Design Steps for prototyping smart SAW sensors and a burst transceiver for interrogation

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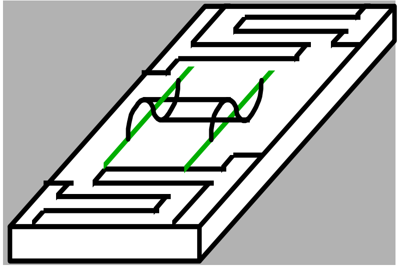
Agenda

- **Wireless SAW passive sensing system**
- **Design Steps for SAW sensors**
  - Introduction to simulation approaches.
  - Overview of simulation software.
  - Simulation Results.
- **Prototype burst transceiver for SAW sensor interrogation**
  - Basic block diagram of transmitter and receiver.
  - Results from the burst transceiver.
  - Wireless sensor range.
- **Summary and conclusions**
- **Acknowledgements**

Surface Acoustic wave devices

- Generated at the free surface of a piezoelectric solid
- Generation of SAW accomplished by application of alternating voltage over metallized grating like fingers (Inter Digitated Transducers: IDTs)
- One of these IDTs acts as the device input and converts signal voltage variations into mechanical surface acoustic waves
- The other IDT employed as output receiver to reconvert electro-mechanical SAW vibrations into output voltages
- Reciprocal in nature
- Propagation area used for sensing
- Amenable to wireless interrogation at Radio Frequencies



Wireless SAW passive sensing system

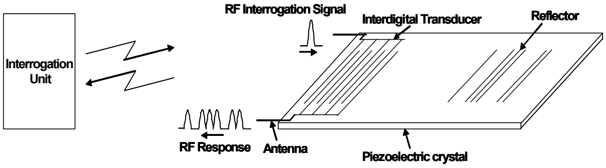
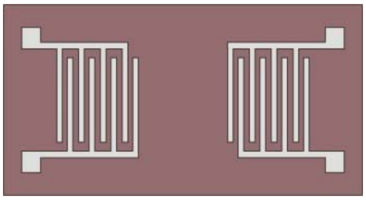


Figure 1: Schematic drawing of a radio-link system based on a passive SAW transponder (ID tag or sensor).

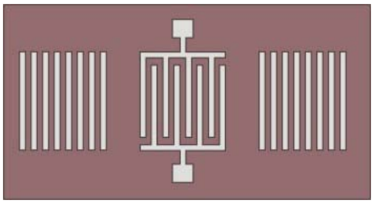
Elements of a radio-link system:

- Interrogation unit
- Radio-link
- Sensor unit

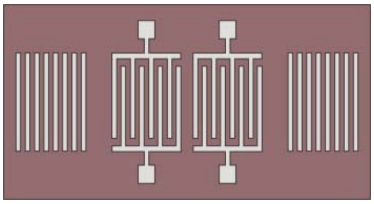
Different SAW Device Configurations



Delay line

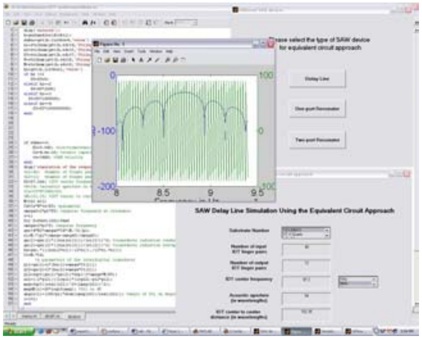


One-port resonator



Two-port resonator

Simulation of SAW devices



ase select the type of SAW device for equivalent circuit approach

SAW Delay Line Simulation Using the Equivalent Circuit Approach

Substrate Number

Number of input IDT finger pairs

Number of output IDT finger pairs

IDT center frequency

Acoustic aperture (in wavelengths)

IDT center to center distance (in wavelengths)

Need for simulation

- Adjust the device design parameters to obtain the desired performance.
- Compare the effects of varying design parameters on the device performance.

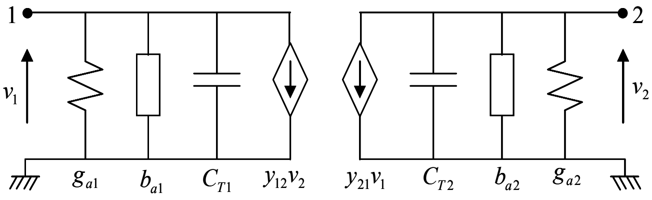
Simulation approaches

- Equivalent Circuit Approach

  - IDT and resonance condition represented by lumped circuit elements.
- Transmission Matrix Approach

  - transmission matrices of individual elements are used to obtain the frequency response.

Equivalent Circuit for SAW Delay line



$$Y = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$$

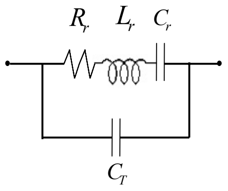
$$S_{21} = \frac{-2y_{21}}{(1+y_{11})(1+y_{22}) - y_{12}y_{21}}$$

$$G_{dB} = 20\log(S_{21})$$

Equivalent Circuit for One-port resonator

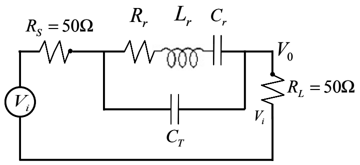
$$S_{21} = \frac{50}{100+Z_{eq}}$$

$$Z_{eq} = Z_r \| Z_{CT}$$



Equivalent circuit

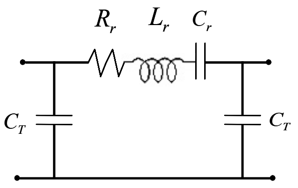
- Z_r is the impedance of the series combination R_r, L_r and C_r.
- Z_{CT} is the impedance due to the IDT capacitance C_T.



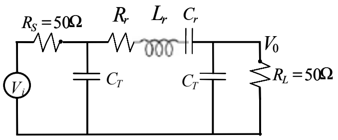
Circuit to measure S_{21}

Equivalent Circuit for two-port resonator

$$S_{21} = \frac{1}{2 + \frac{2Z_r}{Z_T} + \frac{100}{Z_T} + \frac{Z_r}{50} + \frac{50Z_r}{Z_T^2}}$$



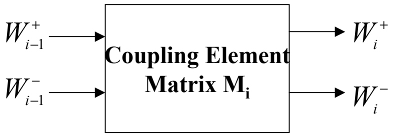
Equivalent circuit



Circuit to measure S_{21}

- Z_r is the impedance of the series combination R_r, L_r and C_r.
- Z_T is the impedance due to the IDT capacitance C_T.

Transmission Matrix Approach-Overview



W_{i-1}^+
W_{i-1}^-

Coupling Element Matrix M$_i$

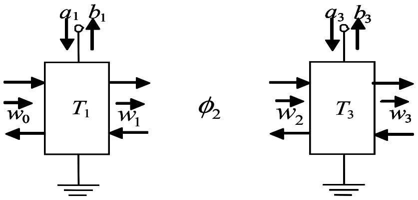
W_i^+
W_i^-

- Transmission matrix equation of a coupling element

$$W_{i-1} = M_i W_i$$

- $W_{i-1} = \begin{bmatrix} W_{i-1}^+ \\ W_{i-1}^- \end{bmatrix}$ and $W_i = \begin{bmatrix} W_i^+ \\ W_i^- \end{bmatrix}$ are the wave amplitudes to the left and right side of the coupling element respectively.
- M$_i$ is the coupling matrix of the ith element.

Transmission Matrix approach-Delay line

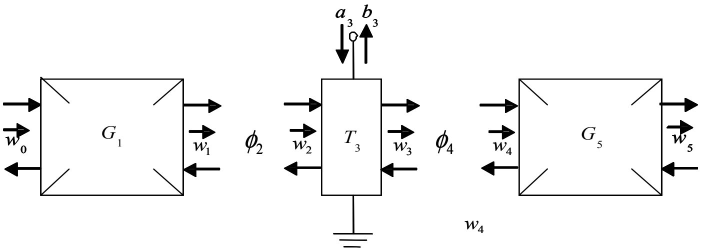


- Delay line with the matrix notations.
- Overall acoustic transmission matrix

$$[M]=[t_1]\cdot[\phi_2]\cdot[t_3]$$

$$S_{21}=\frac{b_3}{a_1}$$

Transmission Matrix approach One-port resonator

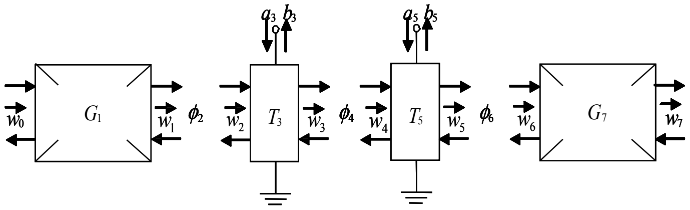


- One-port resonator with the matrix notations.
- Overall acoustic transmission matrix

$$[M]=[G_1]\cdot[\phi_2]\cdot[t_3]\cdot[\phi_4]\cdot[G_5]$$

$$S_{21}=\frac{b_3}{a_3}$$

Transmission Matrix approach Two-port resonator

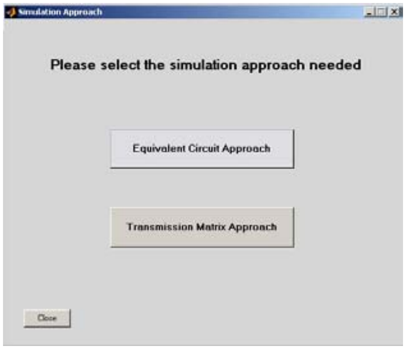


- Two-port resonator with the matrix notations.
- Overall acoustic transmission matrix

$$[M]=[G_1]\cdot[\phi_2]\cdot[t_3]\cdot[\phi_4]\cdot[t_5]\cdot[\phi_6]\cdot[G_7]$$

$$S_{21}=\frac{b_5}{a_3}$$

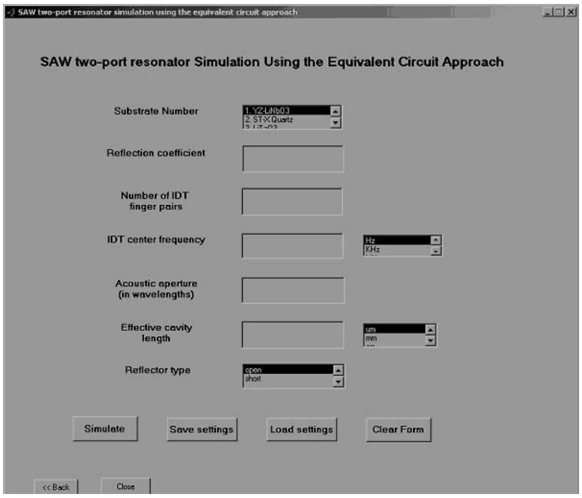
Simulation package using MATLAB™



Please select the simulation approach needed

Please select the type of SAW device
for equivalent circuit approach

Simulation Package User Interface



SAW two-port resonator simulation using the equivalent circuit approach

SAW two-port resonator Simulation Using the Equivalent Circuit Approach

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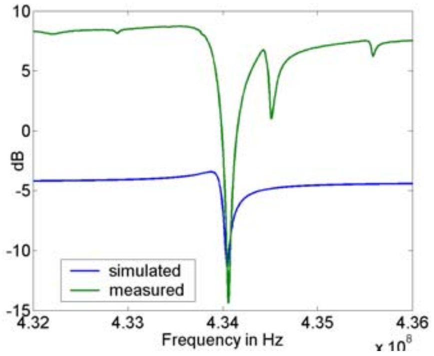
Simulation results- Equivalent circuit approach



Substrate type: ST-X Quartz

f_0= 433.92 MHz

R_r=14 ohms

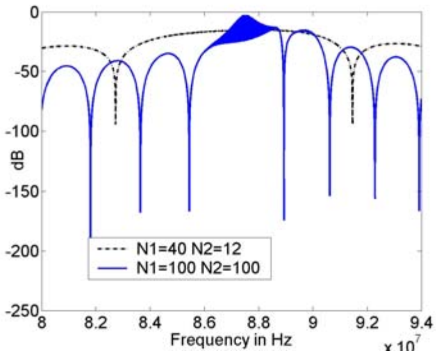
L_r=58 uH

C_r=2.3 fF

C_T=4.1 pF

Measured and simulated S_{21} values of a 433.92 MHz one-port Resonator.

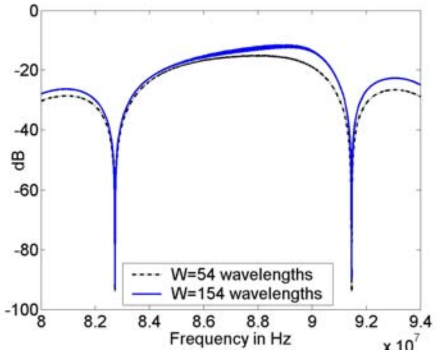
Simulation results- Transmission matrix approach



Substrate type: YZ-LiNbO$_3$
f_0=87.2 MHz
λ_0=40 μm
W=54λ_0
M=152.35λ_0

Frequency response of a 87.2 MHz delay line for two different values of number of finger pairs in IDT N1=40, N2=12 and N1=100, N2=100. The Gain increases by about 15 dB as the number of fingers is increased.

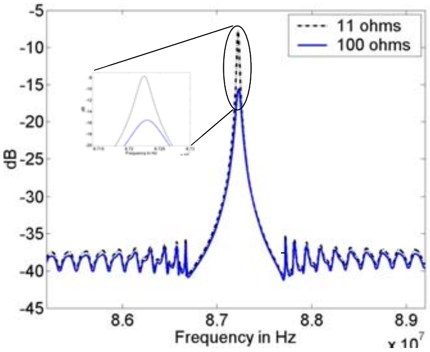
Simulation results- Transmission matrix approach



Substrate type: YZ-LiNbO$_3$
N_1=40
N_2=12
f_0=87.2 MHz
λ_0=40 μm
M=152.35λ_0

Frequency response of a 87.2 MHz delay line for two different values of the acoustic aperture W=54 wavelengths and W=154 wavelengths. The gain increases by about 5 dB as the acoustic aperture increases.

Simulation results- Transmission matrix approach



Substrate type: YZ-LiNbO$_3$

f_0= 87.2 MHz

λ_0=4.97 µm

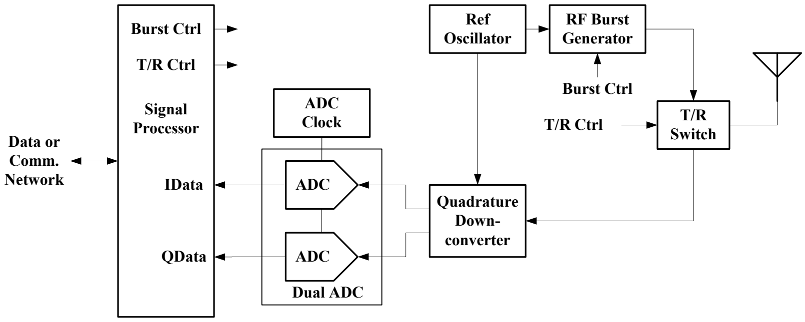
Np=4

W=80λ_0

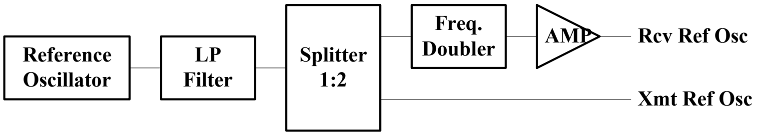
Frequency response for the 87.2 MHz two-port resonator for two different values of lead resistances 11 ohms and 100 ohms. The gain reduces by about 8 dB as the resistance is increased.

Prototype Burst Transceiver - Introduction

- **Time-Division Duplex Burst and Response**
  - Operate on the same frequency. Employ a Transmit/Receive (T/R) switch.
- **Quadrature, Zero-IF Downconversion**
  - Frequency coherent demodulation of transformed burst signal.
- **All-Digital, Software Radio baseband signal processing**



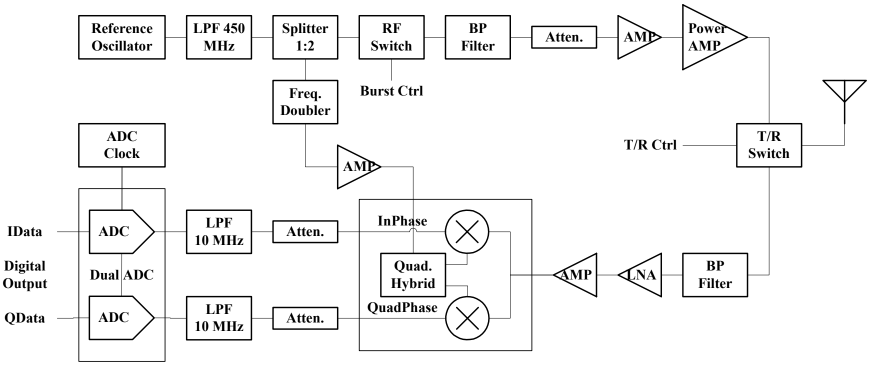
Reference Oscillator



Reference Oscillator
LP Filter
Splitter 1:2
Freq. Doubler
AMP
Rcv Ref Osc
Xmt Ref Osc

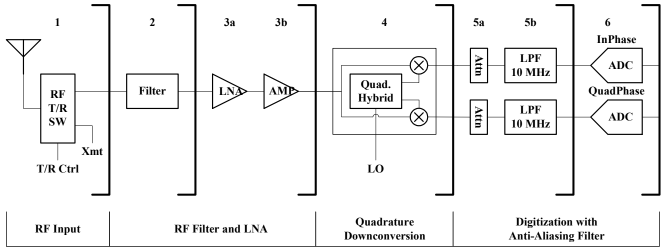
- **Design Goals**
  - Reference oscillator for transmitter and receiver (VCO selected)
  - Available frequency range from 325 MHz to 500 MHz
  - Frequency doubler for 2x receiver reference
  - Upgradeable to a synthesized phase locked loop reference

Transceiver Implementation



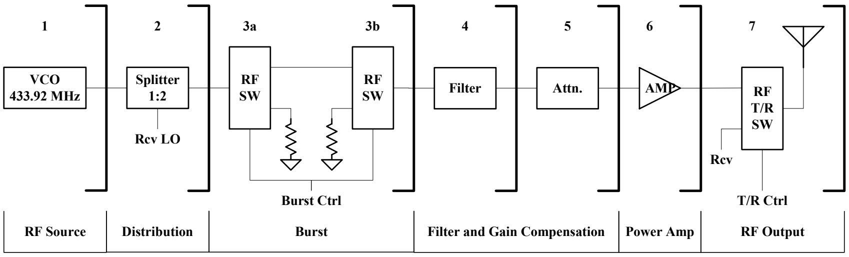
Reference Oscillator
LPF 450 MHz
Splitter 1:2
RF Switch
BP Filter
Atten.
AMP
Power AMP
Freq. Doubler
Burst Ctrl
ADC Clock
T/R Ctrl
T/R Switch
AMP
IData
ADC
LPF 10 MHz
Atten.
InPhase
Digital Output
Dual ADC
Quad. Hybrid
AMP
LNA
BP Filter
QuadPhase
QData
ADC
LPF 10 MHz
Atten.

Receiver Gain and Noise Figure



Stage	1	2	3a	3b	4	5a	5b
Gain (dB)	-0.90	-1.50	20.00	20.00	14.00	-6.00	-3.00
Noise Figure (dB)	0.90	1.50	2.90	5.30	35.00	6.00	3.00
Noise Figure (linear)	1.23	1.41	1.95	3.39	3162.28	3.98	2.00
Total Gain (dB)	-0.90	-2.40	17.60	37.60	51.60	45.60	**42.60**
Total Gain (linear)	0.81	0.58	57.54	5.8E+03	1.4E+05	3.6E+04	1.8E+04
Total NF (linear)	1.230	1.738	3.388	3.430	3.979	3.979	3.979
Total NF (dB)	0.90	2.40	5.30	5.35	6.00	6.00	**6.00**
Input Test Signal (-25.3 dBm)	-28.19	-30.31	-10.27	11.84			
Expected Power (-25.3 dBm)	-26.20	-27.70	-7.70	12.30	26.30	20.30	17.30

Transmitter Gain and Noise Figure



Stage	1	2	3a	3b	4	5	6	7
Gain	0.00	-3.50	-0.90	-0.90	-0.50	-20.00	20.00	-0.90
Noise FIgure (dB)	0.00	3.50	0.90	0.90	0.50	20.00	5.30	0.90
Noise Figure (linear)	1.00	2.24	1.23	1.23	1.12	100.00	3.39	1.23
Total Gain (dB)	0.00	-3.50	-4.40	-5.30	-5.80	-25.80	-5.80	**-6.70**
Total Gain (linear)	1.000	0.447	0.363	0.295	0.263	0.003	0.263	0.214
Total NF (linear)	1.000	2.239	2.754	3.388	3.802	380.189	1288.250	1289.125
Total NF (dB)	0.00	3.50	4.40	5.30	5.80	25.80	31.10	**31.10**
Design Signal Power (dBm)	10.00	6.50	5.60	4.70	4.20	-15.80	4.20	**3.30**
Measured Signal Power (dBm)	10.13	6.48	5.35	4.26	3.92	-16.29	5.65	**4.57**

Wireless Sensor Range

- The range of a wireless communication is dependent upon many system, antenna and environmental factors.
- A first order estimate of the range in free space can be made using the Friis Equation.

$$P_r = P_t \cdot \frac{G_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot R)^2} \qquad (1)$$

where P_r is the received (or transmitted) signal power
G_r is the effective antenna gain for receiving (or transmitting)
R is the distance between the transmitter and receiver, and
λ is the wavelength

Range Estimate

The following assumptions can be made to estimate the free-path range from the transceiver to the remote sensor.

- the transceiver output power is 3.3 dBm.
- the receiver (Minimum Detectable Signal) MDS is –90 dBm.
- the transceiver and sensor antennas provide no gain (0 dB).
- the SAW sensor has a 20 dB loss.

For the sensor system operating at a frequency of 433 MHz, the range is

$$R = \frac{0.69m}{(4\pi)} \left[1 \cdot 1 \cdot \frac{1}{100} \cdot 10^{(33+90)/10} \right]^{1/4} = 3.75m$$

Summary and Conclusions

- Preliminary RF testing has demonstrated that the transceiver performs as expected, meeting the design criteria defined.

- As currently configured, the transceiver is capable of transmitting an RF burst carrier in the frequency range of 200 to 450 MHz at an output power of +3.3 dBm to +24 dBm.

- The receiver section provides sufficient isolation for TDD operation, provides a nominal gain of 42.6 dB to drive the dual ADCs, has a low noise figure of 6.0 dB.

- Combining the receiver and transmitters, the sensor system has a free-space range of 3.75 meters based on conservative system antenna and sensor estimates.

- The software package developed has been able to simulate the frequency response of SAW devices with considerable accuracy.

Achievements and future goals

- A software package has been developed to simulate the frequency response of SAW devices.

- A prototype burst transceiver for SAW sensors has been designed and constructed.

- An integrated smart sensor hosting on-sensor signal processing, which can transmit and receive signals to and from an interrogation unit will be developed.

Publications:

1. M.Z. Atashbar, B.J. Bazuin, and S. Krishnamurthy “Performance evaluation of saw devices by simulation” Submitted to International Journal of Simulation and Modeling (under review).
2. M.Z. Atashbar, B.J. Bazuin, S. Krishnamurthy “Design and Simulation of SAW Sensors for Wireless Sensing” IEEE Sensor 2003, Toronto, Canada (Accepted).
3. M.Z. Atashbar, B.J. Bazuin, S. Krishnamurthy “Design Steps for SAW Devices for Wireless Applications” IEEE/EIT Conference, Indianapolis, Indiana, June 5-6 2003, Session 7A, Conference Proceedings.
4. B.J. Bazuin, M.Z. Atashbar, S. Krishnamurthy “A Prototype Burst Transciever for Smart SAW Sensors”, IEEE/EIT Conference, Indianapolis, Indiana, June 5-6 2003, Session 4C, Conference Proceedings.

Acknowledgements

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