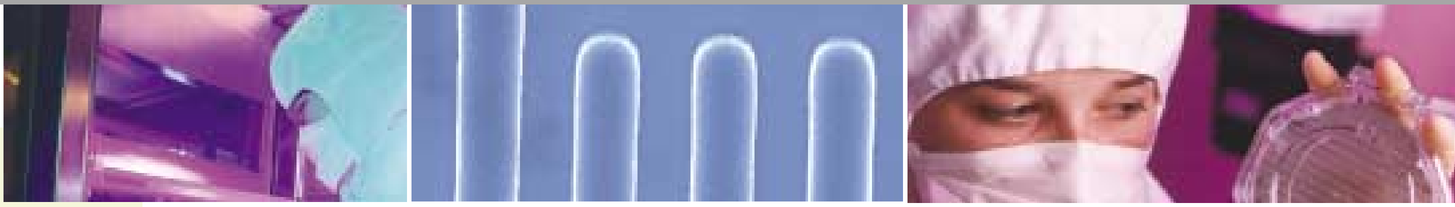
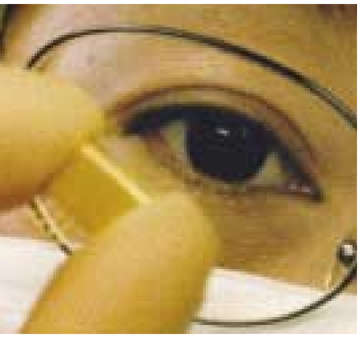
COM DEV
SAW PRODUCTS



COM DEV
SAW Filters

Application Note 102



SAW Bandpass Filters

The simplest type of SAW filter, illustrated in Fig.1, consists of two interdigital transducers (IDTs) on a piezoelectric substrate. The latter is a plate of crystalline material such as quartz. The term ‘piezoelectric’ means that the material has a basic mechanism which couples electrical and mechanical fields. Consequently, an acoustic wave such as a SAW will in general have an associated electric field in such a material. The IDTs have electrodes alternately connected to two bus-bars, so that a voltage applied to the left IDT in Fig.1 causes electric fields in the gaps between the electrodes. The piezoelectric effect couples these fields to mechanical stresses which act as sources of SAWs, and the SAWs travel out of the transducer. At the output transducer on the right, the field associated with the incident wave induces voltages on the electrodes, and hence a corresponding voltage appears on the bus-bars connected to the output.

This device can be regarded as a basic bandpass filter. The reason is that the individual sources (electrode gaps) in the input IDT generate waves with alternating signs, and they add up in phase if the SAW wavelength (λ) equals the transducer pitch. This occurs at the ‘centre frequency’. If the frequency is changed the waves generated by the sources are not quite in phase, and the total amplitude decreases progressively as the frequency is changed. Hence the device has a bandpass characteristic, with the strongest response at the centre frequency. The bandwidth is approximately 1/T, where T is the transducer length in time units (= physical length ÷ SAW velocity). A typical SAW Bandpass Filter characteristic is shown in Fig. 2.

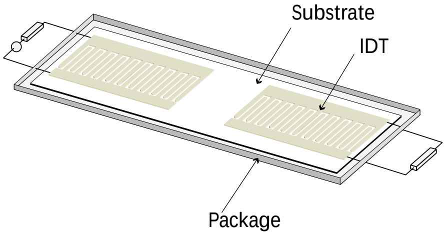


Fig.1 Basic SAW device.

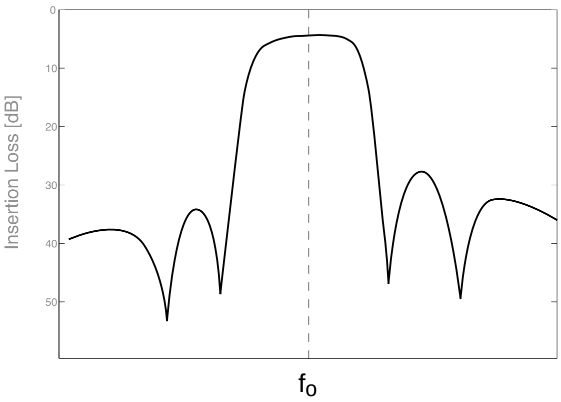


Fig. 2 Bandpass Filter Characteristic.

The device will usually be hermetically packaged to protect the sensitive surface from contamination. Often, one or two reactive components must be added at each end, outside the package. An inductor may be needed because the IDTs have capacitance which may need to be tuned out. Also, L-C circuits are often used to transform the source or load impedance (usually 50 Ω) to an impedance more suitable for the device.

The maximum frequency possible is detemined by electrode width. At the centre frequency the electrodes have spacing $\lambda/2$, and width typically $\lambda/4$. In production, the smallest linewidths obtainable are about 0.3 micron, and for a typical SAW velocity of 3500 m/s this gives a maximum centre frequency of about 3 GHz. A particular advantage is the slow acoustic velocity, much slower than EM waves. This enables long delays to be obtained in a small space.

The performance is constrained by the properties of the substrate material. For SAW devices, the substrate is usually one of a number of ‘standard’ materials already known to have suitable SAW properties. One property of interest is the piezoelectric coupling constant k^2,

which determines the strength of coupling between electrical and mechanical fields. Generally, larger k^2 enables lower insertion loss to be obtained, or wider bandwidth for the same loss. Another important property is the temperature coefficient of delay (TCD), which specifies how the delay varies with temperature (this involves velocity and dimensional changes). This also gives the temperature coefficient for the centre frequency of a filter. Some data for common materials is given in Table 1. Data for maximum bandwidth is only representative.

Quartz has low piezoelectric coupling, but particular substrate orientations give good temperature stability. The TCD is zero at a particular temperature, around 20°C. The fractional delay change is $30 \times 10^{-9}(\Delta\theta)^2$, where $\Delta\theta$ is the deviation from the 'turn-over temperature.' Lithium niobate is the opposite, exhibiting strong coupling but rather bad temperature stability. Lithium tantalate is intermediate in both respects. The 42° rotated lithium tantalate is a special case, giving a 'leaky surface wave,' a special type of SAW which penetrates deeper into the substrate. This tolerates higher power densities and gives strong coupling with reasonable temperature stability. It is often used for RF filters needing low insertion loss.

Table 1. Common Substrate Materials

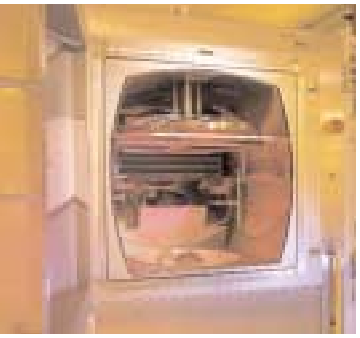
Material	Max. bandwidth	TCD (ppm/deg C)
ST Quartz, 34° Y-X	4 %	0
$LiNbO_3$, 128° Y-X	20 %	75
$LiTaO_3$, X-112° Y	8 %	18
$LiTaO_3$, 42° Y-X	20 %	32

There are many different types of SAW filters, all consisting of a metal film etched to a specificed geometry using a photolithography process similar to that used for semiconductor processing. The variety illustrates the versatility, which follows from the fact that almost arbitrary shapes can be made on the surface. Another factor is that a compact device, with length say 1 cm., can have many SAW wavelengths inside it and hence many degrees of freedom. As for semiconductors, the fabrication is done on a larger 'wafer' so that many devices are made simultaneously, giving economies of scale.

Types of Bandpass Filter

Transversal Filters - Apodization

The basic filter of Fig.1 can be modified in many ways. The electrode overlaps can be varied so that the SAW beams generated by individual gaps have different widths. This means that the response becomes a linear sum of terms, with amplitudes proportional to the overlaps. The filter is a 'transversal filter,' whose impulse response is basically given by the sequence of overlaps. This has a remarkable property - it means that any response at all can be produced, subject to limitations due to finite length and second-order effects. Thus, filters with very complex responses, including dispersion, can be produced.



SAW transversal filters can satisfy extremely exacting performance requirements. For example, the following performance can be achieved:

- in-band ripple can be as low as 0.2 dB p-p,
- stop-band rejection can be 60 dB,
- and shape factors (ratio of bandwidths at 3 dB and 40 dB points) can be as low as 1.1.

These parameters are often the primary considerations when a new SAW filter design is undertaken, and the results are achieved using sophisticated computer optimization methods for design, including compensation for various second-order effects (e.g. diffraction). The main limitation comes about because of unwanted reflections of the SAWs. COM DEV continuously works on its proprietary SAW design software in an ongoing effort to improve rf performance. To obtain low loss, the IDTs can be electrically matched to the source and load (using one or two matching components), but in this condition the IDTs reflect incident SAWs quite strongly. This is a consequence of the fact that the transducers are bidirectional, generating waves equally in two directions. The result is an unwanted signal due to multiple reflections of the waves, giving ripples in the amplitude and phase of the response. This effect is called Triple Transit Response and the ripples are often unacceptable; to minimize them it is necessary to adjust the matching or loading. For this reason, the insertion loss of high-performance transversal filters is usually quite high, for example in the order of 20 dB or more. The length of a transversal filter is related to its skirt width, so filters with narrow skirts are generally very long.

Low-loss Filters - SPUDTs

Many techniques have been developed to obtain low-loss SAW filters without the ripple problem of transversal filters. One method is to employ modified IDTs designed to generate SAWs preferentially in one direction. Commonly, some IF filters use Single Phase Unidirectional Transducers (SPUDTs) for this purpose. The unidirectional behaviour is obtained by using electrodes with different widths. The design involves relatively narrow line widths, restricting the frequencies obtainable, so these devices are usually applied at frequencies below 1 GHz. For this type of device the reflections, and hence the ripples, are minimized when the specified loading is used. So, unlike the transversal filter above, the ripples might be large if no matching components are used. These devices usually have quartz substrates, giving bandwidths up to 2% and losses of typically 5-10 dB.

Compared with a transversal filter, a SPUDT filter has much less loss for a given amount of ripple. In addition, the SPUDTs can often be designed to have a length shorter than that of a corresponding transversal filter. This is advantageous for a compact system such as a mobile phone, and it also reduces the cost of the substrate material and the package. A typical SPUDT Filter characteristic is shown in Fig 3.

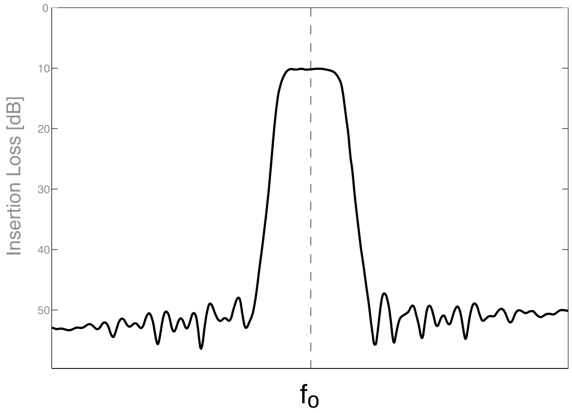
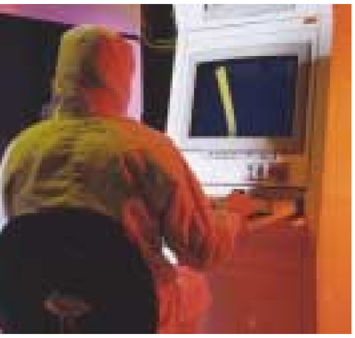


Fig. 3 Typical SPUDT Frequency Response.



Low-loss Filters - TCRs

A quite different technology is based on SAW *resonators*. A resonator can be made using a transducer in between two SAW reflectors. The reflectors are arrays of metal strips with spacing $\lambda/2$, often called gratings. The resonator has two gratings forming a resonant cavity, with an IDT in the cavity to couple it to the electrical terminals, as in Fig.4. The response of this device is basically a one-pole resonance.

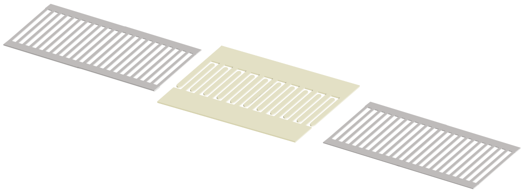


Fig. 4. SAW One-port Resonator.

A transverse-coupled resonator (TCR) consists of two identical resonators fabricated close together, as in Fig. 5 and relies on acoustic coupling between the two resonators. The waves in one resonator extend slightly outside its physical structure, and this enables some energy to leak from one resonator to the other. This couples the two resonators, and the device gives a 2-pole response. The use of resonances enables very narrow bandwidths to be obtained. In fact, this device is limited to bandwidths below about 0.2% because the coupling between the two resonators is weak. Insertion losses are typically 1–2 dB. Because the input and output transducers are in different tracks, not facing each other, the stop band rejection can be good. It is common to cascade two devices to improve this (giving a ‘4-pole’ filter), and a rejection of around 50 dB is obtainable. The response near the pass band is approximately that of a 4-pole filter, so the shape factor is not so small. The substrate is almost always quartz.

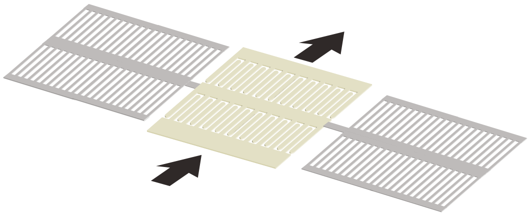


Fig. 5. Transverse Coupled Resonator (TCR).

Longitudinally Coupled Resonators (LCRs)

The LCR is another type of resonator filter. A typical arrangement consists of two transducers in the space between two reflecting gratings. This is somewhat similar to the one-port resonator, Fig.4, but with two transducers. Using IDTs with strong internal reflections, the LCR can be designed to provide a filter with two high-Q poles. A typical configuration is shown in Fig.6. On a strong-coupling substrate such as lithium tantalate or niobate, this gives low insertion losses, e.g. 2 dB, at rf frequencies of 1 GHz and above. Bandwidths up to 5% can be obtained without the need for tuning components. The LCR can also be used on quartz substrates.

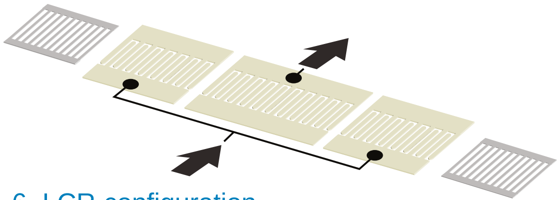


Fig. 6. LCR configuration.

Impedance Element Filters (IEFs) / Ladder Filters

This technology was developed in response to the need for very low loss RF filters at 900 MHz and above, for mobile phone applications. In contrast to other devices, the IEF uses elements that are connected *electrically.* The device circuit is a sequence of resonators connected alternately in series and in parallel, as indicated for a simple case in Fig.7.

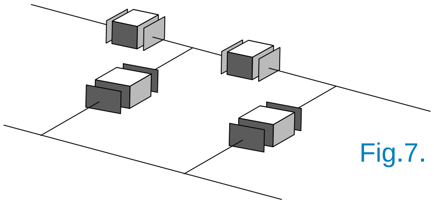


Fig.7. Impedence Element Filter.

The device is designed such that, in the passband, the series resonators have low impedance and the parallel resonators have high impedance, thus giving low loss. Outside the passband the resonators behave like capacitors whose values determine the rejection. The resonators are usually long transducers with strong internal reflections, plus a grating at each end, so that each resonator is basically a one-port resonator as in Fig.4. Using a strong-coupling substrate, such as 42° lithium tanatalate, this filter can give very low loss, e.g. 1 dB at 1 GHz, with up to 5% bandwidth. However, the stopband rejection is not generally as good as other filter types. A typical Ladder frequency response is shown in Fig.8.

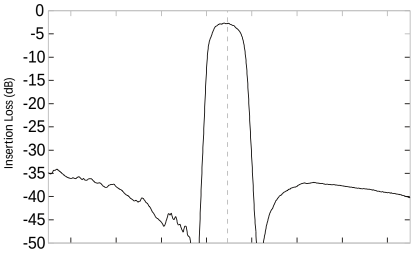


Fig. 8 Ladder Filter
Typical Frequency Response.

The performance of the various types is summarized in Table 2. The data is only indicative of the performance obtainable, and for a specific requirement it is best to consult COM DEV directly. If appropriate, a better assessment can be obtained by doing a preliminary design and simulation. Devices using tantalate or niobate subtrates can often be used without any matching or tuning components if the bandwidth is less than 4%.

Many of these devices can be supplied in balanced form, so as to accept a balanced drive and load. Also, it is often possible to have one port balanced and the other unbalanced, so that the SAW device also serves the function of a balun transformer.

Table 2. Performance Capabilities of SAW Bandpass Filters.

Type	**material**	**Centre freq. MHz (approx)**	**Loss db**	**bandwidth MHz**	**stopband suppression**	**amplitude ripple**	**shape factor**
Transversal	any	30–1500	15–30	< 20 %	< 60 dB	0.1 dB	1.1:1
SPUDT	Quartz	30–1000	5–10	< 2 %	< 45 dB	0.5 dB	2:1
TCR	Quartz	50–400	1–2	< 0.2 %	< 40 dB	1 dB	3:1
LCR	LiTaO$_3$	20–2000	> 2	< 3 %	< 40 dB	1 dB	3:1
IEF	LiTaO$_3$ or LiNbO$_3$	800–3000	1–3	2–5 %	< 40 dB	2 dB	2:1