1 INTRODUCTION

Surface acoustic waves (SAW) have drawn much attention of research workers in the field of VHF/UHF signal processing all over the world following the introduction of the interdigital transducer (IDT) by White and Voltmer[1] in 1965. Various SAW devices[2-3] such as VHF/UHF delay lines, bandpass and chirp filters, oscillators, convolvers, correlators, frequency synthesisers, real-time processors, etc., have found wide applications in radar and UHF singal processing, spread spectrum communication, air traffic control, electronic warfare, microwave radio relays, and consumer electronics such as TV due to their exceptional performance in the frequency range from 10 MHz to 2000 MHz. The stimulating factors behind the steady growth of SAW devices are : a) low velocity of SAW, which is about five orders of magnitude less than the electromagnetic wave velocity, b) availability of SAW at the surface, which allows tremendous flexibility in the design of transducers for frequency shaping and matching and c) compatibility of fabrication process with IC technology.

The IDT first conceived by White and Voltmer[1] is the key element of any SAW device. The IDT consists of a series of interleaved electrodes made from a metal film deposited on a piezoelectric substrate, as shown in Fig. 1.1.1. For maximum coupling of energy the width of electrode is kept equal to the width of the inter-electrode gap. An alternating voltage applied across the transducer terminals will produce, through piezoelectric effect,

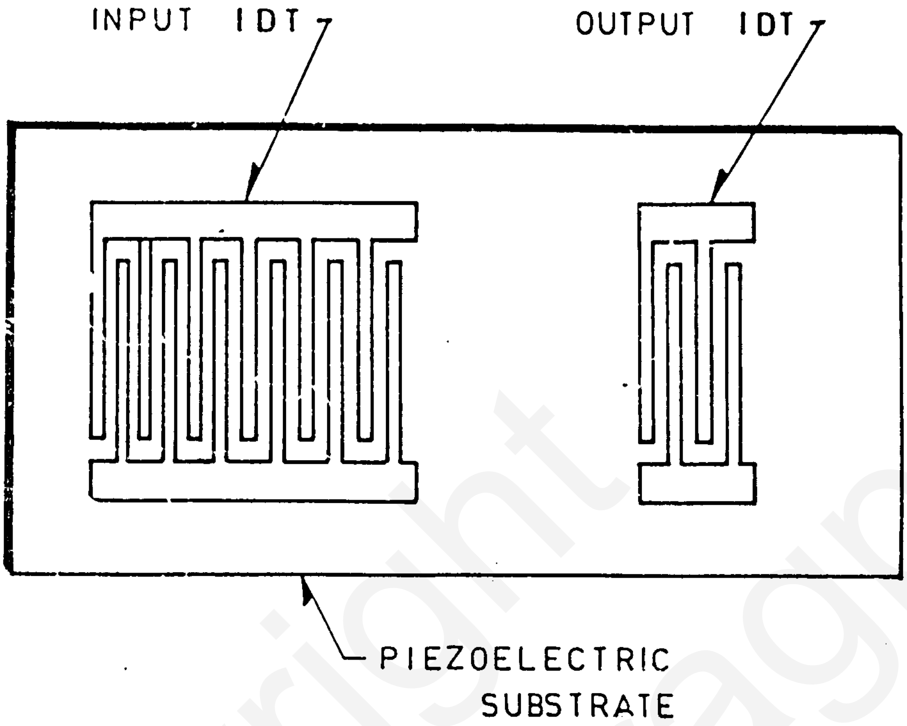

Fig. 1.1.1 Illustration Of SAW Filter

a strain pattern of periodicity λ, equal to the periodicity of electrode structure. If the frequency of the applied signal is such that λ is close to the surface wave wavelength, there will be strong coupling of energy from electrical to acoustical form and vice versa through resonance effect. This leads to generation of Rayleigh waves or surface acoustic waves which propagate over the surface of the piezoelectric substrate in two opposite directions away from the transducer. Thus the IDT launches surface acoustic waves equally in both directions as a result of its structural symmetry. Due to the anisotropy of piezoelectric crystals commonly used for making SAW devices, e.g., quartz, lithium niobate, etc., only certain cuts of crystals and certain alignments of transducer fingers result in energy propagation perpendicular to the electrodes. Some commonly used SAW substrates are Y-cut, Z-propagating lithium niobate (YZ $LiNbO_3$), Y - cut, X - propagating quartz (YX quartz), ST - cut quartz etc. A second IDT placed in the propagation path can be used to detect surface waves, thus forming a delay line or filter. The unwanted surface waves are absorbed at the ends of the crystal by means of black wax or special adhesive tape. An up-to-date data of SAW crystals are given in reference[2].

The IDT has two basic flaws. The first is its relatively high insertion loss resulting from bidirectionality. In a two transducer configuration for delay line or filter applications, only a half of the acoustic energy reaches the receiving transducer where a half of this energy is coupled out and absorbed into the external matched load. Thus the theoretical limit to the minimum insertion loss of a SAW filter consisting of bidirectional transducers (BDTs) is 6 dB. The insertion loss of practical SAW filters using IDTs is in the range from 7 to 20 dB due to different parasitic losses, such as propagation loss, resistive loss in transducers, diffraction loss, bulk wave conversion loss, etc. The second drawback is the relatively large triple transit echo (TTE) which poses a serious problem in SAW delay lines as well as in filters, since it introduces strong in-band ripples[4] in the frequency response.

The highest frequency of operation of SAW filters is limited by the photolithographic resolution. Application of electron beam lithography[4] has pushed the frequency limit to the extreme of L-band (3GHz). Latest design techniques[2-4] for weighting the IDTs may be used to realise SAW bandpass filters with extremely tight specifications and complex frequency response shapes. These advantages are to some extent offset by the higher insertion loss of IDTs, thus narrowing down their range of applications. Improved transducer structures called unidirectional transducers (UDTs)[23-44] have been conceived in order to overcome this drawback. Such transducers which are driven by multi-phase electrical signals have resulted in insertion loss as low as 0.72 dB[34]. But this is achieved at the cost of other good features, viz., frequency shaping which becomes more difficult in the case of UDTs, since their modified structures do not permit as much flexibility as in simple IDTs for amplitude or phase weighting. Considerable work has been done to realise low loss SAW filters with desired frequency response[70], but there is a need of more intensive research in this area to achieve perfection.

A UDT consists of several IDT sections separated physically by a certain fraction of acoustic wavelength such that surface acoustic waves are launched preferentially in one particular direction at resonance frequency and are cancelled in phase in the opposite direction, when these sections are driven by multi-phase electrical signals. Of the various UDT configurations developed so far, the three-phase UDT[5] and the group type quadrature phase UDT (GUDT)[6] are found to be the most attractive for practical applications for their wide bandwidth and low insertion loss.

The author made a thorough review of the different SAW transducers and their performance. Though there appeared in literature a number of good review papers[7-12] on IDTs, their models and applications, no systematic and up-to-date review work on UDTs has so far been published. It initiated the author to carry out a literature survey on the development of different UDTs and their applications. Chapter 2 outlines briefly the above review work, which includes the most up-to-date data on UDTs (within the limitations of the library facilities locally available at the time of submission of this thesis).

Before introducing the topics on which work has been carried out and reported in this thesis, it would be worthwhile to give a gist of some basic work done on SAW devices which are relevant to the present work.

The IDT has been analysed following the Mason equivalent circuit[8] approach or by solving acousto-electric wave equation[12] in the piezoelectric substrate using appropriate boundary conditions. The first method is much simpler than the second and is used for the first order design of SAW devices.

Szabo et al.[7] reviewed the various models used to describe the frequency response of IDTs, These models are : 1) impulse[8] model using crossed field equivalent circuit, 2) impulse (sine wave)[9] model, 3) delta function[10] model, 4) modified delta function[7] model, 5) spectral weighting[11] model, and 6) space harmonic[12] model. The impulse models are useful to calculate approximate values of transfer function and input impedance of the IDT. The delta function model provides the normalised transfer function shape and does not give the absolute insertion loss or input impedance. The spectral weighting and space harmonic models are more accurate but involve lot of computation. The second-order effects pose serious problems in the design of SAW filters. Lot of investigations have been carried out to correct the various second-order effects[13], viz., diffraction, wavefront distortion, surface wave regeneration, RF interference, bulk wave radiation, electrode resistance effect, etc. A fool-proof design which takes into consideration all the second-order effects is almost impossible in practice. Attempts are, therefore, made to eliminate these effects or to compensate for them through the use of split fingers[4], dummy fingers[4], multi-strip coupler[38], good RF shielding between input and output transducers[72], etc.

When a surface acoustic wave is incident on a transducer, a part of it is reflected back, a part is transmitted forward, and the remaining part is converted into electrical energy and absorbed in the load. Similarly, if a RF signal is applied across the transducer, a part of it is reflected back to the source and a part is converted into acoustic waves which propagate in both directions. As it is offen required to estimate the value of different scattering parameters[49] in the design of any SAW device, a simpler analytical method for their quick evaluation at different frequencies is found necessary. With this view, simple analytical expressions that give the frequency and load dependence of different scattering parameters have been derived by the author using crossed-field equivalent circuit model[8]. Chapter 3 presents the above simple scattering analysis for both ordinary IDT and GUDT, and the results of related experimental investigations on YZ-$LiNbo_3$ samples to examine the validity of the theory. The different components of SAW reflection originating from regeneration and piezoelectric field shorting under metal electrodes are investigated in detail both theoretically and experimentally. The simple theoretical formulations are found to yield results comparable to those obtained from more rigorous analyses involving lengthy computations[50]. The results for the scattering parameters of GUDT are particularly useful for the design of low loss filters.

The most attractive feature of SAW bandpass filters is their capability for frequency shaping realisable through different weighting techniques. Amplitude weighting[10] for frequency shaping is implemented in SAW filters by finger withdrawal or apodisation methods. The withdrawal weighting technique offers low loss but it is useful for designing only narrow band ($< 5\%$) filters[73]. On the other hand, apodisation is a more versatile tool to design a SAW filter for small transition bandwidth and large sidelobe rejection.

The apodisation profile for the frequency shaping of SAW transducers may be calculated following an analytic approach similar to that used in design of a digital FIR filter based on window functions[14]. Such design approach is, however, valid for symmetric bandpass filters and does not take into account the second-order effects typical of SAW filters in the first stage of calculation. The latter is normally incorporated as correction terms after the first order design[13]. More versatile methods for the calculation of the apodisation profiles of symmetric or asymmetric SAW bandpass filters are based on purely numerical approach[4] which considers the different second-order effects. Though the available numerical techniques yield excellent results for SAW filters consisting of ordinary IDTs, their suitability for the design of low loss SAW filters consisting of UDTs is yet to be established. According to Tancrell[14], the window function approach is quite efficient and much simpler than other techniques for the design of symmetric bandpass filters.

The available optimum window functions, such as Kaiser-Bessel and Dolph-Chebyshev functions are relatively complex for computation, whereas the simple trigonometric windows meet only limited specifications of a filter[15]. Tancrell[14] has discussed the design of a SAW filter using Kaiser-Bessel window by establishing relations between passband ripple, sidelobe level and transition bandwidth. The drawback of Tancrell approach[14] is that it does not specify the 3 dB bandwidth as an independent parameter.

In Chapter 4, the author has proposed new window functions whose performance is comparable to the Kaiser-Bessel window function. The Kaiser-Bessel window results as a special case of the new family of window functions proposed. The new window functions are much easier to compute as opposed to the Kaiser-Bessel window, or the Dolph-Chebyshev window. Following the Tancrell approach[14], the author has also developed the design methods for SAW filters using the proposed window functions.

Since the apodisation of UDTs with sin(x)/x profile is difficult due to multi-phase arrangement, they are often directly weighted with smooth window profiles. The author has used the new window function for the design of low loss SAW filters with GUDTs. This is included in Chapter 4. Experimental results are also included and compared with corresponding theoretical results. Some experimental results on a new wide-band quadrature phase UDT with a slanted ground busbar are presented at the end of Chapter 4.

SAW UDTs have also been used in specific applications[16-18] other than the low loss filters. One of the earliest applications of the unidirectional property is to FSK system[16] in which a three-phase UDT is used. In another application, Hirabayashi[17] has realised a variable delay line using a quadrature phase UDT. Gautam et al.[18] have utilised GUDT along with two three-phase

UDTs to realise a transceiver switch for short distance communication systems. The forward mainlobe and the reverse strong sidelobe of GUDT are used for switching the receiver and transmitter carrier frequencies.

In Chapter 5, the author has suggested use of UDTs in place of ordinary IDTs in SAW delay line controlled oscillators and reported the results of some experimental studies. The lower delay line loss results in a lower amplifier gain which reduces the overall cost and leads to higher short-term stability and smaller output noise level. Moreover, the unidirectionality property enabled the author to realise a built-in injector on the piezoelectric substrate for the injection locking oscillator(ILO). The author has studied different structures of built-in injectors for SAW ILO applications.

Several workers[19-22] have studied the frequency tuning techniques for SAW delay line oscillators. It is normally difficult to tune a SAW oscillator over a wide bandwidth, since the frequency stability and tuning range are inversely related. The author has studied experimentally the tunability of SAW oscillator with low loss delay line employing different tuning techniques. A new technique using an electrically loaded BDT placed over the propagation path of the delay line has been found to yield interesting results.

Chapter 5 also includes the experimental results on a mode-tunable SAW oscillator containing a SAW comb filter[22] as the delay line. Different comb filter configurations are considered in order to obtain wider separation of stable modes of oscillation. Such oscillators may be useful for frequency synthesis applications.

The last Chapter highlights the salient points of the various theoretical and experimental studies reported in the thesis and draws some important conclusions thereof. The Chapter also discusses the "blanks" which are required to be filled up by future work. For example, the scattering parameters of UDTs need more precise theoretical analyses for a better agreement with experimental results. It is also required to carry out a more detailed investigation of the proposed quadrature phase UDT with slanted ground busbar and the mode tunable SAW ILO. Both may prove to be quite useful for practical applications. Finally, it may be pointed out that the lack of adequate high resolution fabrication facilities has restricted the operating frequencies of SAW devices to a maximum frequency of 30 MHz in all experimental studies. Some of the concepts introduced in the thesis may prove to be more useful at higher frequencies. In particular, the built-in injector of SAW ILO as proposed in Chapter 5 is more advantageous at high frequencies.