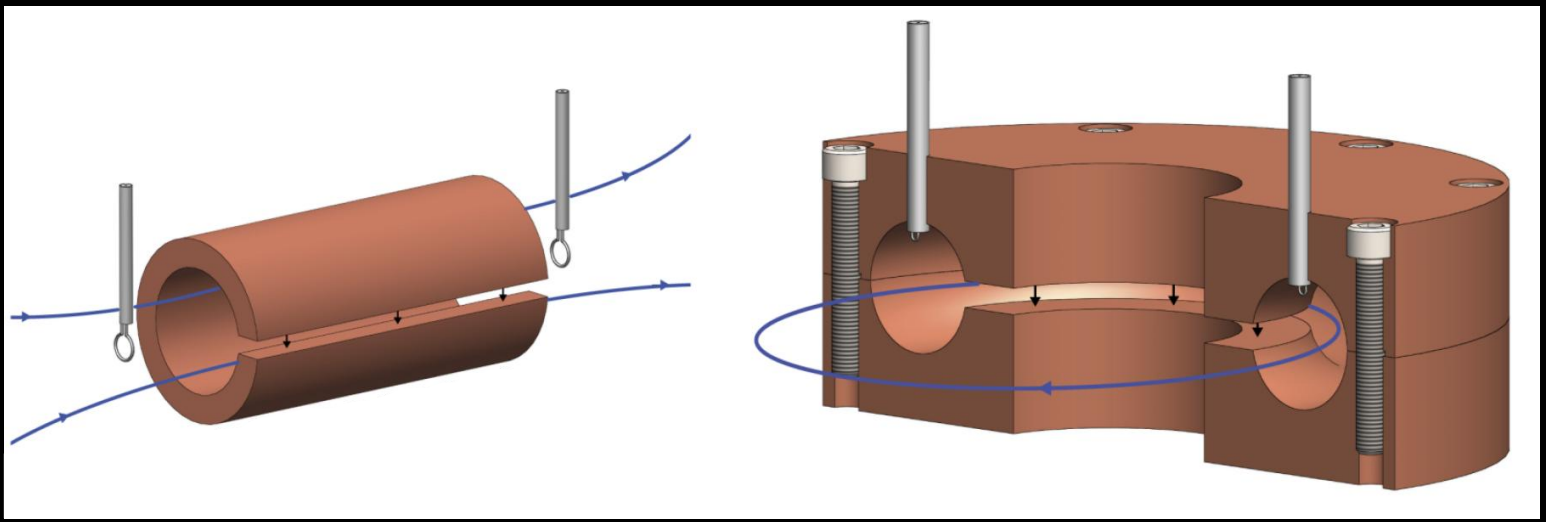
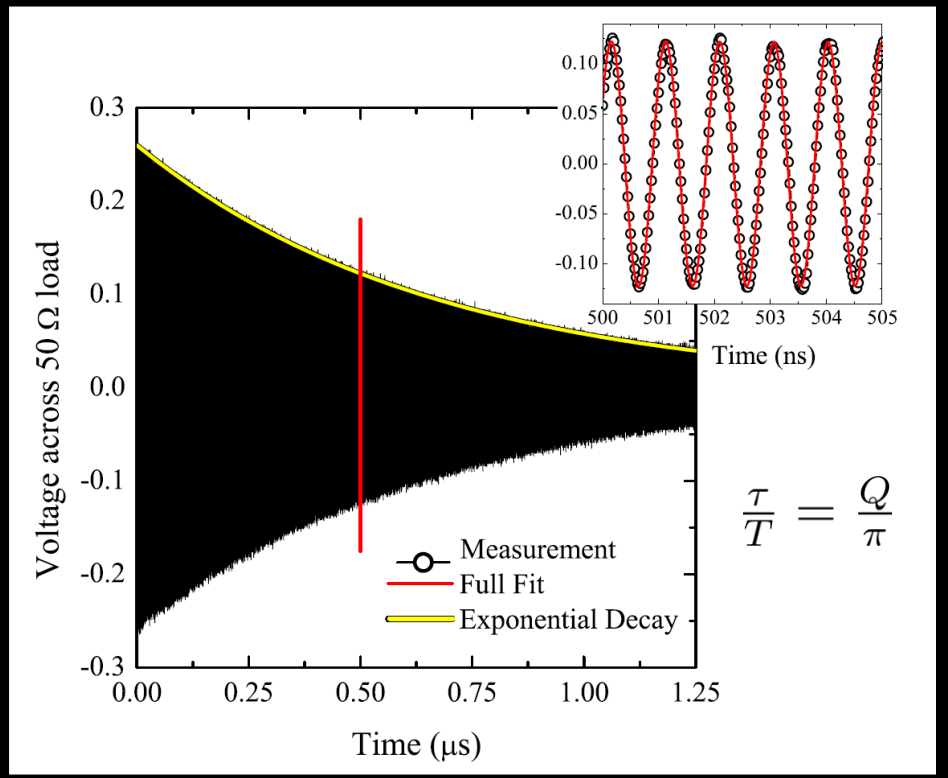
Loop-Gap Resonators: EM Material Properties Measured at Microwave Frequencies





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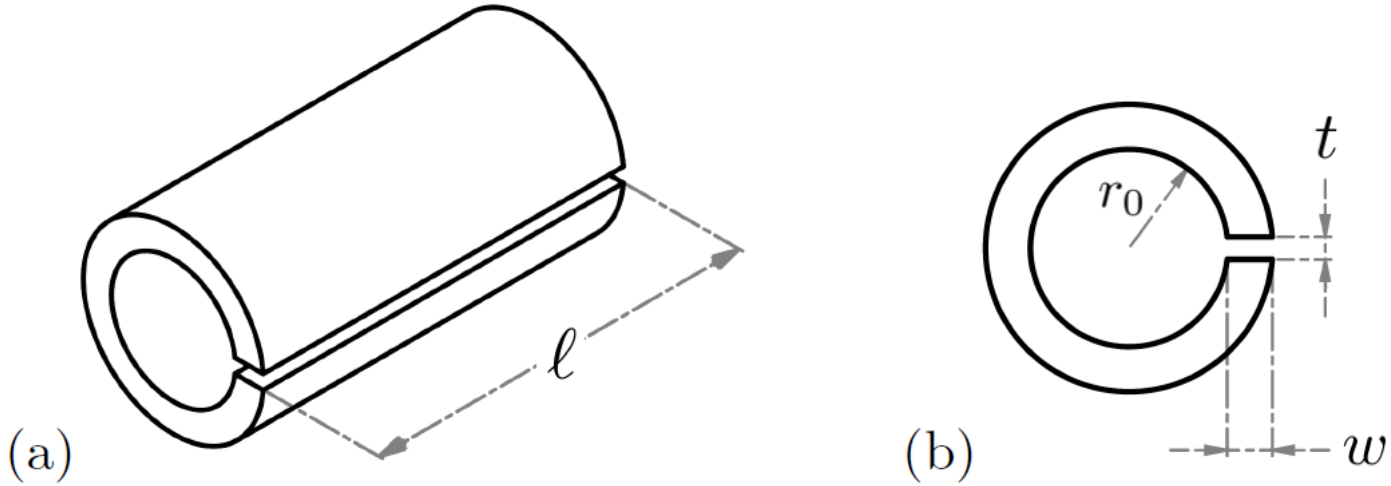
November 18, 2025

Loop-Gap Resonator (LGR)



$$C = \varepsilon_0 w \ell / t$$

$$L = \mu_0 \pi r_0^2 / \ell$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{c}{2\pi r_0}\sqrt{\frac{t}{\pi w}}$$

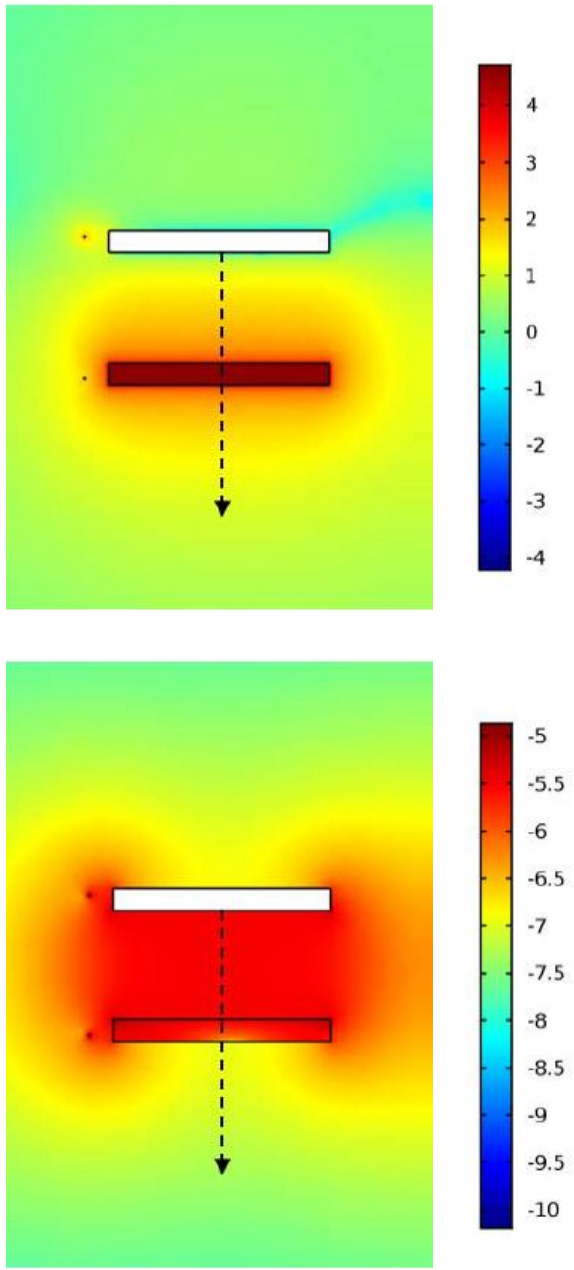
C is plate area divided by plate separation

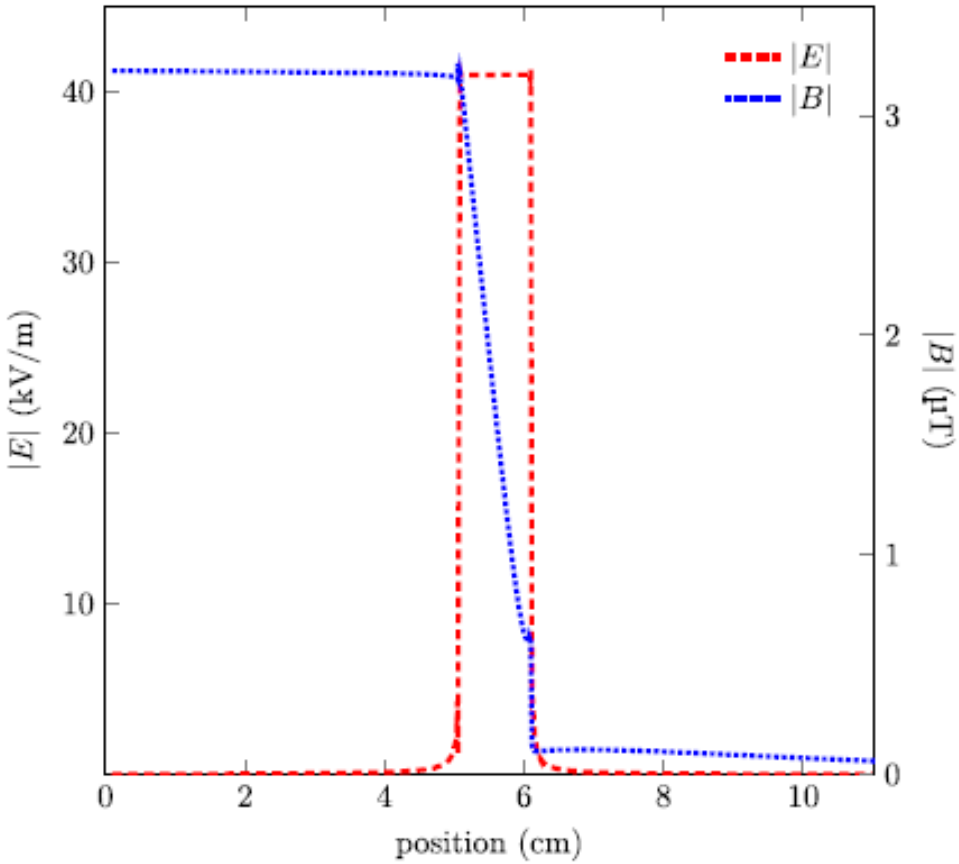
L is cross-sectional area of bore divided by bore length

LGR – Advantage:

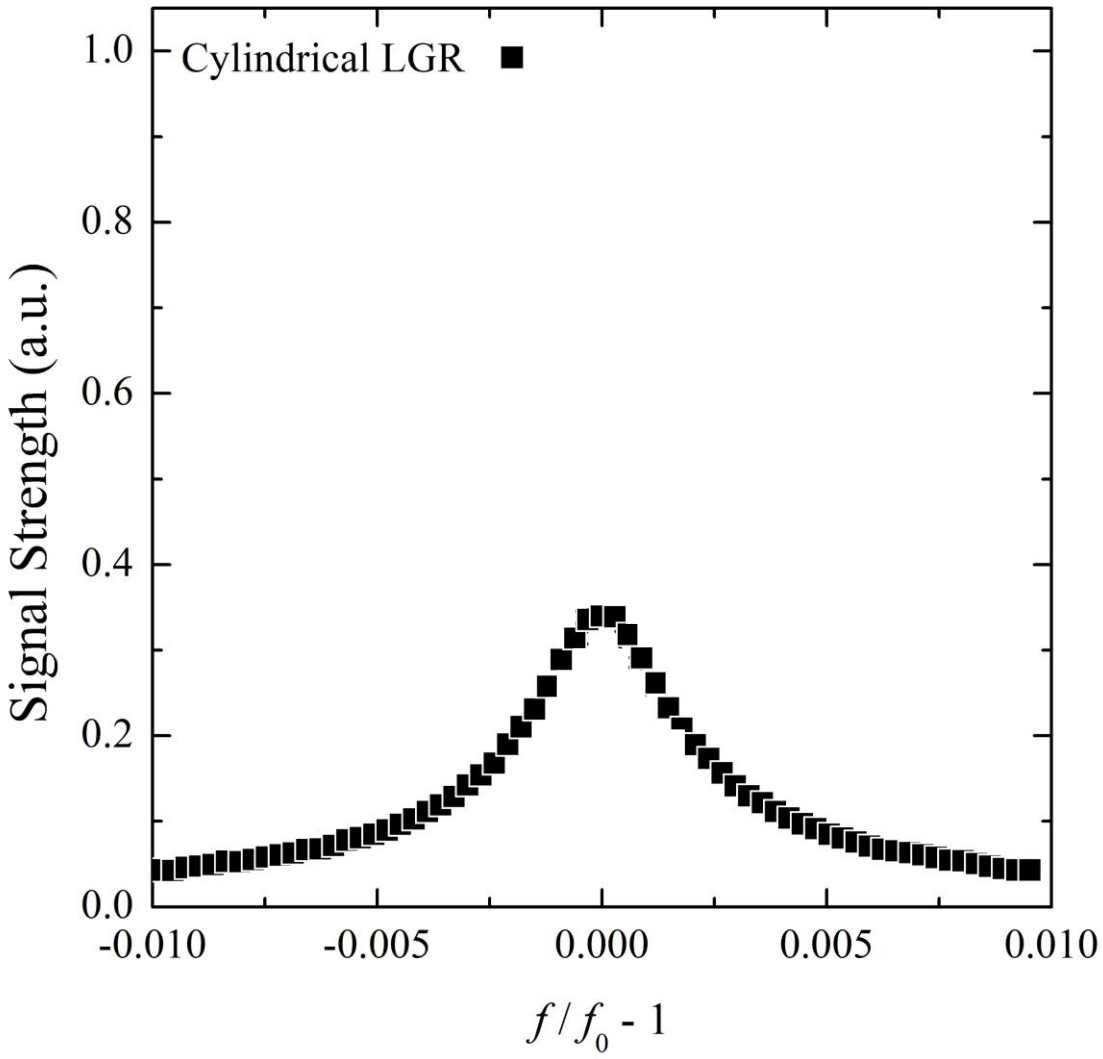
The oscillating electric and magnetic fields are well separated.

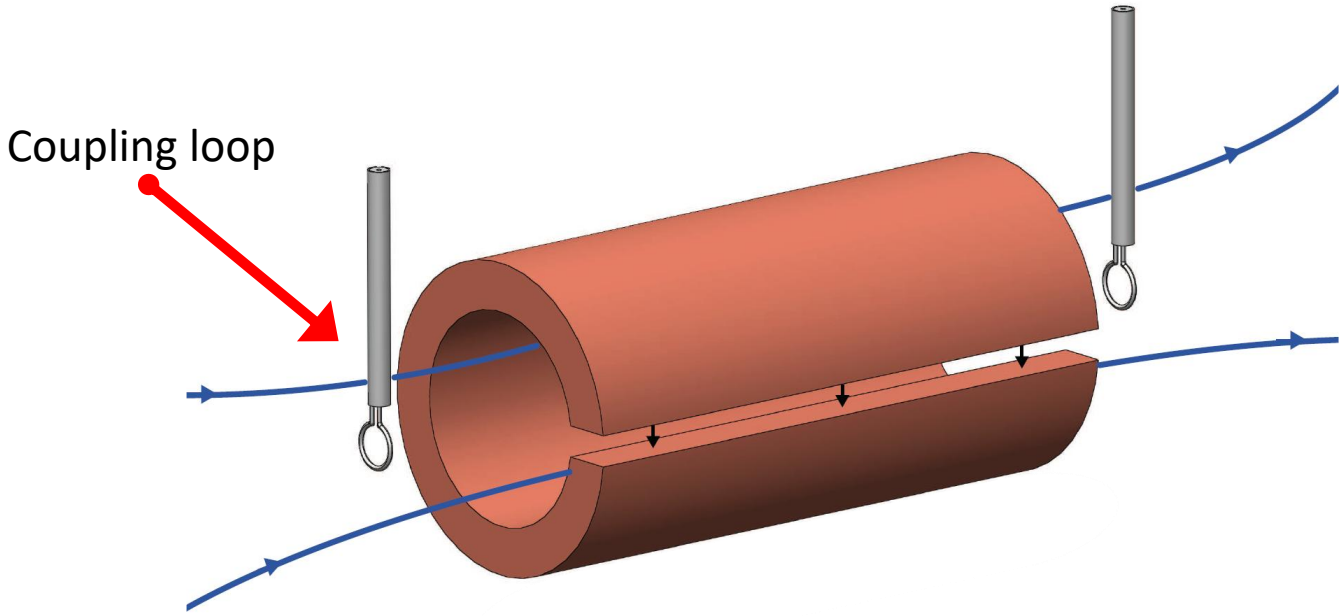
Allows one to use the LGR to separately probe the electric and magnetic properties of materials.





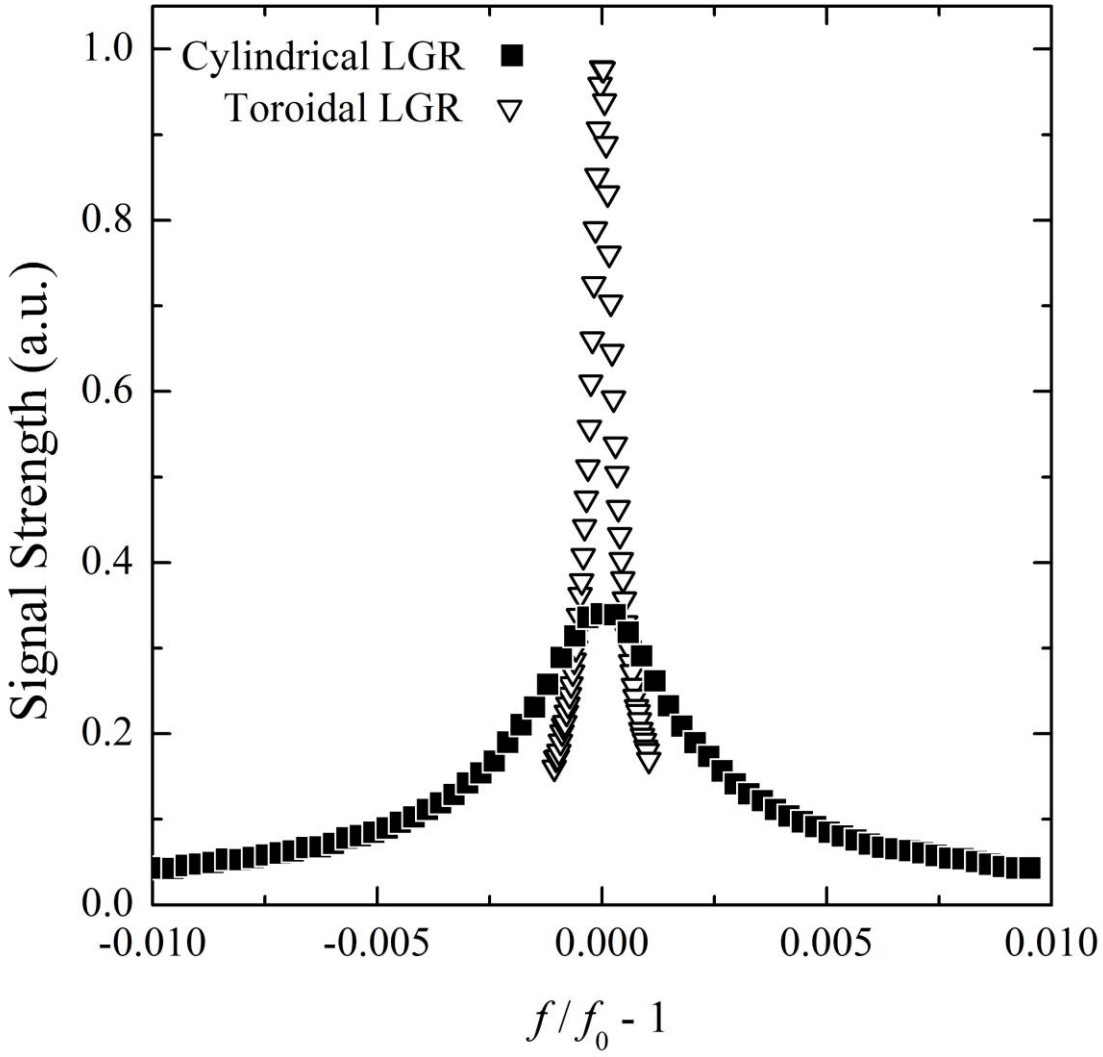
Quality Factor, Q

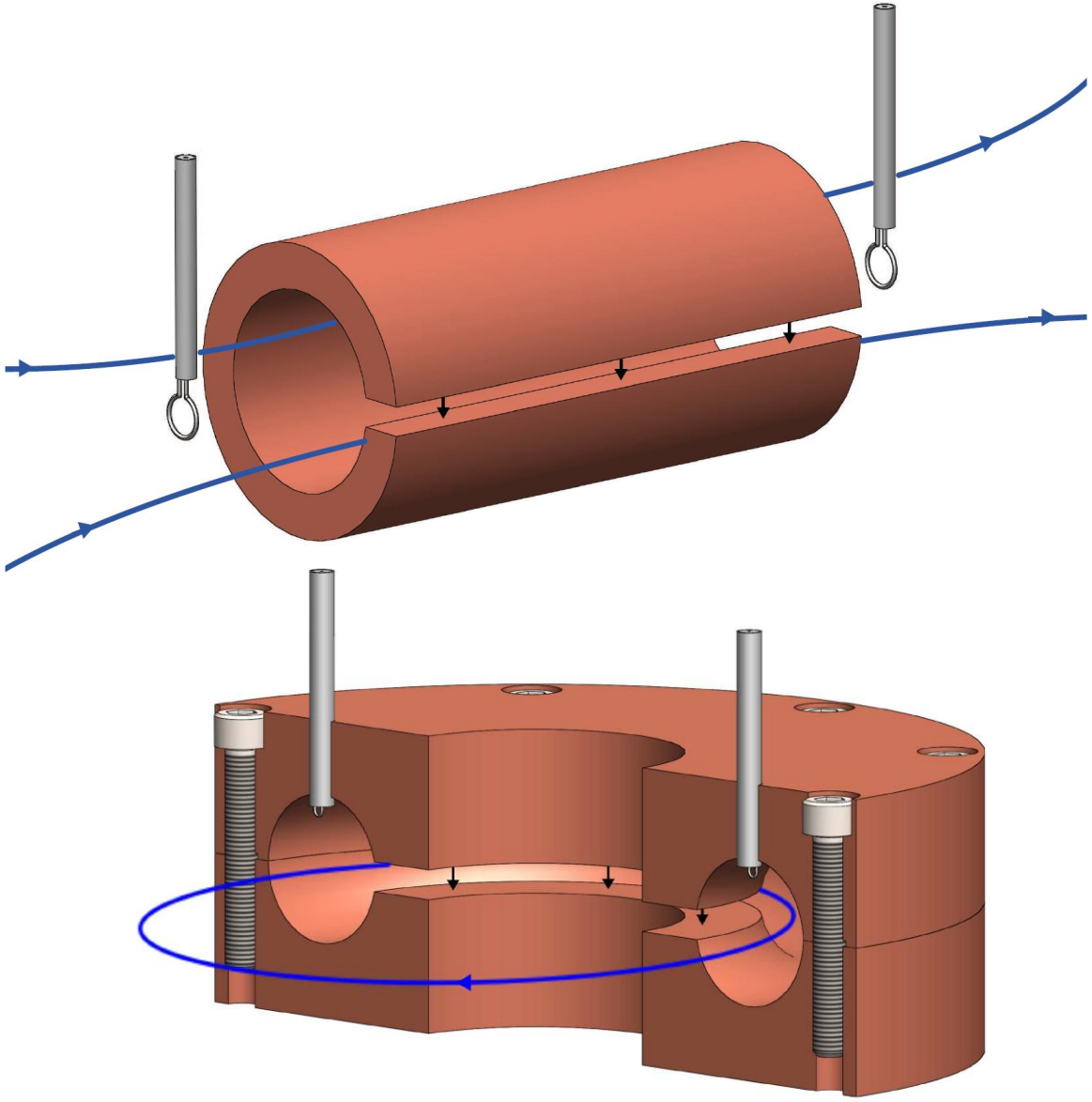




The width (sharpness) of the LGR resonance is determined by power loss per cycle. In the LGR, magnetic energy is radiated into free space, which broadens the resonance (low Q).

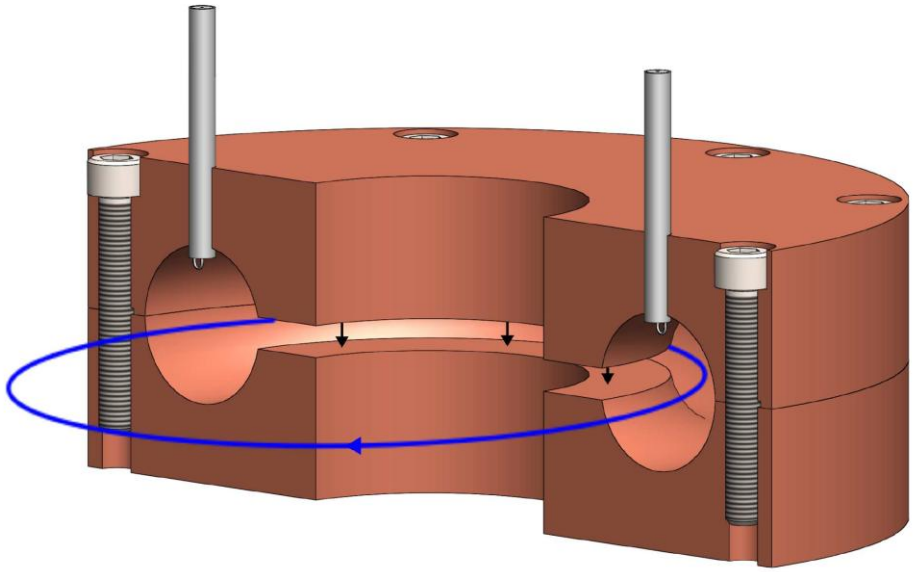
Toroidal Loop-Gap Resonator (TLGR)





The toroidal geometry confines the magnetic field lines thereby supressing radiative losses.

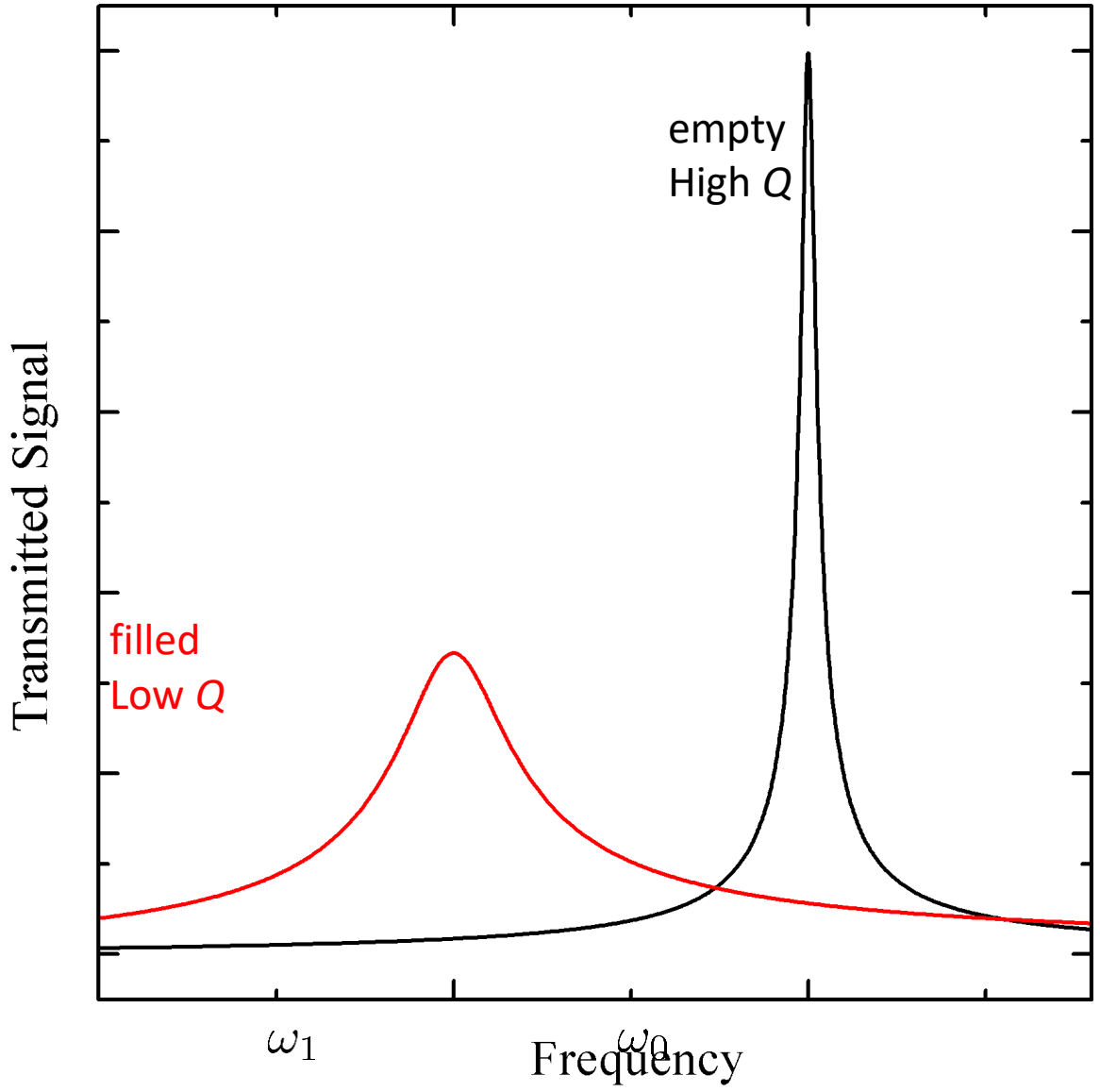
Measuring EM Material Properties



$$Z_C = \frac{1}{j\omega C} \rightarrow \frac{1}{j\omega(\varepsilon' - j\varepsilon'')C} \approx \frac{\varepsilon''}{\omega\left(\varepsilon'\right)^2 C} + \frac{1}{j\omega\varepsilon' C}$$

Loss term

Frequency shift term



Measuring EM properties: Methanol

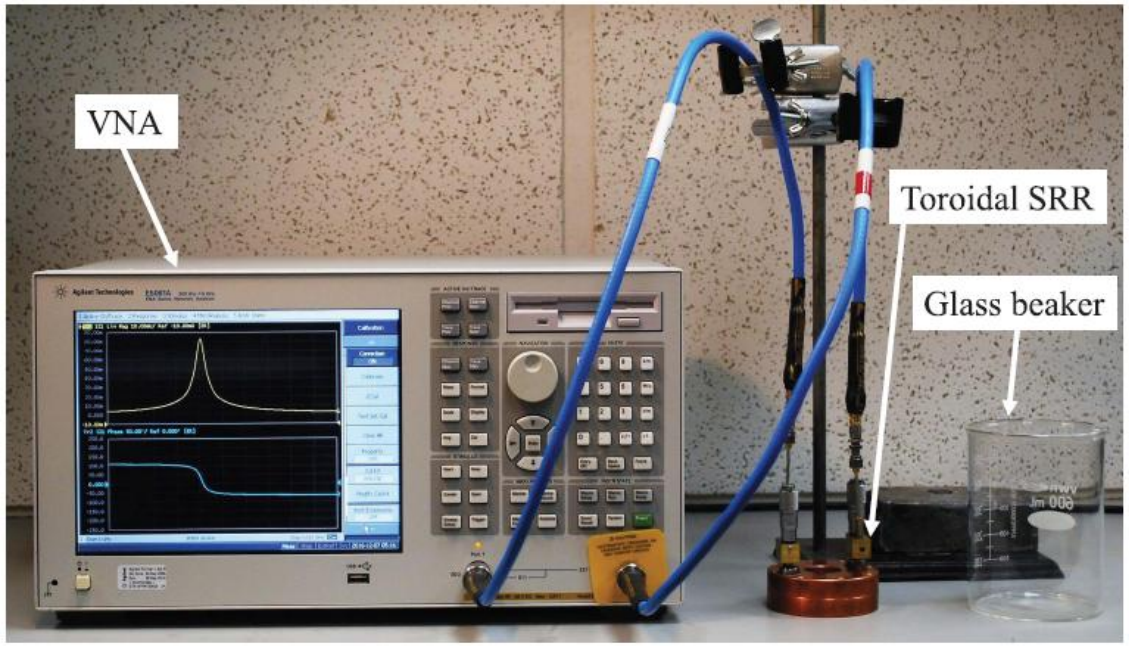
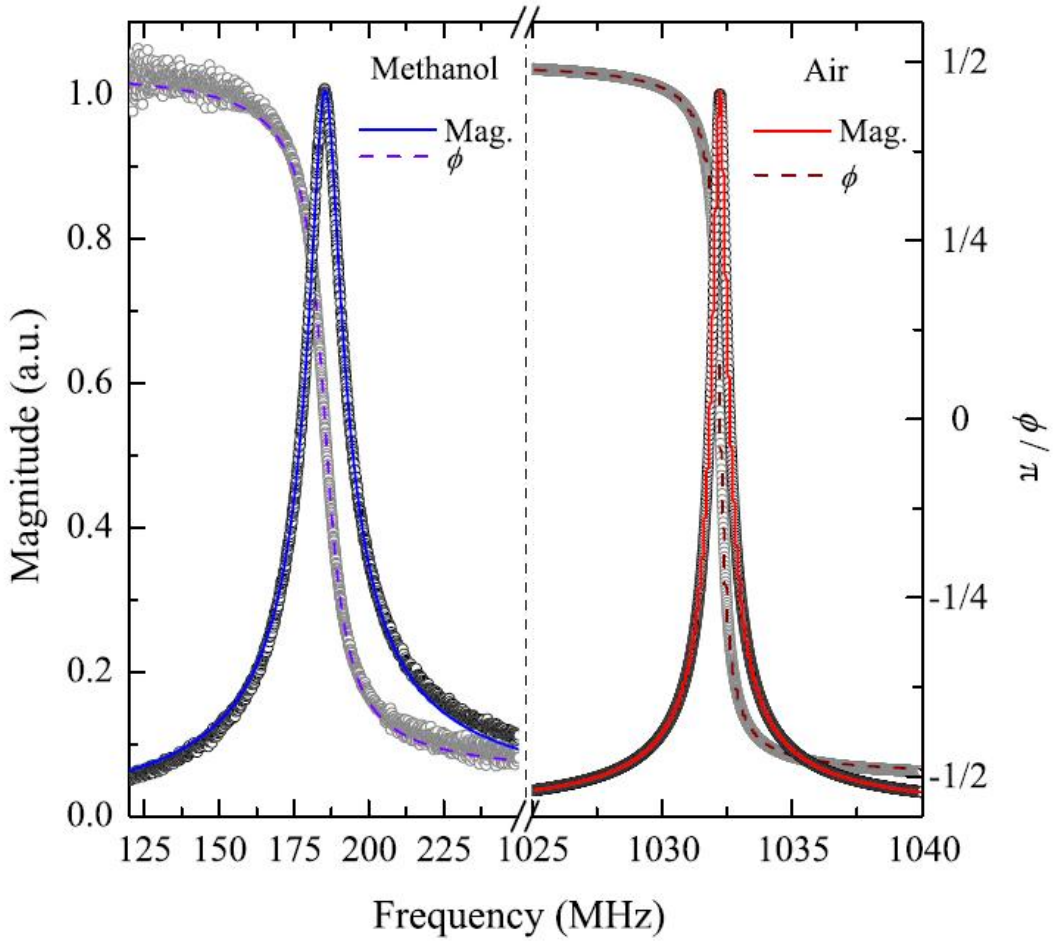


TABLE I

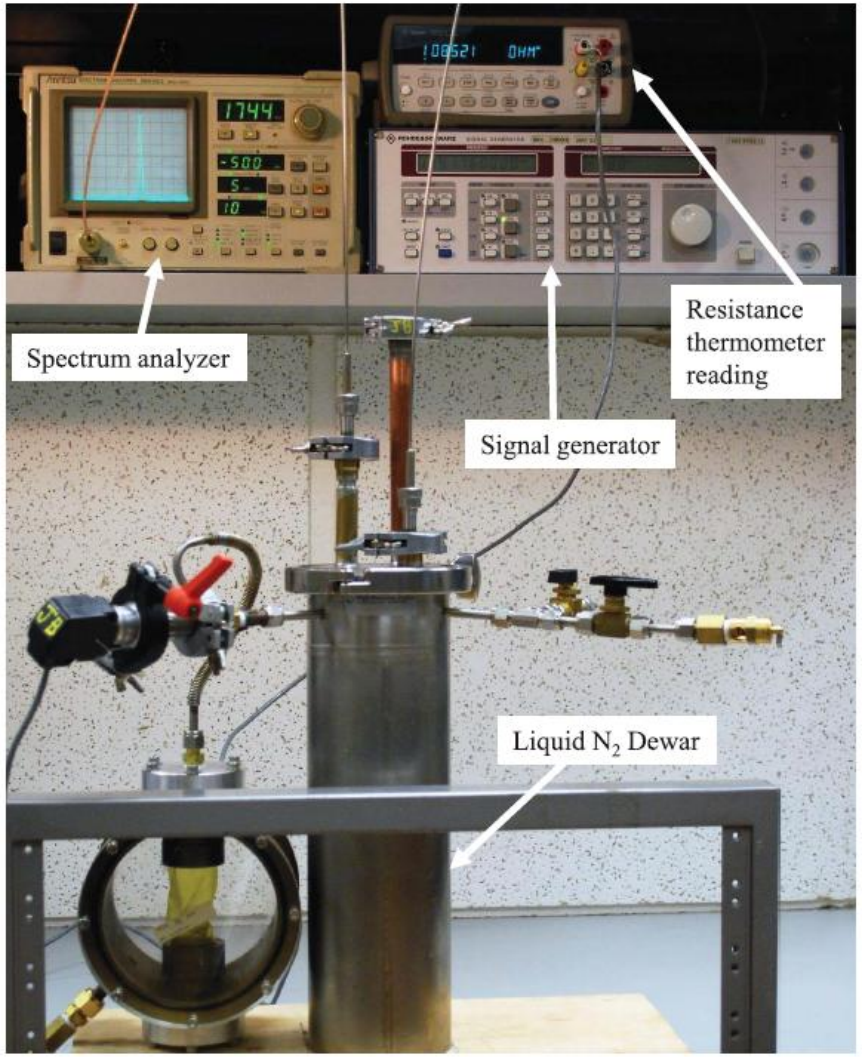
SUMMARY OF FIT RESULTS TO THE DATA IN FIG. 3 ($\Delta f_0 = 400$ Hz)

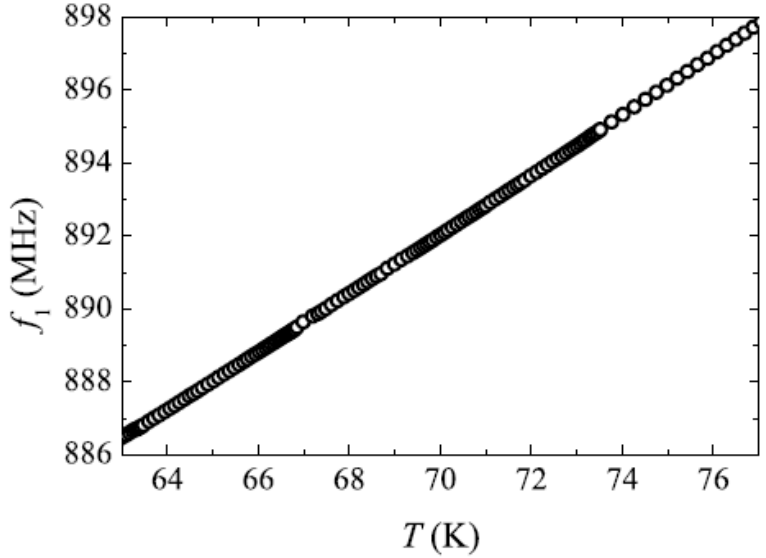
$f_0 = \omega_0/2\pi$ (MHz)	Q_0
1032.52	2024 ± 3

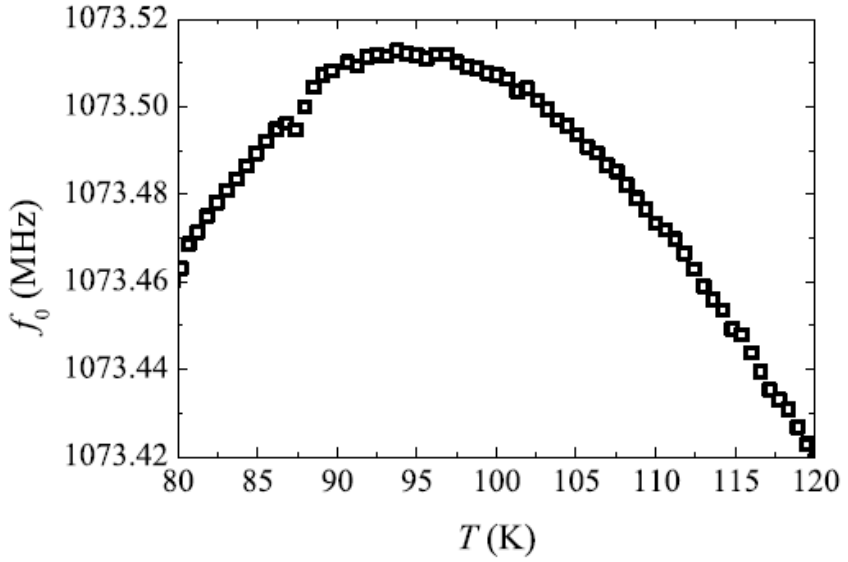
ε'	ε''
30.978 ± 0.006	1.703 ± 0.006



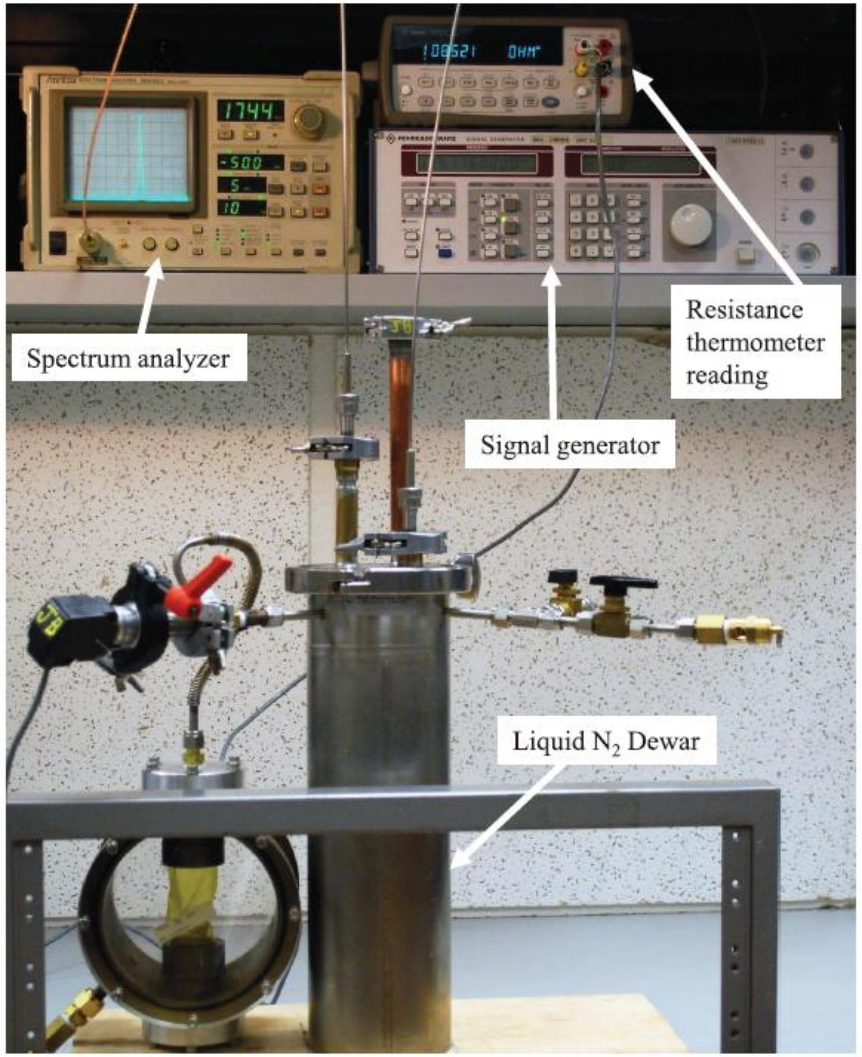
Measuring EM properties: Liquid Nitrogen

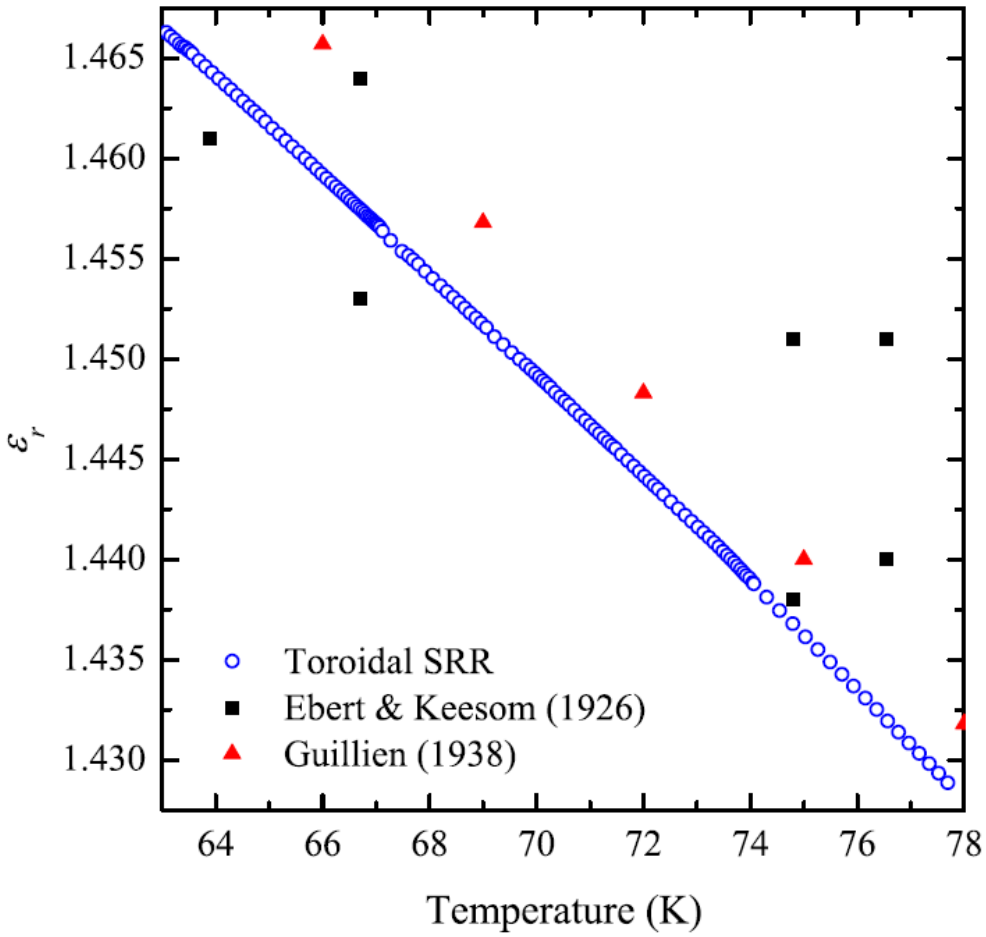






Measuring EM properties: Liquid Nitrogen





Measuring EM properties: Air

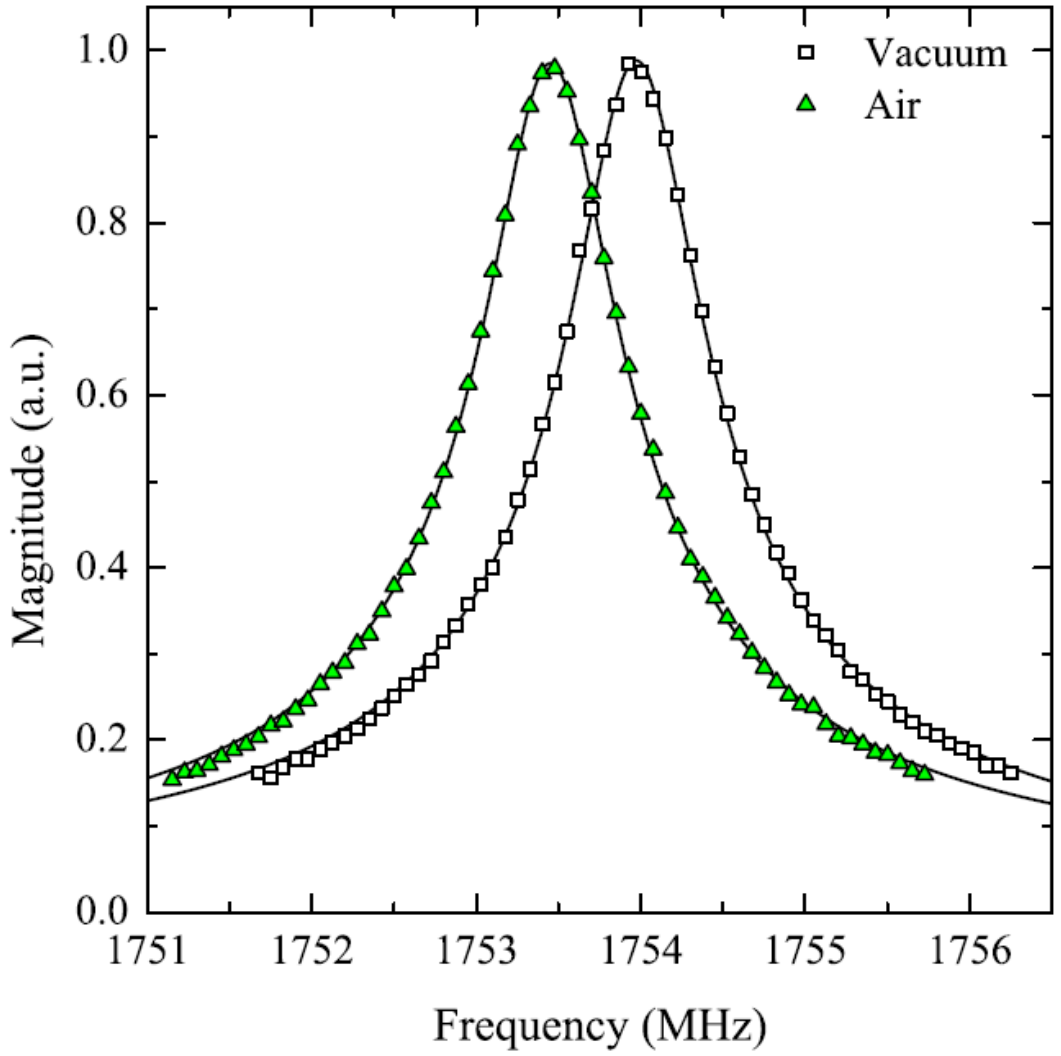


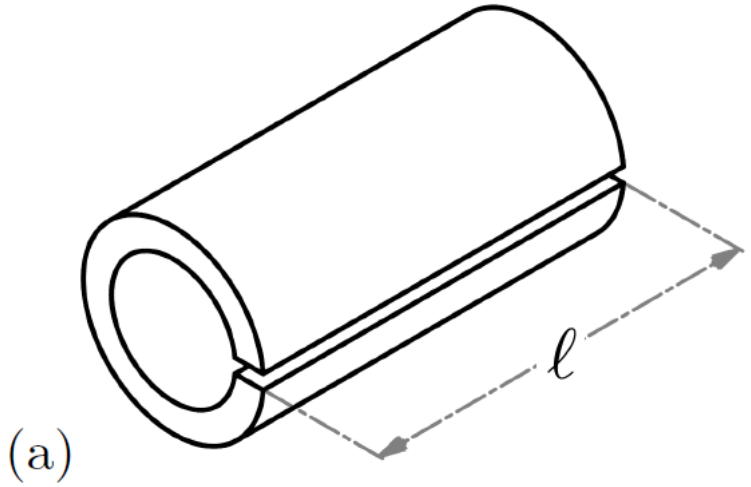
TABLE II

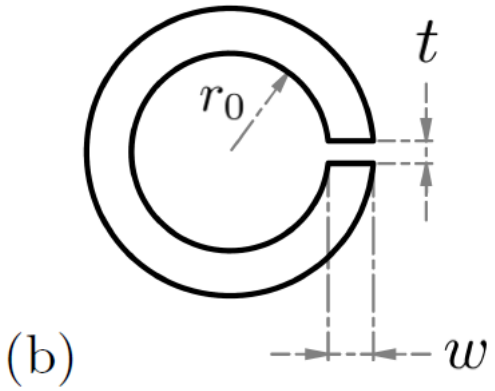
SUMMARY OF FIT RESULTS TO THE DATA IN FIG. 5 ($\Delta f_0 = 2$ kHz)

$f_0 = \omega_0/2\pi$ (MHz)	Q_0
1753.97	2234 ± 13

ε'
1.000 594 0(21)

Loop-Gap Resonator (LGR)





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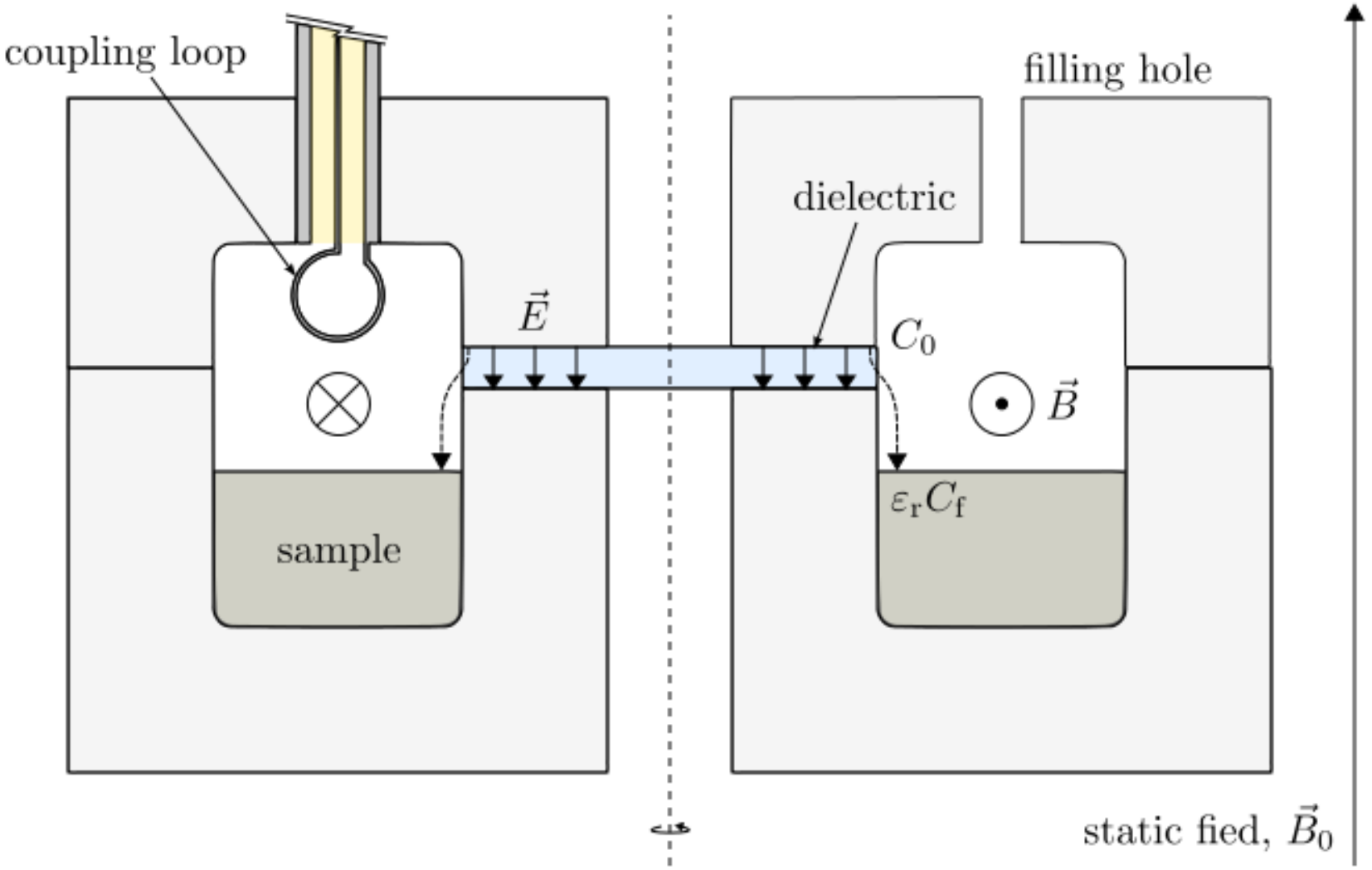
$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{c}{2\pi r_0}\sqrt{\frac{t}{\pi w}}$$

LGR – Advantage 2:

The LGR is "electrically small". That is, it's dimensions can be much smaller than λ at f_0.

Eg: $\ell = 10$ cm, $r_0 = 1.75$ cm, $w = 0.8$ cm, $t = 0.25$ mm ⇒ $f_0 = 270$ MHz, $\lambda = 1.1$ m

Partially-Filled TLGR



TLGR & USPIO Sample

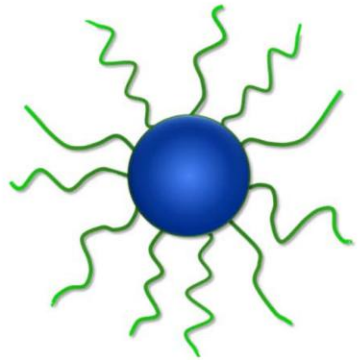
Coupling loop

1.5 inches

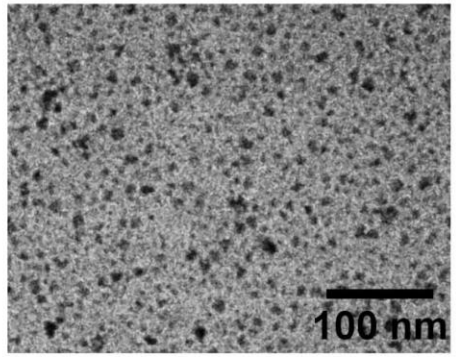
2 mL Molday ION from BioPAL
Fe_3O_4 (magnetite)
nanoparticle suspension

Molday ION

Schematic Representation



TEM



Description

Core-shell nanoparticle with 8 nm core and a carboxydextran shell.

$H(C_6H_{10}O_5)_xOH$

Taylor *et al.*, (2014) PLOS ONE 9(6): e100259

Static Magnetic Field Scan – Al_2O_3