Wide-band extraction of dielectric material parameters preserving full accuracy of classical resonant methods

Wojciech Gwarek [1,2] Life Fellow IEEE

with contributions from M. Celuch, M. Olszewska-Placha & Ł. Nowicki

[1] QWED Sp. z o.o. – co-founder, President 1996-2017

[2] Warsaw University of Technology, Professor retired in 2017

Wojciech Gwarek - brief biography

Degrees: Warsaw Univ. of Tech. MSc 1970; PhD 1977;
Massachusetts Institute of Technology MSc 1970

Professor of the Warsaw University of Technology and head of its Microwave Lab. (until retired in 2017)

Member of Editorial Boards of several leading magazines including IEEE Trans. MTT since 1975

Member (multiple times) of TPCs of IEEE IMS (since 1996) & European Microwave Conference (since 1989)

Proffeseur en sejour sabbatique, ENST Bretagne 1991-1992

Professor and head of Dept. of Electr.&Physics, Ecole Franco-Polonaise of France Telecom, Poznań, 1992-1994

Co-founder of QWED and its President 1996-2017. Presently a QWED consultant.

IEEE Distinguished Microwave Lecturer (2003-2005)

Chair of TPC of MIKON International Conference (Wrocław 2008, Vilnius 2010)

IEEE Fellow since 2000 (presently Life Fellow)

Recipient of IEEE Microwave Pioneer Award 2011 (as an author of publications recognized to be seminal from the perspective of more than 20 years),

Author of European Patent Application (2023) No. EP23461651.4, also: International Patent Application No.PCT/IB2024/056934, “Electromagnetic resonating structure and a method of measuring….”

Outline

- Motivation and state-of-the-art [5,6]
- Discussion of the properties of SPDRs
- Path from SPDRs to Q-choked Sapphire Sandwiched Resonators (Q-SSRs)
- Q-SSR design, prototype, and verification
- Supplement (if there is time). Can we apply SSR to TM modes?
- Conclusions and outlook

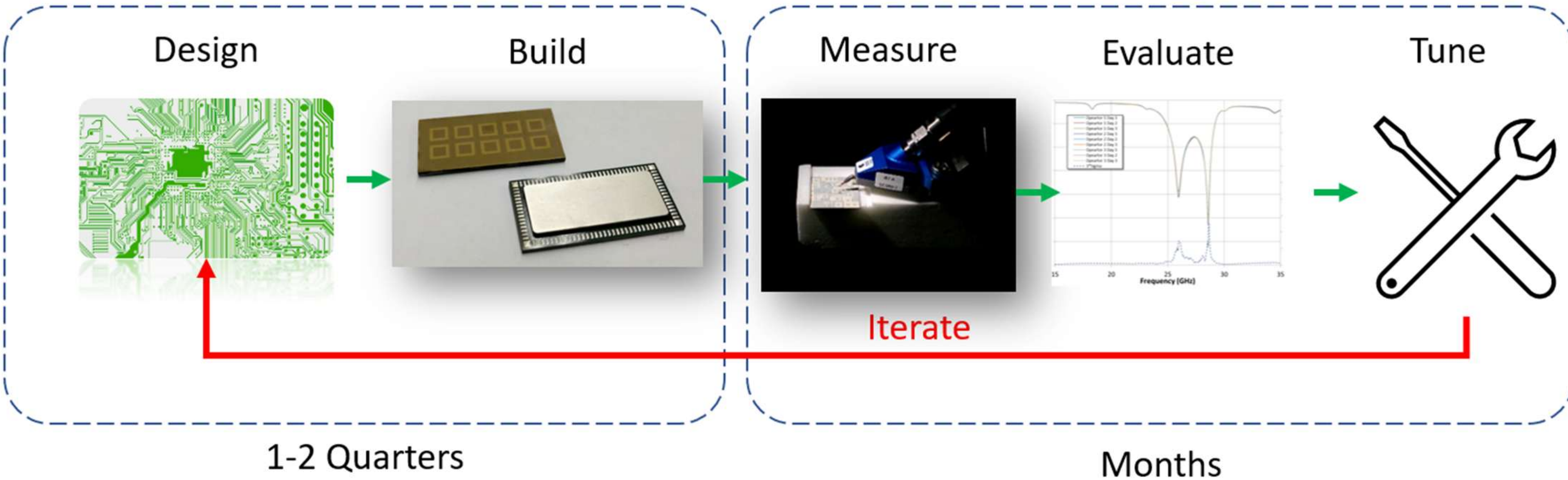
[5] Int. Electron. Manuf. Initiative. (2024). 5G/6G mmWave Materials and Electrical Test Technology Roadmap.
[6] M. Celuch et al, 51st Eur. Microw. Conf. (EuMC), Apr. 2022.

[18] W .K. Gwarek, “Electromagnetic resonating structure and a method of measuring of a material parameter”,
European Patent Application No. EP23461651.4, also: International Patent Application No. PCT/IB2024/056934
[19] M. Celuch et al., IMS2024 and IEEE Microwave and Wireless Technology Letters, June 2024, doi: 10.1109/LMWT.2024.3397912.

Motivation

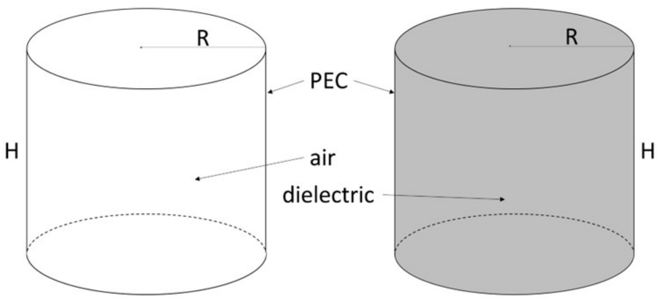
Traditional microwave design:
- ❑ hardware prototyping, trimming, and tuning
- ❑ multiple, time-consuming iterations
- ❑ difficult to tolerate in today's competitive environment

→ discrepancies between design versus actual performance often come from uncertainties in materials' data

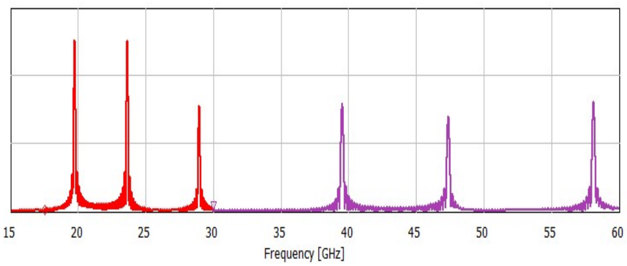


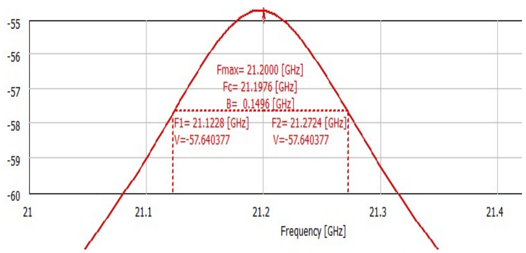
from: M.Hill & M.Celuch, IPC APEX EXPO 2021 (iNEMI project presentation)

Principles of Resonator Measurements



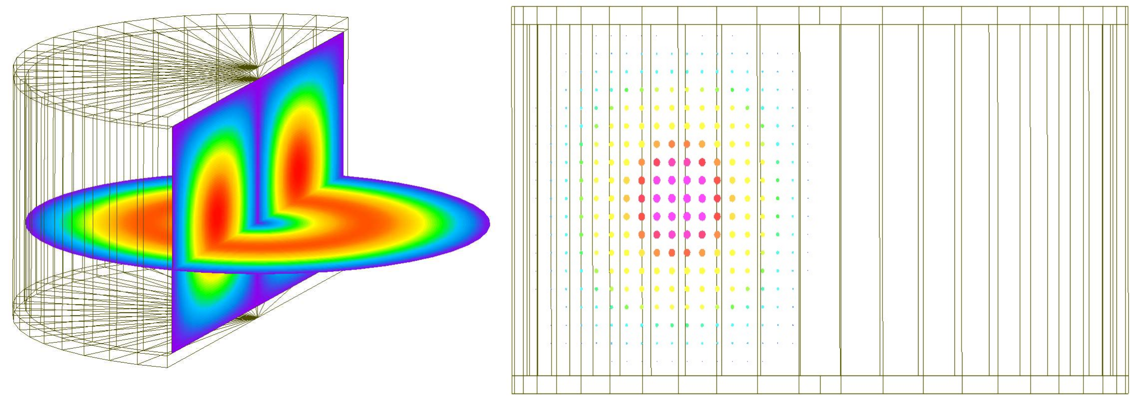
Filling (typically partial) with a non-magnetic low-loss dielectric





TE011 mode most advantageous for such measurements

E



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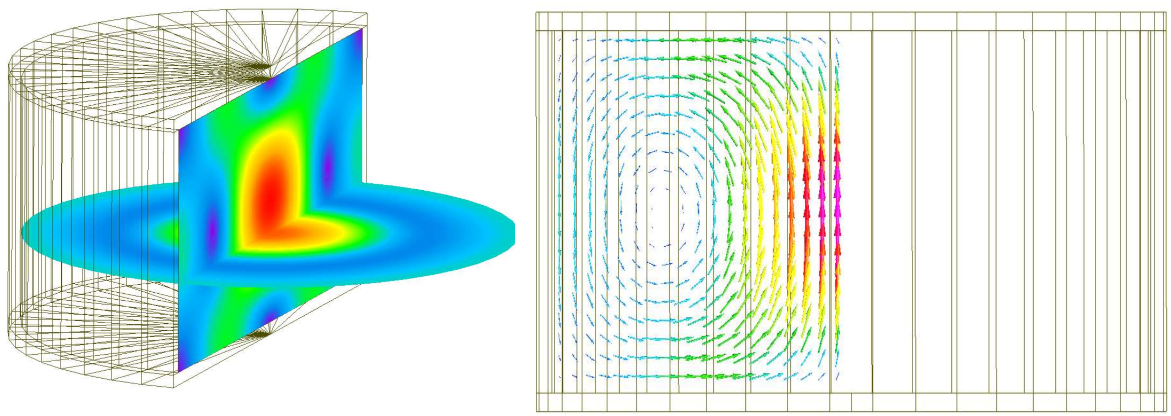
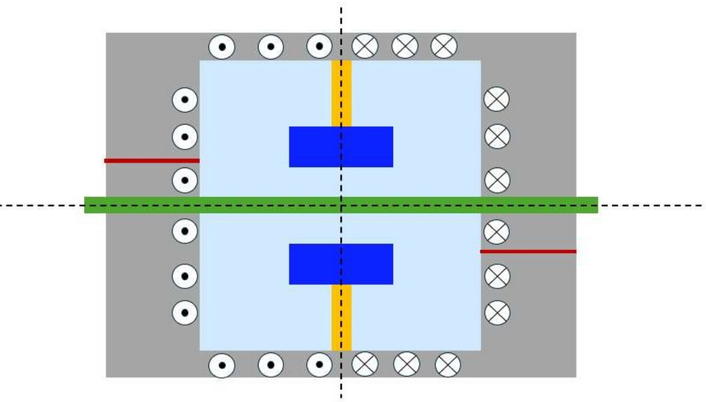
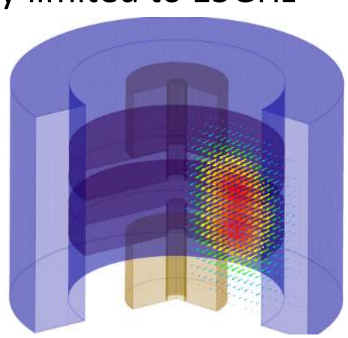


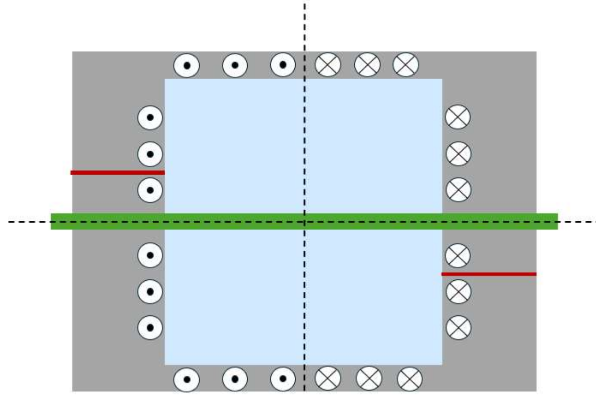
Popular resonators for material measurements



Split-Post Dielectric Resonator (SPDR)

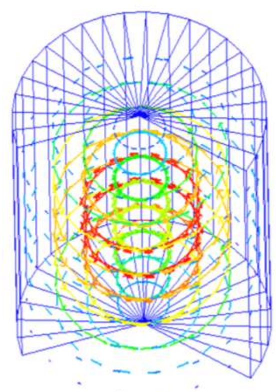
+better repeatability & reproducibility
+applicable to higher Dk / thicker samples
- practically limited to 15GHz

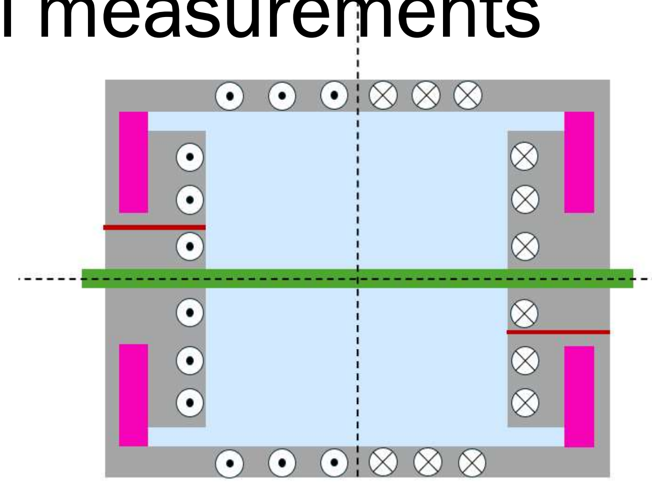


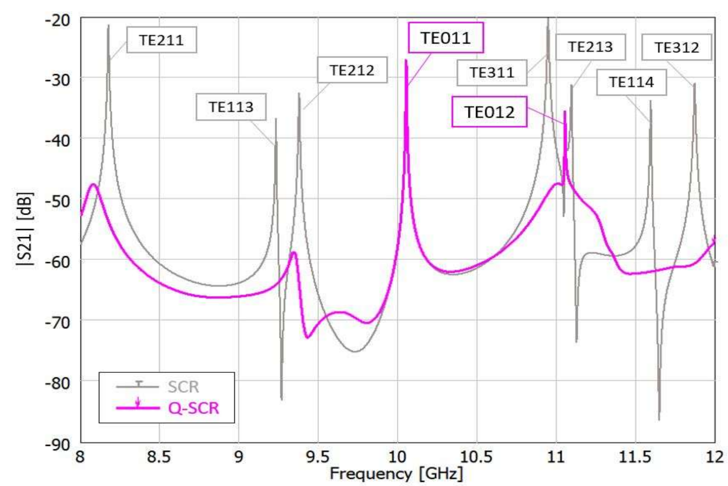


Split Cylinder Resonator (SCR)

+available for higher frequencies
- limited to thin, low-Dk samples







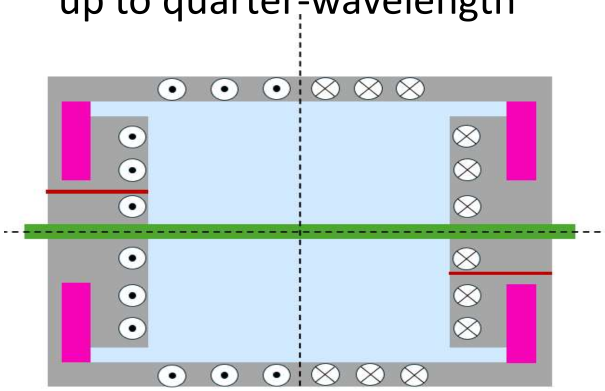
The Q-Choke suppresses modes other than TE0np.

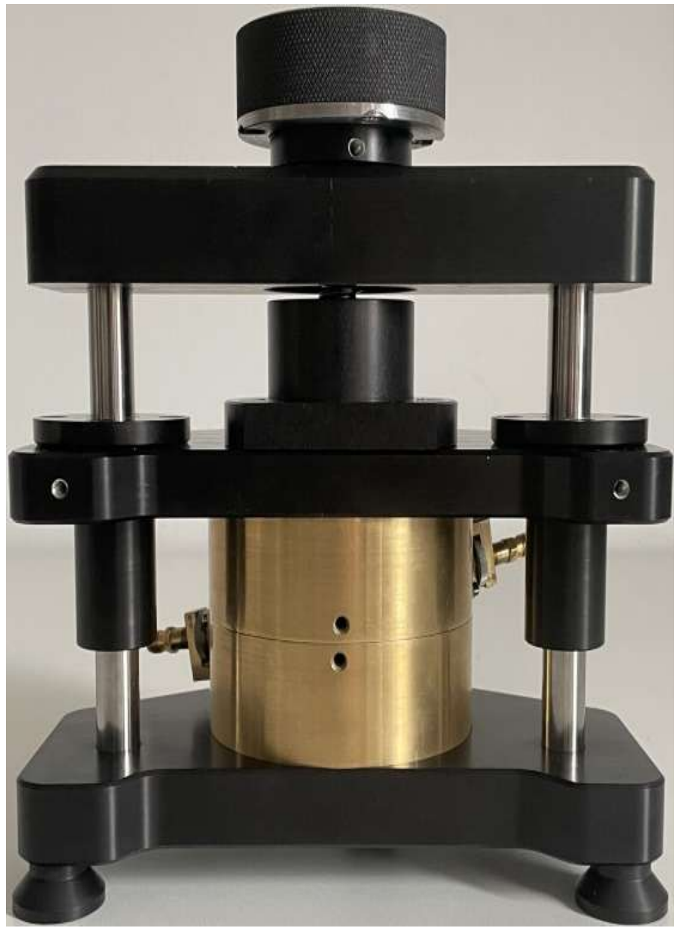
Follow-Up on Q-SCR

QWED New Product Description taken from the presentation of M. Olszewska-Placha

Based on patent application..
by. W.Gwarek

Key results:
measured thick stack
of sapphire samples,
up to quarter-wavelength



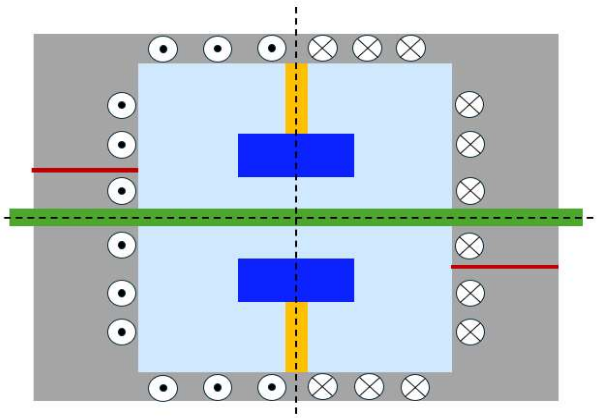


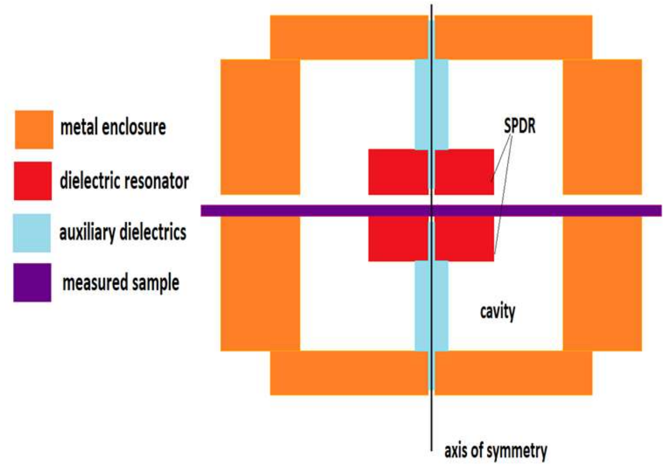
Q-SCR 10GHz operation parameters:

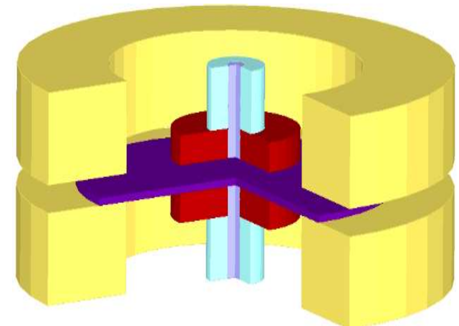
- 10 GHz (*higher frequencies coming soon...*)
- Dk = 1 - 15
- Df > 10^{-6}
- accuracy:
  δDk < 0.2%
  δDf < 2%
- high repeatability:
  for COP 187μm, Dk=3.347,
  → st. dev.=0.0002
- sample dimensions:
  min 40 x 40 mm
  max 100 x 100 mm
- thickness:
  Up to 4 mm for low-loss materials (e.g. sapphire)

https://www.qwed.eu/resonator_qscr.html

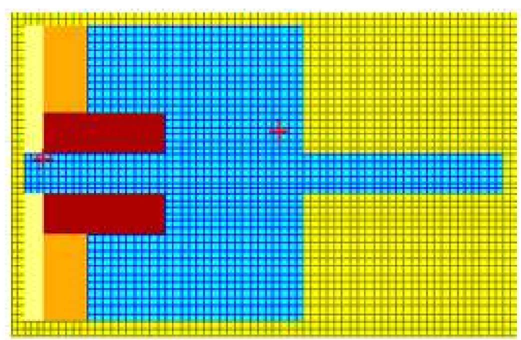
Special attention to Split Post Dielectric Resonators

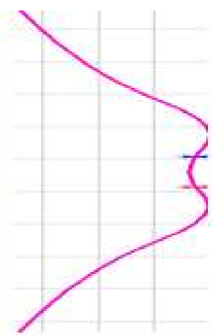


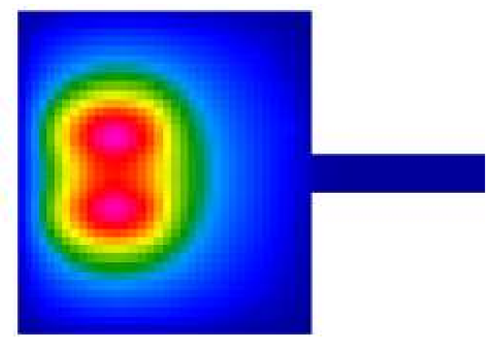




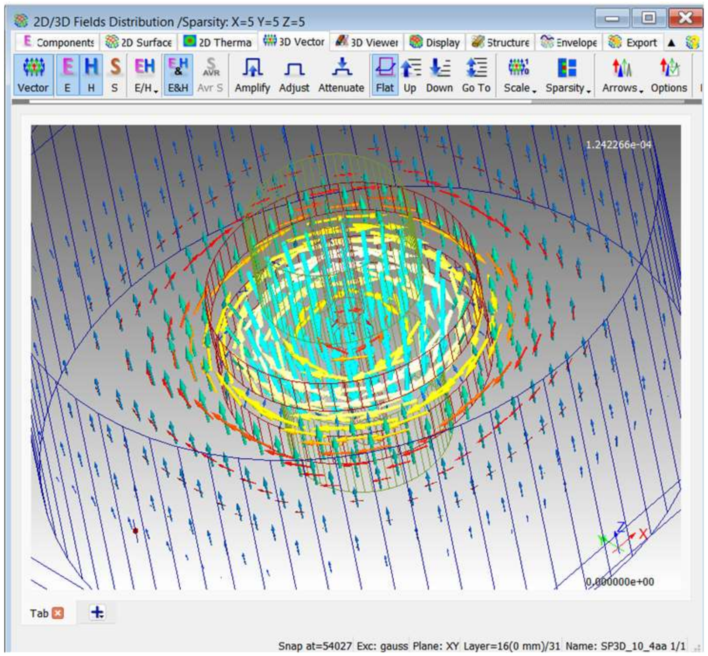
SPDR

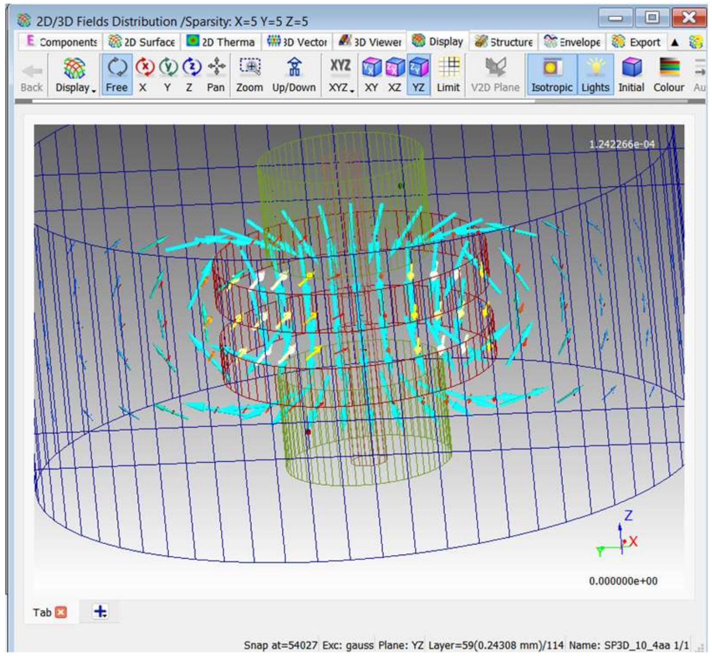






Special attention to SPDRs





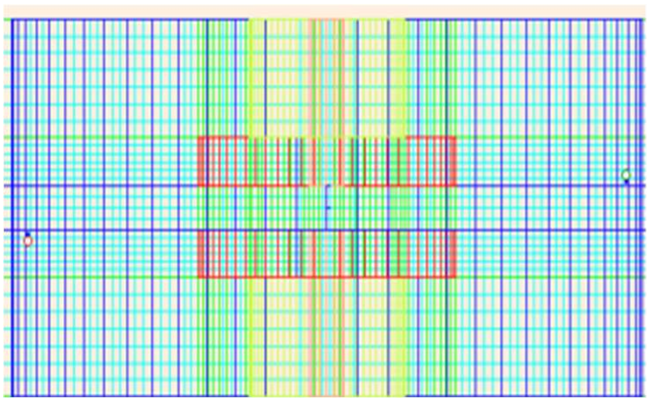
SPDRs in Practice:

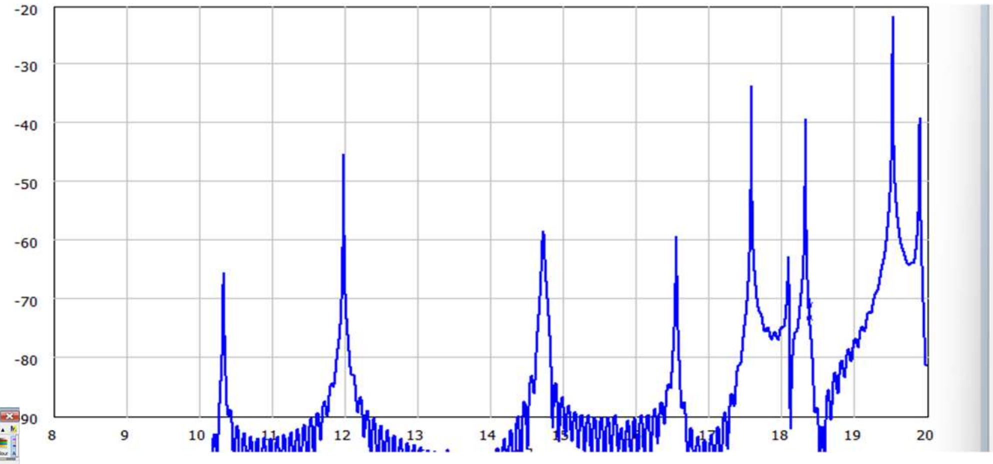
- **designed by J. Krupka**
- **commercialized by QWED since 1998**
- **> 1600 units sold to leading industry and research worldwide**

Properties:

- **Fields concentrated in dielectric posts**
- **No vertical currents in metal walls permitting horizontal slots for insertion of sample;**
- **In-plane measurements**
- **Each of SPDRs is for one frequency**
- **TE011 mode excited by loops inserted through cavity side-walls**

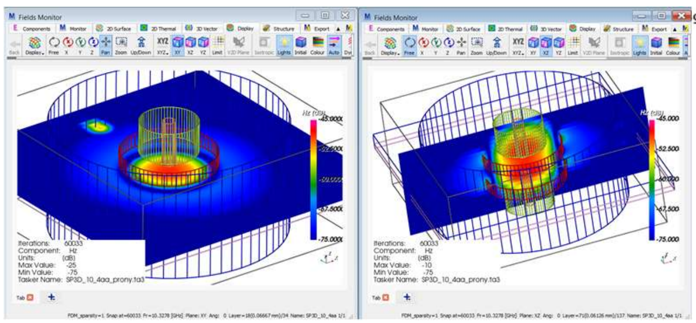
Can SPDR be used at higher resonances?



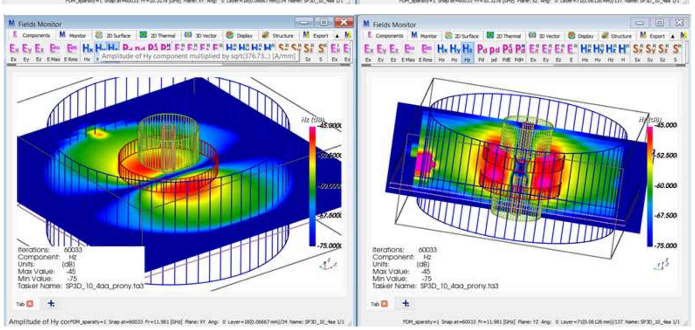


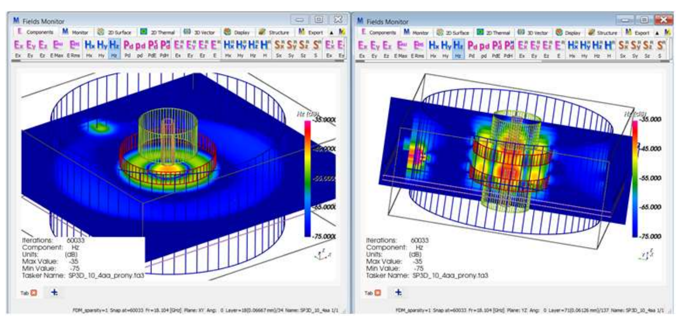
QFactors for signal no: 1		F_i, Ampl_i, Q_i
1.4901925E+10	6.2995769E-06	86.60069
1.4731316E+10	3.0768730E-05	467.3524
1.8110585E+10	5.7817310E-06	1730.755
1.0328418E+10	3.4589175E-06	1334.028
1.6563920E+10	7.5055823E-06	2141.073
2.4062124E+10	0.0000000E+00	3289.470
2.2786339E+10	0.0000000E+00	3261.900
1.9916878E+10	3.8336904E-05	4205.596
1.1981160E+10	1.6546493E-05	3971.701
1.8341710E+10	2.6299746E-05	6692.931
2.3044227E+10	0.0000000E+00	9533.184
1.9543601E+10	1.4470458E-04	9222.640
2.4624822E+10	0.0000000E+00	11804.40
1.7596901E+10	3.7709935E-05	9184.312
QFactors for signal no: 3		F_i, Ampl_i, Q_i
1.8094551E+10	1.6664301E-07	442.7980
2.2784934E+10	0.0000000E+00	1105.585
2.3045296E+10	0.0000000E+00	2048.135
2.4059931E+10	0.0000000E+00	2543.621
1.6562475E+10	1.7150649E-07	1808.599
1.9916741E+10	9.1966194E-07	3921.344
2.4624949E+10	0.0000000E+00	8050.898
1.1980847E+10	2.5997861E-07	4672.075
1.8340370E+10	6.8558677E-07	9653.007
1.9543581E+10	3.4844118E-06	10297.13
1.7596590E+10	9.4517407E-07	11181.07
QFactors for signal no: 4		F_i, Ampl_i, Q_i
1.8094561E+10	1.2560415E-06	442.6028
2.2784930E+10	0.0000000E+00	1105.961
2.3045294E+10	0.0000000E+00	2047.406
2.4059933E+10	0.0000000E+00	2544.967

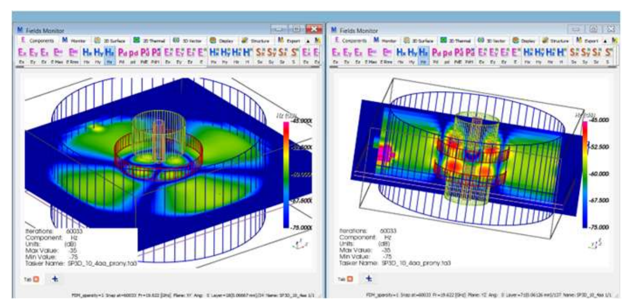
TE011 10.328 **TE111** 11.981 **TE021** 18.104 **TE221** 19.543



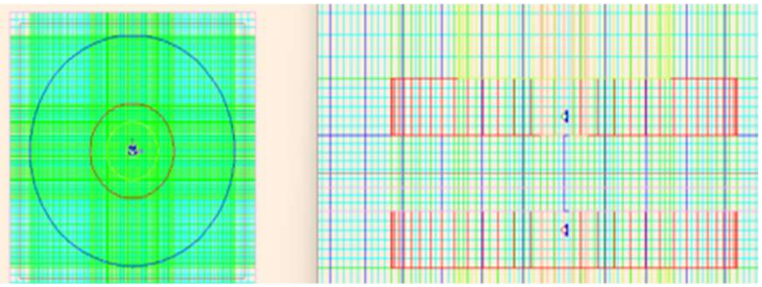
With typical side-wall excitation the next interesting mode (TE021) is practically hidden by neighbor parasitic modes

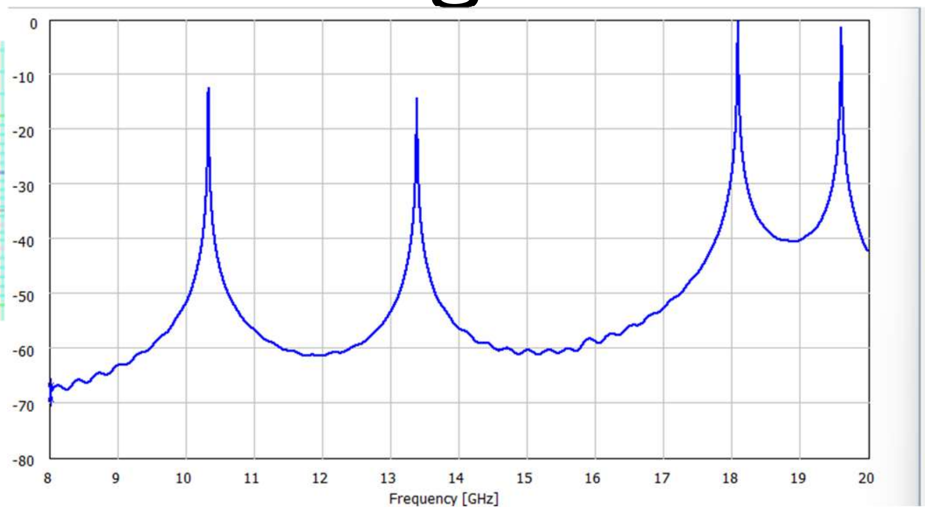






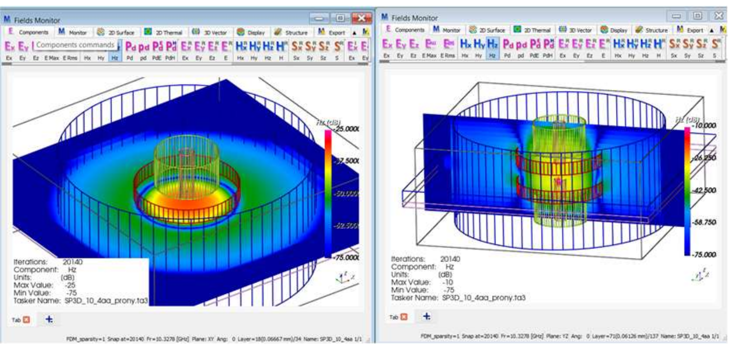
Can SPDR be used at higher resonances?



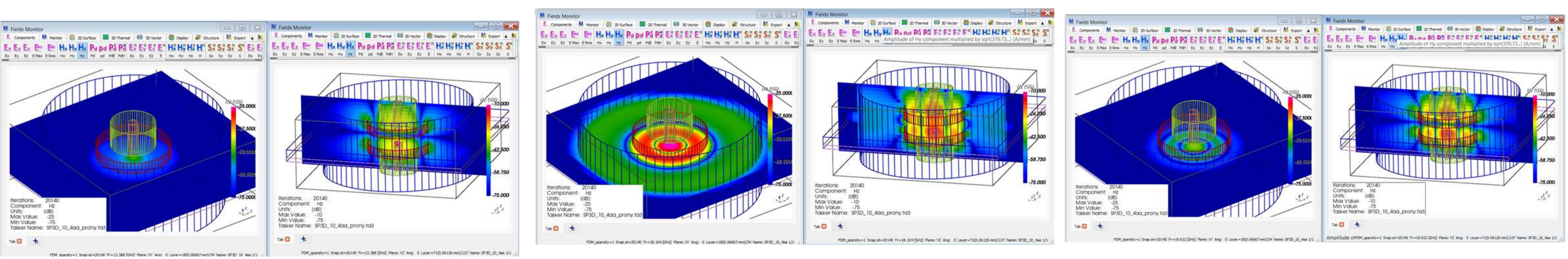


QFactors for signal no: 1 F_i, Ampl_i, Q_i
1.3388576E+10 1.7172942E-03 1595.039
1.9621982E+10 5.5235289E-03 2373.599
1.8104236E+10 6.6874265E-03 2353.268
1.0327181E+10 1.6147555E-03 1454.593
QFactors for signal no: 3 F_i, Ampl_i, Q_i
1.9666643E+10 3.2433722E-04 50.56617
1.8175957E+10 2.0815972E-04 112.2231
QFactors for signal no: 4 F_i, Ampl_i, Q_i
1.9621589E+10 9.1242191E-04 1795.618
1.8104488E+10 1.0281169E-03 1757.238
1.3385922E+10 1.9146191E-04 1472.670
1.0324604E+10 1.3626697E-04 2949.091

TE011 10.328 **TE012** 13.388 **TE021** 18.104 **TE022** 19.60

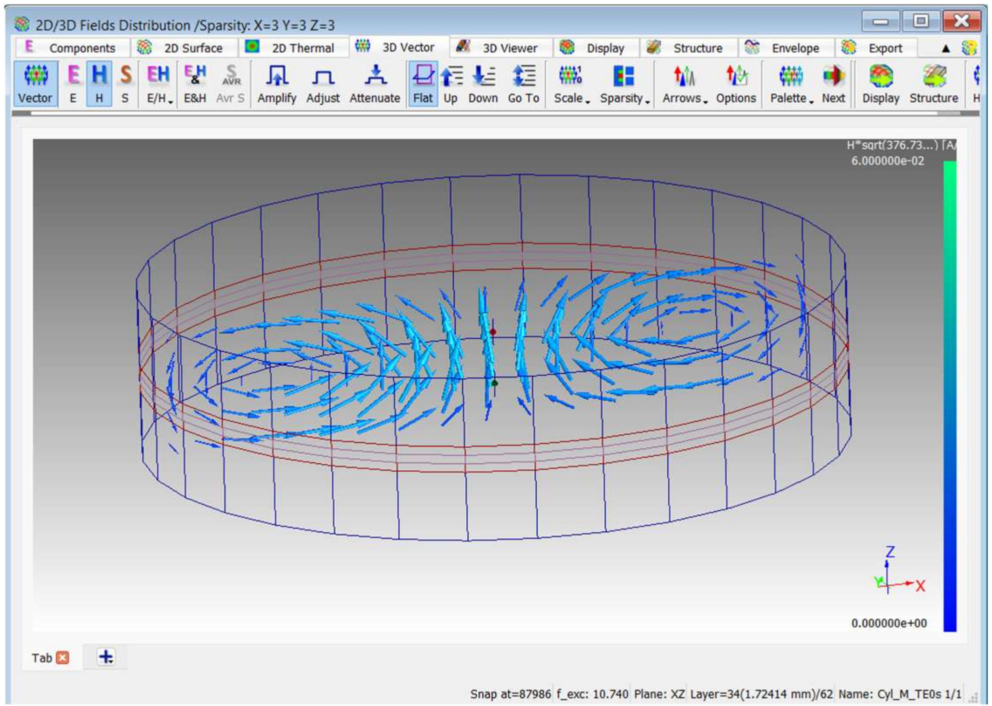


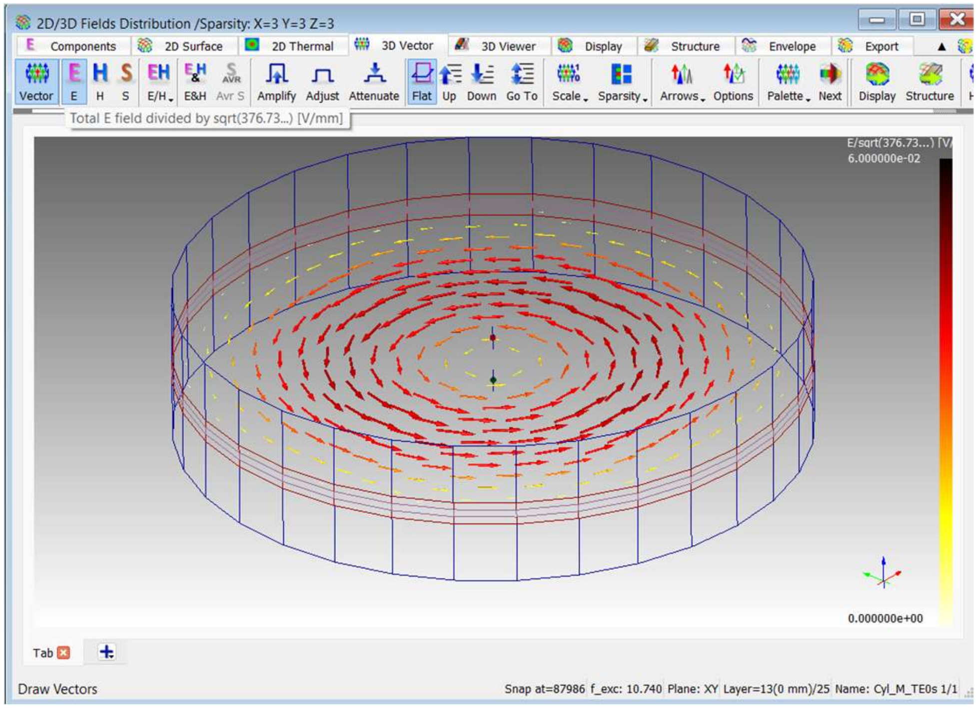
Central excitation by a magnetic monopole in the center would be perfect but it is non-physical



SPDR to QSSR Can we extend dielectric to entire cavity?

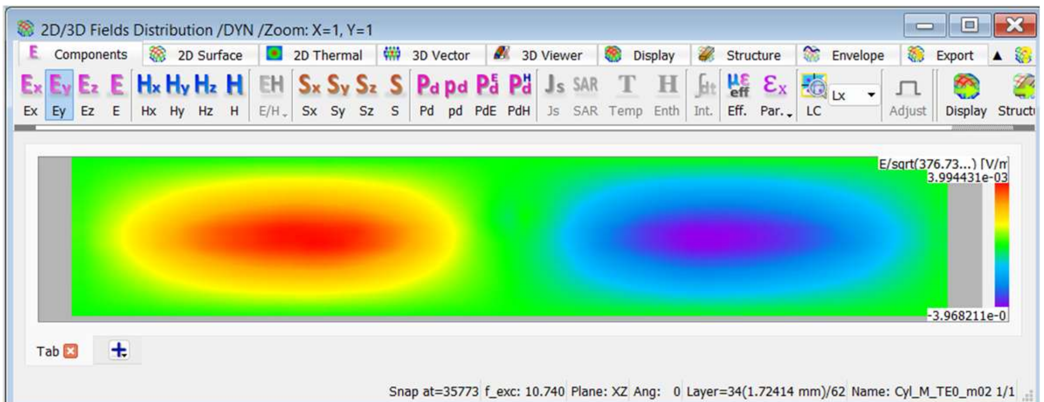
increasing D/h ratio of dielectric insert would enhance the chances of getting more useful (TE0n1) resonances but it would be more difficult to have the dielectric hanged by a central post

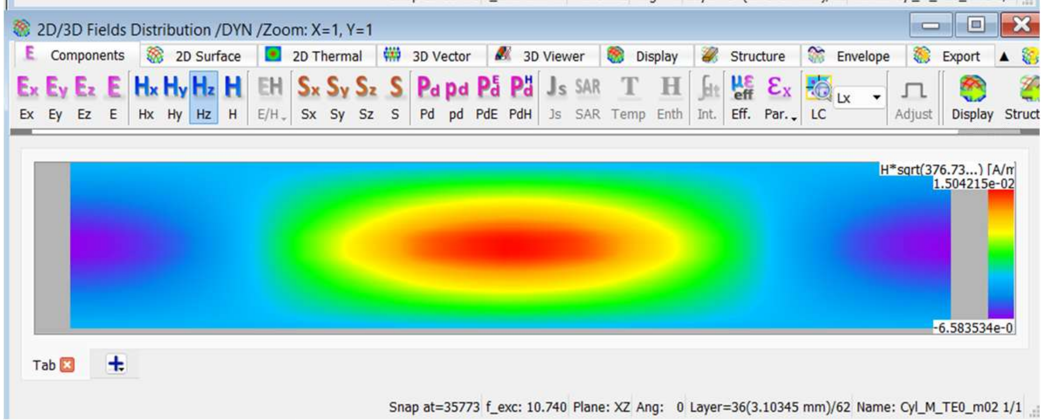


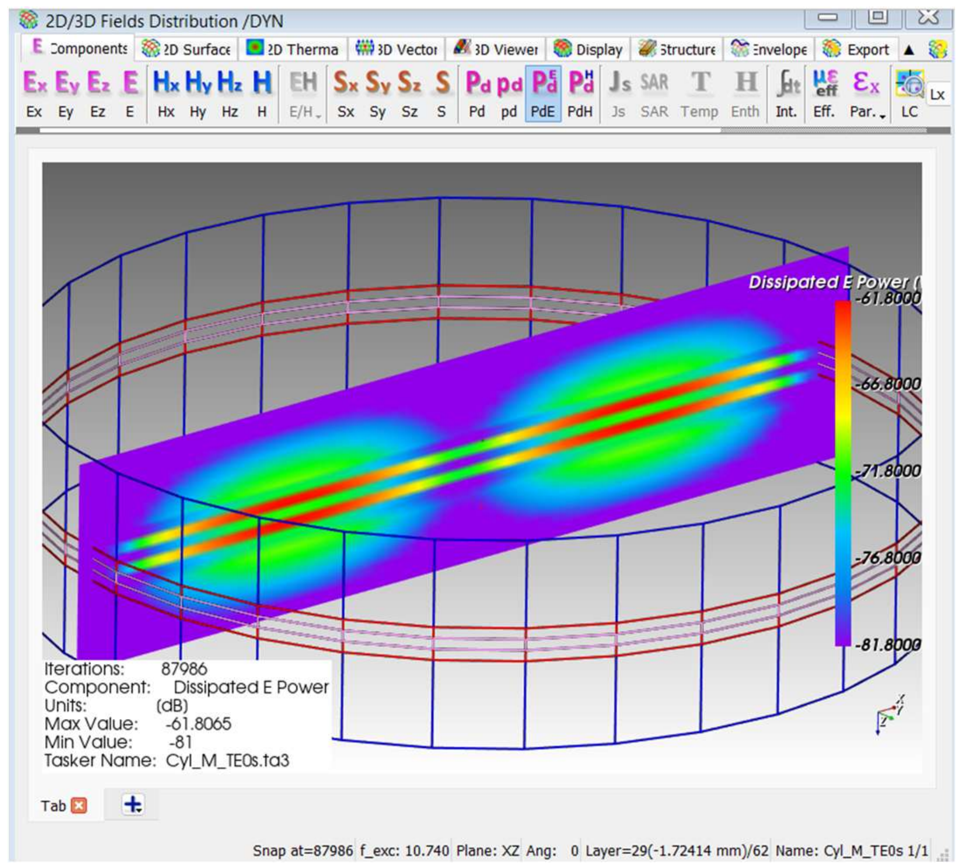


SPDR to QSSR Can we extend dielectric to entire cavity?

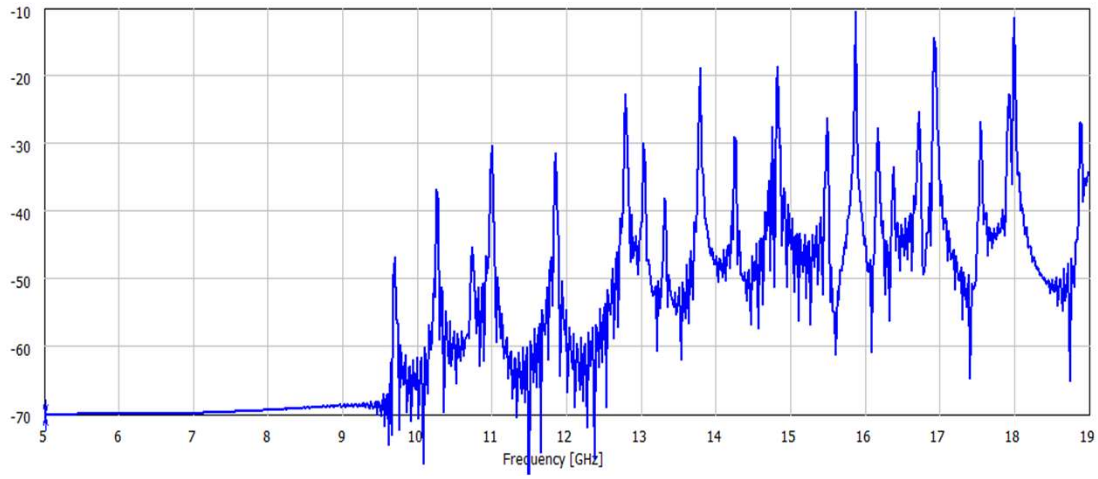
When the dielectric post size matches the size of cavity we may try to eliminate the post hanging.
The horizontal electric field (upper left) is continuous, electric energy is focused in the sapphire and the sample (right).



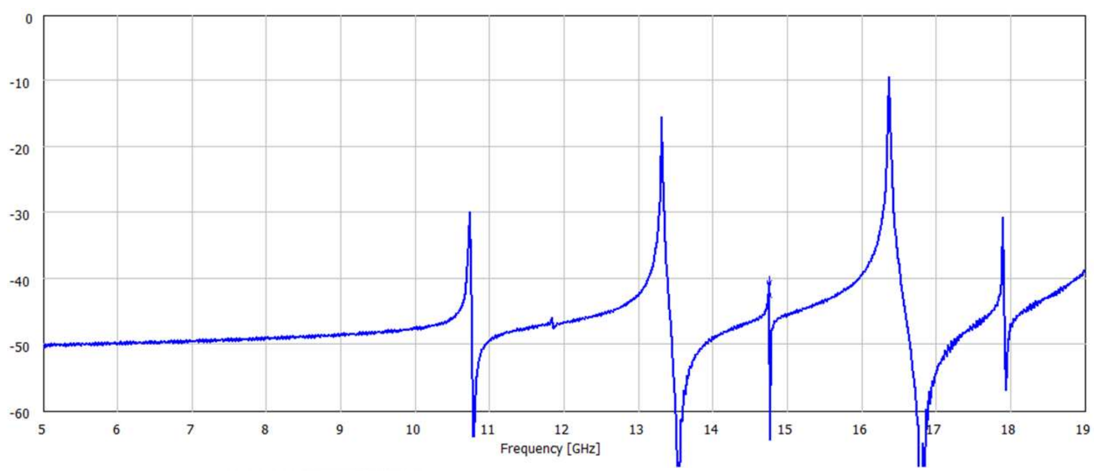




SPDR to QSSR Can we use the side excitation ?



TE011 TE012 TE021



Side excitation (upper drawing:

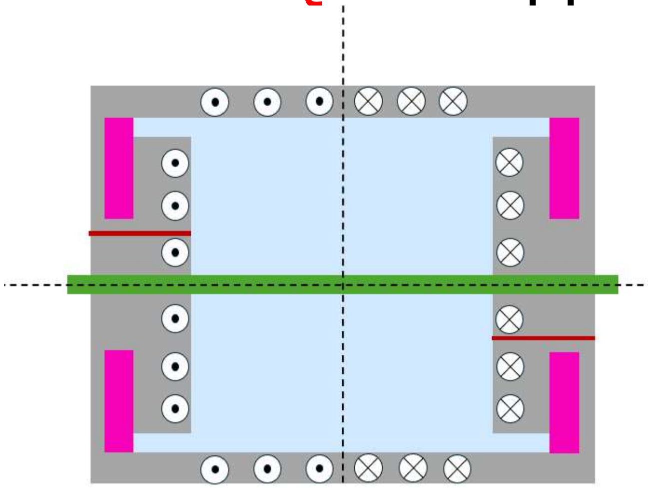
produces a plethora of modes.
Desired TE0n1 is difficult to detect

Excitation by centrally placed ports (lower drawing).

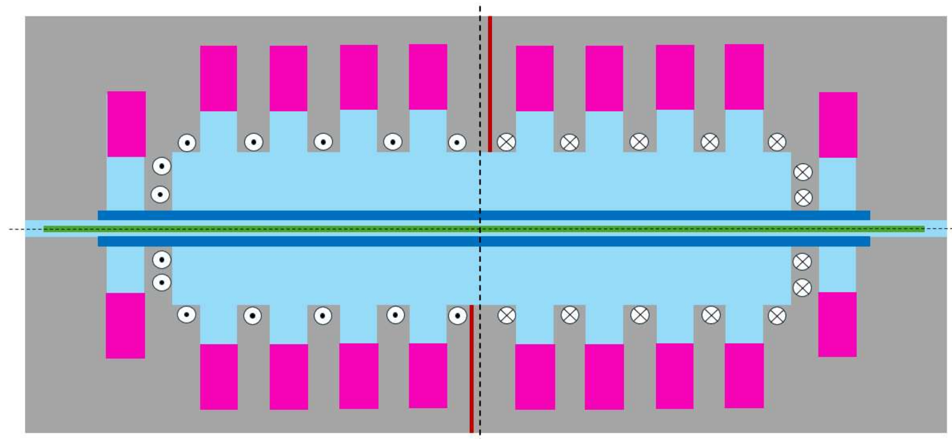
Looks much better,
but there is a problem with feasibility of such excitation.

It is obvious that side excitation would not work in SSR and we should do our best to find the arrangement as close as possible to central excitation.

SPDR to QSSR Application of Q-chokes



Q-Choked Split Cylinder Resonator (Q-SCR)
and currents in its metal encasement

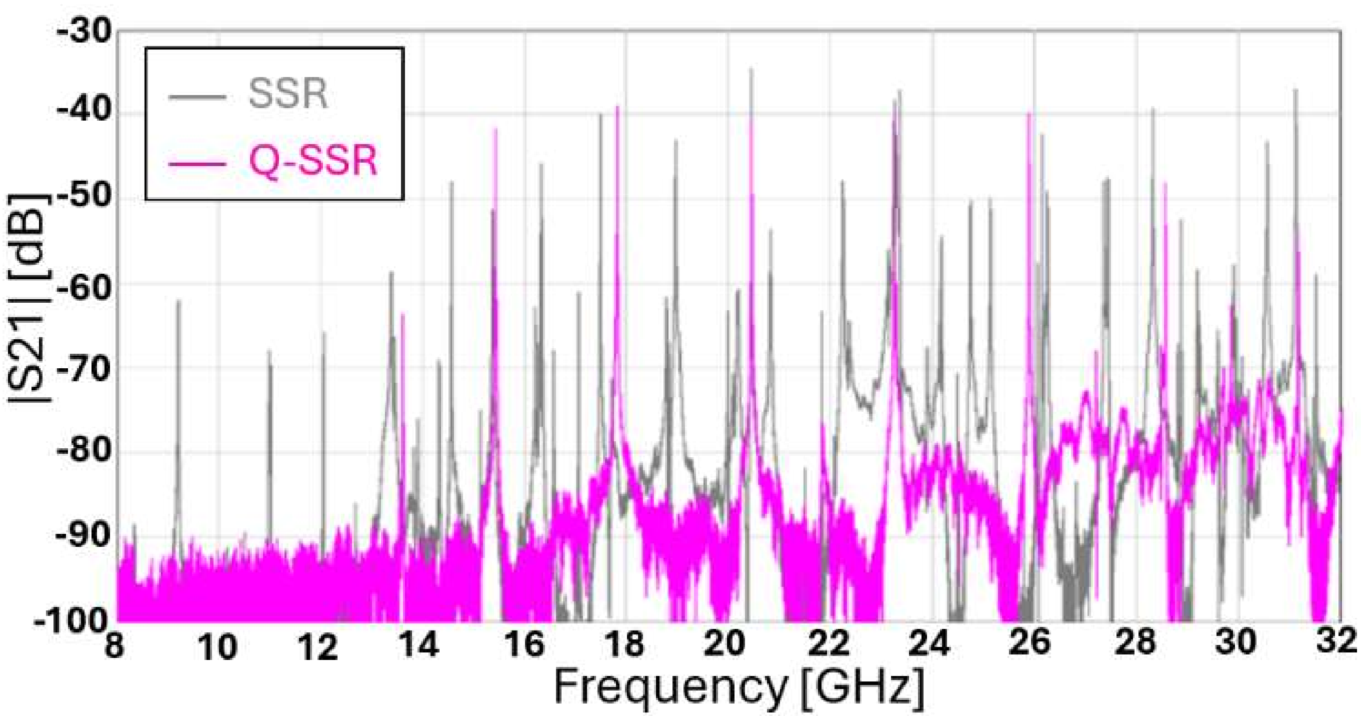


Q-Choked Sapphire Sandwiched Resonator (Q-SSR)
end currents in its metal encasement

Q-chokes in Q-SCR look different from those in Q-SSR, but their work is very similar in both cases.

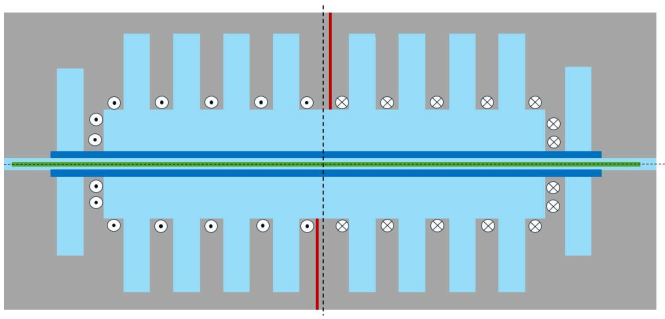
W .K. Gwarek (QWED)
Eur. Patent Appl. No. EP23461651.4, also: Intl. Patent Appl. No. PCT/IB2024/056934

SPDR to QSSR Application of Q-chokes

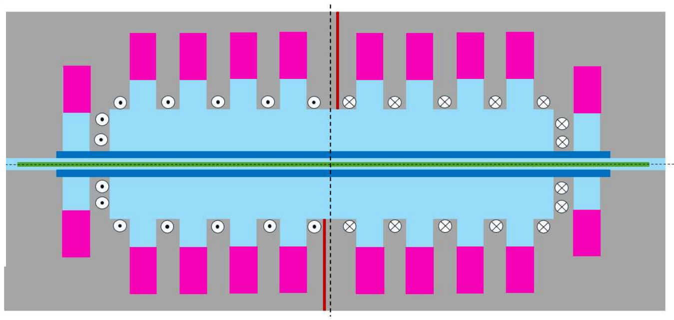


Measured transmission through Q-SSR and SRR (both empty)

SSR (without choke)



Q-SSR (with choke)

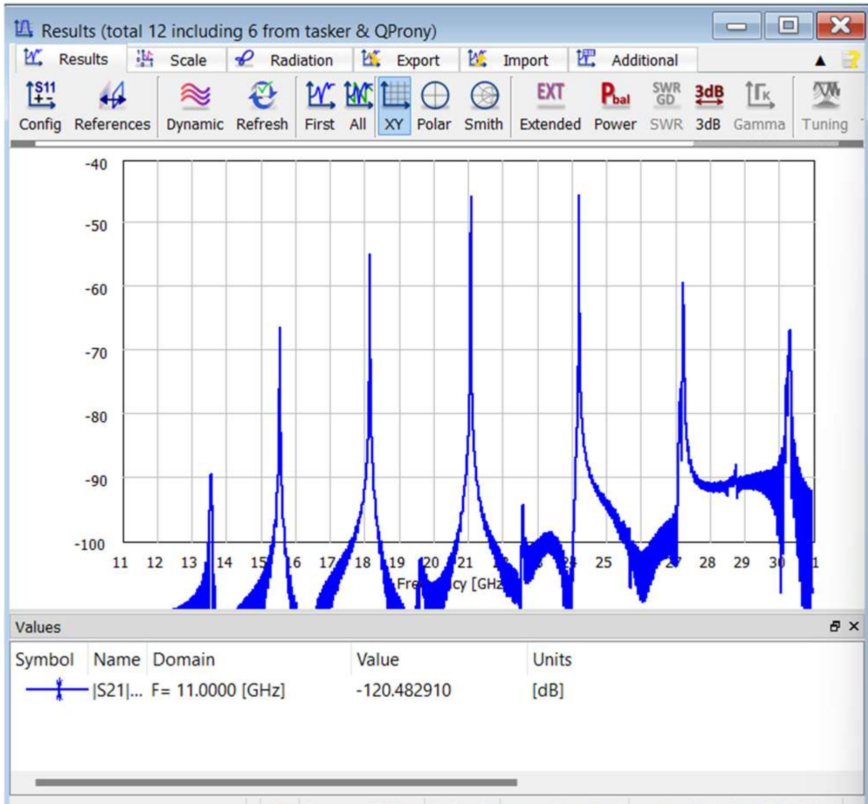


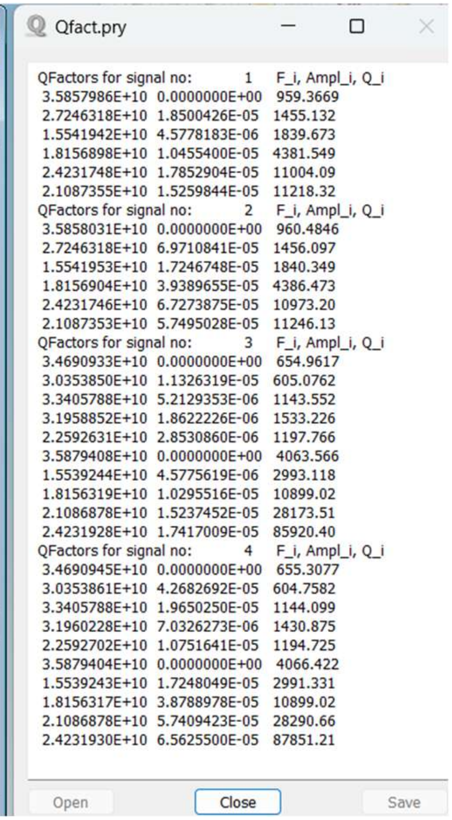
Measured difference of unloaded Q-factors between SSR and Q-SSR

n-th Resonance	1		2		3		4		5		6	
Parameter	Frequency [Ghz]	Q-Factor	Frequency [Ghz]	Q-Factor	Frequency [Ghz]	Q-Factor	Frequency [Ghz]	Q-Factor	Frequency [Ghz]	Q-Factor	Frequency [Ghz]	Q-Factor
SSR – 0.6 mm Gap	11.867	7417	13.381	9320	17.984	14987	21.379	13361	24.778	15486	28.090	4953
QSSR – 0.6 mm Gap	11.823	8147	14.627	11396	17.912	12309	21.270	16092	24.625	17345	27.890	10759

Introduction of the lossy material at the bottom of the choke channels does not cause significant lowering of the Q-factor. Differences between SSR and Q-SSR should be attributed rather to less reliable extraction of Q-factors in multi-resonance environment of SSR.

From an SPDR with extended D/h ratio to QSSR





Qfact.pry

QFactors for signal no: 1 F_i, Ampl_i, Q_i
3.5857986E+10 0.0000000E+00 959.3669
2.7246318E+10 1.8500426E-05 1455.132
1.5541942E+10 4.5778183E-06 1839.673
1.8156898E+10 1.0455400E-05 4381.549
2.4231748E+10 1.7852904E-05 11004.09
2.1087355E+10 1.5259844E-05 11218.32
QFactors for signal no: 2 F_i, Ampl_i, Q_i
3.5858031E+10 0.0000000E+00 960.4846
2.7246318E+10 6.9710841E-05 1456.097
1.5541953E+10 1.7246748E-05 1840.349
1.8156904E+10 3.9389655E-05 4386.473
2.4231746E+10 6.7273875E-05 10973.20
2.1087353E+10 5.7495028E-05 11246.13
QFactors for signal no: 3 F_i, Ampl_i, Q_i
3.4690933E+10 0.0000000E+00 654.9617
3.0353850E+10 1.1326319E-05 605.0762
3.3405788E+10 5.2129353E-06 1143.552
3.1958852E+10 1.8622226E-06 1533.226
2.2592631E+10 2.8530860E-06 1197.766
3.5879408E+10 0.0000000E+00 4063.566
1.5539244E+10 4.5775619E-06 2993.118
1.8156319E+10 1.0295516E-05 10899.02
2.1086878E+10 1.5237452E-05 28173.51
2.4231928E+10 1.7417009E-05 85920.40
QFactors for signal no: 4 F_i, Ampl_i, Q_i
3.4690945E+10 0.0000000E+00 655.3077
3.0353861E+10 4.2682692E-05 604.7582
3.3405788E+10 1.9650250E-05 1144.099
3.1960228E+10 7.0326273E-06 1430.875
2.2592702E+10 1.0751641E-05 1194.725
3.5879404E+10 0.0000000E+00 4066.422
1.5539243E+10 1.7248049E-05 2991.331
1.8156317E+10 3.8788978E-05 10899.02
2.1086878E+10 5.7409423E-05 28290.66
2.4231930E+10 6.5625500E-05 87851.21

Open Close Save

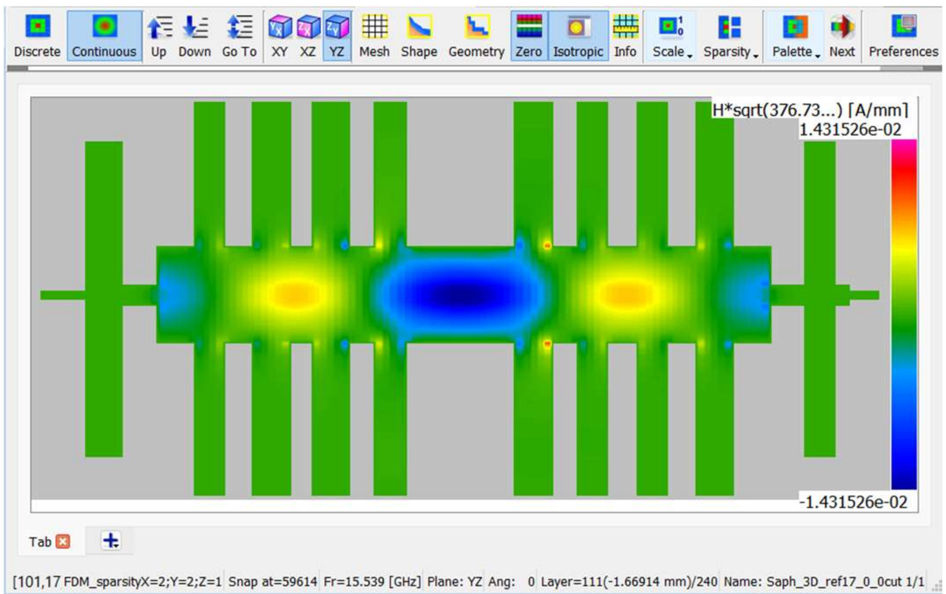
Simulations were performed using QW-3D software by QWED.
Left: abs(S21) obtained by FDTD single simulation with Gaussian pulse excitation and Q-Prony signal-processing module. Center: resonant frequencies extracted by Q-Prony.

On the next slides we present field distributions obtained with similar one-run simulation, but during the second run performing Fourier analysis of fields at particular resonant frequencies obtained from the first run.

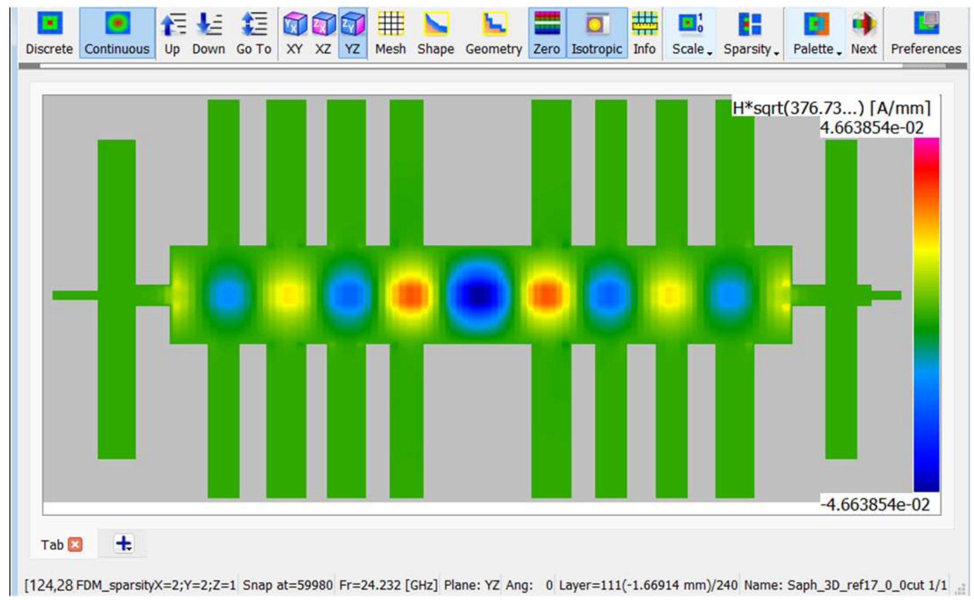
Simulation of a QSSR with cavity diameter of d=36.4mm, h=4mm with two plates of 0.5 mm 2” monocrystal epi-ready sapphire.

Modes in Q-SSR

Hz field patterns simulated with QuickWave 3D FDTD: long-section images at the second and the fifth resonant mode



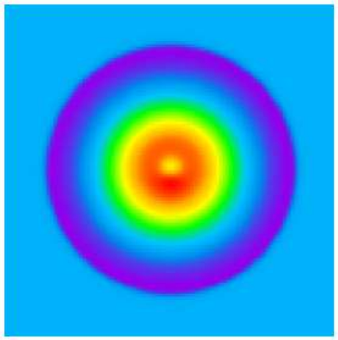
2^{nd} mode



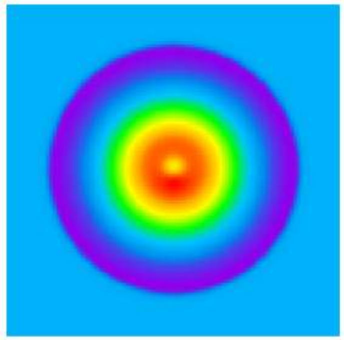
5^{th} mode

Modes in Q-SSR

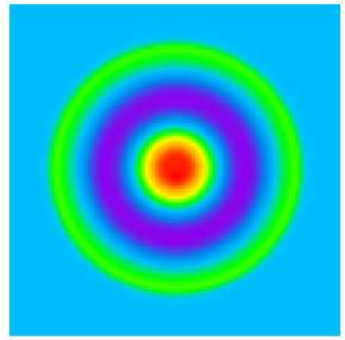
Hz field patterns simulated with QuickWave 3D FDTD: cross-section



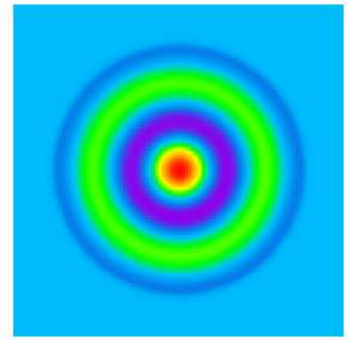
13.62 [GHz]



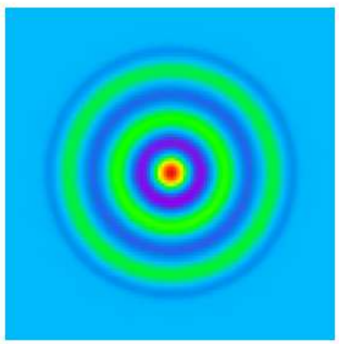
15.54 [GHz]



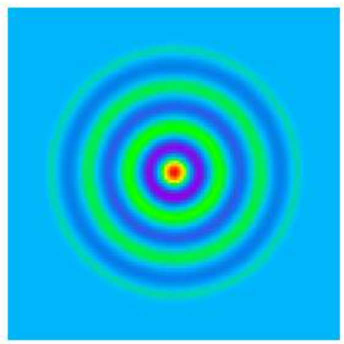
18.07 [GHz]



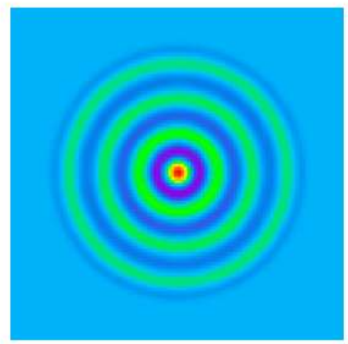
20.89 [GHz]



23.93 [GHz]

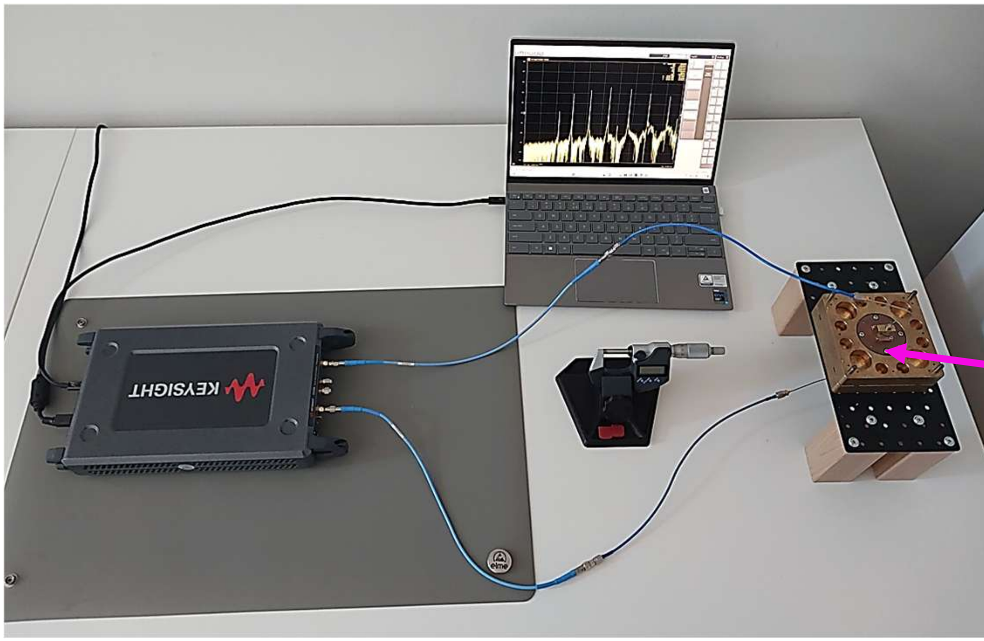


26.85 [GHz]



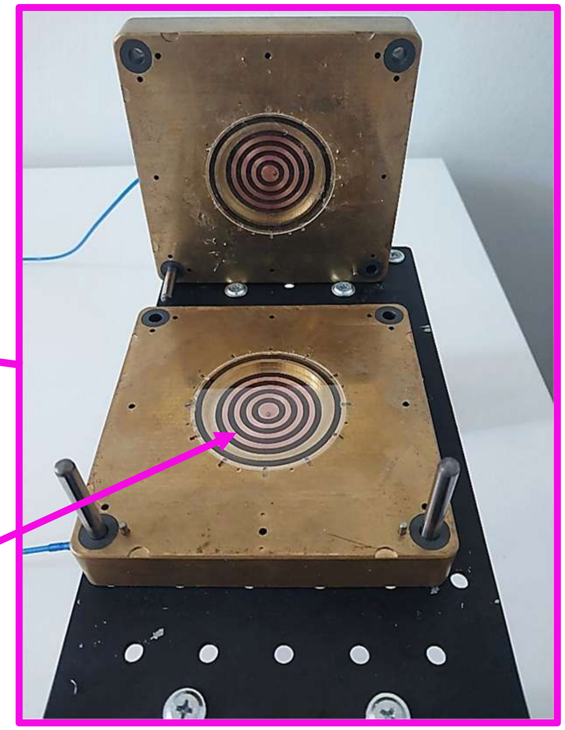
29.83 [GHz]

Q-SSR – Measurement Setup



Q-SSR prototype in the measurement setup

Corrugations
(copper rings partially
filled with conductive PLA)



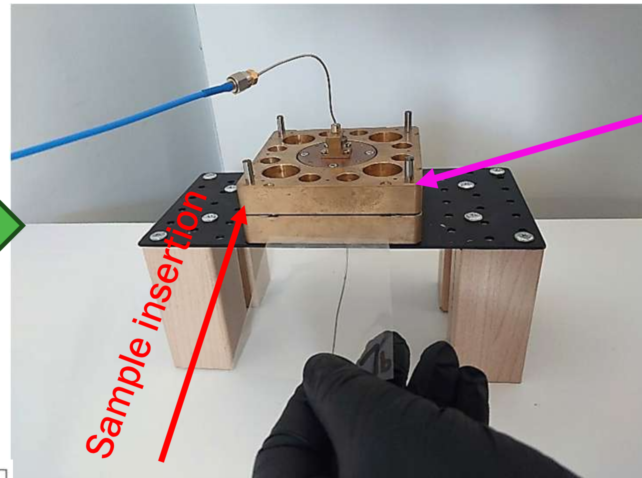
dismantled - open to reveal
its inner construction with Q-Choke.

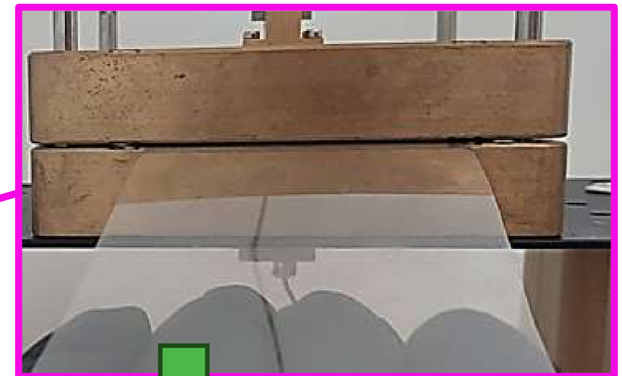
Measurement Procedure

1. Measure resonant frequencies and Q-factors of empty Q-SSR.

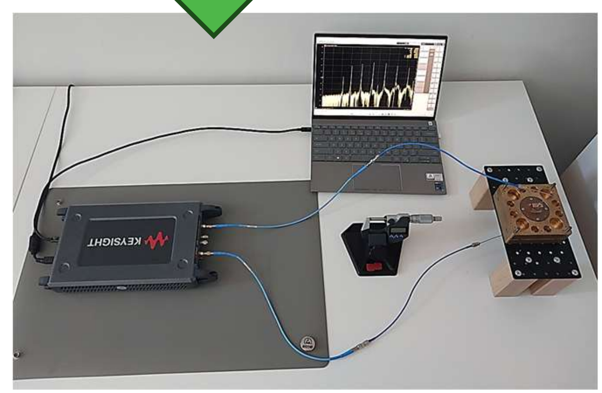
2. Prepare samples, measure thickness

3. Insert sample into Q-SSR slot

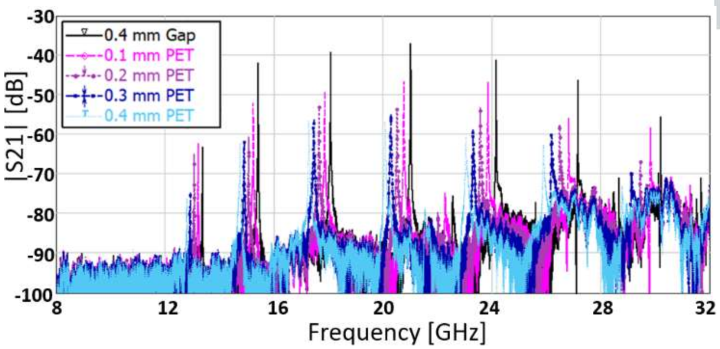




4. Measure resonant frequencies and Q-factors of the Q-SSR with sample



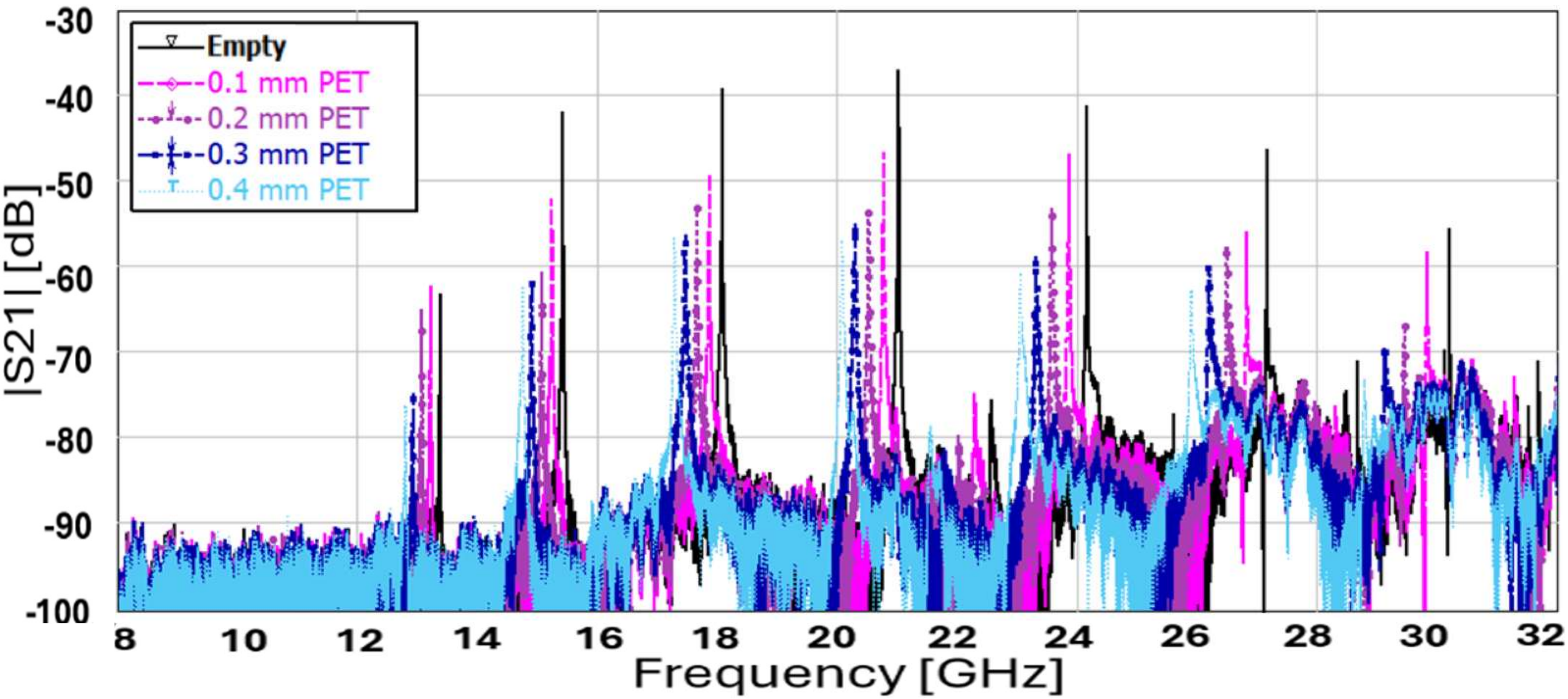
4. Dedicated software Calculate a Dielectric constant ε and loss tangent tanδ



5. Example of 4 PET Samples measured on Q-SSR

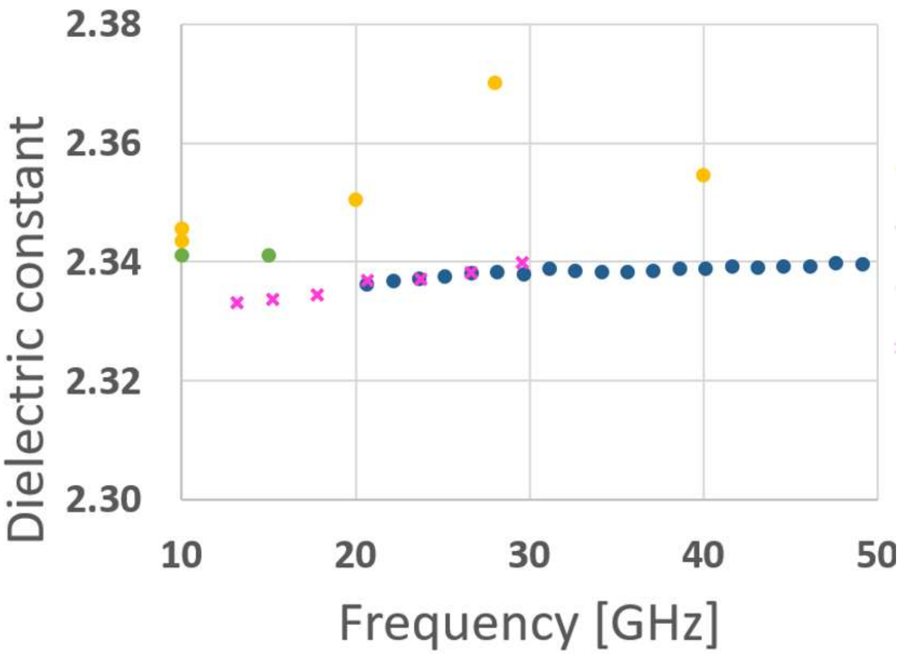
Measurements of stacks of PET samples

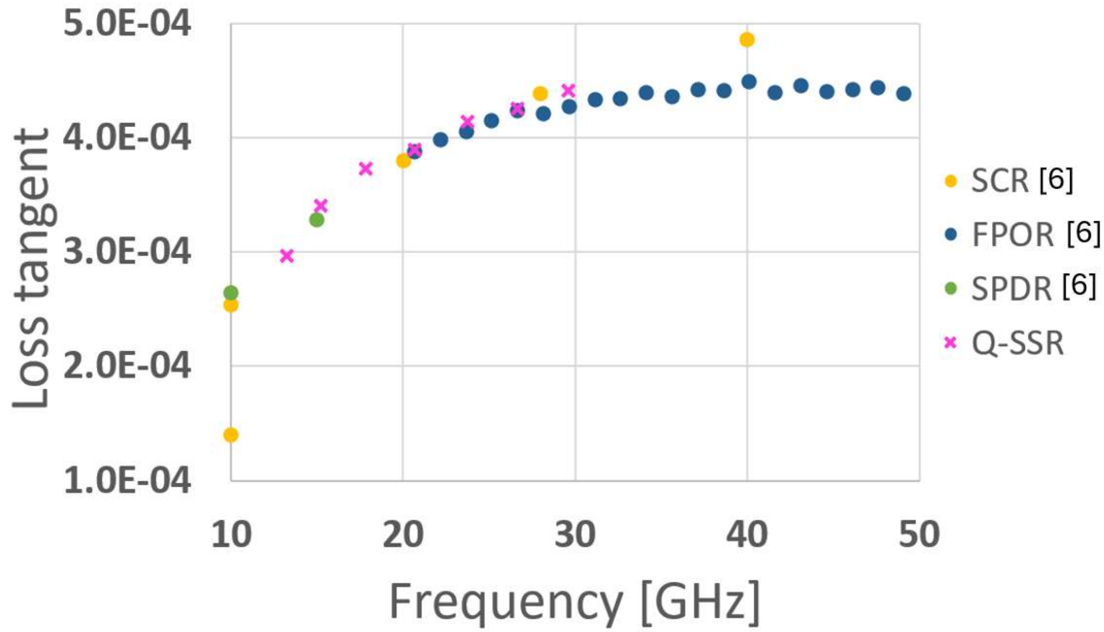
Measured transmission through the Q-SSR prototype: empty and loaded with 1÷4 samples of PET foils, each ca. 0.1 mm thick.



Validation on Industry Benchmark Sample

COP (cyclo-olefin-polymer) sample chosen as benchmark for the industrial round-robin testing in [5]





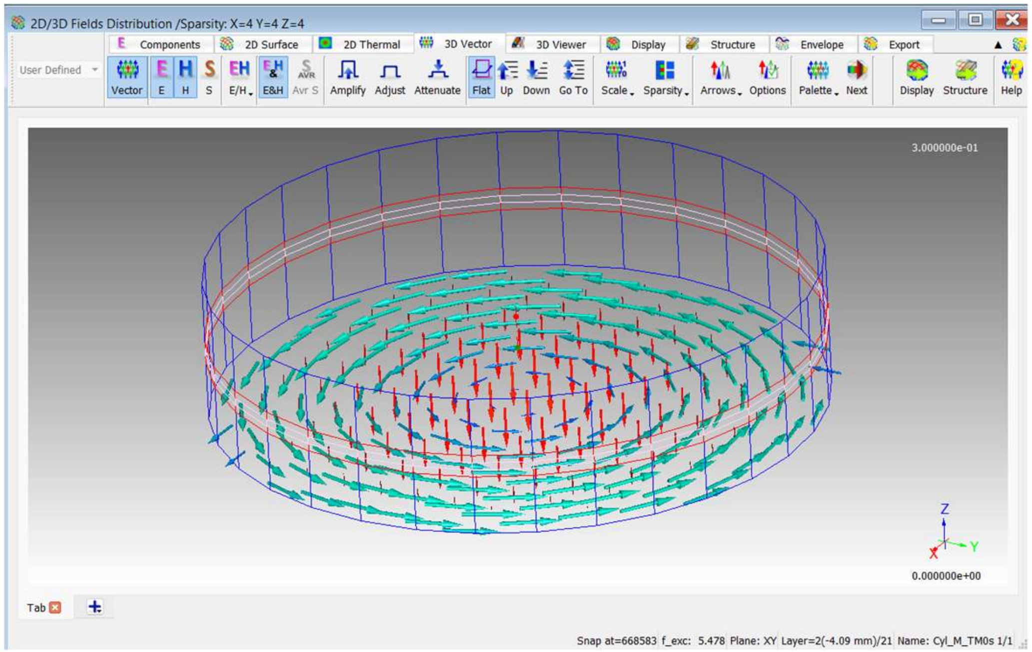
[5] Int. Electron. Manuf. Initiative. (2024). 5G/6G mmWave Materials and Electrical Test Technology Roadmap. [Online]. Available: https://www.inemi.org/article content.asp?adminkey=cc22bf8eb1bfb8248c594509fe54dd9b&article=275

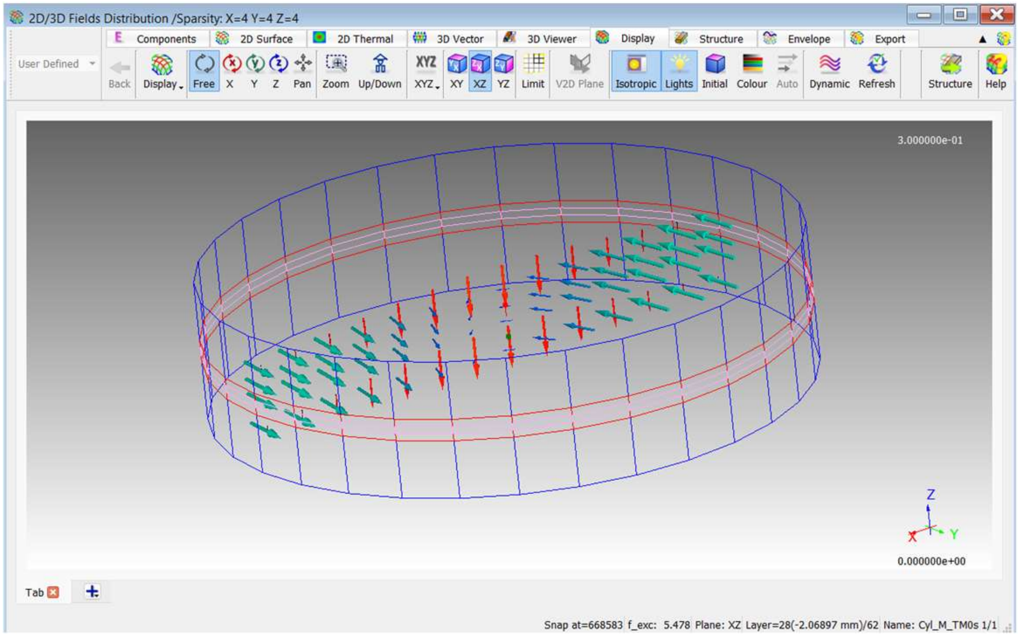
[6] M. Celuch et al., "Benchmarking of GHz resonator techniques for the characterisation of 5G / mmWave materials," in Proc. 51st Eur. Microw. Conf. (EuMC), Apr. 2022, pp. 568–571.

Supplement

Can we use TM modes for measurements in an SSR

Answer : In general yes … but…



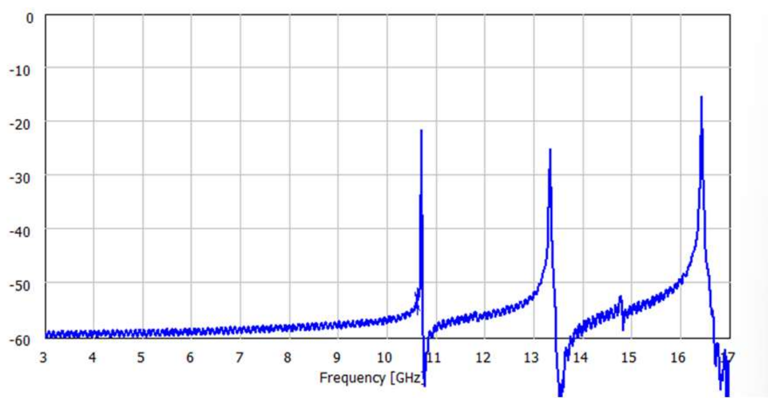


Distribution of E-field (red-to yellow) and H-field (green-to blue) of TM010 mode in SSR

Supplement

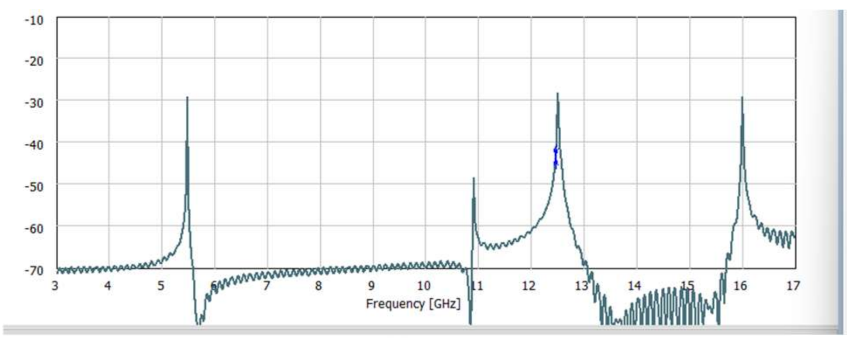
Can we use TM modes for measurements in an SSR?

Answer : In general yes… but…




```
Qfact.pry
QFactors for signal no:        1   F_i, Ampl_i, Q_i
 1.8025339E+10  1.4502328E-05   3238.504
 1.9676000E+10  0.0000000E+00   11691.28
 1.0719850E+10  4.3109114E-05   6502.404
 1.6464181E+10  3.1370937E-04   10913.38
 1.3354578E+10  1.7595300E-04   10921.22
QFactors for signal no:        3   F_i, Ampl_i, Q_i
 1.8026318E+10  4.0981040E-06   5065.090
 1.0719833E+10  7.6336783E-06   5197.083
 1.9675972E+10  0.0000000E+00   11073.58
 1.6464201E+10  8.3203755E-05   11110.94
 1.3354535E+10  3.8338203E-05   10810.04
QFactors for signal no:        4   F_i, Ampl_i, Q_i
 1.8026256E+10  2.9215953E-05   5581.768
 1.0719827E+10  5.3372376E-05   5109.868
 1.9675990E+10  0.0000000E+00   10939.42
 1.6464202E+10  5.9176120E-04   11142.45
 1.3354531E+10  2.6988611E-04   10758.94
```

Simulation of an SSR excited by a vertical H-field source (as considered previously)…




```
QFactors for signal no:        1   F_i, Ampl_i, Q_
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 1.2527652E+10  1.7328276E-03   11146.50
 1.6025271E+10  8.4653840E-04   14441.60
 5.4785587E+09  3.4377250E-04   5362.434
 1.0913507E+10  1.3614036E-04   11044.61
QFactors for signal no:        2   F_i, Ampl_i, Q_
 1.9492235E+10  0.0000000E+00   12934.92
 1.2527651E+10  2.1640912E-03   11063.99
 1.6025275E+10  1.3522106E-03   14551.51
 5.4785326E+09  1.8776572E-04   5375.638
 1.0913498E+10  1.4809296E-04   11533.75
QFactors for signal no:        3   F_i, Ampl_i, Q_
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 1.6025205E+10  2.2235769E-04   13287.38
 1.2527627E+10  3.6632767E-04   11088.60
 1.0913646E+10  2.4690136E-05   15319.87
 5.4785603E+09  3.2171862E-05   8316.657
QFactors for signal no:        4   F_i, Ampl_i, Q_
 1.9492352E+10  0.0000000E+00   13176.86
```
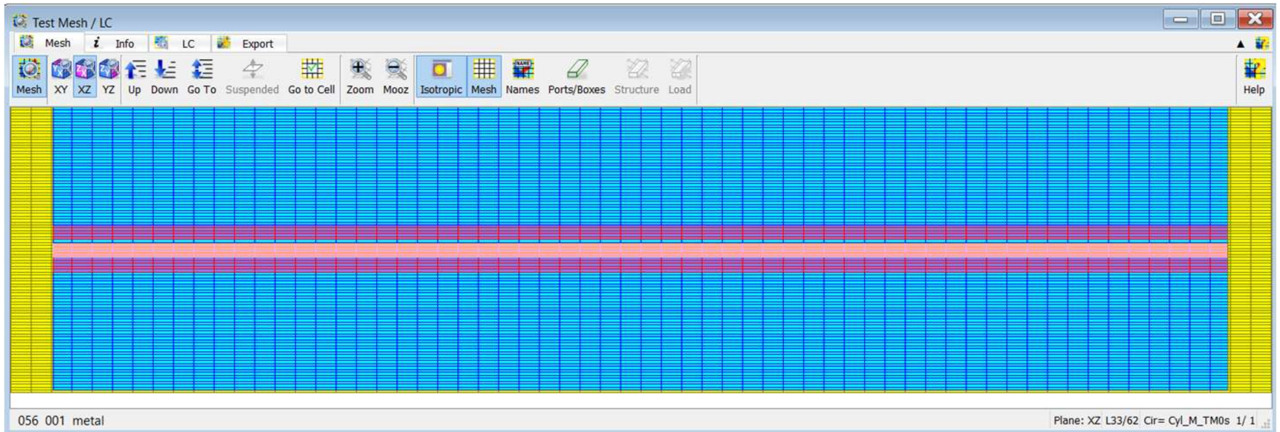
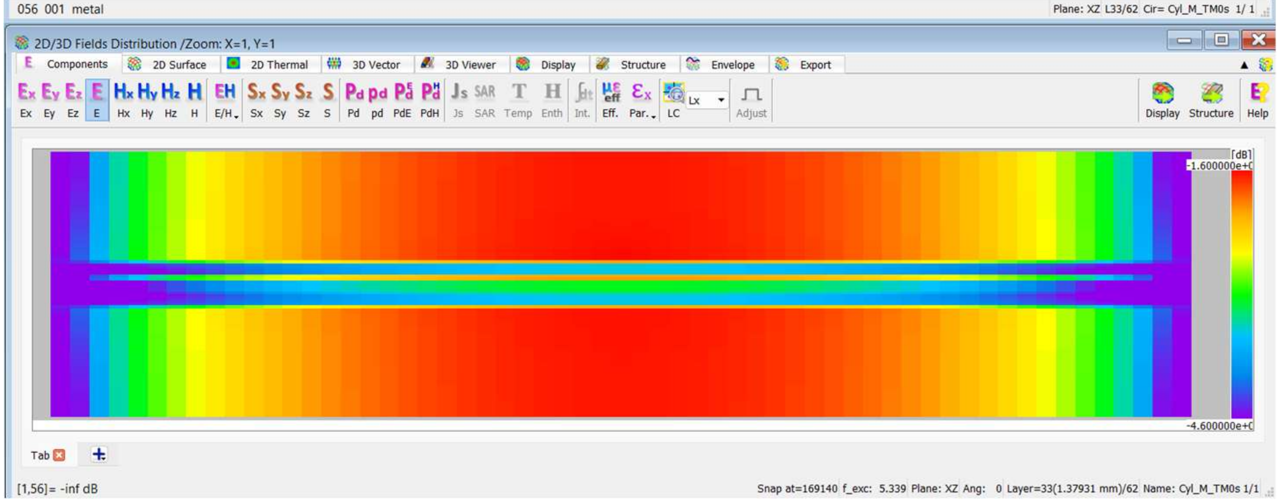

…and by a vertical E-field source. It produces a variety of TM modes including the dominant TM010 at 5.478 GHz (much lower then the TE011 considered before).

Supplement

Can we use TM modes for measurements in an SSR?

Yes, but the accuracy will be very low especially for high-ε samples





Simulation of an SSR with a slot of 0.8 mm partly filled with 0.6 mm sample of relative dielectric permittivity of 6.
Colors of materials in the upper picture air-blue; sapphire- brown; sample-pink.

The TM01 mode produces vertical E-field in the center. Boundary conditions for fields normal to the media boundary produce continuous vertical D-field. That is why lower permittivity of a material produces higher E-field in it

See lower picture with colors showing E-field intensity (scale span 0-20dB). The highest concentration of electrical energy is in the air and the lowest in the sapphire. That influences the resonant f.

Resonant frequency is mostly defined by the shape of the air-filled area. Changes introduced by the properties of the sample would be very small and measurement accuracy-very low.

Comparison of sensitivity of QSSR to other resonator

To compare sensitivity of QSSR to other resonators we introduce FF01 equal to relative change of resonant frequency after inserting a sample of thickness 0.1 mm and relative permittivity 2.
Here is the comparison of FF01 for different resonators

SPDR 10GHz- 1.18 10^{-3} ;
SPDR 5GHz - 0.47 10^{-3} ;
Q-SCR - 1.97 10^{-3} ;
Q-SCR (slot mode) - 1.51 10^{-3} ;
Q-SSR (at the 6-th resonance – 5.5 10^{-3}) ;

Conclusions: QSSR is much more sensitive than other resonators. In fact, the sensitivity of QSSR can be relatively easily changed by applying Sapphire of different thickness, because Sapphire wafers are available in a variety of thicknesses, (thicker Sapphire – lower sensitivity). That is practically impossible in SPDR which uses custom-made dielectric posts.
However, it should be admitted that:

- **Higher sensitivity is not always advantageous because it lowers the range of measurements for high losses;**
- **Sensitivity of Q-SCR can be increased (even to about 5 10^{-3}) by limiting the height of the resonator, although at the cost of lower unloaded Q-factor.**

Summary

The recently invented Q-Choke, which purifies spectra of cylindrical resonators to unperturbed TE0np modes, has been applied in a new **Q-Choked Sapphire Sandwiched Resonator (Q-SSR).**

Q-SSR combines the advantages of SCR, Q-SCR, and SPDR test-fixtures for dielectric material measurement, in particular combines:

- field-focusing by dielectric post in SPDR and its simplicity of operation (fixed slot)
- with spurious-mode-suppression by several Q-Chokes working similarly to the one applied in recent Q-SCR.

Additionally, Q-SSR provides the following features:

- extends application to **multi-modal / multi-frequency measurements** (6-7 modes)
- covers a **broad frequency range** (at least 1:2.5 ratio)
- uses easily-accessible **standard Sapphire wafers** instead of expensive custom-made dielectrics
- filling factor (determinant to **sensitivity**) **can be modified** by applying Sapphire of different thickness

It bridges the gap between traditional cavity / dielectric resonators and emerging **FPOR** instruments.

First prototype has been manufactured and successfully validated on reference industrial samples.

Acknowledgement

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The National Centre for Research and Development

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M-ERA.NET

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I4Bags

eureka eurostars

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5G Foil

We kindly acknowledge the collaborations with our partners in the above European projects.

iNEMI International Electronics Manufacturing Initiative

We acknowledge the iNEMI "5G" partnerships for round-robin experiments and discussions.

Thanks and have a nice visit to Mont Saint Michel

Time to retire

View of the Mt.S. Michel parking in 2008.
Today you will not be able to see it like that and hear an announcement: „Attention: Parking no 2 will be flooded in 30 minutes”. The parking has been moved to mainland,

Photo from an exhibition of Gilbert Garcin in Rennes taken the same day as that of the parking. It is clearly an illustration of the life of a scientist