Characterization of electro-acoustic devices: Surface acoustic wave transducers and delay lines

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Objective

The objective of this lab session is to understand the meaning of quantities measured by a network analyzer during the spectral characterization of an unknown device: impedance, admittance, scattering coefficient, real/imaginary part or angle/magnitude. The initial steps aim at becoming familiar with these general concepts, while the **last questions** will use this prior knowledge to analyze the electric characteristics of surface acoustic wave devices. These last questions **are the most important part of the lab session** and must be answered.

It is assumed that the preliminary work on the electrical characterization of radiofrequency circuits using a network analyzer as found at `http://jmfriedt.free.fr/preliminary_analysis_electrical_measurements.pdf` has already been completed.

1 Surface acoustic wave propagation in anisotropic media

We wish to illustrate the influence of the elastic anisotropy on the propagation properties of surface acoustic waves. To this aim, we investigate the electro-acoustic responses of two sets of samples fabricated on ST-cut quartz substrates (ST-cut: 42.75°-YX quartz):

- The `type T` samples host interdigitated (IDT) transducers emitting along three different propagation directions: parallel to the wafer flat, orthogonal to the wafer flat and oriented at an angle of 45° with respect to the wafer flat;
- The `type DL` samples host SAW delay lines fabricated along orthogonal directions.

The corresponding layout is given in appendix A. The supplier datasheet of the used quartz wafers is given in Appendix B.

The interdigitated transducers all exhibit the same geometrical parameters (see figure below, right):

- 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.

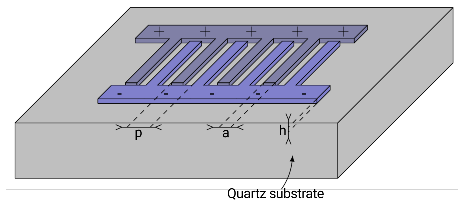


Figure 1: Geometrical parameters of the fabricated interdigitated transducers. h is the electrode thickness, p the electrode pitch and a the finger width.

17. What is the expected wavelength of the acoustic wave propagating on the proposed SAW devices patterned on quartz substrates?
18. Using the slowness curves reported in Appendix C, determine the resonance frequency corresponding to an X-propagating Rayleigh wave.
19. Propose a possible process flow chart for fabricating such transducers. Justify the chosen method for the lithography and deposition steps.

1.1 SAW device measurements

The Siglent SVA1015X vector network analyzer used during the laboratory session is briefly described in Fig. 2.

Configure the instrument with the following settings, based on the description of the device

- mode: VNA (Vector Network Analyzer) as opposed to the spectrum analyzer which only monitors passively radiofrequency emitters
- measurement mode: S_{11} or S_{21} depending whether reflection or transmission devices are measured
- number of measurement points

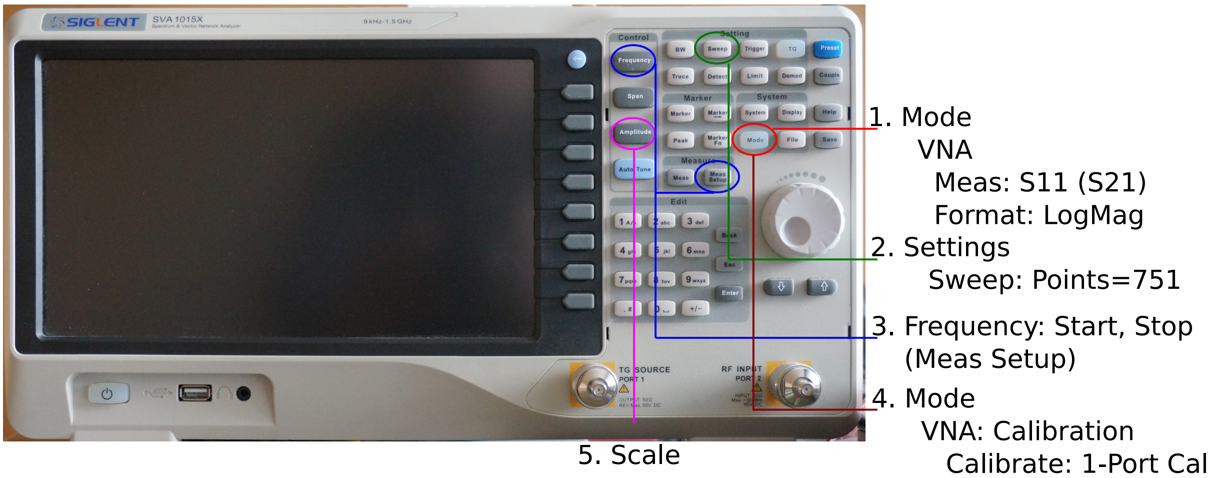


Figure 2: Vector network analyzer front panel.

- **calibrate** de instrument prior to any new measurement (open, short, 50 Ω load and possibly through)
  - Mode → Vector Network Analyzer → Calibration → Calibrate → Response Through for transmission delay line or 1-Port Cal for reflective devices. Check that the calibration is valid on the Smith chart with Measure → Format → Smith
- when saving data, only the displayed curve will be stored in the file. For complex numbers, please select the Smith Chart display.

The data are saved as CSV format since the Siglent network analyzer does not support the standard Touchstone format. Be aware thought that only the quantity displayed on the screen is saved, e.g. magnitude v.s frequency or phase v.s frequency. To save the full complex (real and imaginary part) needed to convert the scattering parameters to admittance, switch to Smith chart before saving: under this setting, both real and imaginary parts of the complex will be saved.

Once the device characteristics have been collected (or using the archive provided at `http://jmfriedt.free.fr/201101_files.tar.gz` if some measurements are missing), process the device according to the following questions:

20. what are the electromagnetic wavelengths associated with the upper and lower frequencies of the considered analysis bandwidth? What are the associated acoustic wavelengths?

21. we want to make use of slowness, electromechanical coefficient and attenuation curves (Appendices C, D and E respectively) to analyse the device responses:
    (a) what is the expected attenuation for a Rayleigh wave propagating on a non-viscous semi-infinite solid substrate?
    (b) analyse the dependency of the electromechanical coupling coefficient as a function of the angular orientation for the Rayleigh wave. What is the meaning of an electromechanical coupling coefficient equal to zero? Does it mean that the Rayleigh wave cannot propagate along specific directions? If not, what does it means?
    (c) refer now to the coupling coefficient chart (Appendix D). Can you comment on the values computed for the wave labelled STW (Surface Transverse Wave)? Do they physically make sense? How do these data compare with one provided for the attenuation (Appendix D)?

22. We now focus on the measurement data. Determine whether the collected measurements are in transmission or reflection.

23. For each the (reflection-mode) acoustic transducer (`type T`):
    (a) Determine the number of resonances and the velocity of the corresponding elastic waves.
    (b) Determine the bandwidth, quality factor and electro-mechanical coupling coefficient of the supplied device. Should you be using scattering parameters or admittance measurements to this aim?
    (c) Use this analysis, along with the provided slowness, electromechanical coefficient and attenuation curves to account for the fact that a single resonance is observed for the `T90` device. Please provide a detailed account of your methodology.

(d) Based on the same principle, identify the different elastic modes involved.

24. For each (transmission mode) acoustic delay line, what kind of wave contributions do you assume to be responsible for the observed frequency responses in transmission for the two orthogonal configurations?

25. Is the in-plane orientation of the IDTs with respect to the quartz substrate, as given in Appendix A, consistent with the experimental results?

26. ST-quartz is an interesting substrate, that supports the propagation of a pure Rayleigh wave with a zero-temperature coefficient of frequency along the X-axis. It also supports leaky (or pseudo-) surface waves. In particular, a very relevant, so-called STW wave (Surface Transverse wave) can be generated.

    - How is this STW wave polarized with respect to the substrate surface? How is a Rayleigh wave polarized?
    - If you were to design a sensor operating in a liquid environment, which of these waves would you select? Would you operate your device in a delay line or in a resonator/transducer configuration? Please justify.
    - If you were to design a radio-frequency filter, which of these two waves would you be likely to use?

References

[1] J. Vig, *Quartz crystal resonators and oscillators – A tutorial*, 2000 at `https://www.am1.us/wp-content/uploads/Documents/U11625_VIG-TUTORIAL.pdf`

A Sample Description

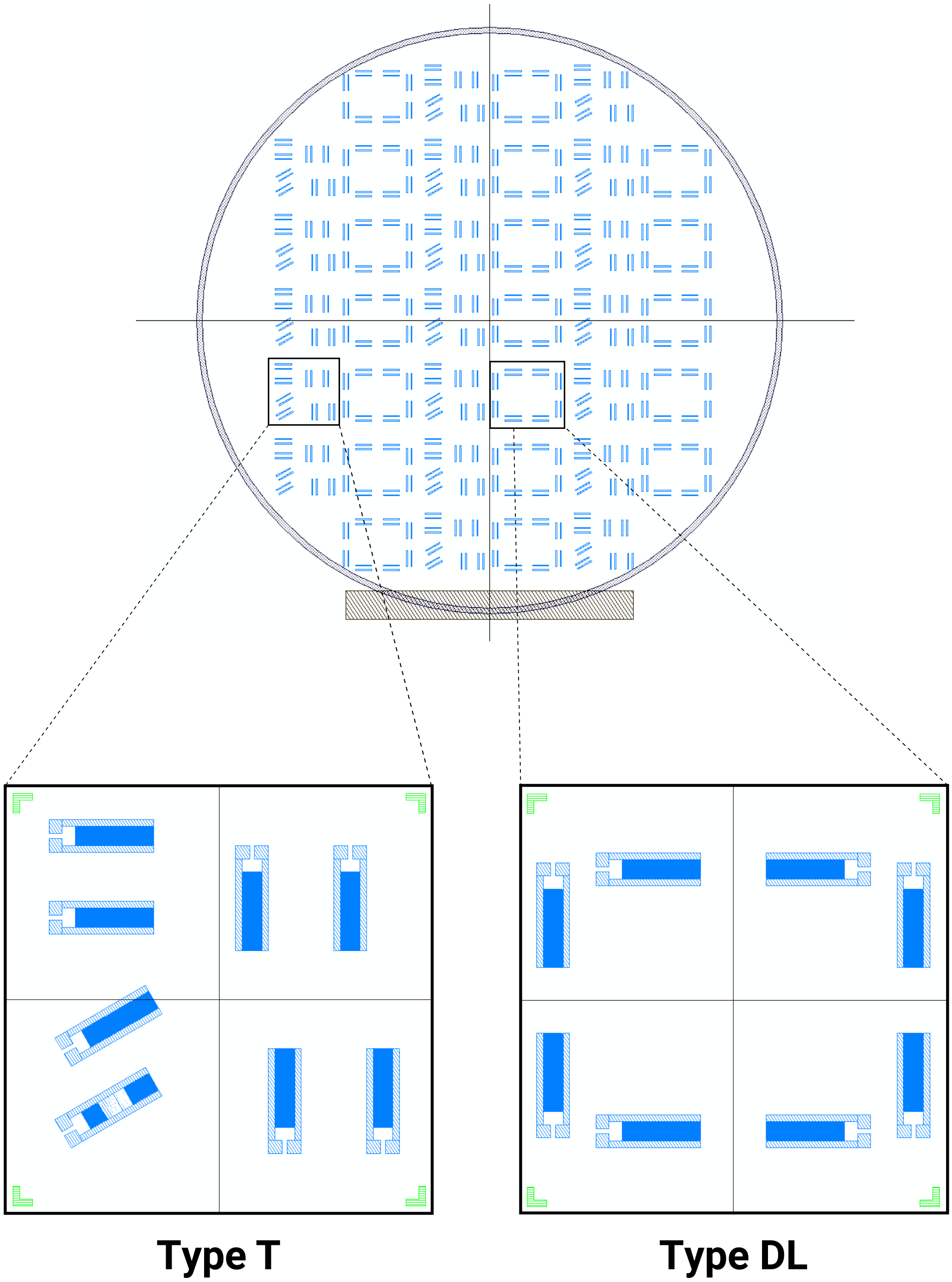


Figure 3: Photomask layout, describing the geometrical configuration of the fabricated transducers (type T) and delay lines (type DL) with respect to the supporting wafer.

B ST-cut quartz wafer datasheet

Saw Wafers

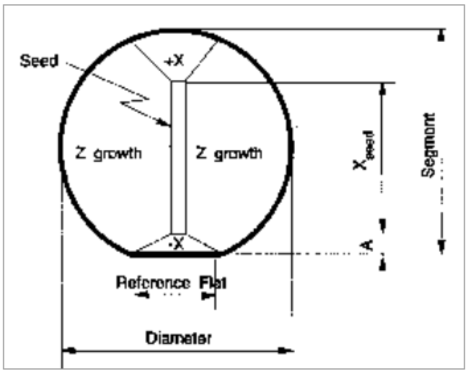
Single crystal cultured quartz substrate wafer is most commonly specified as 3" or 100 mm with a reference flat.

The wafers are Y-cut with rotations specified between about 32° and 42.75° around the X-axis.

A high quality, low damage surface is prepared on one major (propagating) surface by polishing.

The back side is usually lapped to a rough finish to attenuate unwanted vibration modes.

Ex-stock delivery for standard 4" wafer angles : 32°, 34°, 36°, 37°30', 38° and 40°.



Outline Drawing

Typical Specifications

Physical Dimensions

Description		Unit	Tolerance	76.2 ~ 100mm
Diameter		mm	±0.1	76.2 ~ 100.0
Thickness		mm	±0.01	0.35 - 0.50
Total thickness variation		mm	maximum	4.00
Orientation of propagating surface	around X-axis	arc minute	± 6	Customer specified
	around Z´-axis	arc minute	± 15	0.00
Reference flat width		mm	± 3	22/32
Reference flat orientation (xxxx to Y´-axis)		arc minute	± 6	0
Segment		mm	nominal	74.7 / 98.5
X_{seed}		mm	minimum	76
A		mm	maximum	2 / 5
Centricity of seed		mm		within central 5

Figure 4: Datasheet of the ST-quartz wafers used for the fabrication of the measured samples, as provided by the manufacturer.
Source: `http://www.roditi.com/SingleCrystal/Quartz/SAW-Wafer.html`.

C Slowness curves for ST-cut quartz

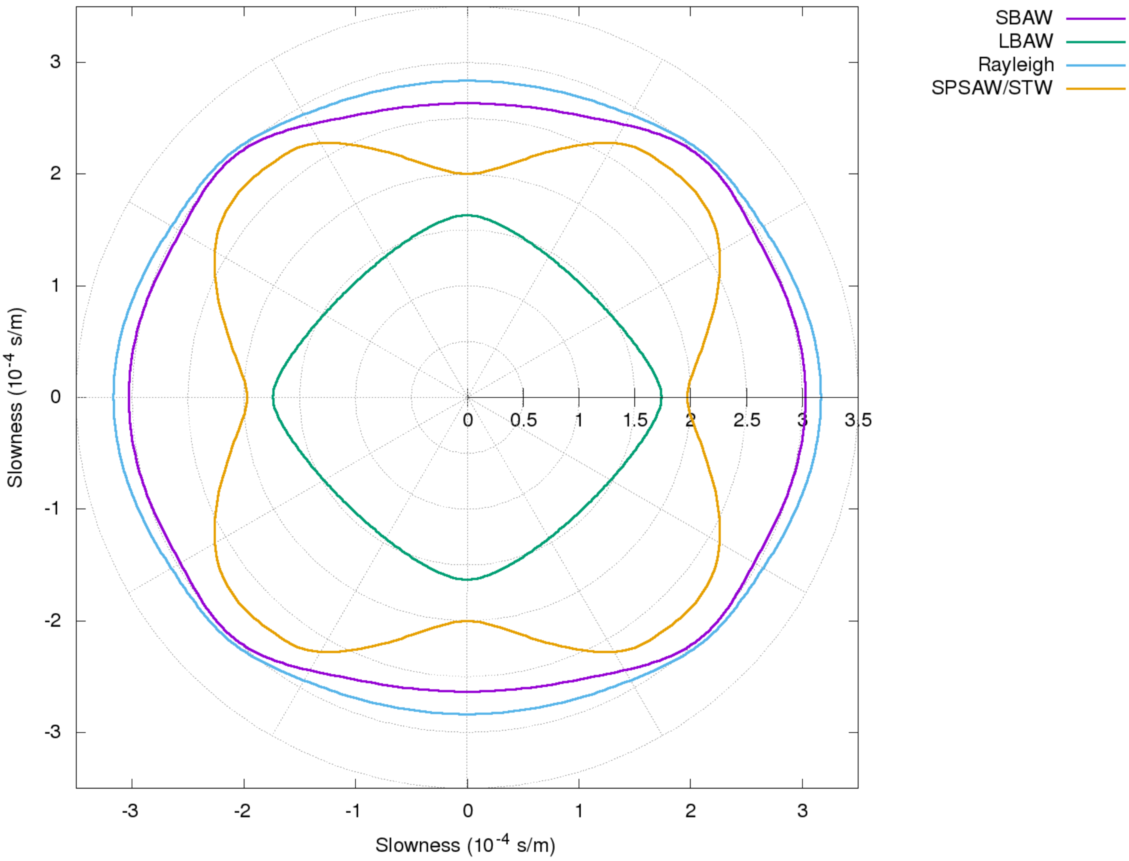


Figure 5: Slowness curves for ST-quartz. The X-axis lies at 0°. SBAW: Shear Bulk Acoustic Wave, LBAW: Longitudinal Bulk Acoustic Wave; SPSAW: Shear Pseudo Surface Acoustic Wave; STW: Shear Transverse Wave.

D Electromechanical coupling coefficients for ST-cut quartz

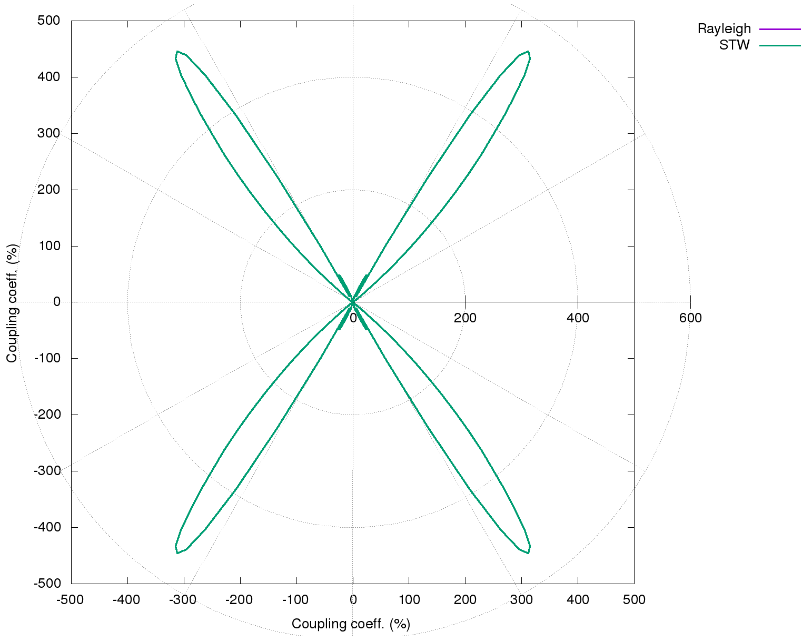


Figure 6: Electromechanical coupling coefficients, provided as is after computation, for the STW and the Rayleigh waves on ST-cut quartz.

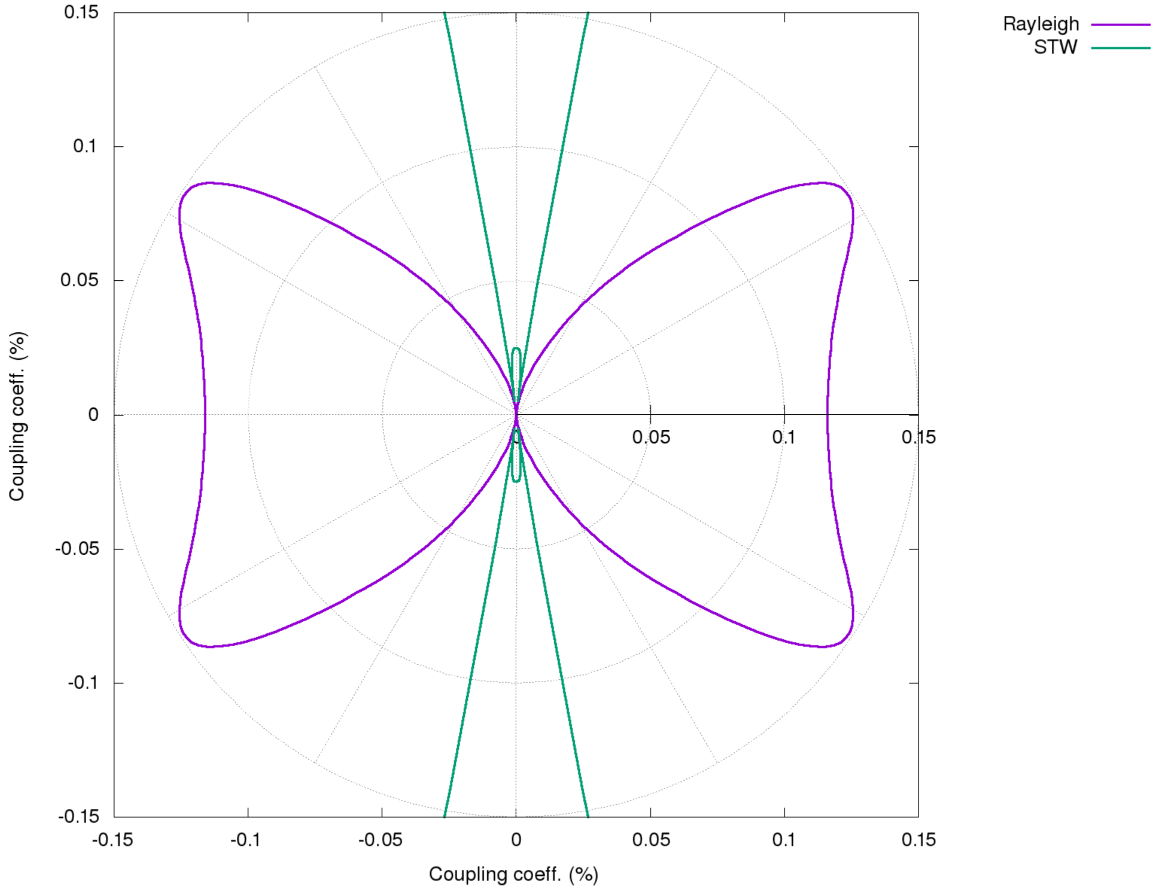


Figure 7: Zoom on the previous dataset.

E Attenuation coefficients for ST-cut quartz

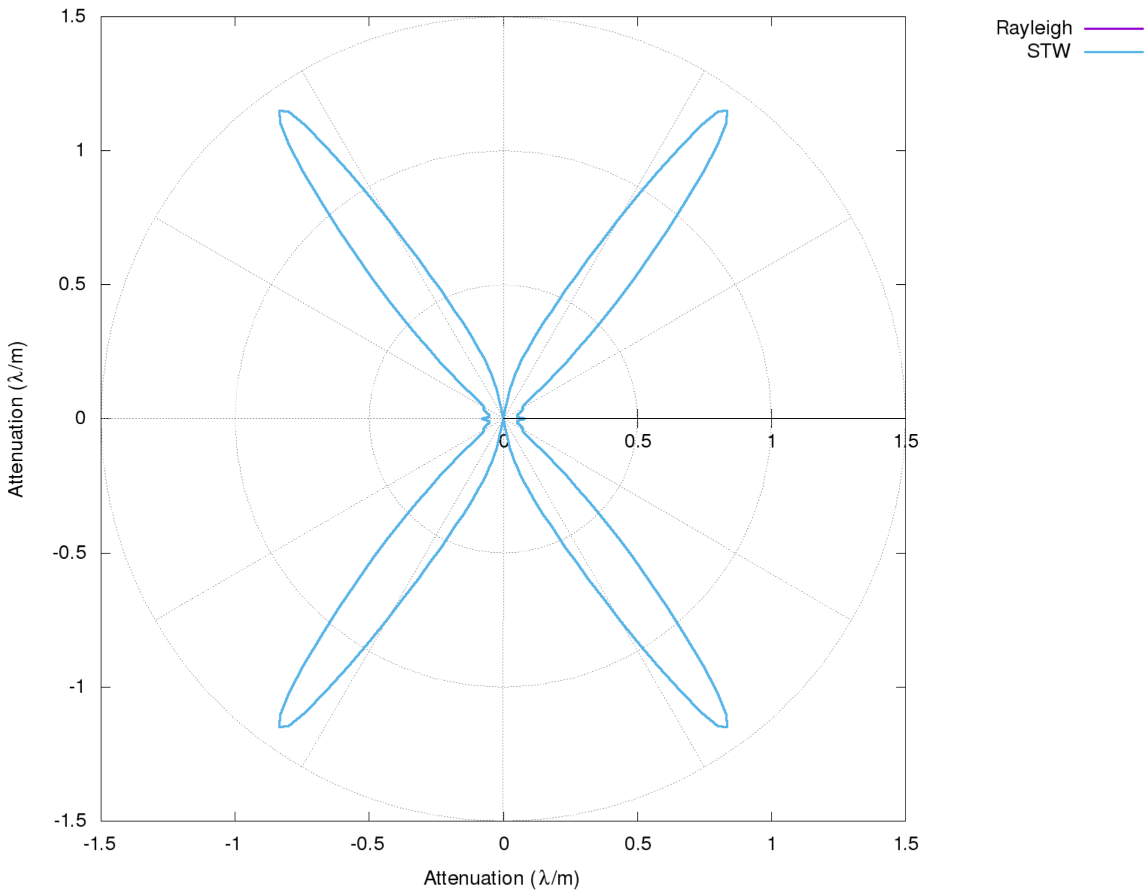


Figure 8: Attenuation, provided as is after computation, for the STW and the Rayleigh waves on ST-cut quartz.

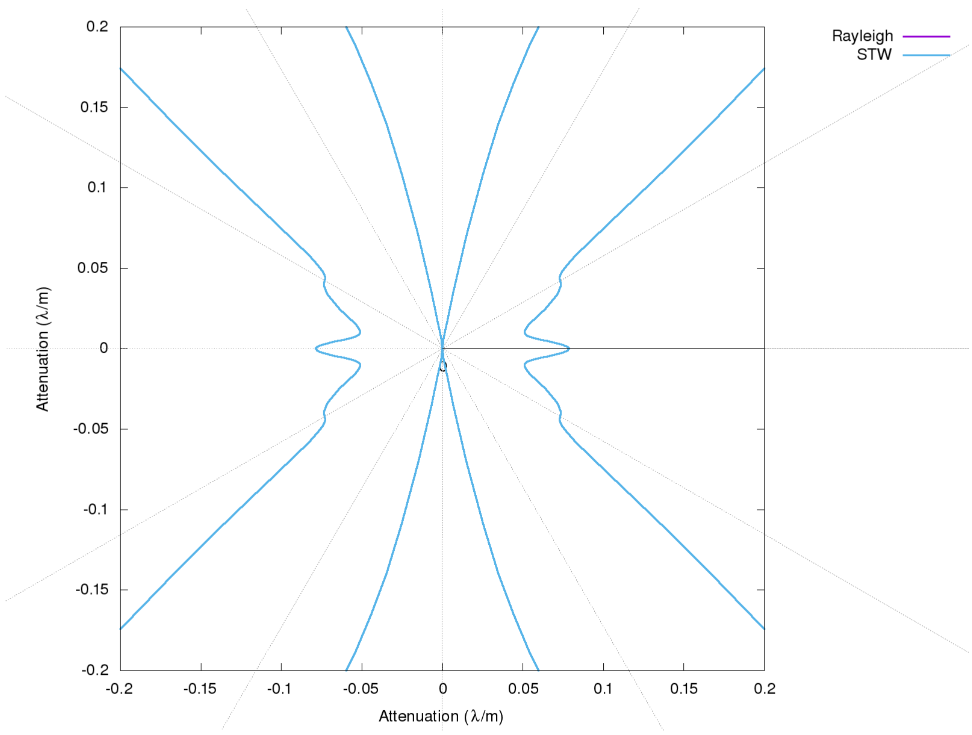


Figure 9: Zoom on the previous dataset.