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Functions concerned
Fonctions concernées

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INTERNATIONAL ELECTROTECHNICAL COMMISSION — COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

Title
Surface acoustic wave (SAW) filters of assessed quality - Part 2: Guidance on use

Titre
Filtres à ondes acoustiques de surface (OAS) sous assurance de la qualité - Partie 2: Guide d'utilisation

ATTENTION
VOTE PARALLÈLE
CEI – CENELEC

L'attention des Comités nationaux de la CEI, membres du CENELEC, est attirée sur le fait que ce projet final de Norme internationale est soumis au vote parallèle. Un bulletin de vote séparé pour le vote CENELEC leur sera envoyé par le Secrétariat Central du CENELEC.

ATTENTION
IEC – CENELEC
PARALLEL VOTING

The attention of IEC National Committees, members of CENELEC, is drawn to the fact that this final Draft International Standard (DIS) is submitted for parallel voting. A separate form for CENELEC voting will be sent to them by the CENELEC Central Secretariat.

FORM FDIS (IEC)/FORMULAIRE FDIS (CEI)
2002-01-15

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SURFACE ACOUSTIC WAVE (SAW) FILTERS OF ASSESSED QUALITY –

Part 2: Guidance on use

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60862-2 has been prepared by IEC technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

This second edition cancels and replaces the first edition published in 1991 and constitutes a technical revision.

The text of this standard is based on the following documents:

FDIS	Report on voting
49/XX/FDIS	49/XX/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

IEC 60862 consists of the following parts, under the general title *Surface acoustic wave (SAW) filters of assessed quality*

– Part 1: General information, standard values and test conditions [1)]
– Part 2: Guidance on use
– Part 3: Standard outlines [2)]
– Part 4: Sectional specification – Capability approval (under consideration)
– Part 4-1: Blank detail specification – Capability approval (under consideration)

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this publication will remain unchanged until 2006. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

[1)] A second edition (generic specification) is under consideration.

[2)] A second edition is under consideration.

INTRODUCTION

This part of IEC 60862 gives practical guidance on the use of SAW filters which are used in telecommunications, measuring equipment, radar systems and consumer products. IEC 60862-1 should be referred to for general information, standard values and test conditions.

The features of these SAW filters are their small size, light weight, adjustment-free, high stability and high reliability. SAW filters add new features and applications to the field of crystal filters and ceramic filters. At the beginning, SAW filters meant transversal filters which have two interdigital transducers (IDT). Although SAW transversal filters have a relatively higher minimum insertion attenuation, they have excellent amplitude and phase characteristics. Extensive studies have been made to reduce minimum insertion attenuation, such as resonator filter configurations, unidirectional interdigital transducers (UDT), interdigitated interdigital transducers (IIDT). Nowadays, various kinds of SAW filters with low insertion attenuation are widely used in various applications and SAW filters are available in the gigahertz range.

This standard has been compiled in response to a generally expressed desire on the part of both users and manufacturers for guidance on the use of SAW filters, so that the filters may be used to their best advantage. To this end, general and fundamental characteristics have been explained here.

SURFACE ACOUSTIC WAVE (SAW) FILTERS OF ASSESSED QUALITY –

Part 2: Guidance on use

1 Scope

SAW filters are now widely used in a variety of applications such as TV, satellite communications, optical fibre communications, mobile communications and so on. While these SAW filters have various specifications, many of them can be classified within a few fundamental categories.

This part of IEC 60862 includes various kinds of filter configuration, of which the operating frequency range is from approximately 10 MHz to 3 GHz and the relative bandwidth is about 0,02 % to 100 % of the centre frequency.

It is not the aim of this standard to explain theory, nor to attempt to cover all the eventualities which may arise in practical circumstances. This standard draws attention to some of the more fundamental questions, which should be considered by the user before he places an order for a SAW filter for a new application. Such a procedure will be the user's insurance against unsatisfactory performance.

Standard specifications, given in IEC 60862, and national specifications or detail specifications issued by manufacturers, define the available combinations of nominal frequency, pass bandwidth, ripple, shape factor, terminating impedance, etc. These specifications are compiled to include a wide range of SAW filters with standardized performances. It cannot be over-emphasized that the user should, wherever possible, select his SAW filters from these specifications, when available, even if it may lead to making small modifications to his circuit to enable standard filters to be used. This applies particularly to the selection of the nominal frequency.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60368-2-1:1988, *Piezoelectric filters – Part 2: Guide to the use of piezoelectric filters – Section One: Quartz crystal filters*

IEC 60862 (all parts), *Surface acoustic wave (SAW) filters of assessed quality*

3 Terms and definitions

For the purpose of this part of IEC 60862, the following terms and definitions apply.

3.1 General terms

3.1.1
surface acoustic wave (SAW)
acoustic wave, propagating along a surface of an elastic substrate, whose amplitude decays exponentially with substrate depth

3.1.2
surface acoustic wave filter (SAW filter)
filter characterized by a surface acoustic wave which is usually generated by an interdigital transducer and propagates along a substrate surface to a receiving transducer

3.1.3
power flow vector
vector, analogous to a Poynting vector, characterizing energy propagation caused by a surface acoustic wave

3.1.4
propagation vector
vector characterizing the phase progression of a wave

3.1.5
power flow angle
angle between the direction of the power flow vector and the direction of the propagation vector

3.1.6
SAW beam steering
SAW propagation phenomenon in anisotropic materials described by an angle of power flow which is not zero

3.1.7
SAW diffraction
phenomenon (analogous to diffraction of light from a source of finite aperture) which causes SAW beam spreading and wavefront distortion

3.1.8
SAW coupling coefficient (k_s^2)
SAW electromechanical coupling coefficient is defined as follows:

$$k_s^2 = 2\left|\frac{\Delta v_s}{v_s}\right|$$

where

$\Delta v_s / v_s$ is the relative velocity change produced by short-circuiting the surface potential from the open-circuit condition

3.1.9
interdigital transducer (IDT)
SAW transducer made of two comb-like conductive structures deposited on a piezoelectric substrate transforming electrical energy into acoustic energy or vice versa

3.1.10
unidirectional interdigital transducer (UDT)
transducer capable of radiating and receiving surface acoustic waves in or from a single direction

3.1.11
multiphase transducer
interdigital transducer having more than two inputs which are driven in different phases. Usually used as a unidirectional transducer

3.1.12
finger
element of the IDT comb electrode

3.1.13
dummy finger
passive finger which may be included in order to suppress wavefront distortion

3.1.14
split finger
finger formed of more than one element, so as to produce antireflection properties

3.1.15
bus bar
common electrode which connects individual fingers together and also connects the filter to an external circuit

3.1.16
weighted-response transducer
transducer intended to produce a specified impulse response by design of the structure (see, for example, 3.1.17 to 3.1.22)

3.1.17
finger overlap or source strength
length of a finger pair between which only electromechanical interaction is generated

3.1.18
apodization
weighting produced by the change of finger overlap over the length of the IDT

3.1.19
withdrawal weighting
weighting by removal of fingers or sources

3.1.20
capacitive weighting
weighting by change of capacitance between electrodes

3.1.21
series weighting
weighting by separation of a finger into individual elements having capacitive coupling between them. The elements may be separated from the busbar

3.1.22
phase weighting
weighting by change in period of finger arrangement inside the IDT

3.1.23
aperture
normalized beamwidth of the SAW generated at centre frequency and normalized to the corresponding wavelength

3.1.24
multistrip coupler (MSC)
array of additional metal strips deposited on a piezoelectric substrate, in a direction transverse to the propagation direction, which transfers acoustic power from one acoustic track to an adjacent track

3.1.25
reflector
SAW reflecting component which normally makes use of the periodic discontinuity provided by a metal strip array or a grooved array

3.1.26
spurious reflections
unwanted signals caused by reflection of SAW or bulk waves from substrate edges or electrodes

3.1.27
triple transit echo (TTE)
unwanted signals in a SAW filter which have traversed three times the propagation path between input and output IDTs caused by reflections from output and input transducers

3.1.28
bulk-wave signals
unwanted signals caused by bulk-wave excitation, detected at the filter output

3.1.29
feed-through signals (signals of electromagnetic interference)
unwanted signals from the input appearing at the filter output due to stray capacitances and other electromagnetic couplings

3.1.30
suppression corrugation
grooves in the non-active side of a substrate for suppressing bulk-wave signals

3.1.31
acoustic absorber
material with high acoustic loss placed on any part of the substrate for acoustic absorption purposes

3.1.32
shielding electrode
electrode intended for the reduction of electromagnetic interference signals

3.1.33
interdigitated interdigital transducer (IIDT)
SAW transducer made of a combination of three or more interdigital transducers. Same as a multi-IDT

NOTE In this standard, IIDT (or multi-IDT) resonator filters are referred to as SAW resonator filters composed of a number of IDTs for input and output in a line alternating with grating reflectors confirming the IDT structure at both ends.

3.2 Response characteristics

3.2.1
nominal frequency
frequency given by the manufacturer or the specification to identify the filter

3.2.2
centre frequency
arithmetic mean of the cut-off frequencies

3.2.3
reference frequency
frequency defined by the specification to which other frequencies may be referred

3.2.4
cut-off frequency
frequency of the pass-band at which the relative attenuation reaches a specified value

3.2.5
total power loss
logarithmic ratio of the available power at the given source to the power that the SAW filter delivers to a load impedance under specified operating conditions

3.2.6
insertion attenuation
logarithmic ratio of the power delivered directly to the load impedance before insertion of the filter to the power delivered to the load impedance after insertion of the filter

3.2.7
nominal insertion attenuation
insertion attenuation at a specified reference frequency

3.2.8
relative attenuation
difference between the attenuation at a given frequency and the attenuation at the reference frequency

3.2.9
pass-band
band of frequencies between which the relative attenuation is equal to, or less than, a specified value

3.2.10
pass bandwidth
separation of frequencies between which the relative attenuation is equal to, or less than, a specified value

3.2.11
pass-band ripple
variation in insertion attenuation within a specified pass-band

3.2.12
TTE ripple
maximum variation in attenuation characteristics caused by TTE within a specified pass-band

3.2.13
minimum insertion attenuation
minimum value of insertion attenuation in the pass-band

3.2.14
stop-band
band of frequencies in which the relative attenuation is equal to, or greater than, a specified value

3.2.15
stop bandwidth
separation of frequencies between which the relative attenuation is equal to, or greater than, a specified value

3.2.16
shape factor
ratio of two bandwidths at specified values of the relative attenuation

3.2.17
group delay
time equal to the first derivative of the phase shift, in radians, with respect to the angular frequency

3.2.18
nominal group delay
group delay at a specified reference frequency

3.2.19
group delay distortion
difference between the lowest and highest value of group delay in a specified frequency band

3.2.20
trap frequency
specified frequency at which the relative attenuation is equal to, or greater than, a specified value

3.2.21
trap attenuation
relative attenuation at a specified trap frequency

3.2.22
transition band
band of frequencies between the cut-off frequency and the nearest point of the adjacent stop-band

3.2.23
reflection coefficient
dimensionless measure of the degree of mismatch between two impedances Z_a and Z_b, given by the expression

$$\left|\frac{Z_a - Z_b}{Z_a + Z_b}\right|$$

where

Z_a and Z_b represent respectively the input and source impedance or the output and load impedance

3.2.24
return attenuation
value of the reciprocal of the modulus of the reflection coefficient expressed in decibels Quantitatively, it is equal to:

$$20\ \log\left|\frac{Z_a + Z_b}{Z_a - Z_b}\right|\ \text{dB}$$

3.2.25
reflected wave signal suppression
relative attenuation of unwanted signals caused by reflection of SAW or bulk waves from substrate edges or electrodes within a specified time window

3.2.26
feed-through signal suppression
relative attenuation which implies the suppression of directly coupled signals by the electromagnetic and electrostatic coupling between the input and output electrodes

3.2.27
unwanted response
response other than that associated with the mode of vibration intended for the application

3.2.28
input value
power, voltage or current level applied to the input terminal pair of a filter

3.2.29
output value
power, voltage or current level delivered to the load

3.2.30
nominal value
power, voltage or current level at which the performance measurement is specified

3.2.31
input impedance
impedance presented by the filter to the signal source when the output is terminated by a specified load impedance

3.2.32
output impedance
impedance presented by the filter to the load when the input is terminated by a specified source impedance

3.2.33
terminating impedance
either of the impedances presented to the filter by the source or by the load

3.2.34
available power
maximum power obtainable from a given source by suitable adjustment of the load impedance

3.2.35
roll-off rate
index describing the rise-up characteristics for digital communication SAW roll-off filters. It is a ratio of the transition band to the ideal cut-off frequency, which is equal to half of the sampling frequency, in the case of cosine roll-off frequency characteristics

3.2.36
intermodulation distortion
non-linear distortion of a SAW transducer or filter response characterized by the appearance of frequencies at the output equal to the differences (or sums) of integral multiples of the two or more component frequencies present at the input

3.3 SAW filter related terms

3.3.1
transversal filter
filter consisting of input and output interdigital transducers on a piezoelectric substrate. The frequency response of the filter is fundamentally given by the impulse response of the transducer

3.3.2
frequency symmetrical filter
filter having a symmetrical frequency characteristic in relation to the reference frequency

3.3.3
frequency asymmetrical filter
filter having a specified asymmetrical pass-band or stop-band characteristic in relation to the reference frequency

3.3.4
dispersive filter
filter designed so as to have group delay which is a function of frequency, usually by varying the finger periodicity

3.3.5
comb filter
filter having two or more pass-bands between three or more stop-bands

3.3.6
resonator filter
filter in which two or more SAW resonators are incorporated

3.3.7
ladder filter
filter having a cascade or tandem connection of alternating series and shunt SAW resonators

3.3.8
lattice filter
filter having at least four SAW resonators connected in series to form a mesh, two non-adjacent junction points are used as input terminals, while the remaining two junction points are used as output terminals (bridge circuit). Preferably it can be used for balanced circuits

4 Preliminary remarks of a technical nature

It is of prime interest to a user that the filter characteristics should satisfy a particular specification. The selection of tuning networks and SAW filters to meet that specification should be a matter of agreement between user and manufacturer.

Filter characteristics are usually expressed in terms of insertion attenuation and group delay as a function of frequency, as shown in figure 1. A standard method for measuring insertion attenuation and group delay is described in 4.5.2 of IEC 60862-1[1)]. In some applications, such characteristics as phase distortion are also important.

Insertion attenuation characteristics are further specified by nominal frequency, minimum insertion attenuation or maximum insertion attenuation, pass-band ripple and shape factor. The specification is to be satisfied between the lowest and highest temperatures of the specified operating temperature range and before and after environmental tests.

[1)] To be published.

SAW filters are classified roughly into two types: transversal filters and resonator filters. Transversal filters are further classified into two types: bidirectional IDT filter and unidirectional IDT filter. Also resonator filters are further classified into three types i.e. ladder and lattice filters, coupled resonator filter and IIDT resonator filter. Fundamentals of SAW transversal filters and SAW resonator filters are described in clauses 5 and 6 of this standard, respectively. In figure 2, the applicable frequency range and relative bandwidth of the SAW filters are shown in comparison with those of ceramic, crystal, dielectric, helical and stripline filters.

5 Fundamentals of SAW transversal filters

5.1 Frequency response characteristics

A brief description of SAW filters is given here to help users unfamiliar with these filters to understand their operating principles and characteristics. The SAW filter uses a surface acoustic wave, usually the Rayleigh wave. The mechanical energy transported by the wave is concentrated in a surface region of the order of a wavelength in depth. The wave travels on a solid surface at a velocity, 10^3 m/s to 10^4 m/s, which offers the possibility of filtering operations in the VHF and UHF regions in practical SAW filters. The SAW filter has a planar structure, in which electrodes are formed on one surface of a piezoelectric substrate, incorporating a suitable configuration of electrodes as a means of conversion between surface acoustic waves and electrical signals.

Figure 3 is a diagram showing the signal flow through a transversal filter. The filter consists of N taps separated by delays D_n. Each tap is weighted by a coefficient A_n. Filtering is achieved by passing the signal through a number of delay paths and adding these delayed signals. The delays correspond to the positions of IDT fingers on a substrate. The coefficients correspond to weighting coefficients given to the IDT fingers. The frequency response of the filter $H(f)$ is given by a discrete Fourier transformation, expressed as the following equation at a frequency f:

$$H(f) = \sum_{n=1}^{N} A_n \exp(-\mathrm{j}2\pi f T_n) \qquad T_n = \sum_{i=1}^{n} D_i \tag{1}$$

where T_n is the accumulated delay at the nth tap.

Both amplitude and phase characteristics of the transversal filter are given by two sets of variables: weighting coefficients A_n and delays D_n of the sampling taps.

The SAW transversal filter is essentially constructed with a pair of transducers on a piezoelectric substrate as shown in figure 4. When an electrical signal is applied to the input IDT, the surface wave is generated by means of the piezoelectric effect and propagates in both directions along the substrate surface. The surface wave is converted again into an electrical signal at the output IDT. If the IDT spatial period $2d$ is uniform, maximum efficiency can be achieved at the frequency for which the surface wave propagates one transducer period synchronously in one RF signal period. The centre frequency f_0 of the IDT is given by this synchronization condition:

$$2df_0 = v_s \tag{2}$$

where v_s is the SAW velocity.

When the SAW transversal filter has two uniform identical transducers, its frequency response is as shown in figure 5. The transfer function $T(f)$ is approximately expressed as

$$T(f) = \left(\frac{\sin x}{x}\right)^2 \tag{3}$$

where

$x = \frac{N\pi(f - f_0)}{f_0}$ and

N is the number of finger pairs.

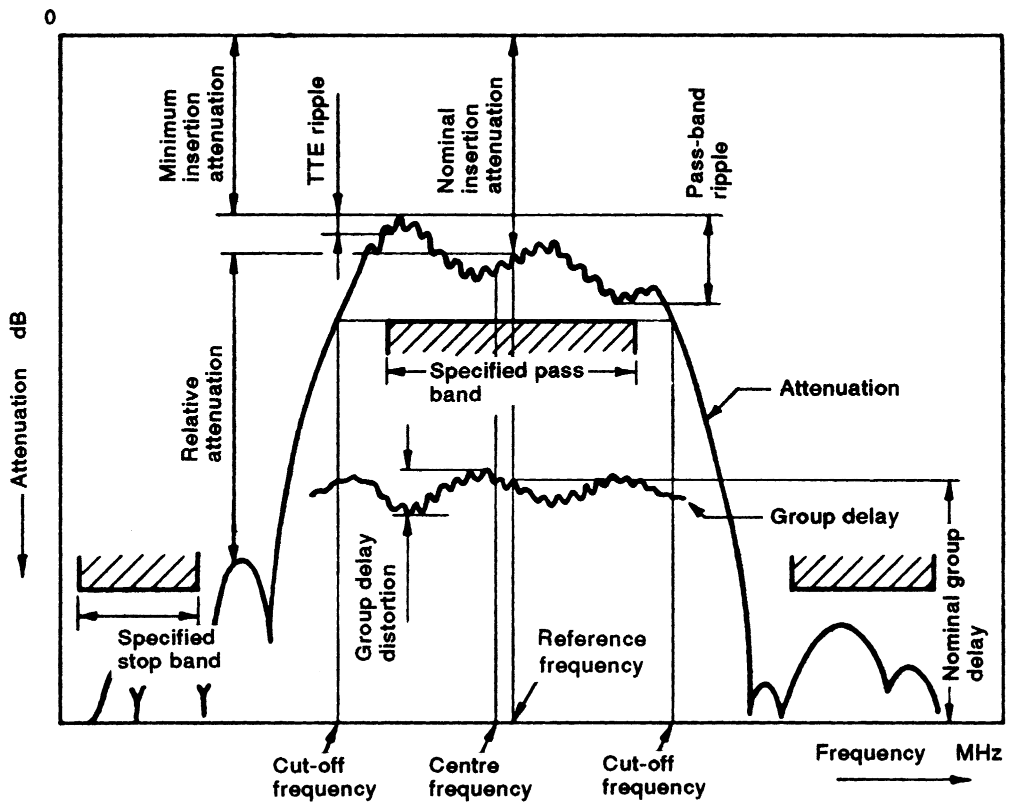

Figure 1 – Frequency response of a SAW filter

5.2 Weighting methods

The IDT operates as a kind of transversal filter with N taps for the weighting. A number of weighting methods are applicable, for example apodization, withdrawal and series (dog-leg) weighting.

a) Apodization weighting

An apodized transducer, as shown in figure 6, is most commonly used to achieve weighting. An acoustic wave is generated or detected only in regions where adjacent electrodes of opposite polarity overlap.

b) Withdrawal weighting

Weighting is achieved by selectively withdrawing electrodes, as illustrated in figure 7, to equate with the desired weighting function.

c) Series (dog-leg) weighting

Weighting is achieved by dividing the voltage by segmenting each electrode pair, as shown in figure 8.

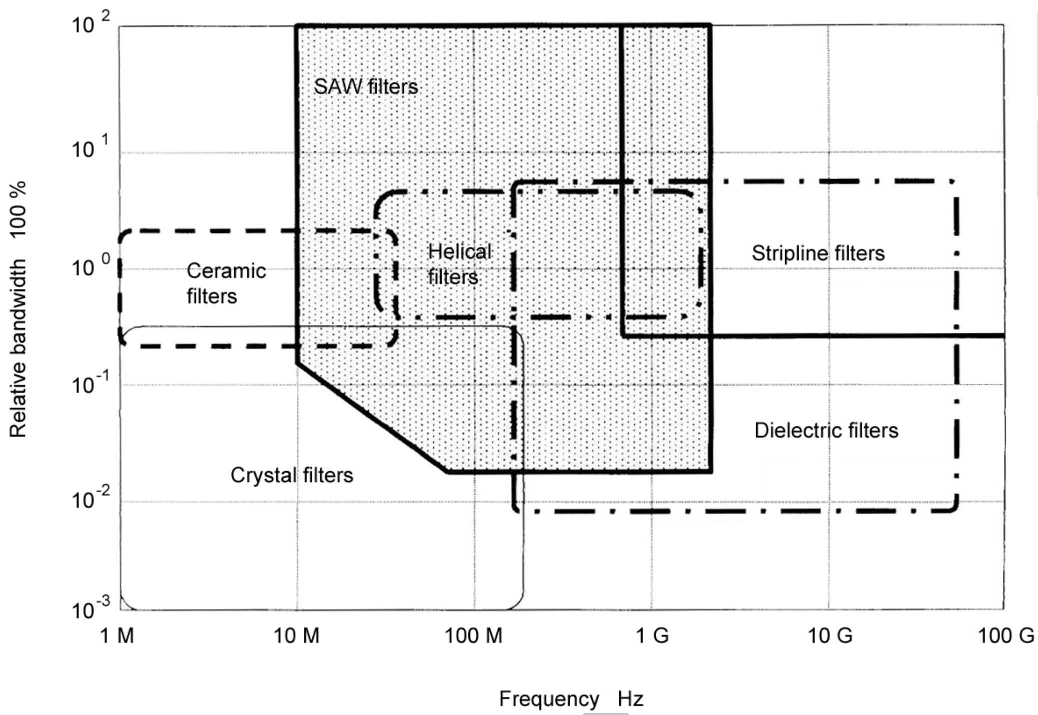

Figure 2 – Applicable range of frequency and relative bandwidth of the SAW filter and the other filters

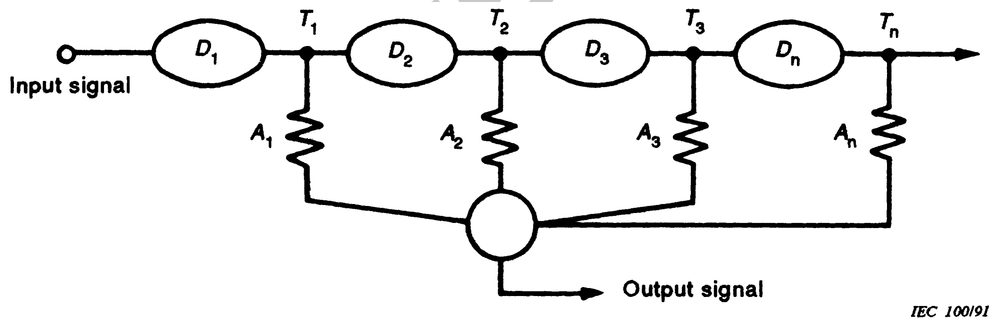

Figure 3 – Schematic diagram showing signal flow through a transversal filter

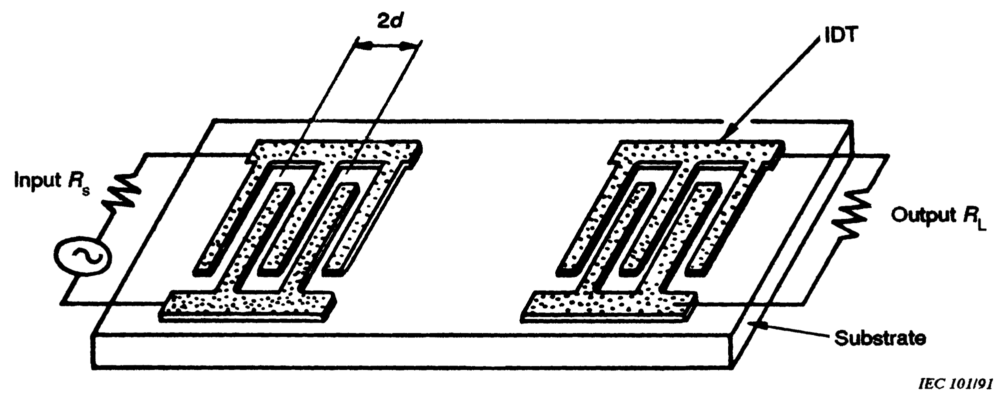

Figure 4 – Basic configuration of a SAW transversal filter

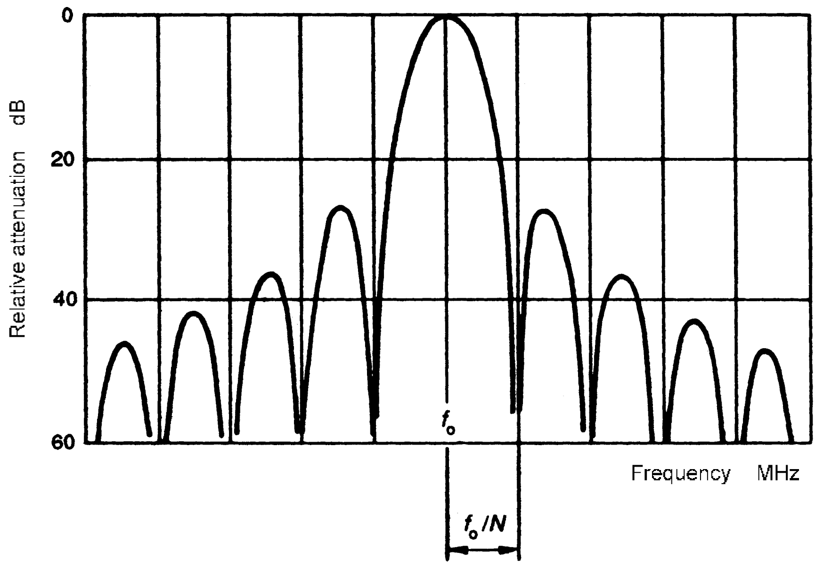

Figure 5 – Frequency response of the SAW transversal filter shown in figure 4, where f_0 is the centre frequency and N is the number of finger pairs of the IDT

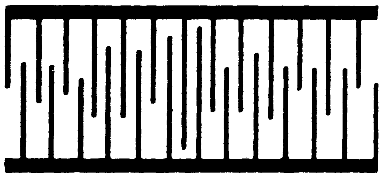

Figure 6 – Apodization weighting obtained by apodizing fingers

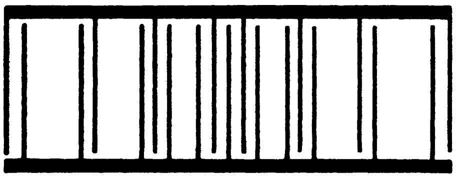

Figure 7 – Withdrawal weighting obtained by selective withdrawal of the fingers

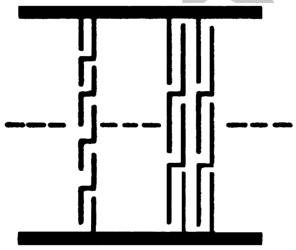

Figure 8 – Series weighting obtained by the dog-leg structure

5.3 Filter configuration and their general characteristics

In some cases, the split-finger (double electrode) configuration, as shown in figure 9, is used to reduce SAW reflections at the metal electrodes. With this geometry, the individual reflections, caused by the discontinuity in acoustic impedances on the surface, are cancelled in each finger pair. This finger configuration is now popular in SAW TV-IF filters, etc.

Ordinary IDTs show bi-directional property. These bi-directional IDTs transmit and receive SAWs to and from two directions respectively. For instance, a transmitting IDT converts an electric signal into SAWs. The SAW propagates both forwards and backwards with the same intensities. A receiving IDT will receive either of them with the same efficiency. This means that bidirectional loss values can be estimated at 3 dB each at the transmitting and receiving IDT. Therefore, the bidirectional loss of 6 dB is inherent and is the minimum insertion attenuation in a bidirectional two-transducer SAW filter. Moreover, in these ordinary SAW filters accompanying the bidirectionality, strong pass-band ripple is induced by the triple transit echo (TTE) when the impedances of transmitting IDT and the receiving IDT are matched to the outer loads.

In order to reduce the bi-directional loss and the triple transit echo (TTE) in SAW transversal filters, multi-IDT (IIDT) filters (including three-IDT SAW filters) and unidirectional IDT filters are utilized.

Additionally, reflector filters (see figures 19 and 20) can be included as one of the transversal filters. Grating technology is widely used as a reflector which changes SAW's propagation direction with some reflection frequency response. The reflector filters utilize not only their own transversal filter characteristics which are derived from the transducers but also the reflection frequency responses of the reflector in various grating constitutions in order to actively shape the filter transfer function and to reduce their chip length by folding the SAW propagation.

A brief summary of the configurations, the principles and/or the characteristics of individual types of SAW filters is given in the following subclauses.

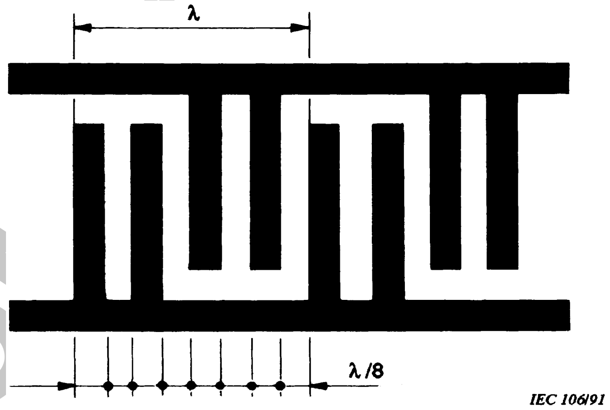

Figure 9 – Split-finger (double electrode) configuration

5.3.1 Bidirectional IDT filters

5.3.1.1 Bidirectional two-IDT filters

In the ordinary bidirectional two-IDT filters, as shown in figure 4, the TTE is reduced to a sufficiently low level at the sacrifice of the insertion attenuation, by mis-matching the IDTs to the outer loads.

a) Frequency symmetrical band-pass filter

The centre frequency and bandwidth for an IDT are given by the periods of the fingers and the number of finger pairs of the IDT, respectively. In phase characteristics, phase lag increases proportionally with frequency. Therefore, group delay is invariant in the pass-band. One typical application of a frequency symmetric band-pass filter is as an IF filter for radio transmission equipment. Linear-phase characteristics and flat pass-band amplitude characteristics are preferable for the system requirement. Figure 10 shows a typical frequency response of a SAW filter whose nominal frequency is 70,0 MHz. High-frequency SAW filters are also available with higher selectivity.

b) Frequency asymmetrical band-pass filter

In the SAW transversal filters, the amplitude and phase characteristics can be designed independently. Asymmetrical pass-band, stop-band and/or group delay characteristics in relation to the reference frequency are obtainable by means of a sophisticated design technique. SAW TV-IF filters have frequency asymmetrical characteristics, as shown in figure 11.

c) Other filter categories

Comb filters have also been proposed and are available. SAW matched filters are applied to recent civil spread spectrum (SS) systems, for example wireless LAN, etc. SAW filters with Nyquist characteristics have been developed for recent communication systems.

5.3.1.2 Multi IDT/interdigitated interdigital transducer (IIDT) SAW filters

Multi-IDT or interdigitated interdigital transducer (IIDT) filters have been developed from three-IDT filters, as demand for low-loss filtering increased. For this reason, a brief explanation for three-IDT filters is given.

a) Three-IDT filters

A three-IDT type SAW filter provides two identical receiving IDTs, symmetrically placed to the central transmitting IDT, as shown in figure 12. When the symmetric central transducer is tuned and matched at the centre frequency, the two opposite directed SAWs are completely absorbed, this being the inverse process to the generation of the two SAWs by a tuned and matched transducer. At the same time, when the two receiving transducers connected are tuned and matched at the centre frequency, the insertion attenuation can be improved to 3 dB, and the TTE is eliminated. A typical frequency response of a 900 MHz range SAW three-IDT filter is shown in figure 13.

This operation principle is extended to the multi-IDT (IIDT) filters.

b) Multi-IDT/Interdigitated interdigital transducer (IIDT) filters

Multi-IDT or interdigitated interdigital transducer (IIDT) filters provide input IDTs inter-digitally placed to output IDTs. This filter, as an example, schematically illustrated in figure 14 comprises (N + 1) input transducers and N output transducers. By this configuration, the bidirectional 6 dB loss in two-IDT filters is reduced to a much smaller value, and the triple transit echo is eliminated when the input and output port are matched to the outer loads.

When the input transducers and output transducers are tuned and matched to the circuit, the insertion attenuation of the filter shown in figure 14 is reduced to the residual bidirectional loss caused by the outermost input transducers, which is inversely proportional to number of the transducers, as follows;

$$10\log\{(N+1)/N\}\ \text{dB}$$

5.3.2 Unidirectional IDT (UDT) filters

5.3.2.1 Configuration

Both low insertion attenuation and excellent frequency characteristics in unidirectional filters are based upon directivity of surface wave propagation. Ideally, the filters have insertion attenuation of less than 1 dB, and both amplitude and phase characteristics can be controlled independently. They are divided roughly into two categories. One is the multi-phase unidirectional transducer, to which electrical fields with various phase differences are applied. The other is the single-phase unidirectional transducer applied with the same phase field.

a) Multi-phase unidirectional transducers

The three-phase unidirectional and group-type unidirectional transducers are representative of the class. The unidirectionability of the three-phase transducers arises from applying three voltages with phase differences of 120° each. In this case, however, a third electrode shall cross over one of the other electrodes using an insulated bridge, making the filter no longer truly planar and less reliable.

The group-type unidirectional transducer shown in figure 15 is capable of overcoming the above shortcomings. The unidirectional transducer with only a few pairs of electrodes, excited with an electrical phase shift of 90°, is thought of as one group. Many groups can then be colinearly arranged, the signal of each group adding in phase with the signals of all the other groups so as to yield a filter with a low insertion attenuation. Conventional weighting techniques are also applicable in this transducer.

b) Single-phase unidirectional transducers (SPUDTs)

These single-phase unidirectional transducers (SPUDTs) utilize internal reflections within the transducer to achieve unidirectional behaviour. The basic arrangement of a unidirectional transducer using internal floating electrode reflection is shown schematically in figure 16. The transducer shown in figure 16a can obtain unidirectionality, caused by the offset arrangement of floating open metal strips from the centre of positive and negative electrodes. Similarly, there are other cases of floating short metal strips and combinations of them, which are shown in figures 16b and 16c respectively.

5.3.2.2 Principle

a) Multi-phase unidirectional transducers

In a group of multi-phase unidirectional transducers, the phase difference between the wave excited by the sending electrodes (applied 90° shifted electrical field in figure 15) and the wave excited by the reflecting electrodes is zero (in phase) in the forward direction and is 180° (opposite-phase) in the reverse direction. The simple and experimental filter configuration shows a minimum insertion attenuation of 1,0 dB and a pass-band ripple of less than 0,2 dB at the centre frequency of 99,2 MHz. Here, the transducer has four pairs and eleven group electrodes. A 128° rotated Y-cut X-propagated $LiNbO_3$ substrate and a 50 Ω coaxial cable have been used as a SAW propagation medium and a 90° phase shifter respectively. Figure 17 shows an experimental attenuation-frequency characteristic of a 70 MHz SAW IF filter for a digital-cellular base-station. Here, the input transducer is an unapodized multi-phase unidirectional transducer, while the output transducer is an apodized bidirectional transducer. These transducers are on a 128° rotated Y-cut X-propagated $LiNbO_3$ single crystalline substrate. This filter shows insertion attenuation of 8 dB and pass-band ripple of 0,2 dB peak-to-peak in the frequency range of 70 MHz ± 1,6 MHz.

b) Single-phase unidirectional transducers

In a single-phase unidirectional transducer, the phase difference between excited and reflected waves is zero (in phase) in the forward direction and is 180° (opposite-phase) in the reverse direction due to the bilateral asymmetry of the internal structure of the transducer. Mass-loading effect, reflector array, change of the electromechanical coupling coefficient and internal floating electrode reflection are used to obtain asymmetry. These transducers are fabricated in one photolithographic process and do not need any phase shifter in the external circuit. Figure 18 shows the experimental result of a single-phase unidirectional transducer using internal floating short and open strips, which is shown in figure 16c. Tuning is achieved for each transducer with a shunt wire wound inductor of 200 nH. The resulting insertion attenuation of 2,3 dB at 97,3 MHz is obtained. The bandwidth of the filter is about 3,0 %.

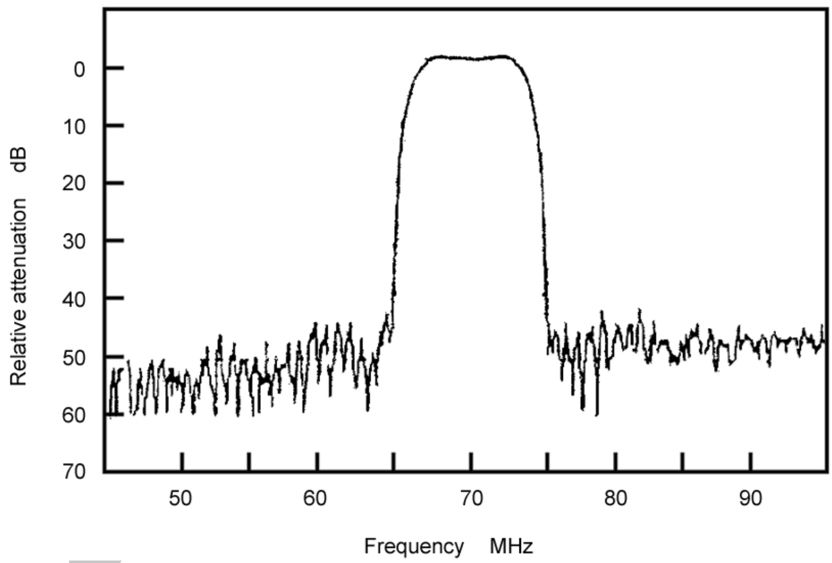

Figure 10 – Typical characteristics of a SAW IF filter for radio transmission equipment (nominal frequency of 70,0 MHz)

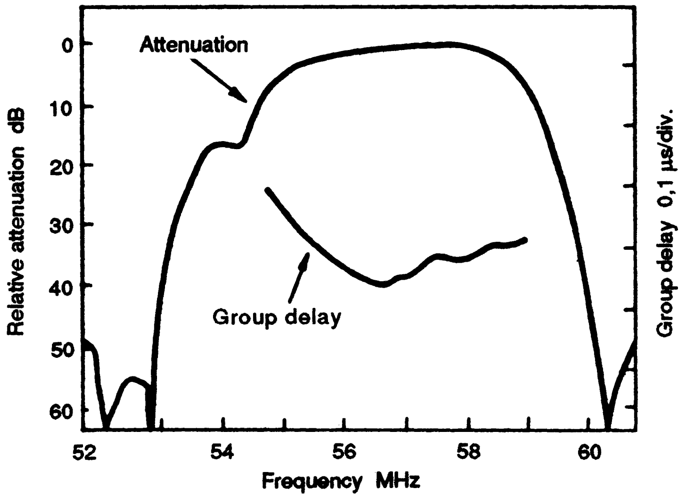

Figure 11 – Typical characteristics of a frequency asymmetrical SAW filter (nominal frequency of 58,75 MHz for TV-IF use)

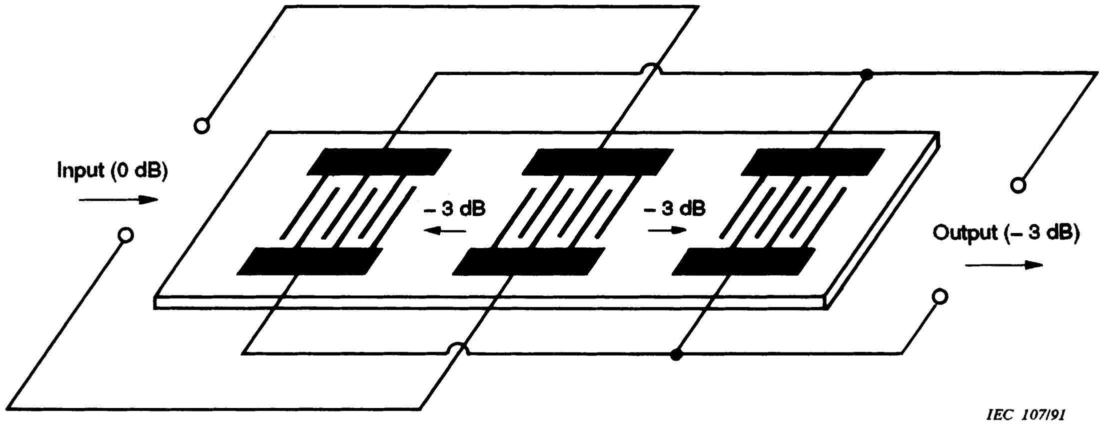

Figure 12 – SAW three-IDT filter

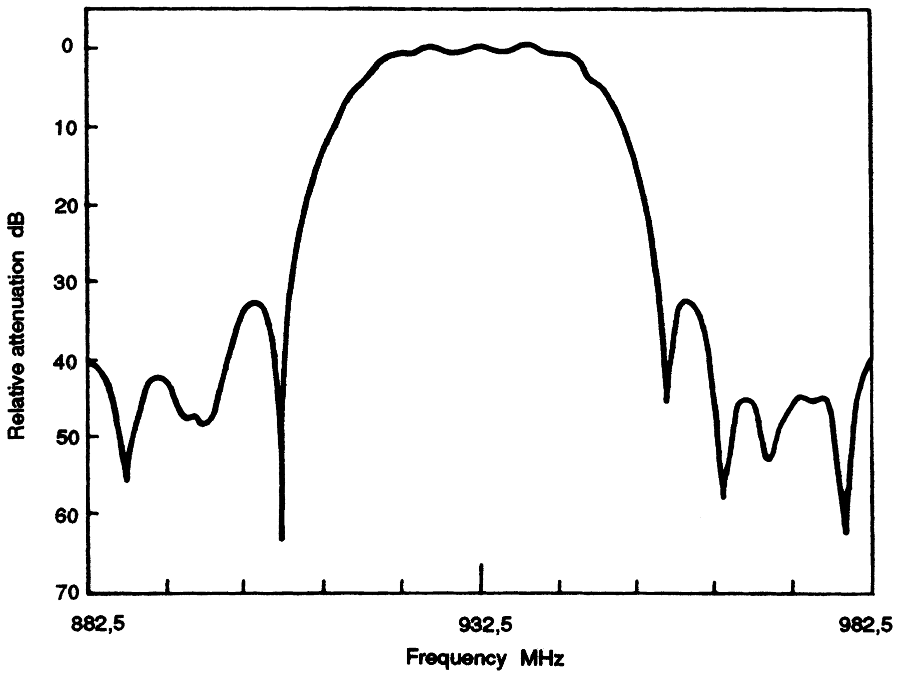

Figure 13 – Typical frequency response of a 900 MHz range SAW filter for communication (mobile telephone use)

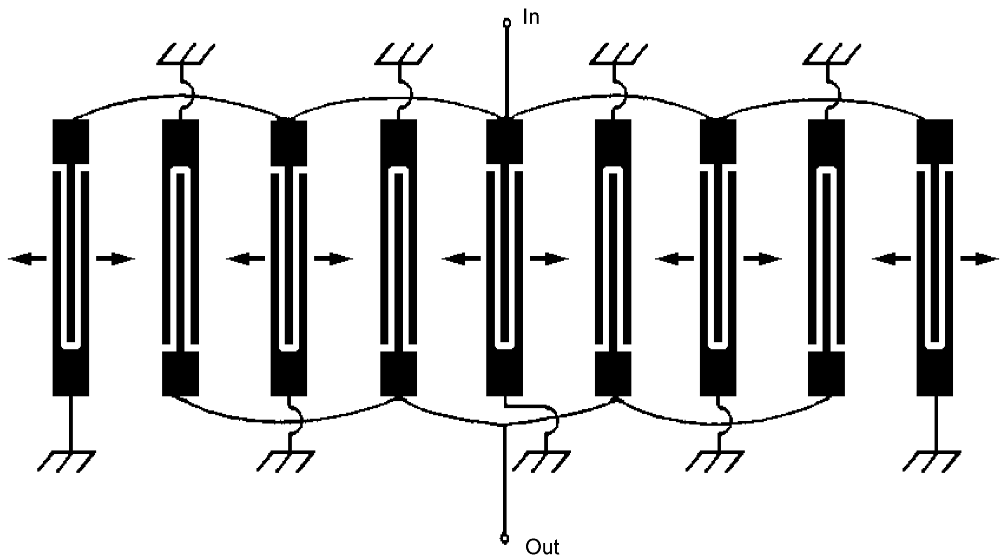

Figure 14 – Schematic of the IIDT (multi-IDT) filter

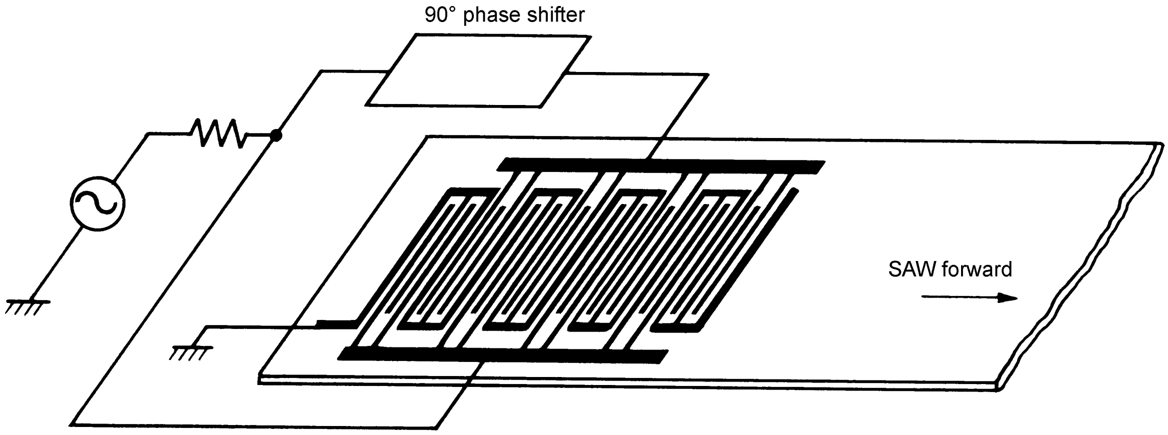

Figure 15 – Multi-phase unidirectional transducer

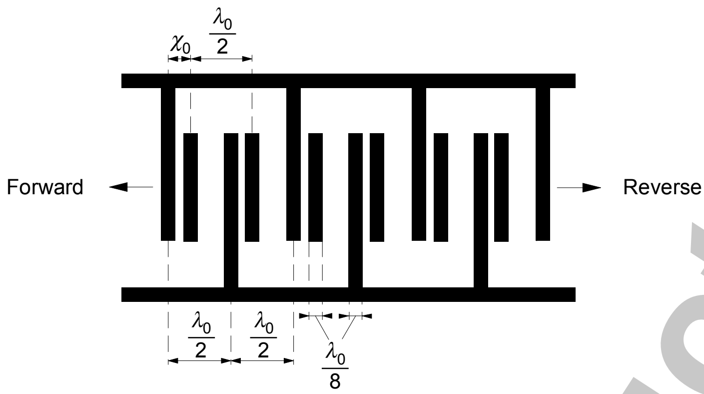

Figure 16a

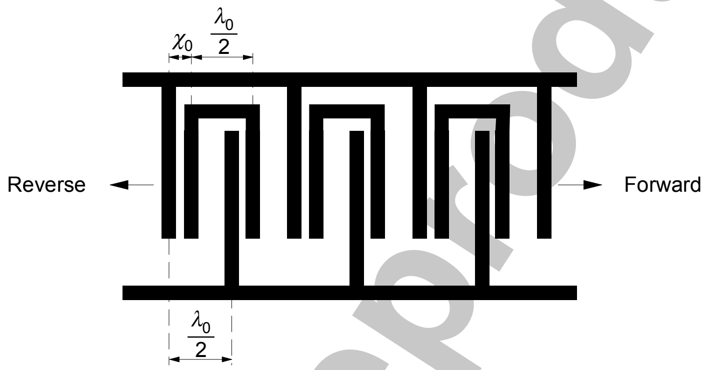

Figure 16b

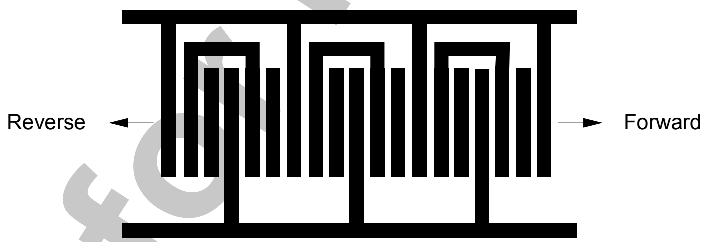

Figure 16c

Figure 16 – Single-phase unidirectional transducers

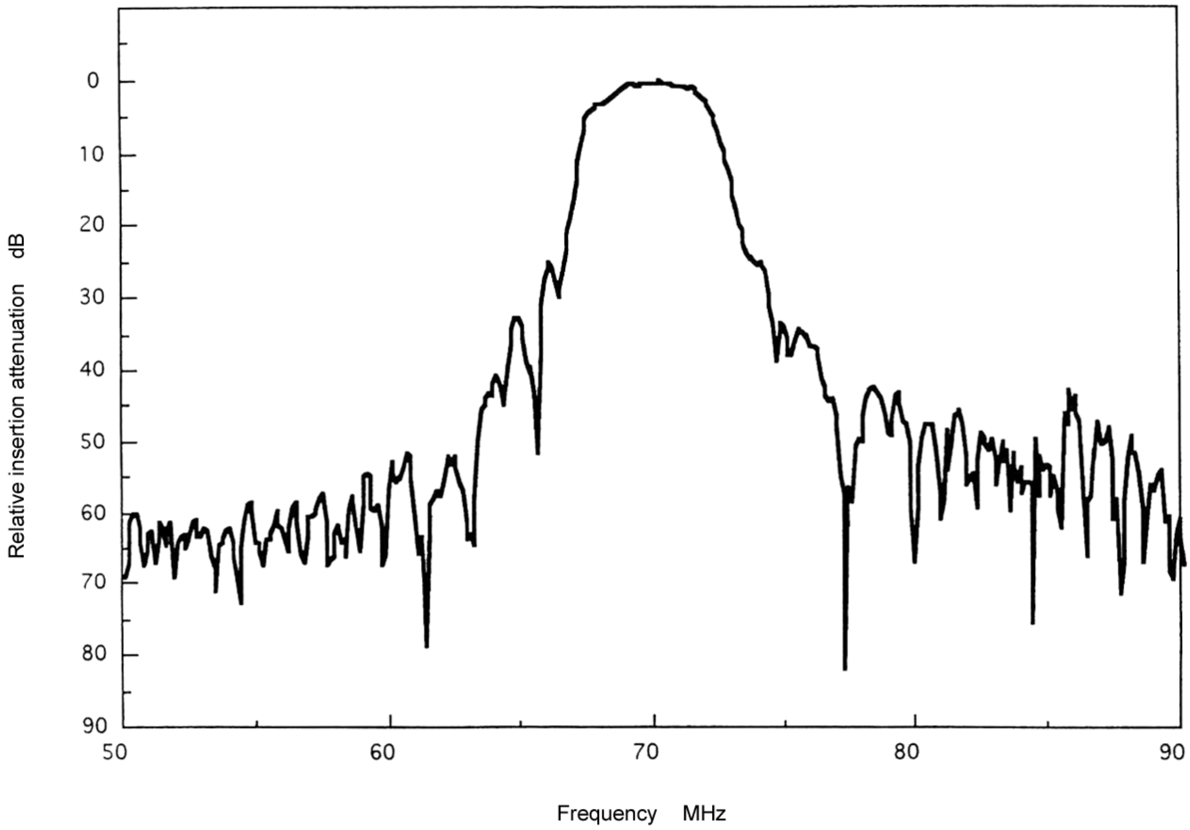

Figure 17 – Frequency characteristics of a filter using multi-phase unidirectional transducers

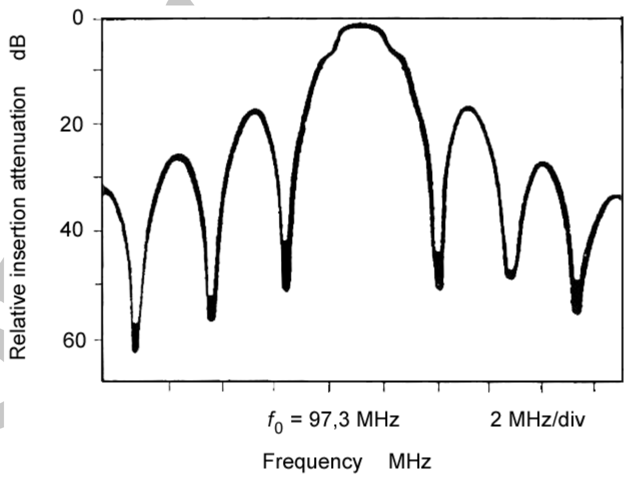

Figure 18 – Frequency characteristics of a filter using single-phase unidirectional transducers

5.3.3 Reflector filters

5.3.3.1 Configuration

Various reflection grating filters have been reported, and their basic configurations are shown in figure 19. All of the configurations utilize the grating reflection functions and they have been used as filter and delay lines.

The most popular reflection grating filter can be said to be the reflective array compressor (RAC) filter shown in figure 19d. By changing array periods gradually along the SAW propagation direction and using doubly 90° (U-shaped) reflections, the acoustic wave propagates and reflects in the U-shape. The RAC filter has been used mostly in radar systems.

Another practical variation is the Z-path filter which is shown in figure 20. This configuration is a modification of the conventional one shown in figure 19e in order to minimize the chip size dimension. An input transducer excites the SAW, and then a pair of weakly inclined reflectors (typically some 4°) serves to couple the wave from the upper track into the lower one where it is detected by the output transducer configuration.

Because the direct-path signal which comes from the input transducer to the output transducer will exist as a high-level spurious signal, the in-line configuration of figure 19a is not useful. However, using the dual-track concept shown in figure 21, the direct spurious signals cancel each other and the filter response is much improved.

Another variation of the dual-track filter is shown in figure 22a. In this case, the reflectors are centred in the middle of both tracks and are designed to be almost identical. The difference between those two tracks is only one reflective electrode distance, i.e. their lengths of $\lambda/2$. Transducers are chosen to be single-phase unidirectional transducers (SPUDT, see 5.3.2) and hence themselves reflective. SPUDT-reflector filters represent an alternative if low attenuation is an additional requirement.

5.3.3.2 Principle

RAC filters have mainly been used as pulse expansion/compression devices with dispersive grating arrays. All of the configurations can be utilized as a band-pass filter with their reflective responses. Z-path filters offer most advantages for fairly narrow band filters (0,2 % to 1 % relative bandwidth) in the frequency range below 100 MHz. The substrate material employed is quartz. The effects caused by the temperature dependence of the reflection angle in the two weakly inclined reflectors are cancelled and the good temperature stability of the crystal is maintained. Insertion attenuations in the range of 6 dB to 10 dB can be achieved. Figure 23 shows the frequency response of a Z-path filter at 71 MHz. The disturbances in the upper stop-band are typical for Z-path designs and stem from direct acoustic feedthrough from input to output.

In the dual-track filter, the four IDTs in the two tracks are arranged in a mutually blind configuration. The two input transducers are electrically driven 180° out of phase, whereas the two output transducers are in phase. The transfer function of the entire filter can be described as the product in the frequency domain of the transfer functions of input and output transducers and of the reflector response. Figure 24 shows the transfer function in the frequency domain of a reflector filter for IF application in mobile communication. The main advantages of this filter configuration lie in a considerable reduction of filter length with respect to conventional transversal designs, in the independent design of transducers and the reflector and in a good stop-band rejection resulting from three cascaded filter mechanisms. Disadvantages are the additional die width needed for two tracks, a somewhat more complex layout and additional loss from signal reflection.

SPUDT-reflector filter provides for four constructive propagation paths from input to output, two in each track, as indicated in figure 22b. The first path travels from input through the centre reflector, then is reflected first by the output transducer and next by the centre reflector until it is detected by the output transducer. Similarly, the second propagation path consists of two reflections before passing through the centre reflector. Consequently, four selection mechanisms, consisting of input transduction, centre grating reflection, one transducer reflection and output transduction, shape the stop-band and an impulse response duration about twice that of transversal filters is available. SPUDT-reflector filters offer moderate bandwidths in the range of 0,5 % to 2 % with an insertion attenuation of some 6 dB to 10 dB. Figure 25 shows the frequency response of a 110 MHz filter on X-cut 112,2° rotated Y propagated $LiTaO_3$.

Generally, reflector filter designs exploit the fact that the reflection function of a grating structure is twice as long in time as the excitation or detection function of a transducer of the same geometrical length. This is because the reflected acoustic signal has to go into the reflector and back out again. A total time domain corresponding to twice the length of the reflector structure is available for, for example, narrow bandwidths, pass-band shaping or pulse expansion and compression. Consequently, reflector filters tend to be shorter than conventional transversal filters.

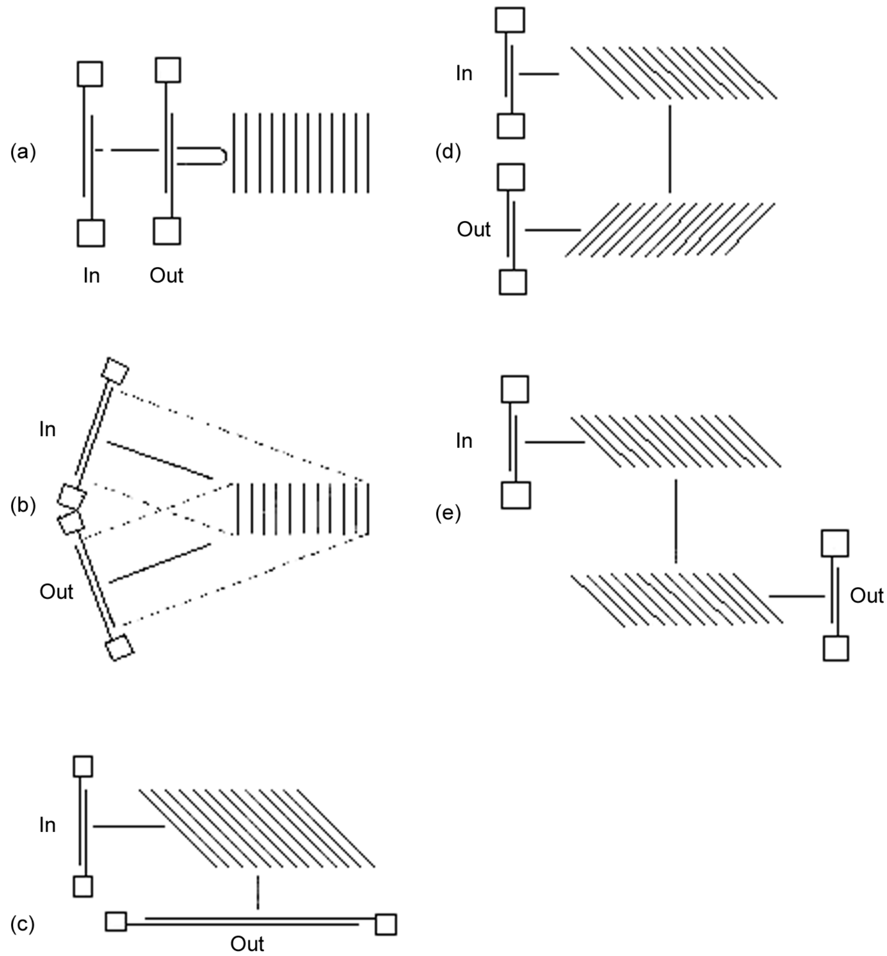

Figure 19 – Various reflector filter configurations

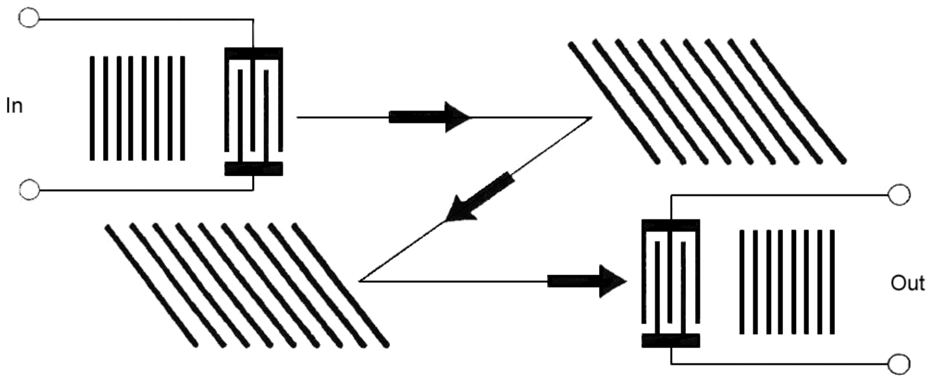

Figure 20 – Z-path filter configuration

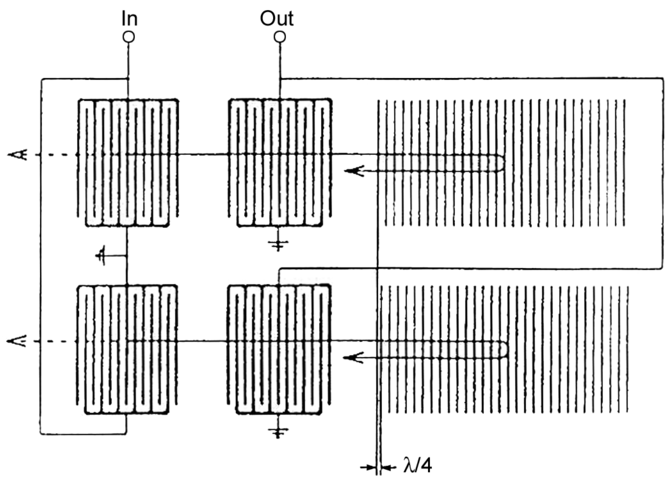

Figure 21 – Dual-track reflector filter configuration

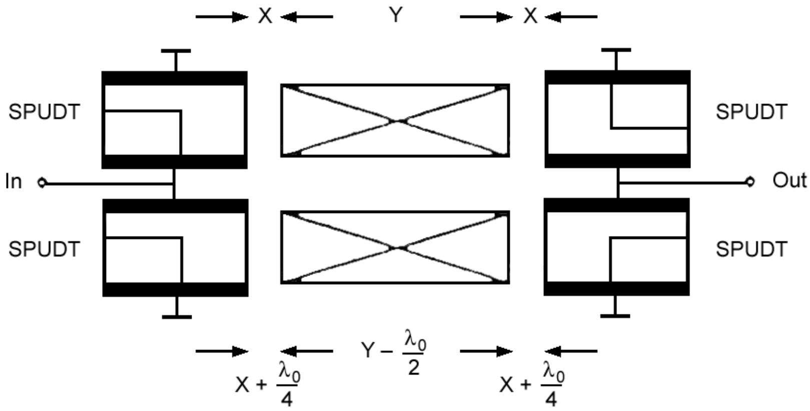

Figure 22a – SPUDT based dual-track filter configuration

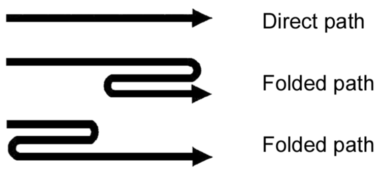

Figure 22b – Propagation paths on SPUDT-based dual track filter

Figure 22 – SPUDT-based dual-track filter

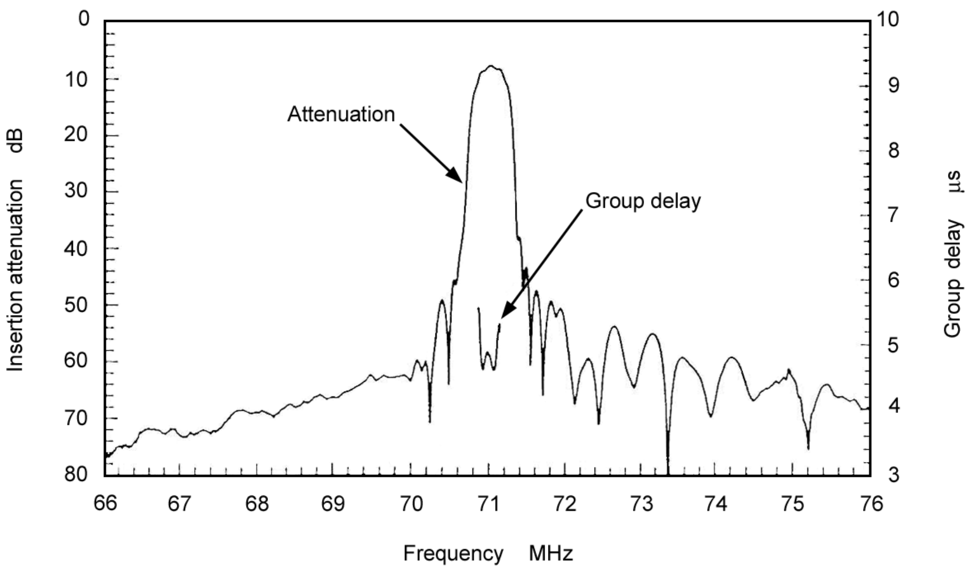

Figure 23 – Frequency characteristics of Z-path filter

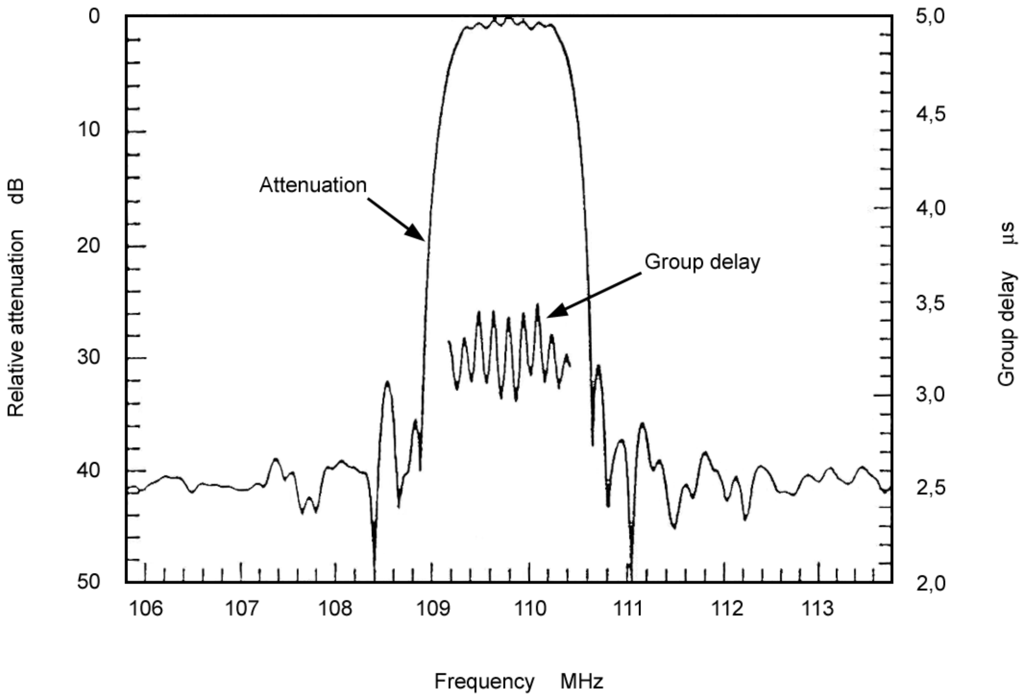

Figure 24 – Frequency characteristics of dual-track reflector filter

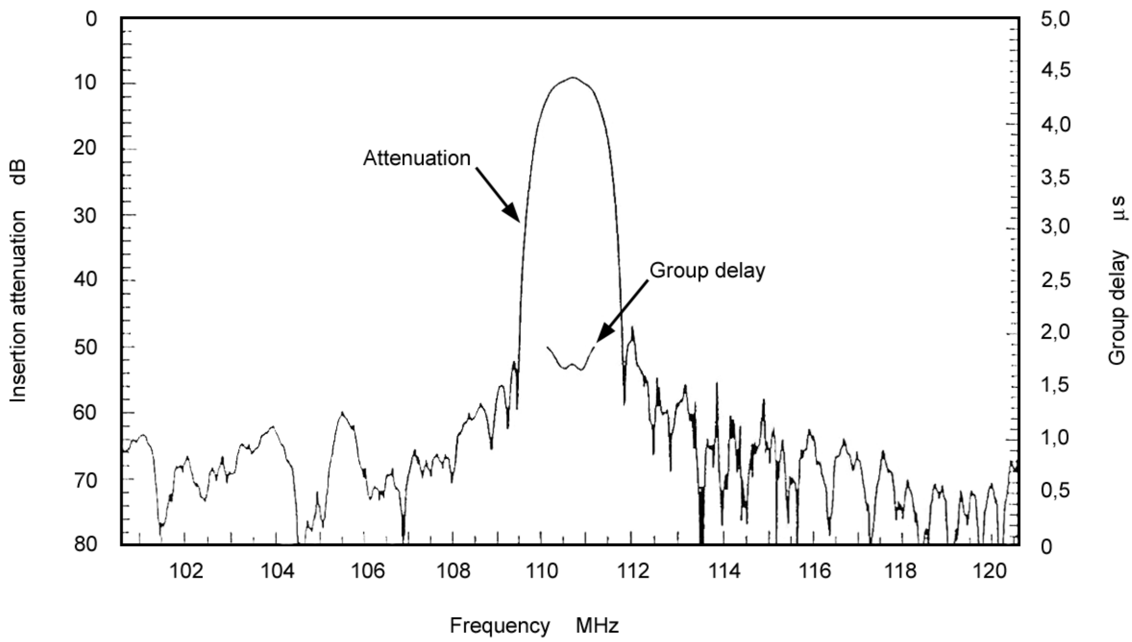

Figure 25 – Frequency characteristics of SPUDT-based reflector filter

6 Fundamentals of SAW resonator filters

6.1 Classification of SAW resonator filters

SAW resonator filters are becoming rapidly popular as SAW low insertion attenuation filters for mobile communication application in addition to the conventional SAW transversal filters. SAW resonator filters can realize low insertion attenuation easily and a smaller size than that of the transversal filters with the same bandwidth. Their feasible bandwidth is, however, limited by substrate materials, design methods and so on, and their amplitude characteristics and phase characteristics cannot be designed independently. It is desirable for users to understand these factors for SAW resonator filters. This standard explains the principles and characteristics of SAW resonator filters.

Various kinds of SAW resonator filters have been proposed and put into practice. Basically, all of them can be represented in and near the pass-band with resonant circuits using lumped elements of inductance L, capacitance C and resistance R. The difference between various resonator filters is in the way the basic resonators are linked together. The concept regarding the resonant circuits is very common and can be applied to other piezoelectric filters like crystal filters. It is helpful to refer to IEC 60368-2-1 to understand the basic concept.

Generally, SAW resonator filters can be classified into two types. One is a ladder and lattice filter, which are constituted by ladder and lattice connection of multiple one-port SAW resonators that correspond to each series resonant arm in the equivalent circuits. The other is a coupled resonator filter and IIDT (interdigitated IDT) resonator filter. Those filters utilize multiple modes which occur in a single cavity simultaneously and enable the filter structure to be simplified.

The concept and equivalent circuit of the ladder and lattice filter is the same as the crystal filter, and the difference is the use of a one-port SAW resonator in place of a crystal resonator. The practical constitution and the filter characteristics are given in 6.2.

The coupled resonator filters utilize multi-mode resonances in a single SAW resonator, and a region of multiple resonances corresponds to its pass-band. They can be classified further to transverse mode type and longitudinal mode type from the point of resonant modes. The transverse mode coupled resonator filters usually utilize double modes which occur transversely to SAW propagation direction. Their concept, equivalent circuit and filter characteristics are very close to those of monolithic crystal filters. Since the longitudinal mode coupled resonator filters utilize resonant modes which occur along the SAW propagation direction, their mode couplings are stronger than that of the transverse mode, and as a result their bandwidth can be wider than that of the transverse mode filter. The constitution and filter characteristics of the two types are discussed in 6.3.

IIDT resonator filters are composed of a number of relatively small-pair IDTs for input and output in a line, alternating with grating reflectors put on the outside of IDTs. This structure can make strong coupling between input and output IDTs and utilize multiple resonant modes. This type is discussed in 6.4.

6.2 Ladder and lattice filters

6.2.1 Basic structure

Two kinds of one-port SAW resonators having slightly different resonance frequencies are designed to be connected in ladder or lattice circuit. The lattice filter is used especially for the balanced circuit.

a) Ladder filter

Figure 26a shows an example of a filter structure and figure 27a shows an example of an equivalent circuit of a half-section of a ladder filter assuming that the resistance is negligible. The half-section of the filter consists of a series-arm resonator (R1) and a parallel-arm resonator (R2). A series-arm resonator has slightly higher resonance frequency than that of a parallel-arm resonator. The resonator has one IDT between two reflectors. SAW resonators' electrodes are formed on a piezoelectric substrate shown in figure 28. The resonators R1′ and R2′ are synthesized resonators. R1′ has half-static capacitance of R1, and R2′ has twice static capacitance of R2.

b) Lattice filter

This type of filter comprises a pair of series-arm SAW resonators (R1) and a pair of parallel-arm SAW resonators (R2) electrically coupled to form a lattice circuit shown in figure 26b. Figure 27b shows an equivalent circuit of a lattice filter assuming that the resistance is negligible. The frequency shift is chosen so that resonance frequency of one pair of resonators approximately coincides with the anti-resonance frequencies of the other pair of resonators.

6.2.2 Principle of operation

a) Ladder filter

Figure 29a shows the variations of X_s and B_p as a function of frequency. Here, the anti-resonance frequency (f_{ap}) of the parallel-arm resonator is nearly equal to the resonance frequency (f_{rs}) of the series-arm resonator. The image transfer constant γ is expressed with X_s and B_p in the following equation:

$$\tanh\gamma = \sqrt{B_p X_s / (B_p X_s - 1)} \qquad (4)$$

where

X_s is the equivalent series reactance of the resonator;

B_p is the equivalent parallel susceptance of the resonator.

According to the theory of image-parameter filters, a filter shows a pass-band characteristic when equation (4) has an imaginary number. However, it shows a stop-band characteristic when equation (4) has a real number. Therefore, the condition $0 < B_p X_s < 1$ gives the pass-band, and the condition $B_p X_s > 1$ or $B_p X_s < 0$ gives the stop-band shown in figure 29a.

b) Lattice filter

Figure 29b shows the variations of X_s and X_p as a function of frequency. In this example, the anti-resonance frequency (f_{as}) of the series-arm pair is nearly equal to the resonance frequency (f_{rp}) of the parallel-arm pair. The image transfer constant γ is expressed with X_s and X_p in the following equation:

$$\tanh(\gamma/2) = \sqrt{X_s / X_p} \qquad (5)$$

A filter shows a pass-band characteristic when equation (5) has an imaginary number. However, it shows a stop-band characteristic when equation (5) has a real number. Therefore, the condition $X_s/X_p < 0$ gives the pass-band. The condition $X_p > X_s$ or $X_p < X_s$ gives the stop-band when the equation (5) has a real number. Condition $X_p = X_s$ gives maximum insertion attenuation shown in figure 29b.

6.2.3 Characteristics of ladder and lattice filters

The pass bandwidth of ladder and lattice filters is affected by a substrate material. It is effective to use a substrate material having a high electromechanical coupling coefficient in order to obtain a filter with a wide pass-band. The insertion attenuation of a filter is determined by the Q factor of the resonators which compose a filter. The stop-band attenuation is basically determined by the capacitance ratio of a parallel-arm resonator to a series-arm resonator and the stage number of the resonators' connection. In the case of a lattice filter, when the static capacitance of a pair of series-arm resonators (R1) is equal to the static capacitance of a pair of parallel-arm resonators (R2) shown in figure 26b, the stop-band attenuation becomes maximum.

a) Ladder filter

As a ladder filter example, the RF filter was designed and fabricated for portable telephone terminals. An Al-Cu sputtered film for the electrodes and a 36° rotated Y-cut X-propagated $LiTaO_3$ crystal for the piezoelectric substrate was used. Figure 30 shows the frequency characteristic of a 1,5 GHz band-pass filter for a digital system. The minimum insertion attenuation of less than 3 dB and the voltage standing wave ratio of less than 2 were obtained without an external matching circuit.

b) Lattice filter

As a lattice filter example, a 1,5 GHz range filter was reported which was designed and fabricated using a quartz substrate. The measured insertion attenuation was 3 dB, the stop-band attenuation was more than 35 dB and the 3 dB bandwidth was about 1 MHz.

6.3 Coupled resonator filters

The operation of coupled resonator filters is similar to that of monolithic crystal filters (MCF). By means of an acoustic coupling between the identical resonators, various kinds of resonance modes having different frequency are generated, which are called symmetric mode, anti-symmetric mode or higher order modes. As these resonance modes have different frequencies and opposite phases, provided the termination is correct, a band-pass filter is achieved.

6.3.1 Transversely coupled type

In the case of a transversely coupled filter with two one-port resonators placed close in the transverse direction as shown in figure 31a, 0 order transverse mode (symmetric mode) which has a symmetric distribution of SAW amplitude and the 1st order transverse mode (anti-symmetric mode) which has an anti-symmetric distribution are generated. The frequency difference is determined by the distance between the two resonators, the aperture of IDTs and the degree of energy trapping. Figure 31b shows the equivalent circuit of this filter. Figure 32 shows typical transmission characteristics of a transversely coupled filter. The bandwidth of this filter is very narrow. In most cases, this type of filter uses substrate material which has stable temperature characteristics such as quartz to keep the pass-band at specified frequency. From the point of view of size, in spite of very narrow bandwidth, this filter is much smaller than the transversal filter the size of which is in inverse proportion to the bandwidth.

6.3.2 Longitudinally coupled type

In the case of a longitudinally coupled resonator filter with two IDTs arranged in series between grating reflectors as shown in figure 33a, 0 order resonance mode (symmetric mode) and the 1st order resonance mode (anti-symmetric mode) are generated in a similar way. Generally, the resonance frequency of the higher order longitudinal mode is lower than that of the lower order mode. The frequency difference of these two modes is determined mainly by the number of IDT fingers, and the degree of energy trapping. Figure 33b shows another configuration of double-mode filter using 0 and 2nd order longitudinal modes. As the frequency of the 2nd order mode is lower than that of the 1st order mode, this filter has wider pass-band than the former one. Figure 34 shows the typical transmission characteristics of a longitudinally coupled resonator filter. This filter, which has stronger acoustic coupling between IDTs, has wider pass-band than the transversely coupled filter. As the pass bandwidth of the coupled resonator filter is restricted by the capacitance ratio of the resonator, it is necessary to reduce the capacitance ratio in order to achieve a wider pass-band. To reduce the capacitance ratio of the resonators, it is effective to adopt substrate material with a high electromechanical coupling coefficient such as $LiTaO_3$ or $LiNbO_3$.

6.3.3 Other characteristics of coupled resonator filters

The insertion attenuation of both types of filters is determined by the Q (quality factor) of the resonators. Higher Q leads to lower insertion attenuation. There are various kinds of spurious responses in these filters. The major ones are caused by the configuration of IDTs and reflectors such as higher order inharmonic resonance modes or responses of IDTs and reflectors themselves. The next ones are caused by different kinds of waves generated in IDTs or converted from SAW in IDTs and reflectors or at the edge of the substrate.

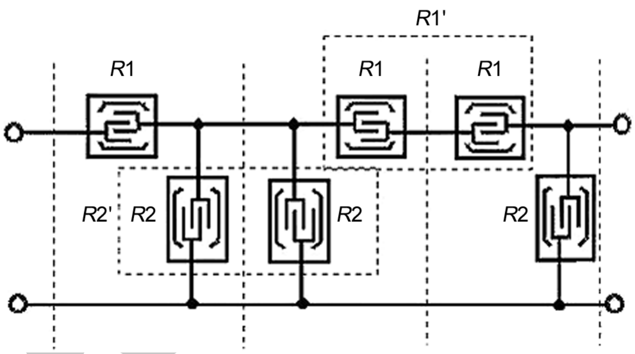

Figure 26a – Ladder filter

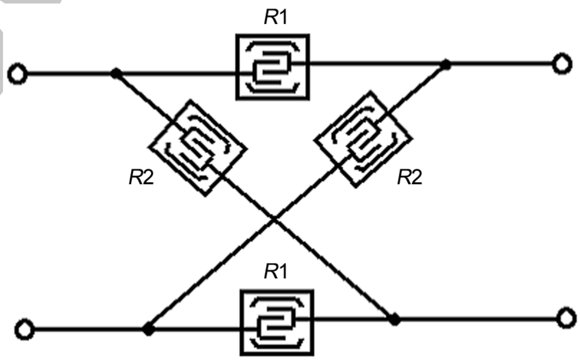

Figure 26b – Lattice filter

Figure 26 – Structure of ladder and lattice filters

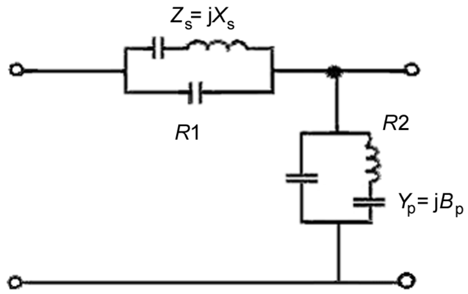

Figure 27a – Ladder filter of half section

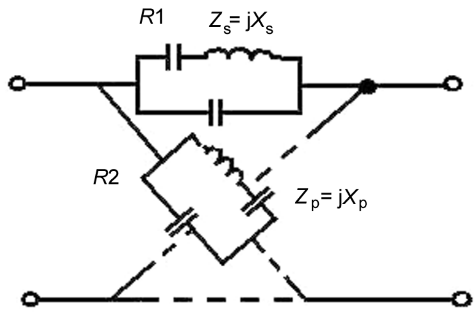

Figure 27b – Lattice filter of full section

Figure 27 – Equivalent circuit of basic section of ladder and lattice filter

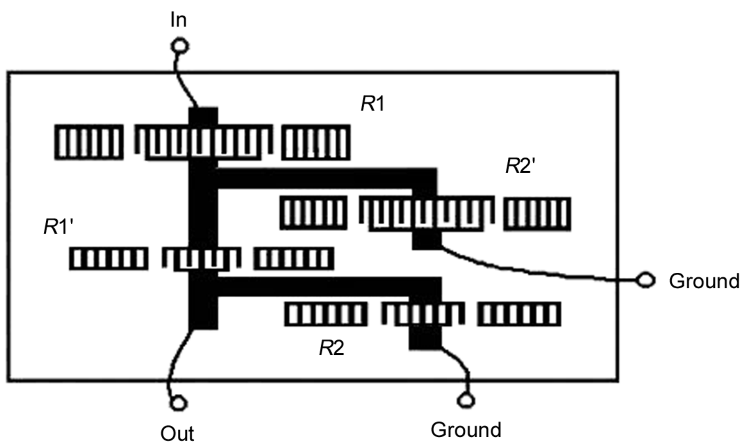

Figure 28 – Pattern layout of ladder filter

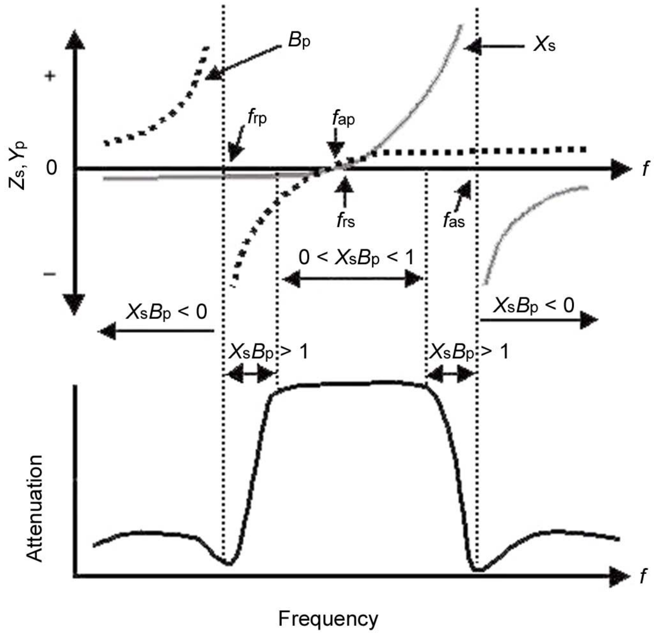

Figure 29a – Ladder filter

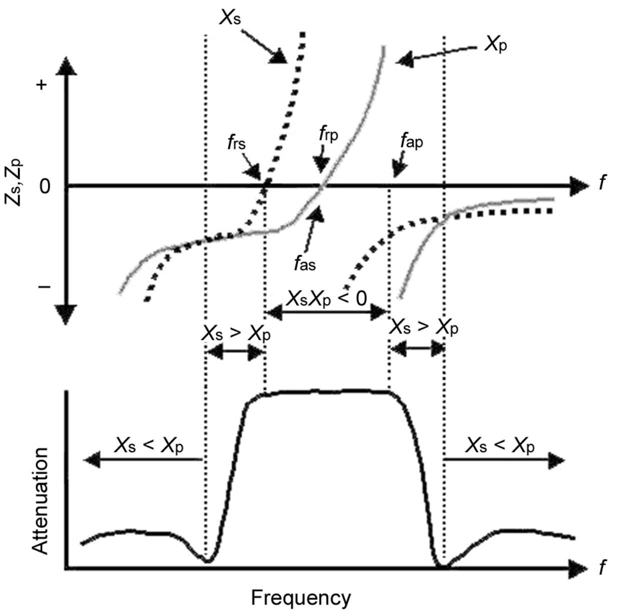

Figure 29b – Lattice filter

Figure 29 – Basic concept of ladder and lattice filter

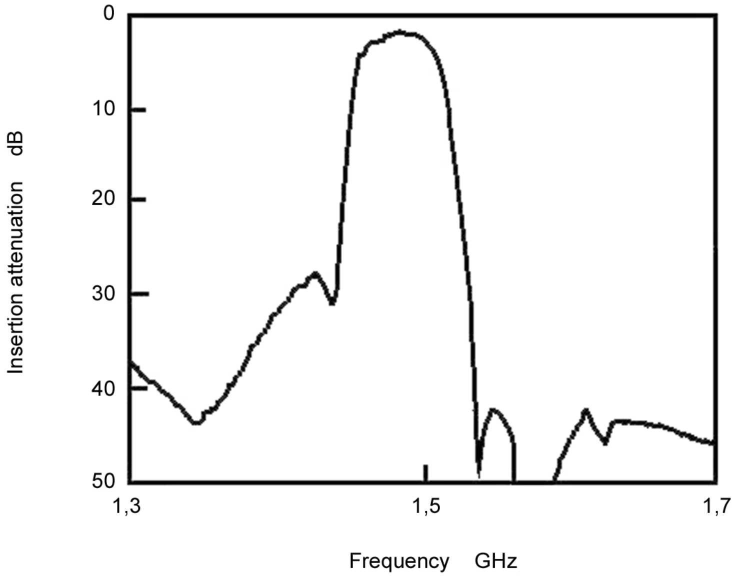

Figure 30a – Stop-band response

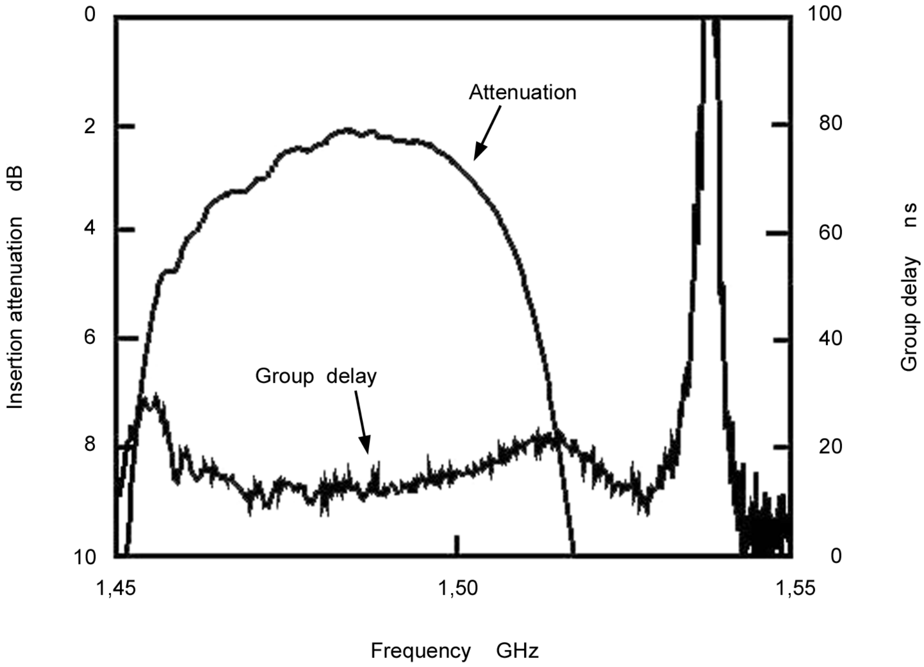

Figure 30b – Pass-band response of amplitude and group delay time

Figure 30 – Typical characteristics of a 1,5 GHz range ladder filter

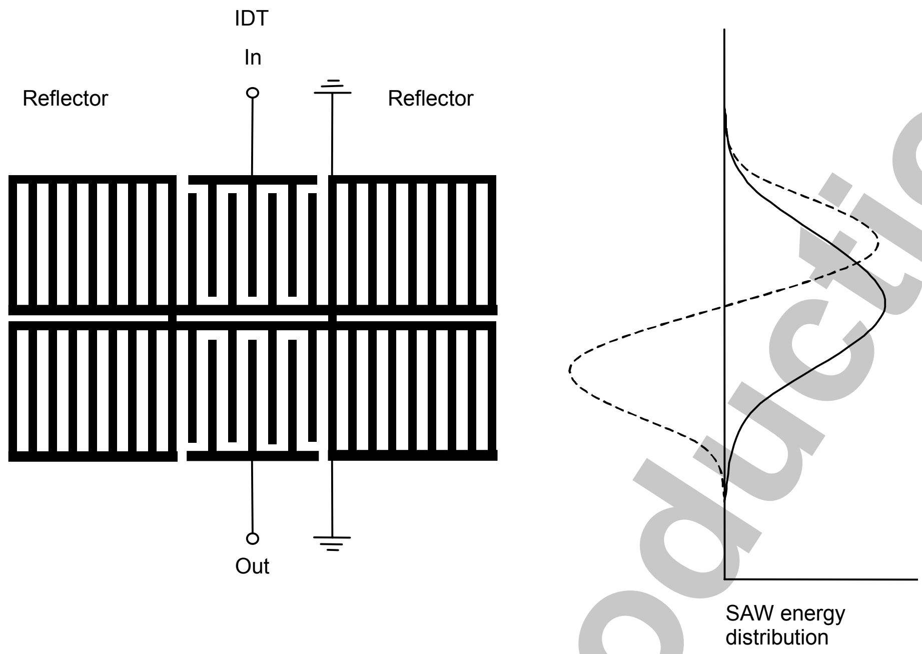

Figure 31a – Basic configuration and SAW energy distribution of transversely coupled resonator filter

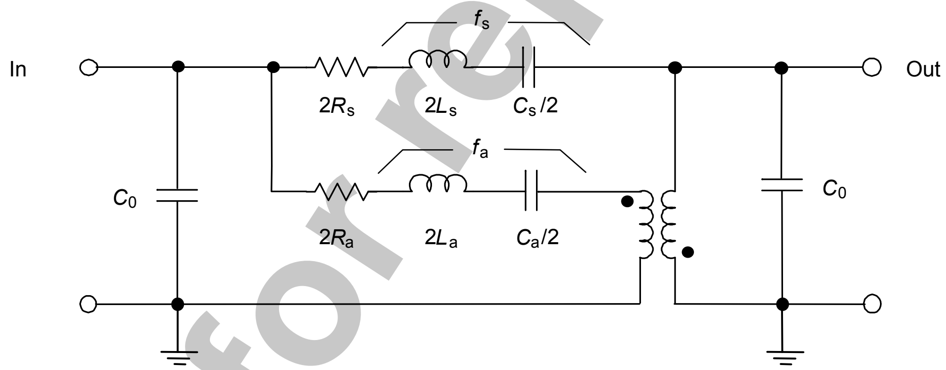

Figure 31b – Equivalent circuit of transversely coupled resonator filter

Figure 31 – SAW energy distribution and equivalent circuit of transversely coupled resonator filter

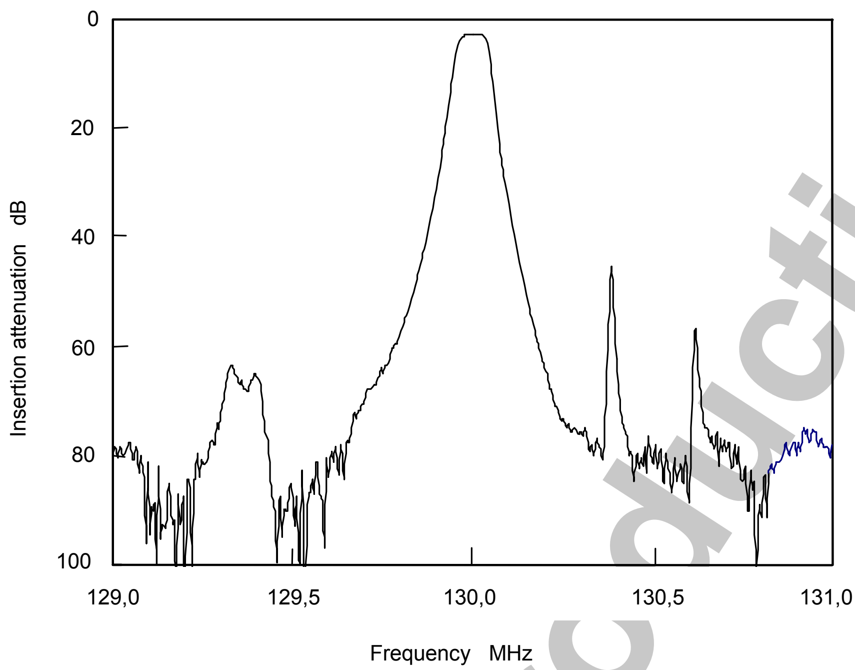

Figure 32a – Stop-band response

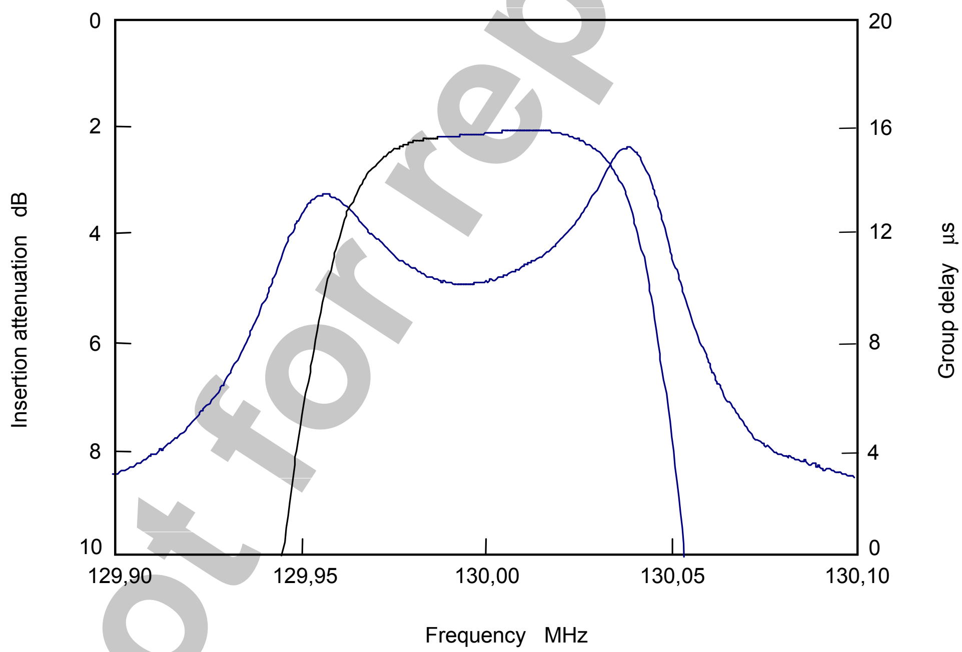

Figure 32b – Pass-band response of amplitude and group delay time

Figure 32 – Typical characteristics of a transversely coupled resonator filter

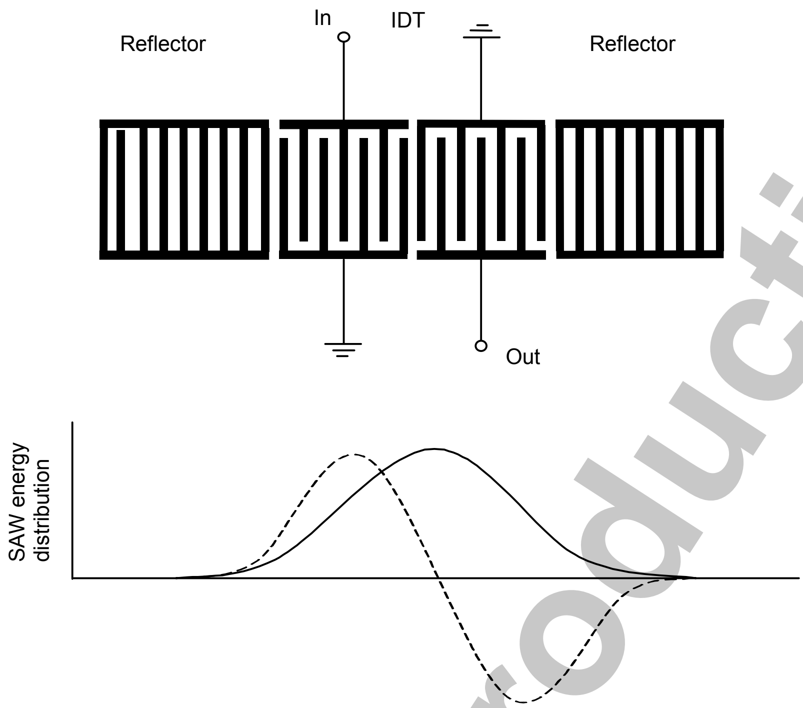

Figure 33a – SAW energy distribution of longitudinally coupled resonator filter using 0- and 1st-order modes

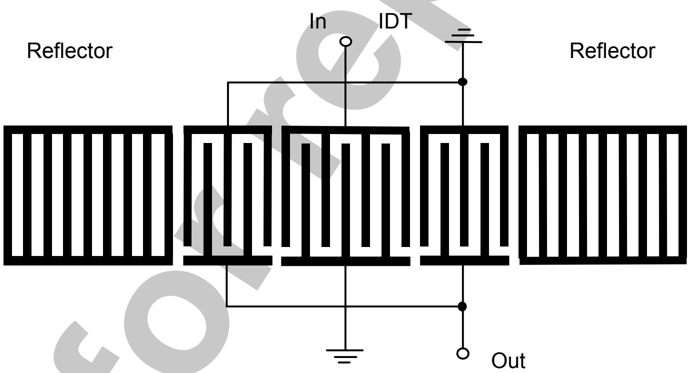

Figure 33b – Resonator filter using 0- and 2nd-order modes

Figure 33 – Basic configuration and SAW energy distribution of longitudinally coupled resonator filter

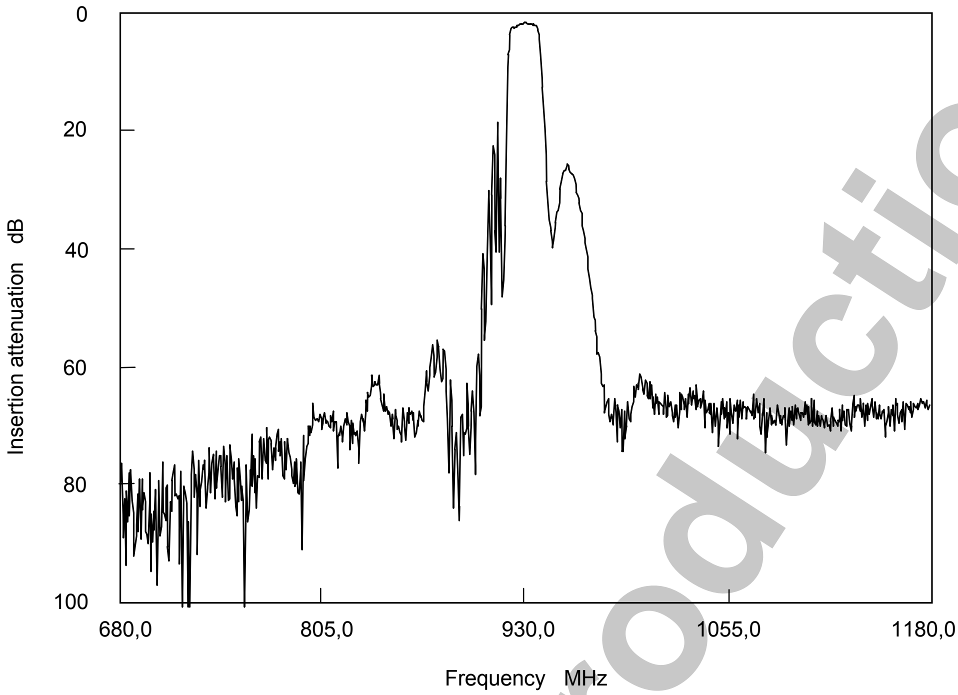

Figure 34a – Stop-band response

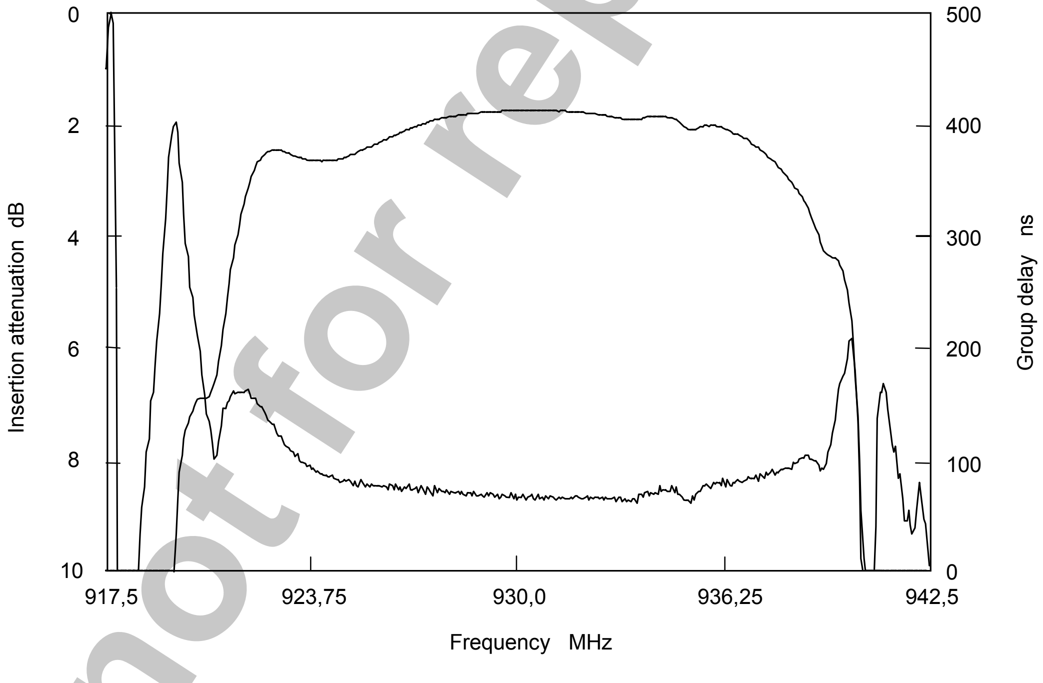

Figure 34b – Pass-band response of amplitude and group delay time

Figure 34 – Typical characteristics of a longitudinally coupled resonator filter

6.4 Interdigitated interdigital transducer (IIDT) resonator filters

6.4.1 Configuration

The IIDT filter described in 5.3 shows residual bidirectional loss caused by the outermost electrodes. For the reduction of such residual losses, several configurations are proposed. As an example, figure 35 schematically shows an IIDT filter equipped with grating reflectors on either side of the IIDT configuration. An increase in the out-band rejection compatible with the loss reduction is required.

6.4.2 Principle

The grating reflectors shown in figure 35 reflect the SAWs launched from the outermost transducers, thereby reducing the residual bidirectional loss occurring at the outermost transducers. Variation in the placement and the finger-pair number of the transducers can give reduced SAW power flow densities at the outermost transducers, thereby reducing the loss.

6.4.3 Characteristics

Some recent IIDT filters have the insertion attenuation lower than 2 dB to 2,5 dB in a 50 Ω circuit with no outer matching element, when the fractional bandwidth is adequate and a high coupling piezoelectric single-crystalline substrate is utilized (for example, 64° rotated Y-cut X-propagated $LiNbO_3$). The frequency characteristics of this type are shown in figure 36. A three-transducer-configuration filter with reflector gratings, as a kind of IIDT, also shows small insertion attenuation lower than 2 dB. Some configuration variations and optimizations methods for IIDT filter designing are discussed in the scientific literature.

7 Application guide

7.1 Substrate materials and their characteristics

Various kinds of piezoelectric substrates are available for SAW filter applications. Piezoelectric substrates for SAW filters are selected according to the following:

a) propagation velocity (v_s);

b) coupling coefficient (k_s^2);

c) temperature coefficient of delay (TCD) or frequency (TCF);

d) relative permittivity (ε_r);

e) propagation loss;

f) reproducibility, reliability and availability;

g) price.

Items a) to e) are constants concerned mainly with materials and items f) and g) are conditions depending on both materials and substrate fabrication techniques. Several kinds of substrates have been developed and put into practical use.

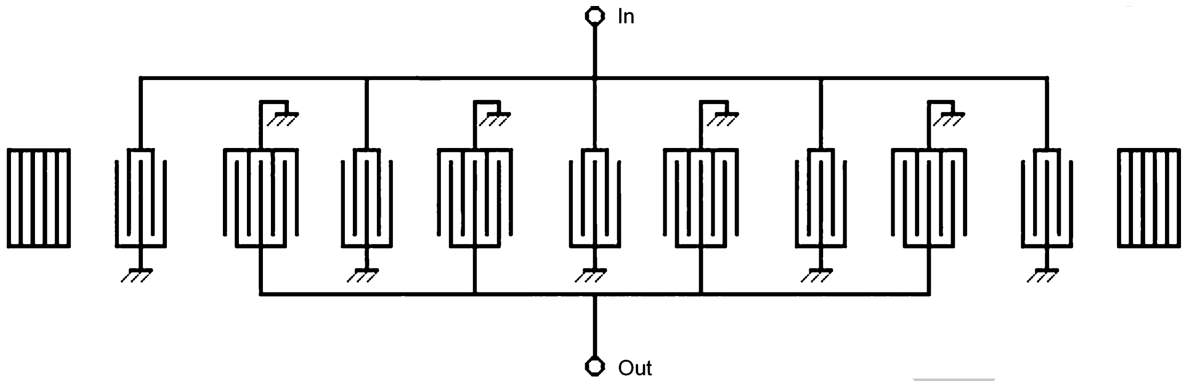

Figure 35 – Schematic of IIDT resonator filter

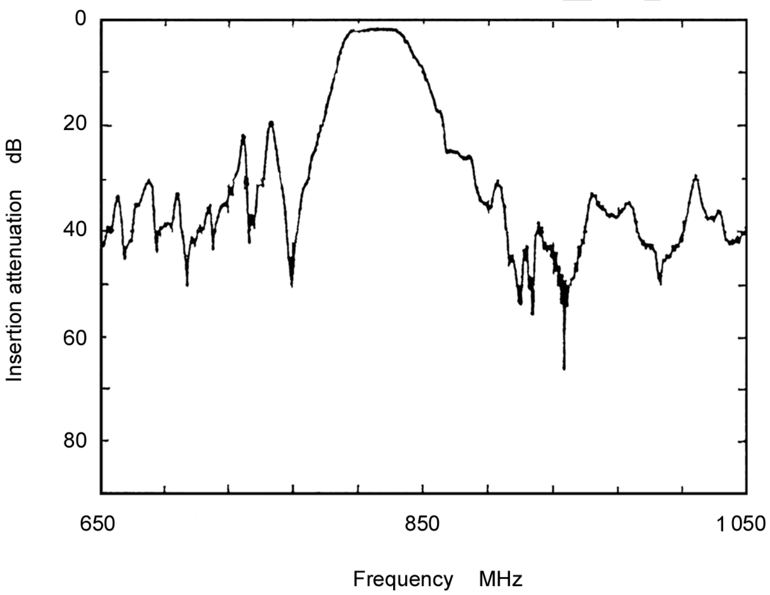

Figure 36 – Frequency characteristics of a 820 MHz range IIDT resonator filter

Ideally, a high coupling coefficient and a zero temperature coefficient are desired. At present, this is not possible, so design trade-offs are required. It is necessary to select a substrate according to the required specifications. Relationships between material constants and filter characteristics are described in the following subclauses.

a) Propagation velocity

Propagation velocity v_s (m/s) is an important factor, which determines centre frequency f_0 (MHz) given approximately by

$$f_0 = v_s /(2d)$$

where

d (µm) is one-half of the IDT periodic length, as shown in figure 4.

For a specified centre frequency, slower velocities require a shorter finger period and, consequently, a smaller chip size. Faster velocity is desirable for high-frequency filters in order to make the IDT fabrication easier. Propagation velocity for a practical substrate is usually in the range of 2 000 m/s to 5 000 m/s.

b) Coupling coefficient

The SAW coupling coefficient k_s^2 is the transformation ratio between the electric energy and the mechanical (SAW) energy. In transversal filters, the minimum insertion attenuation and maximum relative bandwidth depend on the coupling coefficient. This is discussed in 7.2 and figure 37. When the coupling coefficient is large enough, it is possible to reduce the insertion attenuation and broaden the bandwidth. In resonator filters, the coupling coefficient is the principal factor that determines the capacitance ratio r. When the coupling coefficient of the substrate is large enough, it is easy to design a low capacitance ratio SAW resonator; consequently, it is possible to broaden the bandwidth.

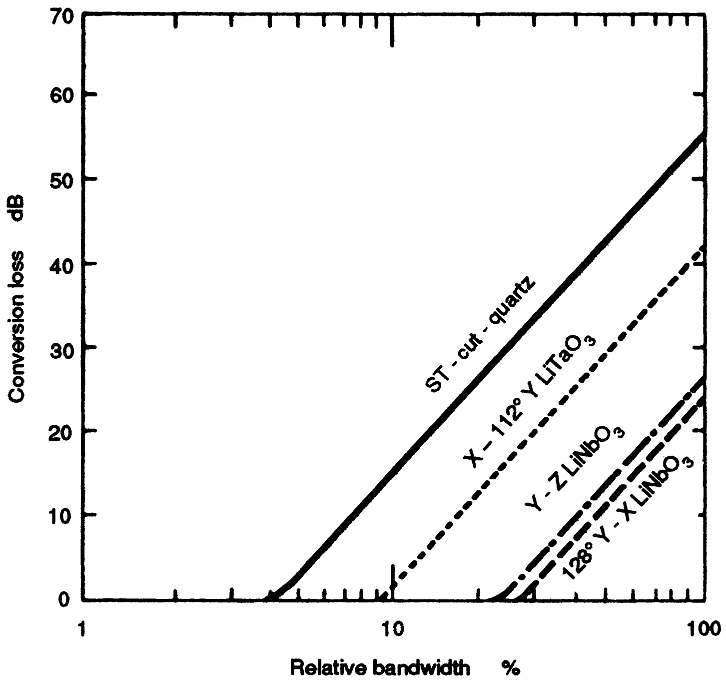

Figure 37 – Minimum theoretical conversion losses for various substrates

c) Temperature coefficient

The frequency response for the filter changes with the ambient temperature. The major problem is the shift in the centre frequency. Most substrate materials exhibit a linear temperature dependence of relative frequency shift, that is, the magnitude of relative frequency shift is almost equal to the product of temperature coefficient of frequency and change of temperature. The temperature coefficient of frequency (TCF) is almost the same in magnitude but opposite in polarity to the temperature coefficient of delay (TCD). Rotated Y cut (around ST-cut) quartz, $Li_2B_4O_7$ and some kinds of ZnO thin films on glasses have zero TCF at a certain temperature.

d) Relative permittivity

The permittivity of the piezoelectric material is a second-order symmetric tensor.

In the case of a normal IDT whose line and space (metallization) ratio is 1:1, the static capacitance of the IDT, C_T, is approximately expressed as

$$C_T = w\,N\,(1 + \varepsilon_r)\varepsilon_0$$

where

w is the IDT aperture;

N is the number of finger pairs;

ε_r is the relative permittivity of the substrate;

ε_0 is the permittivity of vacuum.

The electric field distributions are complicated, therefore, an effective relative permittivity ε_r, defined as $\sqrt{\mathring{a}_{11}\mathring{a}_{33} - \mathring{a}_{13}^2}$, is usually used. Permittivities ε_{11}, ε_{33} and ε_{13} are tensor components of the material. High permittivity value obviously results in high static capacitance. The ε_r value of typical substrates are shown in tables 1, 2 and 3.

e) Propagation loss

There are three factors relating to the insertion attenuation. They are propagation loss, beam-steering loss and air-loading loss. The propagation loss depends on the material and the surface finishing of the substrate. In the case of well-polished high-coupling single-crystal substrate, propagation loss is usually less than 1 dB/μs at 1 GHz.

The propagation loss is proportional to the square of the frequency. Beam-steering loss occurs when the phase-velocity vector direction differs from the acoustic power-flow direction. Generally, substrate orientation is determined so that both the above-mentioned directions coincide. The air-loading loss is caused by acoustic waves radiating into the air, and the loss is proportional to the frequency. This loss is negligibly small, in comparison with other losses.

f) Typical single-crystal materials

Properties of single-crystal substrates are governed by the angle of cut and the SAW propagation direction because of the crystal anisotropy. Single crystals have advantages of reproducibility, reliability, and low propagation loss. However, it is still difficult to obtain a material which satisfies both large coupling coefficient and small temperature coefficient simultaneously. Typical crystals and their angles of cut recommended for SAW filters are listed in table 1 with their material constants.

g) Typical thin-film materials

There are a variety of combinations of thin-film materials, bases and structures in thin-film SAW filters. By a suitable combination and design, it is possible to achieve improvement in coupling coefficient, temperature coefficient, and other properties. The total temperature coefficient can be improved by using a substrate whose temperature coefficient is opposite in polarity to the thin film. Some combinations exhibit zero TCF at a certain temperature. Polycrystalline zinc oxide (ZnO) is usually used as thin-film material for its strong electromechanical coupling. Single-crystal films have also been developed for high-frequency use. Typical combinations are listed in table 2.

h) Typical ceramic materials

Ceramic materials have advantages in that various characteristics can be improved by the selection of material compositions. They exhibit a relatively large coupling coefficient. Ceramics are composed of small crystal grains but because the grain size is around several microns in diameter, the propagation loss is very high in the high-frequency region, for example, >100 MHz. Typical data for ceramics are listed in table 3.

Table 1 – Properties of typical single-crystal substrate materials

Material	Angle of cut	Propagation direction	Velocity v_s	Coupling coefficient k_s^2	Temperature coefficient		Relative permittivity ε_r
	Degrees	Degrees	m/s	%	10^{-6}/K	10^{-9}/K^2	
ST-quartz	42,75° Y	X	3 157	0,16	0	–34	4,5
LST-quartz	–75° Y	X	3 960	0,11	9	(3rd order)	4,5
$LiNbO_3$	Y	Z	3 488	4,82	–94	–	36,7
$LiNbO_3$	128° Y	X	4 000	5,56	–74	–	39,1
$LiNbO_3$	64° Y	X	4 742	11,3	–79	–	
$LiTaO_3$	X	112° Y	3 295	0,64	–18	–	44,0
$LiTaO_3$	36° Y	X	4 178	4,8	–33	–	48,3
$Li_2B_4O_7$	45° X	Z	3 401	1,0	0	–270	9,6

Table 2 – Properties of typical thin-film substrate materials

Thin-film and base materials and structure	Velocity v_s	Coupling coefficient k_s^2	Temperature coefficient	Relative permittivity ε_r
	m/s	%	10^{-6}/K	
p-ZnO/IDT/glass base	2 576	1,4	–11	10,8
Metal/p-ZnO/IDT/glass base	3 200	0,8	–7	10
IDT/s-ZnO/sapphire base	5 500	3,4	–35	10
NOTE p and s represent polycrystalline films and single-crystal films respectively. The glass bases are boro-silicate glass.				

Table 3 – Properties of typical ceramic substrate materials

Material composition	Velocity v_s	Coupling coefficient k_s^2	Temperature coefficient	Relative permittivity ε_r
	m/s	%	10^{-6} /K	
$Pb(Sn_{1/2}Sb_{1/2})O_3$-$PbTiO_3$-$PbZrO_3$	2 420	2,4	–38	270
$0,1Pb(Mn_{1/3}Nb_{2/3})O_3$-$0,9Pb(Zr_{0,74}Ti_{0,26})O_3$	2 430	2,9	–17	460

7.2 Application to electronics circuits

SAW filter characteristics are also governed by the tuning networks and external circuits. In order to obtain a satisfactory performance, certain precautions are required.

a) Insertion attenuation

Insertion attenuation for SAW filters is mainly caused by conversion loss of transducers, ohmic loss of metal electrodes in the IDT, acoustic propagation loss, bulk mode conversion loss, leakage losses from sides of reflectors, loss due to bidirectional propagation, and apodization loss. In practical cases, in the case of the bidirectional IDT filter, the conversion loss and the bi-directional loss are usually the main contributors to the insertion attenuation.

The IDT conversion loss depends on the impedance matching between the IDT and the external circuits. According to the equivalent circuit model, the impedance of the IDT of SAW transversal filters is capacitive. The conversion loss can be minimized by tuning with suitable coils at the centre frequency of the SAW filter. The conversion loss can be ignored, when the impedance matching is perfect, i.e. in the case expressed as:

$$k_s^2 > (\pi/4)(\Delta f / f_0)^2$$

where

k_s^2 and $\Delta f/f_0$ denote the coupling coefficient and relative bandwidth, respectively.

On the other hand, in the case expressed as:

$$k_s^2 < (\pi/4)(\Delta f / f_0)^2$$

the attainable minimum conversion loss is limited and the minimum conversion loss is inversely proportional to k_s^2. Figure 37 gives the minimum theoretical conversion losses for various substrates.

In order to reduce the bidirectional loss of 6 dB, the three-IDT structure is available. The output transducers at the right and left ends are electrically connected in parallel, so that the loss decreases by 3 dB. An ideal unidirectional IDT can make the bi-directional loss zero.

b) Noise figures and other problems in applied circuits

The insertion attenuations for ordinary bidirectional IDT filters are usually larger than those for conventional LC filters. When conventional LC filters are replaced by SAW filters, an additional amplifier with appropriate gain may be required in order to compensate for additional insertion attenuation. There are two kinds of amplifiers, i.e. a pre-amplifier and a post-amplifier, with regard to the SAW filter. Both of them have advantages and disadvantages, which users and circuit designers should duly consider. The following discussion may be of some help.

In the case of a pre-amplifier, since it amplifies the signal at a preliminary stage in the system, the signal becomes so large that the non-linearity in the amplifier may cause interference in cross-modulation and/or intermodulation. To reduce this interference, a negative feedback loop can be applied to the pre-amplifier. It is preferable to keep the gain as low as permissible. In the case of a post-amplifier, the interference problem is solved. The noise figure of an entire system which employs a post-amplifier may possibly be worse owing to the large insertion attenuation of a SAW filter. If the input signal is attenuated at the SAW filter, the noise of the post-amplifier degrades the noise figure of the system. Precise impedance matching is one of the easiest ways to lower the noise figure of the system because it saves conversion loss at the SAW filter. It is recommended that the amplifiers in the front stages be designed with sufficient gain with respect to the system noise figure and sufficient linearity to avoid cross-modulation and intermodulation interference.

c) Triple transit echo (TTE) in a SAW transversal filter

TTE is one of the unwanted signals caused by the multiple acoustic reflections between input and output transducers. This signal has a delay of $2t$ behind the main signal, where t is the delay for the main signal between the transducers. As shown in figure 39, the TTE causes ripples having a period of $1/(2t)$ in the amplitude and group delay characteristics in the pass-band of a SAW filter. A TTE 40 dB below the main signal causes approximately ±0,1 dB amplitude ripple and $\pm 0{,}02t$ group delay distortion. Since TTE arrives at the output with a delay behind the main signal, a television set equipped with a SAW filter in a video intermediate frequency stage exhibits "ghost" interference (duplicate picture) on the screen.

TTE is caused by electrical regeneration of the SAW at the IDT. To reduce regeneration, it is usually effective to increase the terminating impedances and increase the IDT conversion loss. The improvement in TTE suppression can be estimated as twice as much as the increase in the insertion attenuation in decibels. To suppress TTE caused by regeneration the terminating impedance should be much greater than the IDT impedance. In the case where the insertion attenuation is compensated by an amplifier in front of the filter, the output impedance of the amplifier should be as high as possible.

So far as a SAW filter employs ordinary bidirectional transducers, there will always be such TTE problems. A unidirectional IDT filter and an IIDT filter are capable of lowering the insertion attenuation and suppressing the TTE simultaneously. Such SAW filters are designed under a specific impedance matching condition, and impedance mismatching increases the TTE and the insertion attenuation.

7.3 Availability and limitations

The relationship between relative bandwidth and insertion attenuation for each type of SAW filter with the bandwidth of SAW filters used in a typical telecommunication system is shown in figure 38 as a general concept. Because a SAW filter has a complex mechanical structure, there are numerous unwanted responses besides TTE and they may disturb the filter characteristics. Such unwanted responses must be suppressed or reduced below a certain level. In practical use, long-term stability should also be considered.

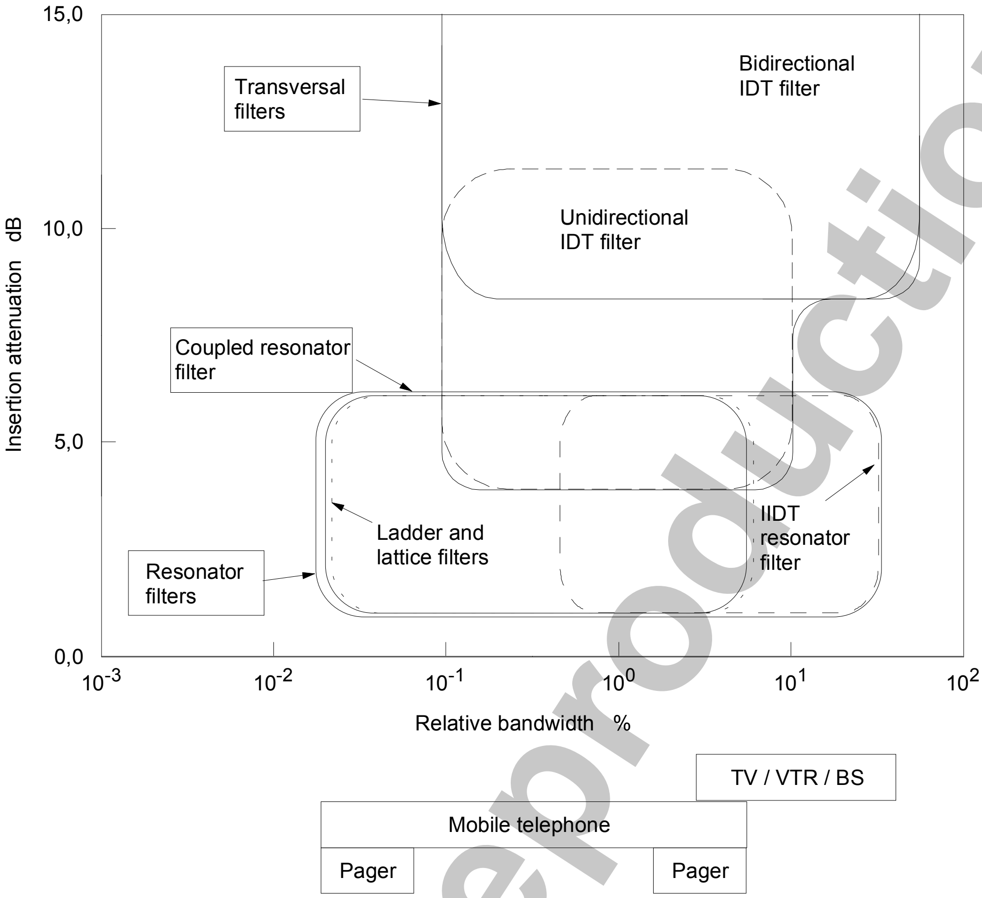

Figure 38 – Relationship between relative bandwidth and insertion attenuation for various SAW filters, with the practical SAW filters' bandwidth for their typical applications

a) Harmonic response signals

Harmonic response signals are also excited in a SAW filter as in a piezoelectric filter and disturb the stop-band characteristics. The spurious level of the harmonic response signal depends on the metallization ratio and the configuration of the electrodes in the SAW filter.

b) Bulk-wave signals

Bulk-wave signals are generated at an input IDT as well as SAW and are detected by the output IDT after reflection from the bottom of the substrate, or directly if they propagate close to the surface. Because they are faster than SAW, they affect the stop-band attenuation at the upper frequency region in the pass-band. In order to eliminate these signals, it is recommended that the bottom of the substrate be roughened and/or a multistrip coupler be deposited between the input and output transducers.

c) Feed-through signals

Because feed-through signals travel directly between the input and output circuits due to the electrostatic or electro-magnetic coupling, they appear at the output terminal instantly when the input voltage is applied. Like TTE, they cause ripple in the pass-band, as shown in figure 39, but the frequency period (δf) is equal to $1/t$, which is twice as wide as that of TTE, where t is the delay of the main signals. Sometimes, they fill the frequency traps in the stop-band and degrade the stop-band characteristics. In order to reduce these effects, a shielding electrode is often placed between the input and output transducers.

d) Reflections from substrate edges

Such reflections cause ripple in the pass-band, but can be easily reduced by inclining the substrate edges and by placing an absorber on the substrate.

e) Ageing performance

SAW filters exhibit excellent long-term stability as well as bulk acoustic wave filters. The long-term ageing rate depends on the input level of a SAW filter, the substrate mounting method, the atmosphere in which the substrate is located, etc. Hermetically sealed packages are usually used for narrow pass bandwidth filters and low insertion attenuation filters.

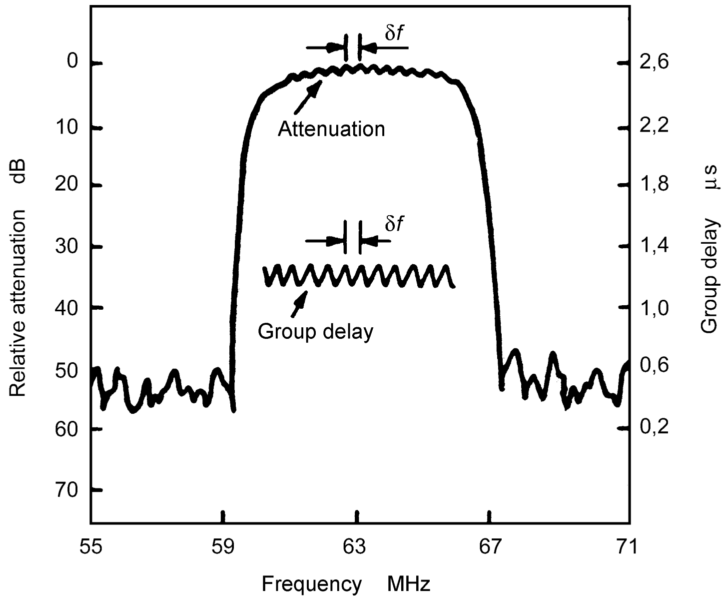

Figure 39 – Ripples in the characteristics of a SAW filter caused by TTE or feed-through signal: $\delta f = 1/(2t)$ for the TTE, and $\delta f = 1/t$ for the feed-through, where t is the delay of the SAW main signal

7.4 Input levels

Drive level performance is limited by

– finger damage;
– frequency shift and/or response change;
– d.c. voltage overdrive;
– power durability.

a) Finger damage

This damage is irrecoverable. The spacing gap between the IDT fingers is usually very narrow. In the case of a 100 MHz IDT, the gap is around 5 µm to 10 µm. When an excessive drive level is applied to such an IDT, a flashover between the fingers is often caused by such a strong electric field. Sometimes, physical erosion of the electrodes is also caused by intense acoustic strains.

b) Frequency and/or response change

SAW acoustic power is confined to the surface of an elastic substrate. Therefore, SAW devices may exhibit non-linear characteristics at lower drive levels more easily than conventional bulk-wave devices.

c) DC voltage overdrive

Even if an RF signal input level is low, d.c. voltage application may damage the SAW filter or affect the filter characteristics undesirably. The d.c. voltage level should be agreed upon with the manufacturer.

d) Power durability

The excessive repeated mechanical stress may induce electrode deterioration, such as voids and hillocks. This brings about centre frequency shift, pass-band distortion and insertion attenuation degradation. The RF signal drive level should be agreed upon with the manufacturer.

8 Practical remarks

An incorrect usage of a SAW filter may at times result in its unsatisfactory performance. It is necessary to take care of direct feed-through, impedance matching conditions, etc.

8.1 Feed-through signals

Feed-through signals are caused mainly by the electrostatic and electromagnetic couplings between the input and output circuits.

There are several ways to reduce the feed-through. The most effective method is to employ a balanced (differential) circuit to cancel the undesirable coupling signals induced by stray capacitance (electrostatic) or current loop (electromagnetic). Integrated circuits (ICs) can easily adopt balanced input and/or balanced output circuits. A balanced output (input) SAW filter connected with a balanced input (output) IC is effective to reduce the feed-through. However, it is not effective to use a balun transformer to connect an unbalanced SAW filter with a balanced IC.

Another method to reduce the electrostatic feed-through is a shield between the input and output circuits on the printed circuit board (PCB). In practice, in most cases, some modifications to the circuit pattern on the PCB, especially the ground configuration, are effective.

In order to reduce the electromagnetic feed-through, it is effective to design the input and output circuit patterns so that the electromagnetic coupling induced by the current loop of the input circuit is totally cancelled at the output circuit. Thus, the circuit pattern should be designed so as to reduce or cancel both the electrostatic and the electromagnetic couplings.

In the case of high-frequency range and low terminating impedance, common residual impedance in input and output ground patterns (commonly called "ground loop") also results in the same effects as feed-through signals. In order to avoid common impedance, input and output ground patterns on the PCB should be designed separately.

8.2 Impedance matching condition

The impedance matching condition affects mainly the pass-band characteristics and is generally more strict for low insertion attenuation SAW filters than for conventional SAW transversal filters.

As for the low insertion attenuation SAW filter, such as a resonator filter, the specified terminating (load) impedances have to be used to obtain the specified performance. Such a SAW filter is designed under specific impedance matching conditions and impedance mismatching increases the amplitude ripple and the insertion attenuation of the SAW filter.

As for the ordinary (high insertion attenuation) bidirectional IDT filter, the impedance-matching condition is not so strict and 10 % variation of matching impedance does not give a large difference in the pass-band characteristics of the SAW filter. The impedance-matching condition is investigated mainly in view of the triple transit echo (TTE) suppression. The TTE suppression is given mainly by the impedance matching condition. The simplest and most effective way to reduce the TTE signal is to increase the insertion attenuation, namely to mismatch the load as much as the circuit gain allows. If the minimum echo suppression is specified in the detail specification, the specified terminating impedances have to be used to obtain the appropriate TTE suppression.

8.3 Miscellaneous

8.3.1 Soldering conditions

Incorrect soldering methods or soldering conditions may at times damage the SAW filter or affect the filter characteristics undesirably. In order to prevent such deterioration, the soldering method has to be an allowable method and soldering conditions have to be within the allowable soldering temperature and time ranges. When the soldering is repeated, the cumulative soldering time should be within the allowable time.

In recent years, surface mounting devices (SMD) type SAW filters have been widely used, especially hand-held equipments such as cordless telephones or cellular terminals. For SMD-type SAW filters, it is necessary to be more careful with soldering conditions than conventional leaded parts.

8.3.2 Static electricity

As the electrode (IDT) gap is very narrow, especially for the high-frequency range, and it might be a cause of degradation or destruction to apply static electricity to a SAW filter, it is necessary to take care not to apply static electricity or excessive voltage while transporting, assembling and measuring.

If the substrate material has large pyro-electricity, excessive voltage may occur during rapid temperature change. In order to prevent such occurrence, it is necessary to take care to reduce the thermal shock. In the soldering process, adequate preheating is effective.

9 Ordering procedure

When the requirements can be met by a standard item, it will be specified in the corresponding detail specification.

When the requirements cannot completely be met by an existing detail specification, the specification should be referred to, together with a deviation sheet. In rare cases, where the differences are such that it is not reasonable to quote an existing detail specification, a new specification is to be prepared in a similar form to that already used for a standard detail specification.

The following checklist will be useful when ordering a SAW filter and should be considered in drawing up a specification.

Checklist

Application

Description

Electrical requirements:

- Test fixture(s) and test circuit(s)
- Reference frequency
- Centre frequency
- Pass-band amplitude characteristics
  - Bandwidth
  - Minimum/nominal/maximum insertion attenuation
  - Pass-band ripple
  - TTE ripple (if necessary)
  - Cut-off frequency (if necessary)
  - Other factors
- Pass-band phase characteristics (if necessary)
- Pass-band group delay characteristics (if necessary)
  - Absolute group delay
  - Maximum distortion
  - Other factors
- Transition-band characteristics (if necessary)
  - Amplitude characteristics
  - Group delay characteristics
- Stop-band characteristics
  - Guaranteed relative insertion attenuation (___ MHz to ___ MHz)
  - Trap frequency (if necessary)
- Unwanted responses
  - TTE suppression
  - Feed-through signal suppression
  - Intermodulation distortion
  - Other factors

- Impedances
- Temperature coefficients
  - Temperature coefficient of delay (TCD)
  - Temperature coefficient of frequency (TCF)
- Input level
  - Absolute maximum input level
  - Testing input level
- Insulation resistance
- DC voltage overdrive
- Ageing
- Power capability
- Time/maximum temperature/signal waveform/signal frequency range (pass-band, stop-band) for power durability
- Other factors

Environmental requirements:

- Temperature ranges
  - Operable temperature range
  - Operating temperature range
  - Storage temperature range
- Temperature cycling
- Soldering temperature
- Shock, vibration
- Acceleration
- Humidity
- Radiation
- Sealing
- Ageing
- Other factors (for example, electrostatic damage, etc.)

Physical requirements:

- Outline dimensions
- Marking
- Solderability
- Terminals and accessories
- Packaging form (for example, bulk, taping, magazine, etc.)
- Other factors (for example, weight, colour, etc.)

Inspection requirements:

- Applicable documents (related specifications)
- Inspection authority
- Type test
- Type test procedure

– Acceptable quality levels

– Other factors

NOTE 1 In a filter with asymmetric filter response, it is recommended that the pass-band and stop-band requirements be specified with reference to specified frequencies.

NOTE 2 It should be clearly stated in the specification whether the filter is required to operate under conditions of shock, vibration or acceleration.

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