RECENT PROGRESS IN SAW FILTERS AT GHZ FREQUENCIES

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Abstract

The wide availability of inexpensive cellular telephones and pagers has made possible world-wide, instantaneous communication for any person within range of a base station. The recent introduction of hand-held and even "wearable" telephone technology has been made practical, in some cases, by the use of miniature Surface Acoustic Wave (SAW) filters. This paper discusses the application of SAW RF filters for use in mobile communication products. We focus on the RF front end of mobile radios for which the band pass filters must provide low insertion loss and high selectivity in very small packages.

Introduction

The world of personal communications is in the midst of a revolution which is rapidly transforming how individuals communicate over a significant part the Earth. The wide availability of inexpensive cellular telephones and pagers has clearly made possible world-wide, instantaneous communication for any person within range of a base station. The introduction in recent years of hand-held and, now, even "wearable" telephone technology is a response to market forces which are driving the technology to ever decreasing size and weight.

Cost, size, weight and battery life are the key issues which determine the attractiveness of cellular telephone products today. Cost is to a large extent determined by economic and competitive forces. However in many cases there is a straight forward tradeoff between radio size, weight and battery life. Reduced size and weight usually require a smaller battery, which, for a given current drain, in turn places a limitation on stand-by and talk times. RF filter technology also indirectly impacts the tradeoff. Very low insertion loss ceramic or stripline filters are commonly found in cellular telephones. However, these devices are relatively large. Surface acoustic wave (SAW) filters, which are generally much smaller, usually exhibit higher insertion loss than competing technologies. The ideal technology for the RF front end of the radio would provide filters which achieve low insertion loss and high selectivity in very small packages. This paper describes recent progress in SAW filter technology near 1 GHz which makes this technology a more attractive alternative to ceramic, stripline and other filter technologies.

RF Front End Applications

The rapid evolution of many technologies, including power amplifiers, RF integrated circuits, batteries, and RF filters has permitted a similarly rapid evolution in radio front end architectures for mobile phones. As the performance of associated circuits improves, the number of filters required to eliminate interfering signals has generally decreased. Many variations on the RF front end architecture are possible. However, a typical design for an analog, duplex radio can have as many as five RF filters (see Figure 1) including (1) a transmitter oscillator clean-up filter, (2) a receive interstage filter between the low noise amplifier and the mixer, (3) a duplexer receive filter and a (4) duplexer transmit filter (frequently in one package), and (5) an IF filter. The character-istics of each of these filters are quite distinct due to the different needs of each application. For example the transmit clean-up filter needs to provide only modest rejection and selectivity and can have higher insertion loss. On the other hand, since the insertion loss of the duplexer transmit filter directly affects the amount of RF power reaching the antenna it directly impacts current drain and, therefore, indirectly affects the key performance characteristics of the product such as size, weight and talk time. Also, since in a duplex system the transmitter and receiver are turned on simultaneously this filter must protect the high sensitivity receiver from exposure to the transmitter power by providing high rejection in the receive band. Similarly the duplex receive filter must not only protect the receiver from the on-board transmitter but it must provide protection from external interfering signals such as from nearby high power transmitters at frequencies just outside its receive band. We will show that SAW filter technology can be very effective in many of these RF front end applications.

To a great extent the characteristics of RF front end filters, SAW or otherwise, are determined by the

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national and international standards which set the channel frequencies, bandwidths and maximum power levels which can be used by the cellular phone providers. Table I shows the channel characteristics of several of the more common standards. Ideally, the receive (Rx) filter must pass signals entering the phone with frequency in the appropriate receive band and must reject all signals outside this band, particularly, those high amplitude, spurious signals inadvertently generated by the phone's own transmitter. Similarly, the transmitt (Tx) filter must pass signals generated by the phone in the transmit band and must protect the delicate receiver circuits by providing significant rejection of spurious transmit energy in the receive band. Therefore, in contrast to IF filter applications, which tend to be very customized and specific to a particular phone vendor's design, the key RF filter requirements are essentially the same for the industry.

A similar, although simpler, situation is found in pager applications. Presently the vast majority of pagers provide receive-only capability. The RF filter must provide very low insertion loss and very high adjacent channel rejection, and must be very low cost. Only 3-4 MHz bandwidth is required for most systems.

SAW Ladder Filter Design

Motorola RF SAW filters use ladder filter techniques, which take advantage of resonant impedance zero-pole response of a piezoelectric resonator. SAW transducers of the proper design exhibit resonant impedance characteristics which are very similar to quartz crystal resonators. That is, the terminal impedance versus frequency will exhibit, in the absence of loss, both a zero and a pole. Using well known circuit theory, it is possible to design a band pass filter by cascading a number of such resonators in a ladder or lattice topology, and properly adjusting the frequencies of the poles and zeroes and the resonator capacitances. In order to achieve the bandwidths for today's communication systems SAW filters for these applications are typically fabricated on high coupling coefficient materials such as lithium niobate or lithium tantalate. The designs usually make use of the so-called "leaky wave" acoustic modes and by proper design the additional loss of such modes can be sufficiently minimized.

It can be shown that a SAW interdigital electrode transducer with two electrical terminals can be modelled by a simple equivalent circuit [1] as shown in Figure 2. With appropriate values for the circuit elements the equivalent circuit exhibits a series resonance (impedance zero) at frequency f_r and a parallel resonance (impedance pole) at frequency f_a. A key design parameter is the capacitance ratio C_m/C_o, which is related to the resonant frequenciesby

$$f_a = f_r\sqrt{1+C_m/C_o}$$

To first order the capacitance ratio depends only on the SAW coupling coefficient of the substrate material. Therefore, the frequency ratio f_a/f_r is also fixed by the choice of substrate material.

An RF filter with a bandpass response can be achieved by combining several SAW resonators. Figure 3 shows a simplifiied ladder filter configuration, which consists of alternately series and shunt connected resonaotors. The series-connected resonators are assumed to exhibit a series resonance at frequency f_r^{ser}, whereas the shunt-connected resonators are assumed to exhibit a parallel resonance at frequency f_a^{sht}. If $f_r^{ser} \approx f_a^{sht}$ then the circuit in Figure 3 will exhibit a bandpass frequency response. Finally, the ultimate rejection will be proportional to the ratio C_o^{sht}/C_o^{ser}.

Application to Mobile Communications Systems

SAW filter technology as described above has been used successfully in a number of mobile communications applications, including, cordless telephones, pagers, analog cellular telephones (AMPS) and in the newer digital systems (GSM). In this section we describe examples of SAW filters which were developed for these applications and are presently in production.

Cordless telephones typically employ narrow band radios which require filters with only a few MHz of bandwidth but which need very low insertion loss and very high out-of-band rejection, due to the very limited RF powers which are permitted. The physical size is not the overriding concern. In Figure 4 we show the response of a filter for a cordless phone application which exhibits 1.5 dB minimum insertion loss and 55 dB out-of-band rejection. The passband is centered at 866 Mhz and provides multiple-channel capability with a 1 dB minimum bandwidth of 9 Mhz. The high out-of-band rejection provides protection against nearby interferring signals and permits the use of a very low power base station in a high signal density, urban environment. The device is fabricated on 36-cut lithium tantalate, which is a substrate which provides medium temperature coefficient and moderately high coupling coefficient. This device was designed to require a single input and output matching inductor which then provides additional wide band low-pass and high-pass filtering for the radio. The device is housed in a in a 5.2 mm X 5.2 mm ceramic surface mount package which is compatible with modern robotic assembly methods. Similarly, the RF filters required for two-way pagers need to provide sufficient bandwidth to support transmit capability in order to respond to incoming pages, with very high rejection, must be quite small and very inexpensive. Figure 5 shows the frequency response of such a filter centered at 935 MHz with 16 MHz bandwidth. The filter exhibits a minimum insertion loss of 1.8 dB and a typical rejection level of 45 dB.

Presently, the most common cellular phone system in the US is AMPS. This application is very well suited to SAW technology. Figure 6 shows the response of a transmit clean-up filter for a typical AMPS cellular telephone which must provide a minimum of 25 MHz bandwidth and only 20-25 dB out-of-band rejection. Low cost and small size are the key issues for these phones. Therefore the SAWs are manufactured in a 3.8 mm X 3.8 mm X 2 mm surface mount package (Figure 7).

GSM has rapidly become the cellular system of choice in Europe and other parts of the globe. The transition bandwidth for the receive filter is slightly smaller than for AMPS, making the filter slighly more challenging. Figures 8 and 9 show the responses of typical transmit and receive interstage filters for GSM. The amplitude characteristics are otherwise similar to that for AMPS. These filters are fully compatible with a very low cost plastic package approach using the SOIC form factor with 8 leads, as seen in Figure 10. The packages have a 6 mm square footprint and less than 1.75 mm height. Although plastic packages are not considered hermetic, these filters have been fully qualified under the same conditions as for hermetic alumina, multi-layer ceraminic packages.

Conclusions

Clearly SAW RF filter technology has proven itself a useful technology for personal communications applications. The remaining challenges are to further reduce insertion loss, to push to high frequencies, to handle higher powers and to continue to reduce cost. As SAW technology continues to develop we expect to find SAW band pass filters in future systems including the new digital systems such as for CDMA, and, possibly, in global satellite telephone systems.

References

1. T. S. Hickernell, “Development of a SAW Ladder Filter for a Portable Phone Sytem”, 16th Piezoelectric Devices Conference, Sept. 1994.

Table I Common cellular phone standards.

System	Transmitt Band (MHz)	Receive Band (MHz)
AMPS	824-850	869-895
ETACS	872-905	917-950
NTACS	893-925	843-870
GSM	890-915	935-960
PCN	1710-1785	1805-1880

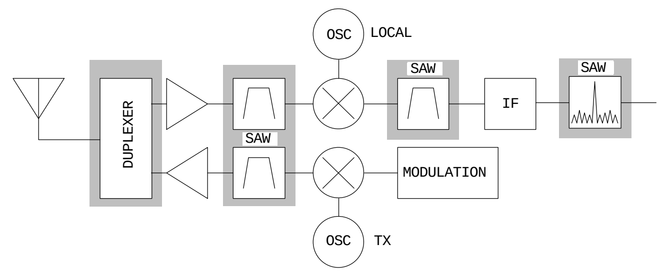

Figure 1. Generic RF front end design for an analog, duplex radio, showing opportunities for SAW filters.

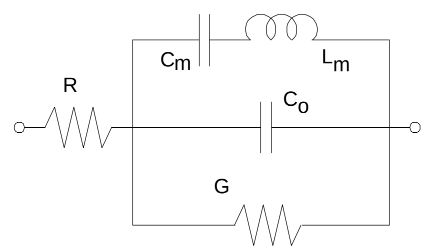

Figure 2. Simplified equivalent circuit model for a SAW transducer resonator.

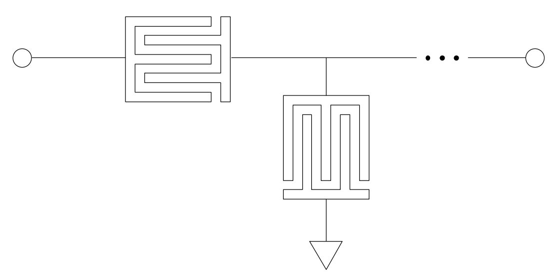

Figure 3. Ladder filter topology consisting of SAW transducer resonators.

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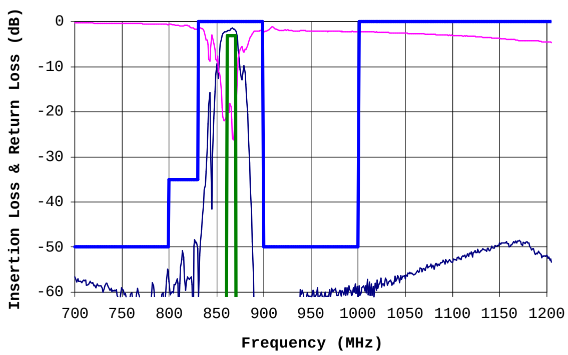


Figure 4. High rejection, low loss, RF front end SAW filter for a cordless phone application.

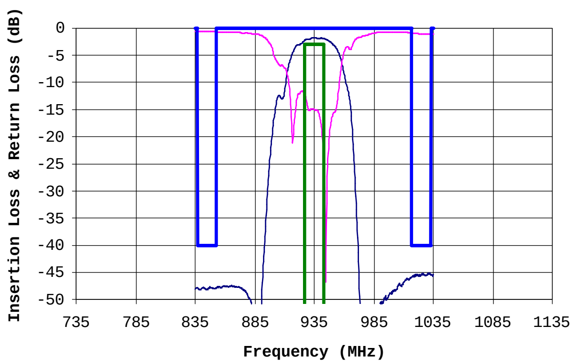


Figure 5. RF front end SAW filter response for a two-way pager application.

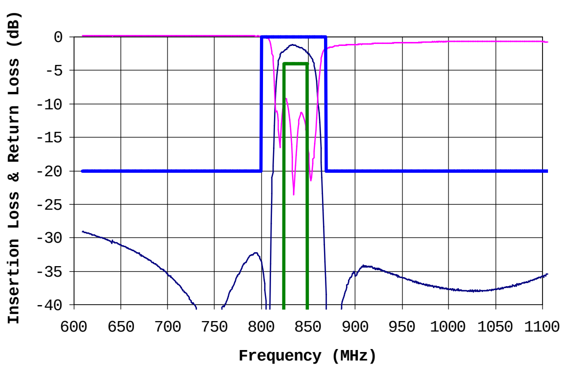
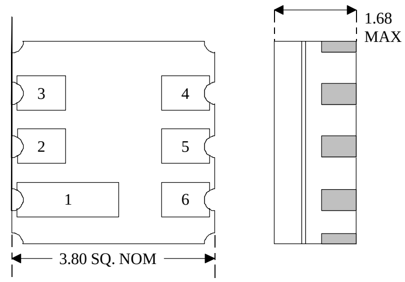


Figure 6. Transmit interstage SAW filter for an AMPS compliant cellular phone.



Dimensions are in millimeters

Figure 7. Industry-standard 3.8mm square ceramic surface mount package for SAW RF filters.

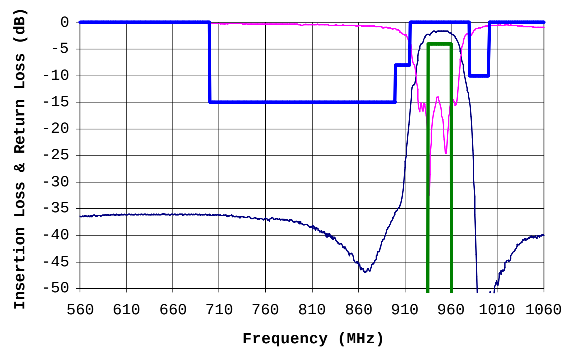


Figure 8. Receive SAW filter response for a GSM cellular phone.

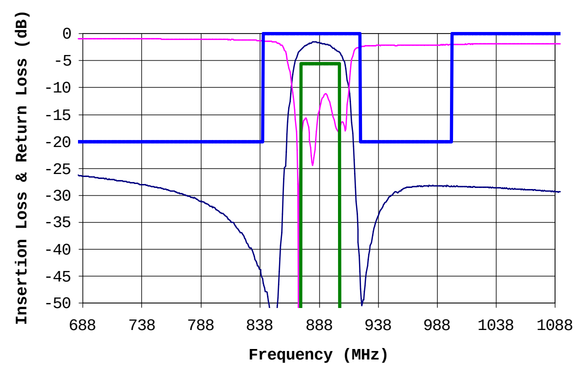


Figure 9. Transmit SAW filter response for a GSM cellular phone.

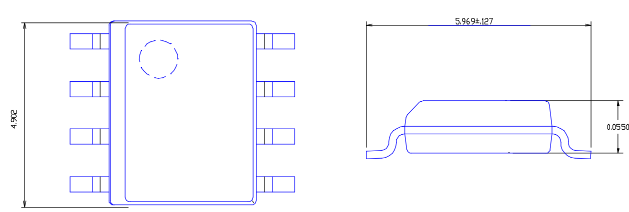


Figure 10. SOIC-style, plastic, surface mount package for low cost RF SAW filters.