

# ***MPR Subwavelength Cavity User Guide***

*Magnetic Plasmon Resonance (MPR) Subwavelength Cavity  
is a measurement fixture applicable to the characterization  
of low- and medium-loss spherical ferrite samples*

**Model 06-5ct  
version 1.0**

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## **UG 1. Introduction, system requirements and installation**

### **UG 1.1. Introduction**

The Magnetic Plasmon Resonance (MPR) Subwavelength Cavity is a manual measurement fixture applicable to the characterization of low- and medium-loss spherical ferrite samples smaller than 0.6 mm. Magnetized ferromagnetic materials exhibit shape- and magnetic-bias-dependent resonant behavior. In spherical specimens at microwave frequencies, the dominant resonance is the MPR, whose nature has been recently unraveled [1]. For electrically small samples, the resonance frequency of the MPR can be approximated by the formula:

$$f_{\text{MPR}} = \gamma H_{\text{ext}}, \quad (1)$$

where  $\gamma \approx 2.8$  MHz/Oe is the gyromagnetic ratio, and  $H_{\text{ext}}$  is the extrinsic magnetic bias (i.e. measured outside the sample). The measurement of the resonance frequency and Q-factor of the MPRs makes it possible to determine the intrinsic (shape-independent) properties of the material under test (MUT).

The MPR subwavelength cavity is essentially a coupling structure enabling accurate and broadband measurement of MPRs in spherical samples up to 40 GHz. Enclosing the sample in the cavity has the effect of suppressing radiation losses, which would decrease the apparent Q-factor, and hence the apparent magnetic losses. Simultaneously, the cavity has been engineered in such a way that electric losses in the cavity walls can be neglected if the intrinsic linewidth is broader than ca.  $\Delta H = 0.1$  Oe. Thanks to the properties of the MPR, dielectric losses of a quartz tube applied to mount the sphere in the cavity are also negligible. Tunable coaxial couplings of the fixture allow to weakly couple to the MUT and, consequently, suppress the difference between the measured Q-factor and the unloaded Q-factor of the MUT.

Using the QtMPR software, the Q-factor and resonance frequency can be extracted from raw  $S_{21}$  complex measurement data. Based on those values, the software computes, amongst others, the intrinsic ferromagnetic linewidth ( $\Delta H$ ), Gilbert damping factor ( $\alpha$ ), and Polder's permeability tensor components, assuming that the permeability of the MUT is governed by the Landau-Lifshitz-Gilbert (LLG) model [2].

### **UG 1.2. Software requirements**

The QtMPR software requires a 64-bit PC or laptop computer with the Microsoft Windows 7/10 operating system and at least 1 USB port.

## UG 1.3. Package list

The package contains:

- 1 cylindrical subwavelength cavity (copper),
- 1 cavity lid (copper),
- 2 coupling fixtures (brass) with 2 adjustable coaxial couplers terminated with 3.5 mm male connectors,
- 2 rings serving as coupling fixture stoppers (PTFE),
- 2 capillaries of ID 0.6 mm and OD 0.84 mm (quartz),
- 2 bristles (polyethylene),
- 1 cap serving as a position marker (polyurethane),
- 1 piece of Styrofoam for positioning the sample in the capillary,
- set of 8 + 1 screws (brass),
- 1 USB stick,
- User Guide.

## UG 1.4. Installation

If needed, run the vc\_redist.x64.exe installer to install the Microsoft Visual C++ 2019 Redistributable (administrator privileges are required). Follow the simple installation instructions appearing in the dialog. To run the application, open the QtMPR.exe file.

\*\*\*\*\*  
*In case of problems with running the software please contact us by e-mail*  
[info@emarges.eu](mailto:info@emarges.eu)  
\*\*\*\*\*

## **UG 2. MPR subwavelength cavity setup**

The MPR subwavelength cavity is shipped fully assembled. It is not advised to disassemble the setup.

### **UG 2.1. Hardware**

The assembled cavity is shown in Figure 1. The insertion depth of the coaxial couplers can be adjusted by turning the knobs. Clockwise turns pull the coupler out of the cavity. The coupling loops can be seen inside the cavity in Figure 2. The sample is to be inserted through the hole seen in Figure 3. The hole on the opposite side of the cavity is blind in order to prevent the quartz tube with a sample from accidentally falling out. The appearance of the shipped cavity might slightly differ from the images shown in this section. One of possible ways to mount the cavity between the pole pieces of an electromagnet is shown in Figure 4.

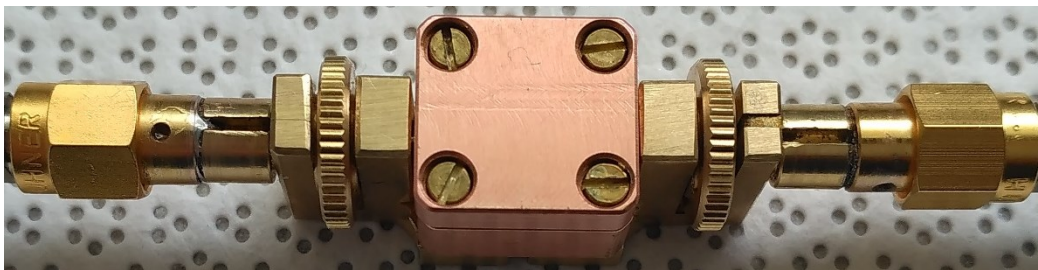


Figure 1. Top view of the MPR subwavelength cavity.

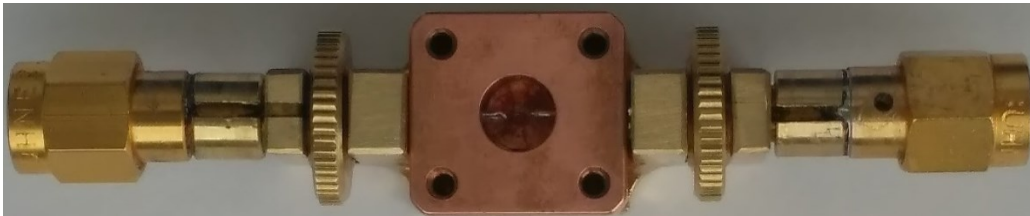


Figure 2. Top view of the MPR subwavelength cavity with the cavity lid removed.



Figure 3. Side view of the MPR subwavelength cavity with the cavity lid removed.



Figure 4. The MPR subwavelength cavity with connecting cables placed between the pole pieces of an electromagnet.

## **UG 2.2. Software**

### **UG 2.2.1. Introduction**

The QtMPR software presented in this Section (see the main window in Figure 5) is intended for extracting the resonance frequency and Q-factor from the MPR complex transmission spectra ( $S_{21}$ ) and, subsequently, computing certain magnetic parameters of the MUT. The resonance frequency and Q-factor are computed with the aid of a linear fractional curve fitting algorithm. Fine-tuning of the fit to  $S_{21}$  complex curve can be performed via a pair of scrollbars whose position determines the beginning and end of the fitting range. The software can be used for the analysis of a single transmission spectrum at a time. It can also be used as a calculator of magnetic properties without necessarily loading and fitting any data. A quick-start guide can be found in UG 2.2.2, and a detailed description of all the controls and indicators in UG 2.2.3. Exemplary raw data can be found in the “examples” folder on the USB stick.

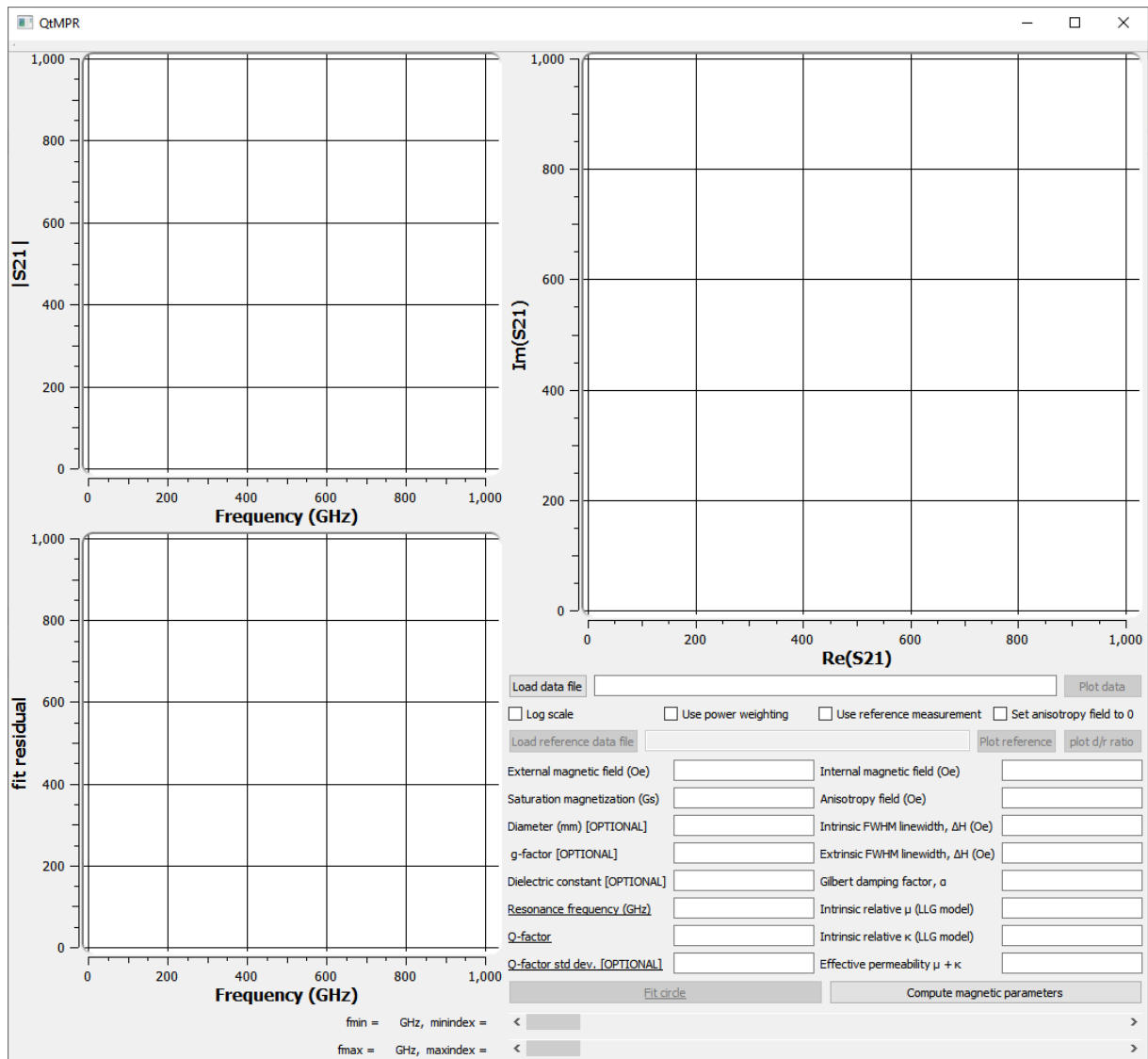


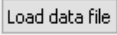
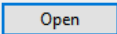
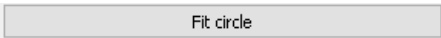
Figure 5. Main window.



## UG 2.2.2. Quick-start guide

### UG 2.2.2.1 Example 1 – low-loss MUT (\*.csv) measurement data

To quickly extract the resonance frequency and Q-factor, follow the steps:

1. To run the application, open the QtMPR.exe executable file. Refer to UG 1.4. in case of errors.
2. Load the file containing the  $S_{21}$  data with the following columns  
frequency (Hz),  $\text{Re}(S_{21})$ ,  $\text{Im}(S_{21})$   
by clicking the “Load data file” button , navigating to the *examples* folder, selecting the *low\_loss\_yig.csv* file and clicking .
3. Click the “Fit circle” button .
4. Adjust the fitting frequency range using scrollbars to obtain a uniform distribution of residuals and a stable (i.e. weakly dependent on small changes of the fitting range) value of the Q-factor and resonance frequency. In this example, one of the suitable positions of upper and lower scrollbars are 812 and 1043, respectively (see Figure 6).

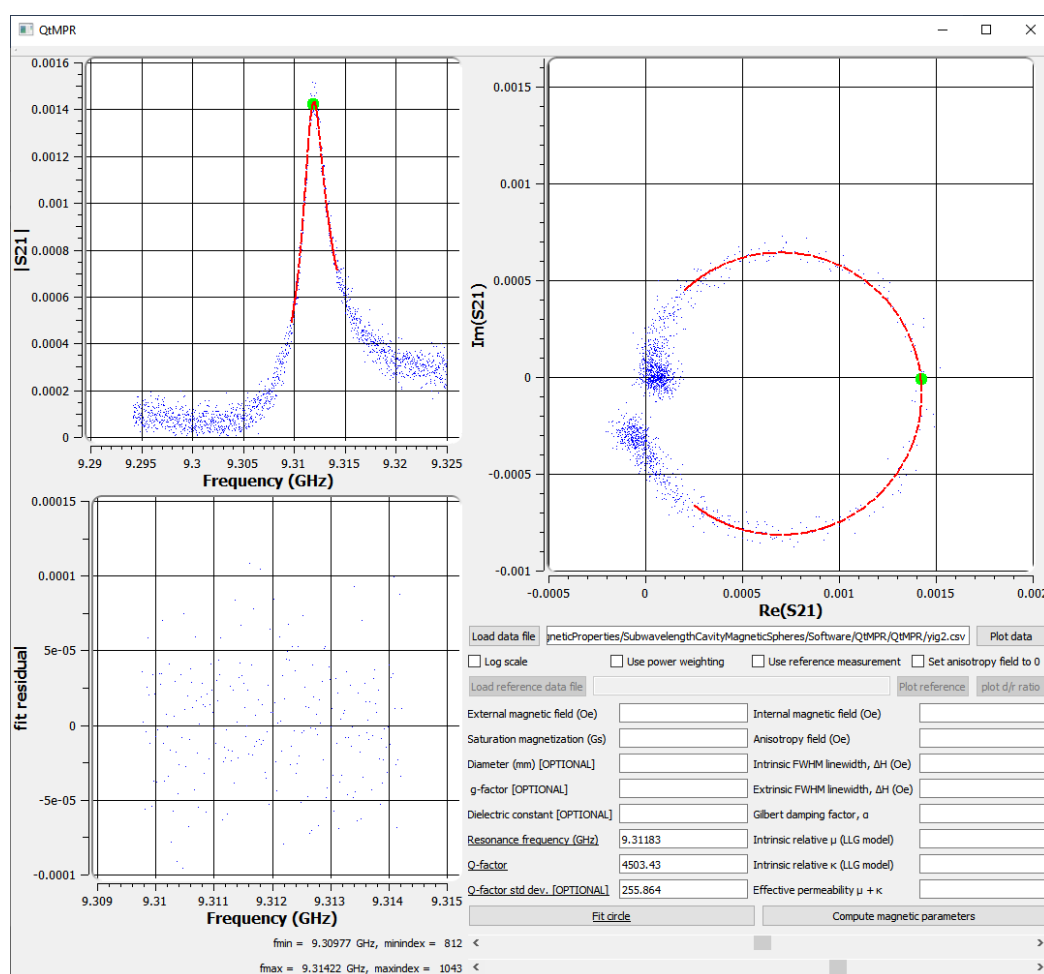


Figure 6. Main window after loading fitting low loss MUT data.

To quickly compute the magnetic parameters based on the fitted frequency and Q-factor, perform two additional steps:

- Provide the external magnetic field value at which the measurement was taken  

External magnetic field (Oe)

Saturation magnetization (Gs)

 and the saturation magnetization of the sample in the left-hand side column. In this example these values are 3300 and 1780, respectively.
- Click the “Compute magnetic parameters” button 

Compute magnetic parameters

.  
 The computed values will be listed in the right-hand side column above the button (see Figure 7).

Internal magnetic field (Oe)	2729.36
Anisotropy field (Oe)	22.6933
Intrinsic FWHM linewidth (Oe)	0.606062
Extrinsic FWHM linewidth (Oe)	0.737814
Gilbert damping factor	0.000111026
Intrinsic relative $\mu$ (LLG model)	-0.352942-1.7928e-05i
Intrinsic relative $\kappa$ (LLG model)	-1.64706+1.7928e-05i
Effective permeability $\mu + \kappa$	-2-1.13859e-11i

Figure 7. Magnetic parameters computed based on the "yig.csv" from the examples folder.

The “Resonance frequency (GHz)” 

Resonance frequency (GHz)

 and “Q-factor” 

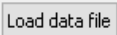
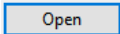
Q-factor


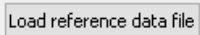
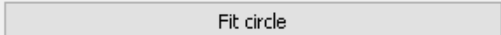
 fields can be filled independently by the user, skipping steps 1-4. All fields must be filled in before the magnetic parameters can be computed, except for those marked as “[OPTIONAL]”.

### UG 2.2.2.2 Example 2 – medium-loss MUT, (\*.txt) measurement data




To quickly extract the resonance frequency and Q-factor, follow the steps:

1. To run the application, open the QtMPR.exe executable file. Refer to UG 1.4. in case of errors.
2. Load the file containing the  $S_{21}$  data measured at a resonance field with the following columns  
frequency (Hz),  $\text{Re}(S_{21})$ ,  $\text{Im}(S_{21})$

by clicking the “Load data file” button , navigating to the *examples* folder, selecting the *medium\_loss\_H1066.3841.txt* file and clicking .

3. To load the reference measurement data (i.e. background  $S_{21}$  data to be subtracted), tick the “Use reference measurement” checkbox  and load the *medium\_loss\_H1066.3841\_reference.txt* file by clicking the “Load reference data file” button  and, subsequently, proceed similarly as in step 2.
4. Click the “Fit circle” button .
5. Adjust the fitting frequency range using scrollbars to obtain a uniform distribution of residuals and a stable (i.e. weakly dependent on small changes of the fitting range) value of the Q-factor and resonance frequency. In this example, one of the suitable positions of the scrollbars are 642 and 1238 (see Figure 9).

To quickly compute the magnetic parameters based on the fitted frequency and Q-factor, perform two additional steps:

6. Provide the external magnetic field value at which the measurement was taken  
External magnetic field (Oe)  and the saturation magnetization of the sample  
Saturation magnetization (Gs)  in the left-hand side column. In this example these values are 1066.3841 and 1120, respectively.
7. Click the “Compute magnetic parameters” button .  
The computed values will be listed in the right-hand side column above the button (see Figure 8).

Internal magnetic field (Oe)	710.996
Anisotropy field (Oe)	17.9452
Intrinsic FWHM linewidth (Oe)	25.266
Extrinsic FWHM linewidth (Oe)	38.5328
Gilbert damping factor	0.017768
Intrinsic relative $\mu$ (LLG model)	-0.187446-0.00670715i
Intrinsic relative $\kappa$ (LLG model)	-1.81147+0.00668378i
Effective permeability $\mu + \kappa$	-1.99891-2.33629e-05i

Figure 8. Magnetic parameters computed based on the “medium\_loss\_H1066.3841.txt” and “medium\_loss\_H1066.3841\_reference.txt” files from the examples folder.

The “Resonance frequency (GHz)”  and “Q-factor”  fields can be filled independently by the user, skipping steps 1-5. All fields must be filled in before the magnetic parameters can be computed, except for those marked as “[OPTIONAL]”.

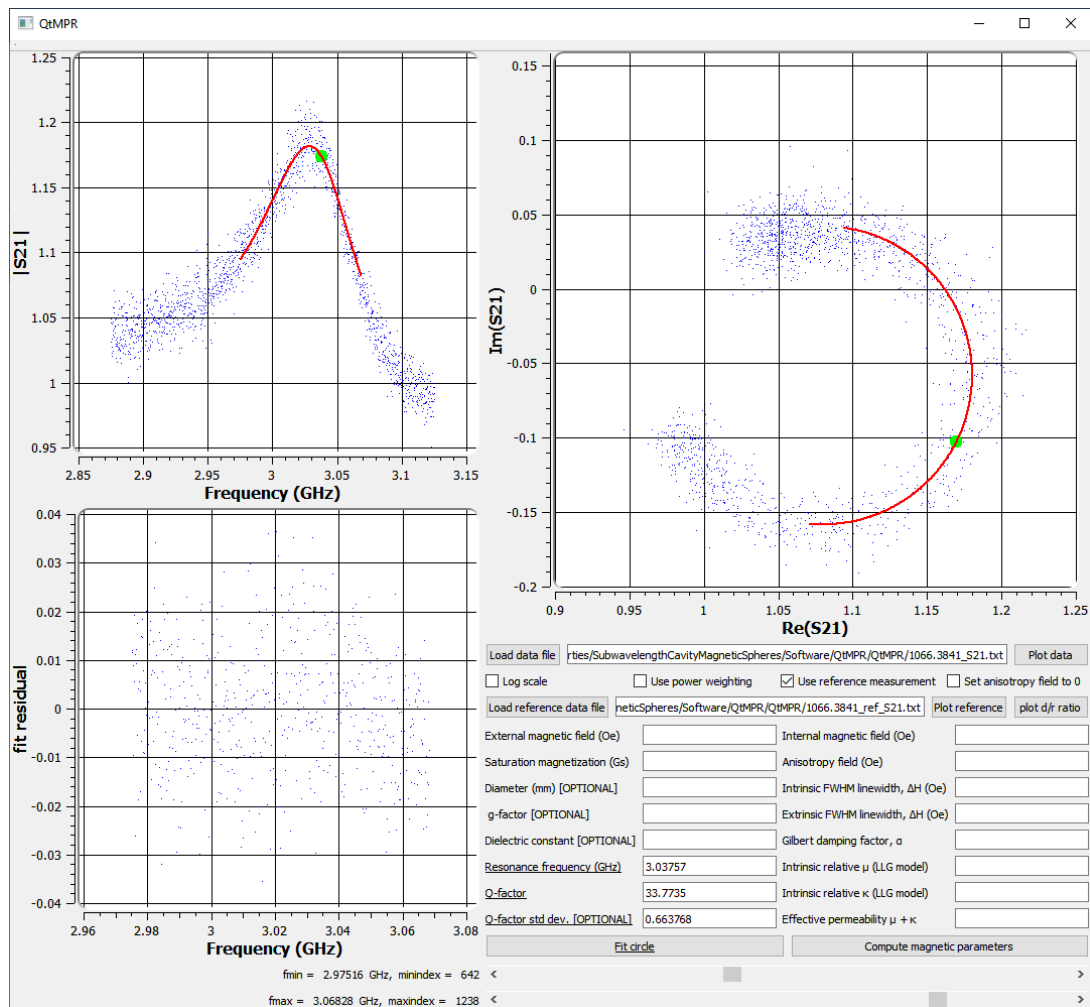


Figure 9. Main window after loading and fitting medium-loss MUT data together with reference data.

### UG 2.2.3. Detailed description

#### UG 2.2.3.1. $|S_{21}|$ vs. frequency plot

It shows the magnitude of the raw data ( $|S_{21}|$ ) and fitted curve. Its scale can be switched between linear and logarithmic via the “Log scale” checkbox (see UG 2.2.3.7). The value of the fitted  $|S_{21}|$  curve at the resonance frequency is plotted with a green dot.

#### UG 2.2.3.2. Fit residual plot

It shows the fit residual vs. frequency. Its scale is linear and cannot be changed.

#### UG 2.2.3.3. $Re(S_{21})$ vs. $Im(S_{21})$ plot

It shows the data and fitted curve on the  $Re(S_{21})$  vs.  $Im(S_{21})$  plane. The point of the fitted curve at the resonance frequency is plotted with a green dot. Its scale is linear and cannot be changed.

#### UG 2.2.3.4. Scrollbars

A pair of scrollbars is provided for fine-tuning of the fitting range. The position of the top (bottom) scrollbar determines the beginning (end) of the fitting range. The current beginning and end of the data range, expressed both in ordinal numbers and GHz, is indicated next to the respective scrollbar. Changing the scrollbar position updates the fitted model and fitted resonance frequency and Q-factor, it does not plot the raw data.

#### UG 2.2.3.5. “Load data file”

Opens a dialog in which the data file to be analyzed can be chosen from the file system. Once the file choice is confirmed, its contents are read into the program memory and the full file path is displayed in the adjacent text field. Additionally, the range scrollbars are set to the full data range. The current data range, expressed both in ordinal numbers of data points and GHz, is indicated to the left of the scrollbars. The application will recognize lines consisting of exactly 3 numbers as data to be read. The 3 numbers are expected to be the resonance frequency expressed in Hz, and the real and imaginary parts of  $S_{21}$ . The numbers may be separated with whitespaces, commas or semicolons. All other lines will be ignored. If lines with more than 3 numbers exist in the file (as e.g. in an \*.s2p file), an error will be issued. A popular data format that meets these requirements is the comma separated file type (\*.csv).

#### UG 2.2.3.6 “Plot data” button

It plots the data loaded into the program memory on two plots: 1)  $|S_{21}|$  vs. frequency plot, and 2)  $Re(S_{21})$  vs.  $Im(S_{21})$  plot (see Figure 10). Any contents of the two plots are cleared beforehand.

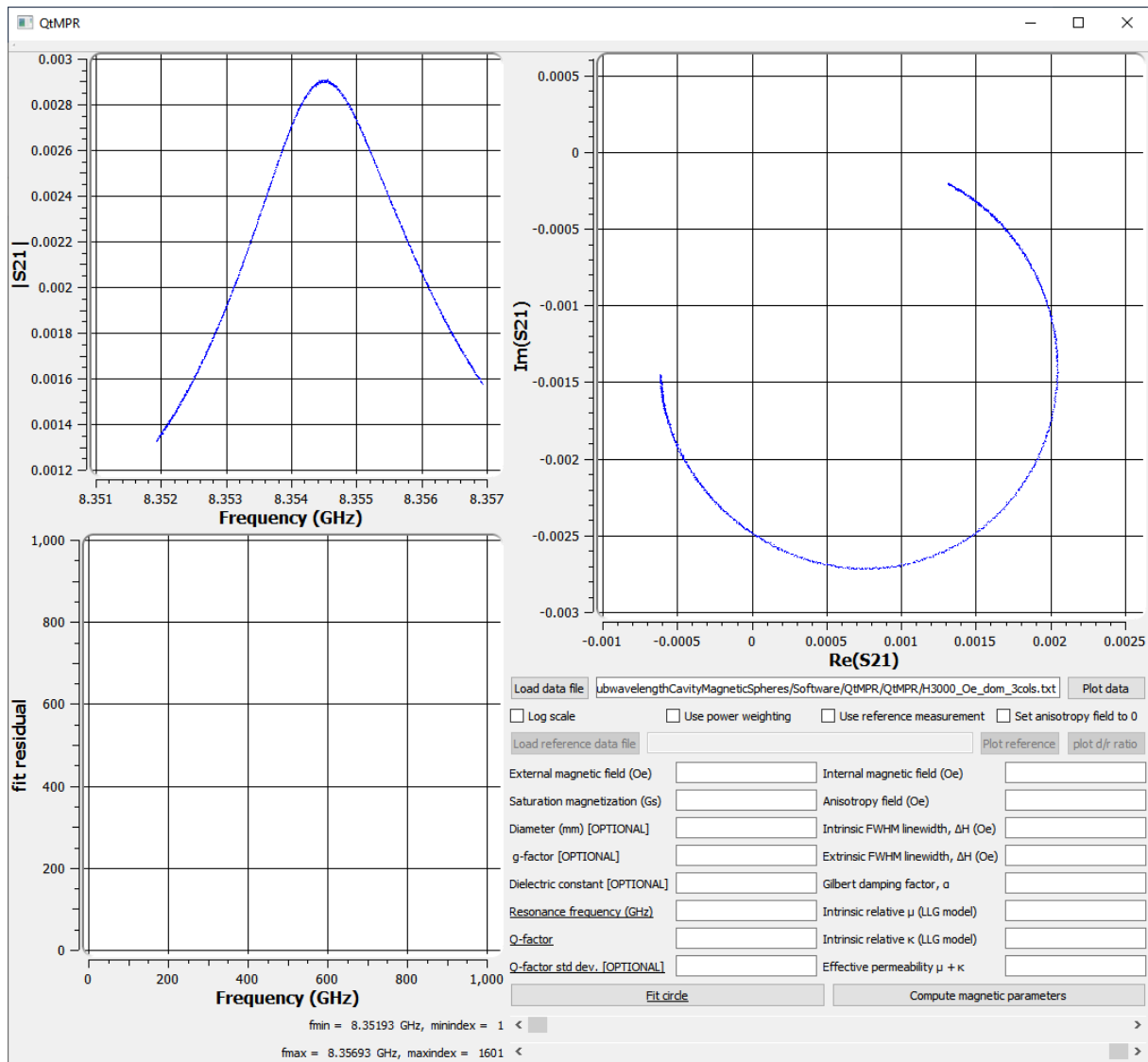


Figure 10. Appearance of the Main Window after loading and plotting typical resonance data of a low-loss MUT.

#### UG 2.2.3.7 “Log scale” checkbox

It enables toggling the  $|S_{21}|$  vs. frequency plot between logarithmic and linear scale.

#### UG 2.2.3.8 “Use power weighting” checkbox

When checked, each data point is assigned a weight equal to  $|S_{21}|^2$  in the curve fitting algorithm. When unchecked, all points have equal weights. Recommended when the resonance data has a typical shape, as in Figure 10. Toggling the checkbox does not re-run the fitting algorithm.

#### UG 2.2.3.9 “Use reference measurement” checkbox

When checked, the application expects reference data to be loaded before a fit can be performed [3].

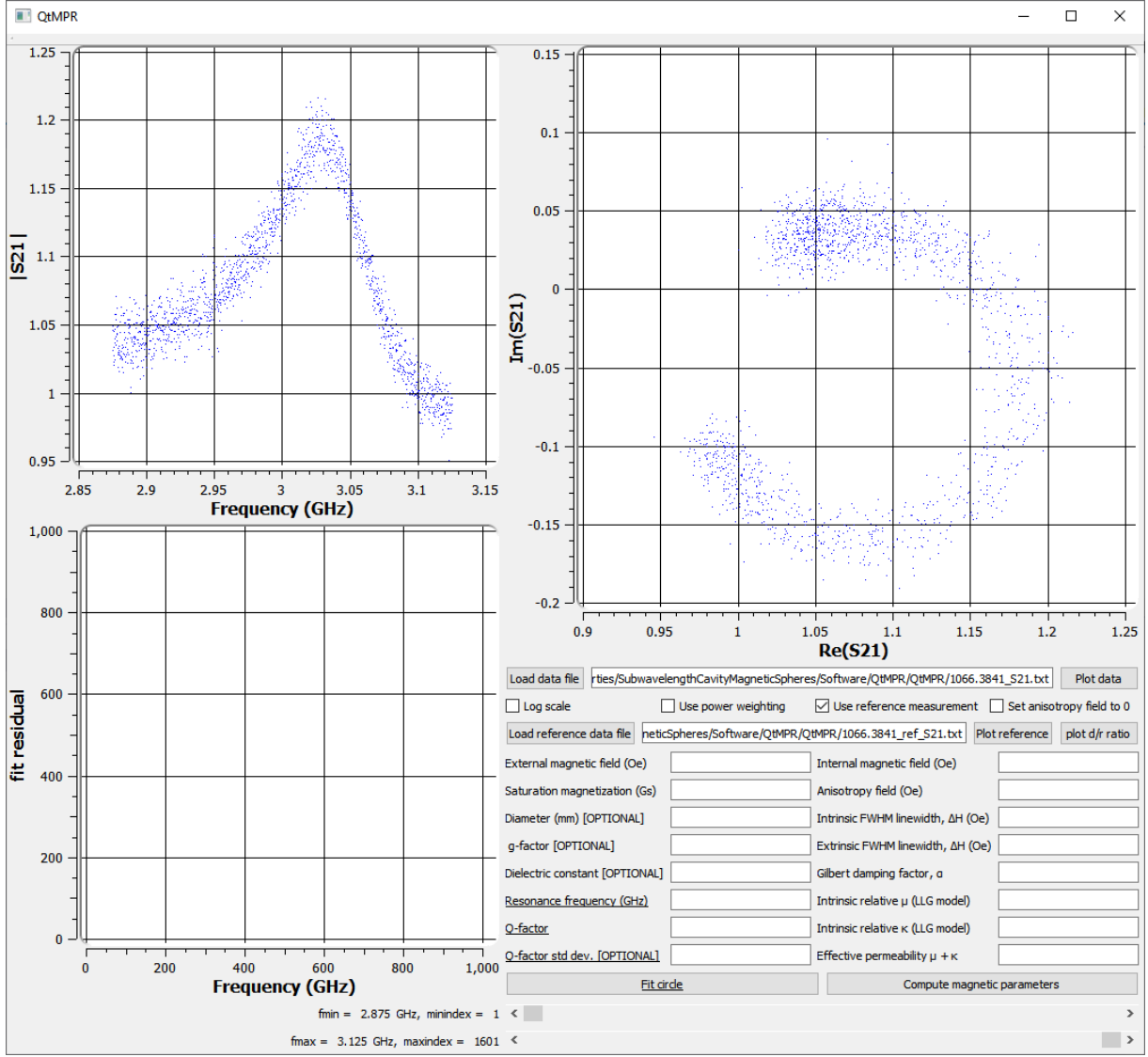


Figure 11. Appearance of the Main Window after loading and plotting the ratio of the data measured in the resonance field and at a reference field for a medium-loss MUT.

#### UG 2.2.3.10 “Set anisotropy field to 0” checkbox

If checked, the anisotropy field is set to zero and the internal magnetic field is computed simply as

$$H_{int} = H_{ext} - \frac{M_s}{3}, \quad (2)$$

where  $H_{int}$  ( $H_{ext}$ ) is the internal (external) magnetic bias field, and  $M_s$  is the saturation magnetization. In this case, the dielectric constant and diameter of the sample are ignored in subsequent calculations. If unchecked,  $H_{int}$  is computed from the equation:

$$f_{MPR} = \gamma \left( H_{int} + \frac{M_s}{3} \right) - \frac{4\pi^2}{90} \gamma M_s (\epsilon_r + 5) \left( \frac{df_{MPR}}{c_0} \right)^2, \quad (3)$$

where  $\gamma$  is the gyromagnetic ratio,  $\epsilon_r$  is the dielectric constant of the MUT,  $d$  is the diameter of the MUT, and  $c_0$  is the speed of light in vacuum [2]. The anisotropy field,  $H_a$ , is then found as

$$H_a = H_{int} + \frac{M_s}{3} - H_{ext}. \quad (4)$$

In this case, the value of  $H_{ext}$  has no effect on any other computed magnetic parameters apart from the anisotropy field  $H_a$ .

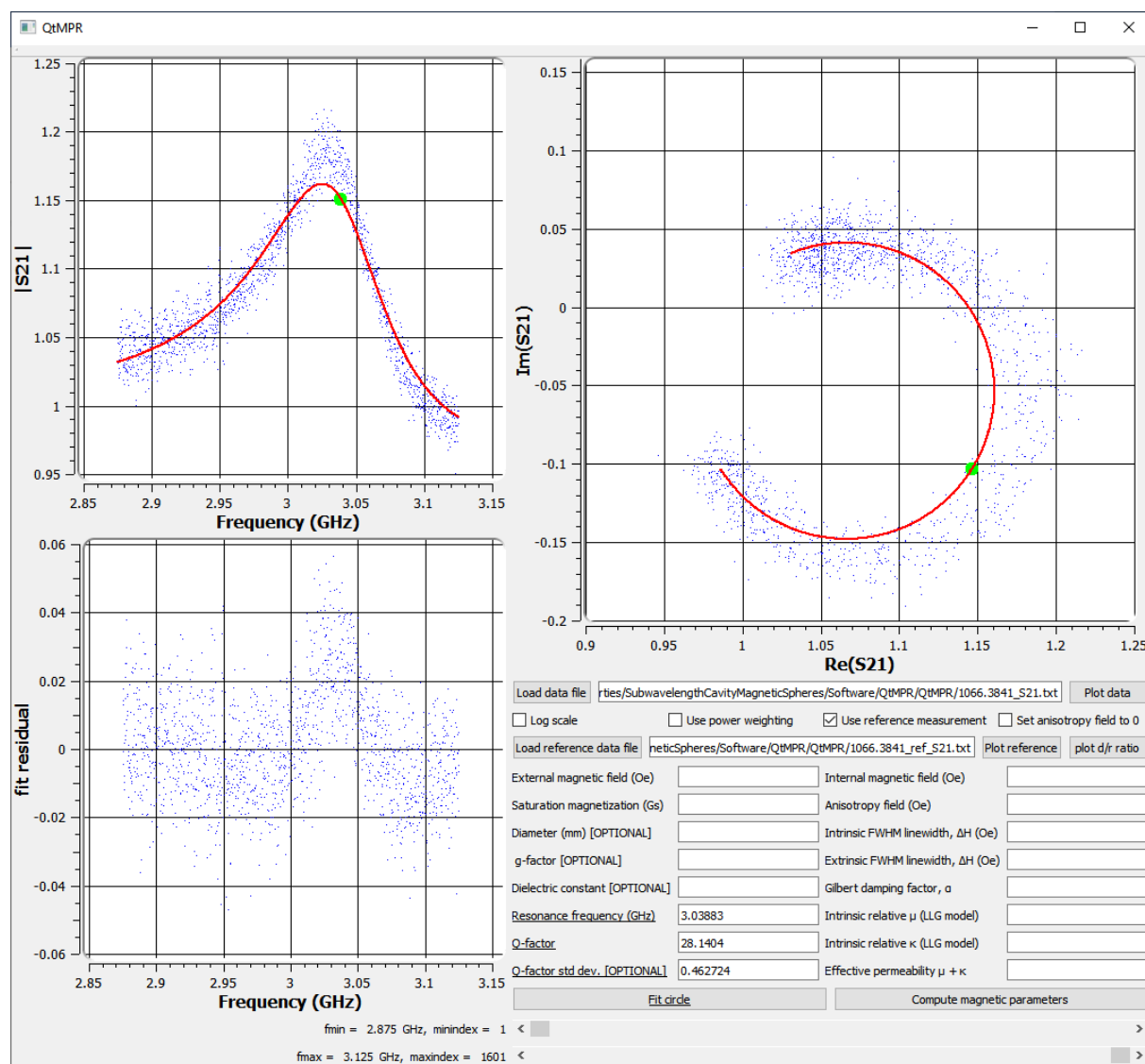


Figure 12. Appearance of the Main Window after loading data, reference data and clicking the "Fit circle" button.

#### UG 2.2.3.11 "Load reference data file" button

It loads reference data in a similar way as the "Load data file" button (see UG 2.2.3.1.). It does not reset the position of the scrollbar.



#### **UG 2.2.3.12 “Plot reference” button**

It plots the reference data file in a similar way as the “Plot data” button.

#### **UG 2.2.3.13 “Plot d/r ratio” button**

It plots the ratio of the data and the reference data. This ratio is expected to be circular-shaped on the  $\text{Re}(S_{21})$  vs.  $\text{Im}(S_{21})$  plane (see Figure 11).

#### **UG 2.2.3.14 “Fit circle” button**

It clears all 3 plots, plots the data points, fits and plots the model. Additionally, it plots the fit residuals and displays the fitted resonance frequency, Q-factor and an estimate of its standard deviation (see Figure 12). The model point at the resonance frequency is marked in green.

#### **UG 2.2.3.15 “Compute magnetic parameters” button**

Inputs:

1. “External magnetic field (Oe)”  
The value of the magnetic bias at which the resonance peak was measured.
2. “Saturation magnetization (Gs)”  
The value of the saturation magnetization of the sample.
3. “Diameter of the sample (mm) [OPTIONAL]”  
If not supplied, the default is 0.5 mm.
4. “g-factor [OPTIONAL]”  
The g-factor of the sample. If not supplied, the default is the electron g-factor (2.00231930436256 [4]).
5. “Dielectric constant [OPTIONAL]”  
The value of the dielectric constant of the sample. If not supplied, the default is 16.
6. “Resonance frequency (GHz)”  
The value of the resonance frequency of the MPR mode. Returned by the curve fitting algorithm. It can be provided by the user independently.
7. “Q-factor”  
The quality factor of the MPR mode. Returned by the curve fitting algorithm. It can be provided by the user independently.
8. “Q-factor std dev.”  
An estimate of the standard deviation of the Q-factor returned by the curve fitting algorithm. It does not take part in the magnetic parameter calculation and therefore is read-only.

**Outputs:**

1. “Internal magnetic field (Oe)”

It is computed in two different ways depending on the “set anisotropy field to 0” checkbox (see UG 2.2.3.10).

2. “Anisotropy field (Oe)”

If the “set anisotropy field to 0” checkbox is unchecked, it is computed via Eqs. (3) and (4) (see UG 2.2.3.10).

3. “Intrinsic FWHM linewidth,  $\Delta H$  (Oe)”

It is the intrinsic full width at half-maximum ferromagnetic linewidth of the sample, which is one of the parameters of the LLG permeability tensor model.

4. “Extrinsic FWHM linewidth,  $\Delta H$  (Oe)”

It is the extrinsic (implicitly dependent on the spherical shape) full width at half-maximum ferromagnetic linewidth of the sample. Typically studied in the literature.

5. “Gilbert damping factor,  $\alpha$ ”

It is one of the parameters of the LLG permeability tensor model [1].

6. “Intrinsic relative  $\mu$  (LLG model)”

It is one of parameters of the LLG permeability tensor model [1].

7. “Intrinsic relative  $\kappa$  (LLG model)”

It is one of parameters of the LLG permeability tensor model [1].

8. “Effective permeability  $\mu + \kappa$ ”

It is the effective relative permeability of the MPR mode. For electrically small samples its real part is close to -2.

## **UG 2.3. Measurements**

### **UG 2.3.1. Sample insertion**

The MUT should be placed in the provided quartz capillary, advisably over a transparent container to minimize the risk of losing the MUT. The recommended procedure is as follows:

1. Place a small piece of Styrofoam (or a different material exhibiting low dielectric losses at microwave frequencies) inside the capillary using e.g. the provided bristle. Make sure the piece does not move easily.

2. Align one end of the capillary with the edge of the cavity lid and position the Styrofoam piece so that one of its edges is roughly aligned with the center of the cavity. Keep in mind that the bottom of the blind hole is only 0.5 mm away from the outer cavity wall.
3. Drop the MUT into the capillary.
4. Use another piece of Styrofoam to sandwich the MUT. For most reproducible results the MUT should be able to rotate freely between the Styrofoam pieces so that its easy anisotropy axis can align with the external magnetic field.
5. For convenience, align one end of the capillary with the lid edge, put the position marker onto the capillary and align it with the outer cavity wall. This will later be helpful to make sure that the capillary has gone all the way inside the cavity.

### **UG 2.3.2. Measurement process**

1. Place the cavity with the sample in an electromagnet in such a way that the magnetic field is perpendicular to the cavity lid. Ensure that the cavity is slightly tilted so that the capillary can rest on the bottom of the blind hole. Do not switch the magnetic field on yet.
2. Connect the VNA to the 3.5 mm male connectors of the cavity. If using adapters, take care not to rotate them when installing. This can weaken the center pin of the cavity connectors.
3. Insert the capillary with the sample into the hole in the cavity all the way in.
4. Screw the couplings all the way in. The PTFE rings will prevent them from going in too deep and possibly damaging the capillary. Check that the  $S_{11}$  and  $S_{22}$  parameters are relatively smooth in the whole frequency range of interest. If any sharp dips are seen, check if all connections are rigid and no excessive twisting force acts on the cables.
5. Bias the sample with a field roughly equal to the saturation magnetization ( $M_s$ ) of the MUT. Search for a resonance peak in the vicinity of the frequency  $f = \gamma M_s$ . If a peak that moves as the magnetic bias is changed can be seen, it means that the sample is of the low-loss type. Calibration of the microwave track is usually not required in this case. Adjust the couplings so that a transmission level through the cavity only is not greater than -45 dB. If forgoing the calibration, possible losses in the cables connecting the VNA to the cavity will require appropriately decreasing the coupling level below -45 dB.
6. If the transmission level changes with the magnetic bias but no resonance peak can be seen, it could still mean that the sample is of the low-loss type but it is too strongly coupled and the broadening of the resonance curve is too large. Try to observe a distinct resonance peak after withdrawing the couplings so that the background transmission is at a level of ca. -40 dB.

7. If the resonance peak still could not be located, either calibrate the microwave track (which should smoothen the  $S_{21}$  background trace) and/or perform two measurements: at the resonance magnetic field and at a reference field. The QtMPR software can read both measurement data files and subtract the  $S_{21}$  background signal. The reference field should be set to a value for which no resonances of the MUT are expected in the measured frequency range and be higher than the resonance field. The difference between the fields should be kept as small as necessary.
8. Once the raw transmission data is saved, it can be analyzed using the provided QtMPR application.

### UG 2.3.3. Exemplary measurement results

In this section exemplary measurement results of two samples are presented. One is a monocrystalline yttrium iron garnet (YIG) sphere of the narrow-linewidth type with diameter  $d = 0.5$  mm and saturation magnetization  $M_s = 1780$  Gs, and the other is polycrystalline YIG of the medium-linewidth type with diameter  $d = 0.56$  mm and  $M_s = 1120$  Gs. Figure 13 and Figure 15 depict the Q-factor vs. resonance frequency dependence, and Figures Figure 14 and Figure 16 the intrinsic ferromagnetic linewidth  $\Delta H$  vs. the internal magnetic bias field  $H_{int}$  dependence. The analysis of  $\Delta H$  as a function of  $H_{int}$  can yield more physically meaningful results than as a function of resonance frequency [2].

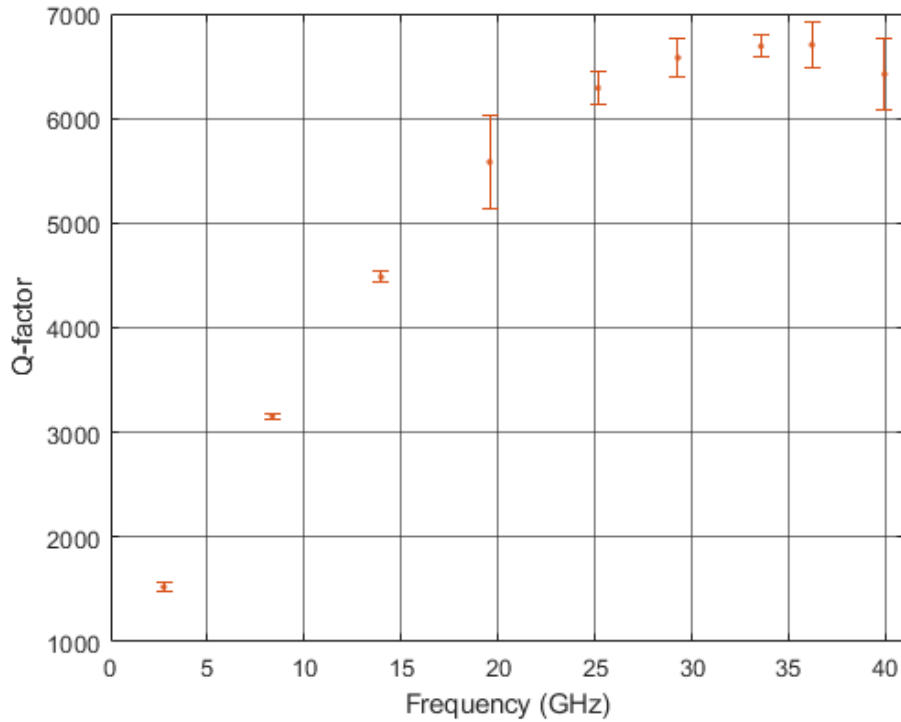


Figure 13. Q-factor vs. resonance frequency of a low-loss monocrystalline YIG sample ( $d = 0.5$  mm,  $M_s = 1780$  Gs). Error bars denote two standard deviation of the measurement.

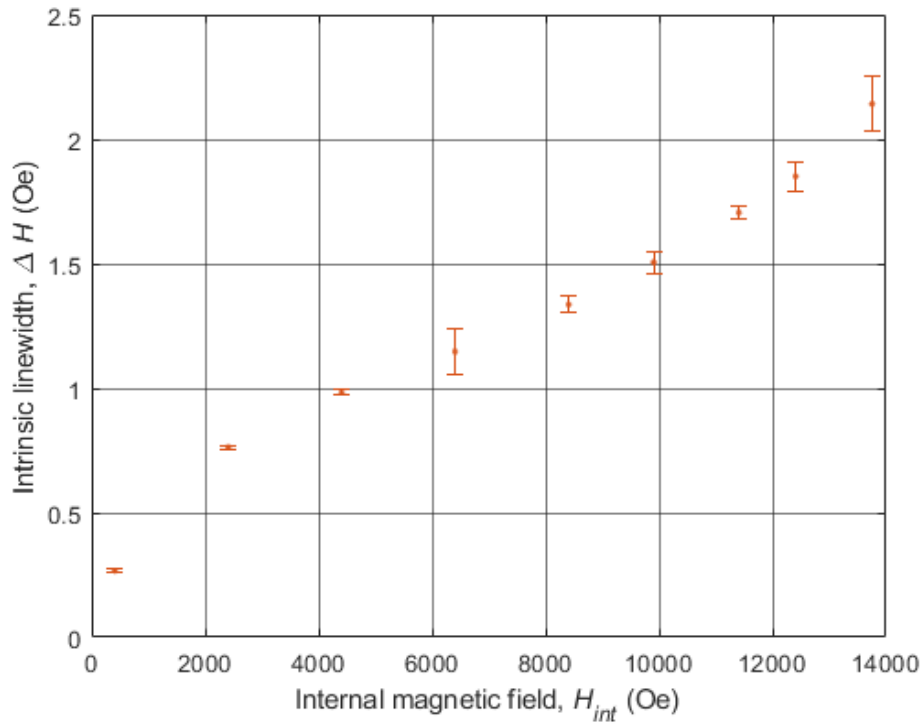


Figure 14. Intrinsic linewidth vs. internal magnetic bias field of a low-loss monocrystalline YIG sample ( $d = 0.5$  mm,  $M_s = 1780$  Gs). Error bars denote two standard deviation of the measurement.

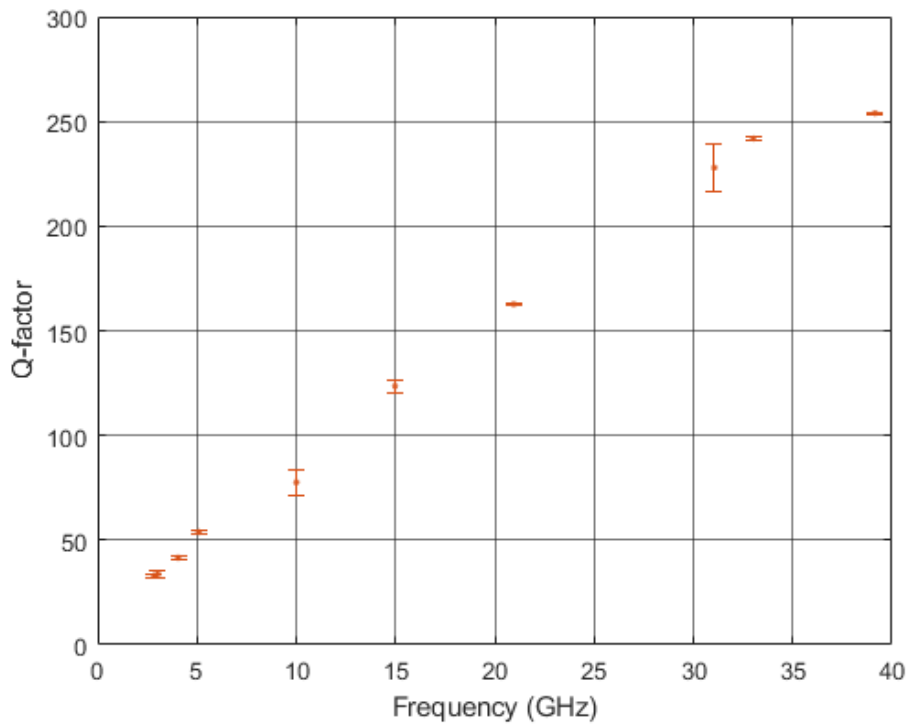


Figure 15. Q-factor vs. resonance frequency of a medium-loss polycrystalline YIG sample ( $d = 0.56$  mm,  $M_s = 1120$  Gs). Error bars denote two standard deviation of the measurement.

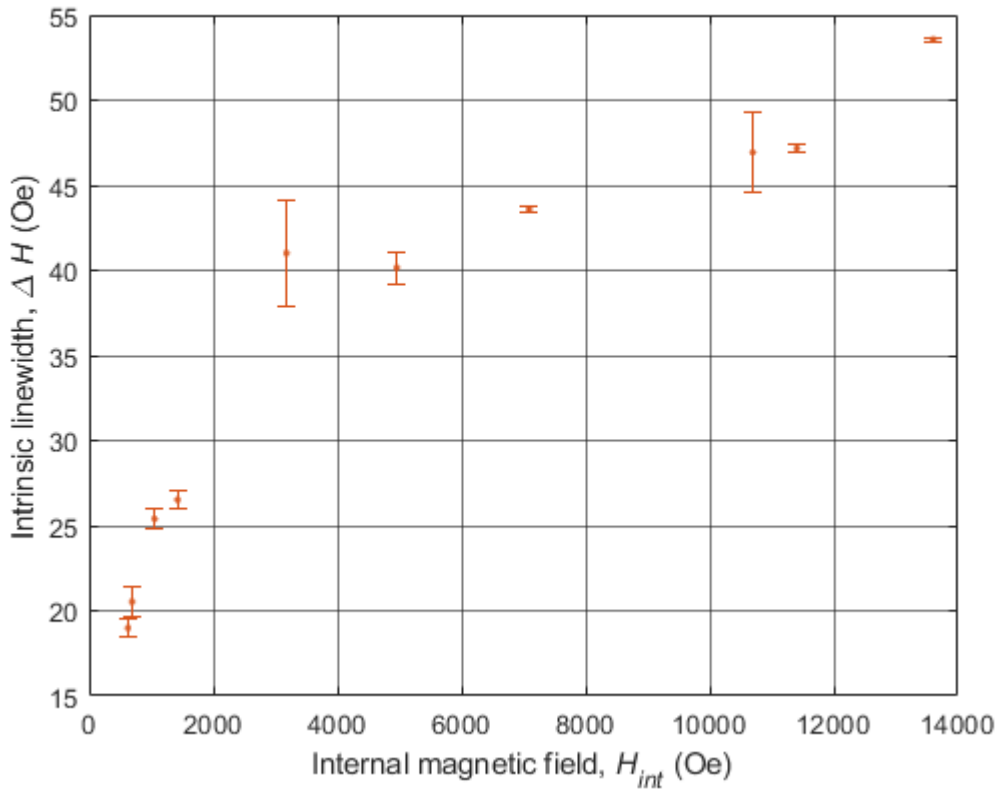


Figure 16. Measured intrinsic linewidth vs. internal magnetic bias field of a medium-loss polycrystalline YIG sample ( $d = 0.56$  mm,  $M_s = 1120$  Gs). The total length of the error bars is two standard deviations.

#### UG 2.3.4. Limitations

Characterization of the MUT requires measuring the Q-factor of the MPR resonance. For high-loss samples with a broad ferromagnetic linewidth, their Q-factors may be too low to be measured reliably. In addition, resonances with a lower Q-factor are more difficult to couple with. Consequently, it is unlikely that the MPR subwavelength cavity can be applicable to samples of broad linewidths (e.g. hundreds of Oe). The upper frequency of 40 GHz is limited by modes of the cavity. Additionally, depending on the diameter of the sample, higher order modes may be excited in the sample at high frequencies, possibly compromising the Q-factor of the MPR mode.

#### UG 2.3.5. Troubleshooting

1. Problem: “The Q-factor significantly depends on the coupling level, especially at higher frequencies. Trace correction is turned off (no calibration).”

Probable solution: The measured (loaded) Q-factor depends on the coupling level. It is practically equal to the unloaded Q-factor if the net coupling level (i.e. level with cable losses de-embedded) is less than -45 dB. Simultaneously, the  $S_{11}$  and  $S_{22}$  traces should be of similar magnitude and smooth around the resonance frequency. Any sharp dips indicate that the coupling is too strong. When the losses introduced by the microwave track are unknown,

it is advised to measure a given resonance for a few different coupling levels to determine the coupling level range for which the Q-factor is stable. It is advised to increase the averaging factor after decreasing the coupling level to make meaningful comparisons.

2. Problem: “Multiple closely-spaced peaks are visible in the spectrum.”

Probable solution: This is common for medium-loss samples at higher frequencies. In many cases, decreasing the coupling level will make higher order modes fall below the noise floor and only the MPR mode will remain visible. While relying on reference measurements in this case should work after a few attempts at choosing the optimal coupling level, it may be much more convenient to turn on trace correction.

3. Problem: “Multiple non-overlapping peaks of similar magnitude are visible in the spectrum.”

Probable solution: Occasionally the MPR mode will not be the most dominant resonance. Try to decrease the coupling level. If unsuccessful, determine which resonance peak is the dominant one by comparing their resonance frequencies. The frequency of the MPR mode should be the closest one to  $\gamma H_{\text{ext}}$ .

4. Problem: “In certain positions of the couplings the spectrum jumps by a few dB at a slight touch of the couplings or cables.”

Probable solution: Most likely the couplings are unbalanced. Check the  $S_{11}$  and  $S_{22}$  levels on the VNA and adjust the couplings so that they are similar. Also check that the screws connecting the couplers to the cavity are not loose.

5. Problem: “The transmission spectrum was measured at the resonance field and at a reference field but the ratio resembles the noise floor.”

Consider the following:

- Whether or not the magnetic field was indeed switched on;
- Whether nor not the reference field was indeed switched on;
- Increase the SNR;
- Screw the couplings in, maintaining balance;
- Check that the sample is roughly in the center of the cavity;

If all the above fails, it may be that the MUT cannot be measured using this method (e.g. its ferromagnetic linewidth is too high).

6. Problem: “The background-subtracted measurement is similar to the one shown in Figure 17.”

Probable solution: Most likely one of the elements of the microwave track is sensitive to changes in the magnetic field. For best results, ensure that the applied reference field is minimally higher than the field at which the MPR is excited (e.g. 1000 Oe).

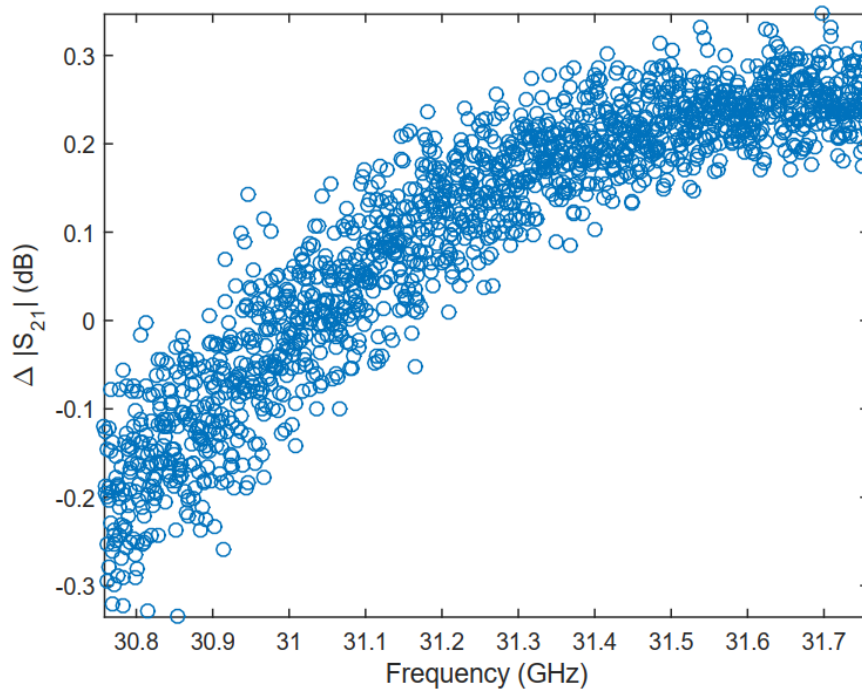


Figure 17. Background-subtracted measurement taken at a reference field which is lower/and or too different from the resonance field.

7. Problem: “The MUT is weakly coupled, but the Q-factor vs. frequency does not follow a smooth curve.”

Probable solution: On rare occasions it is possible to couple with MUT modes other than the MPR which at first glance have a similar Q-factor. Check whether the frequency difference  $f - \gamma H_{ext}$  vs.  $H_{ext}$  follows a relatively smooth curve. Most likely the outliers on the Q-factor vs. frequency plot are also outliers on the  $f - \gamma H_{ext}$  vs.  $H_{ext}$  plot. Also verify if the couplings were well-balanced during the measurement.

8. Problem: “The resonance peak is strongly non-symmetric.”

Probable cause: The combined effect of crosstalk between the ports and phase shift can result in non-symmetric  $|S_{21}|$  vs. frequency plots. However, the  $\text{Re}(S_{21})$  vs.  $\text{Im}(S_{21})$  curve should have a circular shape regardless. The QtMPR software uses a curve fitting algorithm that can accommodate for this effect.

9. Problem: “The  $\text{Re}(S_{21})$  vs.  $\text{Im}(S_{21})$  data has a balloon-like shape. The Q-factor strongly depends on the fitting range.”

Probable solution: Most likely the coupling level was too large and/or the couplings were not adequately balanced.



## UG 2.4. Final remarks

1. The QtMPR.exe executable file depends on several DLL libraries which should be placed in the same folder as the executable. Other locations according to the operating system's rules for loading DLLs should work, although were not tested.
2. The imaginary part of  $\kappa$  returned by the software is typically positive, which would seemingly mean negative losses. This is however in order because both  $\kappa$  and  $-\kappa$  are part of the permeability tensor. Therefore, the sign of the imaginary part of  $\kappa$  has no physical meaning. On the contrary, the effective permeability  $(\mu + \kappa)$  describes the properties of the resonant mode and its imaginary part should always be negative.
3. Feel free to test the fixture at frequencies above 40 GHz. However, avoid measurements in the vicinity of the modes of the empty cavity as mode coupling can occur, possibly compromising the Q-factor of the MPR.
4. The dimension tolerance of the supplied capillaries, as specified by their manufacturer, is 10%.
5. The linewidth  $\Delta H$  is understood as the full width at half-maximum (FWHM) linewidth. It should be noted that some authors use  $\Delta H$  to denote the half width at half maximum (HWHM).
6. At frequencies below  $\frac{2}{3}\gamma M_s$  the input power level needs to be lowered to avoid distortions to the resonance curve arising from Suhl instability [2].

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*Please contact us by e-mail if you are interested in modifications or the further development  
of this solution*  
[info@emarges.eu](mailto:info@emarges.eu)  
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## UG 3. Bibliography

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