Italian National Committee

Commission A: Electromagnetic Metrology, Electromagnetic measurements and standards

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Dielectric characterization of materials at microwave frequencies

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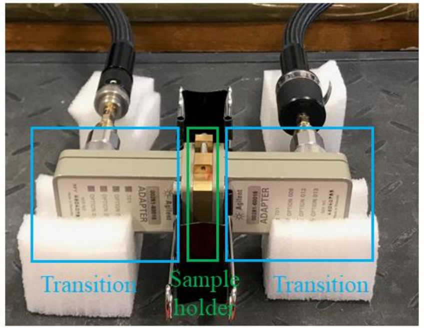
Microwave systems for material characterization and monitoring

- Cultural Heritage Monitoring

- Health Monitoring in Concrete Structures

- Composite Materials Characterization

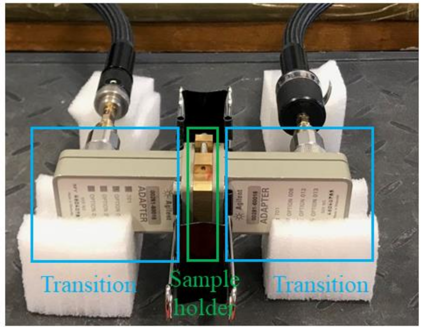


Microwave systems for material characterization and monitoring

- **Cultural Heritage Monitoring**

- Health Monitoring in Concrete Structures

- Composite Materials Characterization



Cultural Heritage Monitoring

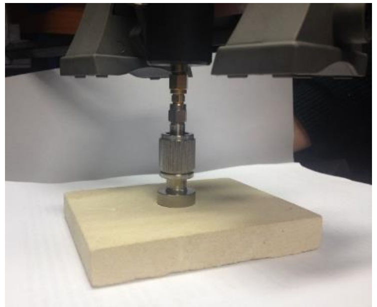
Aim:

non-invasive microwave technique for moisture monitoring in historical buildings

Cultural Heritage Monitoring

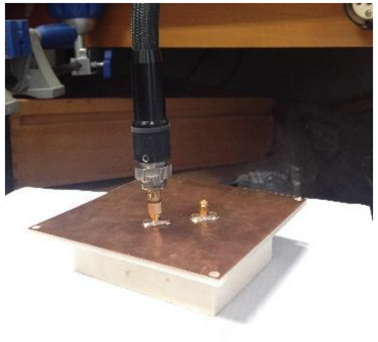
Different methods and probes were comparatively assessed to infer, noninvasively, the water content of stone materials starting from dielectric properties at microwave frequencies

Open Ended Coaxial (OEC)



Open Ended Waveguide (OEW)

Patch Resonator (PR)



- **allow noninvasive approach**
- **easy to use in the field**
- **can be realized in low cost versions**

Agilent E8363C VNA

Campbell Scientific TDR100 reflectometer

Cultural Heritage Monitoring

$\varepsilon_{\mathrm{r,stone}} \cong 5 - 6$ (dry stone)

$\varepsilon_{\mathrm{r,water}} \cong 78$ (25° C)

GENTILE STONE

3.0 cm × 7.7 cm × 10.1 cm

LECCESE STONE

1.5 cm × 8.2 cm × 10.1 cm

SAMPLE MOISTENING PROCEDURE:

(1) drying of the sample (volume V_{stone} in cm^3) in a microwave oven;

(2) weighing of the dry sample, W_{dry} (in g);

(3) bath in deionized water until saturation (which, for the considered samples, took less than two hours);

(4) weighing of the sample, W_i (in g);

(5) assessment of the gravimetric moisture θ_v :

$$\theta_v = \frac{W_i - W_{dry}}{V_{stone} \cdot \rho_W} \times 100;$$

(6) measurements through the different probes and instruments;

(7) oven drying for a limited amount of time, in order to remove part of the moisture.

E. Piuzzi, G. Cannazza, A. Cataldo, E. De Benedetto, L. De Giorgi, F. Frezza, G. Leucci, S. Pisa, **E. Pittella**, S. Prontera, F. Timpani, "A comparative assessment of microwave-based methods for moisture content characterization in stone materials", *Measurement*, Volume 114, 2018, Pages 493-500, ISSN 0263-2241.

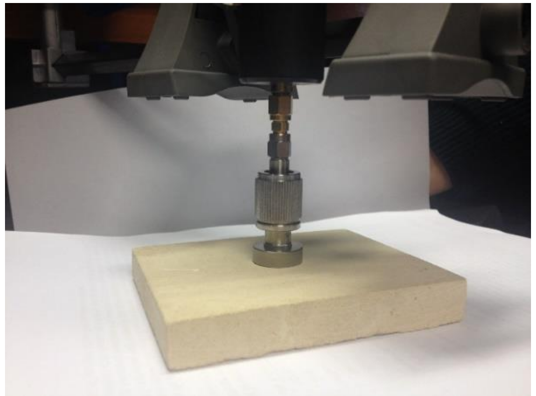
Open-ended coaxial (OEC) probe

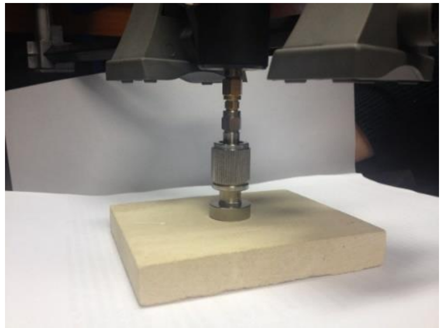
KEYSIGHT HIGH TEMPERATURE PROBE

- range: 200 MHz to 20 GHz
- suitable for permittivity measurements on liquids and solid materials with flat surfaces
- Diameter sample > 2 cm and thickness > $\frac{2}{\sqrt{\varepsilon_r}}$ cm

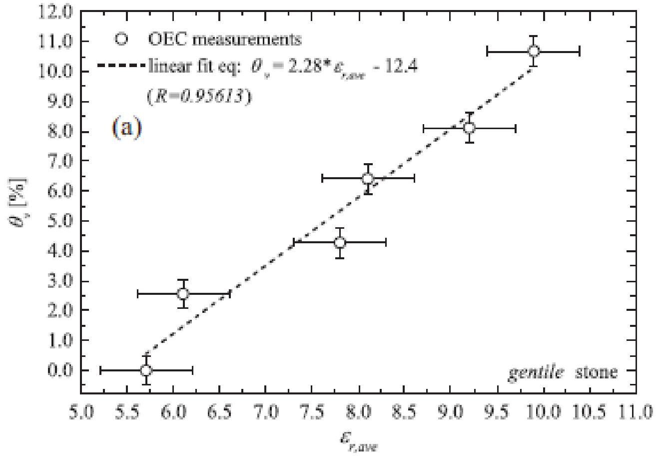
1. System calibration using air, shorting block and de-ionized water
2. S_{11} measured through a VNA
3. $S_{11} \rightarrow \varepsilon_r'$ (custom software [Piuzzi et al. 2013])
4. $\varepsilon_{r,ave}$ on the measurement band

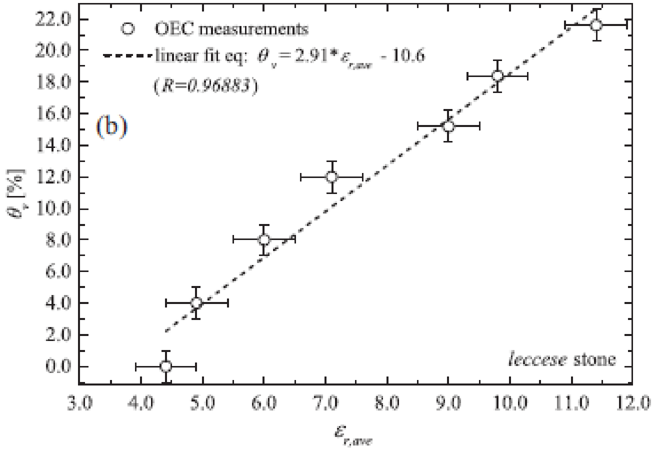
$\varepsilon_{r,ave} \longleftrightarrow \theta_v$



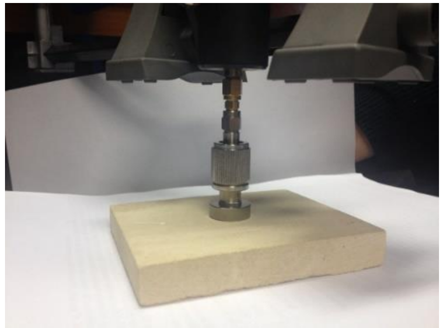
OEC



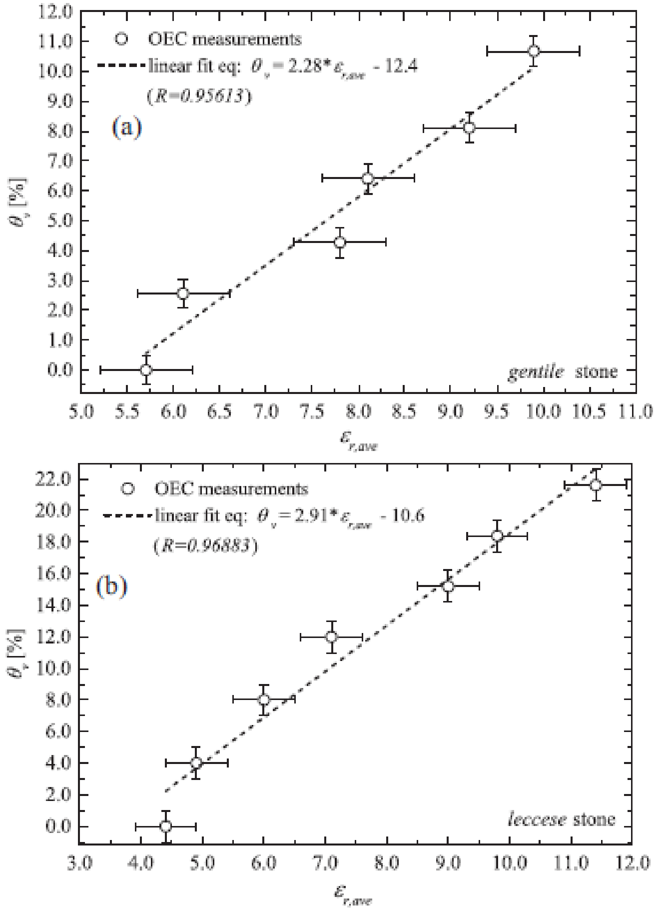


- Good linearity ϑ vs $\varepsilon_{r,ave}$

- Vertical error bars: due to water evaporation during measurement, it can be made negligible by avoiding oven drying
- Horizontal error bars: **scarse measurement repeatibility**
  1. the VNA port cable was kept still, through a mechanical vice; the inevitable mechanical pressure resulted in slight movements, which (although very little) led to movements of the cable changing its phase response
  2. the sensing volume of the probe is limited, the stone non homogeneous and the probe is positioned in different portions of the sample.



OEC



GENTILE

$$\vartheta_v = 2.28\varepsilon_r - 12.4$$

LECCESE

$$\vartheta_v = 2.91\varepsilon_r - 10.6$$

SENSITIVITY
0.35-0.45

MEASUREMENT REPEATABILITY	INSTRUMENTAL MEASUREMENT UNCERTAINTY
$WCU_{\varepsilon,rep} = 0.5$	$WCU_{\varepsilon,syst} = 0.05$

negligible

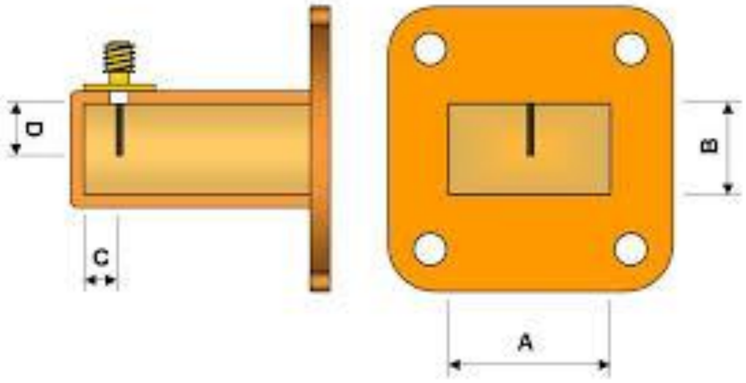
WCU $_{\vartheta_{v,G}}$ **= 1%**

WCU $_{\vartheta_{v,L}}$ **= 1.5%**

Care in the positioning
Scarce repeatability
Costs of the system (VNA + probe)
On-site calibration needed (complex)

Not suitable for in-the-field applications

Open-ended waveguide (OEW) probe

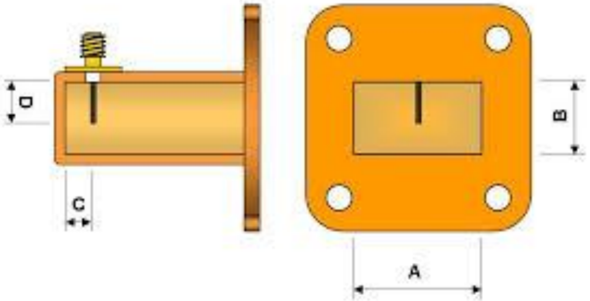


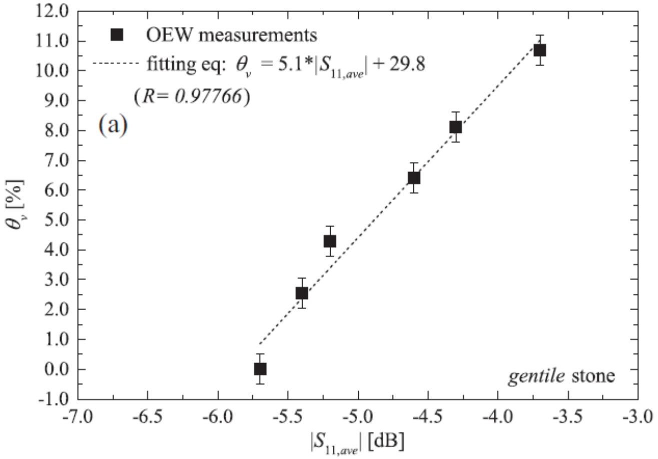
- frequency range: 8.2 GHz to 12.4 GHz (WR90 waveguide)
- dimensions: A = 22.86 mm
  B = 10.16 mm

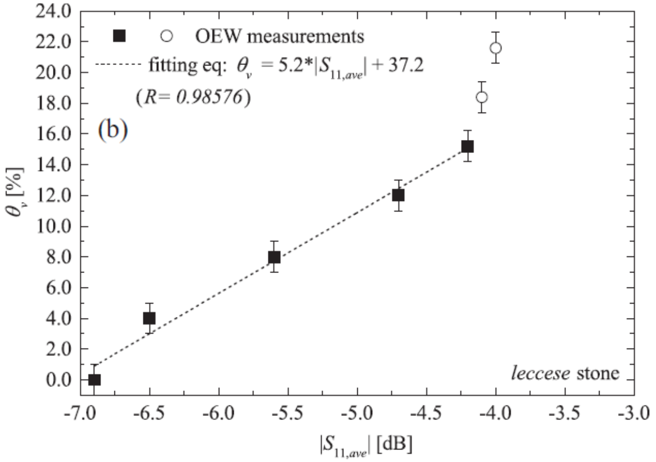
1. System calibration using a TRL mechanical kit
2. S_{11} measured through a VNA
3. $|S_{11,\mathrm{ave}}|$ over the measurement band

$$|S_{11,ave}| \longleftrightarrow \theta_v$$

OEW



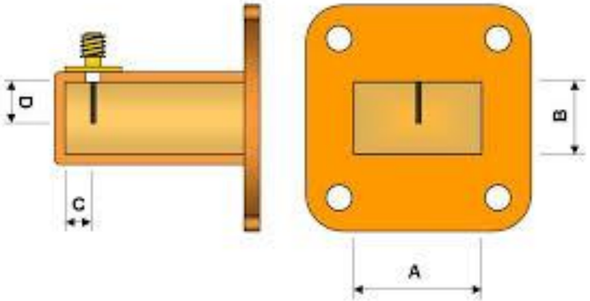


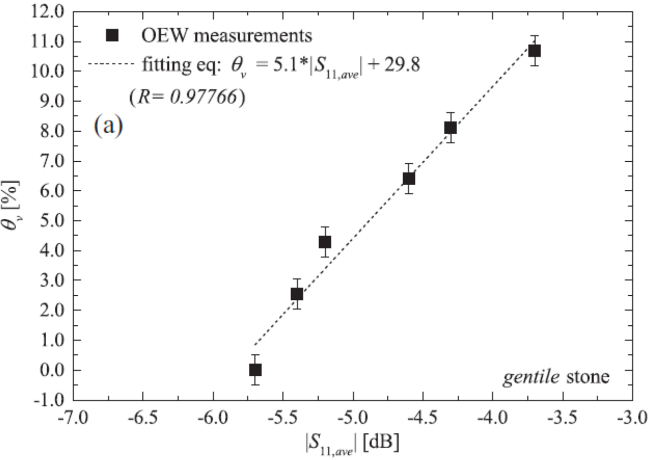


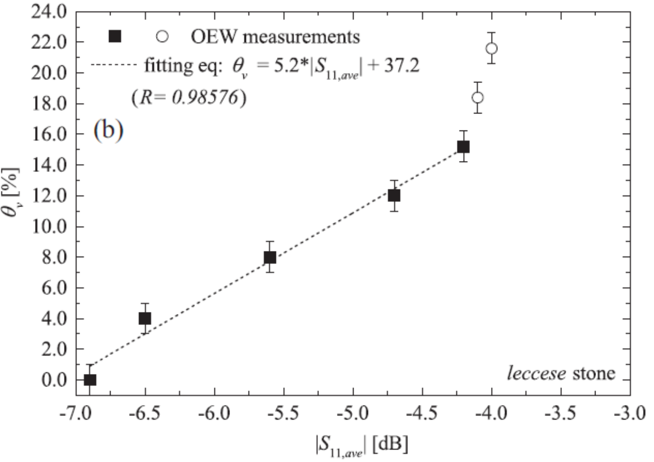
- $|S_{11,ave}|$ increases linearly with the water content, except for ϑ_V >15% (value well beyond commonly experienced moisture levels)

- almost the same angular coefficients (similar S_{11} behaviour for the 2 stones)

OEW







GENTILE

$$\vartheta_v = 5.1|S_{11,\mathrm{ave}}|+29.8$$

LECCESE

$$\vartheta_v = 5.2|S_{11,\mathrm{ave}}|+37.2$$

SENSITIVITY
0.2 dB

MEASUREMENT REPEATABILITY	INSTRUMENTAL MEASUREMENT UNCERTAINTY
$WCU_{S_{11},rep}$ =0.18 – 0.23 dB	$WCU_{S11,syst}$ = 0.1 dB

COMBINED STANDARD UNCERTAINTY

$\sigma_{S_{11},rep-G} = 0.13\ dB$ $\quad \sigma_{S_{11},rep-L} = 0.14\ dB$

$$u_{S11C-G} = \sqrt{\sigma_{S_{11},syst}^{2} + \sigma_{S_{11},rep,G}^{2}} = 0.14\ dB$$

$$\sigma_{S_{11},syst} = \frac{WCU_{S_{11},syst}}{\sqrt{3}} = 0.058\ dB$$ (uniform distribution)

$$u_{S11C-L} = \sqrt{\sigma_{S_{11},syst}^{2} + \sigma_{S_{11},rep,L}^{2}} = 0.17\ dB$$

EXPANDED UNCERTAINTY

hp: gaussian distribution

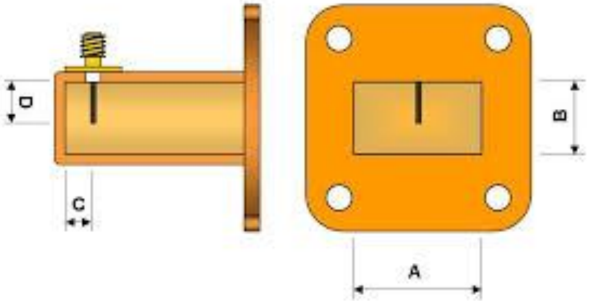
$$k_P = 2$$

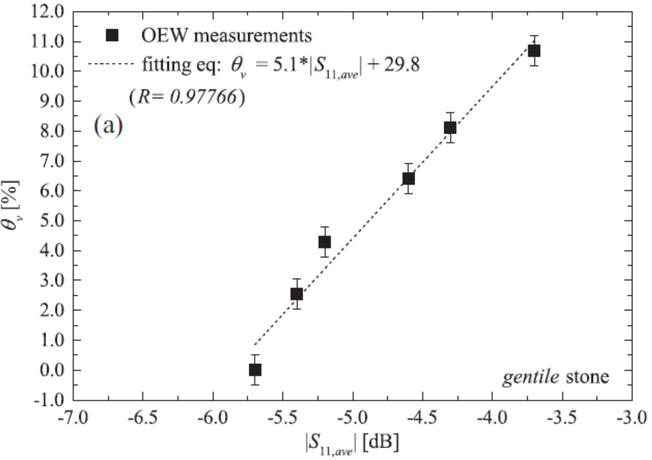
$$U_{S_{11},95\%-G} = 0.28\ dB$$
$$U_{S_{11},95\%-L} = 0.34\ dB$$

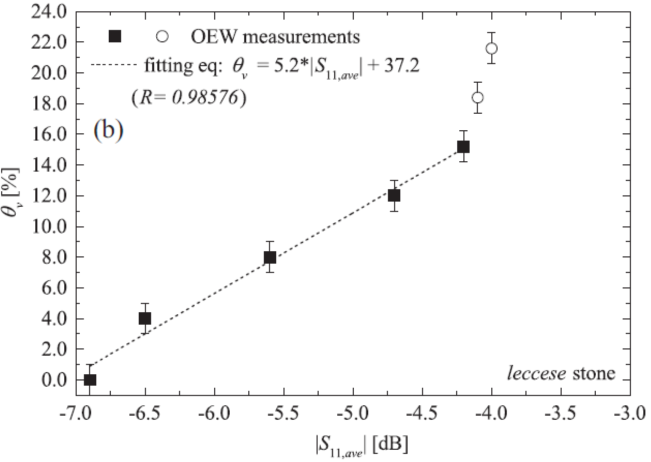
$$\boldsymbol{U_{\theta-G,95\%} = 1.4\%}$$
$$\boldsymbol{U_{\theta-L,95\%} = 1.7\%}$$

E. Piuzzi, **E. Pittella**, S. Pisa, A. Cataldo, E. De Benedetto, and G. Cannazza, "Microwave reflectometric methodologies for water content estimation in stone-made Cultural Heritage materials", *Measurement*, vol. 118, 2018, pp. 275-281.

OEW







GENTILE

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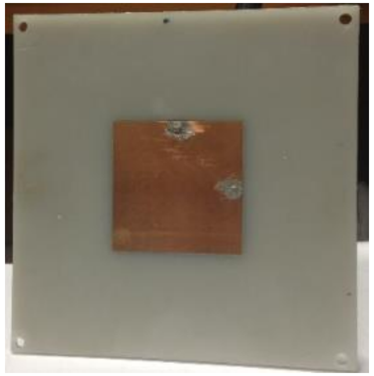
SENSITIVITY
0.2 dB

MEASUREMENT REPEATABILITY	INSTRUMENTAL MEASUREMENT UNCERTAINTY
$WCU_{S_{11},rep}$ =0.18 – 0.23 dB	$WCU_{S11,syst} = 0.1$ dB

Some care in the positioning
Scarce repeatability
Costs of the system (VNA)
On-site calibration needed (easy)

Does not seem a good solution for in-the-field applications

Patch resonator (PR) probe



Dielectric and geometric characteristics of the patch resonator.

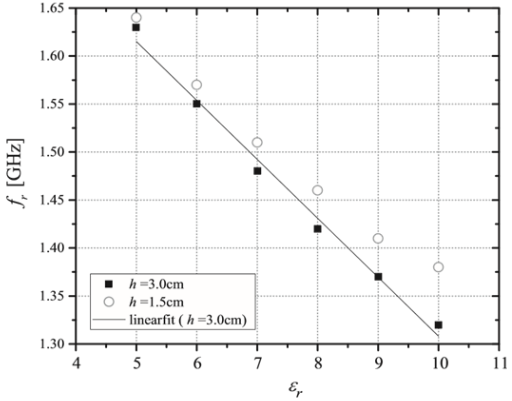
Parameter	Description
Substrate material	Polyflon
Substrate dielectric characteristics	$\varepsilon_{r,sub} = 2.32$
	tg δ = 0.0002
Substrate thickness	3.175 mm
Metallization thickness	35.6 µm (copper)
Patch dimensions	4.8 × 4.8 cm
Resonant frequency (in air)	$f_r \cong 2$ GHz

1. S_{11} measured through VNA or TDR
2. $S_{11} \rightarrow f_r$

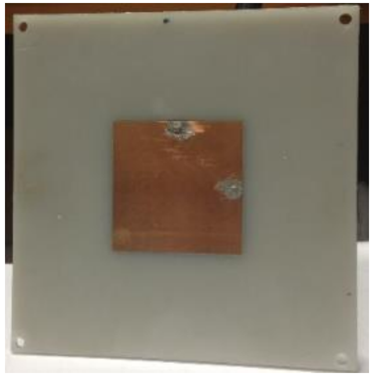
$f_r \rightarrow \varepsilon_r$

$\varepsilon_r \leftrightarrow \theta_v$

Preliminary full-wave simulations CST MWS



Patch resonator (PR) probe



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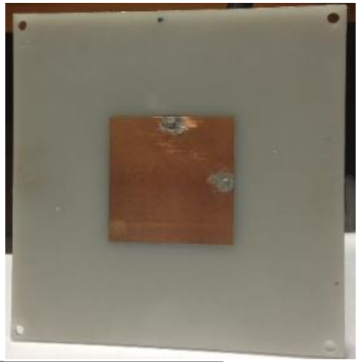
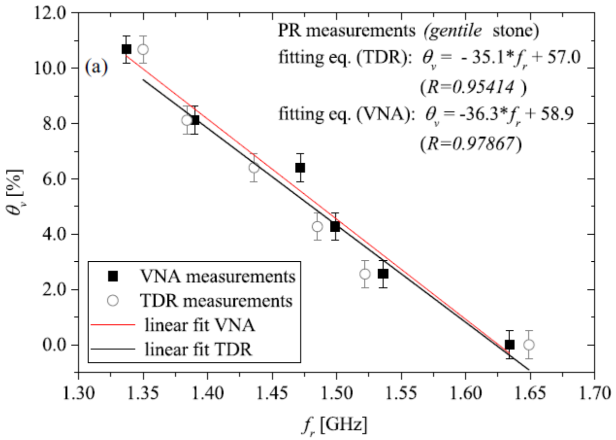
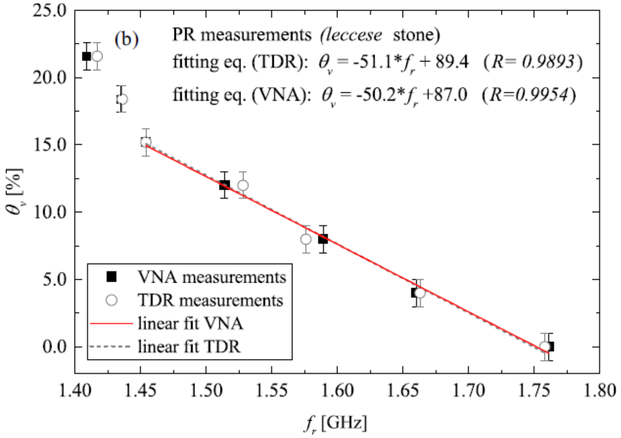
$$\boxed{f_r \longleftrightarrow \theta_v}$$

PR

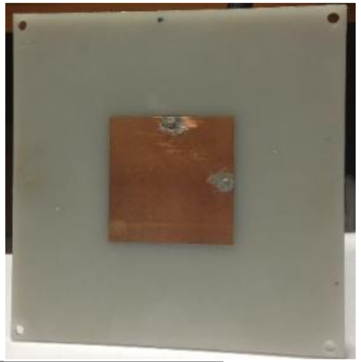


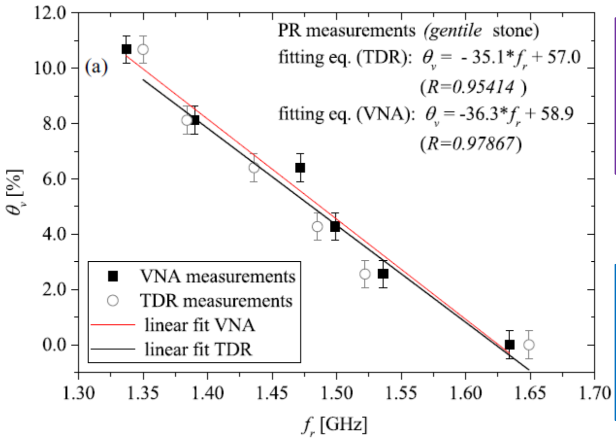


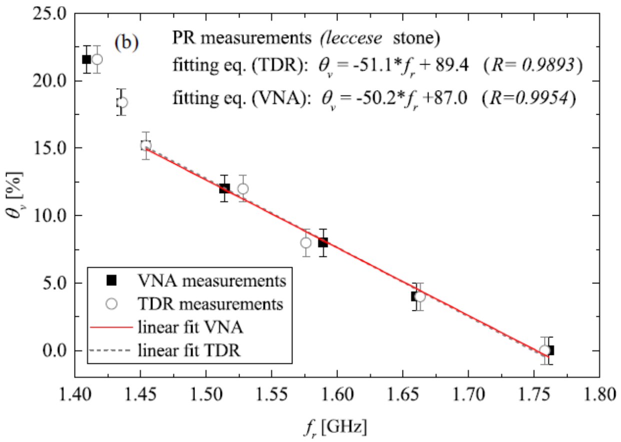


- linear relationship between the two quantities
- f_r decreases linearly with the water content, except for ϑ_V >15% (value well beyond commonly experienced moisture levels)

PR







GENTILE

$$\vartheta_{v\%} = -40 f_r + 59$$

LECCESE

$$\vartheta_{v\%} = -50 f_r + 88$$

SENSITIVITY
0.020–0.025 GHz

MEASUREMENT REPEATABILITY	INSTRUMENTAL MEASUREMENT UNCERTAINTY
$WCU_{f_r,rep}$ = 3.8 MHz	$WCU_{f_r,syst}$ = 2 kHz

negligible

WCU $_{\vartheta_v}$ $\cong \mathbf{0.2\%}$

Repeatability
Ease in positioning
Cheap (TDR solution)
Calibration **not needed**

Suitable
for in-the-field
application

E. Piuzzi, **E. Pittella**, S. Pisa, A. Cataldo, E. De Benedetto, and G. Cannazza, "Microwave reflectometric methodologies for water content estimation in stone-made Cultural Heritage materials", *Measurement*, vol. 118, 2018, pp. 275-281.

Comparative analysis

	MEAS.	INSTR.		CAL.	REPEAT.	POSITIONING	COST	
OEC	$\varepsilon_r \rightarrow \theta_v$	VNA		LIQUID	SCARSE	DIFFICULT	HIGH	
OEW	$S_{11} \rightarrow \theta_v$	VNA		TRL	SCARSE	SOME CARE	MEDIUM	
PATCH	$f_r \rightarrow \theta_v$	VNA	TDR	NO	HIGH	EASY	MEDIUM	LOW

Low cost of the sensor, low-cost instrumentation (TDR), simple positioning, high repeatability, no need for calibration

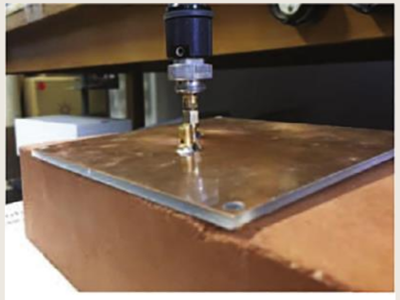
PATCH PROBE SUITABLE FOR IN THE FIELD APPLICATION

E. Piuzzi, **E. Pittella**, S. Pisa, A. Cataldo, E. De Benedetto, and G. Cannazza, "Microwave reflectometric methodologies for water content estimation in stone-made Cultural Heritage materials", *Measurement*, vol. 118, March 2018, pp. 275-281.

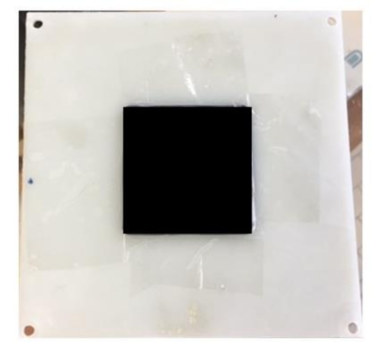
Patch resonator

Types of stones:

- **Gentile**
- **Leccese**
- **Carparo**
- **Red brick**
- **Heat Resistant Red brick**



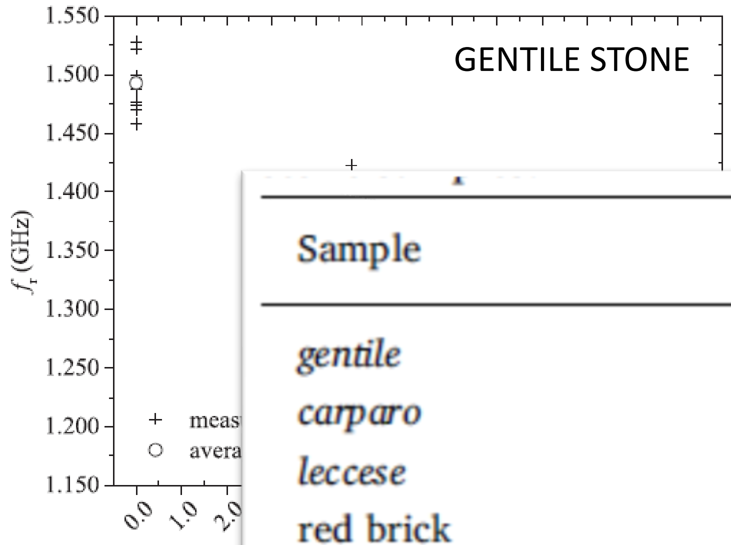
To improve the contact between the planar resonator and the rough surface of the stone, the copper patch was covered with a layer of conductive silicone

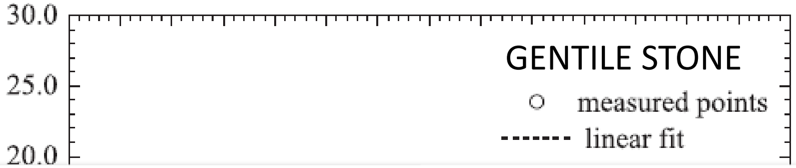


1. For each ϑ_{ref}, ten repeated measurements of $S_{11}(f)$
2. From $S_{11}(f)$ curves, evaluation of the resonance frequency ($f_{r,i}$, i = 1, …, 10)
3. Evaluation of the average f_r and standard deviation
4. f_r linked to the reference moisture ϑ_{ref}

E. Piuzzi, **E. Pittella**, S. Pisa, A. Cataldo, E. De Benedetto, G. Cannazza, “An improved noninvasive resonance method for water content characterization of Cultural Heritage stone materials” *Measurement*, 2018, 125, pp. 257-261.

Stone Results





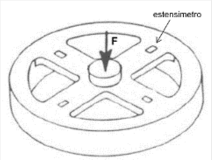
Sample	Calibration equation	R^2
gentile	$\theta = -47.38 f_r + 62.56$	0.98
carparo	$\theta = -41.99 f_r + 79.64$	0.99
leccese	$\theta = -47.38 f_r + 74.83$	0.99
red brick	$\theta = -49.79 f_r + 87.27$	0.99
red brick high temp.	$\theta = -38.30 f_r + 64.17$	0.99

Intercept	[illegible]
Slope	-41.99043 ± 3.26871
Residual Sum of Squares	1.6503
Pearson's r	-0.99103
R-Square(COD)	0.98215
Adj. R-Square	0.97619

E. Piuzzi, **E. Pittella**, S. Pisa, A. Cataldo, E. De Benedetto, G. Cannazza, "An improved noninvasive resonance method for water content characterization of Cultural Heritage stone materials" *Measurement*, 2018, 125, pp. 257-261.

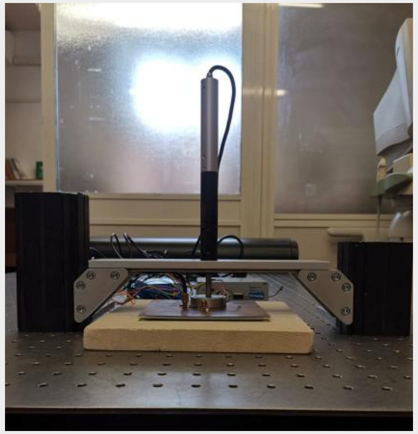
Load cell and portable reflectometry set-up

LOAD CELL

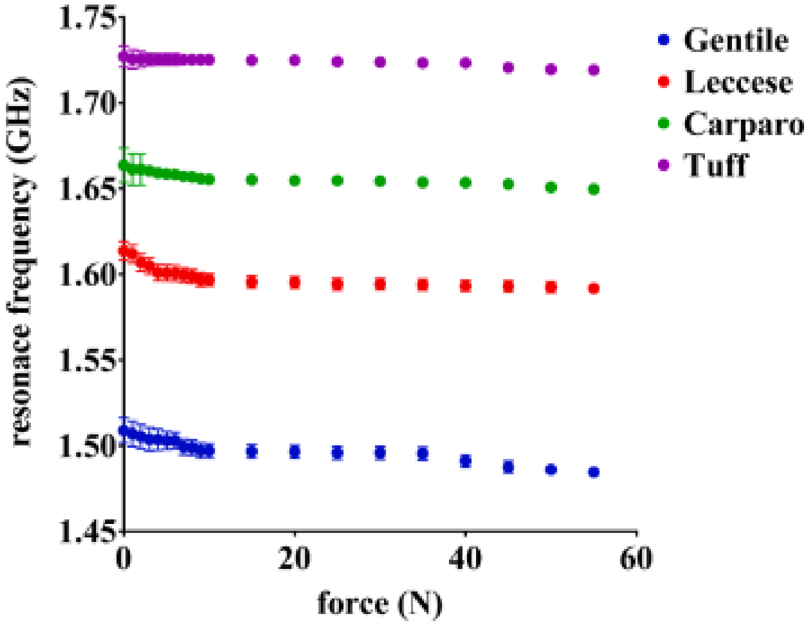


Pancake Cell Features:

- Elastic element subjected to bending
- Ease of implementation and miniaturization
- Patch shape compatibility
- Measuring range: 5 g - 5 kg



miniVNA-TINY



Relationship between the applied force (0 N to 55 N range) and the resonance frequency.

L. D'Alvia, **E. Pittella**, E. Rizzuto, E. Piuzzi, Z. Del Prete, "A portable low-cost reflectometric setup for moisture measurement in cultural heritage masonry unit", ***Measurement***, 2021, 110438, ISSN 0263-2241.

miniVNA-TINY results

Gentile Stone. Comparison between the resonance frequency and the θ_v for the force applied with load cell and without control

Gentile Stone				
humidity	Load cell		Hand	
	f_r (GHz)	2σ (GHz)	f_r (GHz)	2σ (GHz)
0.0%	1.469	0.061	1.465	0.091
1.8%	1.371	0.053	1.370	0.075
3.6%	1.327	0.025	1.325	0.038
5.5%	1.295	0.036	1.288	0.083
7.3%	1.259	0.014	1.261	0.071
9.1%	1.227	0.029	1.228	0.098
10.9%	1.215	0.028	1.213	0.079
12.8%	1.192	0.043	1.196	0.080
14.6%	1.155	0.021	1.154	0.054

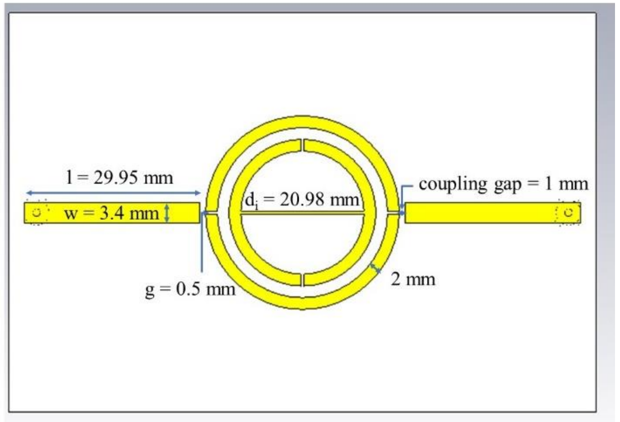
Leccese Stone. Comparison between the resonance frequency and the θ_v for the force applied with load cell and without control

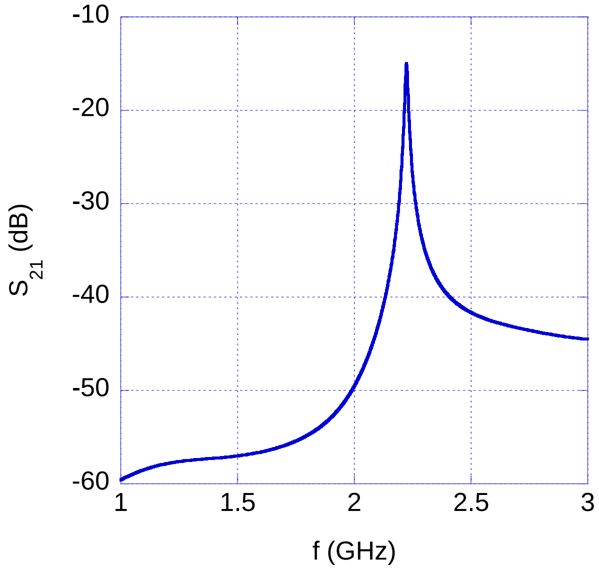
Leccese Stone				
humidity	Load cell		hand	
	f_r (GHz)	2σ (GHz)	f_r (GHz)	2σ (GHz)
0.0%	1.590	0.042	1.591	0.089
3.4%	1.532	0.015	1.547	0.025
8.3%	1.438	0.010	1.417	0.027
10.1%	1.360	0.024	1.373	0.032
13.5%	1.321	0.009	1.327	0.028
16.8%	1.217	0.022	1.211	0.061
20.2%	1.180	0.009	1.175	0.085
23.6%	1.127	0.039	1.128	0.073
26.9%	1.089	0.014	1.086	0.091

L. D’Alvia, **E. Pittella**, E. Rizzuto, E. Piuzzi, Z. Del Prete, “A portable low-cost reflectometric setup for moisture measurement in cultural heritage masonry unit”, ***Measurement***, 2021, 110438, ISSN 0263-2241.

Split Ring Resonator (SRR)

SRR





Resonators characteristic:

- ✓ high sensitivity
- ✓ high quality factor
- ✓ small size
- ✓ do not require a particular sample preparation

Test of the SRR on the following materials:

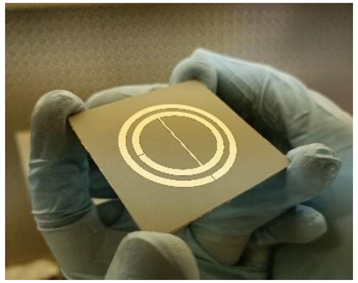
- low density polyvinyl chloride (LDPVC)
- polytetrafluoroethylene (PTFE)
- polymethyl methacrylate (PMMA)
- polycarbonate (PC)

These samples were characterized with the SRR and, for comparison, with the standard reflection/transmission technique, based on the NIST method, through WR430 (at 2 GHz) and WR90 (at 12 GHz) waveguides.

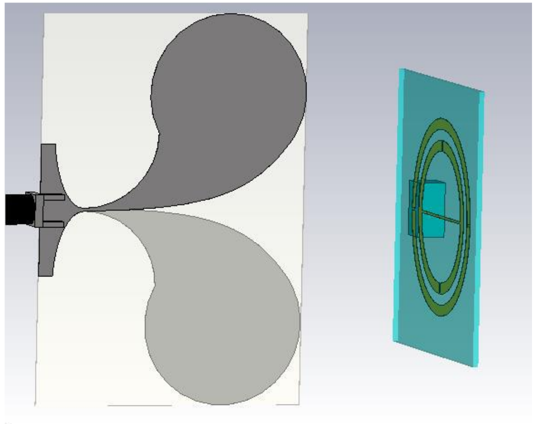
material	ε'_r - SRR	ε'_r - WR430	ε'_r - WR90
LD-PVC	1.6(1)	1.62(3)	1.61(2)
PTFE	1.9(1)	2.06(4)	2.04(2)
PMMA	2.4(1)	2.59(5)	2.59(3)
PC	2.7(1)	2.82(6)	2.81(3)

E. Pittella, E. Piuzzi, "Split ring resonator for complex permittivity measurement", ***24th IMEKO TC4*** *Int. Symp. 22nd International Workshop on ADC and DAC Modelling and Testing*, 2020.

Passive SRR
used to monitor the dielectric characteristics of a MUT excited through an antipodal Vivaldi antenna



Passive SRR

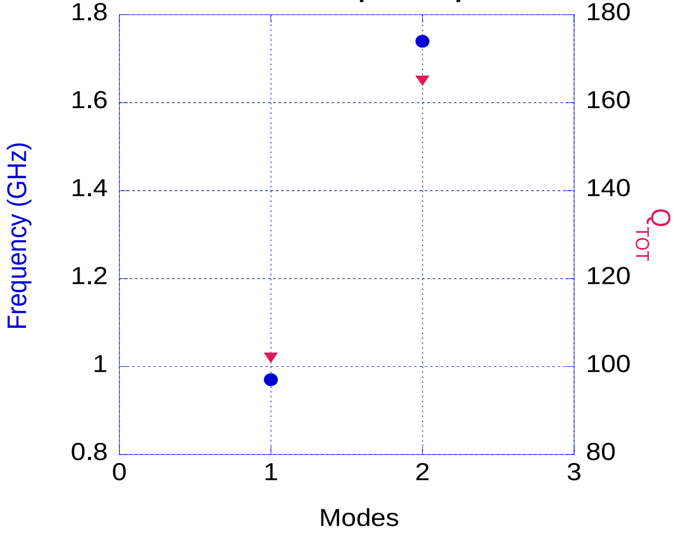


Antipodal Vivaldi antenna

Passive SRR

Idea: to use the system with a portable and low-cost VNA with a typical band not exceeding 3 GHz

Principal modes below this frequency.



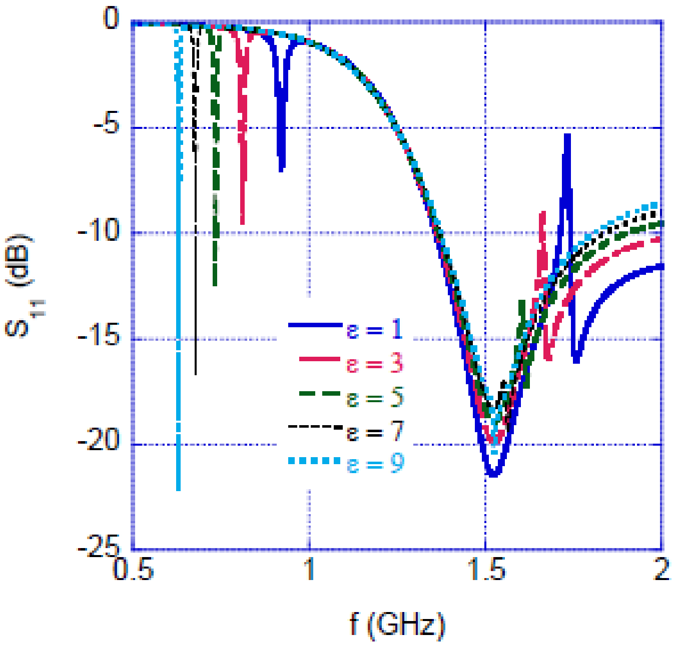
Resonance frequencies (circles) and Q_{TOT} (triangles) of the two principal modes.

Two principle modes:

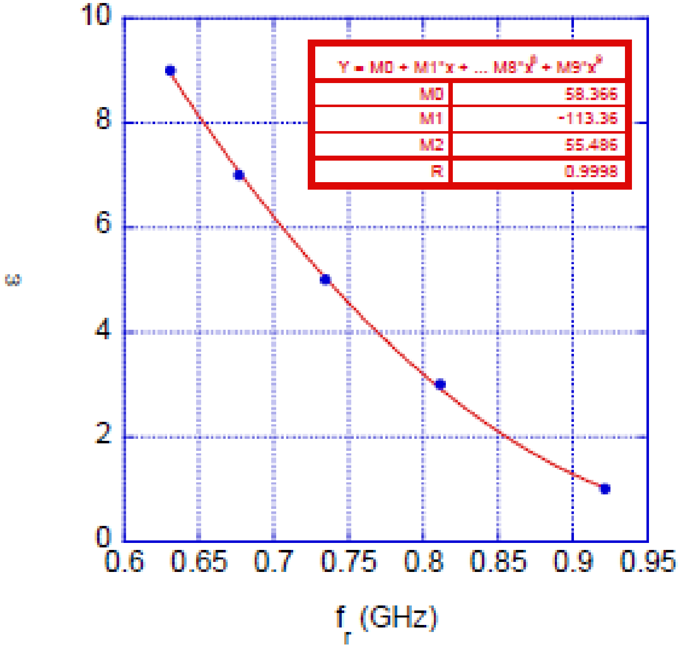
- 0.9 GHz (Q_{TOT} = 102)
- 1.7 GHz (Q_{TOT} = 165).

E. Pittella, A. Cataldo, M. Cavagnaro, L. D'Alvia, F. Fabbrocino, E. Piuzzi, "Wireless Sensing of Permittivity for Cultural Heritage Monitoring Using a Passive SRR", IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage, MetroArchaeo 2023.

Simulation results



S_{11} of the antenna in front of the SRR placed on a MUT with varying permittivity.

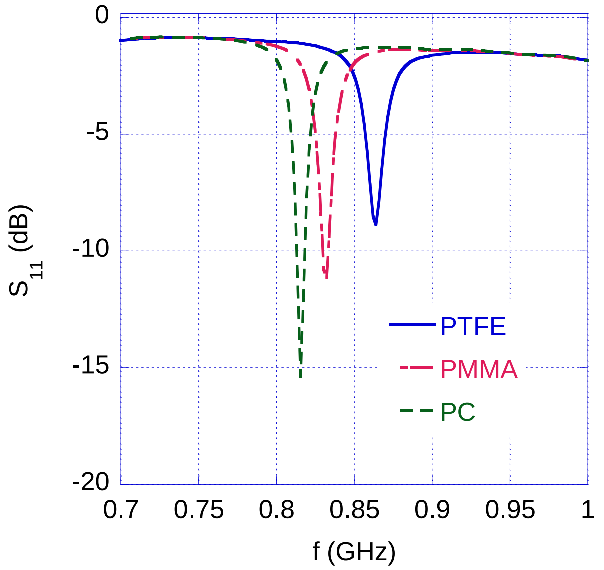


$f_r \rightarrow \varepsilon_r$ *relationship.*

$$\varepsilon = 58.366 - 113.36 \cdot f_r + 55.486 \cdot f_r^2$$

Test of the calibration curves

On well-known materials, previously characterized [1]: PTFE, PMMA, and PC



Material	f_r (GHz)	$\varepsilon_r(f_r)$	ε_r [1]
PC	0.81543	2.82	2.82
PMMA	0.83225	2.46	2.59
PTFE	0.86402	1.84	2.06

Table. Permittivity of test materials computed with the proposed system and comparison with reference data.

maximum relative error is below 10%

[1] A. Alimenti, **E. Pittella**, K. Torokhtii, N. Pompeo, E. Piuzzi and E. Silva, "A Dielectric Loaded Resonator for the Measurement of the Complex Permittivity of Dielectric Substrates," in *IEEE Trans. Instr. Meas.*, 2023.

Measurement results on wood samples

Wood types:

FIR

POPLAR

BEECH

OAK

All samples have the following transversal dimensions: 22.86 mm × 10.16 mm

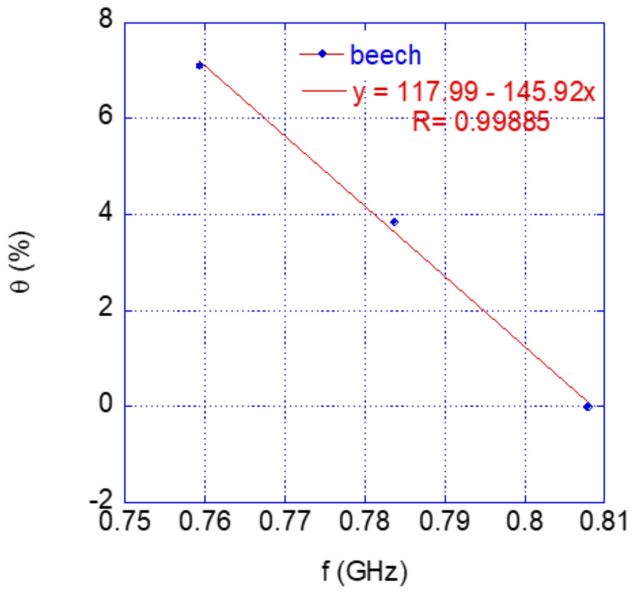


Fig. Calibration curve for θ measurements on beech samples.

Material	$\theta_2(\%)$	$\theta_3\ (\%)$
beech	3.840	7.09
fir	22.72	25.00
oak	4.09	7.37
poplar	8.13	14.29

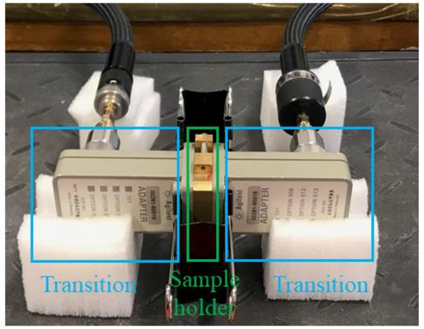
Table. Gravimetric water content of the tested samples.

Microwave system for material characterization and monitoring

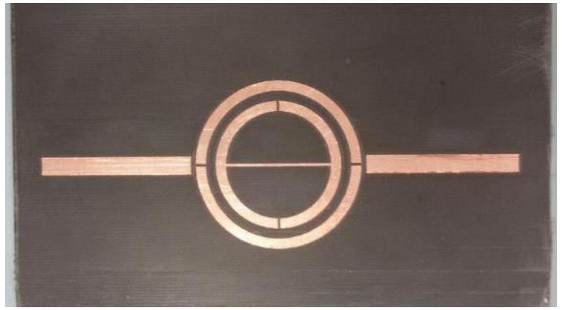
- Cultural Heritage Monitoring

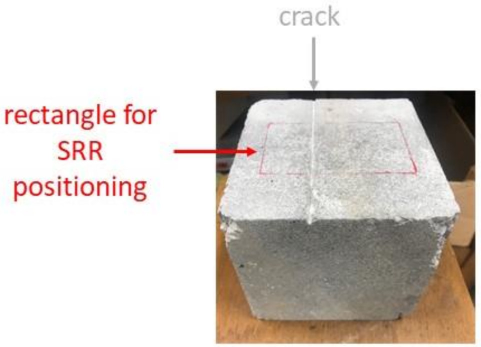
- **Health Monitoring in Concrete Structures**

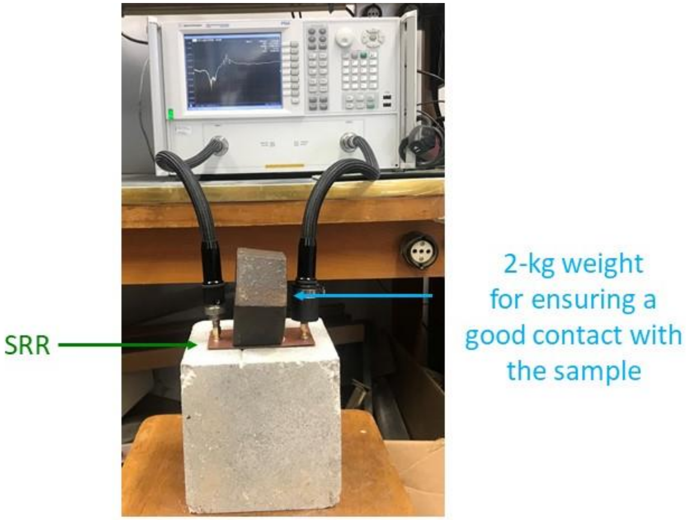
- Composite Materials Characterization

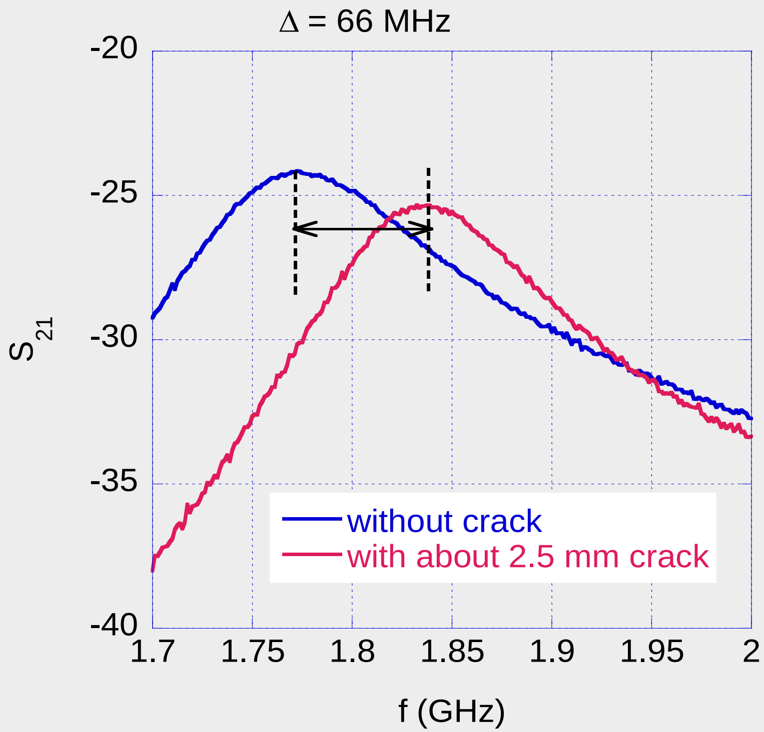


SRR for Health Monitoring in Concrete Structures







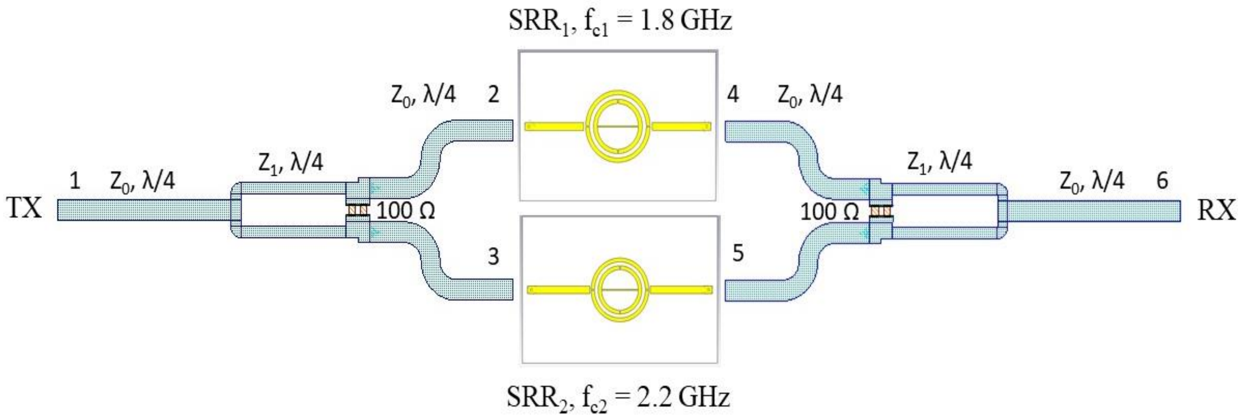


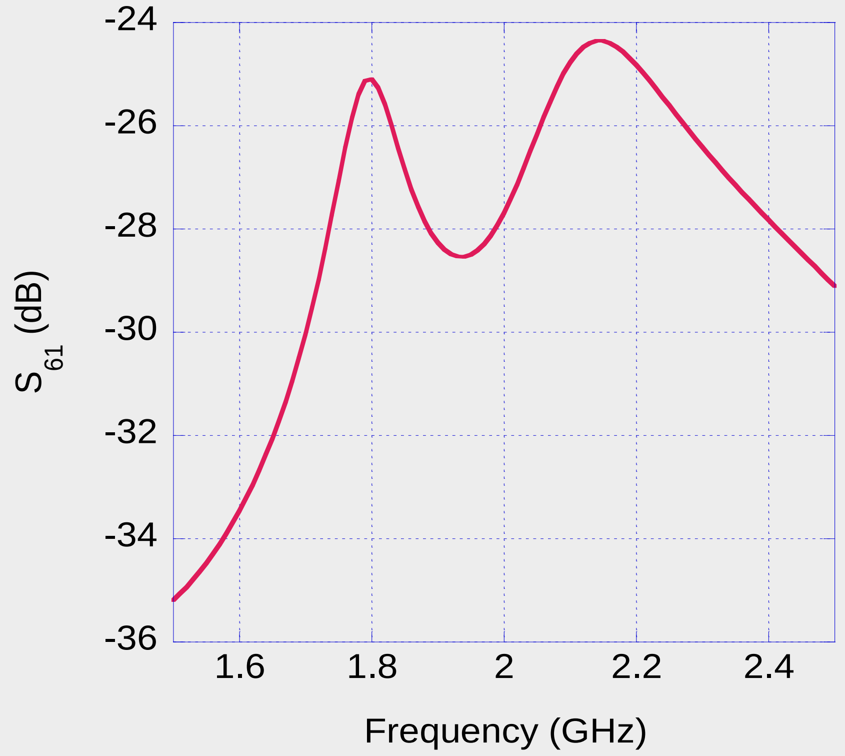
Measurements of the transmission coefficient obtained for the SRR in presence of a concrete block with and without crack

E. Pittella, E. Piuzzi, "Split ring resonator for complex permittivity measurement", ***24th IMEKO TC4*** *Int. Symp. 22nd International Workshop on ADC and DAC Modelling and Testing*, 2020.
E. Pittella, L. Angrisani, A. Cataldo, E. Piuzzi, F. Fabbrocino, "Embedded Split Ring Resonator Network for Health Monitoring in Concrete Structures", ***IEEE Instr. and Meas. Mag.***, 2020.

SRR Network for Health Monitoring in Concrete Structures

Simplified scheme of the proposed monitoring system





Transmission coefficient of the proposed system

cādence
AWR
RF/MICROWAVE DESIGN SOFTWARE

E. Pittella, L. Angrisani, A. Cataldo, E. Piuzzi, F. Fabbrocino, “Embedded Split Ring Resonator Network for Health Monitoring in Concrete Structures”, ***IEEE Instrumentation and Measurement Magazine***, 2020.

SRR Network and Diffused Sensing Element (SE) Embedded in a Concrete Beam for Structural Health Monitoring

Two different and complementary sensors:

- SE → able to detect the variation of the concrete dielectric properties along the whole beam length for a diffuse monitoring
- SRRs → work punctually, in their surroundings, allowing an accurate evaluation of the permittivity

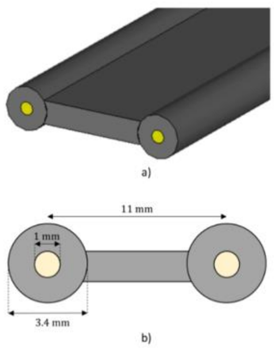


Fig. SE perspective view (a) and cross section (b).

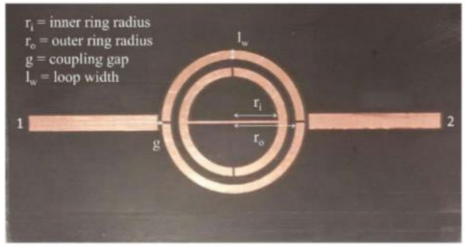


Fig. SRR geometry and its principal parameters.

Table 1. Geometric dimensions of Split Ring Resonators.

SRR	r_i (mm)	r_o (mm)	g (mm)	l_w (mm)
1	14.0	18.0	0.44	2.0
2	12.4	16.4	0.44	2.0
3	11.0	15.0	0.44	2.0
4	10.0	14.0	0.44	2.0

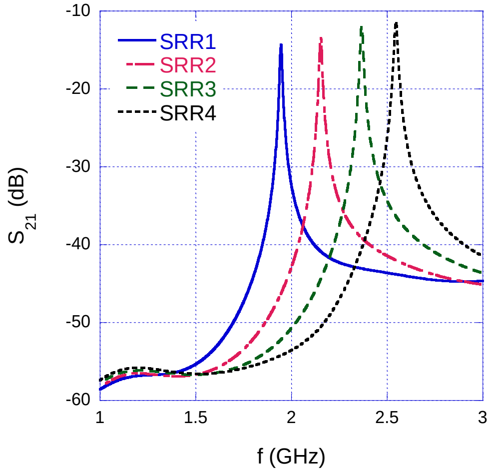


Fig. Transmission coefficients of SRRs in air.

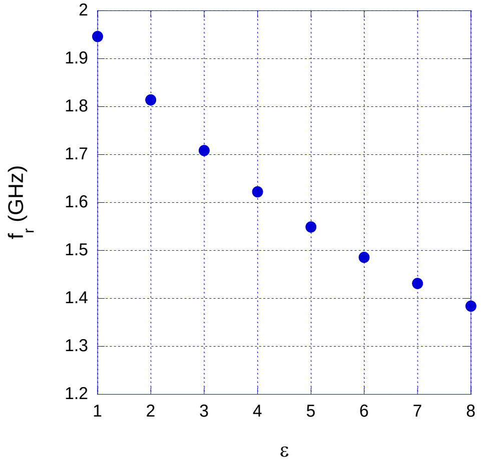


Fig. Relationship between the SRR1 resonance frequency and the permittivity of the surrounding material.

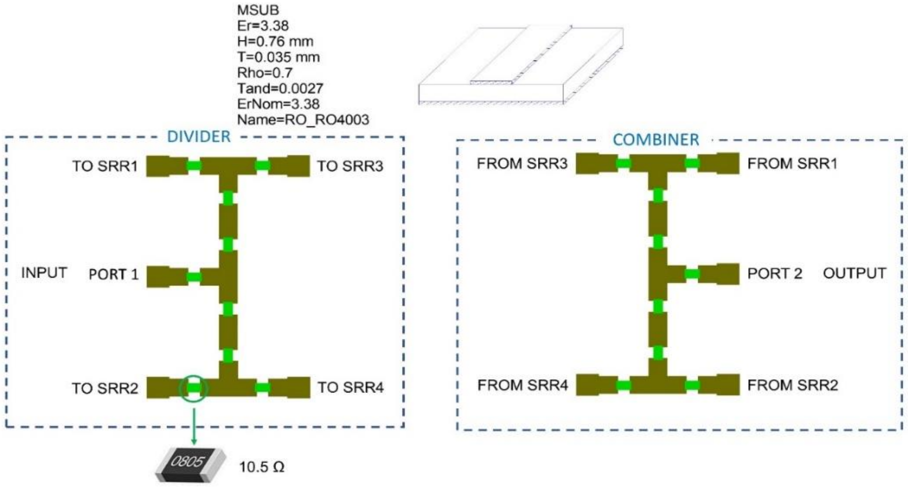
E. Pittella, R. Schiavoni, G. Monti, A. Masciullo, M. Scarpetta, A. Cataldo, E. Piuzzi, "Split Ring Resonator Network and Diffused Sensing Element Embedded in a Concrete Beam for Structural Health Monitoring", *Sensors* 2022, 22, 6398. https://doi.org/10.3390/s22176398

4 Split Ring Resonator Network

Resonance frequency of the four split ring resonators embedded in a material with permittivity ε.

ε	1	2	3	4	5	6	7	8
$f_{r,SRR1}$	1.9461	1.8141	1.7082	1.6224	1.5489	1.4856	1.4313	1.3842
$f_{r,SRR1}$	2.1531	2.0091	1.8894	1.7910	1.7109	1.6407	1.5771	1.5222
$f_{r,SRR3}$	2.3670	2.2101	2.0772	1.9710	1.8819	1.8039	1.7364	1.6737
$f_{r,SRR4}$	2.5464	2.3733	2.2347	2.1231	2.0268	1.9431	1.8690	1.8015

To feed the four SRRs, the design of a power divider has been conducted with Microwave Office by AWR



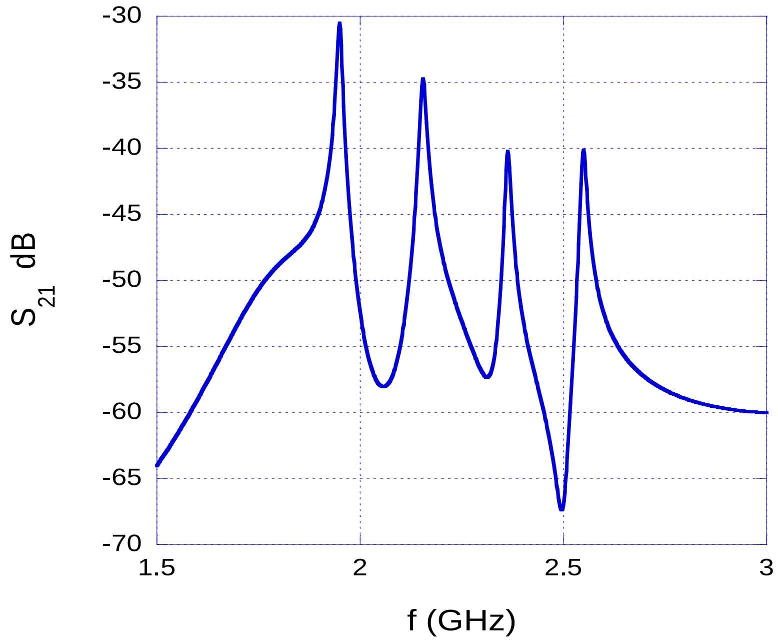


Fig. S_{21} MWO simulation of the designed network.

E. Pittella, R. Schiavoni, G. Monti, A. Masciullo, M. Scarpetta, A. Cataldo, E. Piuzzi, "Split Ring Resonator Network and Diffused Sensing Element Embedded in a Concrete Beam for Structural Health Monitoring", *Sensors* 2022, 22, 6398. https://doi.org/10.3390/s22176398

SRR Network and Diffused SE Results

Fig. View of the four SRRs embedded in the mold.

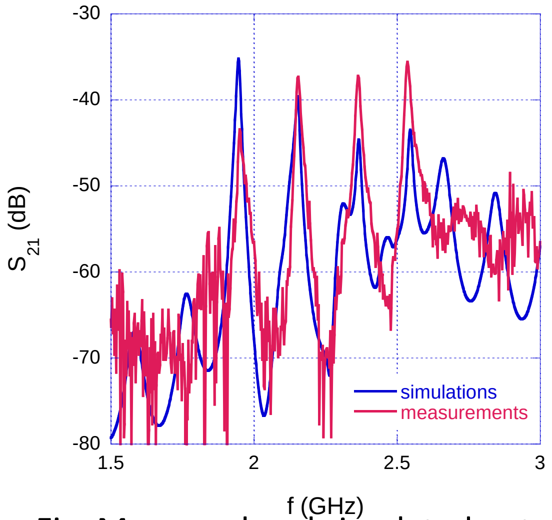


Fig. Measured and simulated network transmission coefficient in air.

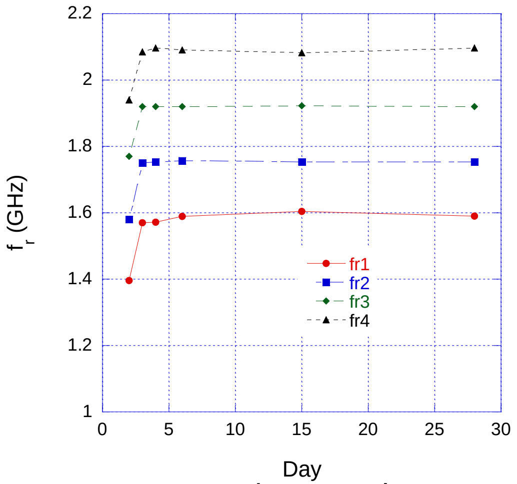


Fig. Computed network transmission coefficient resonance frequency during the curing phase.

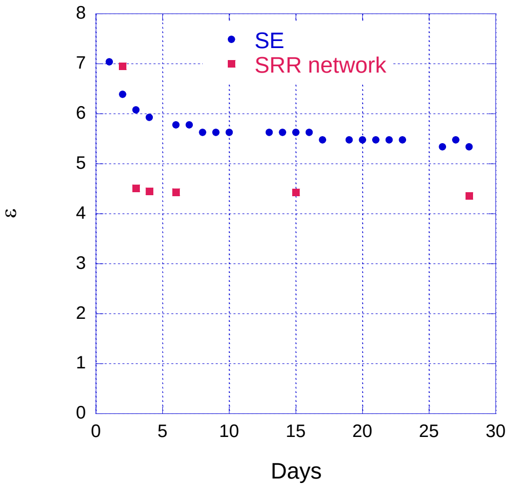


Fig. Measured permittivity during the curing of the concrete

NB:

1. The first day, when the concrete beam contain a considerable quantity of water, the S_{21} as a bell-shaped trend and the four resonances of the SRR network are not clearly visible; they begin to be clearly visible on the second day, when a good amount of water has evaporated
2. difference in concrete permittivity was deliberately made in fact a different mixture of cement was placed around the SRRs

✓ control the presence of water inside the beam & to locate any internal cracks in the beam

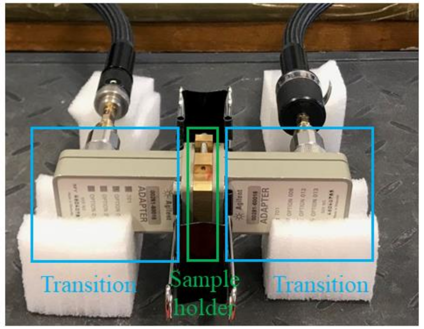
E. Pittella, R. Schiavoni, G. Monti, A. Masciullo, M. Scarpetta, A. Cataldo, E. Piuzzi, “Split Ring Resonator Network and Diffused Sensing Element Embedded in a Concrete Beam for Structural Health Monitoring”, *Sensors* 2022, 22, 6398. https://doi.org/10.3390/s22176398

Microwave system for material characterization and monitoring

- Cultural Heritage Monitoring

- Health Monitoring in Concrete Structures

- **Composite Materials Characterization**



Material Characterization

- Composite materials (GNPs)

PA6

PA6/GNP

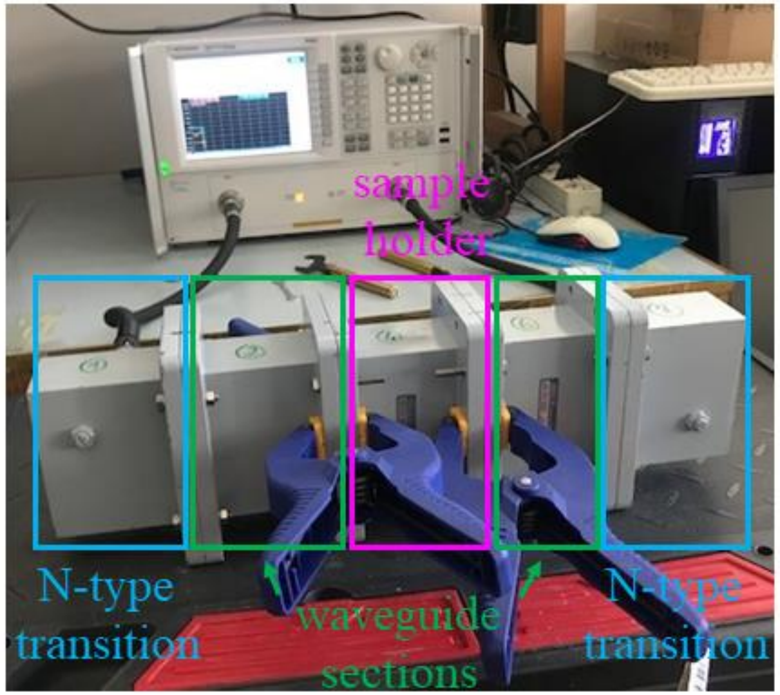
- 3D Printed PLA and PLA/CNT Composites

3D printed PLA

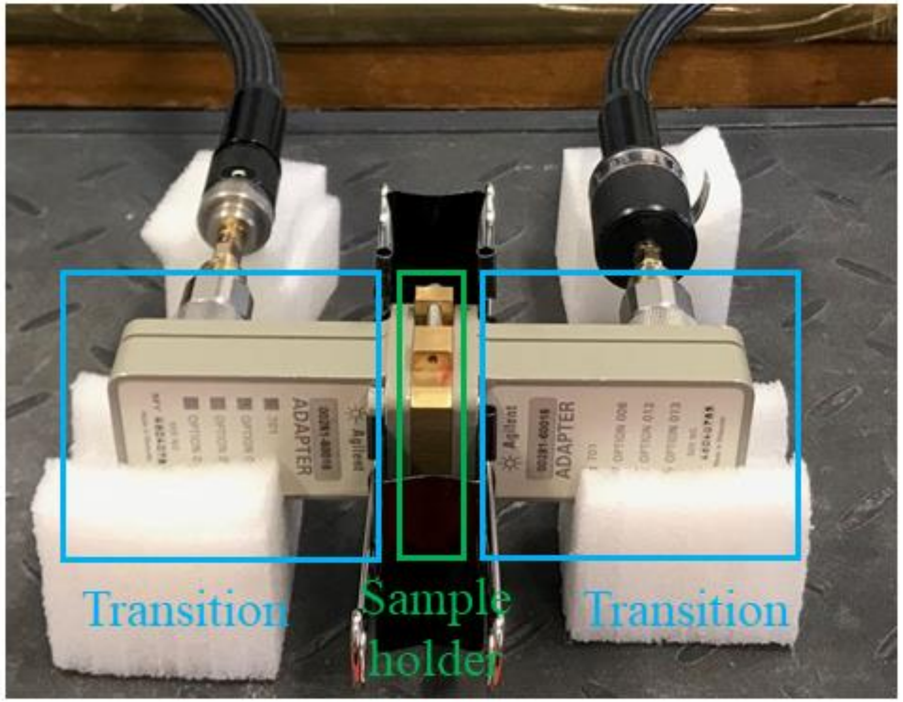
3D printed PLA with CNT

Experimental set-up

WR430 1.7 – 2.6 GHz

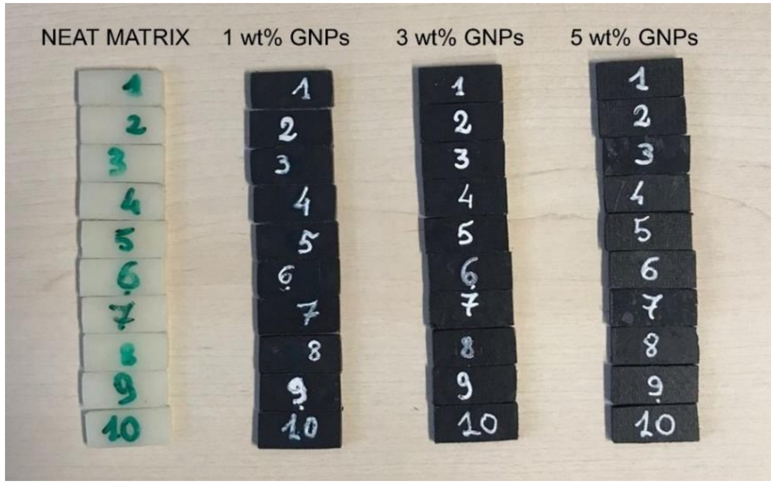


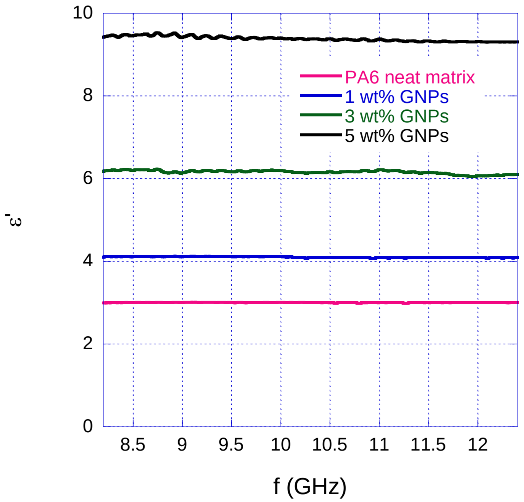
WR90 8.2 – 12.4 GHz

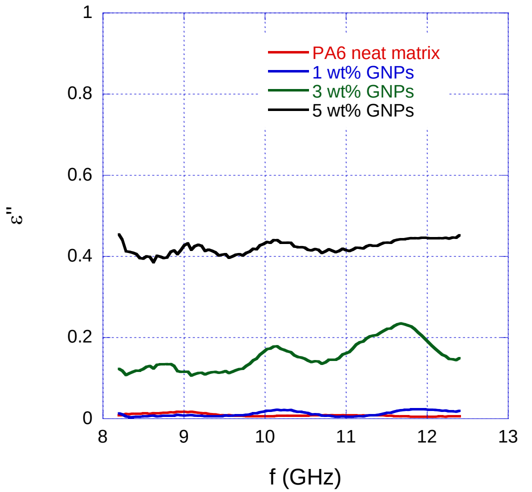


E. Pittella, E. Piuzzi, P. Russo and F. Fabbrocino, “Microwave Characterization and Modelling of PA6/GNPs Composites” , *Math. Comput. Appl. 2022, 27, 41. https://doi.org/10.3390/mca27030041*

Results







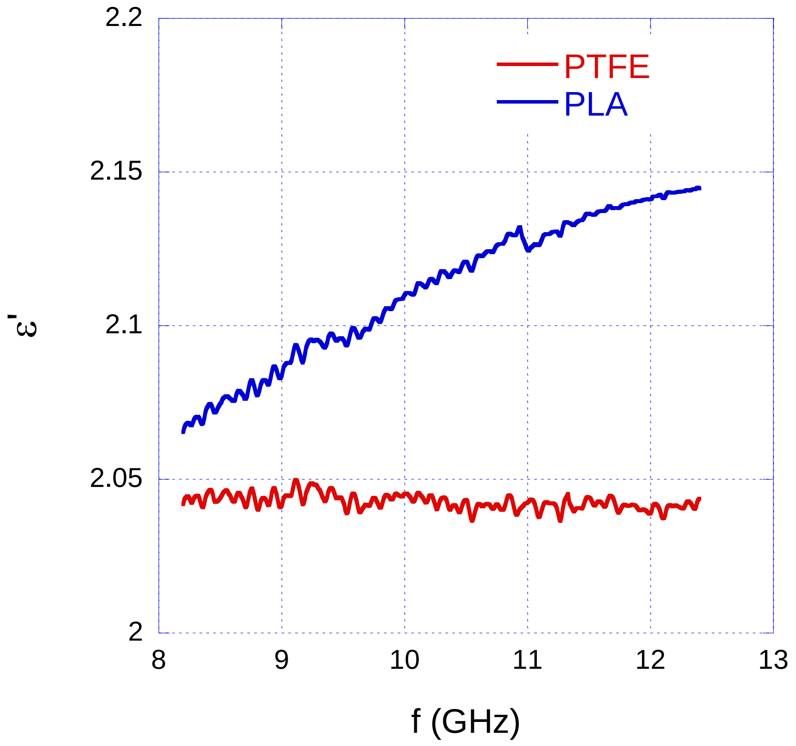
	ε'		ε''	
	WR430	WR90	WR430	WR90
PA6	3.0723 ± 0.0095	2.999 ± 0.0059	0.0107 ± 0.0083	0.0091 ± 0.0045
1%	4.195 ± 0.019	4.100 ± 0.014	0.0227 ± 0.016	0.0120 ± 0.0083
3%	5.846 ± 0.038	6.159 ± 0.043	0.106 ± 0.042	0.155 ± 0.043
5%	10.172 ± 0.069	9.381 ± 0.060	0.493 ± 0.039	0.422 ± 0.030

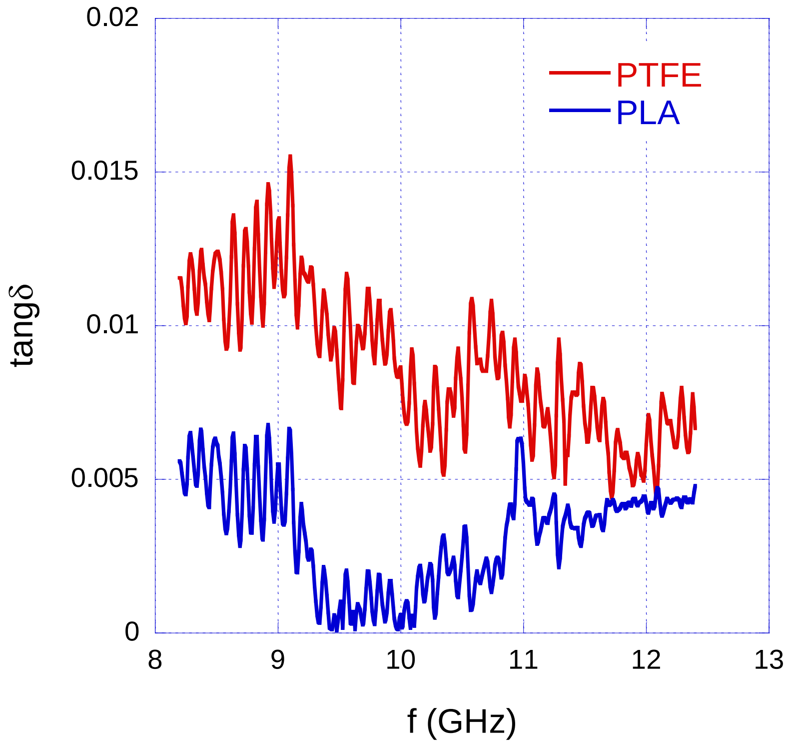
$$\sigma = \omega \varepsilon_0 \varepsilon''$$

E. Pittella, E. Piuzzi, P. Russo and F. Fabbrocino, "Microwave characterization of Polyamide 6 Graphene Nanoplatelet Composites," *2021 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT)*, 2021, pp. 488-492, doi: 10.1109/MetroInd4.0IoT51437.2021.9488529.

Results

Measured complex permittivity for the 3D printed PLA and PTFE

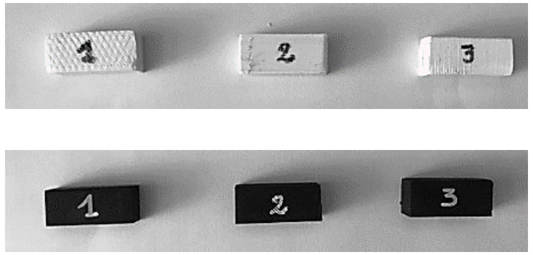




- discrepancy between the two curves can be considered negligible, as the maximum variation is within 3%
- losses for PLA are even lower that PTFE

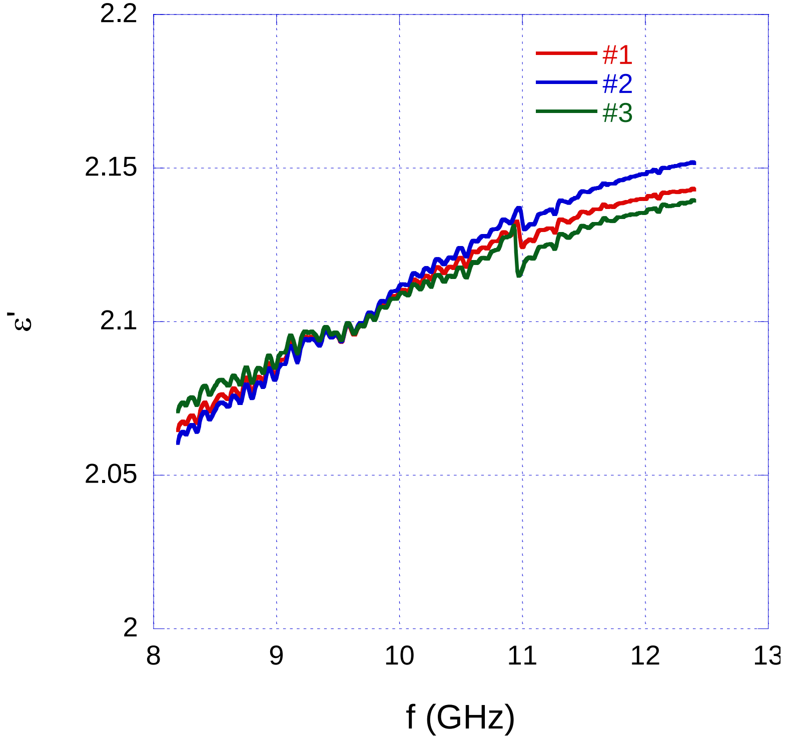
  - PLA can be used to build microwave components

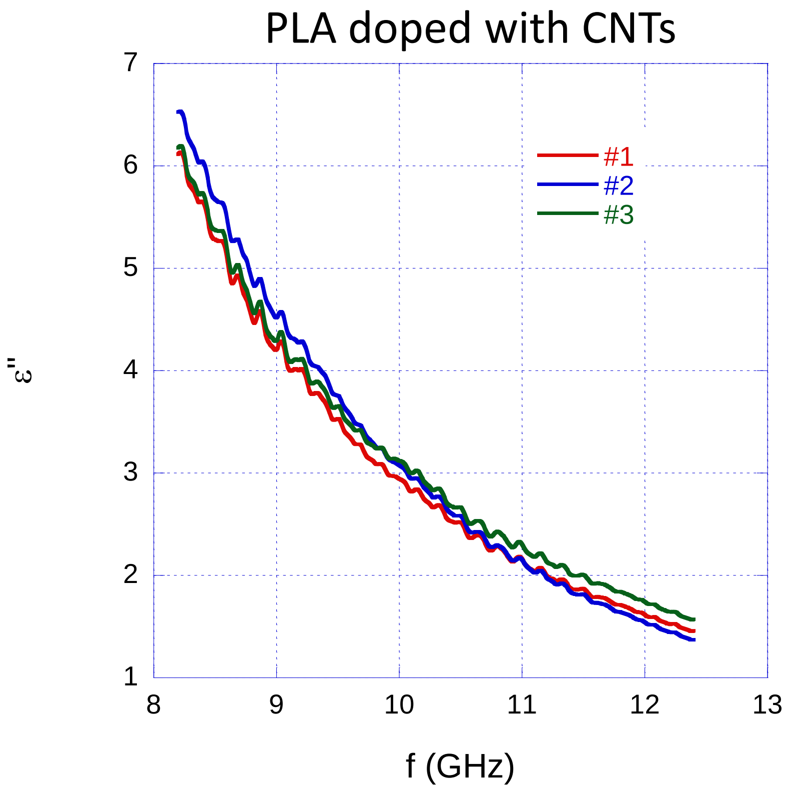
E. Pittella, L. D'Alvia, E. Palermo and E. Piuzzi, "Microwave Characterization of 3D Printed PLA and PLA/CNT Composites," 2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI), 2021, pp. 52-56, doi: 10.1109/RTSI50628.2021.9597226.



Results

Measured complex permittivity for the 3D printed PLA and PLA doped with CNTs





- measured values are consistent with the literature
- no substantial differences between the three ε_c samples → anisotropy **not** significative
- small discontinuity around 11 GHz ← non-perfect planarity of the sample resulting from defects in the 3D-printing process
- quite high value of the imaginary part of the complex permittivity → losses are not negligible (EMI shielding or EM absorber)

E. Pittella, L. D'Alvia, E. Palermo and E. Piuzzi, "Microwave Characterization of 3D Printed PLA and PLA/CNT Composites," 2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI), 2021, pp. 52-56, doi: 10.1109/RTSI50628.2021.9597226.

Conclusions and Future Developments

- **Cultural Heritage Monitoring**
  - ✓ possibility of monitoring the moisture content in materials largely used in artistic artifacts
  - ✓ measurements of the SRR resonance frequency, directly related to material dielectric characteristics
  - ➢ Expanding the set of tested materials, improving the calibration curves, including also the effect of sample size, and assessing whether using both the resonance frequency and the Q value as input data, the accuracy of water content evaluation can be improved

- **Health Monitoring in Concrete Structures**
  - ✓ possibility of monitoring concrete during the important curing phase
  - ✓ highlight the presence of water that could cause deterioration, especially in cases of dams, bridges and structures that are constantly subjected to an important presence of water
  - ➢ It is planned to test the possibility of monitoring the presence of water near one of the SRRs and the localization of artificial cracks, that will be created with mechanical stress in some points of the beam

- **Composite Materials Characterization**
  - ✓ a material with GNPs thanks to the high electrical conductivity yields a good shielding efficiency against microwave radiation
  - ✓ 3D printed PLA can be used to build microwave components
  - ➢ It would be very interesting to investigate these materials in broader band experiments

Italian National Committee

Commission A: Electromagnetic Metrology, Electromagnetic measurements and standards

Dielectric characterization of materials at microwave frequencies

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THANK YOU

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