DESIGN OF A SELECTABLE PERFORMANCE FRONT-END FILTER USING ACOUSTIC SURFACE WAVES

R. Pastore*+, J. A. Kosinski+, W. N. Porter†, and H. L. Cui*

†U.S. Army Communications-Electronics Command
AMSEL-RD-IE-TI, Fort Monmouth, New Jersey 07703-5211

*Department of Physics and Engineering Sciences
Stevens Institute of Technology, Hoboken, New Jersey 07030

Abstract

The design of a selectable performance front-end filter using acoustic surface waves is currently underway. The filter is being designed to allow for selectable center frequency and bandwidth, ideally while maintaining 3 dB insertion loss. This paper explains the theory of operation of the device, and discusses how the critical design goals map into an acoustic surface wave implementation.

Introduction

Communications receivers are often faced with the problem of trying to receive a weak communications signal in the presence of one or more strong interfering signals. Whereas the receiver may have sufficient sensitivity to receive the weak signal against a “quiet” background, when the background includes one or more strong interfering signals, the receiver will be desensitized to a level determined by the strength of the largest interfering signal and the dynamic range of the receiver. In these situations, it is highly desirable to include some sort of front-end filtering to attenuate the interfering signals prior to the first gain stage.

Table I

<table>
<thead>
<tr>
<th>SIGNAL TYPE</th>
<th>FREQUENCY RANGE</th>
<th>SIGNAL BANDWIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Radio</td>
<td>535 - 1605 kHz</td>
<td>10 kHz</td>
</tr>
<tr>
<td>FM Radio</td>
<td>88 - 108 MHz</td>
<td>200 kHz</td>
</tr>
<tr>
<td>Television</td>
<td>54 - 72 MHz</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Television</td>
<td>76 - 88 MHz</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Television</td>
<td>174 - 216 MHz</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Television</td>
<td>470 - 806 MHz</td>
<td>6 MHz</td>
</tr>
</tbody>
</table>

In this paper, we present the design of a selectable performance front-end filter for a multifunction receiver compatible with a variety of signal waveforms, such as the commercial broadcast waveforms as listed in Table I. The filter features selectable center frequency and bandwidth, ideally while maintaining 3 dB insertion loss. The implementation of the filter using acoustic surface waves is discussed.

Design Goals

The critical RF parameters of the selectable performance front-end filter can be derived through a simple analysis of a generic receiver circuit. The analysis begins by considering the weak desired signal/strong interference signal set as illustrated in Figure 1. These signals are applied to the generic, wide-open receiver as shown in Figure 2. The input is considered to be hard limited to a level Psat. The RF amplifier is characterized by gain G, noise figure F, and noise power bandwidth B0, leading to input thermal noise N = kTB0. The detector is characterized by a tangential signal sensitivity TSS.

In a “quiet” RF environment, one can use

\[ G = [\text{TSS} - (N+F)] \]  

for maximum system sensitivity to weak signals. With a “strong” interference signal of \( P > (\text{Psat-G}) \), the AGC will reduce the system sensitivity by 1 dB for each dB of \( P > (\text{Psat-G}) \) up to the hard limit, i.e., there is a potential loss in sensitivity up to value of G. For example, consider a typical detector with TSS ≈ -35 dBm and Psat = +23 dBm. Assuming a 1 GHz RF bandwidth B0 leads to an input thermal noise of -84 dBm. If the RF amplifier has a 1 dB noise figure, then the maximum useful RF gain is 48 dB.
In this case, the system sensitivity without interference is -83 dBm, but degrades to -35 dBm when strong interference is present. This process is illustrated in Figure 3.

One can add a front-end filter to the receiver as illustrated in Figure 4. The filter is characterized by bandwidth B, insertion loss I, and sidelobe (rejection) level S. The interference signal power is reduced by S dB, and thus for S > G, out-of-band interference does not desensitize the receiver. The power in the signal of interest is reduced by I dB, which for a constant noise floor, reduces the receiver sensitivity by I. However, the noise floor is increased by (F/I) and decreased by 10 log(B/B_0): if the decrease in noise floor due to the
Figure 4. Generic receiver with front-end filter.

bandwidth reduction exceeds the noise increase due to the filter noise figure ($=1/l$), then additional RF gain can be added for increased sensitivity. These considerations are illustrated in Figure 5.

Thus, compared to a wide open system with RF bandwidth $B_o$, the sensitivity in a quiet RF environment is degraded by $1+(F/I)-10\log(B/B_o)$ [which may be a net improvement], but the sensitivity in the presence of strong interference is improved by as much as $G-[1+(F/I)-10\log(B/B_o)]$ provided that $S > G$. The net result is a figure of merit for system performance improvement essentially given by sidelobe level $S$, which establishes how well the desensitization is obviated, minus the insertion loss $l$, which establishes how much the quiescent performance is degraded.

The above considerations, of course, presuppose that the filter center frequency and bandwidth are chosen so as to include the signal of interest in the passband, and to exclude the interference. Taking all of these factors into account, the primary RF performance parameters of interest are listed in Table II, along with preliminary performance goals.

Prior Developments

The ability of the filter to meet the performance goals depends in part on the choice of filter topology, and in part upon the technology used to implement the filter.
TABLE II

<table>
<thead>
<tr>
<th>PRIMARY RF PERFORMANCE PARAMETERS</th>
<th>GOAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency</td>
<td>HF/VHF/UHF</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>matched to modulation</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>3 dB</td>
</tr>
<tr>
<td>Rejection</td>
<td>better than 40 dB</td>
</tr>
<tr>
<td>Filter Shape</td>
<td>matched to modulation</td>
</tr>
</tbody>
</table>

Prior developments in this and closely related fields provide useful guidance on these choices [1-53].

Filter and device topologies considered previously include IDT arrays [4,7], filter banks [2,47,50], variable wave velocity devices [3,4,16,27,30,42], dispersive delay devices [10-12,17-19], convolvers, correlators, and matched filters [1,5,6,13-15,20-22,24,26,28,32,34,39,43,49,51], and transversal filters [8,9,29,31,33,35,37,40,41,44-46,53]. These devices have been implemented primarily using SAW technology, with a few references to ACT [50,52] and CCD [24].

IDT arrays have been used to obtain selectable bandwidth. However, this technique requires unrealistically large delay paths to obtain narrow filter bandwidths. The filter bank approaches have achieved good electrical performance over limited ranges of center frequency and bandwidth. However, broadband tunability using this technique would require a substantial number of channels, also leading to prohibitively large devices.

Variable wave velocity has been used to obtain selectable delay time. However, this tuning is limited to a small fraction of the nominal wave velocity. Selectable center frequency also has been demonstrated using structures based on dispersive devices. However these structures are somewhat complicated and have inherent blanking time and bandwidth limitations [12].

Transversal filters [54] have demonstrated selectable bandwidth and selectable center frequency. To date, however, this selectability has been over a limited range determined in part by the use of a conventional input IDT structure. Promising results have been reported in regards to insertion loss (10dB) and dynamic range (>70dB), with less promising results reported for sidelobe levels (35dB) [40].

The full range of physical implementations have been reported, including discrete piezoelectric devices [4,7,14,24,25,27,29-31,33,35,38,40-42,46,49,53], hybrid devices using thin film piezoelectrics deposited on semiconducting substrates [1,3,5,6,13,22,23,26,39,48,51], and monolithic implementations using piezoelectric semiconductors [20,28,32,36,37,44,50].

Silicon [6,13,14,22,23,26,35,41,43,45,46,48,51], SOS [1,3,5,8], and gallium arsenide [28,32,36-38,40,44,53] have been used to implement the required tap weight and control circuits. Silicon has advantages with respect to cost and processing, while gallium arsenide has advantages with respect to critical circuit parameters [40].

Both passive [8,35] and active [1,5,6,13,22,26,28,29,31-34,36,37,40,43,45,46,51,53] tap weight control elements have been implemented. Active tap weight control elements have been based primarily on FETs, with a lone reference to bipolar technology [34]. Switches have been implemented primarily as RF diodes [1,5,38,41,48].

A wide variety of piezoelectric materials have been used to date, including piezoelectric ceramics [3,27], piezoelectric semiconductors [28,32,36,37], piezoelectric thin films (polycrystalline) [5,6,13,22,23,26,48,51], and conventional single crystals [1,4,7,14,18,24,25,27,29-31,33,35,38,40,41,43,45-47,49,53]. The most popular material to date has been single crystal lithium niobate.

Frequency Tuning in Transversal Filters

The RF performance goals listed in Table II can be obtained readily with an ideal transversal filter as illustrated in Figure 6. In the transversal filter, the input signal propagates through a series of delay elements $\tau_n$. The signal is sampled between the delay elements, and the filter output is taken as a weighted sum of the delayed signal samples. Such a filter is, in theory, capable of producing an arbitrary transfer function

$$H(f) = \sum_{n=1}^{N} a_n e^{-j2\pi f \tau_n}.$$ (2)

In conventional SAW devices, the transversal filter is implemented as a tapped delay line using a pair of IDTs deposited on the surface of the piezoelectric substrate. The delay times $\tau_n$ are determined by the finger locations along the propagation direction. The individual tap weights $a_n$ are established by techniques such as overlap, withdrawal, or phase-reversal weighting, and
are implemented as fixed weights determined by the IDT finger geometries. The summation operation is performed by the busbars connecting the IDT fingers.

The SAW device geometry is primarily defined by the IDT finger locations as defined in Figure 7. The transfer function for unapodized IDTs can be written

$$H(f) = \sum_{n=1}^{N} I_n e^{-j2\pi f x_n/v_s} \sum_{m=1}^{M} J_m e^{j2\pi f y_m/v_s}, \quad (3)$$

where $I_n$ and $J_m$ represent the input and output IDT tap weights respectively. For unapodized IDTs, $H(f)$ is of the form

$$H(f) = H_{in}(f) H_{out}(f) . \quad (4)$$

In the programmable transversal filter, the tap weights are not established by the IDT metallization. Rather, they are established by circuit elements interposed between the IDT fingers and the busbars. The programmable transversal filters reported to date have been only partially programmable, in that they have used conventional, fixed input IDTs in combination with tunable output IDTs.

Note that the generic transversal filter as shown in Figure 6 provides for a baseband or lowpass filter response, whereas the SAW implementation produces a bandpass response. This is a result of the polar nature of the piezoelectric effect, which requires that the IDT fingers have alternating polarity. Consequently, the SAW tap weights incorporate a factor of

$$(-1)^n = \cos\left(\frac{2\pi f_0 x_n}{v_s}\right) = \cos(2\pi f_0 T_n) , \quad (5)$$

which is equivalent to frequency translation of the baseband response to a carrier frequency $f_0$. This implicit frequency translation mechanism can be extended to essentially arbitrary frequency translation to $f_c$ by incorporation of an additional factor of $\exp[j2\pi(f_c-f_0)]$ in the IDT tap weights [29].

**Topological Limitations of the Programmable Transversal Filter**

The basic programmable transversal filter topology as considered previously is illustrated in Figure 8 for the case of real tap weights. Complex tap weights are implemented using two parallel channels coupled through $90^\circ$ hybrids at both input and output. While promising in some aspects, these topologies are inherently limited in meeting the performance goals of Table II. Limitations on center frequency tunability arise from the use of a fixed input IDT, in that low insertion loss can only be obtained.
for center frequencies falling within the input IDT coupling bandwidth. Further limitations on bandwidth arise from aliasing effects encountered when using the simpler single channel circuit and real as opposed to complex tap weights. Limitations on bandwidth tunability arise from the minimum and maximum overall time delays which can be accommodated in a realistic substrate and IDT geometry. Limitations on insertion loss arise from bi-directional transducer loss and parasitics.

In order to overcome the tunability limitations, a fully programmable filter architecture is required. This can be accomplished by applying the frequency translation mechanism of [29] to both input and output IDTs, i.e., by incorporating a factor of \( \exp[2\pi(f_c-f_0)] \) in both \( I_n \) and \( J_m \) of (4). This process is illustrated in Figures 9 and 10.

It should be noted that simply applying frequency translation to the input IDT structure does not of itself resolve the passband bandwidth tunability limitations. If the same frequency translation is applied to both IDTs, then the passband bandwidth remains determined by the largest delay time of the IDTs. Similarly, simply applying frequency translation to the input IDT structure does nothing to resolve the aliasing problems associated with using real tap weights. Tunable input/output IDT topologies which address these issues are currently being investigated.

**Implementation Considerations**

As noted previously, the figure of merit for the selectable performance front-end filter is a system performance improvement essentially given by the sidelobe level \( S \), which establishes how well the desensitization is obviated, minus the insertion loss \( I \), which establishes how much the quiescent performance is degraded. Promising results have been reported in regards to insertion loss (10dB), with less promising results reported for sidelobe levels (35dB) [40]. While the insertion loss depends in part on the device topology, both of these parameters are strongly influenced by the hardware implementation.

Insertion loss depends on the device topology as regards schemes for minimizing bi-directional IDT loss, such as using a single input IDT with paralleled output IDTs on either side. However, such schemes require significantly greater circuit complexity. As a consequence, the practicalities of implementing the tap weight circuitry indirectly influences the obtainable insertion loss by limiting the choice of filter topologies.

In addition, parasitic effects specific to the circuit implementation contribute directly to the insertion loss.

![Figure 9](image-url)

**Figure 9.** Nominal (solid) and translated (dashed) frequency response curves calculated for a two-port SAW transversal filter with identical, unapodized 64 finger input and output IDTs.

![Figure 10](image-url)

**Figure 10.** Tap weights for the (a) untranslated and (b) translated frequency responses of Figure 9.
The implementation of the tap weight circuitry has a direct influence on the achievable sidelobe levels, which to date have been substantially higher than desired. Two issues interplay in this regard, namely, 1) the fidelity of the tap weight circuitry in implementing a given set of weights, and 2) the sophistication of the tap weight selection processor and algorithms.

It is well known that digitization introduces a quantization noise of 6 dB per bit. The implication here is that 10 bit resolution is required for the tap weight control circuitry. Dual gate FETs have shown promise with respect to achieving this level of tap weight fidelity, but require further development for this application in order to minimize impedance mismatch effects such as regeneration in the output IDT.

**Conclusions**

The design of a selectable performance front-end filter using acoustic surface waves has been considered. Critical design parameters have been derived for the case of a weak desired signal/strong interference signal set. Performance goals have been delineated with respect to broadband tunability of center frequency and passband bandwidth, jointly with low insertion loss and high sidelobe (rejection) levels.

The partially programmable transversal filter topology developed previously [29] can be extended to a fully programmable topology by incorporating a frequency translation factor in the input IDT tap weights. While this extension addresses the center frequency tunability requirements, it does not satisfy the passband bandwidth tunability requirements. In addition, issues regarding insertion loss and aliasing effects are also not addressed by this extension.

An alternative input/output tunable IDT filter topology which addresses these issues is currently under development.

**References**


