

Metamaterial-inspired multichannel thin-film sensor

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Abstract

A multichannel thin-film sensor is implemented from a set of microstrip-coupled split-ring resonators (SRRs) with different dimensions. Each SRR exhibits a unique high-Q resonance that is sensitive to the presence of a sample in a particular area. Hence, this SRR-based sensor can function (i) to detect different samples simultaneously to increase the throughput or (ii) to characterise nominally identical samples at multiple frequencies to increase the sensor selectivity. The design principle is validated with simulation and measurement. Owing to the optimized design, sensing a low-permittivity film with a thickness as small as one thousandth of the operating wavelength is achievable.

Split-ring resonators (SRR's) are among many fundamental building blocks for metamaterials that can collectively provide customizable values of the permittivity and/or permeability. A SRR is typically made of one or two concentric subwavelength metallic rings (namely single or double SRR, respectively) with a narrow split in each ring [1]. In response to an electromagnetic excitation, it exhibits a strong magnetic resonance whose frequency is determined by its dimensions, geometry, and constituent materials. On resonance, the ring develops an intense and localised electric field at the narrow split. The sensitivity of the resonance frequency to constituent materials, together with the field localisation, subwavelength ring size, and high-Q resonance, makes SRR's ideal for thin-film sensing.

Owing to these properties, SRR's have recently been implemented for biosensors in different configurations. Planar arrays of SRR's were employed for thin-film sensing [2, 3, 4, 5, 6, 7, 8]. However, those sensors require a relatively large amount of the sample to uniformly cover an array with tens to hundreds

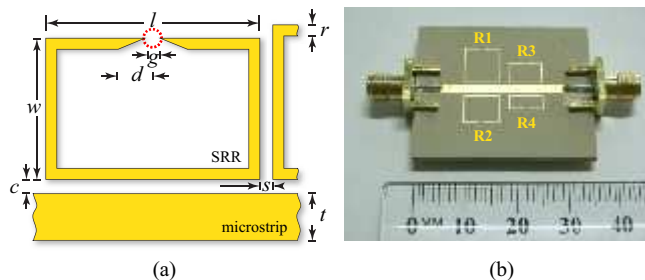


Figure 1: (a) Diagram (not to scale) for each SRR, placed alongside a microstrip line, in the multichannel sensor. The sensing area is indicated by the red dotted circle. (b) Fabricated four-channel sensor containing four SRR's.

of SRR's during the measurement. The constraints of the sample size and uniformity can be eliminated by using either microstrip-coupled SRR's [9, 10, 11] or waveguide-loaded SRR's [12]. Although both microstrip and waveguide arrangements can be used for thin-film sensing, electromagnetic coupling is much stronger in the former case, resulting in its higher immunity against noise and fluctuations.

For the microstrip-coupling configuration, an SRR is positioned in a close proximity to a microstrip transmission line, which builds up a magnetic field around itself in a quasi-TEM wave propagation. This oscillating magnetic field induces circulating current in the SRR loop. In the quasistatic limit, an SRR can be approximated by an inductor and a capacitor in the form of a series LC resonant circuit. Specifically, the ring forms the inductor, and the split forms the capacitor. The resonance takes place in the SRR when the electric energy stored in the capacitor is balanced with the magnetic energy stored in the inductor. Loading a sample onto the SRR surface alters the total capacitance of the structure and hence results in a detectable change in the resonance frequency.

This article presents a multichannel thin-film sensor based on microstrip-coupled SRR's. Several SRR's with different sizes are placed along a microstrip line. Thus, the sensor exhibits multiple resonances, each of which represents a single channel governed by an individual SRR. Each resonance is sensitive to the presence of a sample deposited at the narrow split of the corresponding SRR. Since every resonator possesses a high-Q resonance at a unique frequency, mutual interaction among the resonators is minimal. Therefore, several SRR's can be placed densely without compromising the performance.

Beyond the multichannel sensing capability, this article proposes additionally a strategy to improve significantly the sensitivity of SRR sensors by creating a strong and localized field enhancement in a single spot. In earlier designs, several double SRRs [9, 10, 11] or a single SRR with two splits [12] have been used. In such structures, several distributed capacitors collectively determine the resonance frequency, and a considerable amount of sample is required to change all of these capacitors. If the sample partially covers the structure, the unaffected

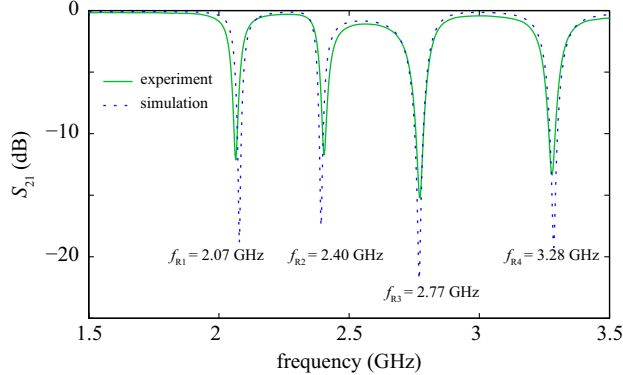


Figure 2: Transmission profiles from simulation and experiment with no sample loading. Each resonance, i.e., channel, corresponds to an individual SRR. The indicated resonance frequencies are extracted from the experimental results.

capacitance reduces the sensitivity in the sensing region as the capacitive change is then not as pronounced. In the present design, each resonance is caused by a single SRR with only one split, as shown in Fig. 1(a), and consequently, only one distributed capacitor is present. A change in this capacitor by sample loading in the small split region has a direct and large impact on the resonance frequency.

Fig. 1(a) also depicts some other important features of the implemented resonators. Each SRR has a rectangular shape to maximize coupling to the microstrip transmission line. This leads to a stronger resonance that is robust to measurement uncertainties. At each SRR split, sharp tips are adopted to concentrate the electric field to a small spot [12]. In terms of a series LC circuit, the tapered shape of the tips decreases the capacitance at the split, and hence increases the resonance Q-factor.

Fig. 1(b) shows the proposed sensor fabricated by using standard photolithography and chemical etching. This particular four-channel sensor is realized from four different SRR's positioned along a $50\text{-}\Omega$ microstrip line. All of the resonators share the same dimensions excepting the width, w , that equals 8, 6, 4.5, and 3 mm for R1, R2, R3, and R4, respectively. This causes a difference in the loop inductance and hence in the resonance frequency among the SRR's. The other dimensions common to all of the SRR's are as follows: $l = 7$ mm, $g = 0.15$ mm, $d = 0.525$ mm, $r = 0.2$ mm, $c = 0.65$ mm, $s = 2$ mm, and $t = 1.7$ mm. The metal for the SRR's, microstrip, and ground plane is copper with a thickness of $35\ \mu\text{m}$, coated with gold to prevent oxidization. The substrate is an RT/duroid 6010.2LM high-frequency laminate (ceramic-PTFE composite) with a thickness of 1.90 mm, a relative permittivity of 10.2, and a loss tangent of 0.0023. This sensor specification yields four high-Q resonances in the microwave S band.

During the experiment, the sensor is connected to a vector network analyzer, Agilent Technologies N5230A, and the transmission parameter S_{21} is registered

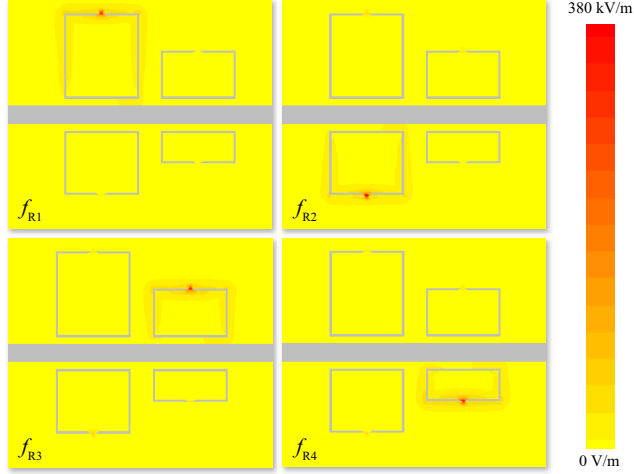


Figure 3: Simulated electrical-field amplitude distribution on the sensor surface at four resonance frequencies. The peak input power supplied to the sensor is 1 W.

at room temperature in the range between 1.5–3.5 GHz with a resolution of 3 MHz. The numerical simulation is carried out with a commercial full-wave electromagnetic solver, CST Microwave Studio, based on the Finite-Integration Technique (FIT). The gap size g in each ring resonator is slightly adjusted in the simulation to reflect the fabrication imperfections, as observed under a microscope.

The measured and simulated transmission profiles of the sensor without any sample are shown in Fig. 2 with small discrepancies caused by fabrication tolerances and limits in simulation accuracy. The results show four non-overlapping resonances corresponding to the four distinct SRR's. The lowest resonance f_{R1} is associated with R1, which has the largest inductance, the second lowest resonance f_{R2} with R2, and so on. No change in the resonances is observed during 5 hours of measurement, demonstrating the thermal stability of the sensor.

Further insight can be obtained from the simulation, as shown in Fig. 3, where the electric-field distribution on the sensor surface is calculated for every channel. At each resonance frequency, only the relevant SRR establishes a strong and highly confined electric field around the capacitive split, and no field enhancement is observed elsewhere. The field enhancement in any active ring is as high as 380 kV/m, given the input power of only 1 W. These calculated field distributions confirm the extreme field confinement achieved with the implemented SRR's, which is a basis for high-performance sensing.

In the next experiment, ethanol is used as a sample under test by the multi-channel sensor. At 3 GHz, ethanol has a relative permittivity and loss tangent of 6.0 and 0.96, respectively [13]. In each measurement, 5 μL of ethanol is dropped by using a high-precision pipette onto the split of a selected SRR chan-

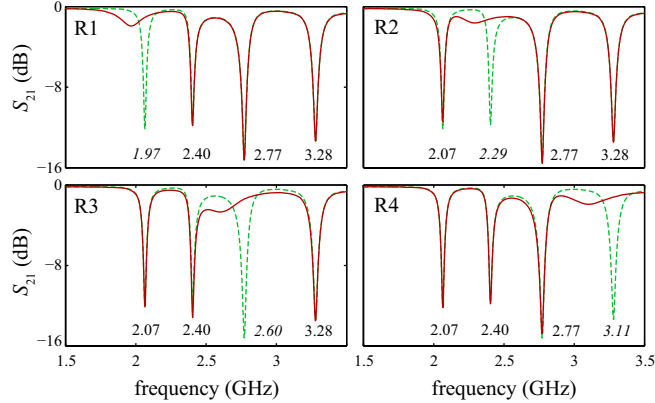


Figure 4: Transmission profiles for unloaded (dotted lines) and loaded (solid lines) SRR's. Each subfigure represents a comparison of sample loading at an individual SRR channel. The specified numbers are the resonance frequencies in GHz of the loaded sensor, and the italization indicates shifted resonances.

nel, and the sensor's response is observed. The transmission results are shown in Fig. 4. The observed resonance shifting and damping indicate the presence of the sample in the selected channel. By comparing the resonance frequencies of the loaded sensor in Fig. 4 with the reference values in Fig. 2, it is clear that non-active SRR channels show no detectable change in the resonance frequency. Hence, it is clear that the four sensing channels can operate independently.

Each SRR can be approximated by a series LC circuit with a resonance frequency $f_0 = 1/(2\pi\sqrt{LC})$, where L denotes the ring inductance and C denotes the split capacitance. The sensitivity of the resonance frequency to the split capacitance can be expressed as [14]

$$S_C^{f_0} = \frac{C}{f_0} \frac{\partial f_0}{\partial C} = -0.5. \quad (1)$$

It can be deduced from this equation that if the relative change in the capacitance formed by the split, $\Delta C/C$, is constant, the relative change in the resonance frequency, $\Delta f/f_0$, is fixed, regardless of the ring inductance. Nonetheless, the relative change in the resonance frequency for the active channel varies between -4.6% and -6.1% among the four channels, despite a fixed volume of sample. This small variation is presumably caused by manual sample deposition, which results in a slight difference in the sample location. This uncertainty can be readily overcome with an automated process.

The sample volume used in the experiment is considerably small. Nevertheless, additional simulations suggest that only one nanolitre of ethanol, i.e., a 0.1-mm cube, is unambiguously detectable with a frequency shift of 15 MHz. In other words, the ratio between the operating wavelength and the film thickness can be as large as three orders of magnitude.

In conclusion, this article presents a thin-film sensor with a series of optimized SRR's as sensing elements. The fabricated sensor successfully performs multichannel detection with an enhanced sensitivity. Scaling down the structure to operate at higher frequencies further reduces the minimum amount of detectable sample. More channels can be added to the sensor provided that resulting resonances are sparse enough to avoid mutual coupling. The resonance of each channel can be positioned at an arbitrary frequency where unique dielectric features of the sample are expected. The realization can be used for on-site disposable sensors, which allow sensing with either high selectivity or high throughput.

Acknowledgments

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