

Enhanced Split-Ring Resonator Sensing Platform for Gas Monitoring in Medical Applications

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Summary:

Split-Ring resonators (SRR) are simple electric structures that can be used for a variety of sensing applications. In this contribution, we focus on their use in medically relevant monitoring systems, and present multiple improvements that make it feasible to use SRRs in patient safety and occupational hazard monitoring during surgeries under anesthesia.

Keywords: Split-Ring Resonator, gas sensing, occupational exposure monitoring, anesthesia safety

Motivation

The detection of very low concentrations of specific compounds is a critical component of many environmental monitoring, safety and security and medical applications. One such application lies in the protection of patients in so-called trigger-free anesthesia, for which exposure limits of below 5 ppm_v of the anesthetic gasses must be observed to avoid malignant hyperthermia [1]. Another application relates to the increasing occupational safety concerns of the long term effects of anesthetic gasses [2]. Monitoring such low concentrations of anesthetic gasses requires an especially sensitive and fast sensor. SRRs can provide such highly sensitive sensor technology, benefitting from simple, low-cost construction and high flexibility, allowing them to be used in a multitude of applications [3–5]. By themselves, however, they are not suitable for selectively sensing volatile compounds in air. Multiple improvements, such as improving selectivity as well as faster data acquisition, need to be made to make SRRs feasible for these types of gas analyses.

Description of the new SRR methodology

Multiple improvements to the SRR sensor system have been made. Firstly, novel 3D split electrodes are used instead of the typical flat split, providing similar benefits to those presented in [6], while making use of cost-optimized and more easily accessible methods of fabrication.

Secondly, Metal-Organic Frameworks (MOFs) are applied to the sensitive region of the resonator. These provide flexible chemical binding sites

[7,8], and thusly allow the SRRs to be used as sensitive and selective gas detectors.

Lastly, the use of our newly designed RF electronics provides a stand-alone solution to SRR handling and electronics, providing improved data acquisition speed and precision as well as thermal control.

Results

Through simulation models as well as experiments, an optimal height for the 3D printed electrodes was found that increases the SRR quality factor to approximately 200, a significant increase over bare PCB SRRs with a quality factor of around 40-80 [4], while also improving resonator sensitivity by optimizing the ratio between unwanted parasitic capacitance C_p and the beneficial split-capacitance C_{split} .

The MOF compound used, a UiO-66 MOF, also proved capable of detecting anesthetic gas concentrations in the low ppm_v region with an integrating sensor behavior, making it highly suitable for the long-term monitoring of occupational exposure. Limits of detection as low as 1 ppm_v are feasible.

Finally, the constructed tracking electronics were able to improve over existing solutions. A dedicated RF mixing path with analog frontend and 24-bit ADC provides fast data acquisition of the S_{21} parameter, with a sampling rate of 1 kSps, sub-hertz frequency resolution up to 1.2 GHz, and an amplitude resolution of below 0.01 dB. This highly sensitive data readout is combined with an on-board data processing system and

specialized software algorithms for fast resonance tracking, providing a tracking precision of below 100 Hz while tracking resonance changes at 50 Sps. This makes it possible to observe sudden and small changes in resonator behavior, making it suitable for precision monitoring applications. It also includes thermal control to keep the SRR temperature at a set level, making it a complete stand-alone solution for SRR management and readout. A plot of the step-response of the new sensor platform is shown in Figure 1. Figure 2 shows a picture of the constructed measurement electronics with annotations to the various highlights and capabilities.

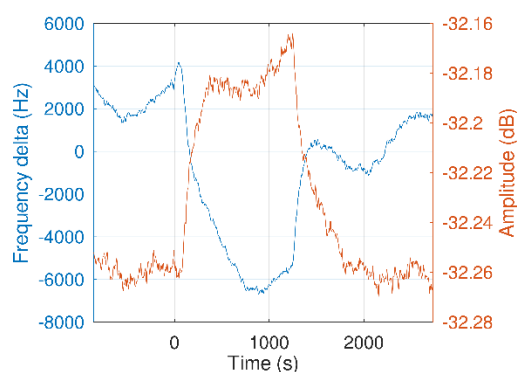


Figure 1: Plot of a measurement using the new electronics with a UiO-66-coated SRR, showing the response to a 500 ppm_v step change in water concentration in dry, synthetic air at 0s. Both amplitude and frequency show a notable shift.

References

- [1] H. Rüffert, B. Bastian, D. Bendixen, T. Girard, S. Heiderich, et al. (2021): Consensus guidelines on perioperative management of malignant hyperthermia suspected or susceptible patients from the European Malignant Hyperthermia Group, *Br. J. Anaesth.* **126**, 120–130; doi: 10.1016/j.bja.2020.09.029.
- [2] K. M. Souza, L. G. Braz, F. R. Nogueira, M. B. Souza, L. F. Bincoletto, et al. (2016): Occupational exposure to anesthetics leads to genomic instability, cytotoxicity and proliferative changes, *Mutat. Res.* **791-792**, 42–48; doi: 10.1016/j.mrfmmm.2016.09.002.
- [3] K. J. Dehning, M. Hitzemann, S. Zimmermann (2024): Split-ring resonator with interdigital Split electrodes as detector for liquid and ion chromatography, *Sens. Bio-Sens. Res.* **44**, 100645; doi: 10.1016/j.sbsr.2024.100645.
- [4] T. Reinecke, J.-G. Walter, T. Kobelt, A. Ahrens, T. Scheper, et al. (2018): Design and evaluation of split-ring resonators for

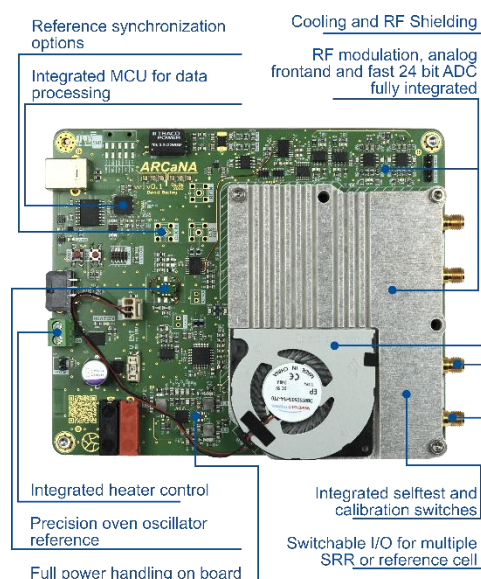


Figure 2: A picture of the completed electronics, with annotations of various highlights.

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- aptamer-based biosensors, *J. Sens. Sens. Syst.* **7**, 101–111; doi: 10.5194/jsss-7-101-2018.
- [5] K. J. Dehning, M. Hitzemann, S. Fisahn, S. Zimmermann (2019): Split-ring resonator: A new detector in liquid chromatography, *Dresdner Sensor-Symposium*, 167–171; doi: 10.5162/14dss2019/P2.02.
- [6] A. Salim, S. Ghosh, S. Lim (2018): Low-Cost and Lightweight 3D-Printed Split-Ring Resonator for Chemical Sensing Applications, *Sensors (Basel, Switzerland)* **18**; doi: 10.3390/s18093049.
- [7] M. Schulz, A. Gehl, J. Schlenkrich, H. A. Schulze, S. Zimmermann, et al. (2018): A Calixarene-Based Metal-Organic Framework for Highly Selective NO₂ Detection, *Angew. Chem. Int. Ed.* **57**, 12961–12965; doi: 10.1002/anie.201805355.
- [8] J. F. Olorunyomi, S. T. Geh, R. A. Caruso, C. M. Doherty (2021): Metal-organic frameworks for chemical sensing devices, *Mater. Horiz.* **8**, 2387–2419; doi: 10.1039/D1MH00609F.