surface-wave group in Plessey Research (Caswell) Ltd. Many of the ideas in the book arose from the work of this group, and most of the experimental results shown refer to devices developed by the group. In particular, I wish to mention R. W. Allen, R. Almar, R. Arnold, R. E. Chapman, R. K. Chapman, J. M. Deacon, R. M. Gibbs (who fabricated most of the devices), W. Gibson, J. Heighway, J. A. Jenkins, P. M. Jordan, B. Lewis, J. G. Metcalfe (who also computed some theoretical figures for the book), R. F. Milsom, J. J. Purcell, D. Selriah and D. H. Warne. Many helpful discussions were contributed by E. G. S. Paige and M. F. Lewis. During the writing of the book the initial drafts were reviewed by E. G. S. Paige, B. Lewis and, in part, by J. J. Purcell, and I am greatly indebted to these gentlemen for their thorough and painstaking efforts; their comments have been of immense value throughout the writing process. Much of the work reported was supported by the Procurement Executive of the U.K. Ministry of Defence, sponsored by DCVD, and this applies in particular to the development of reflective array compressors and convolvers.

Thanks are also due to the management of Plessey Research (Caswell) Ltd. for some of the time involved and for funding the typesetting, and in particular to the Director, Dr. J. C. Bass, for his encouragement and for kindly contributing the Foreword. I am also grateful to the staff of The Alden Press (London and Northampton) Ltd. for their fine work in typesetting the script and preparing the figures.

DAVID MORGAN
Caswell, 1985

Foreword

Surface acoustic wave devices are now used in a considerable range of applications in modern electronics to carry out particular signal processing functions with great technical facility and cost-effectiveness. Their development over the past twenty years been a good illustration of success in research leading to a specialist industrial technology.

It was realised early on that transforming an electronic signal into an acoustic wave pattern which travelled over a surface would result in making the signal very accessible to coupling or interaction methods. The invention of the interdigital coupler itself was the key to launching surface acoustic waves at high radio frequencies. Moreover, couplers could be made at the small size required quite readily by the photo-lithographic techniques of microelectronics, and this opened up the opportunities for research in the 1970's. Then too, as so often happens in science, the basic theoretical description of surface acoustic wave propagation had been provided many years earlier in the 19th century when Lord Rayleigh had established the properties of surface waves in the frequency regime of terrestrial seismic waves.

The combination of available fabrication technology and a basic theory and understanding of surface waves gave what seemed to be a powerful technique able to address many of the requirements and problems of modern electronic signal processing. Fourier transformation methods were obviously relevant theoretically and measurements in the laboratory could provide checks and comparisons with them. This fertile situation led to a spate of activity world-wide in which a whole range of devices were invented and studied. The theory was also considerably extended both analytically and through computation to give very exact descriptions of surface wave behaviour. New piezoelectric materials were also developed and refined as surface wave device substrates.

In the twenty years of research in surface wave devices the field has now reached considerable technical maturity. The important applications such as band-pass filters, pulse compressors and delay line oscillators now constitute a well-proven and reliable component technology for television, radar and communication systems of many kinds.

Dr. David Morgan has been a distinguished contributor to surface wave research for many years, and for the past decade he has been a leading member of the surface wave group at Plessey Research at Caswell. His book is the result of his own very wide experience and it also reflects the activities and interests of the Plessey Group over the years. In fact, the development of the technology in Plessey illustrates the general success of surface wave devices in applications. Our work in the early 1970's was concentrated notably on pulse compression devices for three-dimensional radars, television filters, and in electronic defence applications where we received very positive support from the UK Ministry of Defence (CVD). MoD programmes were also a major stimulus towards the strong British position overall in surface wave research. The work at Plessey Research led in due course to the formation of a Plessey subsidiary company, Signal Technology Limited. This successfully specialises entirely in surface wave devices for professional and commercial applications.

Dr. Morgan has been a major participant and contributor to this activity and I welcome his book as a distillation of his experience for the benefit of further surface wave research and applications.

J. C. BASS

Contents

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

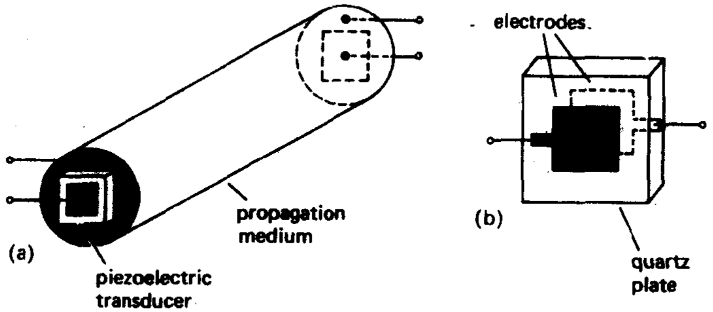

FIGURE 1.1. Devices using bulk acoustic waves. (a) delay line, (b) resonator.

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