MICROWAVE SENSORS: NOVEL TECHNIQUES, TOPOLOGIES, AND MANUFACTURING TECHNOLOGIES

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INTRODUCTION

1. Current Trends of RF/Wireless Technology

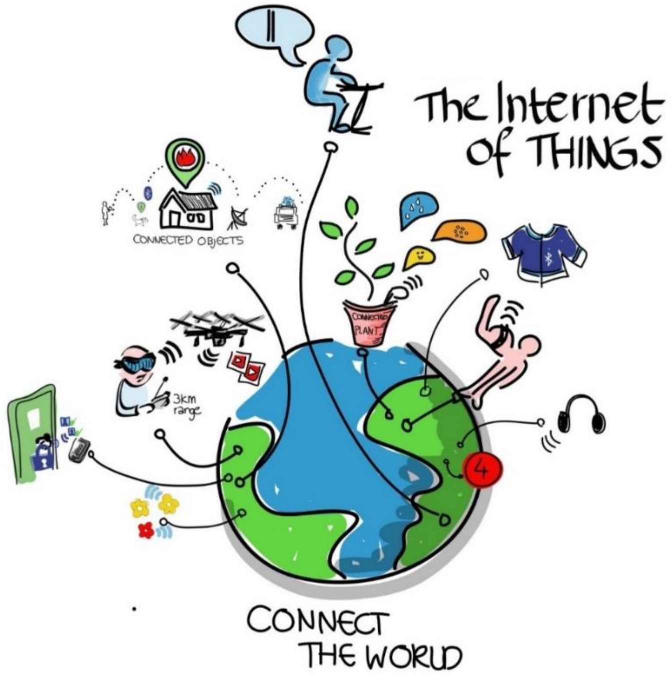
2. Sensors Based on **Planar Technologies**
   - SIW-Based Cavity Sensor
   - Microwave-Based Angular Displacement Sensor

3. **3D-printed** Microwave Sensors
   - SIW-Based Microfluidic Cavity Sensor
   - Pumpkin-Shaped Microfluidic Cavity

4. Sensors Based on **Hybrid Technologies**
   - Microfluidic Sensor in Hybrid 3-D Printing and Laminate Technology

5. Conclusion

EMERGING APPLICATIONS: IOT & 5G



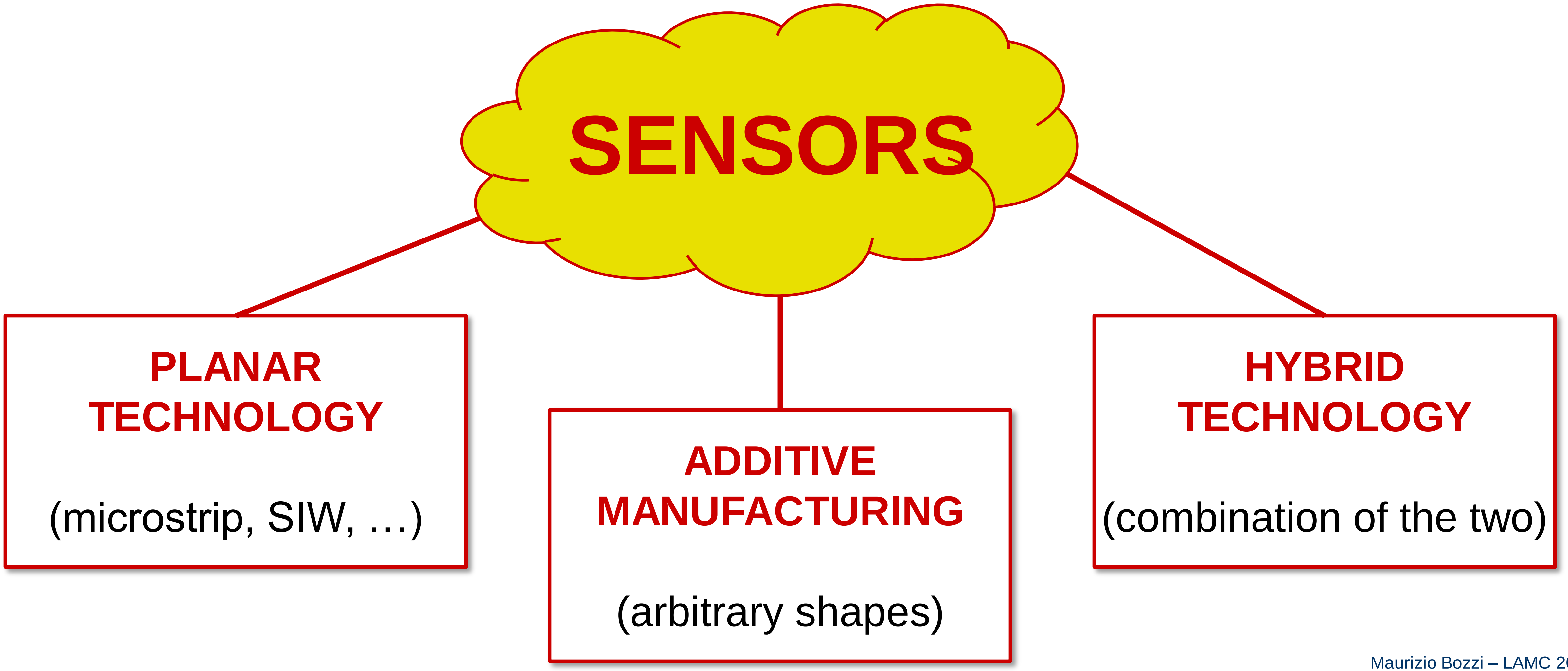
- IT/Networks
- Security/Public safety
- Industrial processes
- Healthcare
- Smart home
- Energy management

5G

Need for sensors!

MICROWAVE SENSORS & IMPLEMENTATION TECHNOLOGIES

The emerging applications in RF and microwave technology demand for



Sensors Based on
Planar Technologies

Planar Technologies: Microstrip Lines

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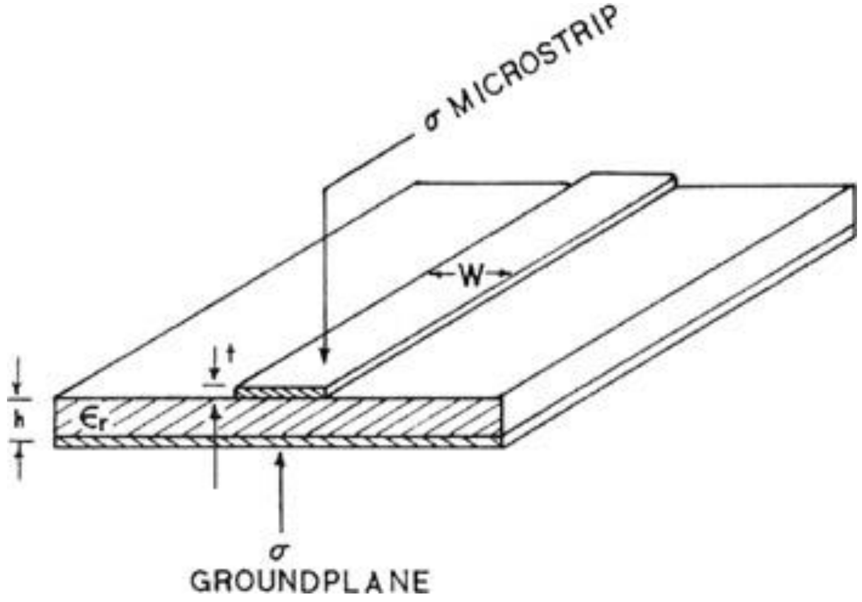
Planar technologies offer a cost-effective and compact solution for the implementation of microwave components, including sensors.

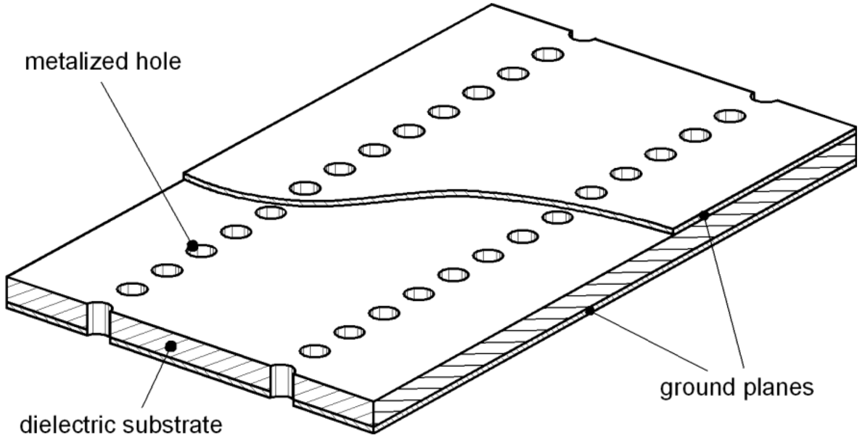


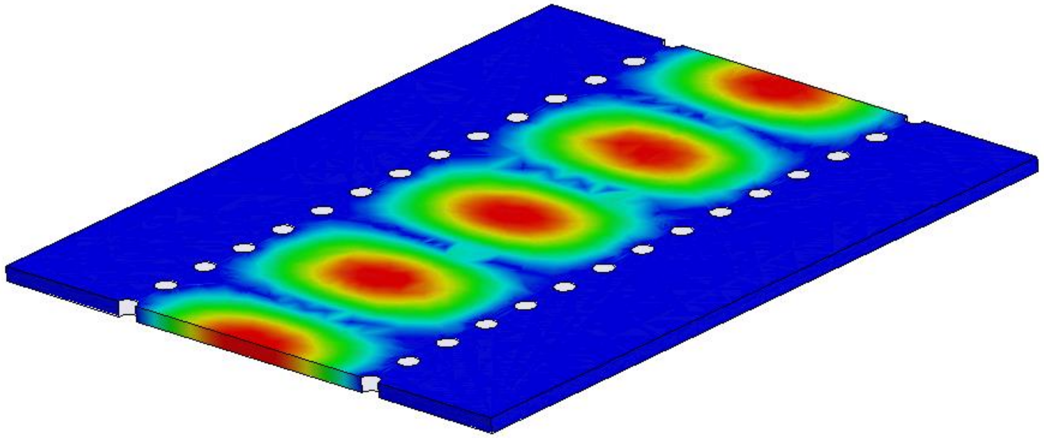
Pros & Cons:

- Light and compact
- Low fabrication cost
- High losses
- High cross-talk

PLANAR TECHNOLOGIES: SIW

The substrate integrated waveguide (SIW) allows implementing waveguide-like components in planar form.



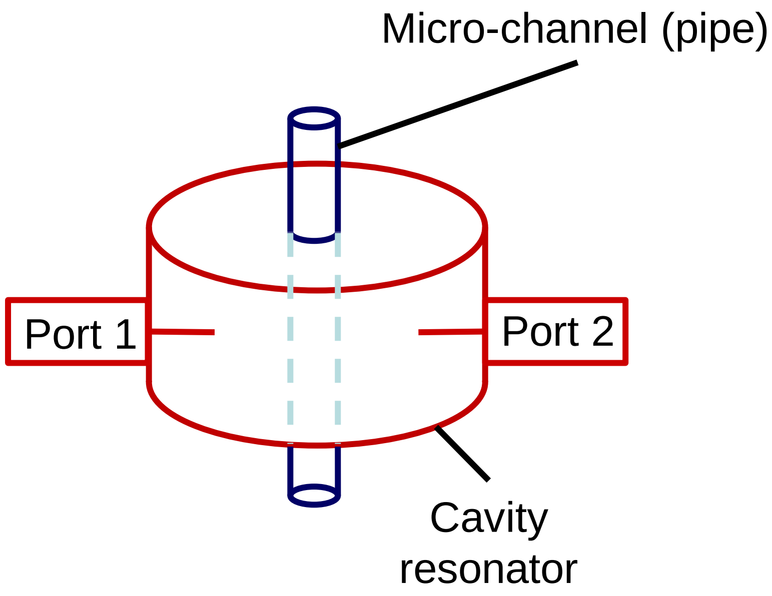


In particular, SIW technology allows implementing cavity resonators with relatively high quality factor.

Cavity Sensors

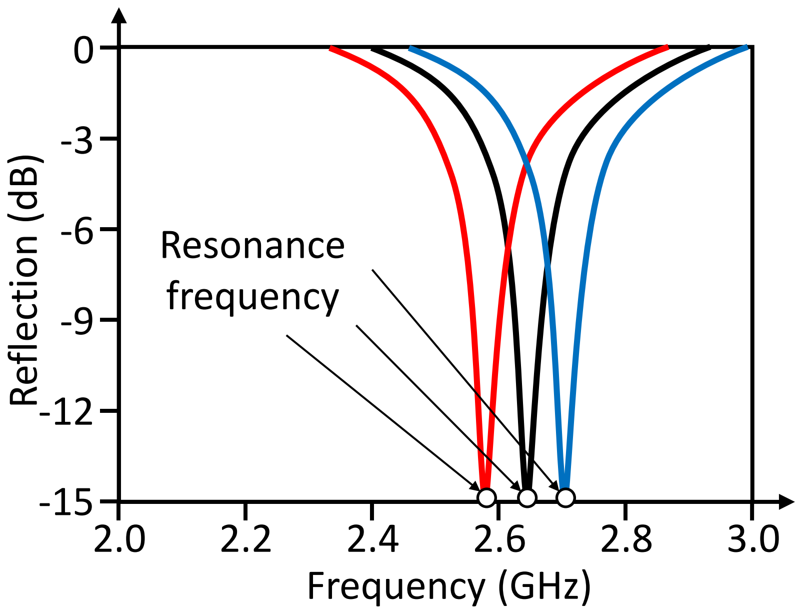
Cavity sensors allow characterizing materials, through the variation of some electrical quantities (e.g., the scattering parameters, the resonance frequency of a cavity, …).

The characterization of liquids can lead to the determination of **complex dielectric permittivity** of the liquid material.



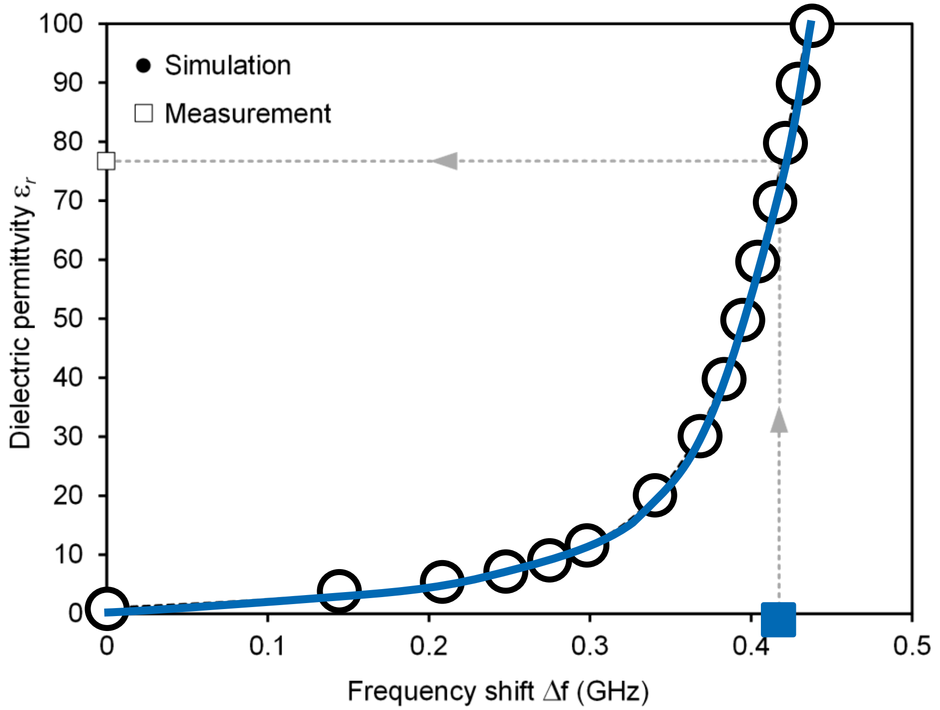
RETRIEVAL OF THE COMPLEX DIELECTRIC PERMITTIVITY

The **shift of the resonance frequency** (with respect to empty pipe) and the **variation of the quality factor** are exploited to retrieve the **dielectric permittivity** and the **loss tangent** of the liquid, respectively.



Retrieval of the Relative Dielectric Permittivity

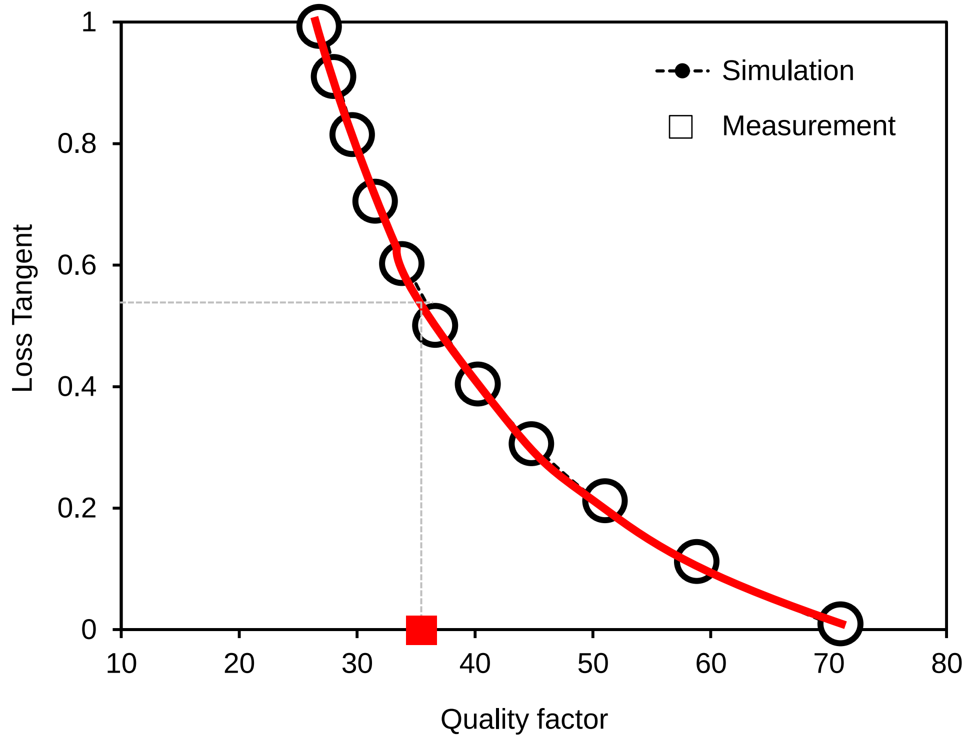
Full-wave simulations are performed, considering the pipe filled with materials with different **dielectric permittivity**, to calculate the corresponding **frequency shift**.



The curve obtained from simulations are used, in conjunction with the **measured frequency shift**, to retrieve the dielectric permittivity.

Retrieval of the Loss Tangent

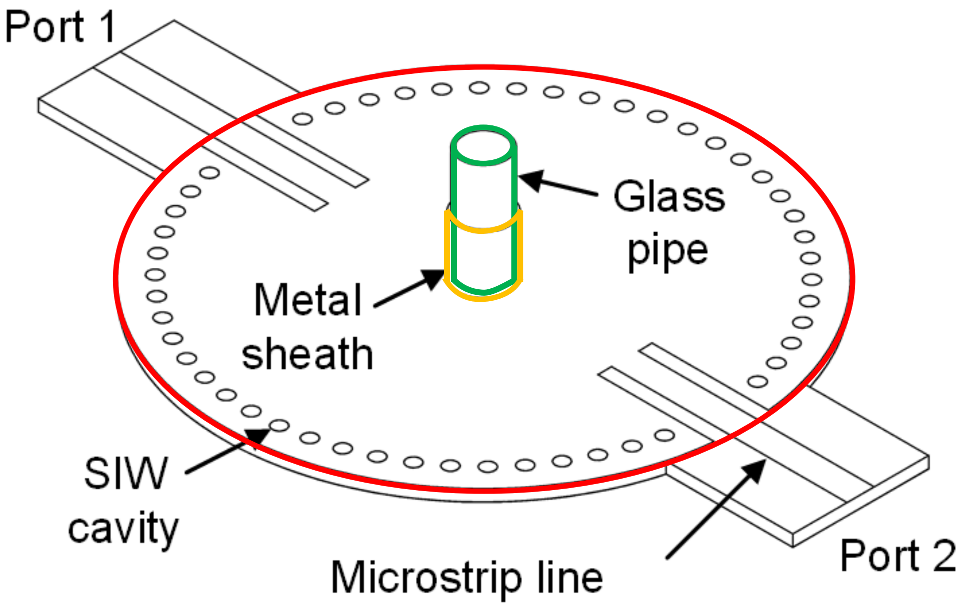
Full-wave simulations are performed, considering the pipe filled with materials with a given permittivity and different values of **loss tangent**, to calculate the corresponding **quality factor**.

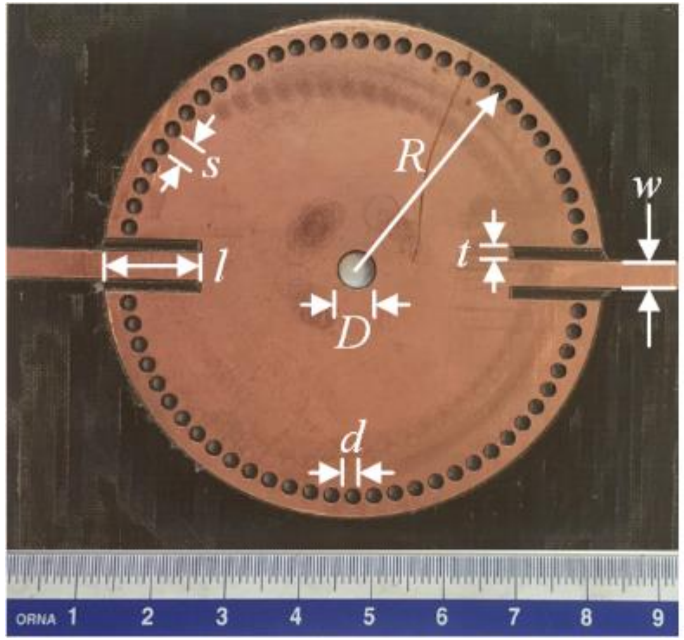


The curve obtained from simulations are used, in conjunction with the **measured quality factor**, to retrieve the loss tangent.

SIW Cavity Sensor

Circular SIW resonant cavity (fundamental mode) with a hole in the center, to insert a glass pipe with the liquid under test. A **metal sheath** improves the performance.

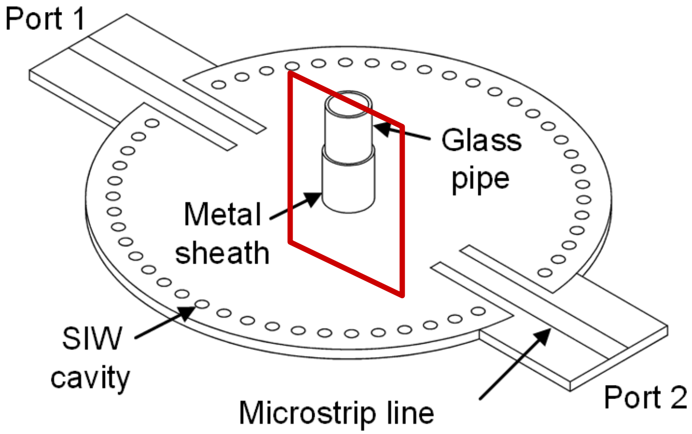


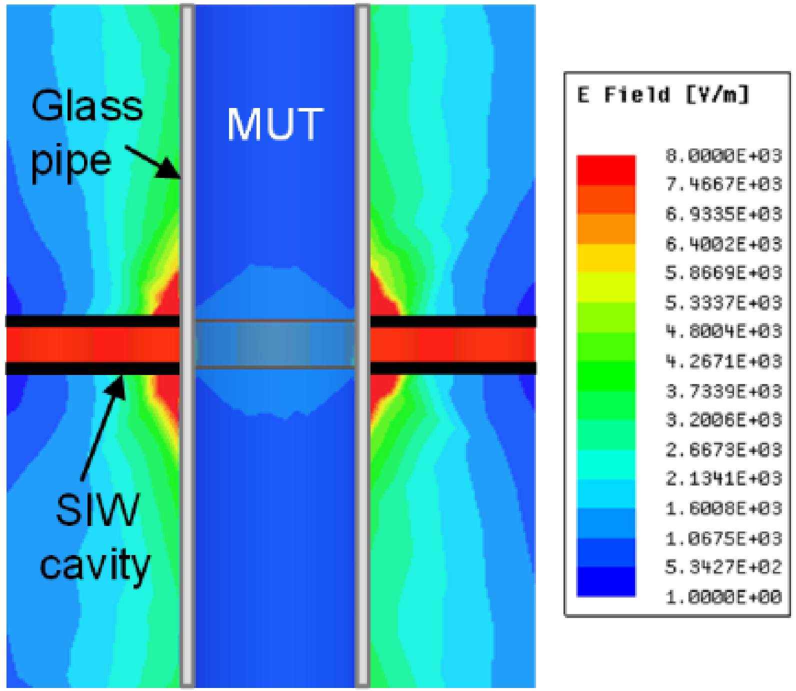


E. Massoni, G. Siciliano, M. Bozzi, L. Perregrini, "Enhanced Cavity Sensor in SIW Technology for Material Characterization," *IEEE Microwave Wireless Components Lett.*, Vol. 28, No. 10, pp. 948–950, Oct. 2018.

SIW Cavity Sensor

The metal sheath allows the field penetrating inside the material under test, thus **increasing the sensitivity**.



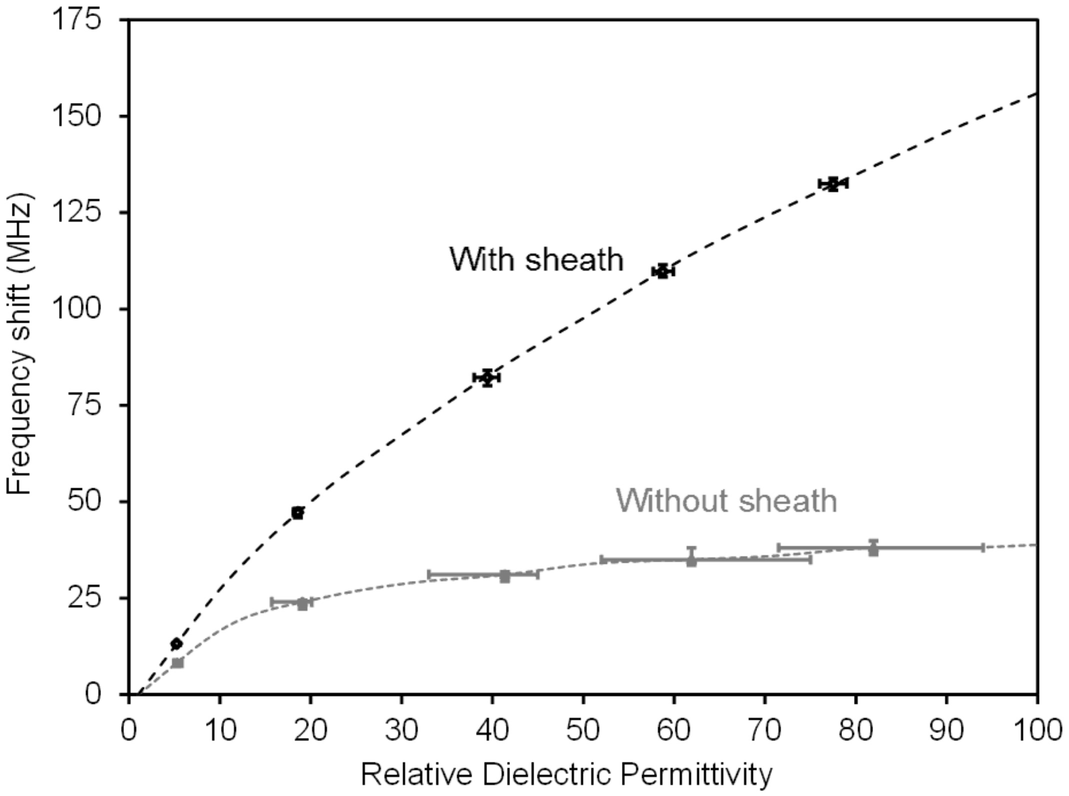


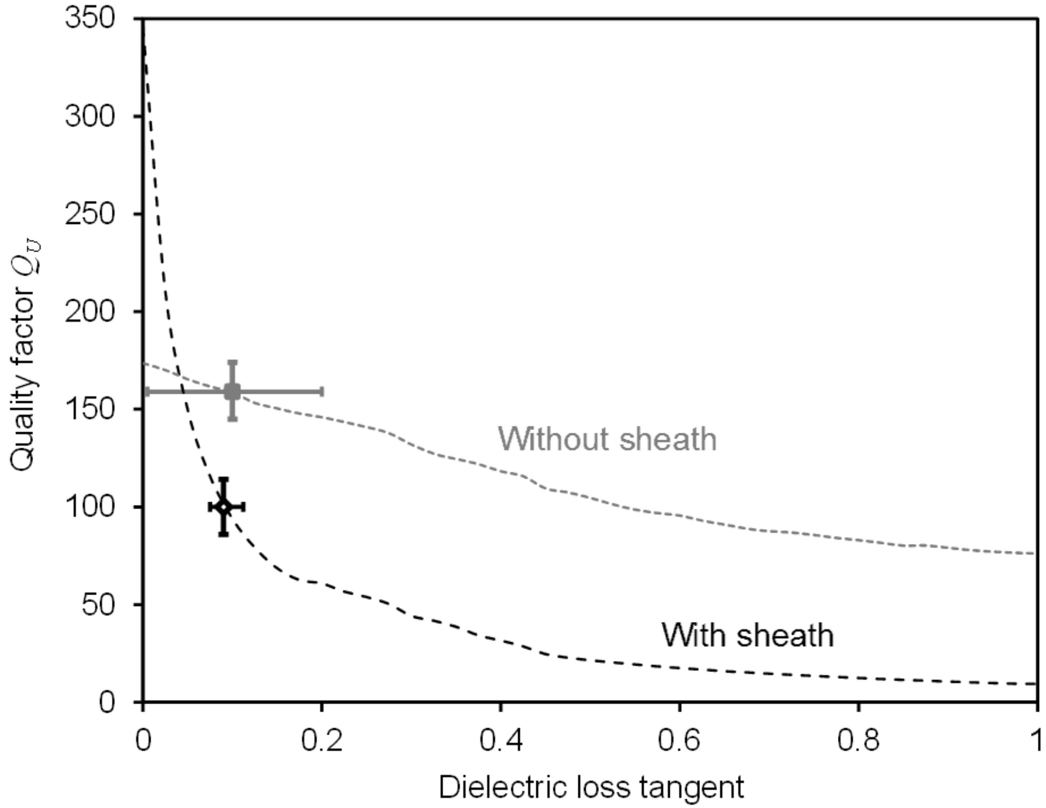
Traditional
(without sheath)

SIW Cavity Sensor

Shift of the resonance frequency ⇨ liquid permittivity

Variation of the quality factor ⇨ liquid loss tangent





SIW Cavity Sensor

TABLE I - Measurement of Dielectric Permittivity and Loss Tangent of Different Liquid Mixtures

Mixture Under Test	SIW Sensor		Coaxial Probe		Difference %	
	ε_r	tan δ	ε_r	tan δ	ε_r	tan δ
100% Isopropanol	5.25	0.68	5.13	0.728	2.28%	6.59%
75% Isopropanol / 25% Water	18.60	0.57	18.36	0.608	1.29%	6.25%
50% Isopropanol / 50% Water	39.45	0.35	39.21	0.375	0.60%	6.67%
25% Isopropanol / 75% Water	58.75	0.22	58.46	0.237	0.49%	7.17%
100% Water	77.50	0.10	77.14	0.119	0.46%	15.97%

RETRIEVAL OF THE DIELECTRIC PERMITTIVITY / 2

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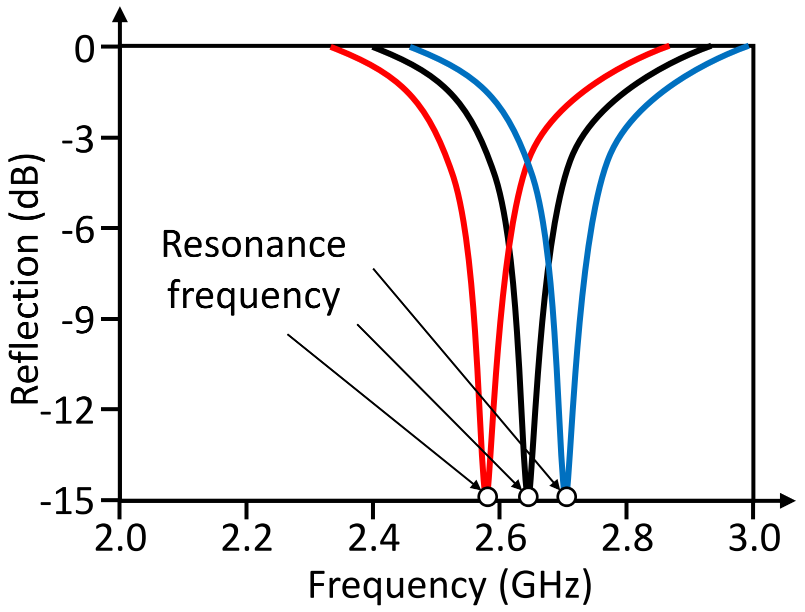
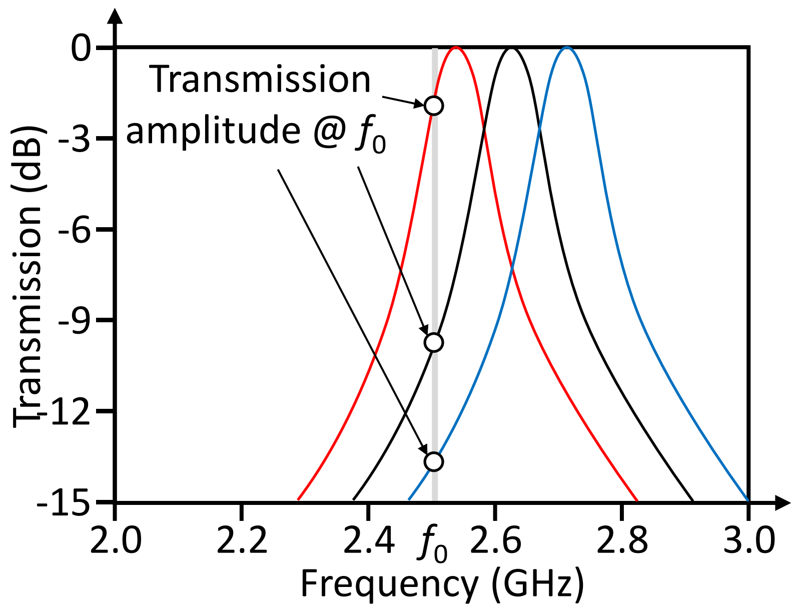
Instead of considering the shift of the resonance frequency (with respect to empty pipe), an **alternative technique** is based on the **variation of the transmission amplitude at a single frequency**.

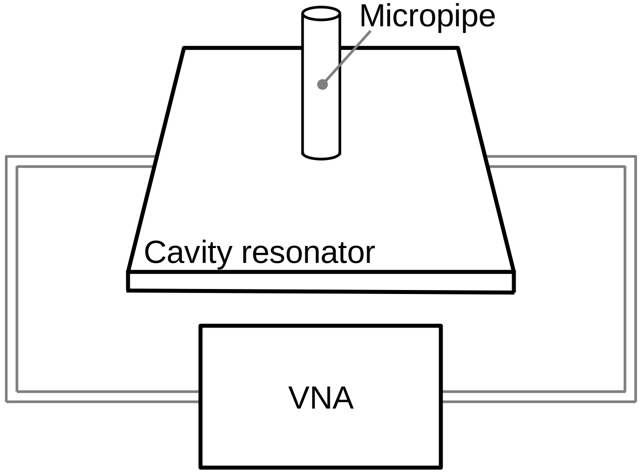




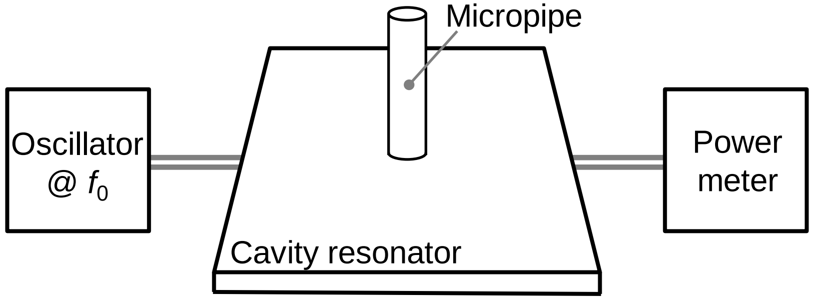
M. Alipour, N. Delmonte, L. Silvestri, L. Perregrini, and M. Bozzi, “A Simple Technique for Liquid-Liquid Percentage Determination Using Single-Frequency Amplitude Measurements,” *IEEE Microwave and Wireless Technology Letters*, vol. 33, no. 7, pp. 1086-1089, July 2023.

RETRIEVAL OF THE DIELECTRIC PERMITTIVITY / 2

The major advantage of the technique based on the **variation of the transmission amplitude at a single frequency** is the **simpler equipment** needed for the measurement.



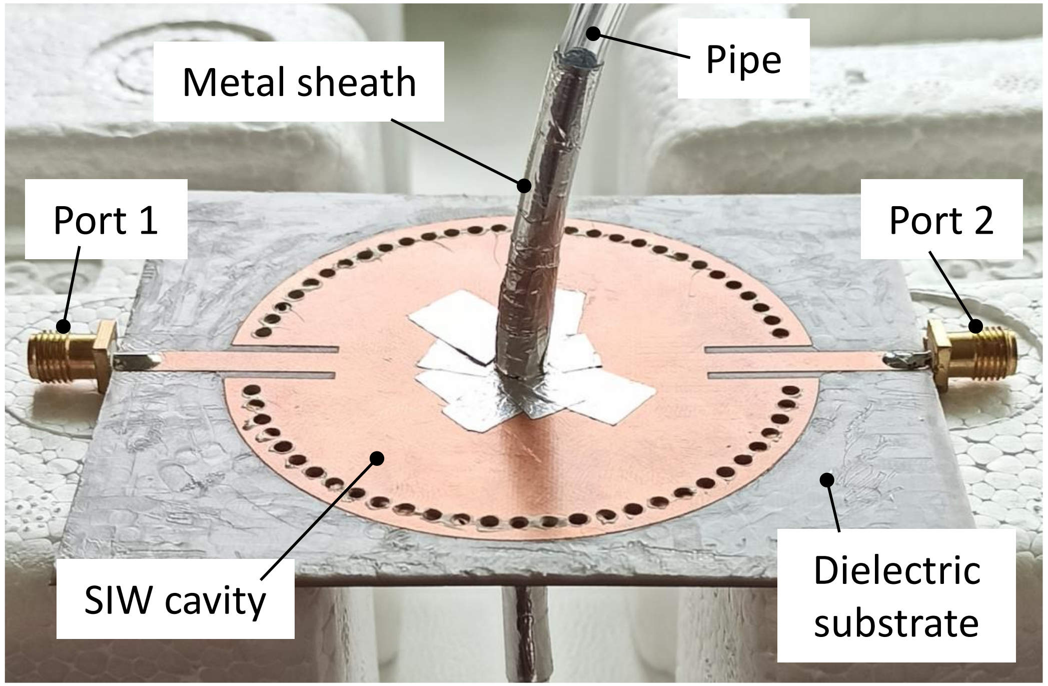
MEASUREMENT OF THE RESONANCE FREQUENCY SHIFT



MEASUREMENT OF THE TRANSMISSION AMPLITUDE VARIATION

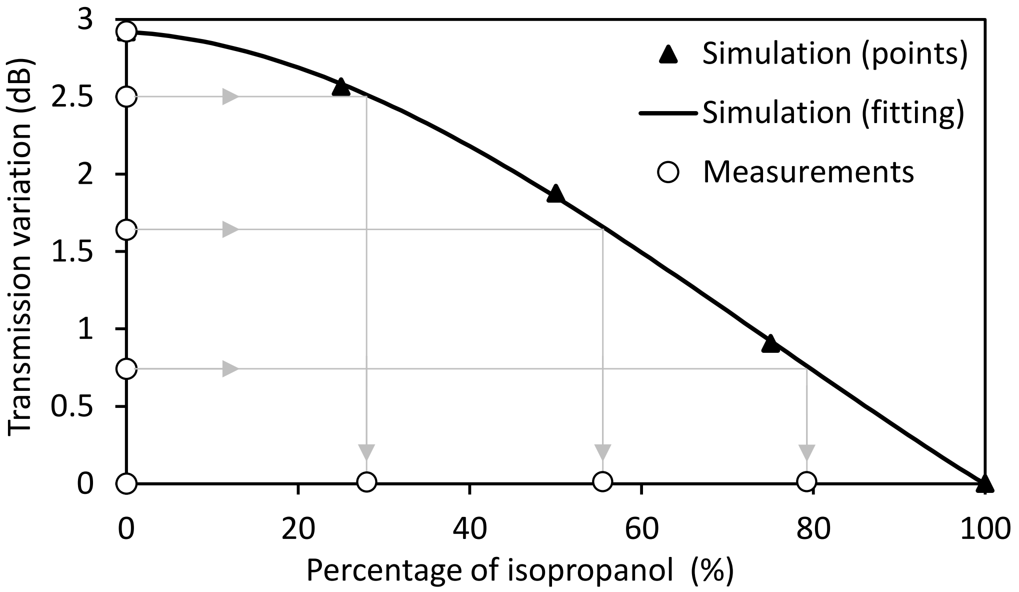
SIW CAVITY SENSOR / 2

An **SIW cavity** similar to the previous one was adopted, to measure the liquid percentage in a mixture of acetone (ε_r = 20.42) and isopropanol (ε_r = 5.21).



SIW CAVITY SENSOR / 2

The **calibration of the sensor** was performed by using the transmission amplitude with 100% acetone and the one with 100% isopropanol.

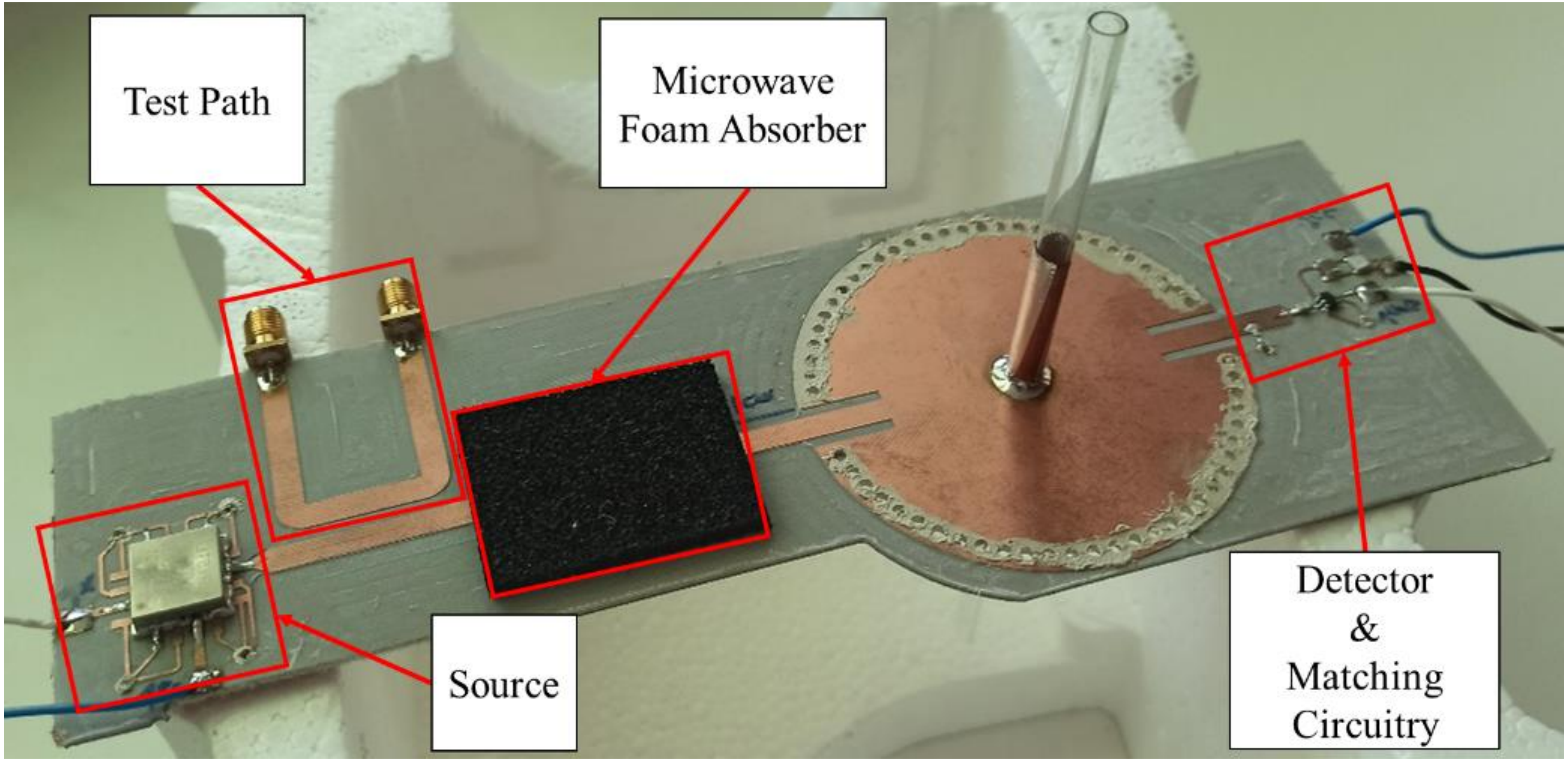


RESULTS FOR THE NOVEL TECHNIQUE (TRANSMISSION VARIATION)

Nominal isopropanol % (ε_r)	Simulated transm. variation	Measured transm. variation	Retrieved isopropanol % (ε_r)	Error in isopropanol %	% Error in ε_r
0% (20.42)	2.92 dB	2.92 dB	0.0% (20.42)	0.0%	==
25% (16.62)	2.56 dB	2.50 dB	28.5% (16.09)	3.5%	3.2%
50% (12.82)	1.87 dB	1.64 dB	56.0% (11.90)	6.0%	7.1%
75% (9.01)	0.91 dB	0.74 dB	79.7% (8.30)	4.7%	7.9%
100% (5.21)	0.00 dB	0.00 dB	100.0% (5.21)	0.0%	==

M. Alipour, N. Delmonte, L. Silvestri, L. Perregrini, and M. Bozzi, “A Simple Technique for Liquid-Liquid Percentage Determination Using Single-Frequency Amplitude Measurements,” *IEEE Microwave and Wireless Technology Letters*, vol. 33, no. 7, pp. 1086-1089, July 2023.

SIW Cavity Sensor / 2

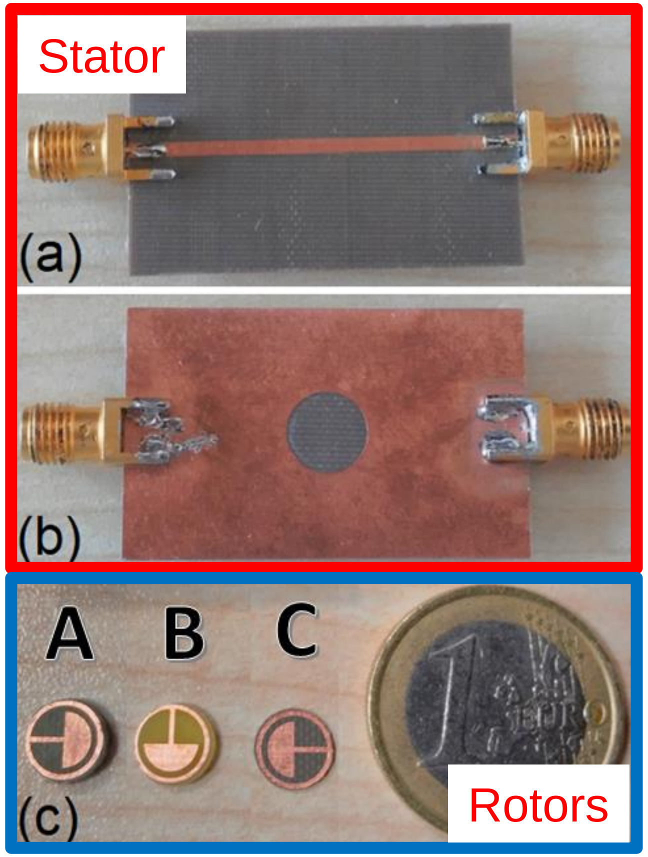


ROTATION SENSOR

This sensor is based on a **modified complementary split-ring resonator** (CSRR).

It can detect angular displacement and direction of rotation with high resolution and sensitivity over a wide dynamic range.

The proposed microwave planar sensor takes advantage of the **asymmetry of the rotor geometry**.

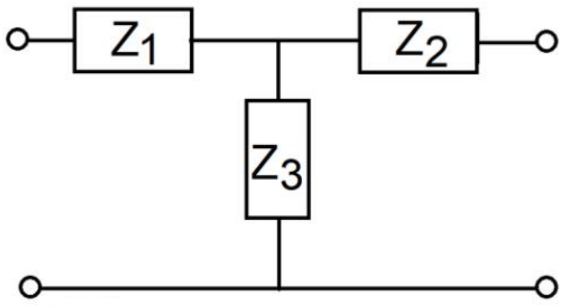


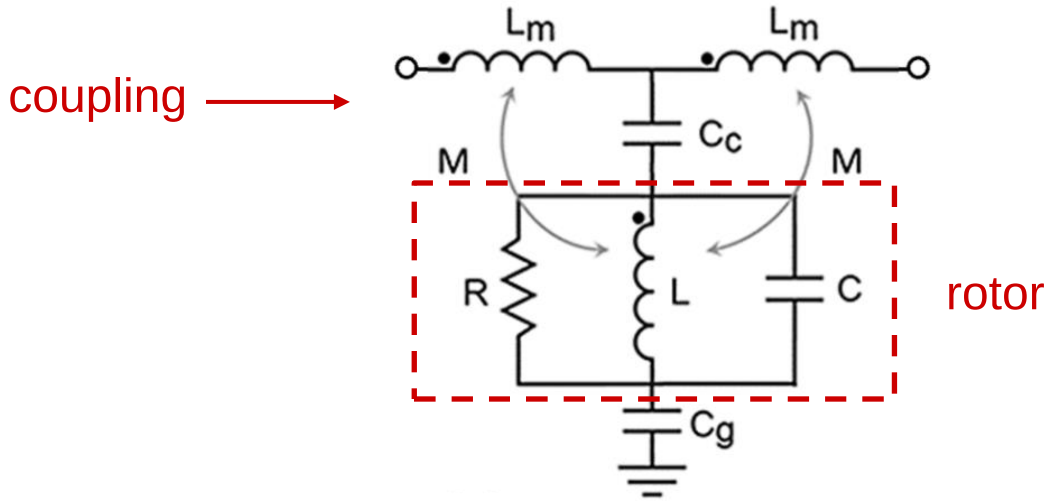
(a) Bottom view of fabricated stator
(b) Top view of fabricated stator
(c) Rotors

A. K. Jha, A. Lamecki, M. Mrozowski, and M. Bozzi, "A Highly-Sensitive Planar Microwave Sensor For Detecting Direction and Angle of Rotation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 68, No. 4, pp. 1598-1609, Apr. 2020.

ROTATION SENSOR

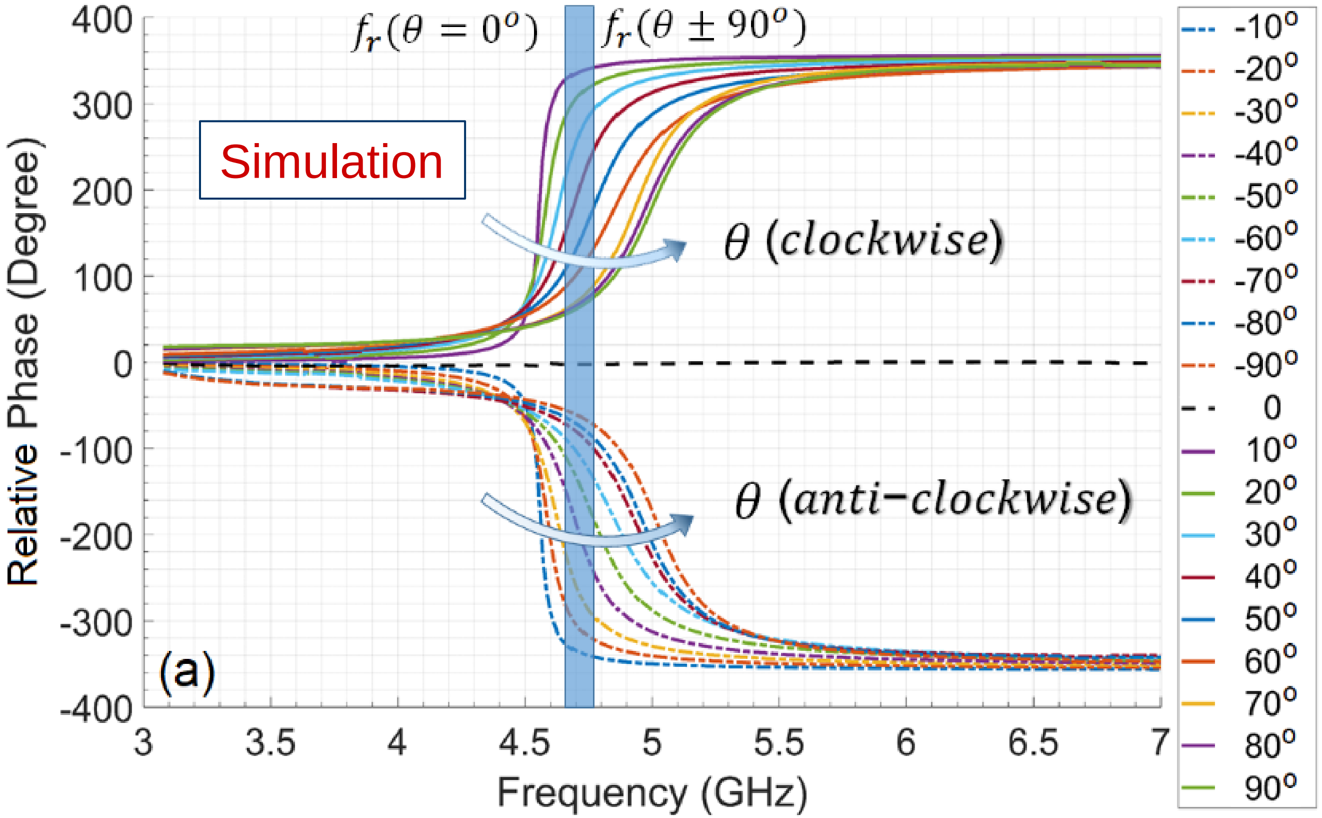
The operation principle of the sensor is based on the variation of the **cross-coupling effects due to the electric and magnetic coupling** when changing the rotation angle.





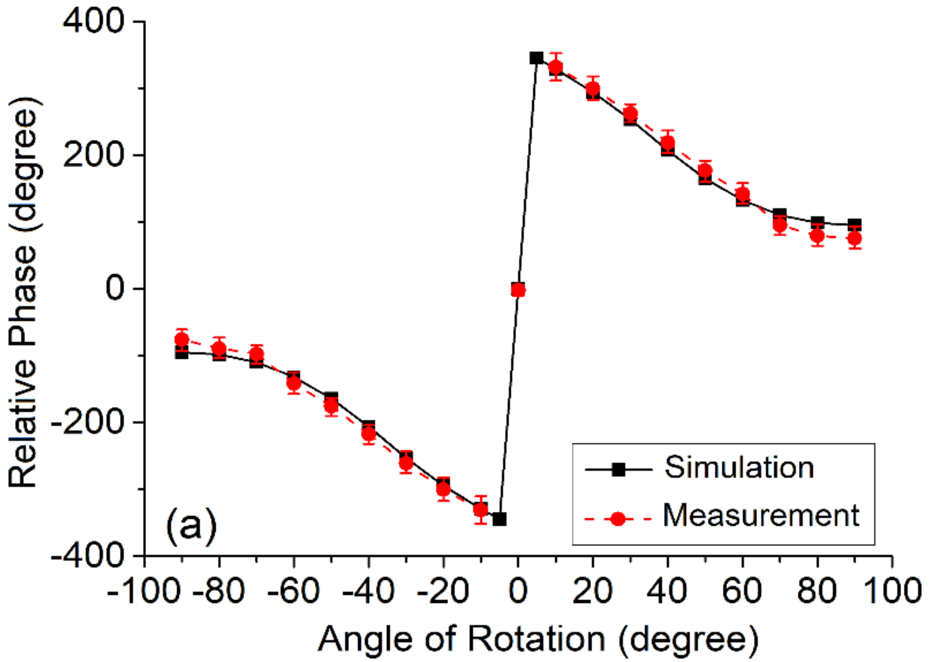
ROTATION SENSOR

This sensor measures the **angle of rotation** in terms of the **change in the relative phase of the reflection coefficient**.



Rotation Sensor

The phase variation was measured at the frequency of the transmission zero.



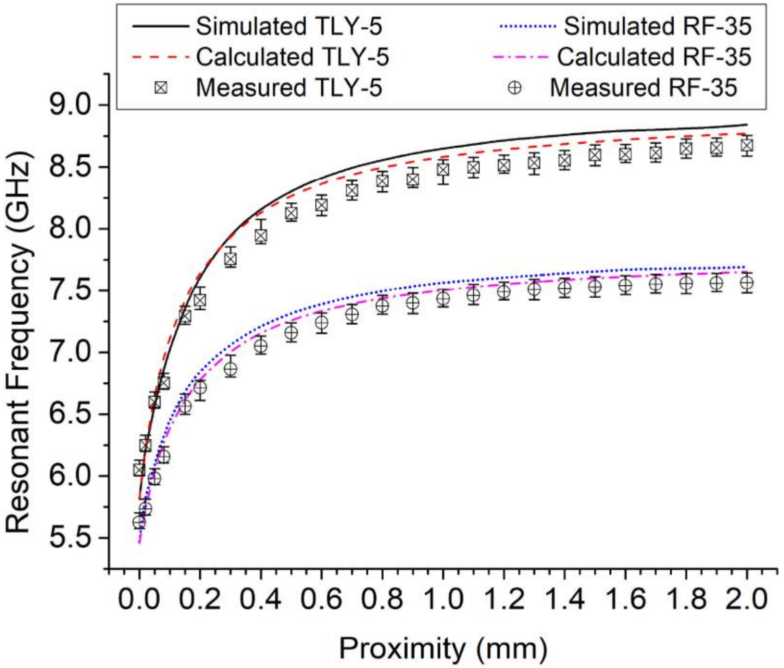
The maximum sensitivity for measuring the angular rotation is found to be a 4.3° change in the relative phase of the reflection coefficient per 1° of rotation.

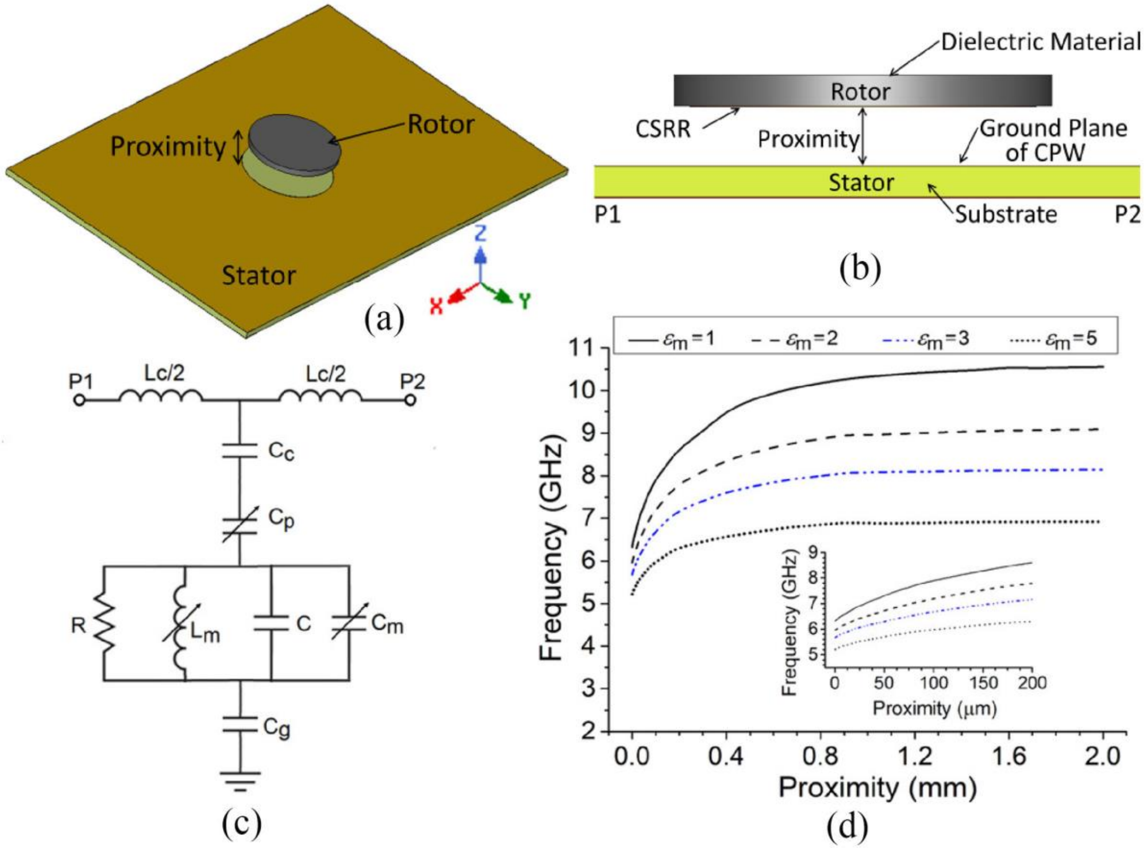
The sensor has an angular measurement range from −90° to +90°.

A. K. Jha, A. Lamecki, M. Mrozowski, and M. Bozzi, "A Highly-Sensitive Planar Microwave Sensor For Detecting Direction and Angle of Rotation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 68, No. 4, pp. 1598-1609, Apr. 2020.

PROXIMITY SENSOR

A similar approach is adopted for proximity measurement, based on the **shift of the resonance frequency**.





A. K. Jha, A. Lamecki, M. Mrozowski, and M. Bozzi, "A Microwave Sensor with Operating Band Selection to Detect Rotation and Proximity in the Rapid Prototyping Industry," *IEEE Transactions on Industrial Electronics*, Vol. 68, No. 1, pp. 683-693, Jan. 2021.

3D-Printed
Microwave Sensors

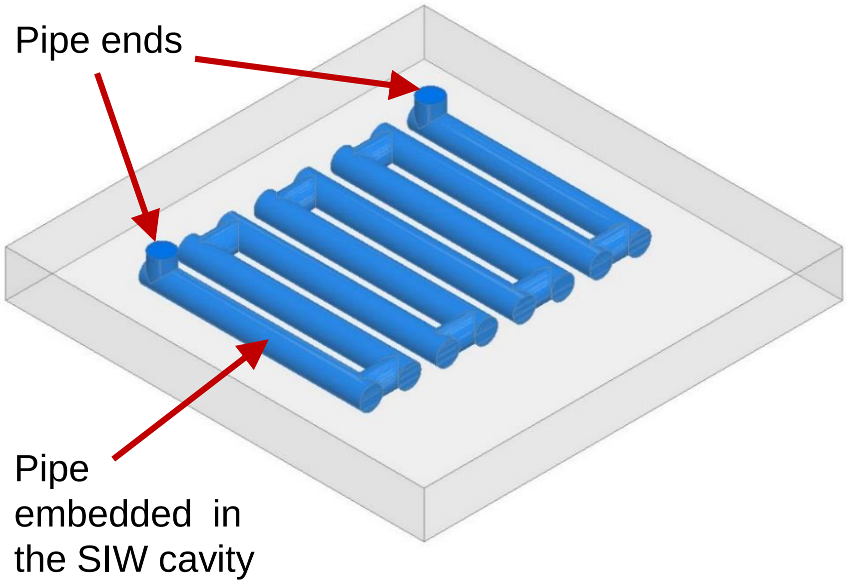
3D PRINTING TECHNOLOGY

The 3D printing (or additive manufacturing) technology offers **additional flexibility** in the implementation of microwave sensors:

- fully arbitrary shape;
- selection of the material;
- one single fabrication step.

SIW-BASED MICROFLUIDIC CAVITY

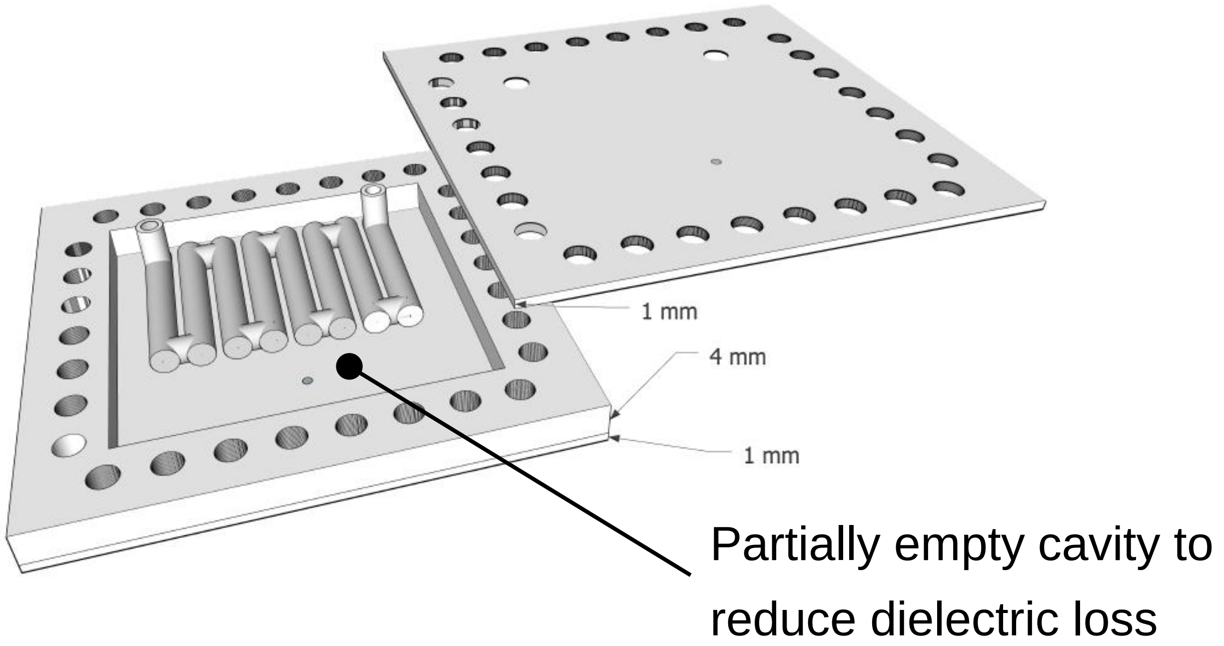
We implemented a **microfluidic cavity** based on the substrate integrated waveguide **(SIW) technology** by using the **additive manufacturing**.

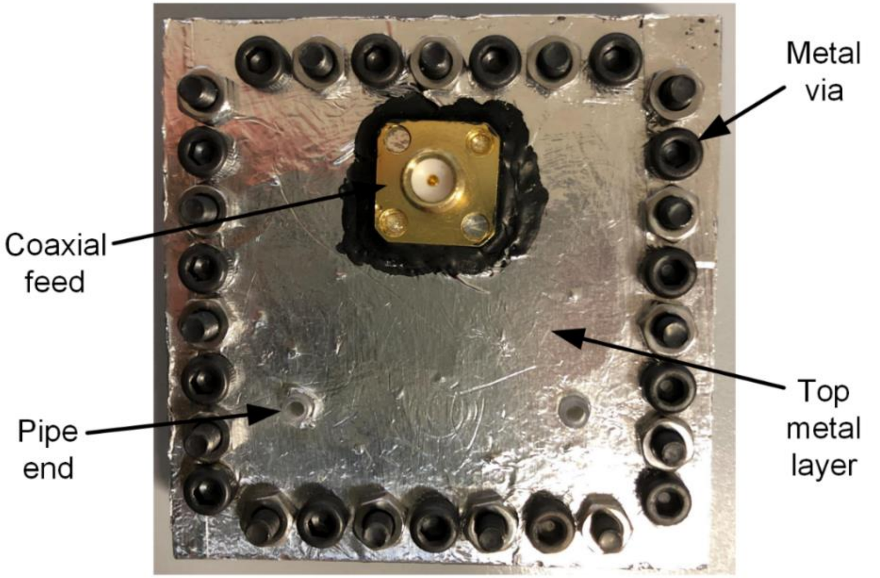


G. M. Rocco, M. Bozzi, D. Schreurs, L. Perregrini, S. Marconi, G. Alaimo, and F. Auricchio, "3D-Printed Microfluidic Sensor in SIW Technology for Liquids Characterization," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 68, No. 3, pp. 1175-1184, Mar. 2020.

FABRICATION PROCESS

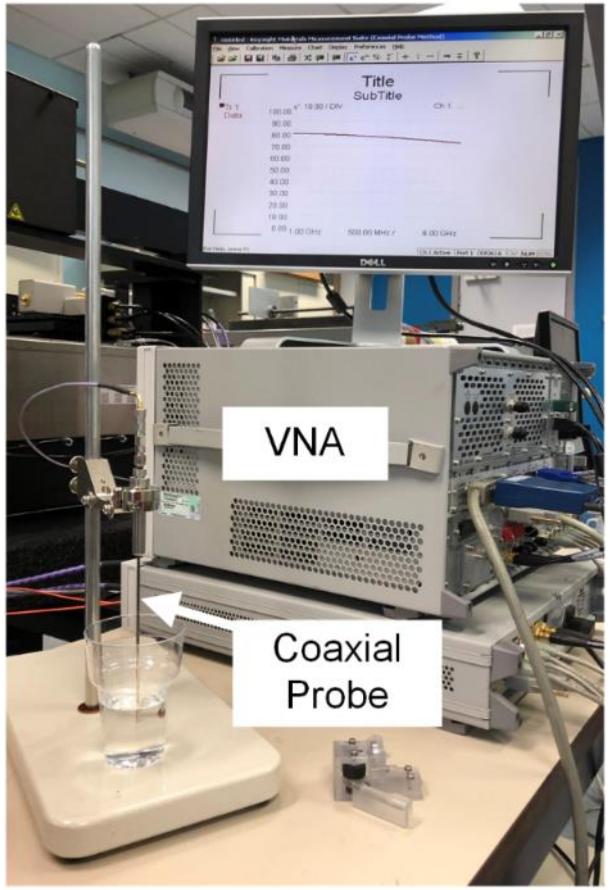
1. Printing of the **substrate** by using a stereo-lithography (SLA) printer
2. Top and bottom **conductive layers**: adhesive aluminum tape
3. **Side walls**: stainless steel screws.
4. The pin of an **SMA connector** was inserted in the printed small hole





MEASUREMENT OF REFERENCE VALUES

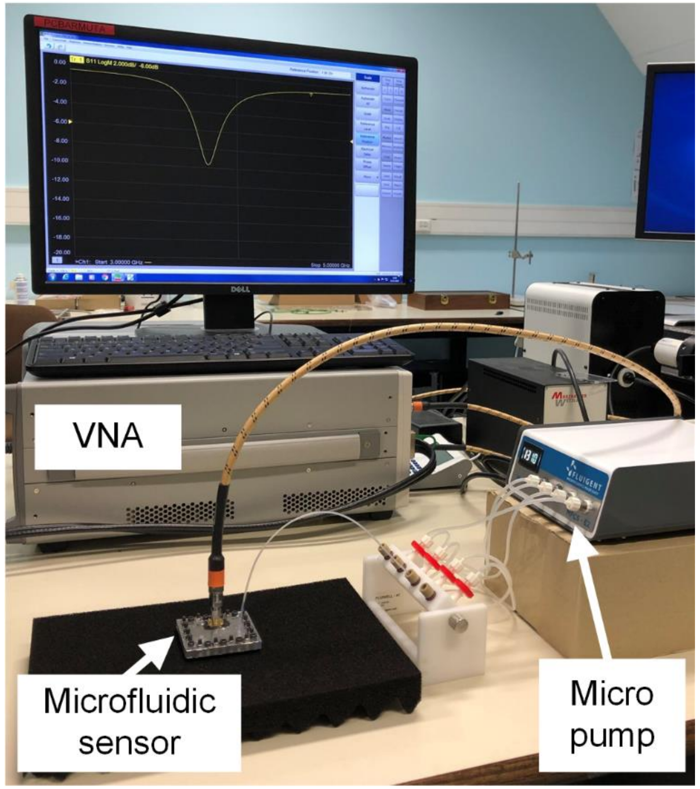
Reference values of dielectric permittivity and loss tangent measured by a **commercial coaxial probe.**



Mixture Under Test	ε_r	$\tan\delta$
Water 100%	75.6	0.17
Isoprop. 10%/Water 90%	64.9	0.24
Isoprop. 20%/Water 80%	59.2	0.36
Isoprop. 30%/Water 70%	49.9	0.45
Isoprop. 45%/Water 55%	35.3	0.57
Isoprop. 60%/Water 40%	24.9	0.67
Isoprop. 75%/Water 25%	14.8	0.78
Isoprop. 85%/Water 15%	8.04	0.81
Isopropanol 100%	3.90	0.55

DATA FROM MEASUREMENTS

The **S-parameters** of the cavity were measured with different mixtures of liquids in the pipe.



Mixture Under Test	Resonance frequency f_0 (GHz)	Frequency shift Δf (GHz)	Unloaded quality factor Q_U^{meas}
Air	3.8267	0	43.12
Water 100%	3.4077	0.4190	36.73
Isoprop. 10%/Water 90%	3.4150	0.4117	34.24
Isoprop. 20%/Water 80%	3.4174	0.4093	31.78
Isoprop. 30%/Water 70%	3.4243	0.4024	29.06
Isoprop. 45%/Water 55%	3.4287	0.3980	27.31
Isoprop. 60%/Water 40%	3.4474	0.3793	24.03
Isoprop. 75%/Water 25%	3.4757	0.3510	21.47
Isoprop. 85%/Water 15%	3.5147	0.3120	18.12
Isopropanol 100%	3.6095	0.2172	17.48

Resonance frequency & **Quality factor** (*for different liquids*)

Retrieval of EM Characteristics

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The values of the electromagnetic characteristics are retrieved from **resonance frequency shift** and **quality factor variation**.

Relative permittivity

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
Water 100%	75.3	75.6	-0.4
Isoprop. 10%/Water 90%	64.7	64.9	-0.4
Isoprop. 20%/Water 80%	59.7	59.2	+0.9
Isoprop. 30%/Water 70%	48.9	49.9	-2.1
Isoprop. 45%/Water 55%	42.0	35.3	+19
Isoprop. 60%/Water 40%	26.9	24.9	+8.3
Isoprop. 75%/Water 25%	16.5	14.8	+11.6
Isoprop. 85%/Water 15%	8.60	8.04	+7.5
Isopropanol 100%	4.20	3.90	+7.1

Average error 6%

Loss tangent

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
Water 100%	0.150	0.174	-13.9
Isoprop. 10%/Water 90%	0.238	0.242	-1.61
Isoprop. 20%/Water 80%	0.331	0.356	-6.93
Isoprop. 30%/Water 70%	0.478	0.451	+6.09
Isoprop. 45%/Water 55%	0.594	0.574	+3.49
Isoprop. 60%/Water 40%	0.755	0.675	+11.86
Isoprop. 75%/Water 25%	0.776	0.775	+0.12
Isoprop. 85%/Water 15%	0.910	0.815	+12.03
Isopropanol 100%	0.597	0.554	+7.79

Average error 7%

How to get better accuracy?

The accuracy of the retrieved results can be improved by **increasing the quality factor of the cavity resonator**.

Higher quality factor (= lower losses) can be achieved by acting on the **shape of the cavity**:

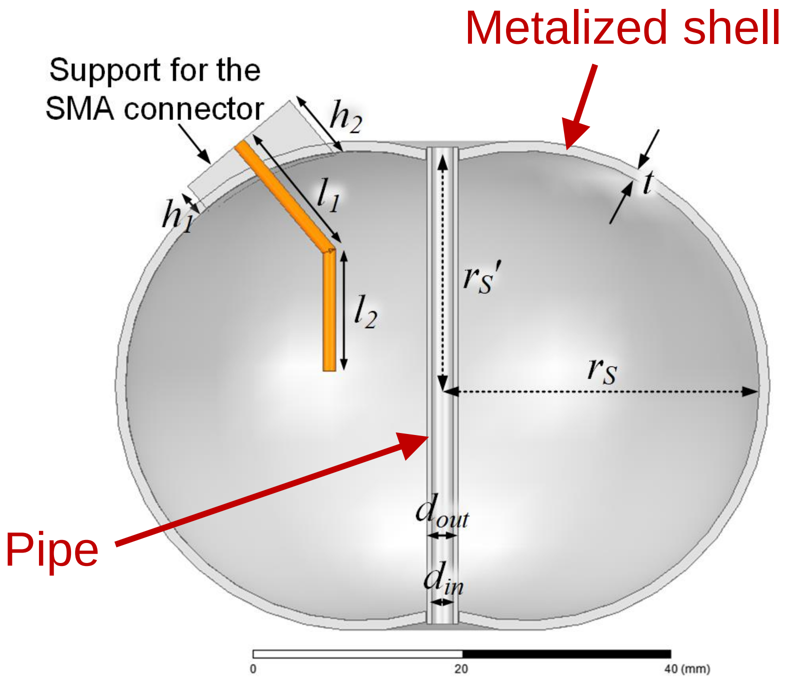
Empty cavity (no dielectric) ⟹ no dielectric loss

Larger dimension

(lower current density) ⟹ lower conductor loss

PUMPKIN-SHAPED MICROFLUIDIC CAVITY

We implemented a **microfluidic cavity** based on the **pumpkin-shaped cavity resonator** by using the **additive manufacturing**.



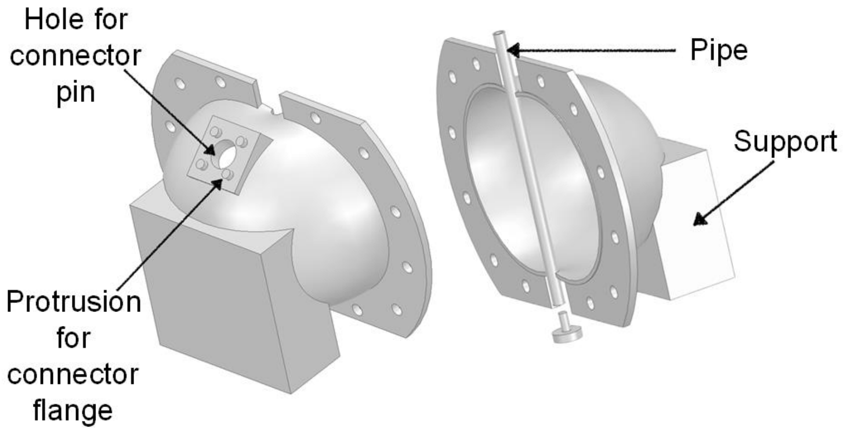
The shape is a **sphere compressed at the poles** (to avoid degenerate modes).

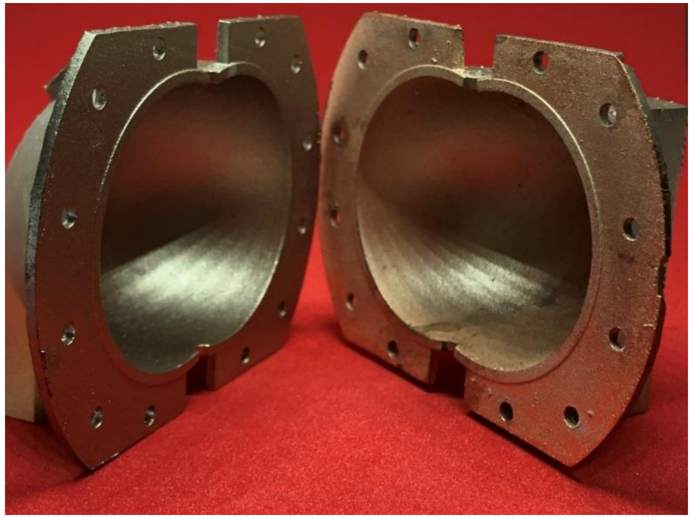
The cavity operated on the **fundamental TM_{011} mode**, with electrical field aligned to the symmetry rotation axis.

G.M. Rocco, N. Delmonte, D. Schreurs, S. Marconi, F. Auricchio, and M. Bozzi, "3D-printed pumpkin-shaped cavity resonator to determine the complex permittivity of liquids," *Microwave and Optical Technology Letters*, Vol. 63, No. 4 pp. 1061-1066, Apr. 2021.

FABRICATION PROCESS

1. The structure 3D printed **in two halves** by **SLA printer**
2. The inner surface of the cavity was metalized by **galvanic electroplating**
3. The **feeding probe** was realized by cutting the SMA connector's pin

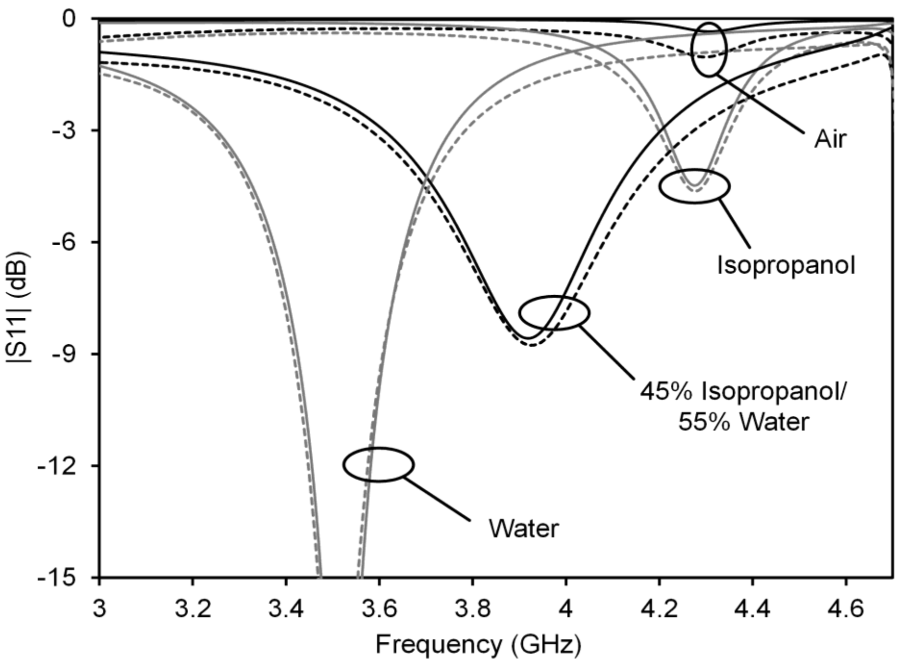




DATA FROM MEASUREMENTS

Quality factor of the empty cavity Q=321

(losses are mainly due to the plastic pipe).



Liquid Under Test	Resonance frequency (GHz)	Frequency shift Δ*f* (GHz)	Unloaded quality factor *Q*
Air	4.3072	0	321
ISP 100%	4.2763	0.0309	74.7
ISP 85%/Water 15%	4.2334	0.0738	27.3
ISP 75%/Water 25%	4.1934	0.1138	18.3
ISP 60%/Water 40%	4.1022	0.2050	11.3
ISP 45%/Water 55%	3.9272	0.3800	7.28
ISP 30%/Water 70%	3.7766	0.5306	6.69
ISP 20%/Water 80%	3.6816	0.6256	7.54
ISP 10%/Water 90%	3.5778	0.7294	9.13
Water 100%	3.5113	0.7959	12.3

RETRIEVAL OF EM CHARACTERISTICS

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The same technique presented in the previous part was adopted.

Relative permittivity

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
ISP 100%	4.27	4.16	+2.6
ISP 85%/Water 15%	8.9	9.35	-4.8
ISP 75%/Water 25%	13	13.6	-4.6
ISP 60%/Water 40%	21.7	22.8	-5.0
ISP 45%/Water 55%	37	37.7	-2.0
ISP 30%/Water 70%	49.7	49.43	+0.6
ISP 20%/Water 80%	58.5	58.66	-0.3
ISP 10%/Water 90%	69.3	69.2	+0.1
Water 100%	77	75.87	+1.6

Average error 2.4%

Loss tangent

Mixture Under Test	Microfluidic Sensor	Coaxial Probe	% Relative error
ISP 100%	0.561	0.539	+4.1
ISP 85%/Water 15%	0.766	0.729	+5.1
ISP 75%/Water 25%	0.763	0.722	+5.7
ISP 60%/Water 40%	0.677	0.662	+2.3
ISP 45%/Water 55%	0.564	0.533	+5.8
ISP 30%/Water 70%	0.448	0.437	+2.5
ISP 20%/Water 80%	0.349	0.330	+5.8
ISP 10%/Water 90%	0.238	0.237	+0.4
Water 100%	0.175	0.166	+5.4

Average error 4.1%

Higher quality factor (better accuracy), **larger cavity size**.

Sensors Based on
Hybrid Technologies

Microfluidic Sensor in Hybrid Technology

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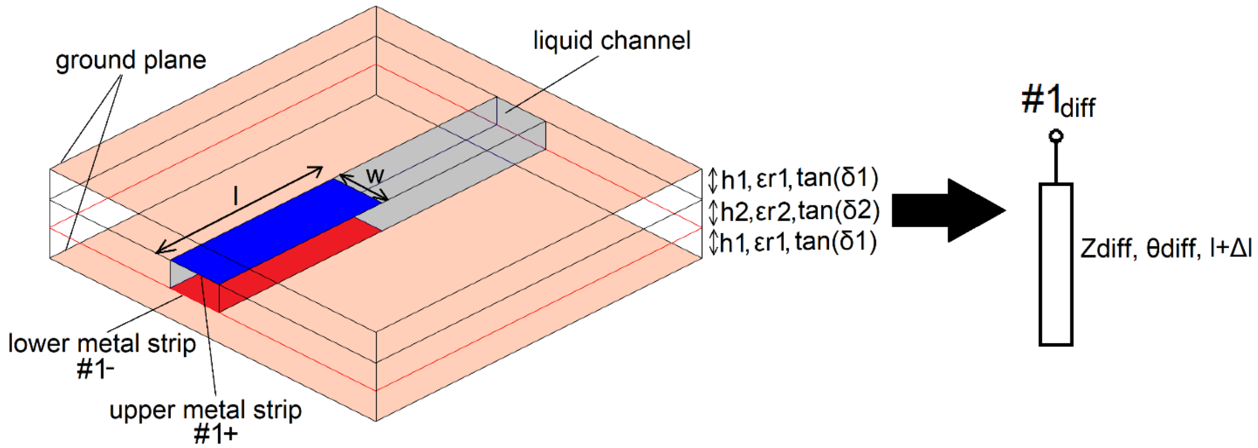
A **broadband microfluidic sensor for liquid chemicals monitoring** consists of an open-ended broadside-coupled-line section, with a liquid channel between the metal strips.



The electrical characteristics of the liquid under test can be obtained from the one-port-differential reflection coefficient, after a proper calibration.

I. Piekarz, J. Sorocki, N. Delmonte, L. Silvestri, S. Marconi, G. Alaimo, F. Auricchio, and M. Bozzi, "Microwave-Microfluidic Sensor in Hybrid 3-D Printing and Laminate Technology for Chemicals Monitoring from Differential Reflection," *IEEE MTT-S International Microwave Symposium* (IMS 2021), Atlanta, Georgia, USA, 21-25 June 2021.

MICROFLUIDIC SENSOR IN HYBRID TECHNOLOGY

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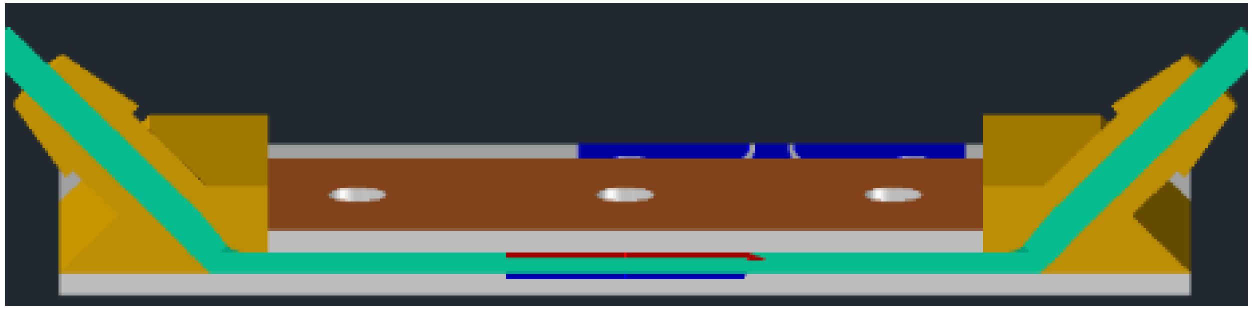
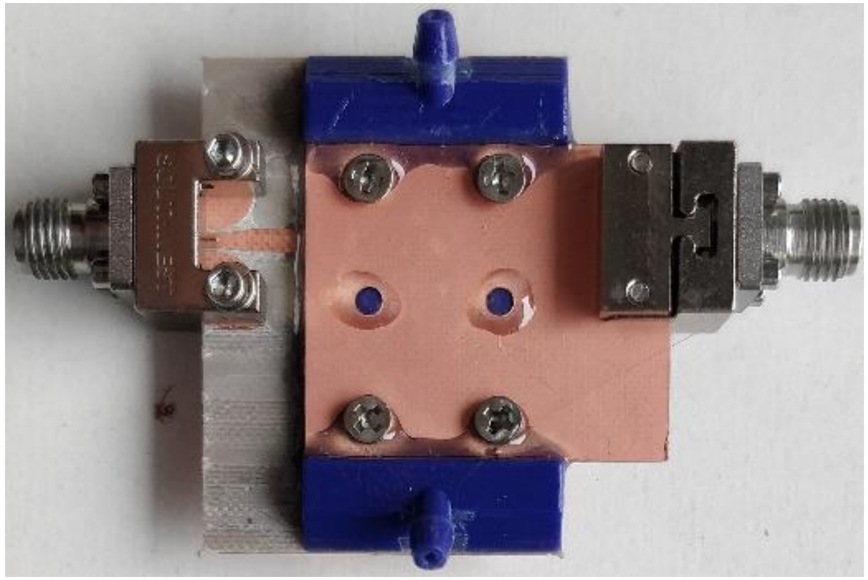
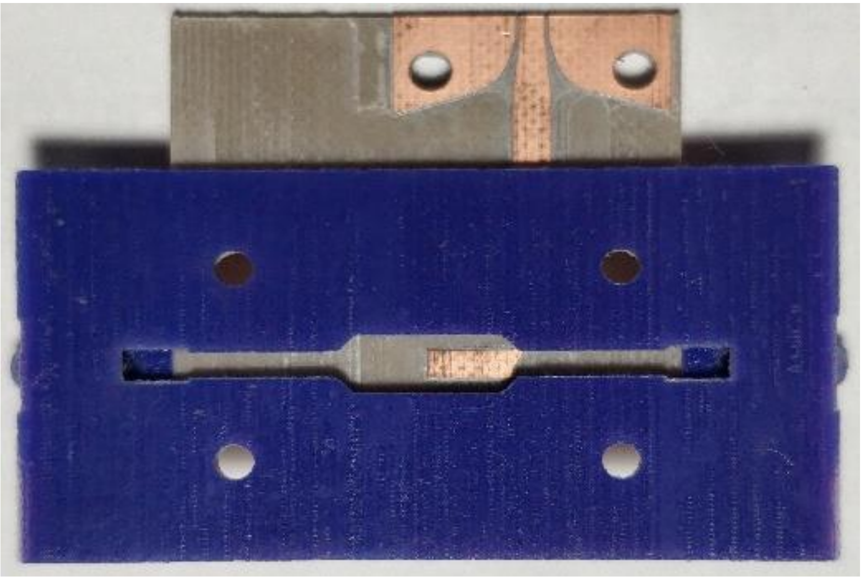
A **hybrid 3D printing and laminate technology** was adopted for the realization of a prototype to ensure good electrical and mechanical performance

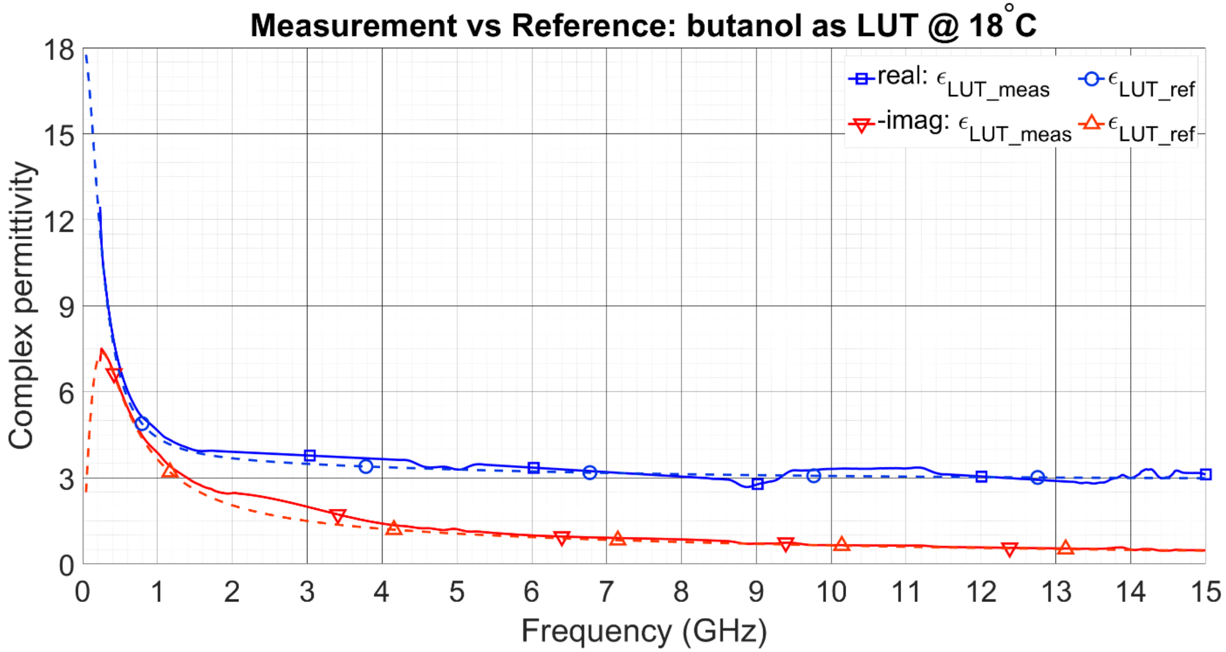




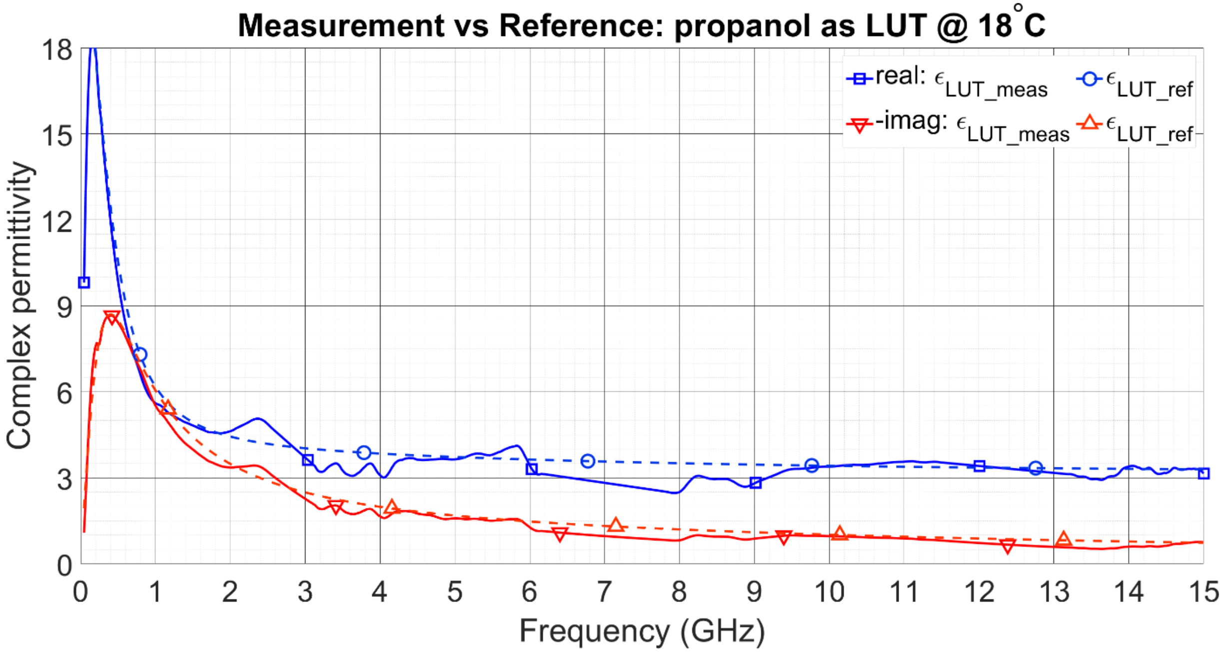


Microfluidic Sensor in Hybrid Technology

Measurement show a **relatively low error over a wide frequency band**.



Butanol



Propanol

CONCLUSION

- **Microwave sensors** are becoming key components for a number of novel RF and microwave applications, in the framework of IoT and 5G systems.

- Various manufacturing technologies were adopted for the implementation of the sensors, including **planar** and **SIW technology**, **3D-printing**, and **hybrid solutions**, to meet the requirements of different applications.

- A **deep understanding of the physical behavior** of the electromagnetic fields in the different cases is mandatory to develop novel solutions.

Microwave Sensors: Novel Techniques, Topologies, and Manufacturing Technologies

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