Vector Network Analyzer for Acoustic Device Characterization

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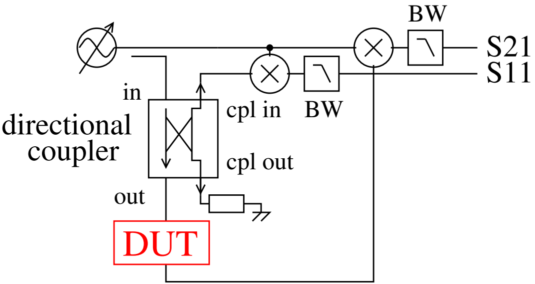
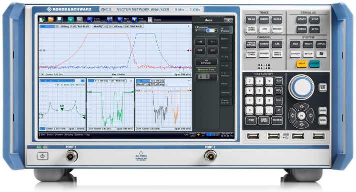
Vector Network Analyzer

A network analyzer is *not* a spectrum analyzer: active source for coherent measurement

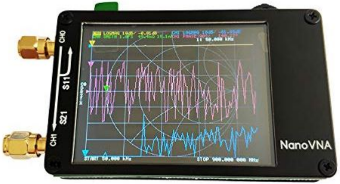
- Network Analyzer: frequency dependent characterization of an unknown Device Under Test (DUT)
- Vector ...: ability to measure a **phase** in addition to magnitude $A\exp(j\varphi)$
- Assumption: linear behavior (inject signal @ frequency f and only measure at f)





Rohde&Schwarz ZNC

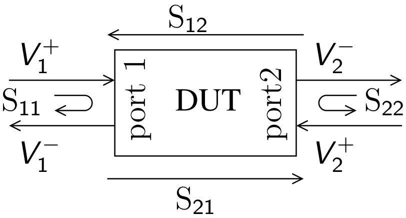
Siglent SVA10xx



NanoVNA

Scattering coefficients

Linear = matrix algebra expression



$$S_{11} = \left.\frac{V_1^-}{V_1^+}\right|_{V_2^+=0}$$
$$S_{21} = \left.\frac{V_1^-}{V_2^+}\right|_{V_1^+=0}$$
$$S_{12} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0}$$
$$S_{22} = \left.\frac{V_2^-}{V_2^+}\right|_{V_1^+=0}$$

$$\begin{pmatrix} V_1^- \\ V_2^- \end{pmatrix} = \begin{pmatrix} S_{11} & S_{21} \\ S_{12} & S_{22} \end{pmatrix} \begin{pmatrix} V_1^+ \\ V_2^+ \end{pmatrix}$$

Scaterring coefficients are ratios of voltages $\Rightarrow$ dB as ratio of power uses $20\log_{10}(S_{ij})$

S-parameter example

Passive component: $|S_{xx}| < 1$ *i.e.* $|S_{xx}| < 0$ dB

Active component: $S_{21} > 0$ dB, emit on port 1 and receive on port 2

MMIC Amplifier ERA-6+

Typical Performance Data

Definitions:

Input Return Loss = -S11 (dB)

Gain(Power Gain) = S21 (dB)

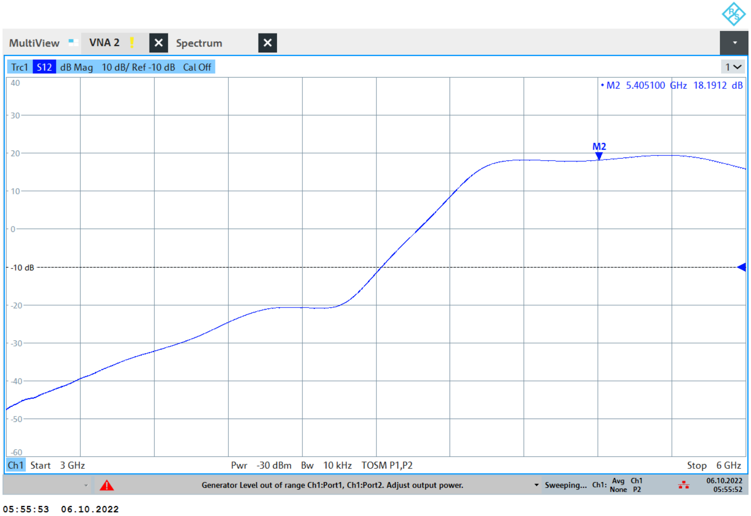
Reverse Isolation = -S12 (dB)

Output Return Loss = -S22 (dB)

TEST CONDITIONS: Icc = 70mA, Vd = 4.84V @Temperature = +25degC

FREQ	Gain	Isolation	Input Return Loss	Output Return Loss	Stability		IP3 Output	1dB Comp. Output	Noise Figure
(MHz)	(dB)	(dB)	(dB)	(dB)	K	Delta	(dBm)	(dBm)	(dB)
50	12.82	18.69	25.03	40.23	1.23	0.51	36.57	17.30	4.44
100	12.79	18.64	25.30	38.49	1.23	0.51	36.42	17.26	4.46
200	12.75	18.67	25.52	36.49	1.24	0.51	36.66	17.36	4.55
300	12.72	18.68	25.56	34.88	1.24	0.50	36.50	17.42	4.55
400	12.67	18.68	25.77	32.90	1.24	0.50	35.97	17.57	4.52
500	12.63	18.68	25.99	31.20	1.25	0.50	35.78	17.60	4.57
600	12.59	18.67	26.35	29.76	1.25	0.50	35.64	17.67	4.58

Amplifier characterization: Skyworks SE5023L (5 GHz, 26 dBm, 32 dB)



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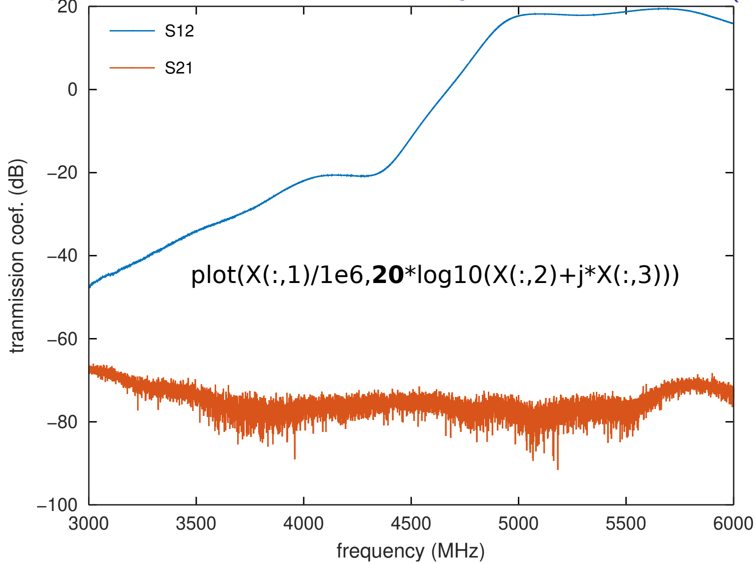
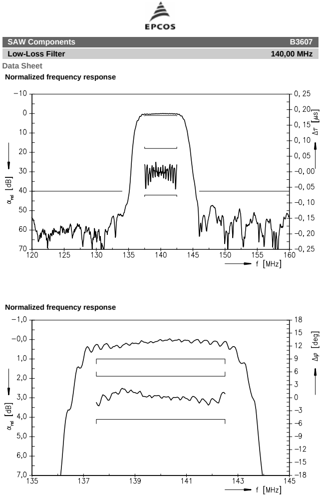
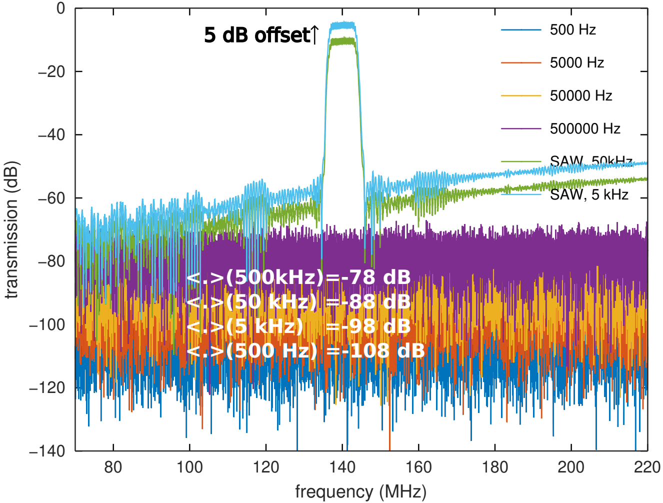


Notice input and output ports + attenuators

Resolution BandWidth (RBW): SAW filter Epcos B3607

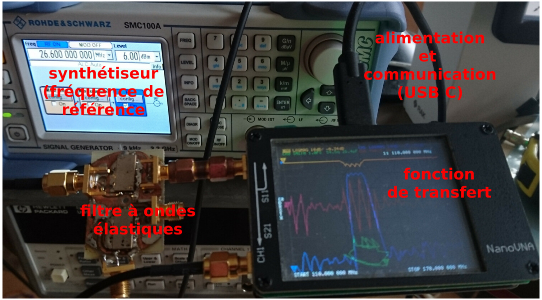
1. Noise power density $N_0 = k_B \times T = -174$ dBm/Hz
2. Noise power $N = k_B \times T \times B$ dBm, B integration banwidth
3. *but* measurement duration $\simeq 1/B$ (23 seconds for 10001 points @ 500 Hz RBW$\simeq 2 \cdot 10^{-3} \times 10^4$)

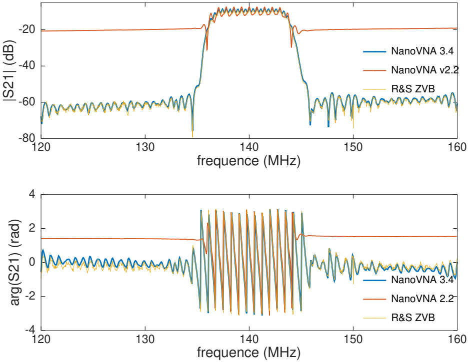




Calibration

- Wave propagation: electromagnetic wavelength is $300/f_{MHz} \times 0.66$ in a coaxial cable
- 40 cm @ 500 MHz: $\lambda/4$ is 10 cm: quarter wavelength transformer [1]
- All cables and connectors excluding the DUT must be included in the calibration
- Three reference impedances to solve the unknowns: short, open, reference impedance (50 Ω) load for S_{11} – check after calibration on the Smith chart that Open and 50 Ω match the expected location
- ... add Through for S_{21}: SOLT (or OSM)





[1] https://en.wikipedia.org/wiki/Quarter-wave_impedance_transformer

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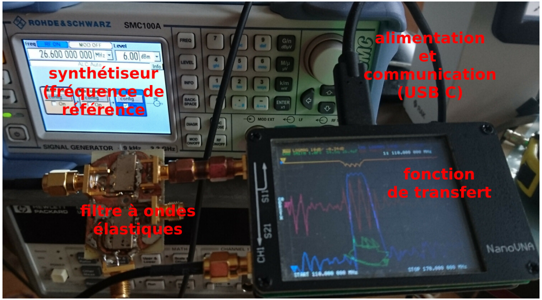
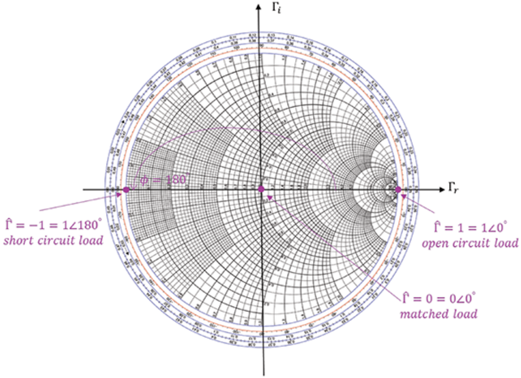




[1] https://incompliancemag.com/article/smith-chart-basics-network-analyzer-calibration/

Scattering coefficient to electrical parameter

- Scattering coefficients represent the transmission line behaviour (match/mismatch)
- Acoustic behaviour is characterized by the equivalent electrical model (cf Butterworth-Van Dyke)

⇒ all acoustic characteristics are deduced from impedance or admittance

$$Y_{11} = \frac{1}{50} \times \frac{1 - S_{11}}{1 + S_{11}}$$

⇒ quality factor is the width at half height of $\mathrm{Re}(Y_{11})$

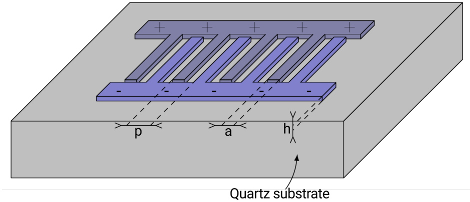
A bel is $\log_{10}$ of a quantity, a decibel is $10\log_{10}$ and converting voltage to power requires $20\log_{10}$

More resources on the network analyzer

- P. Seurre, *VNA Calibration* webinar. Rohde & Schwarz at https://www.rohde-schwarz.com/fr/knowledge-center-france/ressources_locales_r_s_france/webinars/webinar-bien-calibrer-son-analyseur-de-reseau-vectoriel/webinar-bien-calibrer-son-analyseur-de-reseau-vectoriel_253401.html [in French]
- J.-M Friedt, *Introduction à l'analyseur de réseau : le NanoVNA pour la caractérisation spectrale de dispositifs radiofréquences*, to be published Hackable Janvier 2021 at http://jmfriedt.free.fr/hackable_nanovna.pdf [in French]
- NanoVNA source code: https://github.com/ttrftech/NanoVNA/

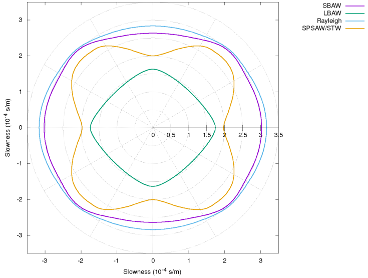
SAW device design (ST-cut quartz)

- Substrate: ST-cut quartz (42.75°);
- Substrate thickness: 500 μm ;
- Electrode material: Al, thickness $h = 290$ nm;
- Transducer finger width: $a = 5$ μm;
- Metallization ratio a/p: 0.5;
- Number of finger pairs: 150.

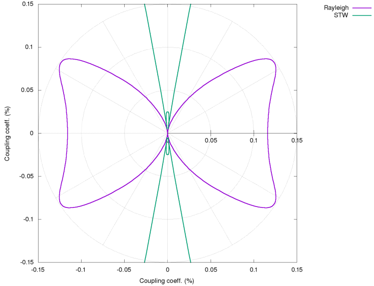


h: electrode thickness, p: electrode pitch, a: finger width.

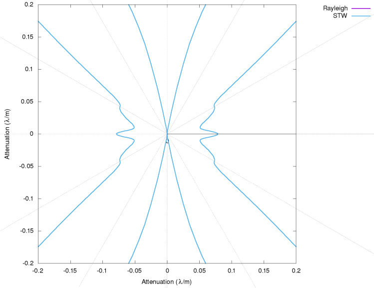
Slowness



Electromechanical coupling coefficient



Attenuation



X-axis: 0°. SBAW: Shear Bulk Acoustic Wave, LBAW: Longitudinal Bulk Acoustic Wave; SPSAW: Shear Pseudo Surface Acoustic Wave; STW: Shear Transverse Wave.

Analysis (reflection)

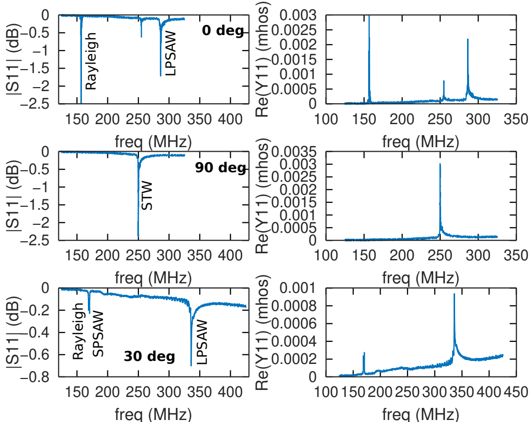
```
# # Hz S RI R 50
# ! 20/10/2021 14:17:46 config : ...
# ! Sweep type : LIN, Start : 1.25e+08, Stop : 3.25e+08, Pts : 10001, Pow : -10, Del : 0, BW : 10000
# [Number of Ports] 1
# [Number of Stimulus] 10001
# [Network Data]
# !Freq Re(S11) Im(S11)
1.25E+008       0.9579685       -0.2812306
1.2502E+008     0.9579669       -0.280802
1.2504E+008     0.9586094       -0.2807577
...
```

$\lambda = c/f \Rightarrow c = \lambda \cdot f = 20 \times \{156.74, 254.88, 286.24\}$
$= \{3135, 5098, 5725\}$ m/s
$= 1/\{1.75, 2.00, 3.19\} \cdot 10^{-4}$ s/m

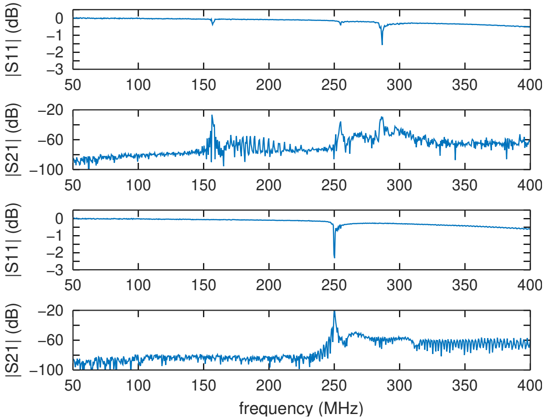
$\lambda = c/f \Rightarrow c = \lambda \cdot f = 20 \times \{250.00\}$
$= \{5000\}$ m/s
$= 1/\{2.00\} \cdot 10^{-4}$ s/m

$\lambda = c/f \Rightarrow c = \lambda \cdot f = 20 \times \{168.9, 170.4, 336.0\} = \{3378, 3408, 6720\}$ m/s
$= 1/\{1.49, 2.93, 2.96\} \cdot 10^{-4}$ s/m

$a/p = 0.5$ & $a = 5\ \mu m \Rightarrow p = 10\ \mu m$ & $\lambda = 2p = 20\ \mu m$



Analysis (transmission)



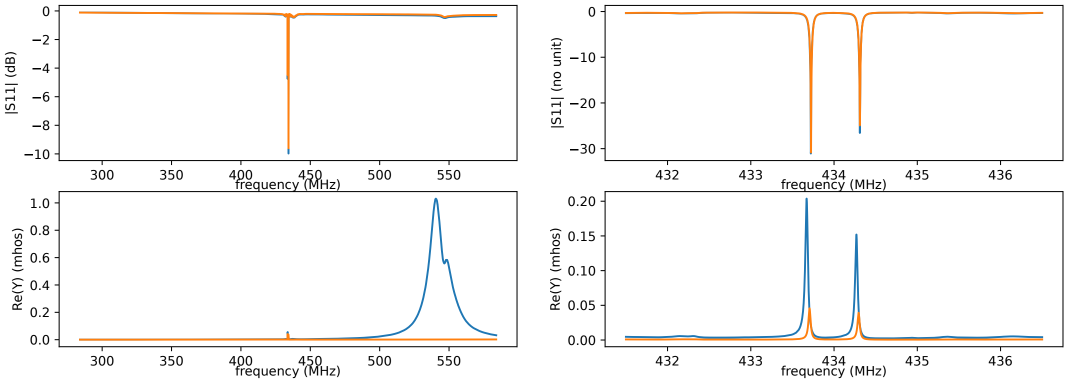
- SAW propagation followed by (faster) bulk acoustic waves
- S_{11} = SAW generation (K^2)
- S_{21} = SAW propagation (losses)
- For a lossless Rayleigh wave, $max(S_{21})$ is driven by K^2 since

  transmitted power = generated power × losses

- For Rayleigh wave: $K^2 \simeq 0.12\%$
  $\Rightarrow 10 \times \log_{10}(0.12 \cdot 10^{-2}) = -29.2$ dB

SEAS10 (dual resonator temperature sensor)

Top = S_{11}, bottom = admittance
Blue = uncalibrated, orange = calibrated

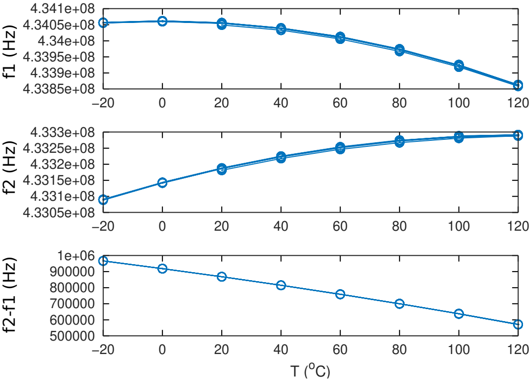


Q = width at half height of $Re(Y)$

goseas10.py

SEAS10 (dual resonator temperature sensor)

```
a2 =

  -1.352254227776077e+01  -3.000358080420133e+01   4.340608007902552e+08

F02 = 434051599.1118115
CTF12 = -1.626835832737804e-06
CTF21 = -3.115422752832057e-08

a1 =

  -9.761310191706251e+00   2.407203382106941e+03
  4.331421267614142e+08

F01 = 433196206.0270970
CTF11 = 4.430181626294261e-06
CTF21 = -2.253323102994966e-08

a21 =

  -3.761232086046266e+00  -2.437206962912538e+03   9.186740288411591e+05

A0 = -323.9905045947966
A1 = 349218.0103886827
A2 = -0.265870325766358
```



$$T = A_0 + \sqrt{A_1 + A_2 \Delta f}$$

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```
a2 =

  -1.352254227776077e+01  -3.000358080420133e+01   4.340608007902552e+08

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```
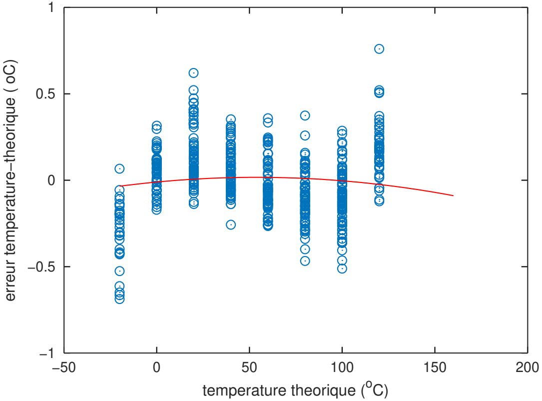
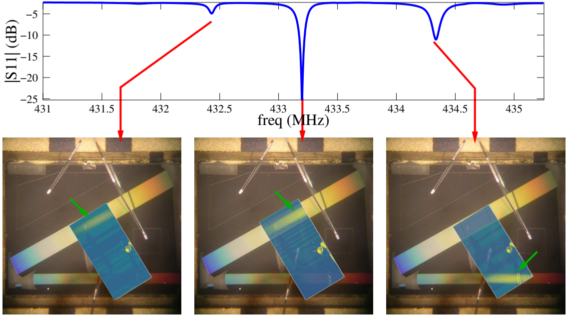



$$T = A_0 + \sqrt{A_1 + A_2 \Delta f}$$

SAW characterization

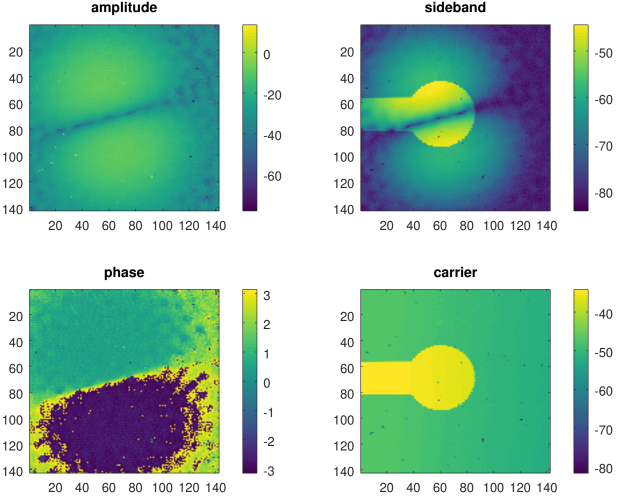


434 MHz SEAS10 dual resonator temperature sensor ↑

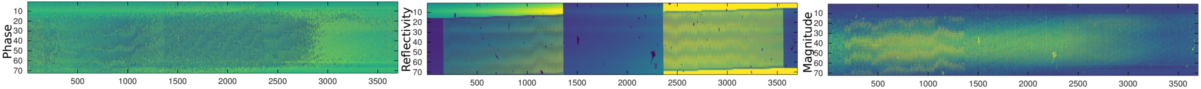
Measurement duration: **25 ms/sample** ⇒ 1 h for 200 MHz SAW, 8 min for BAW

Vibration amplitude: 3–8 nm →

BAW characterization



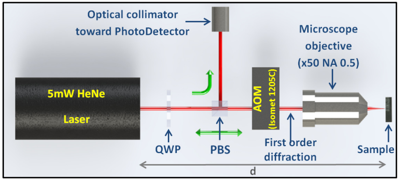
200 MHz Rayleigh wave quartz transmission delay line ↓



Phase   Reflectivity (IDT and bus pattern)   Amplitude

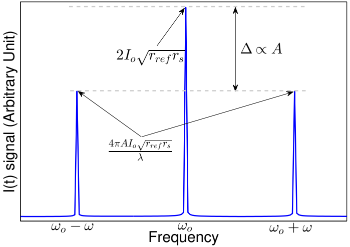
Heterodyne optical probe setup for acoustic transducer characterization

Mapping surface acoustic field for acoustic propagation mode identification and energy confinement/leak mechanism assessment



Heterodyne Michelson interferometer setup.

- Bulk and surface acoustic wave generated on piezoelectric substrates: electrical to mechanical conversion
- Phase measurement for velocity measurement
- Radiofrequency devices operating in 5-5000 MHz range: $\lambda \in [1000-1]$ μm
- Out-of-plane measurement using an interferometric (Michelson) setup

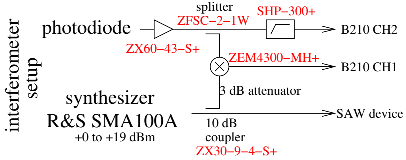


Radiofrequency signal spectral components.

- Get rid of static phase drift by using a heterodyne setup
- Get rid of sample reflectivity variation by using the ratio of the sideband (acoustic modulation) to carrier ratio

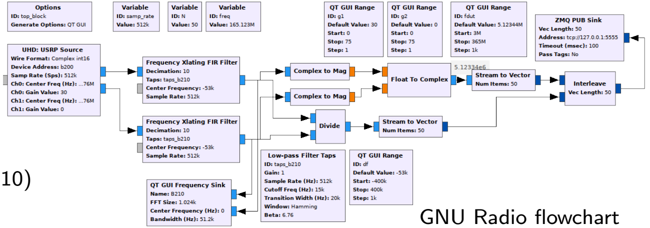
SDR instrumentation

- Fully digital data acquisition for flexibility
- Cost effective approach to radiofrequency instrumentation
- General purpose SDR receiver (Ettus Research B210) for radiofrequency signal acquisition
- Analog Devices AD9361 frontend: synchronous dual input, signal $\in [70..6000]$ MHz



Both B210 channels collect signals at the same frequency: optical carrier shifted to sideband frequency by mixer.

- Dynamic range issue: 8 bit (48 dB) is insufficient, 12 bit (72 dB) mandatory for the sideband to carrier ratio to eliminate sample reflectivity
- need to synchronize radiofrequency datastream with positioning table commands
- data collected only when position is stable



GNU Radio flowchart

```
pkg load zeromq
pkg load instrument−control
s1 = serial("/dev/ttyUSB0");
set(s1, 'baudrate', 115200);
...
srl_write(s1,"SVO 2 1\n");
for y=ymin:2*dy:ymax
  ch=['MOV 1 ',num2str(y),"\n"];srl_write(s1,ch);
  pause(table_delay);
  for x=xmin:dx:xmax
    ch=['MOV 2 ',num2str(x),"\n"];srl_write(s1,ch);
    pause(table_delay);
    sock1 = zmq_socket(ZMQ_SUB);
    zmq_connect  (sock1,"tcp://127.0.0.1:5555");
    zmq_setsockopt(sock1, ZMQ_SUBSCRIBE, "");
    recv=zmq_recv(sock1, total_length*8*2, 0);
    value=typecast(recv,"single complex"); % char −> float
    mesure1(m,p)=mean(value(1:length(value)/2));
    mesure2(m,p)=mean(value(length(value)/2+1:end));
    zmq_close (sock1);
  end
...
```

- ZeroMQ non-blocking (publish-subscribe) **continuous** datastream to GNU/Octave collecting data and controlling the positioner