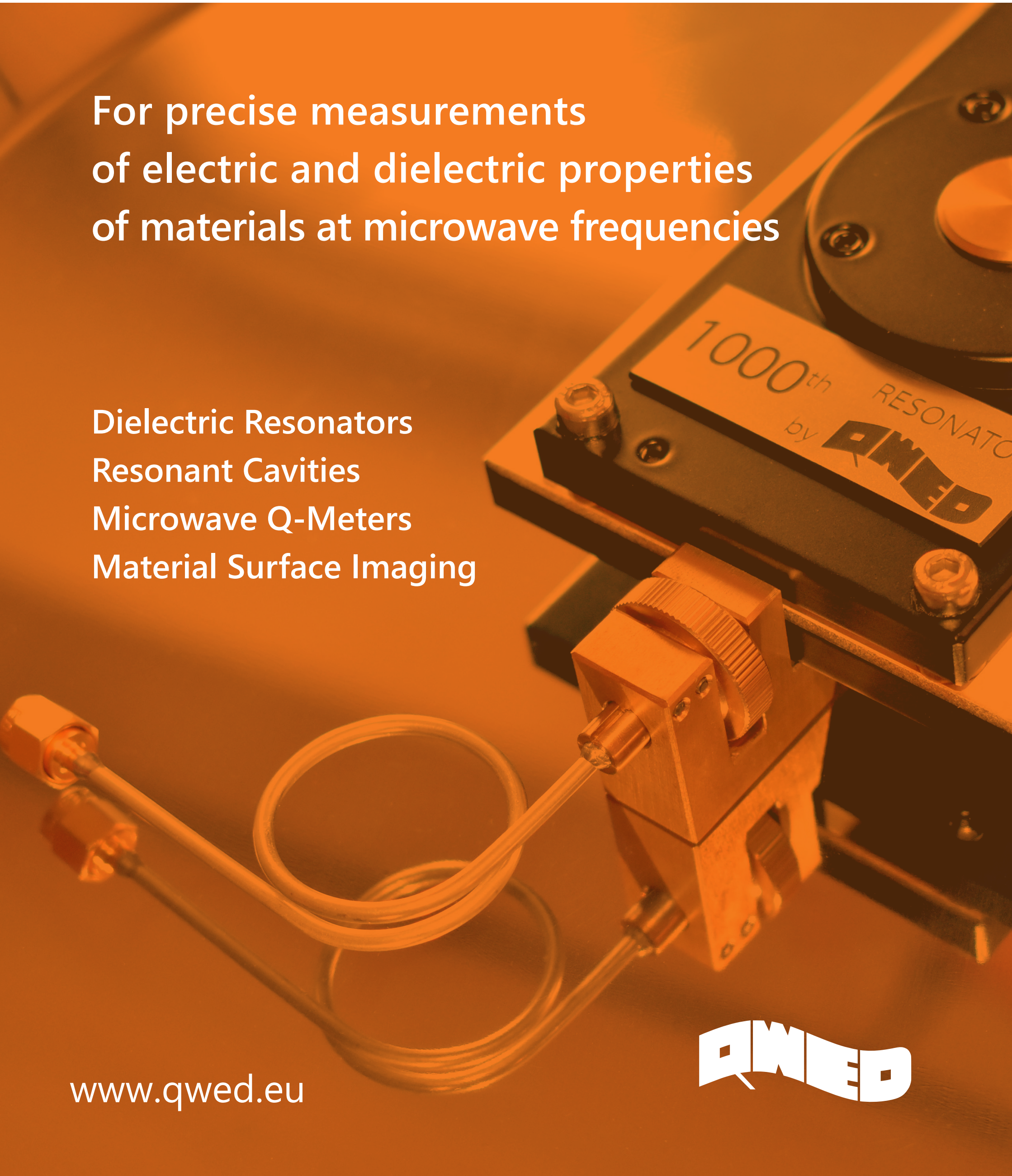
Test Fixtures and Setups



For precise measurements of electric and dielectric properties of materials at microwave frequencies

Dielectric Resonators
Resonant Cavities
Microwave Q-Meters
Material Surface Imaging

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This material concerns measurements of dielectric properties (permittivity) and electric properties (conductivity or loss tangent) at microwave frequencies basically in the range between 1 and 20 GHz with some applications extending beyond that band. The following notation for description of the material properties is used here:

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon_r^{'} - j\varepsilon_{rd}^{''} - j\frac{\sigma}{\omega \varepsilon_0}) = \varepsilon_0 (\varepsilon_r^{'} - j\varepsilon_r^{''}) = \varepsilon_0 \varepsilon_r^{'} (1 - j\ tan\delta) \qquad (3)$$

Where – *tan δ* is the total dielectric loss tangent:

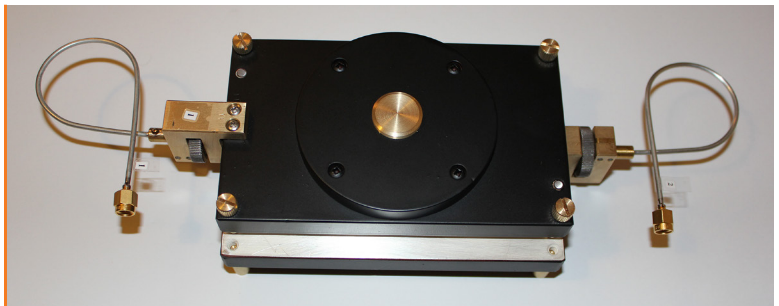
$$tan\delta = tan\delta_d + \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r^{'}} \qquad (4)$$

ε_r – relative complex permittivity
w – angular frequency
s – conductivity [1/(Ωm)]
$\varepsilon_0 = 1/(c^2 m_0) \approx 8.8542 \times 10^{-12}$ [F/m] denotes permittivity of vacuum
$tan\ \delta_d$ – dielectric loss tangent incorporating all other dielectric loss mechanisms except conductivity

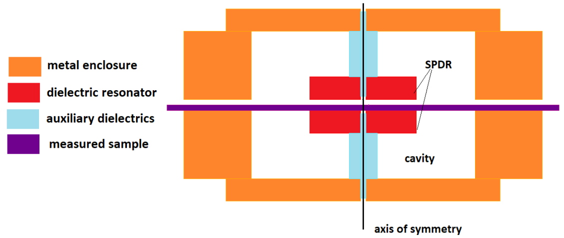
The aim of our measurements will be to extract the values of ε_r' and *tan δ* at some specific frequencies with the highest possible accuracy and repeatability.

Split-post dielectric resonators (SPDR)

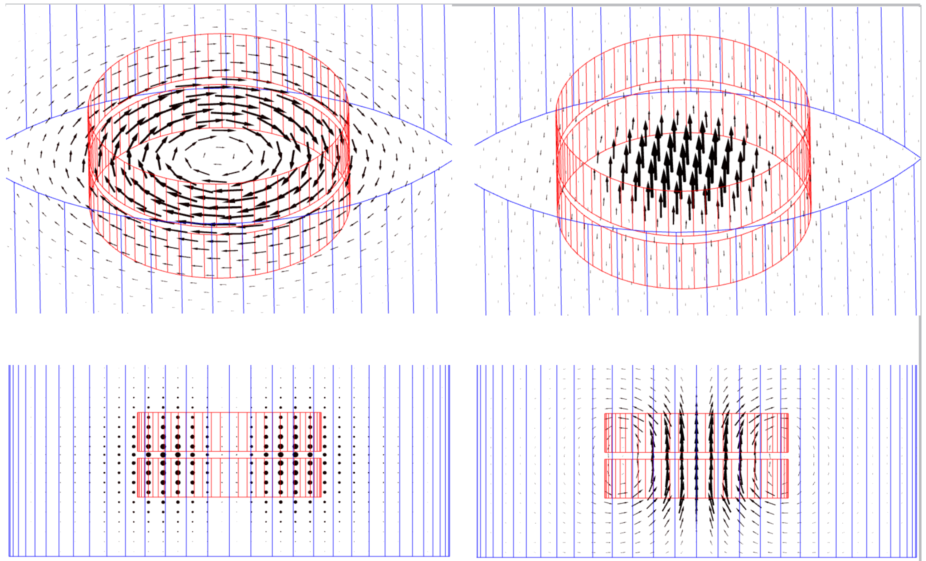
The application of SPDR consists in precise measurement (using an external electronic device like VNA) of the resonant frequency and loaded Q-factor of the resonator alone and the same resonator loaded by the measured sample. The actual material properties are extracted from those measurements using customised software supplied with the resonator. The software is based on electromagnetic simulations but includes also post-manufacturing corrections concerning a particular copy of the SPDR.



A photograph showing a 2.5 GHz SPDR manufactured by QWED. At both ends we can see the SMA type connectors and mechanism for adjusting coupling input/output loops.



Schematic diagram of a split-post dielectric resonator.



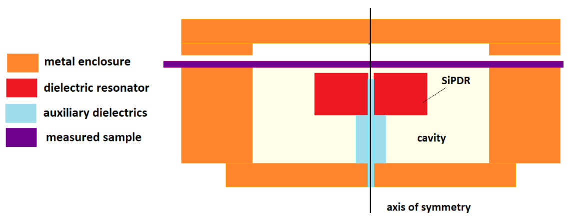
Field distributions in a cylindrical air-filled cavity (marked in blue) with a split-post dielectric resonator (marked in red) operating in $TE_{01\delta}$ mode, as obtained with QuickWave-3D software. Both fields (E-field in the left picture and H-field in the right picture) are marked with black arrows. They are shown in the horizontal section at the half-height of the cavity (up) and in the vertical section across the cavity diameter (down).

The properties of the SPDR method of measurements described above make it a top choice, where both high accuracy and convenient operation are desired. The accuracy of extraction of relative permittivity is typically of the order of 0.3%. The measurements by SPDR are performed at a single frequency. Precisely speaking each resonator has its own resonant frequency with no sample inserted into it. That frequency is close to one of the set of nominal frequencies of the QWED offer. Those frequencies are: 1.1, 1.9, 2.5, 5.1, 10, 15 GHz. It has to be noted that in the case of dielectric materials applied in electronics dependence of their parameters on frequency is typically slow and quite predictable.

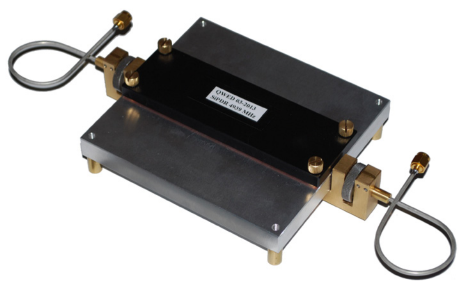
Table 1. Description of the set of standard SPDRs manufactured by QWED.			
Nominal frequency [GHz]	Minimum size of sample [mm] (diameter D or square D x D)	Maximum thickness of sample [mm]	Maximum width of the sample in standard version
1.1	120	6.00	150
1.9	70	4.00	100
2.5	55	3.10	100
5.1	30	1.95	90
10	22	0.95	90
15	14	0.60	40

Single-post dielectric resonators (SiPDR)

Materials with high losses cannot be measured in SPDRs because of difficulties in measurement of the resonance. Moreover, with *tan* δ significantly bigger than unity, the real part of permittivity becomes irrelevant and we are interested entirely in the imaginary part of permittivity ε_r'' referred to also as a "loss factor". Alternatively we may describe the losses by conductivity in *1/(Ωm)*. In semiconductor industry a typical measure is resistivity expressed in *Ω cm*. In the case of surface deposited materials we are mostly interested in the inverse of the product of conductivity and the material thickness. It is called the surface resistivity and is expressed in *Ω*. Most often we refer to the unit as Ohm per square [*Ω/sq*]. In case of lossy materials the setup of choice is usually Single-Post Dielectric Resonator (SiPDR).



Schematic diagram of single-post dielectric resonator.



Photograph of the QWED's 5GHz SiPDR.

The semiconductor industry is often interested in measurements of both low-loss and lossy semiconductor materials. The first case concerns intrinsic semi-insulating semiconductors and the second case, the doped ones with the level of doping determining the conductivity. Table 2 presents a typical range of application of SPDRs and SiPDRs in terms of the sample conductivity or resistivity.

SiPDRs are also frequently used for measurements of susceptors applied in microwave heating applications. Typically, the susceptors have sub-micrometre thickness. Thus, the thickness is well below the penetration depth in a wide frequency range between 1 and 10 GHz. In that range the surface resistivity practically does not change with frequency. QWED offers a standard SiPDR designed for 5 GHz. SiPDRs for other frequency ranges have been manufactured in the past and thus, can be considered upon special request.

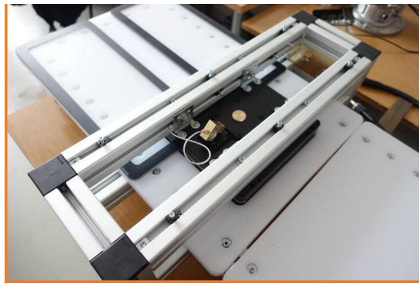
Table 2. Typical ranges of applications of SPDRs and SiPDRs			
	Conductivity [1/(Ωm)]	Resistivity [Ω cm]	Surface resistivity [Ω/sq]
Range od SPDR applications	$2\ 10^{-3}$ to 0.5	from $2\ 10^{2}$ to $5\ 10^{4}$	from $2\ 10^{3}$ to 10^{7}
Range of SiPDR applications	0.1 to 10^{6}	from 10^{-4} (*) to 10^{3}	from 10^{-1} to $2\ 10^{4}$

*) low resistivity range depends on the thickness of the sample and for very low resistivity (exceeding the range specified above) $TE_{01\delta}$ cavity method can be considered.

SiPDRs have been successfully applied in measurements of many other lossy planar materials sheets made of material mixtures such as polymer composites including metals (e.g. silver powders) or carbon (e.g. nanotubes, nanofibres, graphene nanoplatelets) inclusions.

Customised SPDRs for large size material samples

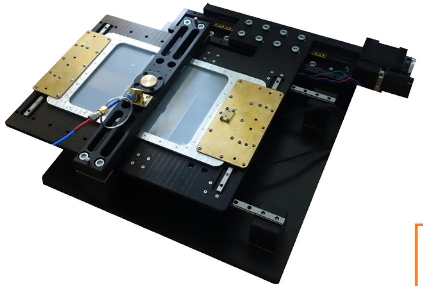
Below we present a customised version of SPDR 1.9 GHz prepared for measurements of big glass panes. The frequency 1.9 GHz was chosen so that it is close enough to the microwave oven frequency of 2.45 GHz while allowing insertion of the panes of glass 4 mm thick into the SPDR slot. The SPDRs like the one presented here are not standard "off-the-shelf" products however QWED is open to manufacturing similar customer-oriented products upon a special request.

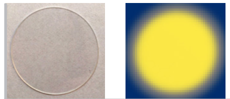


The QWED's SPDR customised for measurements of large panes of glass.

Material Surface Imaging

Quantitative and qualitative testing of materials uniformity and homogeneity across their effective surface became an important aspect due to increased need for miniatirization and packaging of semiconductor or telecommunication devices and components fabricated on a single material wafer, which are expected to exhibit the same performance. Responding to those needs QWED offers two types of devices allowing for 2D imaging of material parameters across its surface: 10 GHz SPDR scanner and 10 GHz iSiPDR (inverted Single-Post Dielectric Resonator) scanner. The 2D scanners cooperate with a user-friedly computer application, controlling, invoking, and running surface imaging procedure in a fully automated operation regime.

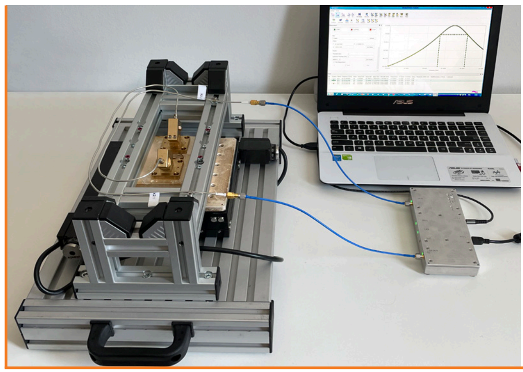




Quartz sample and its 2D surface map of electric permittivity measured with 10GHz SPDR automatic scanner.

10GHz SPDR automatic scanner, developed in EU H2020 MMAMA project.

2D 10 GHz SPDR scanner is applied to surface imaging of laminar dielectrics and high-resistivity semiconductors, delivering 2D maps of complex permittivity (dielectric constant, loss tangent, resistivity). It has been successfully applied in materials testing of dielectric sheets for 5G applications and organic semiconductors for light and power applications.

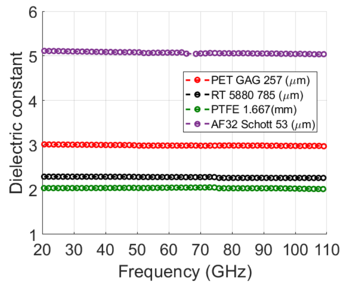


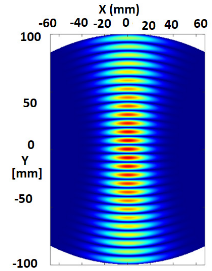
10GHz iSiPDR automatic scanner developed in H2020 NanoBat project.

10 GHz iSiPDR scanner is dedicated to low-resistivity semiconductors and thin films, delivering 2D maps of resistivity and surface resistance, respectively. Next to its application to electronic materials like semiconductor wafers, it is applicable to quantitative and qualitative testing of anode materials for lithium-ion battery cells such as those composed of graphene based composites.

Fabry-Perot Open Resonator

Fabry-Perot Open Resonator (FPOR) is an automated broadband and precise resonant measurement setup applicable to the characterisation of low-loss dielectric materials in the upper microwave and milimetre wave frequency bands. The available solution allows for material characterisation in the 20 - 110 GHz frequency range. The FPOR system is equipped with a specialised software controlling the measurement process and extracting complex permittivity of the material under test from the measured frequency and quality factor.





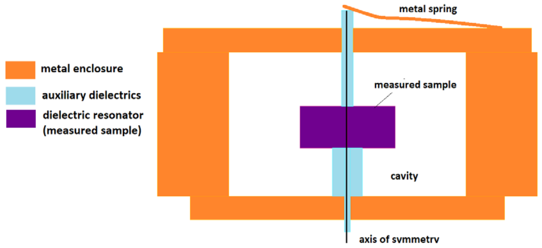
Photograph of the QWED's Fabry-Perot Open Resonator and simulated electric filed distribution of mode $TEM_{0,0,27}$ in such a resonator and dielectric constant measured with FPOR for several dielectric materials.

Cavities for measurements of low loss dielectric materials

SPDRs are destined for measurements of low-loss dielectric materials. However, the range of measurable *tan* δ is limited at lower end at approximately 3 10^{-5}. That limit is mostly due to the losses in the dielectric resonator itself. When the losses of the measured sample are lower we can apply a $TE_{01\delta}$ resonator, but that time build of the measured material itself. Here, it has to be mentioned that while $TE_{01\delta}$ mode is being used for many types of measurement setups, the name of "$TE_{01\delta}$" cavity is traditionally used for the setups in which the measured sample itself resonates in that mode.

QWED offers such specially designed "$TE_{01\delta}$" cavities for the purpose of measurements of very low-loss material. The cavities are supplied with the software for calculation of the material parameters from the measurements of the resonant frequency and the Q-factor of the self-resonating sample enclosed in that cavity. The user needs to prepare a precisely machined cylindrical sample of the material and place it in the cavity using the dielectric supports provided with the cavity. The advantage of such an approach is that we are able to determine the level of *tan* δ down to approximately 5 10^{-7}. That is possible since the losses in the cavity metal walls and dielectric supports may correspond to the unloaded Q-factor above 300 000.

The $TE_{01\delta}$ cavity have been used in the past also for measurements of the changes of media parameters versus temperature.



Schematic diagram of the $TE_{01\delta}$ cavity used for measurements of extremely low loss materials.

A disassembled QWED's $TE_{01\delta}$ cavity.

Measurements of surface conductivity of metals

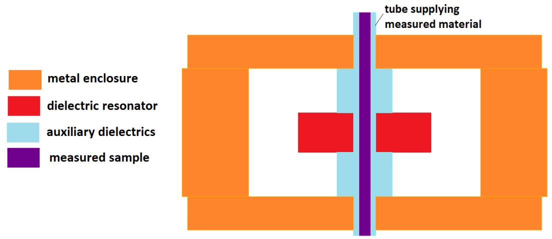
Conductivity of metals can be relatively easily measured at DC or low frequencies. Using directly the low-frequency results at microwave frequencies typically does not lead to good approximation of the physical reality. At microwave frequencies the penetration depth is small and for typical metals used in electronics is measured in micrometres. Thus, practically we are interested in surface resistivity of the metal.

QWED has also experience in practical realisation of setups for measurements of the surface resistivity of metals used in electronics. The setup applied for that purpose must include a dielectric resonator made of a very low-los material (typically sapphire). The hardware & software are not one of the standard solutions offered by QWED, but can be considered upon a special request of an interested customer.

Measurements of conductivity of powders or liquids

The specific properties of the $TE_{01\delta}$ mode can be also used for measurements of the properties of lossy liquids and powders. The scheme of the possible setup and its practical realisation is shown below. The setup arranges a flow of liquid or powder through the centre of the dielectric resonator in a dielectric tube extending outside the cavity (typically made of quartz or Teflon).

The inner diameter of the tube needs to be precisely calibrated and stable, which is challenging especially with a Teflon tube. The hardware & software are not one of the standard solutions offered by QWED, but can be considered upon a special request of an interested customer.

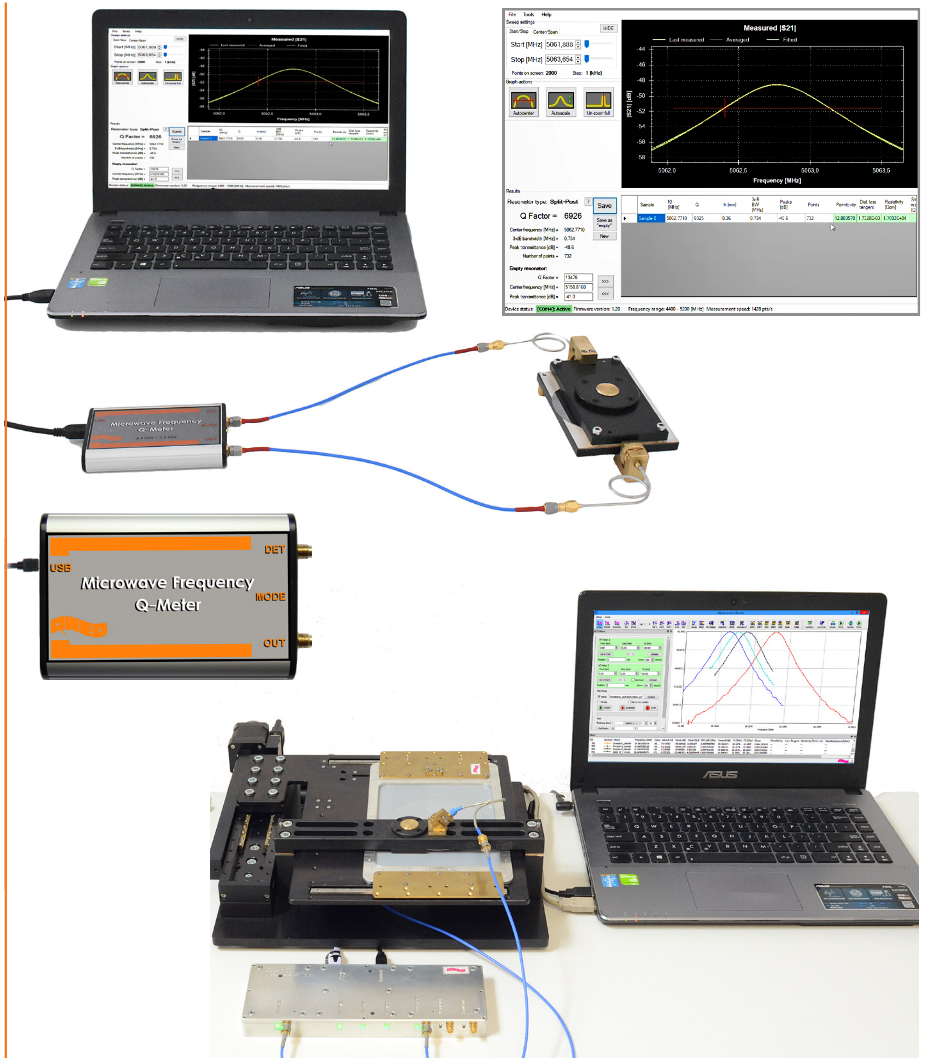


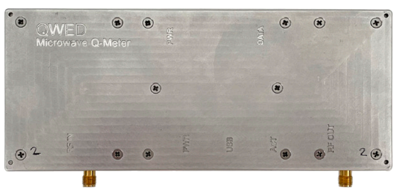
A schematic diagram of the $TE_{01\delta}$ mode dielectric resonators used for the measurements of the complex permittivity of liquids or powders.

Photograph of the QWED's $TE_{01\delta}$ mode dielectric resonator used for the measurements of the complex permittivity of liquids or powders at 2.5 GHz.

Microwave Frequency Q-Meters

The application of all QWED test fixtures is based on measurements of the resonant frequencies and Q-factors. For that purpose, VNA's are often used by QWED customers. Most popular are those manufactured by Keysight Technologies, but also by other manufacturers active on the global market. However, VNA's have also some disadvantages including very high price and also quite complicated operation, requiring a well trained personnel. Therefore, a VNA may not always be the best choice. This concerns for example material companies needing a fast quality control outside a well-equipped microwave laboratory. For that purpose QWED has come up with a product replacing the VNA while being much less expensive and much easier to operate. That product is called a Q-Meter and it is connected to a standard PC computer used for automatic processing and display of the results of measurements. QWED manufactures Q-Meters for the following frequency ranges: 0.7 - 1.3 GHz, 1.4 - 2.6 GHz, 4.4 - 5.2 GHz, 8.4 - 10.4 GHz, and 20 - 40 GHz.





QWED Q-Meters and their working assembly including SPDR and 10GHz SPDR scanner and PC.

QWED consultancy and custom designs

Beside the typical products mentioned so far QWED offers also consultancy in the areas of design of microwave systems and in particular the systems destined for measurements of material properties at microwave frequencies. The solutions initially developed and tested in research projects which can be offered as a subject of customised design or a seed of new projects launched in cooperation with other parties include:

- Reentrant cavity resonators for material parameters measurements in the range of 0.2-1 GHz.
- Measurements of electric properties of foods and other materials at the microwave heating frequencies of (typically at 0.915 GHz and 2.45 GHz).
- Setups for defectoscopy of composite materials including carbon reinforced composites.
- Measurements of properties of ferromagnetic materials.
- Investigation of the properties of periodic structures and metamaterials.

References

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[7] QWED home page: www.qwed.eu

[8] EU H2020 MMAMA project home page: www.mmama.eu

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