Introduction to Surface Acoustic Wave (SAW) Devices

Part 1: What is SAW Device?

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Contents

• SAW Transversal Filter
• SAW Unidirectional IDT Filters
• SAW Resonator Filters
• SAW Wireless Tags and Sensors
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Surface Acoustic Wave

Bulk Acoustic Wave (BAW):
- Longitudinal Wave (Primary Wave)
- Transverse Wave (Share Wave, Secondary Wave)

Surface Acoustic Wave (SAW): (Rayleigh SAW)

Propagation of Seismological Waves
Surface Acoustic Wave (SAW) Device

- Mass Production by Photolithography
- Low loss, Miniature & Low price
- Operation in VHF-UHF ranges

Line width $\lambda/4 = 0.5\mu m$ ($f=2GHz$)
SAW Transversal Filters

• Independent Control of Amplitude and Phase Responses
Impulse Response  Frequency Response

\[ h(t) = \int_{-\infty}^{+\infty} H(f) \exp(+2\pi jft) df \]

\[ H(f) = \int_{-\infty}^{+\infty} h(t) \exp(-2\pi jft) dt \]
Why Acoustic Wave Devices?

- Temperature Stability

\[
\frac{\text{GSM Bandwidth (200kHz)}}{\text{GSM1900 Center Freq. (1.9GHz)}} \approx 100\text{ppm}
\]

cf. For Si, 3000ppm/°C

\[
I = I_0 [\exp(qV / kT) - 1]
\]

For watch, \(\frac{1\text{ sec.}}{1\text{ day}} \approx 10\text{ ppm}\)
Trade-Off Between Temp. Stability & Bandwidth

(a) Wider Transition Bandwidth

(b) Narrower Transition Bandwidth

Efficient Use of Frequency Resources ⇔ Narrow Transition Bandwidth (Or Improve Production Yield)
Fourier-Transform-Based Design

Ripple due to truncation [Gibb’s Phenomenon]
Influence of Truncation

Convolution Relation

\[ H_w(f) = \int_{-\infty}^{+\infty} H_d(\xi)W(\xi - f)\,d\xi \]
Hamming: $w(t) = 0.54 + 0.46 \cos(2\pi t/T)$

Blackmann: $w(t) = 0.42 + 0.5 \cos(2\pi t/T) + 0.08 \cos(4\pi t/T)$

Blackmann-Harris: $w(t) = 0.35875 + 0.48829 \cos(2\pi t/T) + 0.14128 \cos(4\pi t/T) + 0.01168 \cos(6\pi t/T)$
Frequency Response of Window Functions with same $T$

- rectangular
- Hamming
- Blackmann
- Blackmann-Harris

Amplitude in dB vs. Relative frequency
SAW Transversal Filter for CATV

Ref. 15dB

10 dB/div

FREQUENCY (MHz)

37, 41, 45, 49, 53

1 dB/div

FREQUENCY (MHz)

39.75, 41.75, 43.75, 45.75, 47.75

50ns/div
SAW IF Filter for IS-95

Effects of Diffraction
(2D SAW Propagation)

Courtesy of Fujitsu Labs.
(a) For Wide Aperture
(b) Narrow Aperture

Variation with Aperture Size

For Weighted IDT
Low Frequency Design

- Power source
- Load

$R_L = R_S$ for Maximum Power Transfer

High Frequency Design

- Power source
- Load

$R_L = R_S$ for Maximum Power Transfer

How about for this case?
Triple Transit Echo (TTE)

Interdigital Transducers (IDT)

- Mechanical Reflection + Electrical Regeneration $\Rightarrow$ Mutual-Connection Dependent
- Trade-Off: TTE $\Leftrightarrow$ Insertion Loss
- Intrinsic for Bidirectional IDTs
Influence of TTE

Insertion loss in dB

Relative Frequency

$S_{21}$

$S_{21}^0$
Bragg Reflection

Bragg Condition

\[ p = \frac{n\lambda}{2} \]

Single-Electrode IDT

Double-Electrode IDT
Absorbers for Suppression of Reflection at Substrate Edges

Dummy Electrode for Suppression of Reflection and Charge Concentration at Edges

Guard Electrode for Suppression of EM Feedthrough
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Heterodyne Transceiver

Red: SAW Devices
Single Phase Unidirectional Transducer (SPUDTs)

(a) Combination with Reflector (Simple but Narrowband)

(b) Inlayed Reflector (Complex but Wideband)

- TTE Suppression
- Low Loss
- Frequency Response ⇒ Weighting for Excitation Profile
- Reflection Bandwidth < IDT Bandwidth ⇒ Reflector Weighting
  Independent Weighting to both Excitation and Reflection
For \( +X \) Direction, \(- 2\beta \Delta + \angle \Gamma = 2m\pi\)

For \(-X\) Direction \(- 2\beta(p_I - \Delta) + \angle \Gamma = (2n + 1)\pi\)

Unidirectional Cond. \( \angle \Gamma = \pm \pi / 2, \Delta = \pm \lambda / 8 \)
For Independent Weighting to Excitation and Reflection

(a) Excit.-Less, Ref.-Less
(b) With Excit., Ref.-Less
(c) Excit.-Less, With Ref.
(d) With Excit. & Ref.

EWC(Electrode-Width-Control)/SPUDT
Filter Response with Reduced TTE

\[ L_I = 20p_I \]
\[ L_T = 50p_I \]
\[ \kappa p_I = 0.02\pi \]

Low Loss and Suppressed TTE
Resonant SPUDT (R-SPUDTs)

Reversed Reflection Weighting
Direct Pulse
Multiple Echoes
Extension of Impulse Response
• Skirt Characteristics are Defined by Impulse Response Length
• Out-of-Band Characteristics are Defined by Excitation Profile
Described Example

\[ L_I = 34p_I \]

\[ L_T = 0 \]

\[ |S_{21}| \]

\[ \kappa p_I |_{\text{max}} = 0.1\pi \]

Sharp Passband Shape + Flat Group Delay
Optimized weighted function

Weighting Function

Relative Position

Excitation

Reflection

Forward
Weak Resonant SPUDT Filter

Courtesy of EPCOS AG
Strong Resonant SPUDT Filter

![Graph showing frequency response of a Strong Resonant SPUDT Filter. The graph displays the magnitude in dB against frequency in MHz. The peak at approximately 71 MHz is prominently visible.](image)

Courtesy of EPCOS AG
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Homodyne Transceiver

- Circuit Simplification ⇒ Reducing Component Number
- No Image Signal ⇒ Relaxing Specs to RF Filters
SAW Resonator

(a) 1-Port Resonator

(b) 2-Port Resonator Filter
Application of Electric Field to Piezoelectric Material,

\[ M \frac{dv}{dt} + \eta v + k \int v dt = F \propto V \]

(a) Electric + Mechanical Circuit

(b) Electrical Equiv. Circuit

Analogies between \( V \leftrightarrow F \) and \( I \leftrightarrow v \) reduce to

\[ M \leftrightarrow L, \ h \leftrightarrow R, \ k \leftrightarrow \frac{1}{C} \]
• Resonance Frequency $\omega_r = 1/\sqrt{C_m L_m}$
• Anti-Resonance Frequency $\omega_a = 1/\sqrt{L_m (C_m^{-1} + C_0^{-1})^{-1}}$
• Resonance Q (Steepness of Resonance) $Q = \omega_r L_m / R_m$
  
  $\Rightarrow$ Determine Insertion Loss and Skirt Characteristics

• Capacitance Ratio (Weakness of Piezoelectricity)
  $\gamma = C_0/C_m = [\left(\frac{\omega_a}{\omega_r}\right)^2 - 1]^{-1}$
  
  $\Rightarrow$ Determine Insertion Loss and Bandwidth
- Resonance Frequency $\omega_r = \frac{1}{\sqrt{C_m L_m}}$
- Anti-Resonance Frequency $\omega_a = \frac{1}{\sqrt{L_m (C_m^{-1} + C_0^{-1})^{-1}}}$
Transverse Mode

In-harmonic Resonance

Admittance
Frequency

$G$
$B$
$\omega_r$
$\omega_a$
Ladder-Type SAW Filter

- Low Loss
- High Power Durability
- Moderate Out-of-Band Rejection

Topology
Null Generation at Both Sides
Performance of Ladder-Type SAW Filter

Fujitsu FAR-F6CP-2G1400-L21M

W-CDMA-Rx
Antenna Duplexer for US PCS

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Attenuation [dB]</th>
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<tbody>
<tr>
<td>1800</td>
<td>-2.0</td>
</tr>
<tr>
<td>1900</td>
<td>-4.0</td>
</tr>
<tr>
<td>2000</td>
<td>-6.0</td>
</tr>
</tbody>
</table>

![Diagram of Antenna Duplexer](Image)

Courtesy of Fujitsu Labs.
Temperature Compensation (1)

Bonding with Small Thermal Expansion Coef.


Fujitsu Labs.
Temperature Compensation (2)

Depositing SiO₂ with Negative Temp. Coef.


Murata MFG

Fig. 11. Frequency characteristics of Tx of US-PCS SAW duplexer using conventional Al-electrode/ 36°Y-X-LiTaO₃ substrate at temperature of -30°C, 25°C, and 80°C.

Fig. 12. Frequency characteristics of Rx of US-PCS SAW duplexer using new substrate at temperature of -30°C, 25°C, and 80°C.
Double Mode SAW (DMS) Filter

Symmetrical & Anti-symmetrical Resonances

Electrically Isolated I/O

- Good Out-of-Band Rejection
- Balun Function
- Transformer Function
- Low Loss
- Lower Power Durability

\[ \omega_r^s \quad \omega_r^a \]

Insertion loss (dB)

Frequency \( \omega \)
Structure of **Pitch-Modulated IDT & Reflector**

**Conventional Structure**

**Pitch-Modulated Structure**

Presented at IEEE 2004 UFFC Conf.
**DMS Filter with Modulated Structure**

![Graph showing Scattering parameter $S_{21}$ [dB] for frequency [MHz] range 800 to 1050, with peaks at specific frequencies.]

Fujitsu FAR-F5EB-942M50-B28E
Integrated RF Circuit

(a) Balanced I/O

(b) Unbalanced I/O

Current Antenna and RF Stage are Unbalanced
DMS Filter (Ideally No Common Signal)

Acoustically Coupled but Electrically Isolated

Common Signal Generation by Parasitics
Z-conversion by DMS Filter
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Quartz Micro-Balance (QMB)

- Temperature Stability
- Phase (or Frequency) Output $\Rightarrow$ High Resolution
- Low Price

Sensor Applications: Physical (Film Thickness, Pressure), Chemical (Gas, Liquid), Bio
• High $f (\Delta f = -K f_0^2 \Delta m) \Rightarrow \text{High Sensitivity}$
• Moderate Temperature Stability
• *Surface Protection (Packaging)*?

Area $1 \text{ mm}^2$ & $f_0=1 \text{ GHz}$ give $K f_0 \sim 10^7 / \text{ kg}$
$\Rightarrow 1 \text{ ppm of } f \text{ deviation} = \text{Resolution 0.1 pg.}$
SAW Sensor Configuration

Frequency Detection

Phase Detection

\[ \Delta f \sim \Delta m \]

\[ \Delta \phi \sim \Delta m \]
SAW Chemical Sensor

- Sensitive Layer: A calixarene (10 nm)
- Object: tetrachloroethene
- \( f_0 \): 434 MHz
Pattern Recognition with Sensor Array

Sensor Array

Sensor: Sensitive Film
A Calix[4]resorcinearene 1
B Calix[4]resorcinearene 2
C Cyclodextrine-functionalized polymer 1
D Cyclodextrine-functionalized polymer 2
What is SAW ID-TAG?

- Wireless, Batteryless
- Large Group Delay (Separation with Environmental Echoes)
Separation of SAW Signal in Time Domain

Excited Signal

Environmental Echo

Sensor Echo

RF Response
Which Frequency?

- **5.2 GHz (ISM Band)**
  Wideband (100MHz), Short Accessible Distance (<1m), Hard to Realize SAW Devices

- **2.45 GHz (ISM Band)**
  Wideband (22MHz), Short Accessible Distance (2-3m), Price of SAW Devices?

- **433.92 MHz (RKE Band)**
  Narrowband (1.7MHz), Long Accessible Distance (>10m), Low SAW Device Cost
SAW ID Tag with 5 reflectors in one track ($f_0 = 2.45$ GHz) using pulse position coding
Baumer Ident (2.45 GHz ISM)
Brake temperature of a train entering a station

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature °C</th>
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<tbody>
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<td>60,00</td>
<td></td>
</tr>
<tr>
<td>70,00</td>
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<td>80,00</td>
<td></td>
</tr>
<tr>
<td>90,00</td>
<td></td>
</tr>
<tr>
<td>100,0</td>
<td></td>
</tr>
</tbody>
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Brake (with attached SAW temperature transponder, not seen)

reader antenna
The dynamic range of monitoring the torque with SAW can be up to several tenths of kHz.
SAW pressure sensor

antenna

diaphragm

adhesive

cover-plate

closed cavity with reference-pressure

Two Track Railway Crossing

Adjacent Water Channel

pressure [Bar]

1.00 1.20 1.40 1.60 1.80 2.00 2.20 2.40 2.60 2.80 3.00


time