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Split-Ring Resonator as Transducer for Metal-Organic Framework Based Sensors

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Summary:
Split-ring resonators are electrical circuits, which enable highly sensitive readout of split capacity changes via measuring the shift in resonance frequency. Thus, functionalization of the sensitive area allows the development of selective sensors, where molecular interactions cause a change in permittivity and therefore a change in split capacity. Therefore, the split of a resonator is functionalized with metal-organic frameworks and the sensor response is investigated. Preliminary measurements show that introducing the anesthetic sevoflurane results in a significant shift in the resonance frequency.

Keywords: Split-ring resonator, SRR, UiO-66, metal-organic framework, MOF

Introduction

Split-ring resonators (SRRs) are easy-to-manufacture electric circuits built of two microstrip lines structured on printed circuit boards. One microstrip line is formed to a ring with a split that serves as the sensitive area, resulting in a resonator. The second microstrip line is used for coupling an electromagnetic wave into and out of the split-ring structure. The split-ring structure works as a RLC series resonant circuit where the conductor is the resistor, the ring is the coil, and the split is the capacitor. At resonance frequency, the electromagnetic wave couples into the split-ring structure and the transmission via the second microstrip line reaches a minimum. The resonance frequency changes with a change in the permittivity and conductivity of the sample in the split, resp. sensitive area. Therefore, SRRs are highly sensitive to changes of the electromagnetic properties at the sensitive area and can be used as sensitive sensors to measure the properties of liquids [1,2] or gases [3,4]. Graphene or carbon nanotubes are frequently employed as active surfaces for the detection of gases. An alternative approach uses metal-organic frameworks, which are currently being investigated in the context of sensor development [5].

Split-Ring Resonator

In the most basic setup, SRRs consist of a simple PCB with two microstrip lines, as shown in Fig. 1(a). Split-ring resonators can be described as RLC series resonant circuit with the basic equivalent circuit in Fig. 1(b).

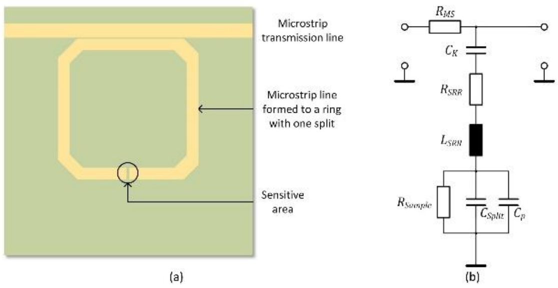

Fig. 1. (a) Schematic of a SRR consisting of a PCB with two microstrip lines, one for coupling electromagnetic waves (transmission line) into the other formed to a ring with a split; (b) equivalent circuit of the SRR with the electrical resistance of the transmission line R_{MS}, the coupling capacitance C_K, the electrical resistance of the ring R_{SRR}, the inductance of the ring L_{SRR}, the capacitance of the split C_{Split} and the parasitic capacitance C_p. Ohmic and dielectric losses of the split capacitor C_{Split} are represented by R_{Sample} [2]

From this very simple equivalent circuit diagram, the resonant frequency is obtained as a first approximation according to eq. (1), where C_K corresponds to the coupling capacitor, C_{Split} is the split capacitor including the dielectric, C_p summarizes the parasitic capacitances and L_{SRR} is the inductance of the ring.

$$f_{res} = \frac{1}{2\pi\sqrt{L_{SRR} \cdot C}}, C = \frac{C_K \cdot (C_{Split} + C_p)}{C_K + C_{Split} + C_p} \quad (1)$$

MOF UiO-66

Metal-organic frameworks (MOFs) are inorganic-organic hybrid materials composed of inorganic metal- or metal-oxo-nodes and organic linker molecules, which build up a framework structure with void spaces. Due to their high porosity and extensive chemical tunability through e.g. linker modification or post-synthetic methods, MOFs have received considerable attention over the last two decades in fields such as gas storage and separation, catalysis or sensing [6]. This tunability allows MOFs to engage in selective and high-affinity interactions with specific target molecules, enhancing their versatility in various applications. However, most MOFs lack chemical and thermal stability. A notable exception to this is the UiO-66-series, which displays exceptional stability due to its highly connected framework structure, formed by strong Zr-O coordination bonds [7]. We aim to employ UiO-66-type MOFs for gas sensing applications. Although this MOF has previously been used for both liquid and gas sensing, sophisticated detection methods, such as quartz-crystal microbalances, have been required to monitor analyte incorporation [8].

Measurements

Volatile anaesthetics are a potential hazard during occupational exposure, pregnancy or in individuals with existing disposition to malignant hyperthermia [9]. Sevoflurane was therefore selected as the analyte with the objective of developing a cost-effective sensor for trigger-free anaesthesia, which, up to now, can only be assessed using larger measuring systems [10].

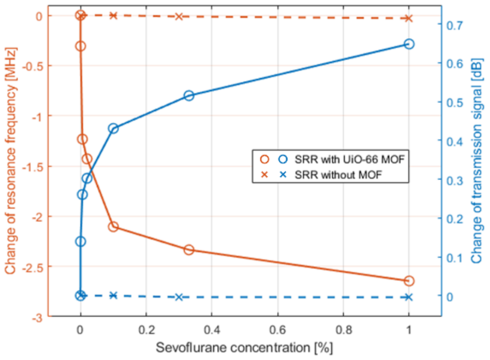

Fig. 2. Change of resonance frequency and transmission signal of the SRR functionalized with UiO-66-MOF (circles) and the unfunctionalized SRR (crosses) plotted against the sevoflurane concentration.

Fig. 2 shows the correlation between the sevoflurane concentration and the SSR response when functionalized with UiO-66-MOF in comparison to the SRR without functionalization. The functionalized SRR shows a significant resonance frequency shift of -1.23 MHz at a concentration of 58.8 ppm of sevoflurane and a difference in amplitude attenuation of 0.26 dB.

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