

# Inkjet-Printed Dual Microfluidic-Based Sensor Integrated System

W. Su, J. R. Cooper, B. S. Cook, and M. M. Tentzeris  
School of Electrical and Computer Engineering  
Georgia Institute of Technology  
Atlanta, Georgia USA  
wsu36@gatech.edu

C. Mariotti and L. Roselli  
Department of Engineering  
University of Perugia  
Perugia, Italy

**Abstract**—Demonstrated is a novel method to the fabrication of microfluidic devices utilizing a dual-sensor approach. The fabrication incorporates the use of poly(methyl-methacrylate) (PMMA) and inkjet-printing techniques. PMMA, a low-cost, robust material with low dielectric loss, is ideal for sensor fabrication. In addition, inkjet-printing polymer (SU-8) as a bonding layer dramatically improves the bonding strength and pressure handling. Furthermore, this system integrates two independent sensors in the same circuit, enabling concurrent calibration of two fluids. Based on the reaction in one sensor, response in another sensor for the same fluid can be predicted. The two sensors both have a sensitivity over  $21\%/log(r)$  and a good independence in calibrating fluids. The sensor system works at microwave frequency, enabling applications in wireless sensing including various chemical analysis.

**Keywords**— microfluidics; inkjet printing; additive manufacturing

## I. INTRODUCTION

Microfluidics is an emerging technology that is widely used in manufacturing control, biomedical sensing, chemical assay and lab-on-chip applications, due to its capability of manipulating extremely small quantities of liquid. Traditional microfluidics devices are fabricated with photolithography and associated technologies [1], since these technologies were widely used in fabricating microelectronics and microelectromechanical systems (MEMS), and can be easily transplanted to microfluidics. However, traditional fabrication process requires a cleanroom environment and there is an increasing number of novel and low-cost fabrication approaches. Inkjet printing have been recently involved in fabricating microfluidics with advantages of low cost and zero waste [2]. In general, paper plays an important role in inkjet-printing microfluidic-based sensors [3], [4], while functionalities and endurance of these sensors are limited by paper's relatively high dielectric loss and fragility. In this work, efforts have been made to replace paper with PMMA, which is a low-cost, robust material with much lower dielectric loss.

In addition, most sensors contained a single sensing element [2]–[4]. When calibrating two or more fluids, the experimenter needs to do multiple duplicate tests with several sensors. If there is a calibration system which integrates multiple independent sensors together to enable concurrent measurements, it would save the experimenter's time, resource and energy. In

this work, we aim to study the functionality of a multi-sensor integrated system. As a proof of concept and without loss of generality, we start our study with a dual-sensor approach.

## II. PRINCIPLE OF OPERATION

The design, as shown in Fig. 1, consists of two T-resonators in parallel, which are integrated with fluid-tunable varactors. The varactor operates based on a capacitor in where a fluidic cavity is placed over the gap in order to shift the effective permittivity between the plates and thus the capacitance. As fluids with different mixing ratio (e.g. water-glycerol mixture [5]) have different effective permittivity [6], the ratio can be learned by frequency shift.

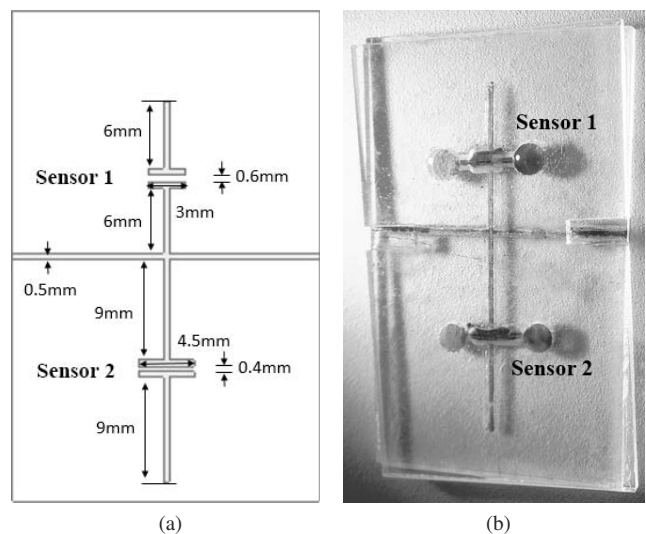


Fig. 1: Pictures of the prototype. (a) Pattern of conductive traces with dimensions. (b) Photo of fabricated sensor system (without ground).

The dimensions of the two sensors can be found in Fig. 1a. These two T-resonators, with their different physical sizes, resonate at different frequencies. The smaller sensor is named as sensor 1 and the larger one is sensor 2 as in Fig. 1. Sensor 2 is 1.5 times larger than sensor 1 so that the resonance of the sensors without any fluid are around 6 GHz (sensor 1) and 4

GHz (sensor 2), respectively. The cavities on the gap and the channel for feeding fluids to the cavity have dimension in I. In order to have similar sensitivity, sensor 1 and sensor 2 have a ratio of 3:2 for the gap width in the varactors and the cavity size. As the two T-resonators are in parallel, and resonant at different frequencies, the frequency shift of each sensor can be read independently.

TABLE I: Dimensions of microfluidic cavities and channels

Name	Dimensions (mm)		
	Length	Width	Height
Cavity in sensor 1	3	1.6	0.5
Cavity in sensor 2	4.5	1.4	0.5
Channels(each)	0.5	1	0.75

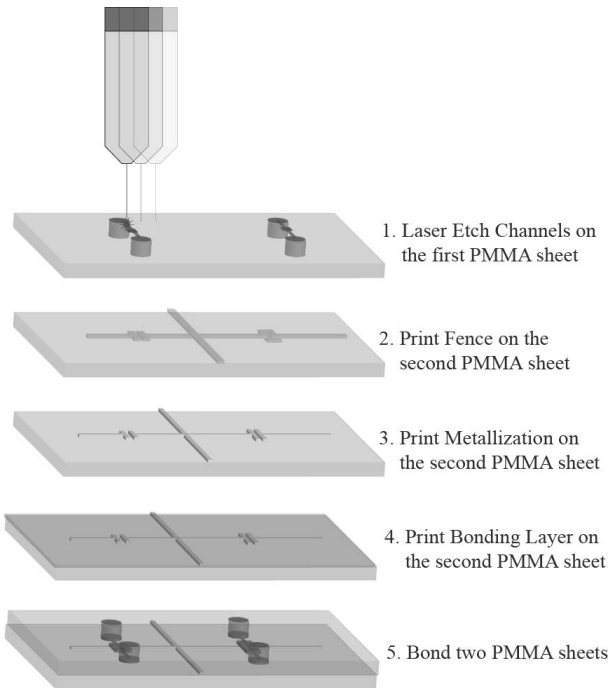


Fig. 2: Fabrication process (3D view).

### III. FABRICATION

The fabricated prototype and the fabrication process are in Fig. 1b and Fig. 2 respectively. The materials used for the fabrication are: two sheets of PMMA to construct the main structure; SU-8 ink for bonding two PMMA sheets; and silver nanoparticle ink to pattern the microwave circuit. With an Epilog Legend 36EXT laser, the first sheet of PMMA is etched to get microfluidic cavities and channels. Another PMMA sheet is inkjet-printed a  $7\mu\text{m}$ -height fence with SU-8 ink by a Dimatix DMP-2831 printer. Without this fence, the silver ink would spread out and lose the shape, as the surface energy of the PMMA is relatively low so the ink has a relatively low contact angle. After curing the SU-8 fence with UV exposure and heat, the conductive pattern is printed with ANP Silver-Jet-55LT-25C silver nanoparticle ink. The laser is

used again to cure the silver ink, as PMMA cannot endure the high temperature normally used to cure the ink. After that, a  $20\mu\text{m}$  thick SU-8 is printed to bond two sheets. Due to the surface tension of deposited SU-8, it will automatically fill and level up to cancel the unevenness brought by the fence. The two sheets of PMMA are hold together with  $10\text{N}/\text{cm}$  force on a hot plate at  $80^\circ\text{C}$  while curing the SU-8. A copper tape is attached to the back of the PMMA as a ground plane. To finalize the system, two fluid connectors with tubes connected are installed into fluids inlet and outlet to feed the fluids to the system.

### IV. SIMULATIONS AND MEASUREMENTS

Ethanol, hexanol, glycerol, water and glycerol-water mixtures are used to test the device's performance(see Tab. II for electrical properties). For the microwave measurement, two SMA connectors are installed into each side of the microstripline and the insertion loss of the system with different fluids is measured with a Rhode and Schwartz ZVA-8 VNA in Fig. 3. Two sensors work at 3.8 GHz and 6.3 GHz respectively and match the simulation very well. From empty to water filled cavity, resonant frequencies shift 42.8% and 39.4% for two sensors respectively, which provides a sensitivity over  $21\%/\log(r)$  for both sensors.

TABLE II: Permittivity of different fluids [7]–[9]

Name	Permittivity	
	Real part	Imaginary Part
Hexanol	3	2.5
Glycerol	4	0.4
Ethanol	6	7
Water	73	8

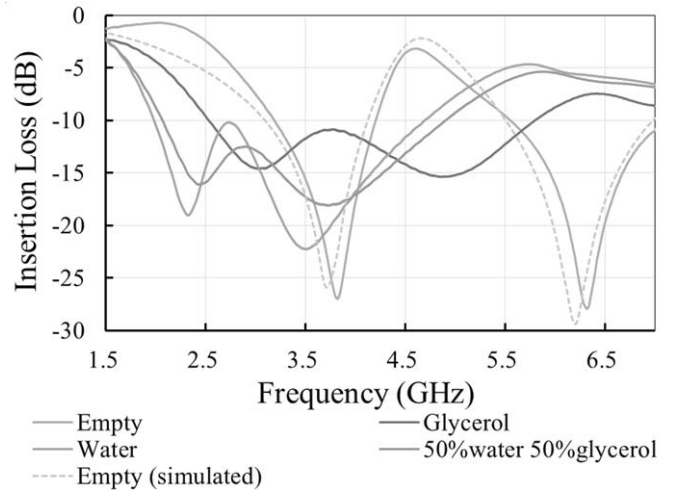


Fig. 3: Measured and simulated insertion loss of the sensor system with air, ethanol, hexanol, glycerol, water and glycerol-water mixtures in both sensors.

The independence of the two sensors is demonstrated by filling one channel with fluids while keeping the other one empty. In Fig. 4, the resonant frequency of the empty-cavity

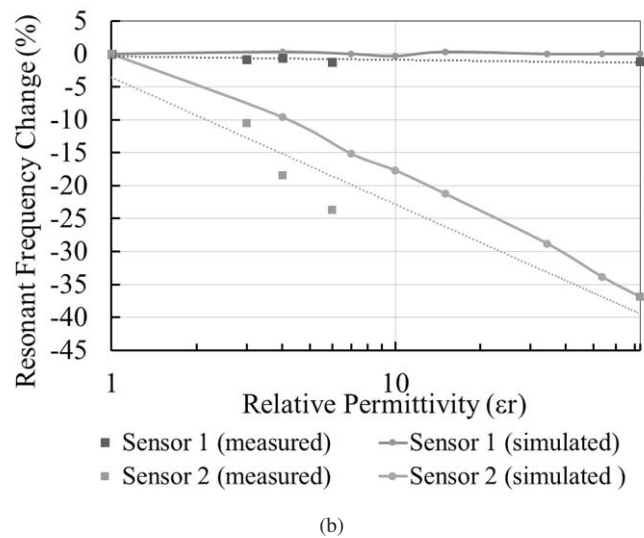
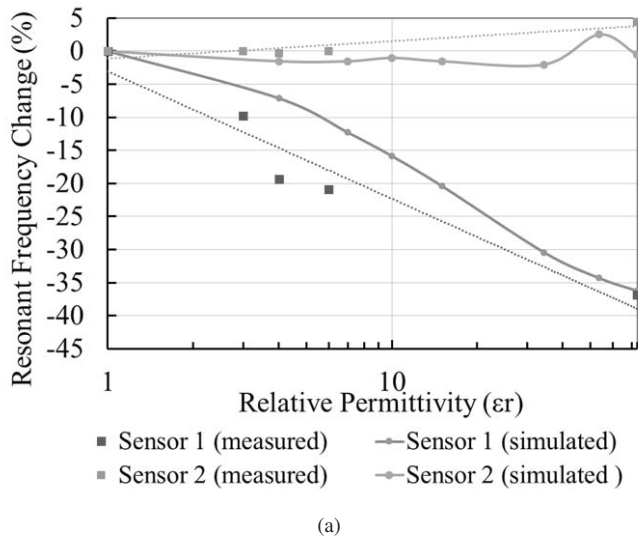


Fig. 4: Measured and simulated resonant frequency change with different fluids of different relative permittivity in only one of the two sensors. (a) Fluids are in sensor 1 while sensor 2 stays empty. (b) Fluids are in sensor 2 while sensor 1 stays empty. A high level of independence between two sensors can be found.

sensor stay almost constant while the sensor with different fluids filled has frequency shift similar as in Fig. 3, where both sensors are filled with fluids. In Fig. 4a, the sensor 2's little positive shift when permittivity in sensor 1 is more than 40 is due to the influence of sensor 1's shifted resonance as two sensors have very close resonant frequencies in this situation. Considering when we calibrate two similar fluids, the relative permittivity difference of two fluids is much less than 40 in most cases, overall this calibration system have a high independence between two sensors. In addition, a good logarithmic linearity with similar slope can be found for two sensors. Based on the resonant frequency shift in one sensor, the shift in another sensor for same fluid can be calculated, indicating that the two independent sensors can work together as a calibration and measurement set.

## V. CONCLUSION

This paper presents a microfluidics-based dual-sensor integrated system fabricated by a novel method which incorporates the use of PMMA and inkjet-printing techniques. The two sensors both have a sensitivity over  $21\%/log(r)$  and work independently in calibrating fluids, which enables concurrent calibration of two fluids. The initial results will be extended to creating a multi-sensor calibration platform which can be used in a vast array of applications ranging from chemical analysis to manufacturing control.

## ACKNOWLEDGMENT

The authors would like to thank NSF-EFRI program for the support.

## REFERENCES

- [1] G. M. Whitesides, "The origins and the future of microfluidics," *Nature*, vol. 442, no. 7101, pp. 368–373, 2006.
- [2] B. S. Cook, J. R. Cooper, and M. M. Tentzeris, "An inkjet-printed microfluidic rfid-enabled platform for wireless lab-on-chip applications," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 61, no. 12, pp. 4714–4723, 2013.
- [3] W. Su, B. Cook, M. Tentzeris, C. Mariotti, and L. Roselli, "A novel inkjet-printed microfluidic tunable coplanar patch antenna," in *Antennas and Propagation Society International Symposium (APSURSI), 2014 IEEE*. IEEE, 2014, pp. 858–859.
- [4] W. Su, C. Mariotti, B. Cook, S. Lim, L. Roselli, and M. Tentzeris, "A metamaterial-inspired temperature stable inkjet-printed microfluidic-tunable bandstop filter," in *European Microwave Conference (EuMC), 2014 44th*. IEEE, 2014, pp. 9–12.
- [5] R. Behrends, K. Fuchs, U. Kaatzte, Y. Hayashi, and Y. Feldman, "Dielectric properties of glycerol/water mixtures at temperatures between 10 and 50 c," *The Journal of chemical physics*, vol. 124, no. 14, p. 144512, 2006.
- [6] A. Sihvola, "Mixing rules with complex dielectric coefficients," *Subsurface Sensing Technologies and Applications*, vol. 1, no. 4, pp. 393–415, 2000.
- [7] A. Tidar, S. Shafiyoddin, S. Kamble, G. M. Dharne, S. S. Patil, P. W. Khirade, and S. Mehrotra, "Microwave dielectric relaxation study of 1-hexanol with 1-propenol mixture by using time domain reflectometry at 300k," in *Applied Electromagnetics Conference (AEMC), 2009, Dec 2009*, pp. 1–4.
- [8] R. Nigmatullin, M. A.-G. Jafar, N. Shinyashiki, S. Sudo, and S. Yagihara, "Recognition of a new permittivity function for glycerol by the use of the eigen-coordinates method," *Journal of Non-Crystalline Solids*, vol. 305, pp. 96 – 111, 2002. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0022309302011250>
- [9] K. Shibata, "Measurement of complex permittivity for liquid materials using the open-ended cut-off waveguide reflection method," in *Microwave Conference Proceedings (CJMw), 2011 China-Japan Joint*, April 2011, pp. 1–4.