LINEAR PHASE IF SAW FILTERS

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Abstract - The introduction of wireless digital communication standards, such as CDMA, created a demand for new types of linear phase IF filters. Competition resulted in a rapid reduction in the size and cost of these filters. Today the IF filters used by these wireless terminals employ highly specialized device and design technologies. This paper presents an overview of the device technologies presently employed and many of implementation problems associated with implementing these technologies.

I INTRODUCTION

The introduction of direct sequence spread spectrum communication systems into the commercial sector has produced large markets for linear phase IF filters.

At present, the largest of these markets is represented by IS-95 CDMA systems in the 900 MHz and 1900 MHz bands. Emerging markets include WLAN systems and 3G cellular phone systems.

These IF filter markets are intensely competitive. In a relatively short period of time, this competition has resulted in dramatic reductions in the size and cost of linear phase IF filters.

These reduction have come about through the development of specialized SAW filter technologies. Table 1 lists the largest linear phase SAW IF filter markets and the specialized SAW technologies most commonly applied in designing each systems' IF filters. The listed technologies include;

- Dual Track RSPUDT: The dual track resonant SPUDT [1, 7], are well suited for linear phase IF filters on ST-Quartz with relative bandwidths up to about 2%. This technology enables the size of the die to reduced by as much as 70% as compared to in-line structures.

- Recursive Z-Path: The recursive Z-path [2, 13, 14] is well suited for linear phase IF filters on ST-Quartz with relative bandwidths up to about 0.6% [13]. Like the dual track RSPUDT, this technology also enables the length of the to be reduced by as much as 70%, as compared to in-line structures.

- Tapered SPUDTs: Tapered SPUDTs [3, 5, 6] are well suited for IF filter applications with fractional bandwidths up to and exceeding 50%. This technology's novelty is its flexibility in passband amplitude and phase equalization of low shape factor SAW filters.

Markets	SAW Technology
Cellular CDMA	RSPUDTs
PCS CDMA	RSPUDTs
	Recursive Z-Path
WLAN	Tapered SPUDTs
3G CDMA	Tapered SPUDTs

Table 1: IF filter technology by market.

Year	Package Size
1996	19.0x6.5 mm^2
1997	16.0x6.5 mm^2
1998	13.5x6.5 mm^2
2000	11.8x5.0 mm^2
2001	9.0x5.0 mm^2
200?	7.0x5.0 mm^2

Table 2: 900 MHz band CDMA IF filter sizes.

The 900 MHz band CDMA systems are the most mature. Therefore, the reduction in size (and price) of these IF filters has been the greatest. Table 2 illustrates the substantial reduction in size these filters have experience over the last several years. In the last 5 years, the size of 900 MHz band CDMA IF filters has been reduced by more than a factor of 2.5. The reduction in the price of these filters has been even more dramatic. In 1996 prices for these IF SAW filters were in excess of $5, and today the prices for these filters are approaching $1.

This paper will give an overview of the SAW technologies applied to each of these markets. This overview includes a description of these specialized technologies and the problems which must be overcome in order to successfully apply them to the design of SAW filters.

II RSPUDT IF FILTERS

These IF filters are constructed using the dual track RSPUDT [7] introduced into the market by Thomson Microsonics. A simple schematic of a dual track RSPUDT filter is shown in Fig. 1. Figures 2-4 illustrate the performance of a typical dual track RSPUDT IF filter on ST-Qaurtz, for an

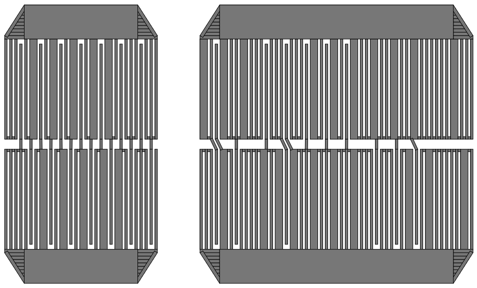

Figure 1: Schematic of a dual track RSPUDT.

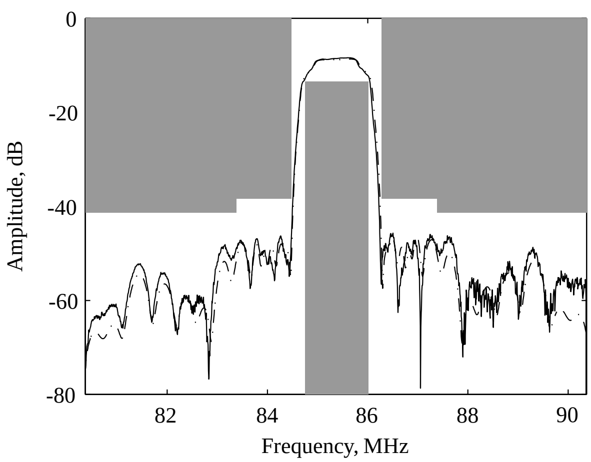

Figure 2: Frequency reponse of a dual track RSPUDT. Both theory $(- \cdot -)$ and experiment $(-)$ are shown.

IS-95 CDMA handset in the 900 MHz band. This IF filter technology is well suited for filters with bandwidths up to about 2%.

Cellular telephone CDMA systems, such as those in the Unitied States and Korea, require IF filters with a bandwidth of 1.26 MHz. Dual track RSPUDTs [1, 7] are well suited for this filter requirement. This is particularly true of the 900 MHz band CDMA IS-95 systems, where the IF filters are approximately 1.5% wide. The dual track RSPUDTs are also well suited for 1900 MHz band systems. However, in the 1900 MHz band, they must compete with the recursive Z-path.

These RSPUDTs differ from past SPUDT filter designs. These devices are challenged by the required short length of the die. In the past, (1) a specification was made, (2) a filter was designed, (3) the size and complexity of the filter determined its cost, and (4) the price was determined. To a great degree, in today's competitive market place, this procedure has been reversed. The price now takes precedence. The price determines the cost and therefore the size of the die. The design must accomodate the market; it is not longer assumed that the market must accept the limitations of today's technology.

The reduction of die size is made possible by the incease

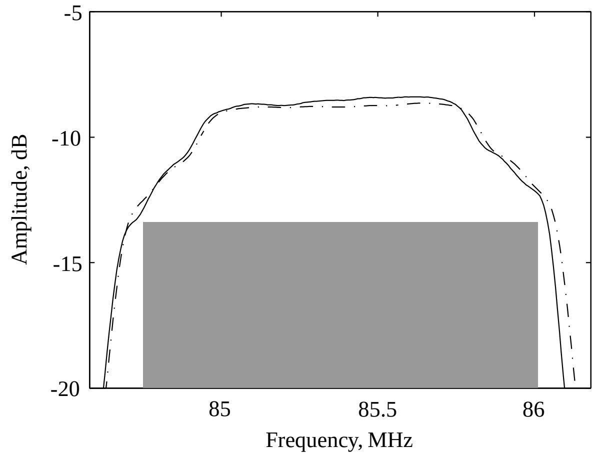

Figure 3: Passband response of a dual track RSPUDT. Both theory $(- \cdot -)$ and experiment $(-)$ are shown.

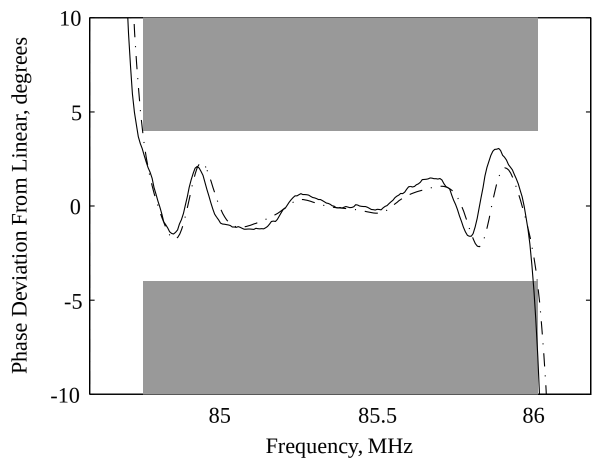

Figure 4: Phase deviation from linear of a dual track RSPUDT. Both theory $(-\cdot-)$ and experiment $(-)$ are shown.

in impulse response length, as compared to the chip length. This reduction in length is brought about by each transducer's recursive nature, the resonant interaction of the transducers, and the reduction in null bandwidth brought about by the superposition of the parallel tracks.

The successful design of these dual track RSPUDT filters was made possible by three innovations.

1. RSPUDT filters: Each track of these filters, see Fig. 1, is an RSPUDT filter [1]. These RSPUDT filters differ from the classic SPUDT type. The RSPUDT's reflectivity has been substantially increased and resonant cavities introduced in and between the transducers for the purpose of extending the impulse response length of the filter. The degree to which the impulse response length may be increased is illustrated in Fig. 5.

2. The dual parallel tracks: While RSPUDTs are effective in lengthing the impulse reponse, this increased length

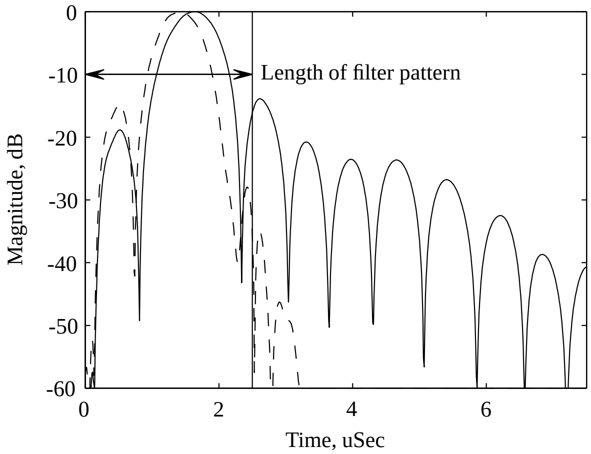

Figure 5: Impulse response for the dual track RSPUDT with $(-)$ and without $(--)$ reflectivity. The total length of the filter pattern on the die is noted.

does not result in a significant decrease in the filter's null bandwidth. However, the introduction of the 2nd track does accomplish this task. This can be seen in Fig. 6. Fig. 6 illustrates the response of each track and their combination. The decrease in null bandwidth is even more significant for the US-PCS CDMA IF filter shown in Fig. 7.

3. Constrained non-linear optimization: The successful implementation of the dual track RSPUDT requires the synthesis of transduction and reflection weighting functions for each of the 4 transducers. These functions are very complex. A design engineer's intuition is insufficient for the successful synthesis of these weighting functions. The synthesis of these weighting functions requires the use constrainted non-linear optimization routines [10, 11].

Once the dual track RSPUDT has been successfully synthesized, other obstacles are still present. These are itemized below.

- Phase errors in the implementation of transduction and reflection must be avoided.
- Withdrawal weighting must be used to implement the transduction and reflection weighting functions.
- An interconnection scheme [7] is required between the two tracks to maximize the aperture of the tracks.
- Acoustic absorbtion is required at the ends of the die.

SAW designers are generally well aquainted with these issues. However, particular attention should be paid to the first, *phase errors*. These filters are very sensitive to phase errors. Much more so than the classical SPUDT filters designed for low loss and/or reduced triple transit echos.

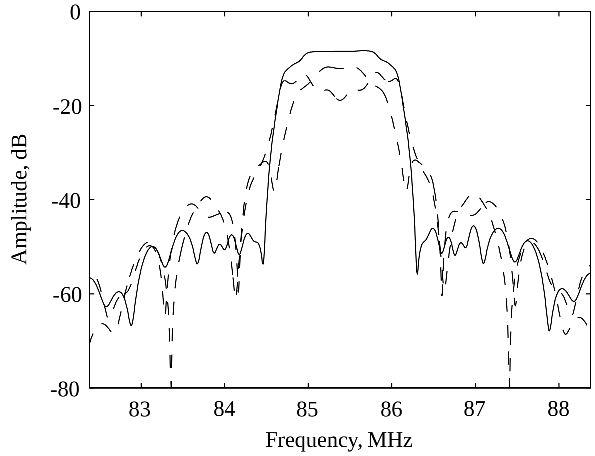

Figure 6: 900 MHz band CDMA IF filter $(-)$. The frequency response of each track is shown dashed $(--)$.

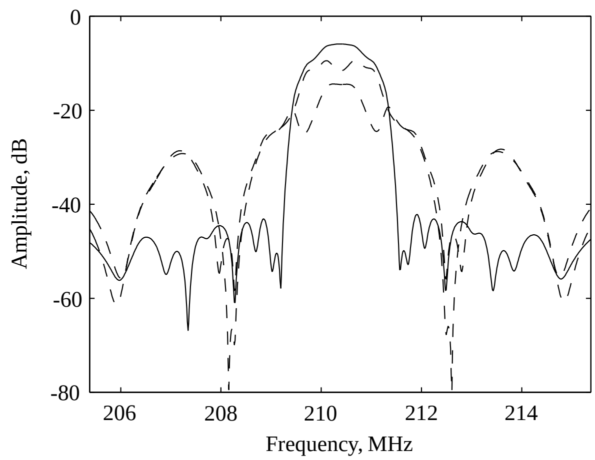

Figure 7: 1900 MHz band CDMA IF filter $(-)$. The frequency response of each track as shown dashed $(--)$.

Fig. 8 illustrates the degree to which phase errors can impact the response of a dual track RSPUDT filter. Fig. 8 shows two responses, (1) a filter designed without consideration for phase errors, and (2) a successful implementation of a dual track RSPUDT filter.

The primary source of phase errors in SPUDTs result from irregularities in the SAW velocity. The irregularites in the phases of transduction/reflection most often result from improper design of the SPUDT structure [8, 9]. The irregularites in the SAW velocity result from the differences in the local velocites which result from changes in the reflection weighting. Fig. 9 illustrates two sections of DART SPUDT, one with a reflecting electrode and the 2nd without. These two sections have differing metalization patterns. These differences in structure introduce velocity irregularties which introduce significant phase errors into the device. To compensate for these sources of phase errors the structure of the transducer must be locally modified. In the case of the trans-

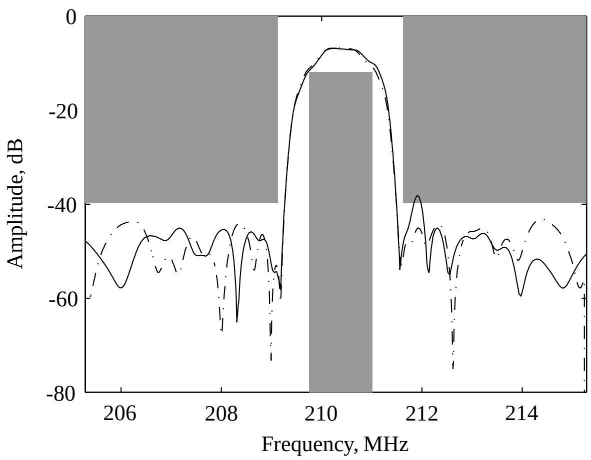

Figure 8: The effects of the local velocity varaitions are illustrated. The solid curve $(-)$ represents a device with no correction for these velocity changes. The dash-dot curve $(- \cdot -)$ represents the measured response for a filter with correction for local the velocity changes.

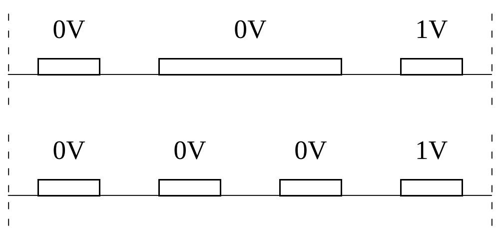

Figure 9: DART with and without reflection. Local changes in the transducer structure results in local changes in the SAW velocity.

duction/reflection phases this requires that the position and widths of the electrodes be locally modified. To compenstate for the velocity irregularities the transudcer period must be locally modified to ensure that the phase of the surface wave remains synchronous with the transducer's transduction and reflection weighting.

III RECURSIVE Z-PATH IF FILTERS

Previous IF filter generations for the CDMA handsets in the 1900 MHz band used single track RSPUDTs and were mounted in a 13.3x6.5mm^2 size package. The introduction of the dual track RSPUDTs and recursive Z-path filters have made it possible to fulfill the IF filter requirment in the 1900 MHz band in a 5x5mm^2 package.

Recursive Z-path IF filter technology was introduced by Epcos (previously Seimens) [2]. A simple schematic of a recursive Z-path filter is shown in Fig. 10. The inclined reflectors couple the wave from the input transducer to the output transducer by folding the propagation path. As compared to in-line filters, this folded propagation path allows

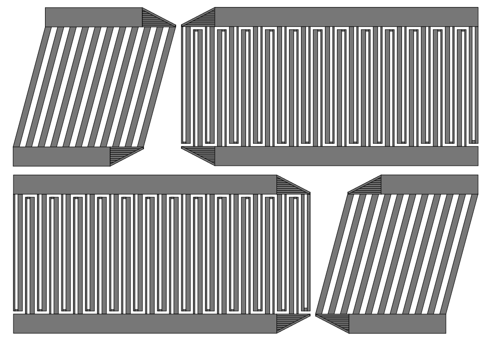

Figure 10: Schematic of a recursive Z-path IF filter.

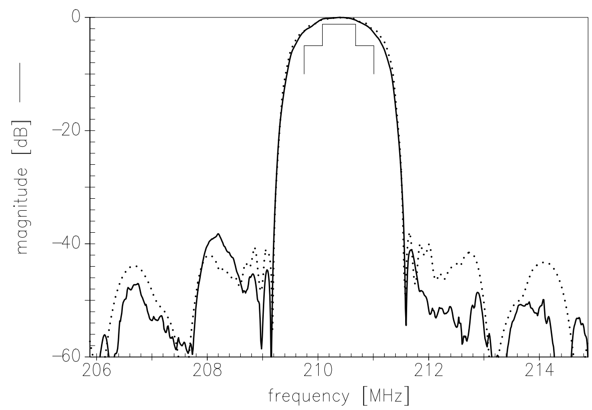

Figure 11: Measured $(-)$ and predicted $(\cdots)$ frequency response of a recursive Z-path 1900 MHz CDMA IF filter.

for a substantial reduction in die lengths without the need for shortening the transducer's lengths.

Using an ST-Quartz substate, this IF filter technology is well suited for linear phase IF filters with bandwidths up to about 0.6% [13].

Figures 11 & 12 illustrate the performance of a recursive Z-path IF filter for an IS-95 CDMA handset in the 1900 MHz band.

The successful design of the recursive Z-path can be attributed to 3 innovations.

1. RSPUDT transducers: Fig. 13 illustrates the improvements made possible by the recursive nature of these transducers. The solid curve in Fig. 13 represents a transducer's response in the absense of reflectivity. The dashed curve represents the transducer's response with the reflectivity included. This improvement in flatness and steepness comes as the result of the recursive nature of the RSPUDT transducers.

2. Folded propagation path: The folded propagation path is particulary advantageous. This innovation allows the overall die length to be substantially reduced without the need for shortening the length of the transducers. Additionally, the inclined reflectors used to fold the

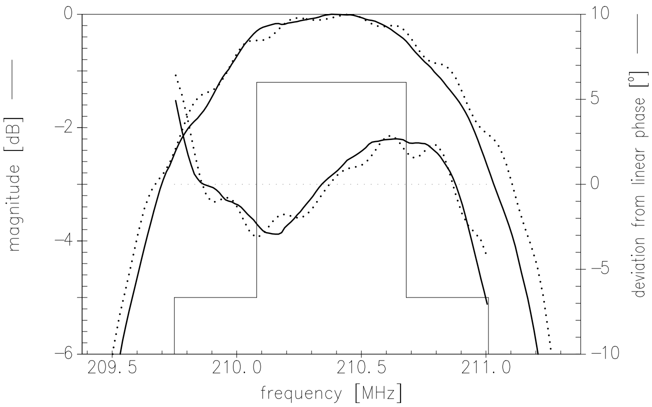

Figure 12: Measured $(-)$ and predicted $(\cdots)$ passband response of a recursive Z-path 1900 MHz CDMA IF filter.

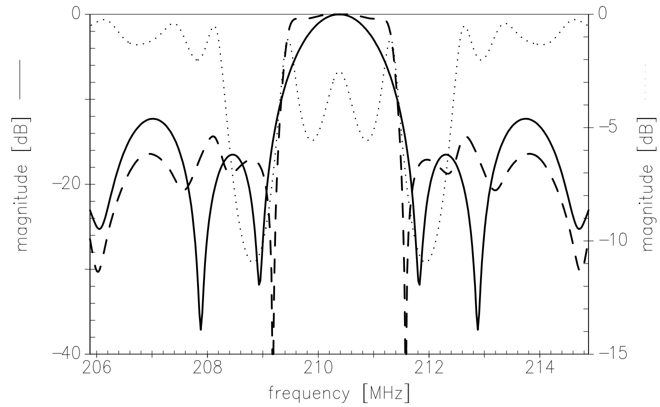

Figure 13: P_{23} of the input transducer with $(-)$ and without reflecitivity $(--)$. P_{21} $(\cdots)$ is also show, and illustrates the resonances present in this transducer.

propagation path provide additional filter selectivity and bulk wave suppression. In Fig. 10 the additional transducer length allowed by the folded propagation path is evident. Fig. 14 illustrates, to first order, the contribution of the transducers $(--)$ and $(\cdots)$, and inclined reflectors $(-\cdot-)$ to the overall filter's frequency response $(-)$.

3. Non-linear constrained optimization: Nearly identical design and optimization strategies that are used for in-line can be applied. This is particularly true when unweighted inclined reflectors are used.

As with the dual track RSPUDTs, once a Z-path filter has been synthesized several obstacles must still be overcome.

- Phase errors in the implementation of transduction and reflection must be avoided.
- Withdrawal weighting must be used to implement the transduction and reflection weighting functions.
- The inclinded reflectors and folded propagation path must be modelled accurately.
- Due to the close proximity of the input and output transducers, electromagnetic coupling between the input and output can cause a significant degradation in the filters stopband attenuation [14]. In Fig. 15 the frequency responses of two filters are illustrated. The response of the Z-path filter with $(\cdots)$ and without $(-\cdot-)$ gating are shown. The response of an second filter $(-)$ constructed to suppress the electromagnetic feedthru is also shown.
- Acoustic absorbtion is required at the ends of the die.

The concerns with respect to the phase errors are essentially the same as those discussed for the dual track RSPUDT. The same may be said for the issues of withdrawal weighting and acoustic absorbtion. The issues related to the

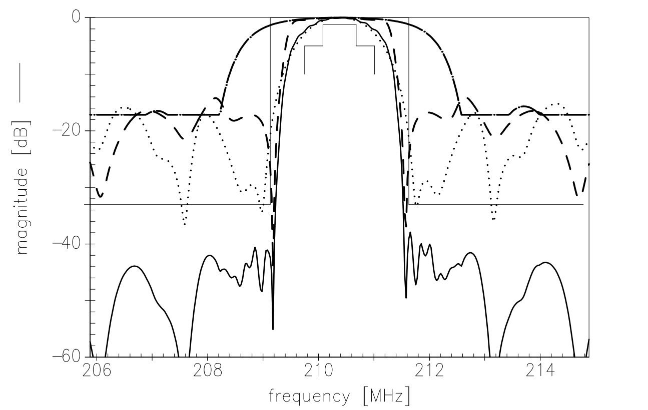

Figure 14: The overall frequency response of a recursive Z-path is comprised of the input transducer $(--)$, output transducer $(\cdots)$, and the inclinded reflectors $(-\cdot-)$ which fold the propagation path.

folded propagation path and electromagnetic coupling resulting from the close proximity of the input and output are unique to the Z-path approach. An excellent description of the electromagnetic problem and its solution is given by A. Bergmann et. al.[14].

IV TAPERED SPUDT IF FILTERS

Tapered, or slanted, SPUDT IF filters [3, 15, 6] have found acceptance in IF filter applications with relatively broad fractional bandwidths and low shape factors. These include WLAN and 3G IF filter applications where relative bandwidths of greater than 2% are common. Z-path IF filters are unable to produce the low shape factor and larger bandwidths required. Although the dual track RSPUDT can produce the necessary bandwith, it cannot produce a passband with sufficiently low distortion. This is largely the result of the inability of these technologies to vary the reflection weighting across the filter's passband while maintaining low loss.

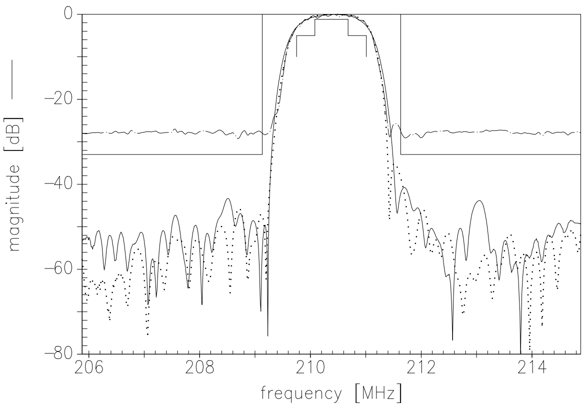

Figure 15: The frequency reponse of a filter without feed through cancellation is illustrated with $(\cdots)$ and without $(- \cdot -)$ time gating. The 3rd reponse $(-)$ is that of a filter with feed through cancellation.

The tapered SPUDT is uniquely suited for filter applications requiring low insertion loss and relatively wide fractional bandwidths. This is due to the ability to independently weight transduction and reflection across the filter's passband while maintaining low insertion loss.

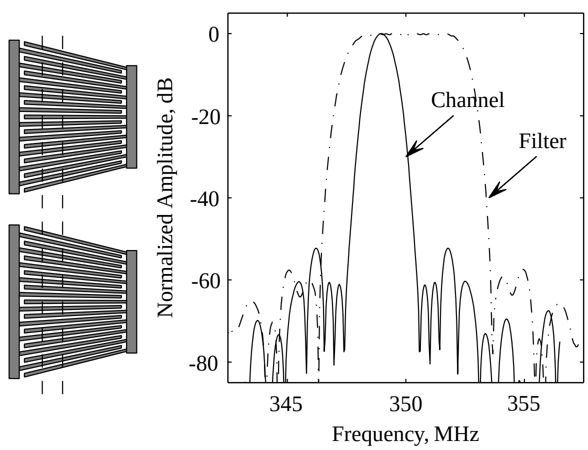

Figure 16: Tapered transducer filter $(- \cdot -)$ showing a single narrow channel $(-)$.

Fig. 17 represents a die for a WLAN handset. This design is for a Lithium Niobate substrate and includes two tapered transducers; one with block weighting and one using withdrawal weighting. The frequency response, and passband response of this filter are illustrated in figs 18, 19, and 20. The low passband distortion seen in fig 19 would not be possible using conventional SPUDT design approaches.

Using tapered transducers, filter designs with substantially steeper skirts are also possible. Figures 21 & 22 illustrate the performance of the 3G basestation IF filter constructed on Langasite. This filter, with a center frequency near 400 MHz, has low passband distortion and excellent shape factor.

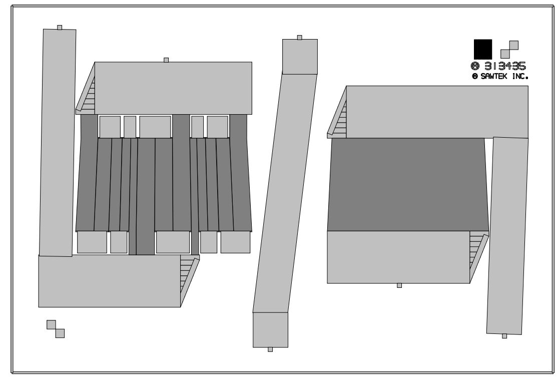

Figure 17: Simplied schematic of the WLAN tapered SPUDT IF filter. Block weighting is applied to the left transducer and withdrawal weighting to the right transducer.

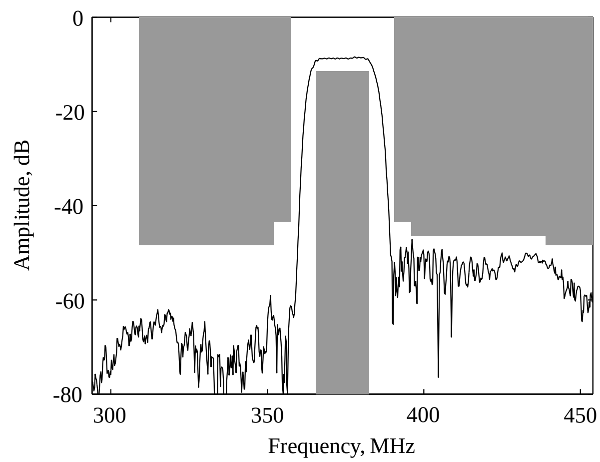

Figure 18: Frequency response for the tapered SPUDT WLAN IF filter.

The successful design and implementation of tapered SPUDT filters was made possible by several innovations.

1. Tapered transducers: The tapered transducers were originally studied by researchers in the late 1960's and early 1970's [3, 4]. This technology gives the SAW design great flexibility in the equalization of the filters amplitude and phase response across relatively wide fractional bandwidths.

2. Tapered SPUDTS: The introduction of tapered SPUDTs allowed low loss filter technology to be applied to SAW filters with relatively broad fractional bandwidths.

3. Accurate Analysis: These filters require analysis methods which are quite different than convention in-line structures.

4. Non-linear constrained optimization: A variant of the optimization procedures used for in-line structures may be used in the design of tapered SPUDTs.

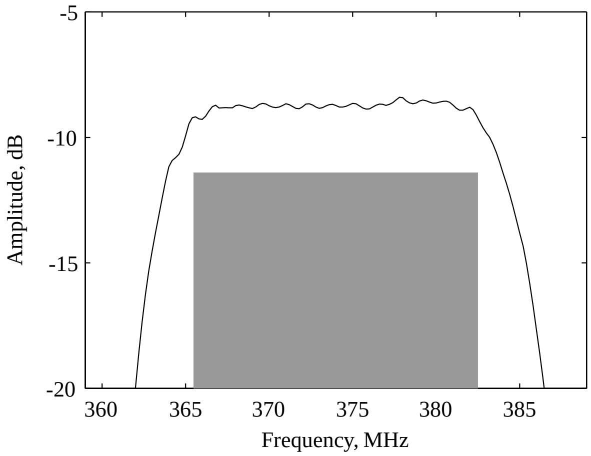

Figure 19: Passband response for the tapered SPUDT WLAN IF filter.

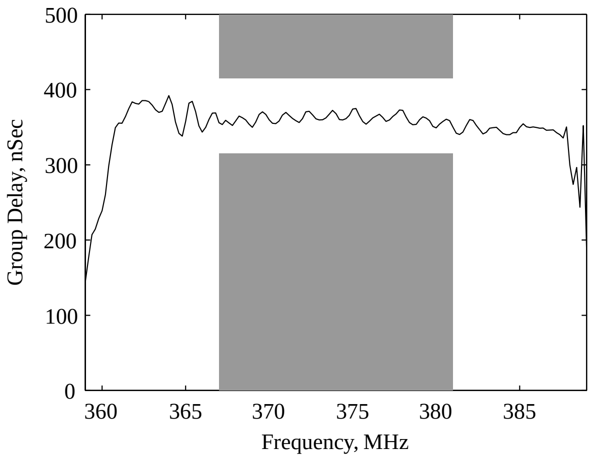

Figure 20: Group delay for the tapered SPUDT WLAN IF filter.

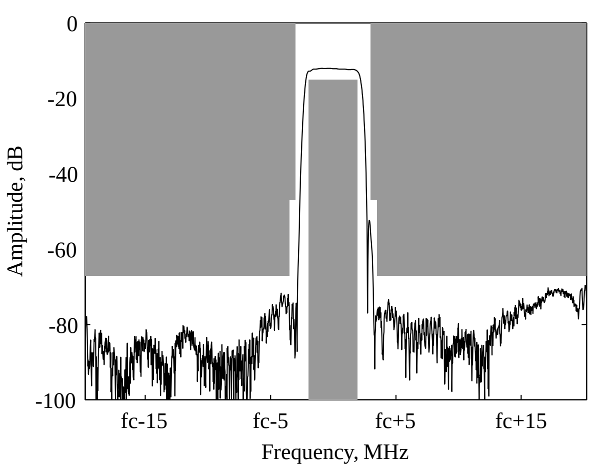

Figure 21: Response of a tapered SPUDT IF filter on Langasite for a 3G basestation.

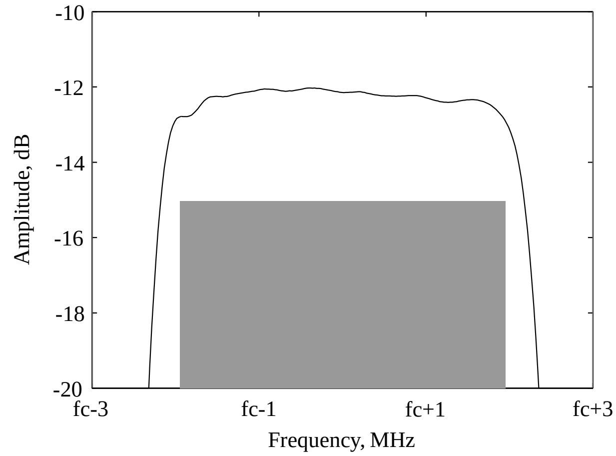

Figure 22: Passband of a tapered SPUDT IF filter on Langasite for a 3G basestation.

Routine analysis of these devices using robust approaches is generally beyond the capabilities of today's computers. However, by making reasonable approximations [15] analyses with sufficient accuracy for design and optimization is possible.

As with the dual track RSPUDTs and recursive Z-path, the tapered SPUDT must overcome its own obstacles to be successfully implemented. Many of these issues are shared with these other technologies. However, tapered structures also must overcome issues unique to them.

- Because the effective aperture at each frequency is considerably narrower than the total aperture, the device's performance can be degraded by diffraction more than a non-tapered device of the same aperture. This restricts the choice of substrates that can be used to those with reduced diffraction such as YZ-$LiNbO_3$ and the recently identified minimal diffraction cuts on Quartz and Quartz like materials [16, 17].

- The long transducer lengths required for the steep filter skirts result in unusually low impedances. Without correction these impedances can be much less than 1 ohm.

- Refraction occurs as a result of the slanted nature of the electrodes. In order to ensure that input and output transducer tracks are properaly aligned, refraction correction must be included in the design of these devices.

- Like the RSPUDT, phase errors in transduction and reflection are a concern.

- Acoustic absorbtion is required at the ends of the die.

To overcome the low transducer impedances resulting from the long transducer lengths, block weighting [6] is used. The block weighting transforms the transducer's impedance up to a level sufficient for matching.

The sensitivity of the RSPUDTs to phase errors are a result of the resonant cavities present in the transducers. In general, no resonant cavities are present in the tapered SPUDTs. In the case of the tapered transducers, the sensitivity to the phase errors result from the extremely long transducers over which small local phase variations can accumulate into significant distortions.

V CONCLUSION

The market's demand for less expensive filters has driven the introduction of several innovations. Taken as a whole, these innovations have produced very specialized SAW filter technologies. These technologies are well suited for the linear phase requirements of today's wireless handsets as well as the market's cost objectives.

This paper has examined the specialized IF filter technologies presently being applied to satisfy the linear phase requirements of today's wireless telecommunications handsets.

The introduction of more powerful DSPs is producing an immediate threat to the necessity of SAW IF filters in all these markets. This is particularly true in single mode cellular phone systems such as 3G. This places additional pressure on the size and prices for these linear phase IF SAW filters. Therefore, the size and price reductions of these filters are expected to continue.

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