SECOND EDITION

SURFACE ACOUSTIC WAVE FILTERS

WITH APPLICATIONS TO ELECTRONIC COMMUNICATIONS AND SIGNAL PROCESSING

DAVID MORGAN

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With Applications to Electronic Communications and Signal Processing

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PREFACE

'The history of science teems with examples of discoveries which attracted little notice at the time, but afterwards have taken root downwards and borne much fruit upwards'

Lord Rayleigh
(Presidential Address to the British Association, Montreal, 1884)

In the context of surface acoustic waves, this statement could hardly be more prophetic. In 1885 Rayleigh described an acoustic wave motion which plays an important part in seismology, and recently this has taken on a quite different significance as the basis for a huge range of electronic devices. The potential for electronics applications was first suggested in the 1960s, noting that the waves could provide substantial signal delays which would be inconvenient to obtain by conventional methods. They also give substantial versatility because transducers for generation and reception can be located anywhere in the propagation path, and lithographic fabrication techniques can provide almost arbitrary geometries with high precision. Consequently, a wide variety of devices have been developed, and they have found their way into many branches of electronics, including signal processing for radar and communications systems. The most notable application area is in bandpass filtering for communications, including the ubiquitous mobile telephone systems.

A previous book on this subject, *Surface-Wave Devices for Signal Processing*, was published by Elsevier in 1985, coincidently the centenary of Rayleigh's 1885 paper. At that time, in 1985, many devices had been established in practical electronic systems, including signal processing devices and bandpass filters for communications and television systems. These devices remain in widespread service now. However, the 1980s were something of a watershed for surface waves. The rise of communications systems such as mobile telephony demanded new capabilities, particularly for low-loss bandpass filters satisfying exacting specifications. In response, a considerable variety of novel devices emerged. A common factor here was the use of reflecting structures, either in the form of reflective transducers or as components in resonators. Reflectivity is employed in various types of single-phase unidirectional transducers for bandpass filtering at intermediate frequencies. Resonators are found in various low-loss bandpass filters for radio frequencies, as well as in surface-wave oscillators. In parallel, many new surface-wave materials were established, some using new types of surface wave. The theory of surface-wave generation and propagation, particularly in reflective structures, has developed substantially and become much more complex. The continual vigor of the subject is well illustrated by the constant stream of publications, as shown by the many recent references quoted here.

This new book expands the coverage of the earlier one to include the recent developments. The earlier material is described in Chapters 2 to 7. This includes various acoustic waves (Chapter 2), surface excitation (Chapter 3), propagation effects and materials (Chapter 4), quasi-static transducer theory (Chapter 5) and non-reflective bandpass filters (Chapter 6). Devices for correlation, used in pulse-compression radar and spread-spectrum communications, are in Chapter 7. These accounts are similar to those of the earlier book, but to allow space for new material, there is some compression and some topics have been omitted. Some results for transducer analysis, derived from the earlier sections, are summarized in Section 5.3 of Chapter 5.

New areas include filters using unidirectional transducers (Chapter 9), waveguiding and transversely-coupled resonators (Chapter 10), and resonator filters (Chapter 11). Preceding these, Chapter 8 describes the theory of reflective transducers and gratings, including analysis using the Reflective Array Model (RAM) and Coupling-of-Modes (COM) theory. At the beginning, Chapter 1 gives a survey of the whole subject. This is intended to be readable independently of the rest of the book.

The book is written at a post-graduate level, assuming some familiarity with topics such as matrix algebra and the Y- and S-matrix descriptions for linear devices. However, much of the material should also be comprehensible at an undergraduate level, particularly the survey in Chapter 1. A prior knowledge of acoustic waves is not necessary, since this topic is summarized in Chapter 2. In fact, much of the theory in Chapters 3 and 5 follows simply from the assumption, often valid, that a piezoelectric substrate supports surface-wave propagation with velocity dependent on whether the surface is free or metallized. This approach is adequate for many devices, and it requires little further knowledge of acoustic waves. The theoretical developments make much use of Fourier analysis, and the required relations are summarized in Appendix A. Since the original book was published, it has become common to describe the behavior of unapodized transducers and gratings in terms of a scattering matrix called the *P*-matrix, so the present book makes use of this form. Appendix D considers the reciprocity and power-conservation constraints on this matrix, and also cascading techniques for analyzing devices with several components such as resonators. This Appendix also considers the all-important topic of multiple-transit signals in surface-wave devices.

An initial reading of the book might start with the survey in Chapter 1 and then skip to Section 5.3 of Chapter 5, which summarises properties of non-reflective transducers as given by the quasi-static theory. This leads on to the use of non-reflective transducers for bandpass filtering (Chapter 6) and matched filtering in radar and communications (Chapter 7). The topic of internal reflections is then introduced in Chapter 8.

The book has benefitted from interactions with many colleagues, particularly in the Nippon Electric Company, the University of Edinburgh and Plessey Research (Caswell). Many of the ideas in the 1985 book arose from work in the Caswell group, consisting of R. Allen, R. Almar, R. Arnold, R.E. Chapman, R.K. Chapman, J. Deacon, R. Gibbs, W. Gibson, J. Heighway, J. Jenkins, P. Jordan, B. Lewis, J. Metcalfe, R. Milsom, J. Purcell, D. Selviah and D. Warne. There was also much interaction with E.G.S. Paige and M.F. Lewis at RSRE Malvern (now part of Qinetiq). The Foreword to the 1985 book was contributed by Dr. J. Bass, Director of Plessey Research (Caswell). In 1991 a soft-cover edition was published with a Foreword by E.G.S. (Ted) Paige, who sadly passed away in 2004. Many of the surface-wave workers in the UK in the 1970s and 1980s, including the Caswell group, owe a debt to Ted for the inspiration he showed as director of the surface-wave group in RSRE Malvern and sponsor of much of the UK research effort in this field.

Other colleagues with whom discussions have been helpful include B. Abbott, I. Avramov, S. Biryukov, C. Campbell, D.-P. Chen, X. Chen, J. Collins, M. DaCunha, C. Hartmann, K.-Y. Hashimoto, J. Heighway, V. Kalinin, J. Koskela, C.S. Lam, M. Lewis, C. Liang, D. Malocha, R. Milsom, R. Peach, V. Plessky, C. Ruppel, M. Salomaa, M. Sharif, K. Shibayama, J.-B. Song, T. Thorvaldsson, M. Weinacht, K. Yamanouchi and S. Zhgoon.

For the present book, I am grateful to colleagues for providing some figures, namely B. Abbott (Fig. 1.4), C. Ruppel (Fig. 1.14) and M. Solal (Fig. 9.6). S. Zhgoon and A. Shvetsov provided data for leaky-wave dispersion (Figs. 11.22 and 11.23) calculated using finite-element analysis. K.-Y. Hashimoto is thanked for making sophisticated surface-wave software available publicly, and for its use here in Figs. 3.2, 11.19, 11.22 and 11.23. Helpful comments on initial drafts of the book have been made by B. Abbott, V. Plessky, D. Malocha , C. Ruppel, M. Solal and S. Zhgoon.

Finally, it is a great pleasure to thank Professor Sir Eric Ash for providing the Foreword to this book. In the early days, Eric was one of the few who recognized the potential future of the subject and initiated its development, and my own work in this field started as one of his students at University College London in the 1960s. I have spent nearly all of my working life in this fascinating subject, and this Foreword now brings it to a full circle. Or perhaps I should say, since the subject continues apace, a further turn of a helix. I hope that readers will find the book both helpful and enlightening.

David Morgan
Northampton, 2007

FOREWORD TO SECOND EDITION

It is a digital world – and has been for a long time. The transformation toward digital electronics which started in the middle of the last century gathered increasing momentum in the early 1970s with the arrival of the microcomputer. Thereafter analog electronics, except where it is intended to interface directly with our human senses, was doomed to an ever diminishing role. Game, set, match for digital? Actually not quite! Just at that moment, there appeared a new and completely unanticipated technology, that of ultrasonic signal processing, and specifically the use of surface acoustic waves – the subject of this book.

Surface acoustic waves were hardly new – they had been discovered by Lord Rayleigh in 1885 theoretically, and their reality confirmed by their appearance in seismic records. The fact that these sub-one Hertz waves, when translated to frequencies six to nine orders of magnitude higher, could perform useful tasks in signal processing came as a great surprise. So what is so good about surface acoustic waves? Firstly for a given frequency their wavelength is very small. As compared, for example, with microwaves one can achieve a great deal in a very small space. The second merit is that surface waves hug the surface; they can be influenced by electrodes placed on the surface. The third merit is the existence of single-crystal piezoelectric materials in which propagation losses are very small, and which provide the opportunity for efficient transformation, in both directions, between electrical and acoustic signals. Surface-acoustic-wave signal processing is therefore a *planar* technology, based on the use of photolithography to define the structures. It shares this feature with semiconductor microelectronics, but differs in that it normally requires just a single photolithographic mask. The common use of masks has enabled surface-wave devices to benefit from the huge advances in mask technology made by the semiconductor industry.

The first and still dominant use of surface acoustic waves is for the realization of bandpass filters, followed secondly by resonators. David Morgan has been a very major contributor to the whole field since its inception. The book provides a brilliant exposition of the subject – in this following the much admired clarity of his earlier book of 20 years ago. Much has happened in the interim. Morgan's book illuminates the whole field, including the rapid developments in the theory of the basic wave types involved and the conceptual advances in wave manipulation. These are advances which have led to performance achievements which could not be approached two decades ago.

Surface-acoustic-wave devices play a very large role in modern electronics. Oddly enough this is known only to those very directly involved – it is almost a secret society! Few people appreciate that a mobile phone will contain at least two and sometimes as many as six distinct surface-acoustic-wave filters. These filters have specifications on passband shape, stop-band rejection, temperature performance which are as rigorous as have *ever* been attempted in telecommunication systems. Most television receivers have two such filters. In addition surface-acoustic-wave devices are used extensively in advanced radar systems for pulse expansion and compression. The total annual production of surface-acoustic-wave filters is at least four billion and possibly nearer seven billion per annum.

Surface-acoustic-wave devices are sensitive animals. They are affected by stress, pressure, proximity of chemical substances, temperature, all of which must be carefully considered in the design of filters and resonators to ensure that when exposed to the real world, they remain within specification. But the other side of that coin is that these elements can act as sensors, with applications for a wide range of sensing needs. They can be used for stress and torque measurements. One notable developing interest is the possibility of their use as selective biosensors. There are intriguing possibilities of incorporating them in car tyres to provide a permanent record of pressure – a potentially very large market.

For all those engaged in advancing the science, the art and the applications of surface acoustic waves, David Morgan's book will provide an invaluable and coherent guide to what is known, and to how current knowledge can be applied toward the further advances in this fascinating area of applied science.

Eric Ash
London, 2007

FOREWORD TO PREVIOUS EDITION (1991)

It is a source of amazement that, given a mask with which to perform the photolithography, all you need is a single crystal with a thin metal film deposited on its surface in order to make a surface acoustic wave device with outstanding performance. It can function as a band-pass filter, passing most of the signal in the pass band but providing 60 dB or more rejection out-of-band. It can be made into a matched filter capable of extracting a signal for noise when the strength of the signal is four orders of magnitude below the prevailing noise. How is it that such a seemingly simple device can achieve so much? An important part of the answer lies in the fact that it is dependent for its performance on *intrinsic* properties of the single crystal-surface acoustic wave velocity and piezo-electric constant. But a vital ingredient is the design of the mask for here is where the subtlety and sophistication enters. It is the design of the mask which makes the difference between a SAW device having either excellent or mediocre performance; the design of the lithography mask can be equated to the design of the device.

A major strength of Dr. Morgan's book is the logical and coherent development of those topics which underpin or are relevant to the design of SAW devices. This book provides a clear and careful treatment of topics ranging from the basic theory of bulk and surface acoustic waves, the electrical excitation and detection of surface waves, material properties, through to the design, performance and application of a range of key SAW devices. Though originally planned as a reference book for the SAW device design engineer, the development of the material is well suited to undergraduate and MSc courses. Students will appreciate not only the clear exposition of the central subject matter but also the linkage with such topics as the application of Fourier Transform techniques and signal processing as applied to radar, and to video and audio telecommunication systems.

Dr. Morgan's book, making its first appearance exactly one century after Rayleigh's classic paper recording his discovery of elastic surface waves, is now five years old. It says much for the original choice and treatment of the subject that virtually all is as relevant today as the day it was written.

E.G.S. PAIGE
November 1990

CONTENTS

1

BASIC SURVEY

Acoustic devices have been used in electronics for almost a century, as described in the historical introduction of Royer and Dieulesaint's book [1]. In 1915 the first transducers were developed for sonar in submarines, making use of the piezoelectric effect in quartz to generate acoustic waves in the sea. A piezoelectric plate can serve as an electrically coupled acoustic resonator, and the use of this for stable oscillators began development around 1920. Today, the quartz resonator is of familiar and widespread use for regulating oscillator frequencies. Among the attractions of acoustic waves are the low velocities (giving a compact device for a given frequency) and, in suitable materials, low losses leading to good resonator Q-values.

In the 1960s it was first suggested that *surface* acoustic waves (SAWs) might also be useful. This type of wave motion, guided along the surface of a solid material, introduces the possibility of accessing the wave within its propagation path, and it enormously increases the potential versatility of the devices. A key requirement is some means for generating and detecting the waves, and many methods were known at the time though they were not suitable for electronics applications because of clumsiness or inefficiency. The key starting point was the advent of the interdigital transducer (IDT) in 1965. With this component, the surface-wave device becomes a suitably shaped metallic thin film deposited on the surface of a piezoelectric crystal such as quartz or lithium niobate. This development immediately changed the practicality of the subject, because such devices could be made easily and cheaply by lithographic techniques borrowed from semiconductor manufacture. In addition to the IDT, a range of other components were developed, particularly reflecting gratings which are widely used in surface-wave resonators.

In the subsequent years, a very wide variety of devices have been developed, including delay lines, bandpass filters, resonators, oscillators and matched filters, all having a variety of forms. The devices are found in many practical