Fabry-Perot open resonator

EM material characterization

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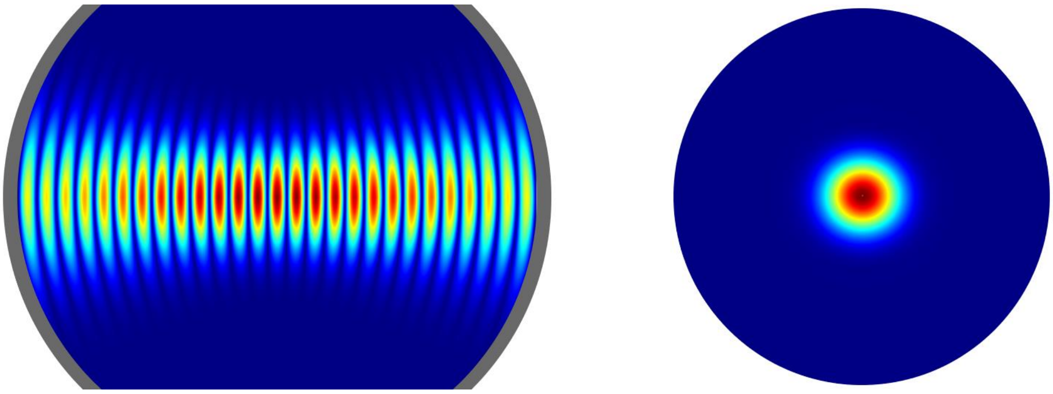
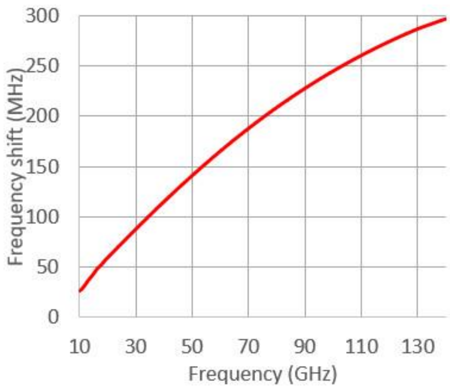
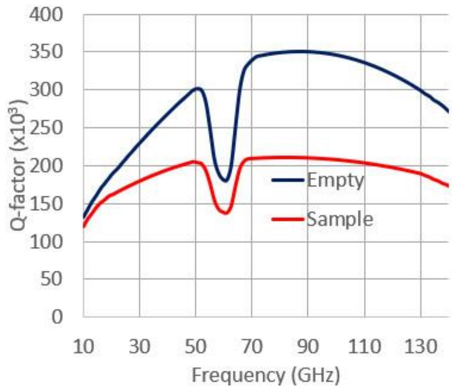
Fundamentals

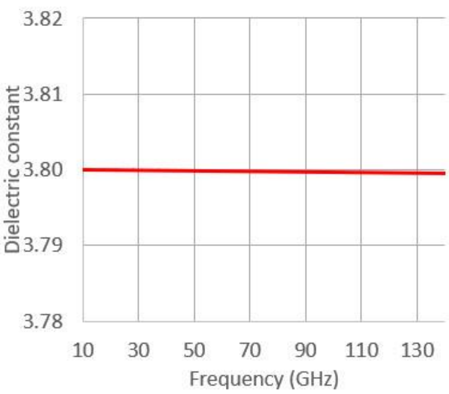


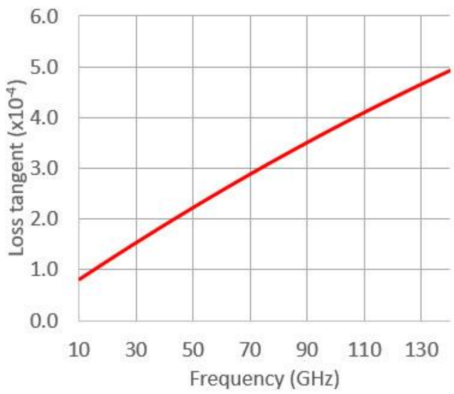
Odd $TEM_{0,0,q}$ **Gaussian modes**, where q is a longitudinal mode order, are exploited in the extraction of the complex permittivity of a dielectric sheet inserted exactly in the middle of the cavity.





By comparing measurement results with the EM model of the FPOR, resonance frequency shift is translated into the **dielectric constant** (Dk) and Q-factor's decrease into the **loss tangent** (also known as dissipation factor, Df) of a material under test.





Hardware

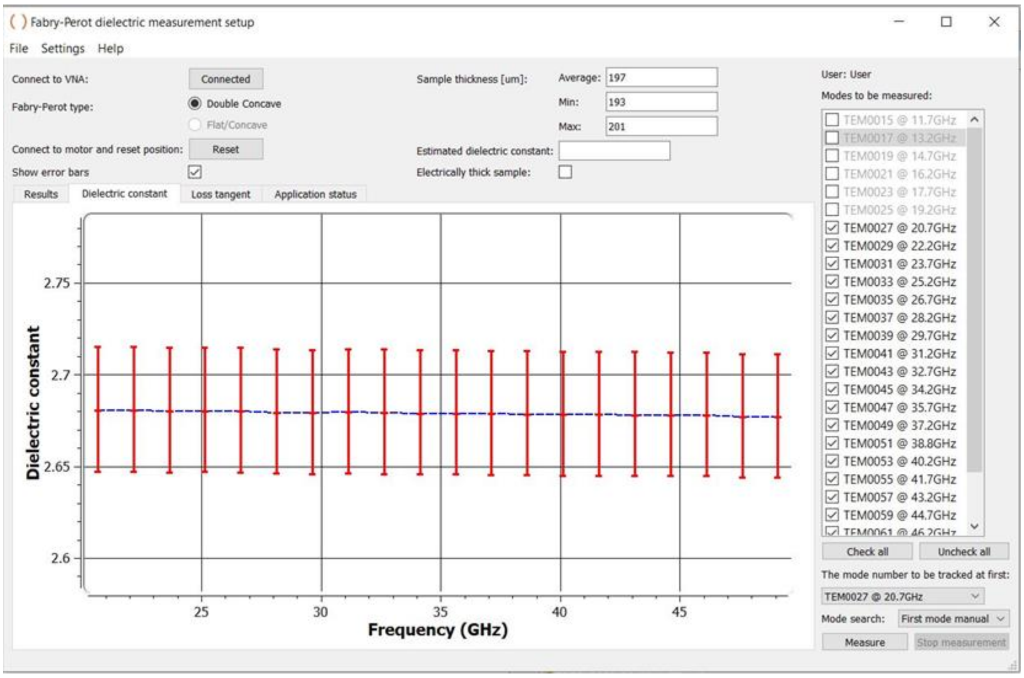
Main features:

- Two **spherical mirrors**
- Three mirror **mounting legs**
- Sample diameter: **50 – 150 mm** (depending on the frequency range)
- Distance between the mirrors: 200 mm
- Aperture diameter: 200 mm
- Fully rotatable sample holder (needed for **in-plane anisotropic samples**)
- Automated sample positioning and alignment
  (**larger thickness limits** due to mode coupling suppression)
- Automated iris (**smooth loss tangent** due to spurious mode suppression)
- Automated coupling level adjustment (broadband **SNR control**)
- Thermal compensation (Dk/Df **thermal drifts suppressed**)
- Two polycarbonate doors (**suppressed loss tangent fluctuations** due to air flow)

Software

Main features:

- **VNA communication** via USB, LAN, or USB-GPIB interface
- Automatic **mode identification** and 3D sample positioning
- Assessment of **dielectric constant uncertainty** due to thickness uncertainty
- Assessment of **loss tangent uncertainty** due to Q-factor uncertainty
- **Climatic compensation** suppressing drifts due to temperature and humidity
- Full data storage
- Results recalculation for the modified thickness
- Manual mode tracking (full control over the measurement)
- Mode tracking only at the first mode (substantial measurement **speed-up**)
- **Adaptive averaging** (for the loss tangent uncertainty reduction)
- Automatic and manual **interruption mode** (for challenging samples)
- Frequency-dependent VNA settings (**optimized measurement efficiency**)



Measurement time:

- **>1 minute** for 10-50 GHz bandwidth
- **>3 minutes** for 10-130 GHz bandwidth

Dielectric constant

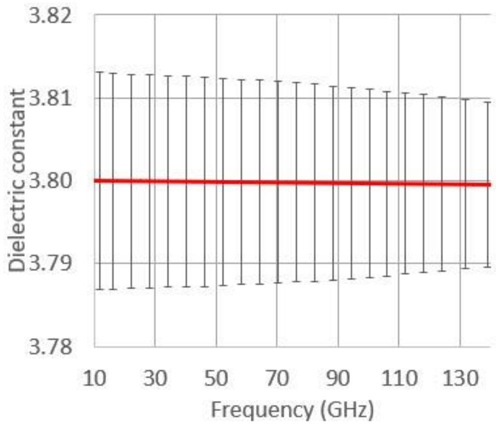
Accuracy and Uncertainty

Accuracy of the dielectric constant results mainly from the EM model of the FPOR, which is exploited to generate a look-up table of the resonance frequency as a function of the thickness and dielectric constant. It is estimated to be **less than ±0.2%** provided that other limits described later do not apply.

The main reason for the **uncertainty** of the dielectric constant is thickness variation, δt. For electrically thin samples, it can be estimated as follows:

$$\delta Dk \cong -A\sqrt{Dk}\,\delta t \qquad\qquad A \cong 0.25 \ldots 1$$

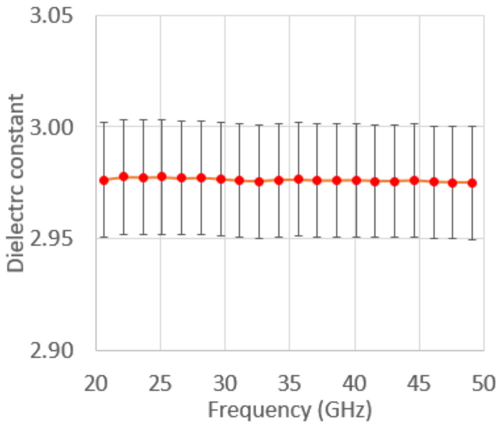
which indicates that it is crucial to keep a high quality of the sample.



Fused silica

Thickness: 214 ± 1 μm (± 0.5%)

Average Dk: 3.8 ± 0.013 (± 0.3%)



PET GAG foil

Thickness: 157 ± 2 μm (1.3%)

Average Dk: 2.976 ± 0.025 (0.84%)

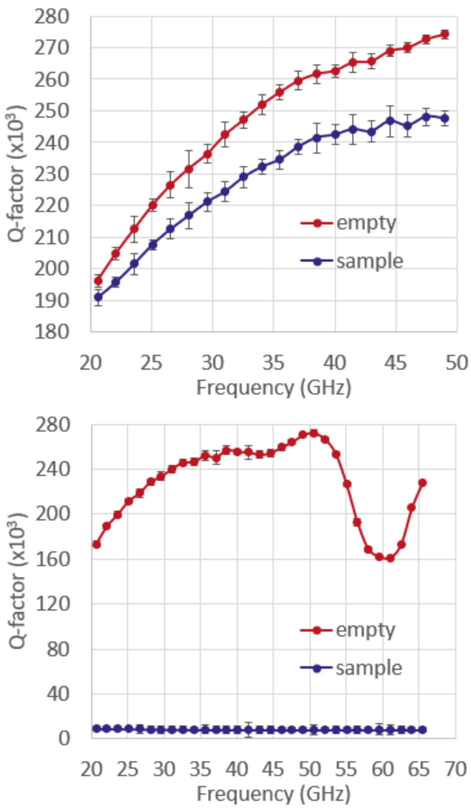
Uncertainty bars on the dielectric constant plots are computed rigorously for min/max thicknesses (or ±3σ) provided in the software.

Loss tangent

Accuracy and Uncertainty

Loss tangent inaccuracy mainly results from of the accuracy of the electric energy filling factor estimation with the aid of the frequency incremental rule and it is **less than 0.1%**.

Loss tangent **uncertainty** (LTU), δDf, is usually much larger than the aforementioned inaccuracy and it results from the uncertainty of the Q-factor, which is estimated in the software with a circle-fitting algorithm.



For **low-loss** samples:

$$\delta Df \cong 2\frac{\sigma_0+\sigma_t}{Q_0-Q_t} \quad for \quad Q_t \cong Q_0$$

where Q_t (Q_0) is the Q-factor with (without) the sample and σ_0 (σ_t) is the corresponding uncertainty.
Since resonance curves with and without the sample are similar in shape for low-loss samples, both Q-factor uncertainties are **equally important** as compared to the Q-factor change, $Q_0 - Q_t$.

For **high-loss** samples:

$$\delta Df \cong 2\frac{\sigma_t}{Q_t} \quad for \quad Q_t \ll Q_0$$

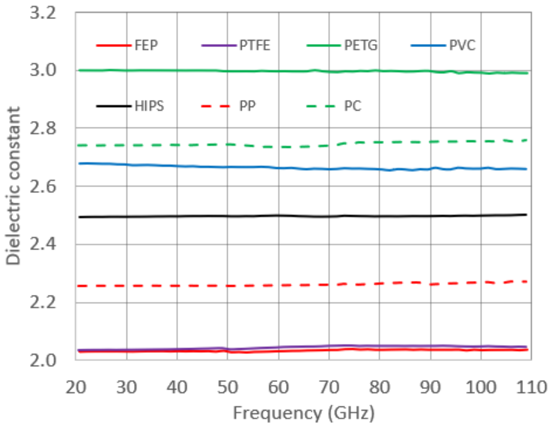
In such case, the quality of the resonance curve with the sample plays a **dominant role**, whereas the one corresponding to the empty resonator is of minor importance.

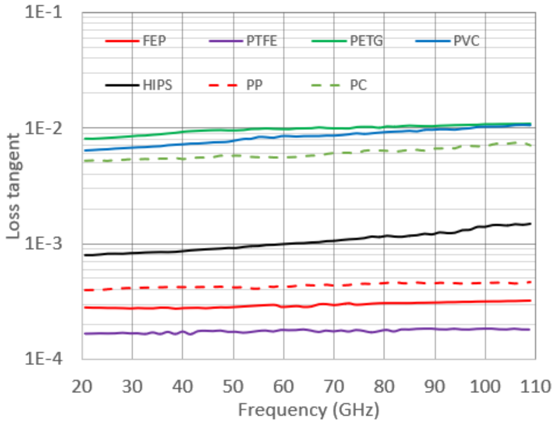
Q-factor uncertainty can be controlled by adjusting **VNA settings**, such as IF bandwidth, averaging factor, and power level, as well as reduction of mechanical **vibrations**, **air flow**, and maintaining temperature/humidity stable. Moreover, the **coupling level** can be increased (decreased) via the coaxial couplers when the sample is thick or lossy (thin or low-loss).

For given VNA settings, the lowest LTU at the level of **2%** can be typically achieved when $\mathbf{Q_t \cong 0.4 \ldots 0.5\ Q_0}$

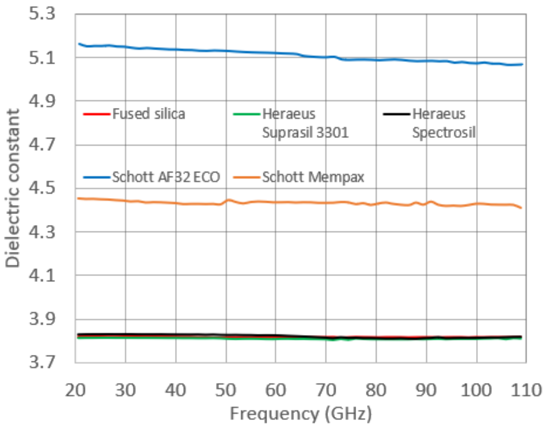
In-Plane Isotropic Materials

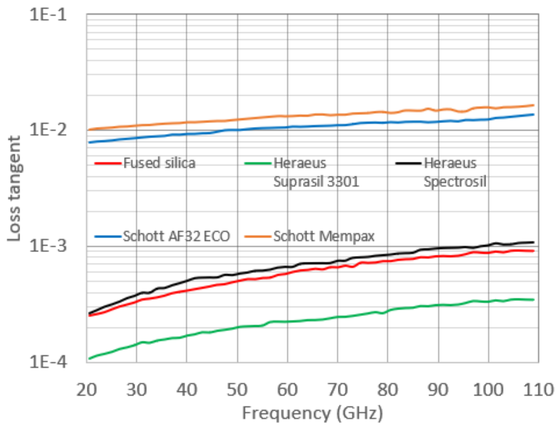
FPOR is well-applicable to the measurement of in-plane isotropic materials, such as **polymers** ...



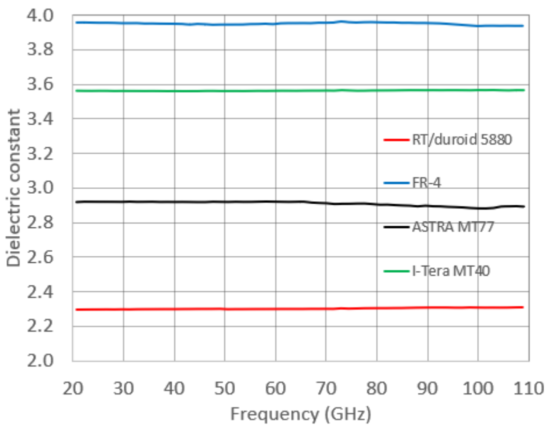


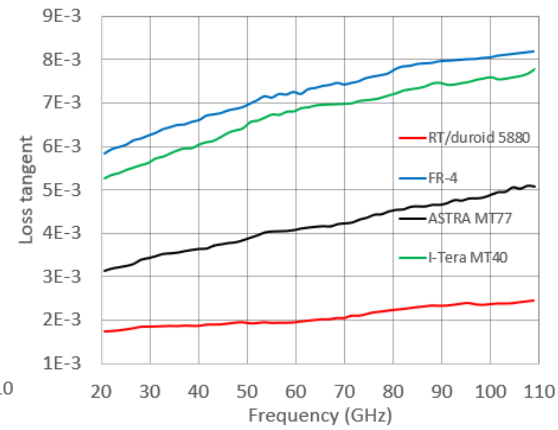
... various kind of **glasses** ...





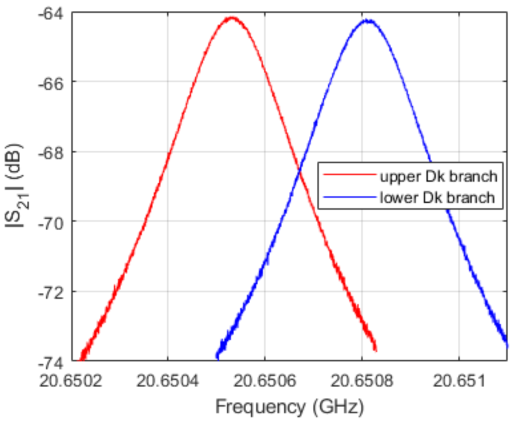
... and **laminates**.



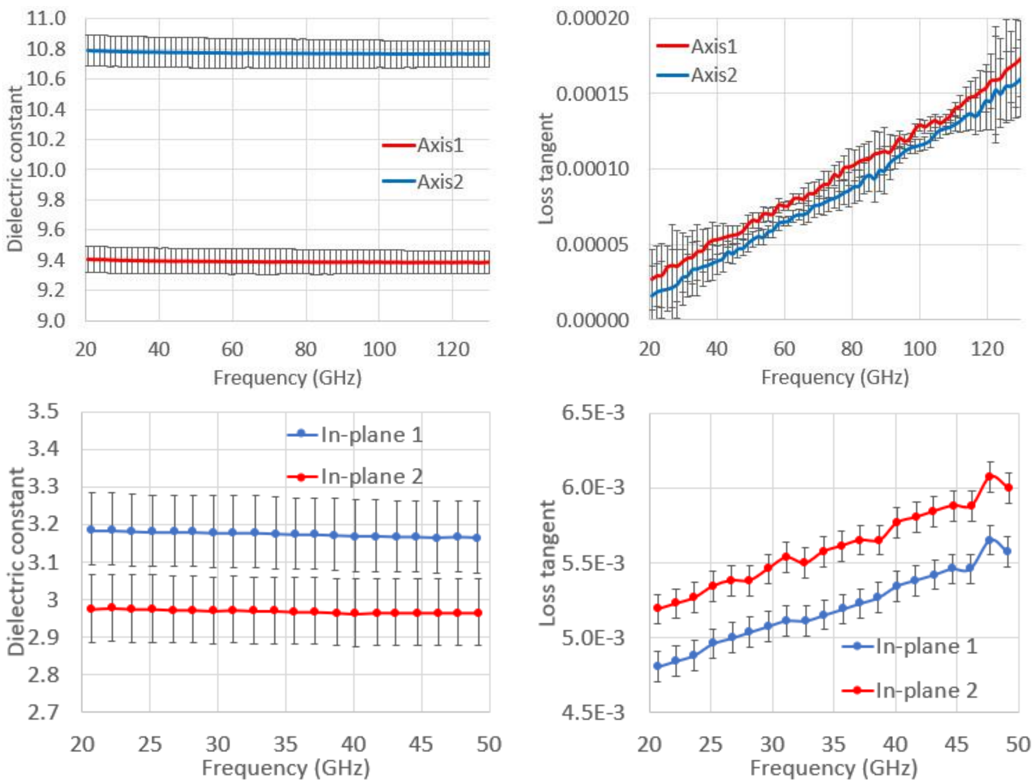


In-Plane Anisotropic Materials

Since Gaussian modes are **linearly polarized** in the FPOR, in-plane anisotropy of the sample can be measured. For that purpose, one needs to rotate the sample in the FPOR until only one mode (corresponding to aligning the electric field polarization with one of the two orthogonal anisotropy axes) is visible on a vector network analyzer (VNA). Consequently, measurement has to be performed **twice**.



It is essential to note that besides crystals, polymers, such as PET foil or high-impact polystyrene, can also exhibit in-plane anisotropy.



X-cut sapphire

Thickness:

115 ± 1 μm

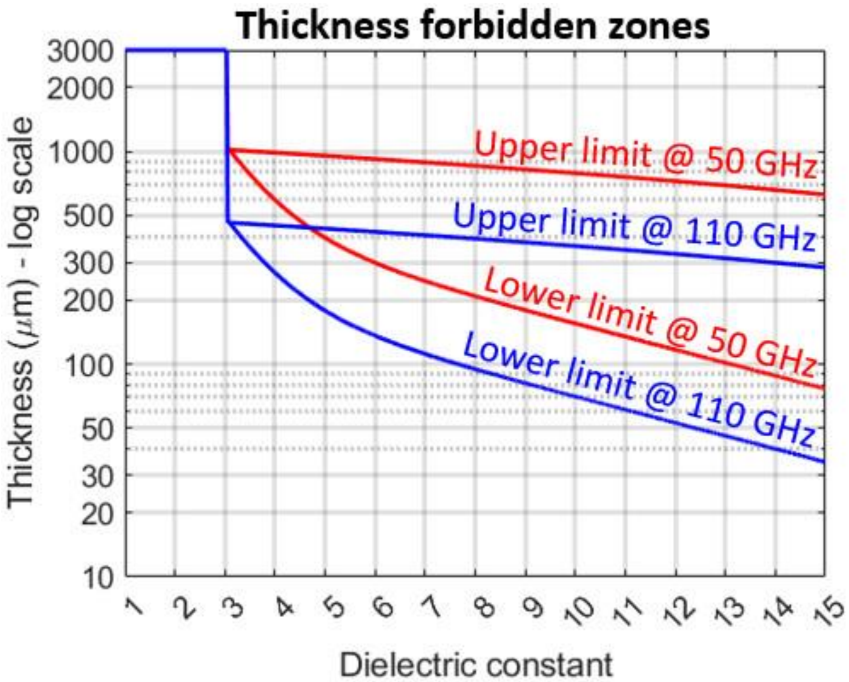
PET foil

Thickness:

100 ± 3 μm

Measurement Limits

In a double-concave FPOR, odd $TEM_{0,0,q}$ Gaussian modes can couple with higher-order **spurious modes**, in turn, disturbing the extraction of the dielectric constant. Consequently, the **±0.2% accuracy** is maintained regardless of the sample thickness only when **Dk < 3**. Otherwise, additional thickness limits apply. The plot below indicates **thickness forbidden zones** for the measurements undertaken up to 50 GHz and 110 GHz. For instance, if Dk = 4 and f_{max} = 50 GHz, it is not recommended to measure the sample with the thickness within the 595 - 990 µm range. Those limits can violated, however, at the expense of the accuracy of about ±0.5%.



If stable measurement conditions are maintained and thermal compensation is on, the measured **loss tangent** can be as low as **5×10^{-6}** (e.g. 267-µm-thick Z-cut sapphire at 15 GHz). On the other hand, the largest level of losses that can be safely measured can be as high as **5×10^{-2}** provided that the thickness of the sample is not too large (e.g. 244-µm-thick FR-4). As it has already been mentioned on page 7, the corresponding loss tangent uncertainty depends on several factors. If they are appropriately selected, the LTU can be as low as 2%.

Our Products & Services

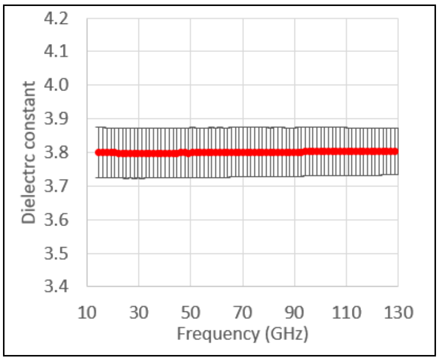
Fabry-Perot Open Resonator

Our flagship product dedicated to accurate and robust characterization of dielectric sheets in the 10-130 GHz frequency band in just a few minutes. It provides dielectric constant and loss tangent with the inaccuracy less than 0.2%.

Fabry-Perot Open Resonator for Liquids

Our new product dedicated to automated broadband and accurate measurements of dielectric properties of low-loss liquids in 15 – 50 GHz frequency range. It provides dielectric constant and loss tangent with the inaccuracy less than 1%.

Material Characterization



Instead of acquiring own material characterization system, you can always commission our team to undertake the measurement of your samples at our laboratories equipped with necessary hardware operated by professional staff.

Major features

A double-concave Fabry-Perot open resonator is a tool dedicated to automated accurate characterization of dielectric sheets.

- **Frequency range:** 10-130 GHz
- **Dielectric constant:** Dk = 1 - 15 (accuracy: ±0.2%)
- **Loss tangent:** Df > 5×10^{-6} (achievable accuracy: 2%)
- **Thickness:** 1μm – 3mm (see the thickness limits)
- **Diameter:** 50 – 150 mm (optimum: 80 – 100 mm)
- In-plane **anisotropic** materials can be measured
- Measurement time: **>1 minutes**

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