Th2B-4

A New Microwave Oscillator-Based Microfluidic Sensor for Complex Permittivity Measurement

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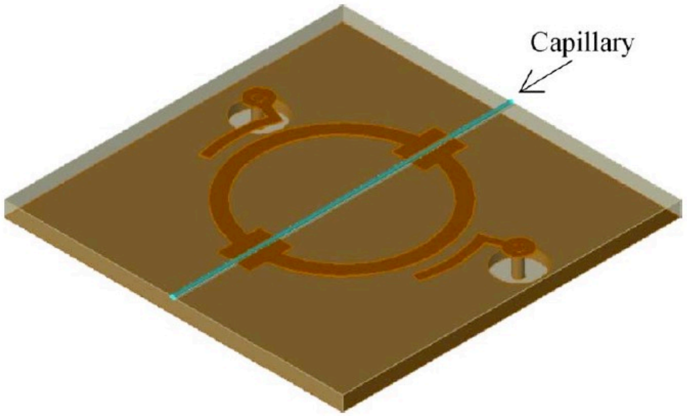
Outline

- Motivation
- Design of permittivity sensor
  - Modified coplanar strip resonator (MCSR) design
  - Sensing oscillator design
- Experimental results
  - Sensor calibration
  - Permittivity measurement
- Conclusion

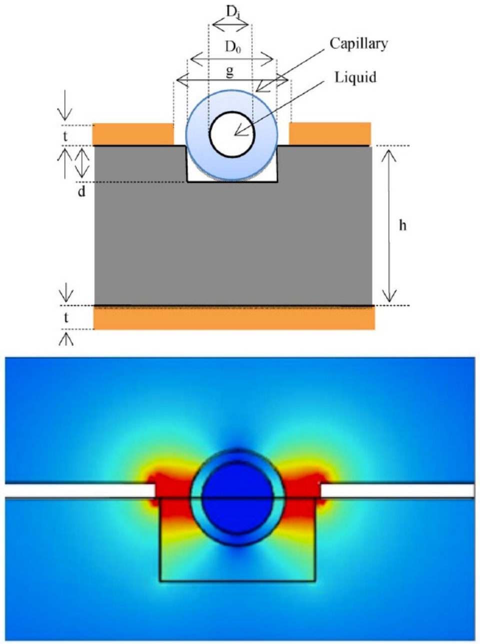
Motivation

- SRR microfluidic sensor

sensor schematic



sensing mechanism



Pros:

- Two gaps of the SRR are used to sense the liquid under test in the capillary.
- The machining valley has benefits for placing capillary tube and making the electric field uniform distribution.

Cons:

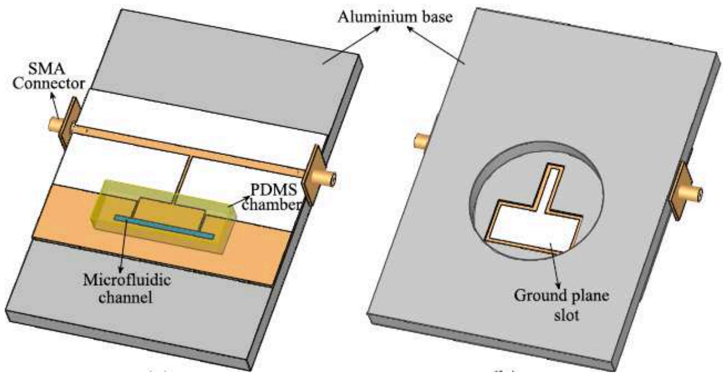
- Need expensive and bulky vector network analyzer.

A. A. Abduljabar, D. J. Rowe, A. Porch, and D. A. Barrow, “Novel microwave microfluidic sensor using a microstrip split-ring resonator,” IEEE Trans. Microw. Theory Techn., vol. 62, no. 3, pp. 679–688, Mar. 2014.

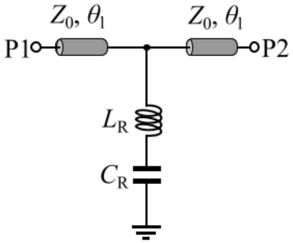
Motivation

- LC-lumped microfluidic sensor

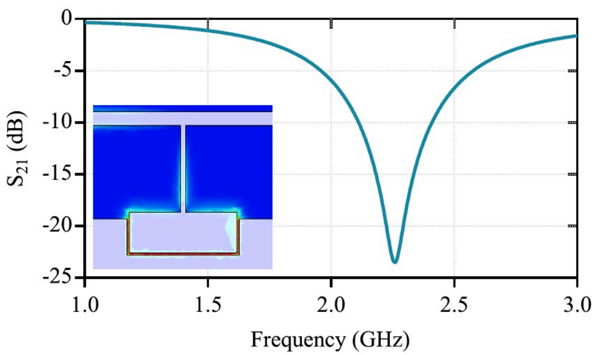
sensor schematic



sensor equivalent circuit



sensing mechanism



Pros:

- The distributed LC resonator sensor is used to reduce the sensor size and test liquid volume.

Cons:

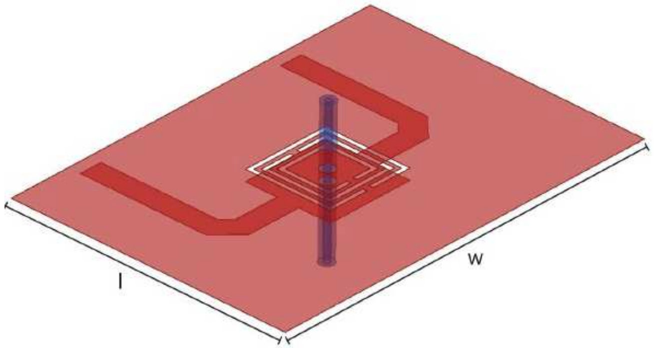
- The fabrication process is more complicated.
- Need expensive and bulky vector network analyzer.

A. Ebrahimi, J. Scott, and K. Ghorbani, "Ultrahigh-sensitivity microwave sensor for microfluidic complex permittivity measurement," IEEE Trans. Microw. Theory Techn., vol. 67, no. 10, pp. 4269–4277, Oct. 2019.

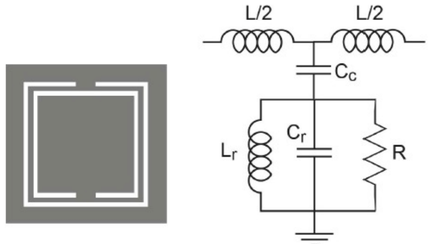
Motivation

- CSRR microfluidic sensor

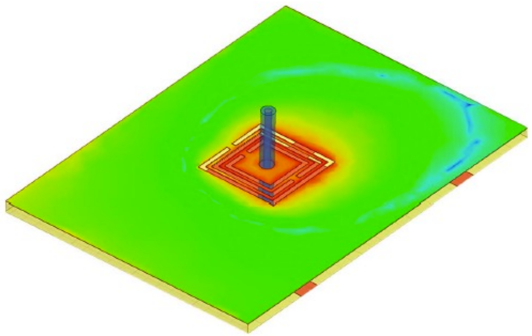
sensor schematic



sensor equivalent circuit



sensing mechanism



Pros:
- The concentrated electric field is used to sense the liquid under test.
- The two-turn structure is used to reduce sensor size.

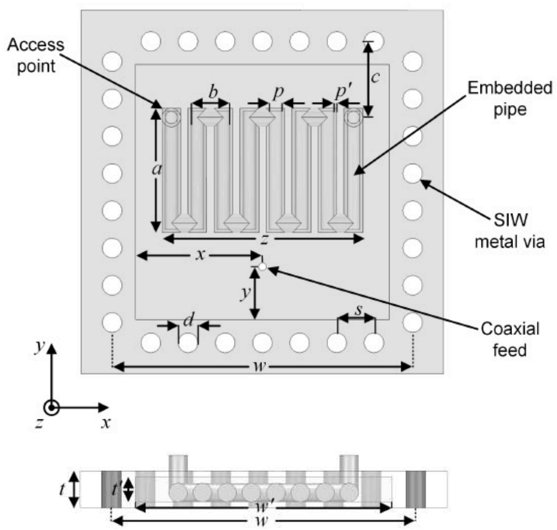
Cons:
- The capillary should be perpendicular to the CSRR.
- Need expensive and bulky vector network analyzer.

E. L. Chuma, Y. Iano, G. Fontgalland, and L. L. B. Roger, "Microwave sensor for liquid dielectric characterization based on metamaterial complementary split ring resonator," IEEE Sensors J., vol. 18, no. 24, pp. 9978–9983, Dec. 2018.

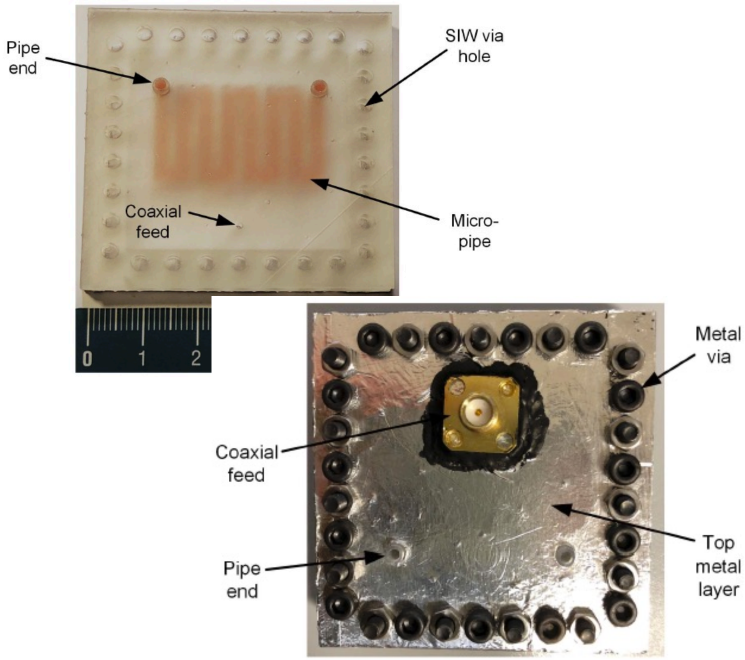
Motivation

- SIW microfluidic sensor

sensor schematic



sensor photograph



Pros:

- The sensing electric field is confined inside the SIW cavity, and has better immunity to environmental effects.

Cons:

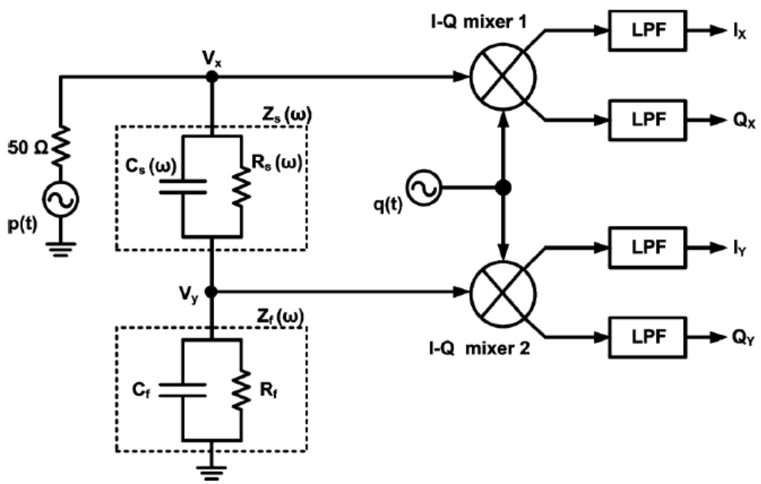
- The sensor has a larger size.
- Need expensive and bulky vector network analyzer.

G. M. Rocco et al., “3-D printed microfluidic sensor in SIW technology for liquids’ characterization,” IEEE Trans. Microw. Theory Techn., vol. 68, no. 3, pp. 1175–1184, Mar. 2020.

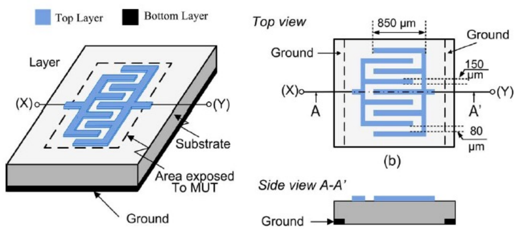
Motivation

- microfluidic sensing system

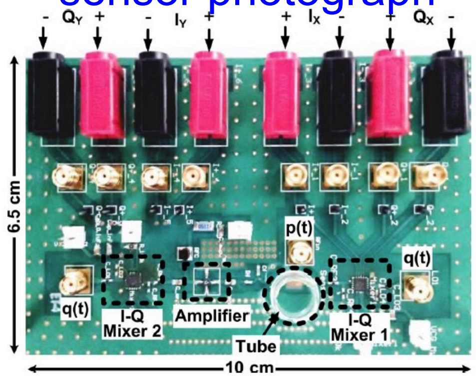
system block diagram



sensor schematic



sensor photograph



Pros:

- The sensor provides I/Q output channels for calculating complex permittivity.
- Do not need VNA

Cons:

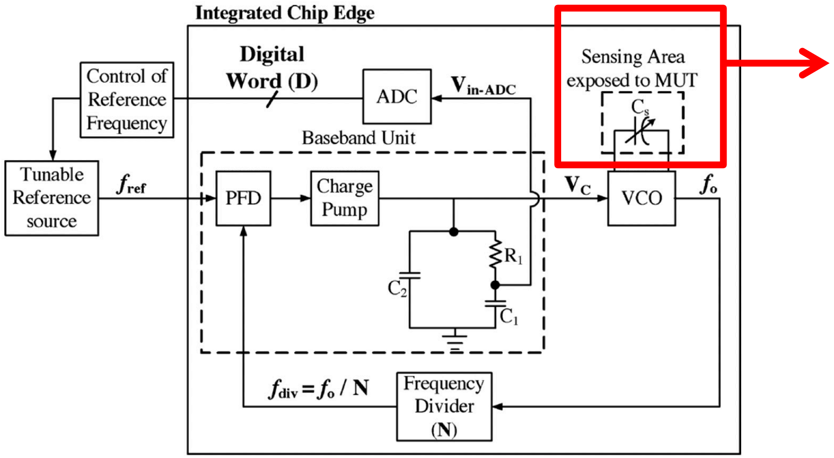
- The sensing area is a fixed spot zone, not flexible to fit various types of microfluidic channels.

A. A. Helmy, S. Kabiri, M. M. Bajestan, and K. Entesari, "Complex permittivity detection of organic chemicals and mixtures using a 0.5-3 GHz miniaturized spectroscopy system," IEEE Trans. Microw. Theory Techn., vol. 61, no. 12, pp. 4646–4658, Dec. 2013.

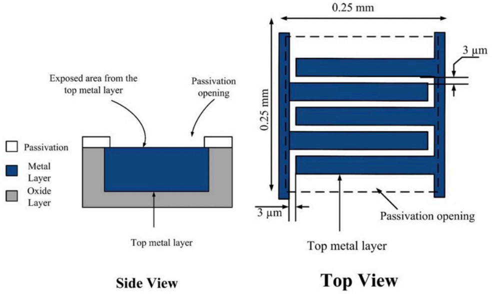
Motivation

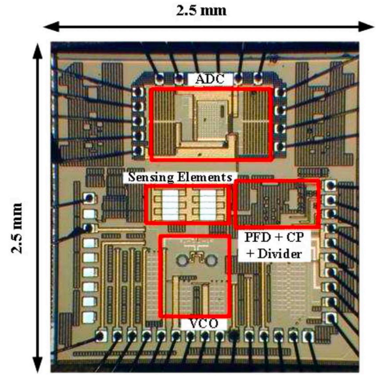
- CMOS microfluidic sensing system

system block diagram



sensor schematic





Pros:

- The sensor is designed using CMOS process to reduce the sensor size and test liquid volume.

Cons:

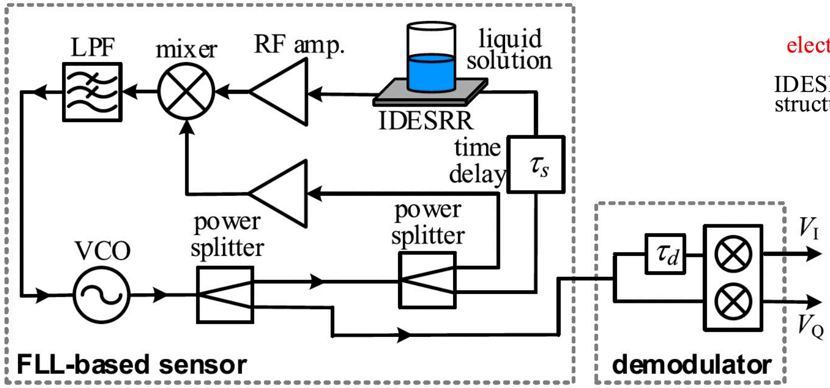
- The sensing area is a fixed spot zone, not flexible to fit various types of microfluidic channels.
- Measure the real part of permittivity only.

A. A. Helmy et al., "A self-sustained CMOS microwave chemical sensor using a frequency synthesizer," IEEE J. Solid-State Circuits, vol. 47, no. 10, pp. 2467–2483, Oct. 2012.

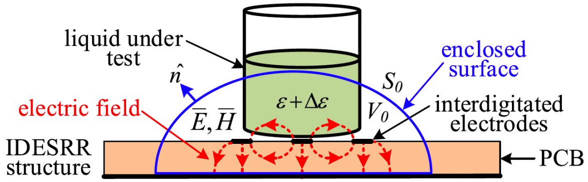
Motivation

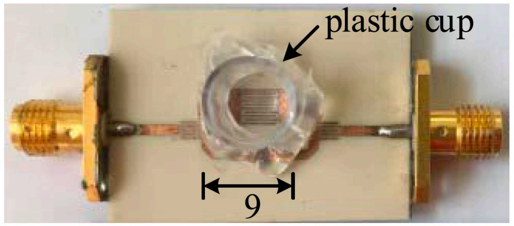
- FLL microfluidic sensing system

system block diagram



sensor schematic





Pros:

- The sensor can be flexibly designed to have a specific electric-field distribution.
- Do not need VNA

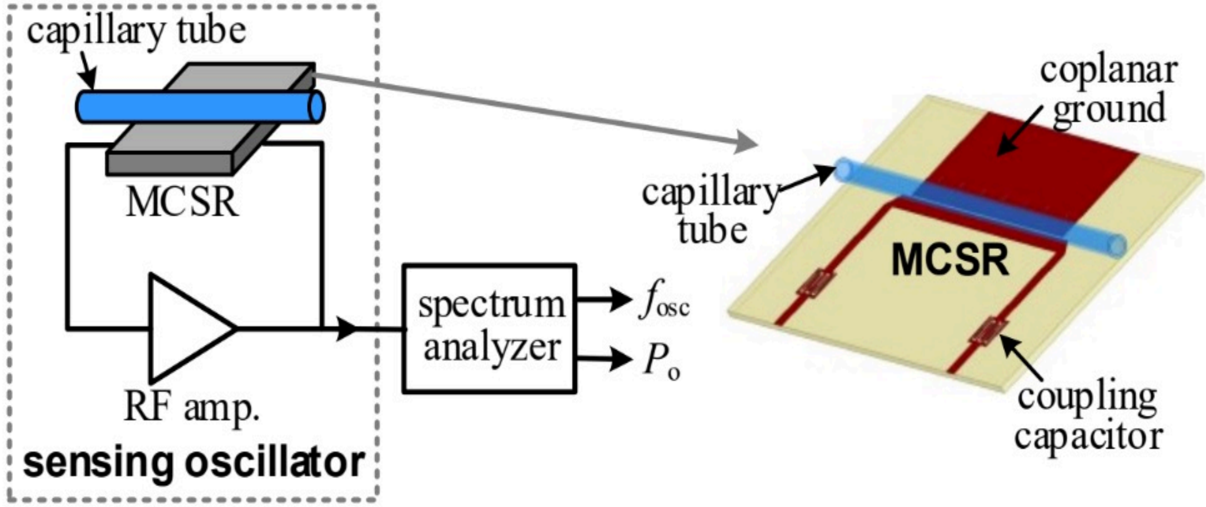
Cons:

- The sensing system size is large.

C.-H. Tseng and C.-Y. Yang, “Novel microwave frequency-locked-loop-based sensor for complex permittivity measurement of liquid solutions,” IEEE Trans. Microw. Theory Techn., vol. 70, no. 10, pp. 4556–4565, Oct. 2022.

Design of permittivity sensor

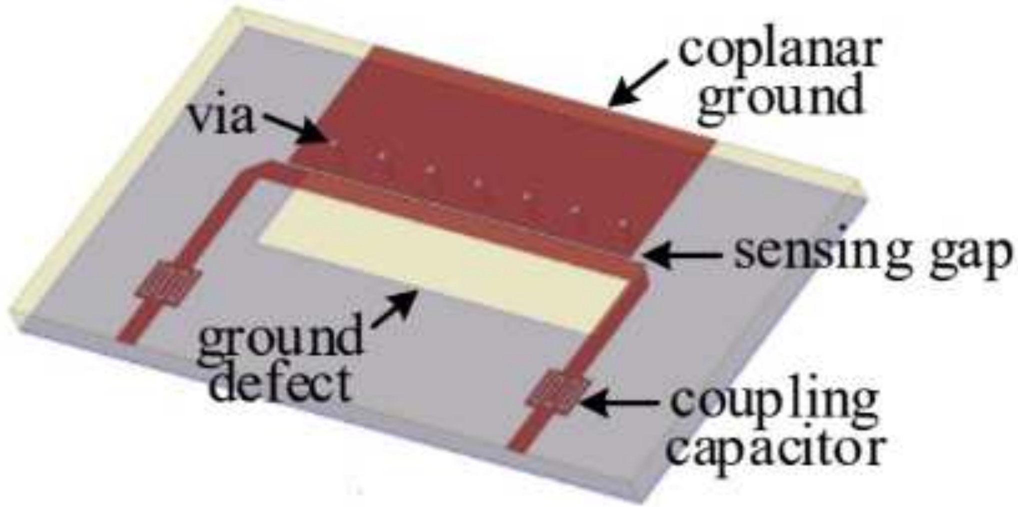
- System block diagram of the proposed microfluidic sensor



- A microfluidic sensor using a sensing oscillator with a modified coplanar strip resonator (MCSR) to have a more flexible sensing field distribution for complex permittivity measurement.

Design of permittivity sensor

- MCSR design

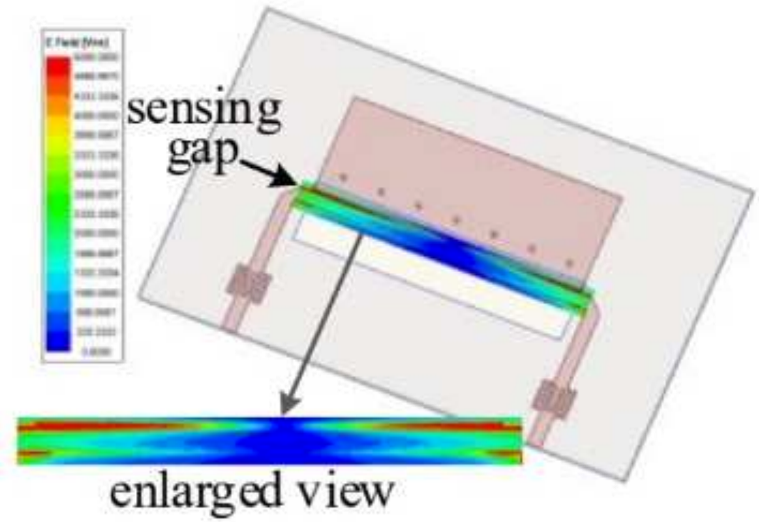


- The MCSR is mainly a half-wavelength transmission-line (TL) resonator, and a portion of the TL is replaced by a conductor strip with a coplanar ground plane.

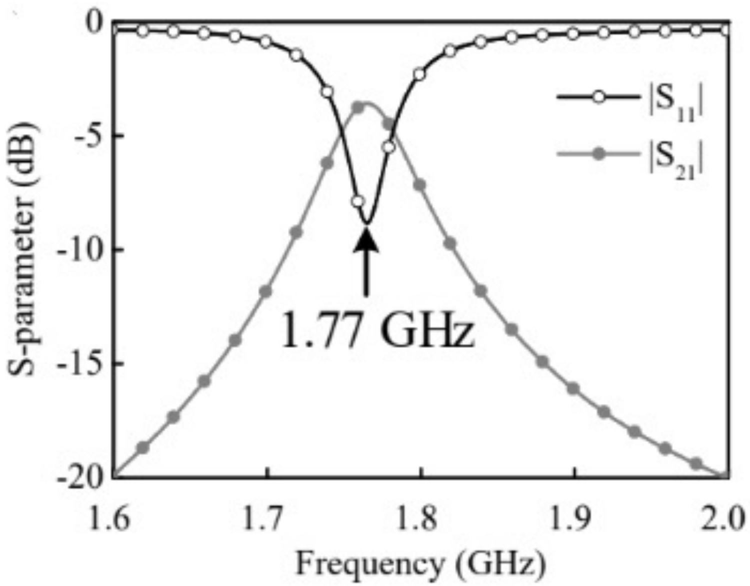
Design of permittivity sensor

- MCSR design

simulated electric-field distribution



measured S-parameters

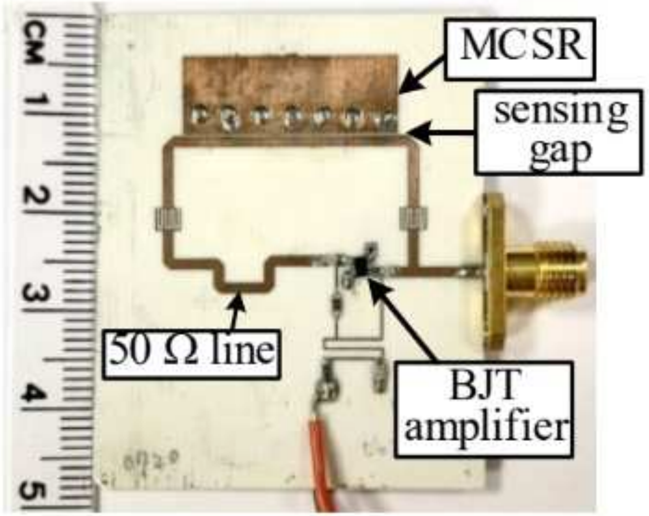


- MCSR is designed on a 20-mil RO4003 substrate.

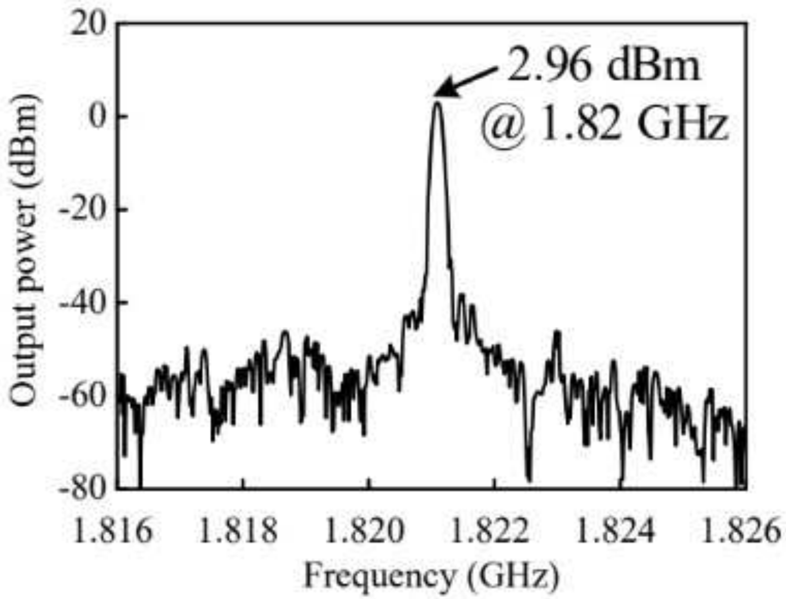
Design of permittivity sensor

- Sensing oscillator design

photograph of sensing oscillator



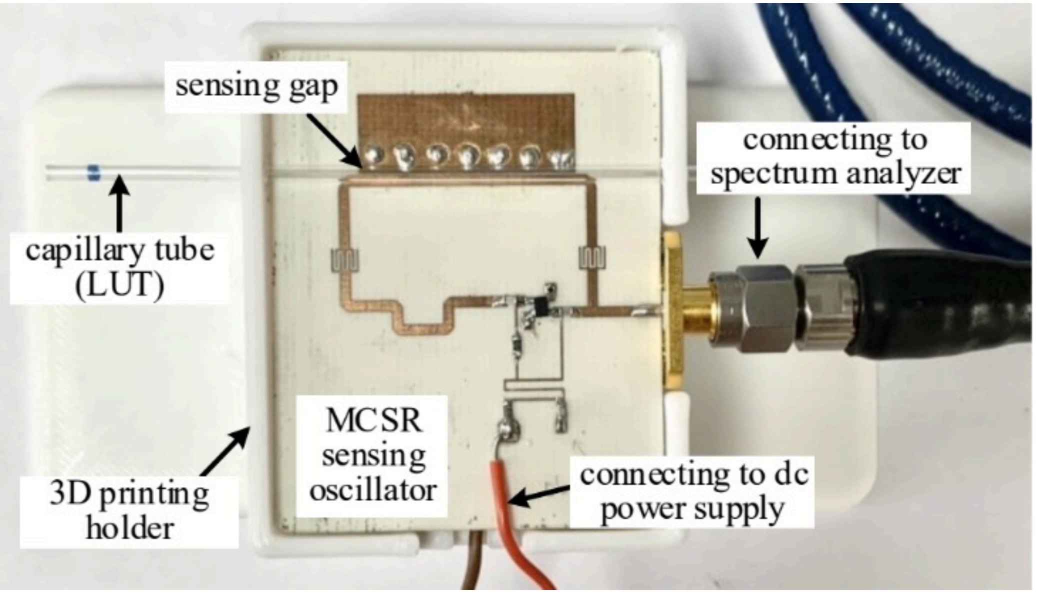
measured frequency spectrum



Experimental results

- Permittivity measurement setup

Measurement setup



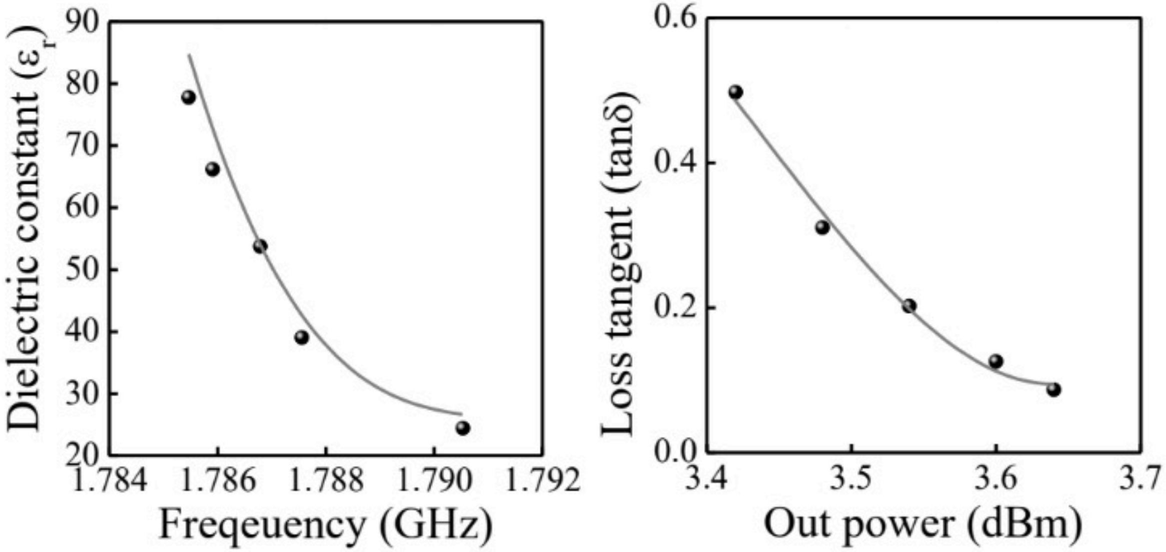
Measured f_{osc} and P_o results

EVF (%)	f_{osc} (GHz)	P_o (dBm)	cal. ε_r	cal. $tan\delta$
0	1.78547	3.64	77.76	0.0868
20	1.78591	3.60	66.16	0.1256
40	1.78679	3.54	53.74	0.2021
60	1.78756	3.48	39.02	0.3104
80	1.79053	3.42	24.40	0.4975

Experimental results

- Sensor calibration

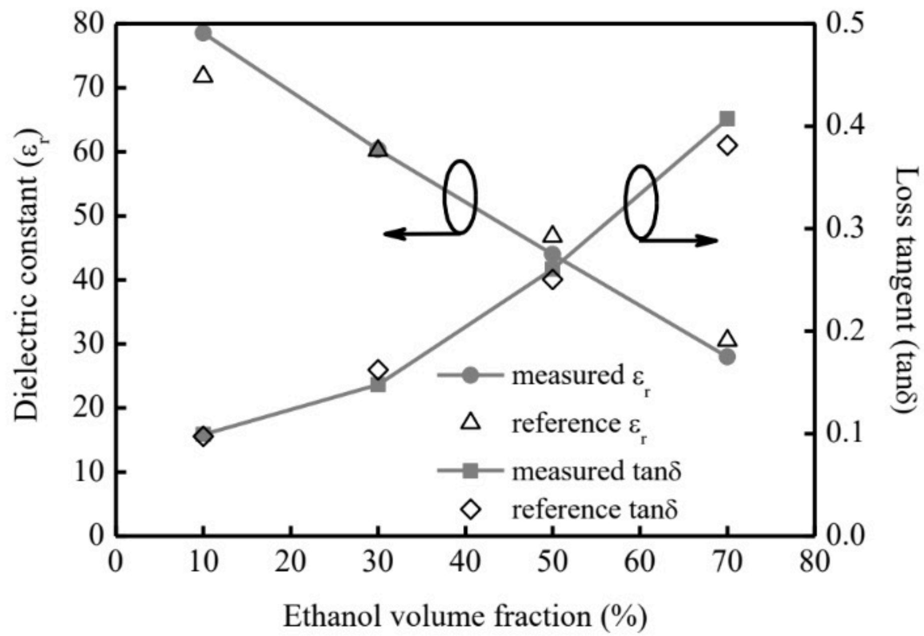
> - The measured ε_r and $tan\ \delta$ results can be calculated by substituting the measured f_{osc} and P_o into equation.



- $\varepsilon_r = -12.27\left(\frac{f_{osc} - 1.78846}{0.003455}\right) + 28.41\left(\frac{f_{osc} - 1.78846}{0.003455}\right)^2 - 24.87\left(\frac{f_{osc} - 1.78846}{0.003455}\right)^3 + 34$
- $\tan\delta = 0.6552\left(\frac{P_o - 3.485}{0148}\right) + 0.07113\left(\frac{P_o - 3.485}{0148}\right)^2 - 0.3604\left(\frac{P_o - 3.485}{0148}\right)^3 + 0.3189$

Experimental results

- Permittivity measurement



- The maximum errors of ε_r and $tan\ \delta$ are 9.45% and −8.84%, respectively.

EVF (%)	ε_r	ref. ε_r	error	$tan\delta$	ref. $tan\delta$	error
10	78.52	71.74	9.45%	0.0991	0.0974	1.75%
30	60.30	60.16	0.23%	0.1478	0.1621	-8.84%
50	44.01	46.78	-5.92%	0.2604	0.2505	3.97%
70	28.01	30.55	-8.32%	0.4072	0.3813	6.79%

Experimental results

- Performance comparison

Performance comparison of active liquid permittivity sensors from literature and the proposed microfluidic permittivity sensor

	Frequency (GHz)	Sensor technology	LUT (Volume)	ε_r error	$tan\delta$ or ε'' error
[1]	0.5-3	interdigital capacitor with IQ mixers	isopropanol-methanol (150 μL)	$< 1.5\%$	$< 1.5\%$ (ε'')
[2]	7-9	PLL-based sensing oscillator	6 different chemicals (20 μL)	$< 3.5\%$	–
[3]	5.798	FLL-based sensor	water-ethanol (100 μL)	$< 2.66\%$	$< 9.94\%$ ($\tan\delta$)
This work	1.78	oscillator-based sensor	water-ethanol (23 μL)	$< 9.45\%$	$< 8.84\%$ ($\tan\delta$)

[1] A. A. Helmy, S. Kabiri, M. M. Bajestan, and K. Entesari, “Complex permittivity detection of organic chemicals and mixtures using a 0.5-3 GHz miniaturized spectroscopy system,” IEEE Trans. Microw. Theory Techn., vol. 61, no. 12, pp. 4646–4658, Dec. 2013.

[2] A. A. Helmy et al., “A self-sustained CMOS microwave chemical sensor using a frequency synthesizer,” IEEE J. Solid-State Circuits, vol. 47, no. 10, pp. 2467–2483, Oct. 2012.

[3] C.-H. Tseng and C.-Y. Yang, “Novel microwave frequency-locked-loop-based sensor for complex permittivity measurement of liquid solutions,” IEEE Trans. Microw. Theory Techn., vol. 70, no. 10, pp. 4556–4565, Oct. 2022.

Conclusion

- A new microwave oscillator-based microfluidic sensor was proposed, designed, and experimentally verified to measure the complex permittivities of water-ethanol mixtures.
- An MCSR sensing device is proposed in this paper to concentrate the electric field in a narrow gap and treated as a frequency-selective element for the sensing oscillator design.
- The maximum measured errors of ε_r and $\boldsymbol{tan\ \delta}$ of the water-ethanol mixtures were well controlled below 10%.

Thank You