

Evolution of the SAW Transducer for Communication Systems

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Abstract – This paper will review the evolution of SAW transducer technology for communication systems. Applications of TV sets, radars, satellite communications, mobile phones and a wealth of others have driven a diversity of transducer embodiments. Some of the diverse sets of transducers include: bidirectional, multi-phase unidirectional, single phase unidirectional, chirped, coded, slanted, resonant and others. Scientists and engineers continually push the limits on materials, device design and manufacturing, leading to lower loss, broader bandwidths, smaller size and lower cost devices. Over the past 3 decades competing technologies have rose to challenge SAW devices, such as CCDs, ceramic filters, film bulk wave devices, MEMs and others, however, SAW transducer technology has been remarkably robust in adapting to system needs and continues to fill vital positions in communication transceivers. Connections between past military requirements, commercial communication systems and current consumer applications have driven the transducer technology in varied directions culminating in today's diverse, application specific devices. This paper will take an historical view of the SAW transducer's diverse embodiments, practical implementations, and innovative problem solutions, through the eyes of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control (UFFC) society publications.

I. Introduction

This paper will discuss the evolution of the SAW transducer for communication systems. The paper was proposed in recognition of the 50th Anniversary of the Ultrasonics, Ferroelectrics and Frequency Control Society (UFFC_S). The presentation highlights the development through the "eyes" of the UFFC publications, not necessarily crediting or citing the first publication, inventor, etc. There is a large body of contributions in other publications, patents, worldwide symposiums, non-English journals, etc., which makes it virtually impossible to site the first disclosure of ideas. However, every significant SAW transducer embodiment has eventually graced the pages of UFFC publications. Therefore, a comprehensive view of the many SAW transducer embodiments and citations to a wealth of other references can be obtained. Two excellent historical reviews were presented at this symposium. A discussion of the IDT conception was provided by White entitled "Two Bits of History: Thermoelastic Wave Generation and SAW Transduction" [1]. A second presentation by Gulyaev and Hickernell entitled "Acoustoelectronics: New Ideas for a New Era" [2] gave a more global historical review of SAW technology development. Additionally, a very good reference on the

history of SAW technology was provided by Morgan in 1998 [3].

This paper will be organized in sections based on the type of transducer embodiment. A strict chronological order will not be followed in the citations since similar transducer embodiments evolved over time, sometimes being resurrected from the past as needed due to new applications.

The SAW transducer has a variety of parameter degrees of freedom which include:

- Electrode amplitude and/or length
- Electrode phase (electrical)
- Electrode position (delay)
- Instantaneous electrode frequency

In addition, there are device infrastructure degrees of freedom which include:

- Material Choice
- Thin Films on the Substrate
- Spatial Diversity on the Substrate
- Electrical Networks and Interface

This paper will present examples of the use of all these degrees of freedom in various SAW transducer embodiments. Every SAW transducer inherently exhibits, to some degree, transduction, reflection, regeneration and non-linearity; this presentation will not discuss non-linearity. In general, filters will not be presented unless necessary to demonstrate the use of the transducer embodiments. A decision by the author excluded discussion all multistrip coupler embodiments. Finally, not every transducer innovation can be discussed, but the author has attempted to highlight the most significant and diverse embodiments which were developed over the years.

II. Fundamentals and Unweighted Transducers

The basic IDT is a three port structure which has 2 acoustic and 1 electric ports. When an electrical signal is input, a SAW is launched from both acoustic ports. Similarly, when a signal is input on one acoustic port, a wave is launched from the other acoustic port, as well as an electric signal developed across the buss bars due to the voltage developed across the IDT electrodes. This 3 port nature causes transduction and regeneration which causes some effects which must be controlled, most notably the 3 dB bidirectional loss and the triple transit echo (TTE).

A great amount of work has been spent on the development of unweighted transducer structures. An unweighted transducer has one degree of freedom, the electrode configuration. The basic IDT has two electrodes per wavelength, an electrode period of $\frac{1}{2}$ wavelength and a width to period ratio of $\frac{1}{2}$. This initial configuration provided efficient transduction but was plagued with internal mechanical edge reflections which distorted the

symmetry of the passband. In 1972 in 2 adjacent papers, the split- or double- electrode configuration was introduced as a means to eliminate the in-band mechanical reflections and quickly became very popular in filter designs [4,5]. In

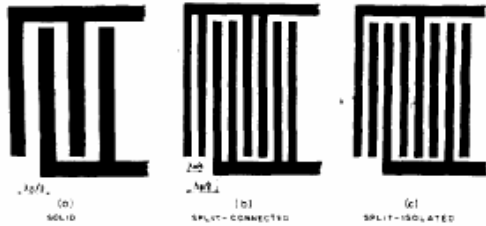


Figure 1 a) Basic IDT, b) Double electrode IDT and c) Floating electrode IDT, reprint from [4].

addition in De Vries' paper, the first picture of a floating electrode transducer, shown in Fig. 1, is used later in several transducer embodiments. In 1972, Weiglan and Nudd [6] first showed that the electrode width to period ratio affected the transduction strength at the fundamental and harmonic frequencies, an effect used in many later transducer/filter configurations. In 1975, Engan presented a general analysis when using an integer number of electrodes per wavelength in an IDT [7]. The paper showed the effects of the electrode configuration on the IDT fundamental and harmonic responses. This is also one of the first publications on the use of basic sampling theory applied to an IDT. Atzani, et. al. showed the first dual track or balanced transducer structure in 1972 [8], which is now used in many filter applications, including balanced amplifier applications. At the time, the paper was principally addressing transduction efficiency and proper electrode weighting and phase, but does describe a balanced network driver. The unweighted, uniformly sampled SAW IDT has been used in countless filters since it provides simple, efficient transduction, a uniform beam profile with frequency, and provides the well known sampling function frequency response. One example of the usefulness of a simple unweighted transducer structure: Lewis introduced the interdigitated interdigital transducer (IIDT) in 1982 [9], with an embodiment shown in Fig. 2. The low loss structure uses interleaved input and output transducers; eliminating the inner transducers bidirectional loss. Hikita, et. al., further refined the filter in 1983 by varying the length of the transducers within the IIDT input/output transducer structure providing better filtering [10].

III. Apodization and Time Sampling

In 1969 Tancrell made a quantum leap forward in the development of SAW technology by introducing modern signal processing techniques for application to SAW transducers [11]. His classic paper described the transversal filter concept: define a required frequency response using a finite impulse response (FIR) filter, obtain the time IR via the Fourier transform, and map the tap weight amplitudes and delays into the transducer. In 1975, Hunsinger and Kansy demonstrated that classical sampling

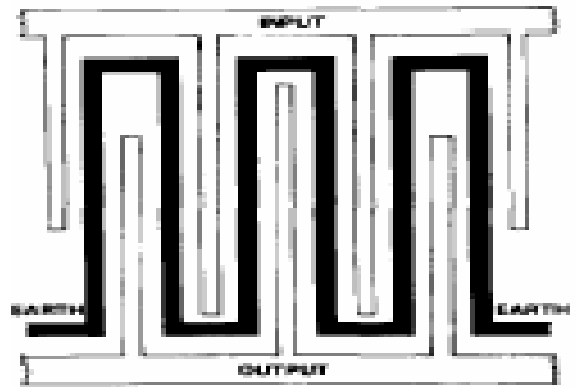


Figure 2 Schematic of the shortest embodiment for an IIDT, reprinted [9].

theory applies to the IDT and any desired sampling frequency can be chosen, subject to the Nyquist criteria, extending the work of Engan [12] and Tancrell. An example of sampling versatility is shown in a dual passband filter by Potter and Shoquist in 1977 [13]; using the main and image response to meet a required filter specification.

Tancrell realized that amplitude weighted and spatially weighted time responses, as shown in Fig. 3, contained the same information except one had a uniform

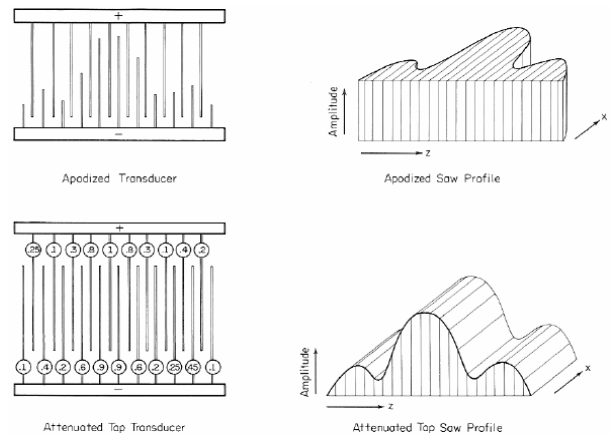


Figure 3 Top: Apodized schematic SAW has uniform amplitude vs z, and bottom: amplitude weighted schematic; SAW has varying amplitude versus z.

spatial response and varying amplitude while the other has constant amplitude but a varying spatial response. The spatial mapping of time domain information into an electrode pattern was called apodization, as shown in Fig. 3. An apodized transducer produces a varying and non-uniform beam profile as a function of frequency, as shown in Fig. 4 and the IDT launches SAW energy even at null points in the transfer function. However, the integral of the SAW amplitude profile across the beam yields the actual transfer function, as shown in Fig. 4. This is why almost all filters use an apodized IDT and a uniform beam profile IDT. There are many apodized IDT embodiments to yield a

given IR. The most obvious was the one shown by Tancrell where the electrode overlaps are symmetrically centered about the beam center, as depicted in Fig. 4. This was the embodiment used for several years since the time–spatial mapping was quite obvious. Dummy electrodes were added to maintain the constant phase velocity across the aperture, defined as electrodes which do not generate SAW because adjacent electrodes are of the same polarity. This produced better filter responses partially because of uniform velocity, but also because the dummy electrodes provided a uniform electrostatic profile, as later published in back-to-back papers in 1978 by Datta and Morgan [14,15], respectively. In 1975, Meyer introduced the slant-apodized IDT for the purpose of eliminating the electrode breaks from being in-

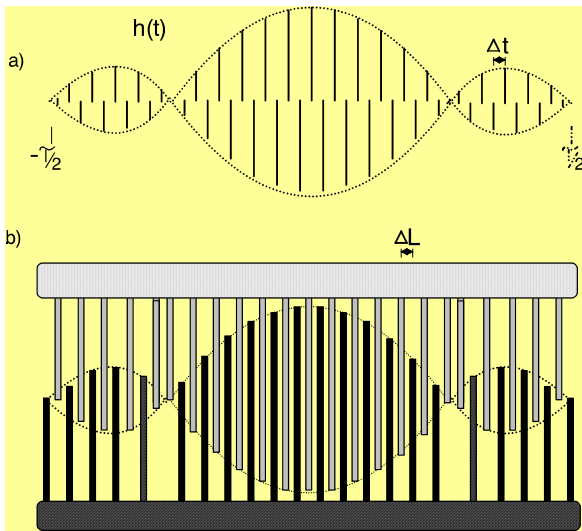


Figure 4 a) Schematic representation of an impulse response mapping into b) an apodized IDT.

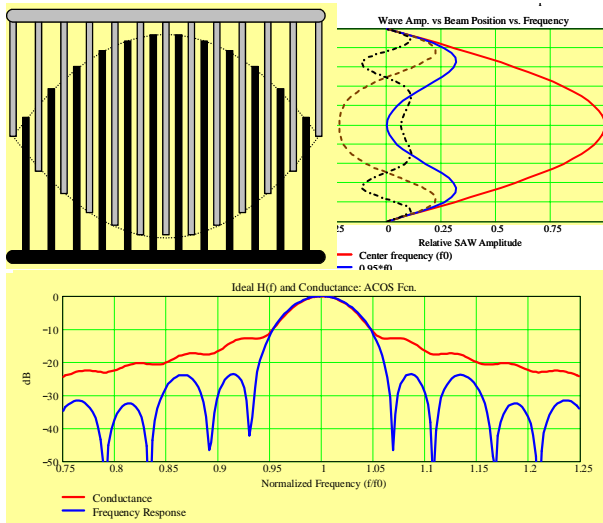


Figure 5 Top: Schematic of IDT and beam profiles at 4 differing frequencies and b) transfer function and conductance versus normalized frequency.

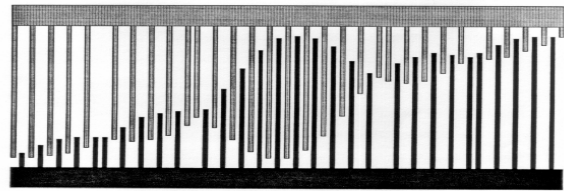


Figure 6 Example of a slant apodized transducer. Dummy electrodes are removed for clarity.

line[16]. The apodization pattern is symmetric about a straight-line extending from the lower left to upper right or lower right to upper left of the IDT beam width. A very important side-effect was to more uniformly distribute the tap weights across the beam which yielded a more uniform conductance versus frequency. In 1984, Vigil, et. al., [17] showed the effects of various apodization patterns on the conductance and electrical network effect; showing the advantage of the slant apodized pattern. In 1980, Hikita, et. al., and Yamanouchi, et. al., published new apodization patterns called phase and distance weighting, respectively, which demonstrated other versatile apodization approaches [18,19].

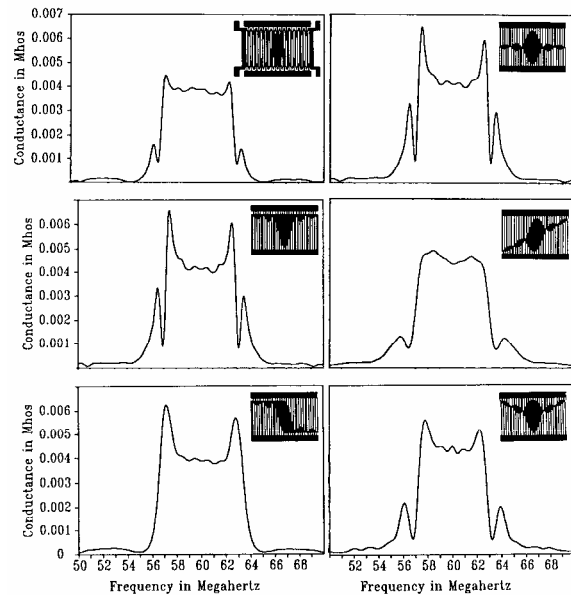


Figure 7 Example of conductance plots versus frequency for various apodization embodiments. Each embodiment has the same IR. Spreading the energy across the beam provides a smoother conductance response.

IV. Non-Apodized Weighting Techniques

A. Phase Coding

In 1971 Jones, et. al., introduced a non-apodized phase coded transducer [20]. The IDT could easily encode a BPSK signal by changing electrode polarities to match the binary code sequence, thereby having a uniform amplitude but phase reversals. This was a very useful IDT embodiment for spread spectrum communication systems

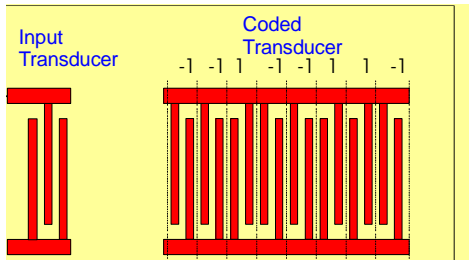


Figure 8 Schematic of a BPSK phase coded SAW filter used in spread spectrum communication systems.

using a fixed code sequence and is an idea later applied to tagging.

B. Withdrawal and Group Weighting

Techniques were also developed where the acoustic beam aperture had no apodization or electrode breaks but did allow passband shaping and sidelobe control. These embodiments were a necessary development in order to produce better or unique filters. In 1972, Bristol used the grouping of uniform electrodes to approximate a Hamming function IR [21]. This was the introduction of approximating an IR by grouping/removing uniform electrodes. In 1973, Hartmann [22] generalized this approach, called withdrawal weighting, where an algorithm is written to optimize uniform electrode placement within an IDT. The original work placed electrode pairs at the calculated positions and left gaps where electrodes were missing. Most current withdraw embodiments put in dummy electrodes for uniform phase velocity and ease of calculating the electrostatic effects, as previously mentioned. In 1979 Malocha, et. al., [26] extended withdrawal weighting, whereby any IR is approximated by variable but discrete tap weights, yielding better filter responses. It is applicable to any amplitude or apodized weighting scheme. Combinations of weighting techniques can be used to provide better filter performance, as shown by Sandy in 1979 [25].



Figure 9 Example of a withdrawal weighted IDT transducer, reprinted from [22]. The dotted lines represent removed or “withdrawn” electrodes.

C. Capacitive Weighting

In 1974 Engan, introduced series capacitive weighting which breaks the beam width into an integer number of series electrode segments and the input voltage is divided equally on each segment [23], as shown in Fig. 10. This embodiment produces an amplitude weighted SAW, but only allows quantized tap weights. In 1975, Malocha and Hunsinger, [24] introduced a capacitive tap weighting technique fabricated using thin film capacitors in a bridge type network. The approach provided a fully dynamic

amplitude weighted SAW approach, but a multi-level fabrication is required which is not cost competitive compared to single level metallization.

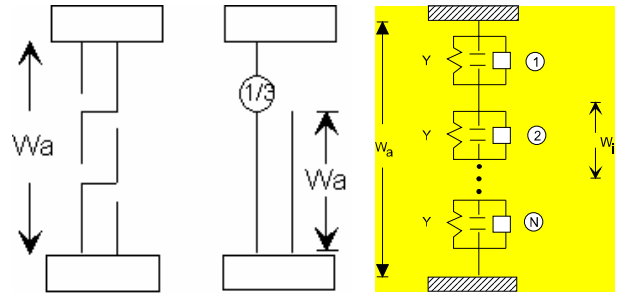


Figure 10 Example of a series capacitive weighted transducer schematic with 3 segments, the equivalent tap weight, and its modeled equivalent circuit [23].

D. Slanted Transducers

The devices discussed thus far all used a uniform sampling rate throughout the IDT. However, it is possible to vary the local frequency in any IDT section by changing the electrode periodicity. In 1969, Tancrell introduced the concept of a linear dispersive device, called a chirp. In 1973, Daniel and de Klerk [27] provided a first analysis and data on an in-line and a slanted chirp transducer. The in-line dispersive varies the electrode period, but has a uniform SAW beam profile with frequency. Another embodiment is the slant-dispersive transducer which also has a varying group delay but the local frequency is varied across the beam, as described by Potter and Hartmann in 1977 [28]. When used in conjunction with a similar slant-dispersive IDT, the filter eliminates the Fresnel ripple problem of the in-line structure. If the filter dispersive transducers are complex conjugates in frequency, then a linear phase filter is obtained. The slanted transducer for linear phase filters had little development until 1982 when Campbell, et. al., [29] demonstrated very good filtering results for wideband filters. In 1998, Solie reviewed various methods for

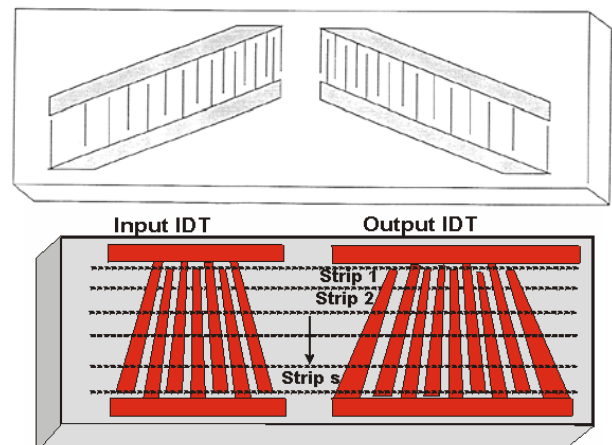


Figure 11 Top: Example of a slanted down-chirp filter and bottom: example of a linear phase slanted transducer (from Campbell).

weighting slanted IDTs, including slant variation, capacitive and block weighting [30].

V. Multiphase Unidirectional Transducers

A. Three Phase Unidirectional Transducers

The traditional two bidirectional-transducer filters have a 6dB insertion loss, 3dB per bidirectional transducer, and have a triple transit echo (TTE). The TTE level, in dB, is approximately $\{(2 \times \text{insertion loss}) + 6\text{dB}\}$ which requires fairly high loss to minimize the TTE to an acceptable level. In 1972, Hartmann, et. al., [31] introduced the first multiphase unidirectional transducer (UDT), shown in Fig. 12. The embodiment uses three electrical ports, 3 electrodes

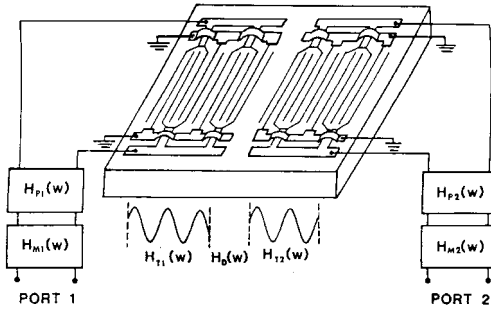


Figure 12 Schematic of a three phase UDT filter with matching and phasing networks.

per period, each electrode separated by $\lambda/3$, and one electrode per period connected to alternating electric ports. The unit cell is one wavelength of center frequency and so no sub-harmonics are generated. Fractional bandwidths of 20% can be achieved with low loss, and a strong second harmonic exists due to sampling. The embodiment requires multi-level fabrication for bridge crossovers. The UDT can be analyzed as 3 collinear transducers having a spatial offset of $\lambda/3$, or 120 degrees at center frequency. In order to achieve UDT operation, it is necessary to provide an electrical phasing network which also provides a 120 degree phase shift, at center frequency, between adjacent electrodes. This is illustrated as at center frequency as forward and reverse direction vectors, as shown in Fig. 13. Phasing is easily accomplished with two reactive elements on two of the electrical ports with the third port grounded. In addition, a one or two reactive element matching network is required to match the UDT to the load impedance.

In 1979, Malocha presented a three phase UDT where the electrodes and the phasing network were in quadrature and the structure also required bridge crossover technology in fabrication [32].

B. Group-Type Unidirectional Transducers

In order to overcome the multilevel fabrication approach, Yamanouchi presented the group type UDT (GUDT) in 1975 [33]. The GUDT embodiment also uses three electrical ports with one port grounded. One port is termed in-phase (I) and the other quadrature (Q), since the two ports are an integer plus one-quarter wavelength offset from each other. Unlike the three phase UDT, the GUDT

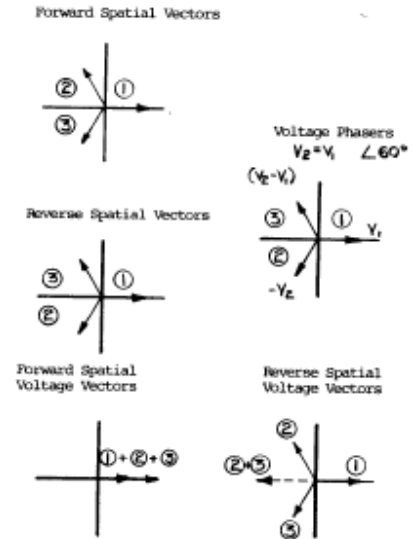


Figure 13 Center frequency vector analyses of the spatial and electrical phasors necessary to achieve unidirectionality for a 3 phase UDT.

can have many embodiments depending on the length of the unit cell. The unit cell length is visualized as two transducers of equal length, but variable by design; offset by an integer plus one-quarter wavelength. Because the unit cell spans multiple wavelengths, sub-harmonics are generated. Usually the filter is composed of 2 GUDTs which have differing unit cell lengths in a manner to minimize the subharmonic filter response. In general, the GUDT also requires two reactive phasing elements providing a 90 degree electrical phase shift between the I and Q ports. The GUDT has the unique property that the input impedance, after phasing, is pure real. This means that proper choice of beam width can eliminate need for matching components to a real load.

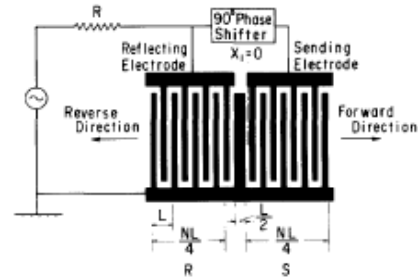


Figure 14 GUDT schematic with required electrical phase shifter with connections to an external generator, reprinted from [33].

VI. Single Phase Unidirectional Transducers

The multiphase UDT reduced the filter loss, and also eliminated the TTE for many required specified fractional bandwidths, but required phasing and matching networks. In 1976, Hanma and Hunsinger [34] devised a transducer that used the internal reflections from electrodes to cancel the regenerated wave, which minimized the TTE.

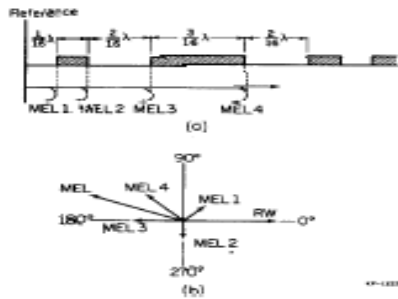


Figure 15 Original SPUDT disclosure which demonstrated the ability to cancel the filter TTE using regeneration and mechanical reflections, reprinted from [34].

This technique's primary purpose is to eliminate the TTE around center frequency but as a consequence, also lowers the filter loss. By proper transducer design and a single matching element, the filter's TTE could be minimized while also lowering the insertion loss; unlike bidirectional filters where insertion loss increases as the TTE decreases. This approach uses a single electrical phase, single level metallization, and varied width electrodes, as shown in Fig. 15. In 1982, Hartmann, et. al., [35] reintroduced the technique using a multi-level fabrication technique and

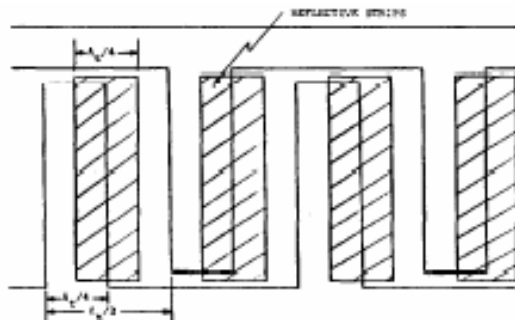


Figure 16 SPUDT using a multi-level reflector grating, reprinted from [35].

called it the single phase UDT (SPUDT), which is now the common term. There are many SPUDT embodiments which subsequently evolved from these first two disclosures. In 1983, Lewis [36] demonstrated a single level SPUDT by removing regions of transduction and replacing them with a reflector bank. The structure is very

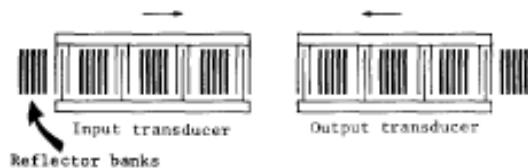


Figure 17 Single level SPUDT using a reflector bank in region of removed transduction electrodes, reprinted from [36].

simple but creates sub-harmonics, reduces coupling, and lacks design flexibility. In 1984, Yamanouchi, et. al., [37] introduced the floating electrode SPUDT (FEUDT), shown in Fig. 18. The shorted or open electrode configuration within a unit cell changes the transduction/reflector

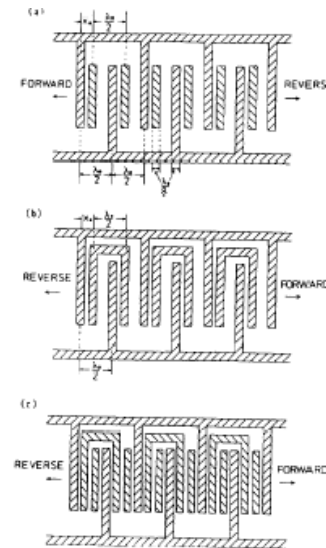


Figure 18 FEUDT configurations, reprinted from [37]. Forward and reverse directivity is controlled by changing the floating electrode placement within the unit cell.

interaction and "selects" forward/reverse directivity. In 1986, Kodama, et. al., introduced the distributed acoustic reflecting transducer SPUDT (DART) [38], shown in Fig. 19. By segmenting the reflecting electrodes, a variable reflectivity can be achieved to give greater design capability when canceling the net reflection and transduction effects. In 1989, Hartmann and Abbott [39] discussed the electrode width controlled (EWC) SPUDT, which demonstrates ways of controlling transduction and reflection independently within a unit cell which allows better filter performance to be achieved.

Periodic reflectors are inherently narrowband which limits the SPUDT fractional bandwidth of the previously discussed embodiments. C.B. Saw and Campbell [40] introduced the slanted SPUDT for wide band low loss filters in 1982. This embodiment utilizes many of the parameters and configurations previously discussed in an extremely creative manner. By using spatial diversity in the slanted structure, the reflection and transduction electrodes are localized in the beam within a narrow band around the local carrier frequency. Each track segment in the beam width can be optimized over a narrow fractional bandwidth, but the sum of the parallel tracks provides a wide band SPUDT response. Solie showed excellent SPUDT results using this technique, in conjunction with various weighting techniques [30]. In 1994, Venture, et. al., [41] introduced the resonant SPUDT (RSPUDT) in which adjacent cells of a UDT have their forward and reverse ports mirrored. This embodiment sets up a short, local resonant

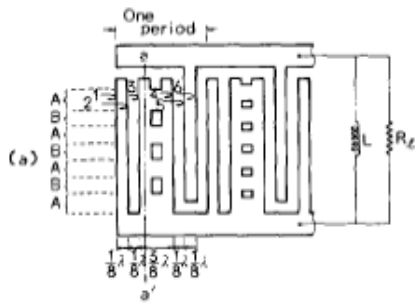


Figure 19 DART SPUDT structure, reprinted from [38]. By segmenting the reflector electrode, reflective is spatially varied across the beam. This provides a variable reflectivity at a given point in the transducer's beam and tap delay.

cavity which provides another degree of freedom in the SPUDT design and provides better filter performance. In 2002, Martin, et. al., [42] introduced the waveguide SPUDT structure, shown in Fig. 21. The SPUDT uses transverse wave coupling of adjacent tracks to provide SPUDT operation. Also in 2002, Jian, et. al., introduced the slanted harmonic SPUDT [43], shown in Fig. 22. In this

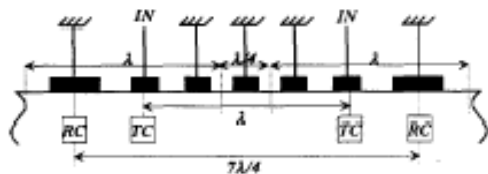


Figure 20 RSPUDT schematic showing the localized resonant cavity produced by mirroring a unit cell, reprinted from [41].

embodiment, the harmonic operation of the SPUDT is used to operate at high frequencies and the slant provides the advantages previously discussed. Finally, a SPUDT was introduced by Wright, et. al., [44] which is able to use the natural offset between the center of transduction and reflection in a $\frac{1}{2}$ wavelength period IDT to produce a SPUDT, termed a natural SPUDT (NSPUDT). The operation of the NSPUDT is unique to only certain crystal cuts and orientations which need to be identified. The inherent advantage is tarnished by the fact that the



Figure 21 Waveguide SPUDT, reprinted from [42]. The SPUDT is achieved by using the transverse wave coupling between tracks.

NSPUDT's forward and reverse directivity is fixed, i.e., the input transducer and output transducer launch/receive waves in the same direction. In designing a filter, an NSPUDT must be used in conjunction with some other type SPUDT in order for the transducer's forward directions to be "looking" at each other.

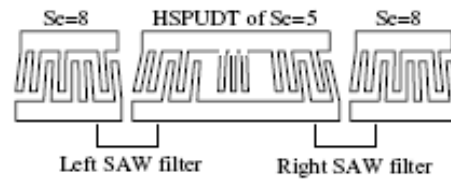


Figure 22 Harmonic SPUDT, reprinted from [43].

VII. Conclusion and Discussion

This presentation has attempted to highlight the most significant SAW transducer embodiments for communication applications over the past 40 years. The approach was to use the UFFC publications as the sole reference source, with the understanding that it would be impossible to correctly cite all disclosures made worldwide. As in the case of any review, the author has made some personal decisions as to what to include in the presentation, based on his professional understanding and/or bias. It is hoped that the paper gives a good overview with major highlights and that cross references will fill in gaps that may have been inadvertently missed or omitted.

The SAW transducer has undergone many transformations from its conception as a simple comb structure. The transducer provides a finite impulse response and bandpass characteristics. Many concepts found in signal processing texts are applicable to SAW technology, including sampling, modulation, phase coding, filtering, Fourier transform techniques, convolution, etc. which provide enormous versatility for complex signal processing applications. Many of these concepts are used in the varied transducer embodiments discussed in this paper. The bidirectional transducer is still used in many IF filter applications where the emphasis is on filter performance and higher insertion losses can be tolerated. The multi-phase unidirectional transducers were important in the 1980's and early 1990's when low loss and high performance were a requirement, especially military applications. However, the requirement for phasing and matching networks has reduced their popularity in commercial applications. The slanted transducer, in various embodiments, is still used in many applications, including dispersive devices. It can be bidirectional or SPUDT, dispersive or non-dispersive, and has very good filter performance where wide fractional bandwidths and a near brick-wall filter response is required. Phase coded transducers are still a simple and accurate way of producing a coded waveform at RF frequencies and have limited military applications. The SPUDT filters are commonly used in commercial applications because of their moderate

loss, TTE suppression, good filtering capabilities and easy manufacturing.

The highest volume commercial SAW filters are the ladder/lattice SAW resonator filters. Since it is a filter and not just a transducer embodiment, they were not discussed. They use a simple transducer and reflectors to form a resonant cavity, called a resonator. Multiple resonators are used as impedance elements in conventional electrical networks to produce low loss, RF filters. These filters are manufactured by the millions per day at costs below one dollar. These are an important class of filters which are left for a future author's discussion.

The discussion was focused on the SAW transducer embodiments. Many of these embodiments are directly applicable to the launching of the many other types of similar waves, which can be coarsely referred as pseudo_SAW. These waves travel near the surface and have differing particle motion than SAW, but can have very efficient transduction with many of the transducers discussed.

New SAW transducer/filter embodiments continue to be developed to meet ever demanding filter specifications. Current transducer developments are more incremental and are often devised to meet a specific application specification. Recently, the SAW technology evolution has been fueled by the cellular phone market which has pushed filters to lower loss, lower cost, smaller size and integration. With the advent of silicon zero-IF technology, many SAW IF filters are being displaced, especially in mobile receivers. Now there is a greater push for development of SAW RF filters in the 900 MHz to 2.4 GHz range, which makes development and manufacturing challenging. In addition, multimode radios will require multiple RF bands, which have lead to development of integrated multi-band RF modules. This increases the number of SAW RF filters used in each cellular phone, thereby increasing the SAW filter volumes required. Until a competing technology emerges in these frequency bands that can surpass all the filter requirements, SAW technology should enjoy a good future.

Acknowledgement

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