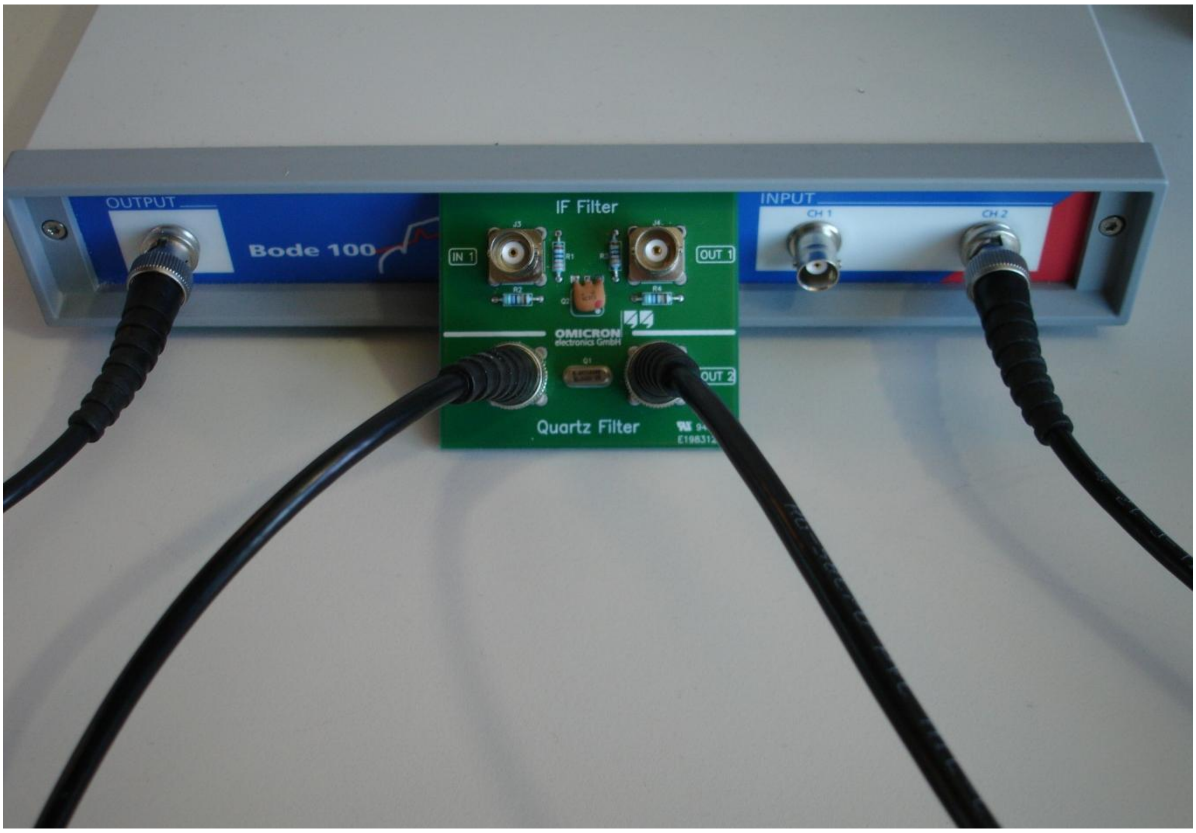
Equivalent Circuit Determination of Quartz Crystals



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Contact support@omicron-lab.com for technical support.

Table of Contents

Note: Basic procedures like setting-up, adjusting and calibrating the Bode 100 are described in the user manual of the Bode 100.

Note: If you perform the shown measurements using your DUT the results may differ due to part tolerances.

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V2.30 SR1. Use this version or a higher version to perform measurements according to this application note.

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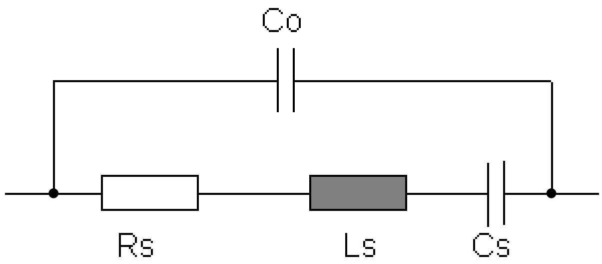
1 Executive Summary

This application note explains how to measure the equivalent circuit parameters of a quartz crystal with the Bode 100.
You will be given an insight on resonance frequency measurements and impedance measurements with the Bode 100.

2 Measurement Task

Each quartz crystal has resonance frequencies. This resonance behavior can be modeled with an equivalent electronic circuit. An equivalent description of a quartz crystal is given by the following circuit. It is valid in the frequency region of a single series - parallel resonance combination. These series – parallel resonance combinations occur at odd multiples of the fundamental series resonance frequency.



Quartz equivalent circuit model

Based on this model with the circuit parameters L_s, C_s, C_0 and R_s the resonance frequencies and the quality factor can be calculated using the following equations:

Series resonance frequency f_s $$f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$$

Parallel resonance frequency f_p: $$f_p = f_s\sqrt{1+\frac{C_s}{C_0}} \approx f_s\left(1+\frac{C_s}{2C_0}\right)$$

Quality factor at f_s: $$Q = \frac{1}{R_s}\sqrt{\frac{L_s}{C_s}}$$

With the Bode 100 the values for C_o, f_s and f_p can be measured. When rewriting the equations from above C_s and L_s can be calculated from the results of these three measurements.

$$C_s = 2C_0\left(\frac{f_p}{f_s}-1\right)$$

$$L_s = \frac{1}{4\pi^2 \cdot f_s^2 \cdot C_s}$$

The following pages show how to set up your equipment, how to use the measurement methods of the Bode 100 and formulas to calculate the equivalent circuit parameters of the delivered test object quartz crystal. Further on the quality factor of the crystal will be measured.

3 Measurement Setup & Results

3.1 Measurement Equipment

- Bode 100 Vector Network Analyzer
- Test object (delivered test board with quartz filter)
- Measurement accessories (BNC cables, 50 Ω BNC termination, BNC short)

3.2 Measuring the Quartz

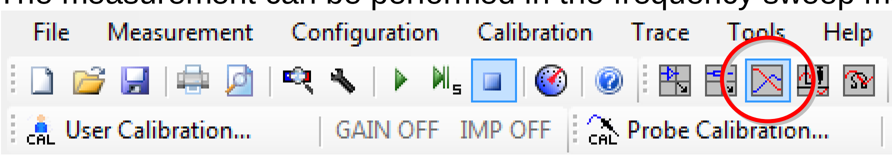
The used test object is the crystal mounted on the test PCB, which is delivered with Bode 100. In a first step we will determine the equivalent circuit values at the fundamental frequency.

Test board with quartz filter

3.2.1 Determination of the Parallel Capacitance

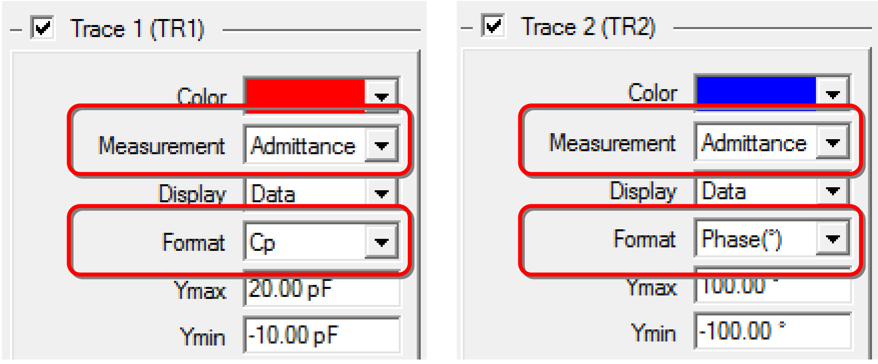
The quartz crystal has a nominal series resonance frequency of 12 MHz.
To measure C_0 we need to measure the impedance of the crystal at a frequency which is well apart from the series- parallel resonant frequencies. For this 12 MHz crystal a measurement frequency of 10.5 MHz will be a good value. We expect a pure capacitive reactance as a measurement result.

The measurement can be performed in the frequency sweep mode.



The following settings are applied:

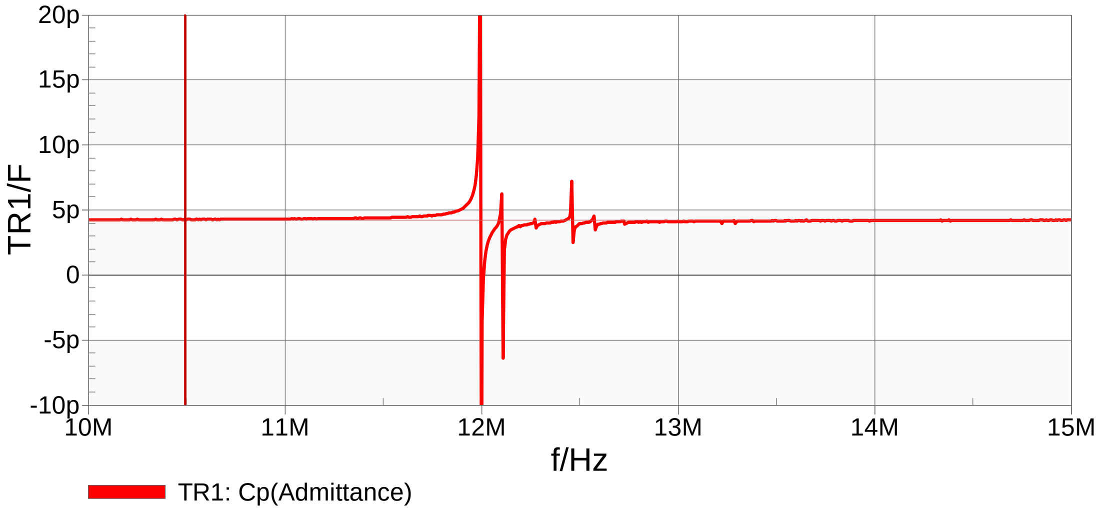
- Start frequency f=10 MHz
- Stop frequency f=15 MHz
- Receiver Bandwidth 100 Hz



OPEN, SHORT and LOAD calibration have to be performed to remove the cable influence. Details on the calibration can be found in the Bode 100 User Manual.

Connect the measurement cable to the "IN 2" BNC connector of the quartz filter and connect a short at the "OUT 2" BNC connector of the quartz filter. Start the measurement and use right click "optimize" to display the measured data:

The following graph shows the result for the parallel capacitance C_0:



Setting the cursor to the measurement frequency of 10.5 MHz leads to the following results:

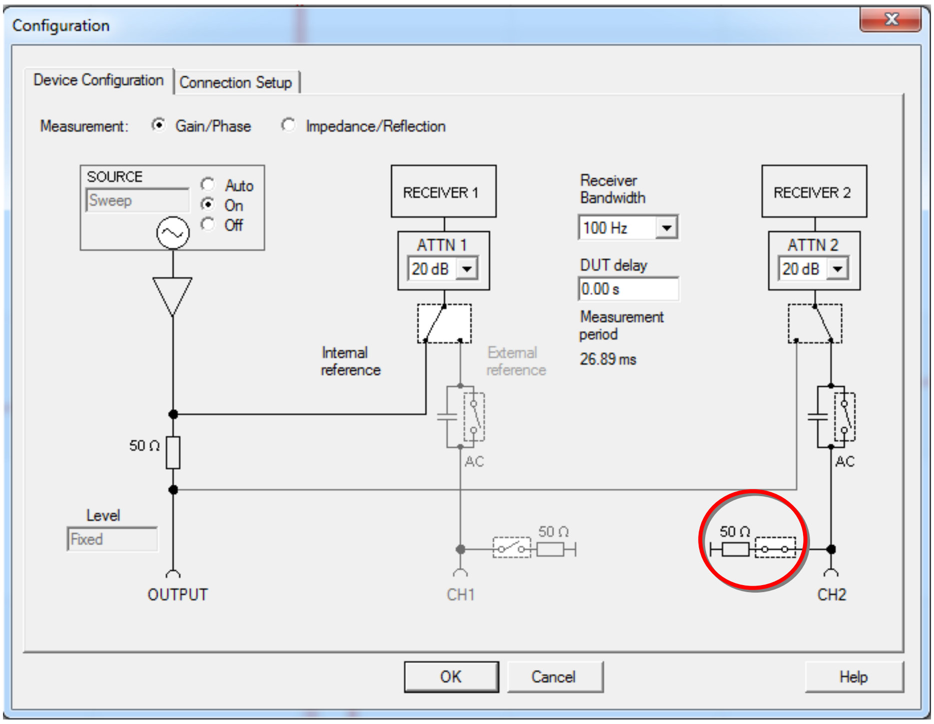
	Frequency	Trace 1		Trace 2	
Cursor 1	10.500 MHz		4.242 pF		89.205 °

The parallel capacitance beyond the resonance frequencies equals $C_0 = 4.24\text{pF}$.
The value of the admittance phase with 89.2° shows nearly perfect capacitive behavior at the measurement frequency.

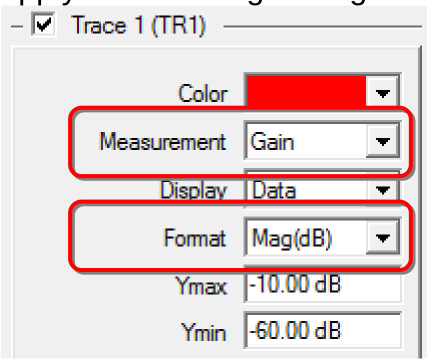
3.2.2 Measuring the Resonance Frequencies

To measure the series and parallel resonance frequency we perform a frequency sweep gain measurement. The input of the quartz filter is connected to the Bode 100 output and the output to channel 2 of the Bode 100. (See following figure)

Open the configuration window and switch "on" the 50 Ω termination resistor:

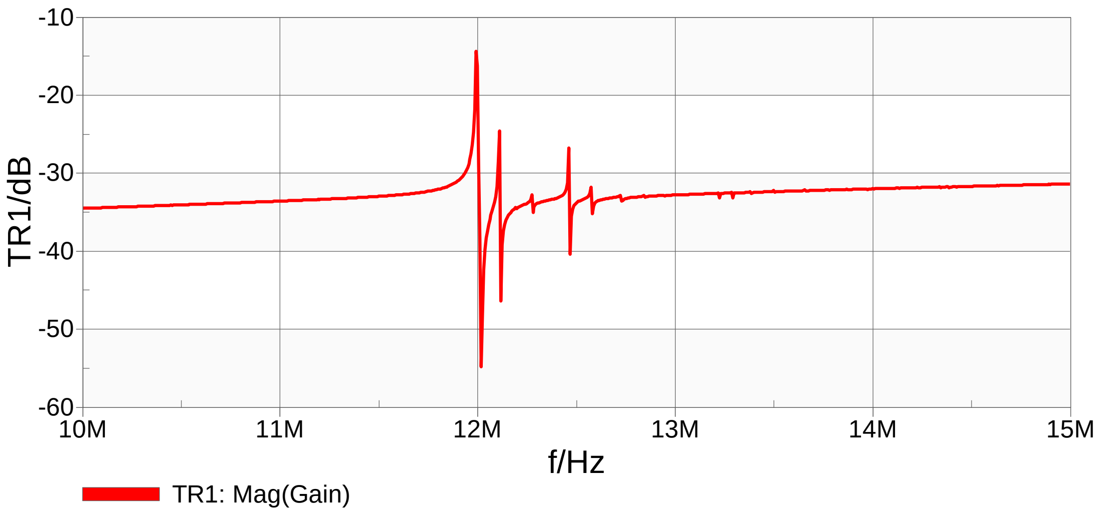


Apply the following settings to trace 1:



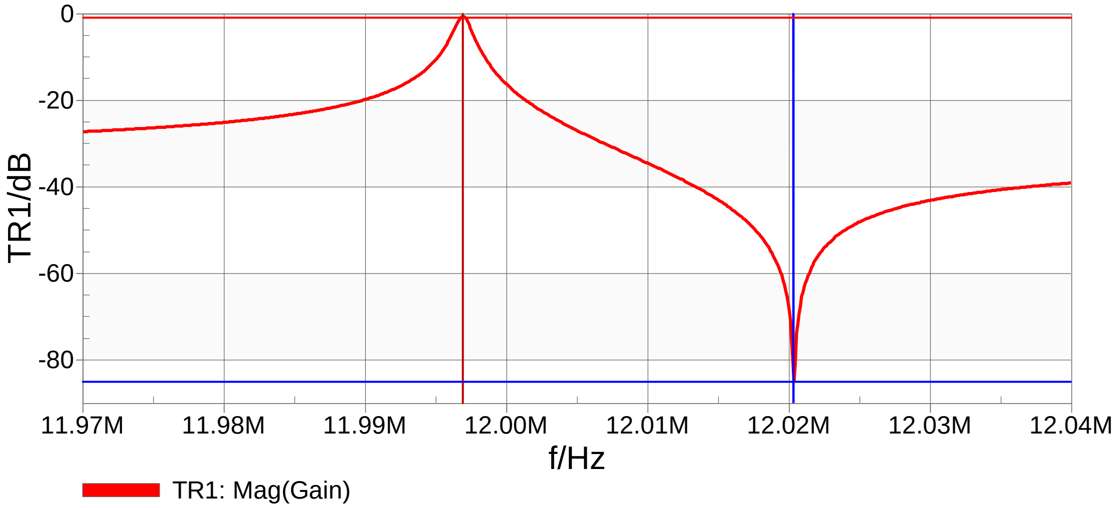
To remove the cable influence a THRU calibration has to be performed:

After performing the THRU calibration connect the DUT and start a frequency sweep:



The transmission measurement shows multiple resonance frequencies. As we are only interested in the first parallel and series resonance we have to change the frequency range. For that you can zoom into the graph. (You can activate the zoom menu by right clicking anywhere into the graph). It is recommended to zoom into a window that has a f-range from approximately f(min)=11.97 MHz to about f(max)=12.04 MHz for this measurement.

Performing a measurement in this range shows the first series and parallel resonance frequencies:



Using two cursors and setting them to the maximum and minimum of the curve (use right click, cursor – jump to min/max) leads to the resonance frequencies:

	Frequency	Trace 1	
Cursor 1	11.996950 MHz		-0.748 dB
Cursor 2	12.020400 MHz		-85.011 dB
delta C2-C1	23.450 kHz		-84.263 dB

The measured resonance frequencies are:

$$f_s = 11.99695\ \mathrm{MHz}$$
$$f_p = 12.0204\mathrm{MHz}$$

Using the equations from page 3 and the measured parallel capacitance the series capacitance and the series inductance can be calculated:

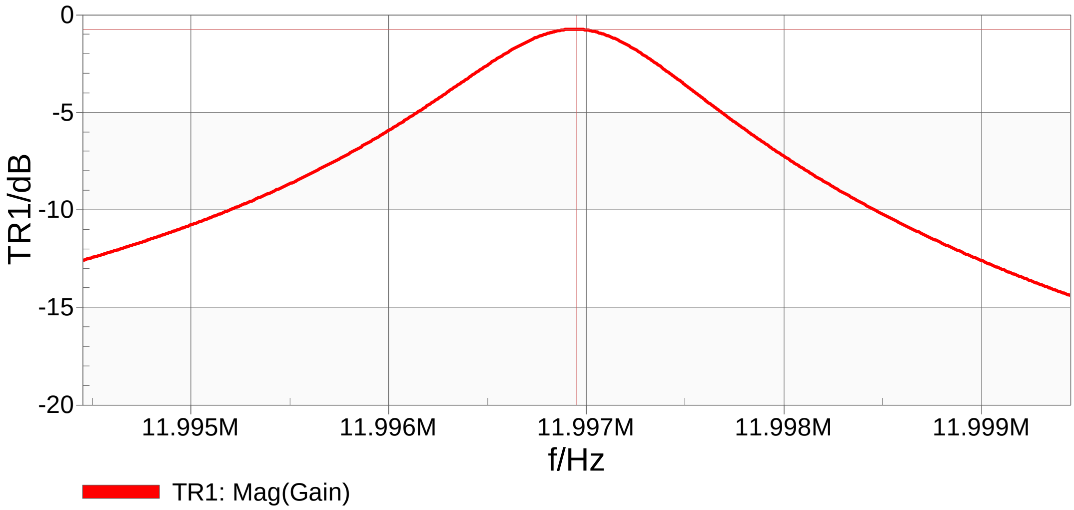
$$C_s = 2C_0\left(\frac{f_p}{f_s} - 1\right) = 16.5\ \mathrm{fF}$$

$$L_s = {}^{1}/_{(4\pi^2 f_s^2 C_s)} = 10.6\ \mathrm{mH}$$

3.2.3 Determination of the Series Resistance

The last value we are missing for the equivalent circuit model of the quartz is the series resistance R_S. To measure this resistance we adjust the Bode 100 center frequency exactly to the series resonance frequency f_s and set the span to 5 kHz.

Performing a sweep measurement leads to the following result:

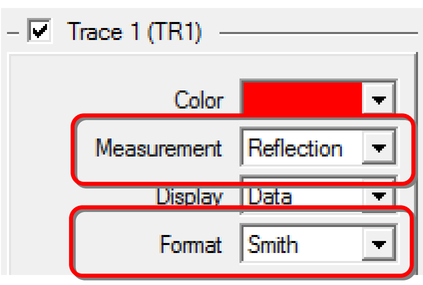


The cursor shows an attenuation of 0.747dB at the series resonance point. Using the following equation the series resistance can be calculated from the attenuation value.

$$R_s = 2R\left(10^{\frac{-a}{20}} - 1\right) = 100\left(10^{\frac{0.747}{20}} - 1\right) \cong 9\Omega$$

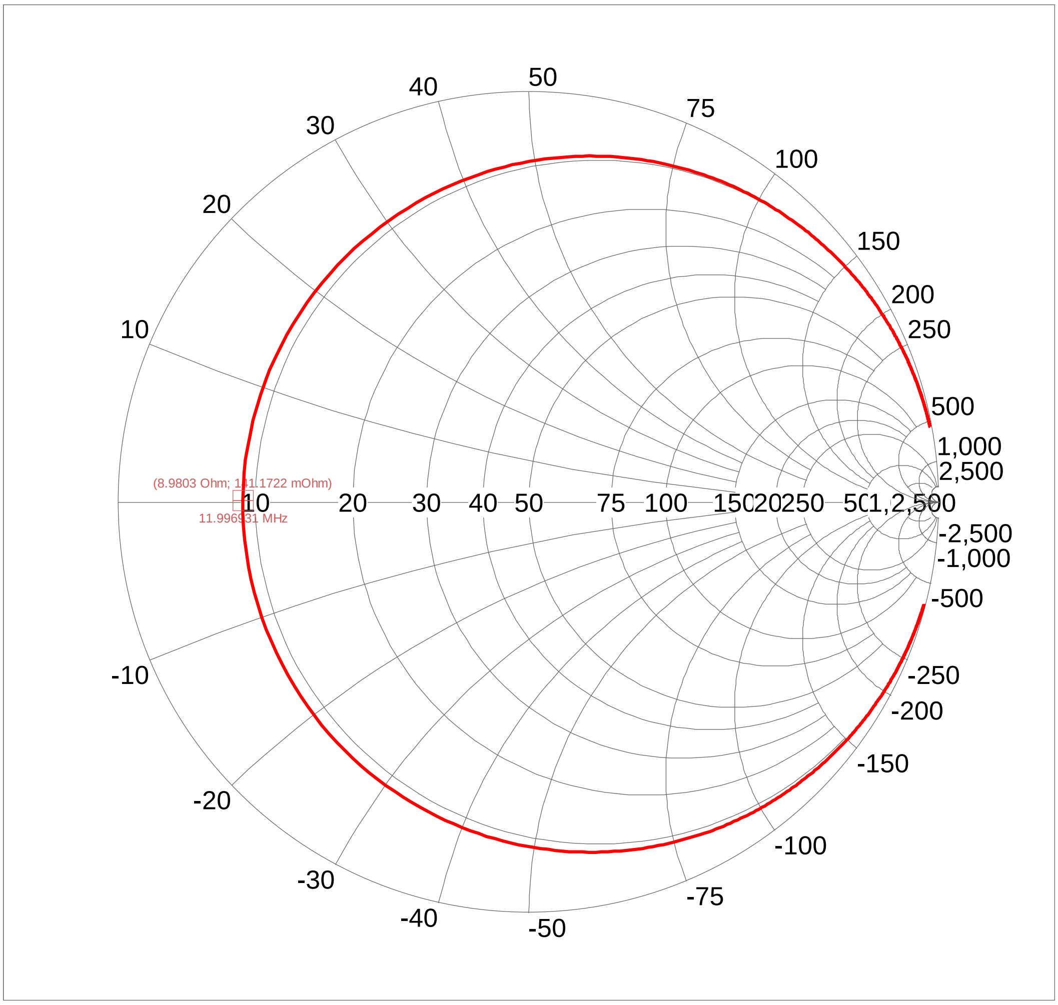
With: a ... attenuation in dB
R … reference resistance (50Ω)

The series resistance can also be directly measured using the Bode 100.
Set the measurement to reflection and format to Smith (Smith Chart).



Perform an impedance calibration (OPEN, SHORT and LOAD) and connect the quartz filter as shown on the picture above.

Start a single sweep with the same frequency span as before. Set the cursor to the series resonance point (this is the point where the reflection circle intersects with the horizontal axis of the smith chart).



TR1: Reflection

The cursor shows a resistance of 9 Ω which equals the calculated series resistance from before

.

	Frequency	Trace 1	
Cursor 1	11.996931 MHz	8.980 Ω	141.172 mΩ

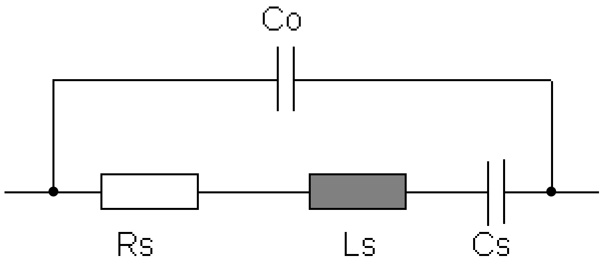
3.2.4 Determination of the Quality Factor

The quality factor Q of the quartz can be calculated using the measured values of the equivalent circuit model. The quality factor of the quartz is calculated as follows:

$$Q = \frac{1}{R_s}\sqrt{\frac{L_s}{C_s}} = \frac{1}{9\Omega}\sqrt{\frac{10.6\text{mH}}{16.5\text{fF}}} = 89057$$

As a result of the performed measurements we are now able to describe the tested quartz crystal filter with a series – parallel equivalent circuit as follows:

$C_0 = 4.24\text{ pF}$
$C_s = 16.5\text{ pF}$
$L_s = 10.6\text{ mH}$
$R_s = 9\ \Omega$
$Q = 89057$



4 Conclusion

The Bode 100 together with the Bode Analyzer Suite offers several useful functions to measure resonance frequencies or equivalent circuit parameters of any device under test.

The cursor functions help to find the exact measurement values at desired points. Predefined parameter measurements for series and parallel equivalent circuits reduce the users calculation effort and enable easy and fast measurements.