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ADVANCED MANUFACTURING

Microwave Resonator-based Microfluidic Sensors Fabricated Using 3D-Printing Technology

Microwave resonators can be utilized as precision, fast, selective, and non-invasive sensors for reagent and material characterisation. The quality factor (Q-factor) of a microwave resonator determines its dielectric sensing performance, and the value of Q-factor can be improved by the resonator structure optimisation. However, conventional microwave resonator fabrication can be a complex, time-consuming process that constrains the device prototyping and development. Here we present a low-cost, fused filament 3D printing method to effectively fabricate integrated, split-ring microwave resonators with fluidic inducts, operating in the frequency range 2 to 4 GHz. Finite element modelling is employed to simulate the microwave resonation of sensing aqueous droplets in continuous mineral oil flow, using COMSOL Multiphysics software. We evaluate the sensing performance of different 3D-printed microwave resonators with geometrical variations of ring shapes, sizes, and numbers of split gaps, focusing on the increase of their Q-factors for improved sensitivity. Our work demonstrates a rapid prototyping approach to optimise microwave resonator, that can be applied to flow chemistry and engineering biology applications for functional soft material development purposes.

Keywords:
Split-ring resonator, microwave engineering, COMSOL modelling, 3D-printing, microfluidic.

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INTRODUCTION

Microwave resonators is the generic term for electronic devices resonant from 300 MHz to terahertz frequencies [1]. They have been widely applied to various research fields, including material characterisation and sensing, diagnosis, and healthcare applications [2]–[4]. Recently, integrated, microwave-microfluidic devices have been developed as miniaturised systems to sense and characterize low-volume reagents, flowing in a fine capillary, in real time [5]–[9]. Microwave resonators also can be used to heat samples to accelerate chemical reactions and excite biological specimens for chemistry and life science studies[10]–[13].

The performance of a microwave resonator can be quantified by its quality factor (Q-factor), a dimensionless number formed from the ratio of stored EM energy to energy loss per cycle. The Q-factor is governed by the microwave losses in the resonator substrate materials (plastic and metal) and can be maximised by using high conductivity metals (e.g. copper) of low surface roughness and dielectrics of low loss tangent. The fabrication of planar microwave resonator sensors can be a complex and time-consuming process that involves laser machining and clean room technologies [14]–[16]. Flexible microengineering and integration methods are required to form advanced microwave resonator with associated micro-sized components.

We have developed a rapid, 3D printing approach to fabricate microfluidic-microwave resonator devices based on split-ring resonators, incorporating a liquid metal as an electrode. Complex 3D microwave resonant structures with embedded droplet-forming fluid ducts can be devised and simulated using FEM (COMSOL) modelling. Optimised designs can be rapidly prototyped and tested to improve the device performance, e.g. via maximized Q-factors, by varying the resonator shapes, sizes, and number of gaps in the resonators' rings. Such devices are used for non-invasive characterization of liquid precursors and high-order emulsions, building towards functional soft matter materials.

MATERIALS AND METHODS

Cyclic olefin copolymer (COC) filament (CREAMELT) was used to fabricate microfluidic-microwave resonator devices using an Ultimaker S5 ProBundle 3D printer. We have shown that this material has a very low dielectric loss. The conductor part of microwave resonator was formed by the injection of gallium indium eutectic (Sigma Aldrich). A copper ground plane was applied to the chip base before soldering to two SMA connectors. Gallium Indium eutectic was then inserted into the ring cavity space. UV curable glue was used to seal the liquid metal and microfluidic inlets.

RESULTS

3D-printed, microfluidic-microwave resonator devices were used to sense the segmented flow of water in a continuous oil phase; the experiment setup is shown in Fig. 1. All reagents were purchased from Sigma Aldridge. Positive displacement syringe pumps were used to inject liquid into the 3D-printed device. An optical microscope was used to record the droplet movement within the fluidic duct.

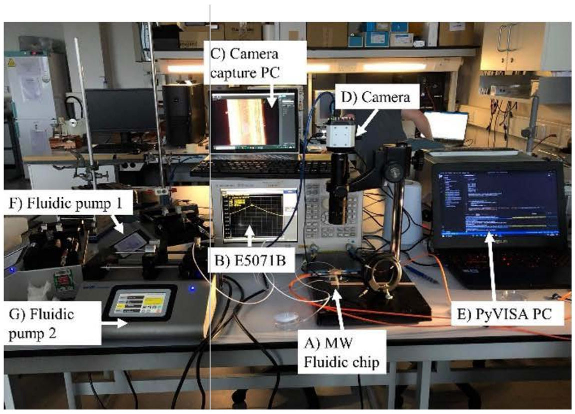


Fig. 1. Experiment setup. A is the MW and Microfluidic chip. B is the ENA. C and D are the camera control PC and imaging camera respectively. E is the PC running the automated script. F and G are the micro-litre pumps.

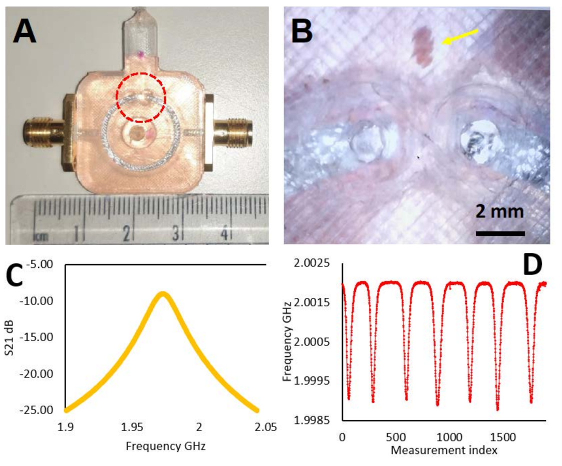


Fig. 2. A shows the microfluidic chip with two S from Sigma Aldridge. MA connectors, two microfluidic inlet ports and a liquid metal ring (gap is highlighted). B is the droplet flow through the gap. C shows a resonant S21 plot for an empty duct, 1.975 GHz center frequency and Q of 100. D shows the repeatable 3 MHz change as droplets continually pass through the gap.

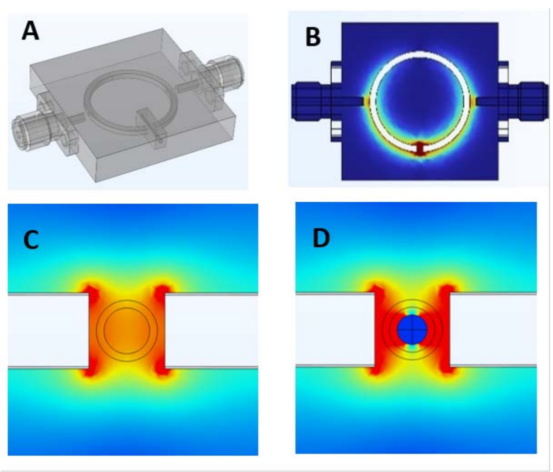


Fig. 3. COMSOL simulation geometry, electric field and droplet perturbation measurements. A. The 3D geometry rendered in COMSOL. B. E field with concentrated E field at the ring gap. C and D shows the electric field distribution between the gap with a CoC channel; with and without a droplet D respectively.

Finite element, multi-physics modelling was conducted using COMSOL (version 6.1). Fig. 2A shows an example printed device. The silver ring structure is formed by the injection of liquid metal. Split rings are coupled via pairs of SMA launchers, with a copper film ground plane, and measurements of S_{21} performed using a vector network analyser. Fig. 2B shows an aqueous droplet (brownish) flowing in an oil phase inside the fluidic duct through the gap of the split ring resonator. Fig. 2C shows the central resonant frequency (2.0906 GHz) of the 3D-printed microwave resonator device, when the duct is filled with air. Fig. 2D shows an example microwave resonation reading of water-in-oil emulsion. Each signal drop indicates a water droplet passing through the gap of the ring split.

Fig. 3 a COMSOL Multiphysics model and EM wave simulation of a split ring resonator, which was used to develop Table 1. The CoC channel in Fig C has no effect on the field distribution between the gap, retaining Q and hence sensitivity to droplets. Moreover, placing a droplet, as shown in Fig. D, depolarizes the field which subsequently changes the E field and resonant frequency. As a droplet passes through the ring gap, a periodic frequency shift of 3 MHz is observed.

Table 1 shows different microwave resonator structures that can be 3D-printed. The different design iterations were to study different concepts of split ring resonators. Rectangular resonators have greater uniformity of E-field within the gap. The number of gaps increases the resonant frequency and the corresponding Q-factor, compared with a single gap model. 3D plots for electric field were simulated to determine the effectiveness of these new designs for droplet sensing, The dual gap rectangular resonator was found to have the highest Q Factor. An increased aspect ratio, i.e. the length to width ratio of the resonator, accounts for the increase in Q. As the aspect ratio increases the electric field becomes more confined to edges of structure, leading to reduced radiation losses.

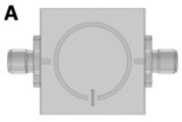
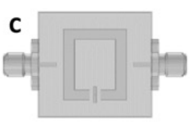
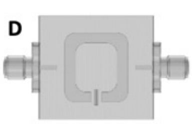
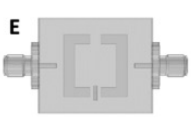
	Centre Frequency (GHz)	Quality Factor	E-field Max (V/M)
A 	1.97	128.06	12396.7
B 	1.81	145.11	16555.4
C 	2.03	177.97	20349.1
D 	2.31	170.77	18230.9
E 	3.83	498.91	18776.6

Table 1. A Single Split Ring Resonator Model, B Dual Ring Single Gap Split Ring Resonator, C Single Gap Rectangular Resonator D Single Gap Rectangular Resonator with Rounded Edges, E Dual Gap Rectangular Resonator.

DISCUSSION

The Q-factor of a microwave resonator sensor quantifies its sensitivity for dielectric measurement, with higher values giving greater sensitivity. In our experiments, we controlled the geometry of the split-ring resonator, such as shape, aspect ratio and dimensions. In theory, rectangular shaped resonators have a more uniform electric field and higher sensitivity in comparison with the circular shaped ones, as shown in the modelling results of Table 1. In addition, increasing the number of gaps can also improve the Q-factor, as the total energy stored in the increases via the electric field. A double split, setting up a higher order mode, as shown in Table 1:E, doubles Q factor and enables time dependent resolve of droplets in flow. However, single splits were chosen as the preferred geometry as the maximum electric field, to be utilized in microwave heating of droplets, shows no meritable improvements.

3D-printing provides a rapid prototyping approach to fabricate and test different microwave structures without significant post processing. Printable, dielectric substrate materials play a key role to determine the resonator performance. In our experiments, COC is selected as the substrate material, due to its low microwave losses. Additionally, COC is hydrophobic. This allows water segment flow in a continuous oil phase. High printing resolution and low surface roughness of liquid metal filling duct can improve the Q-factor, which can be achieved with high-end 3D printers and optimised printing settings, leading to more precise and efficient microwave sensing systems.

Our work demonstrates that monolithic, 3D-printed microfluidic-microwave devices can be applied to detect and analyse water-in-oil emulsions. This paves the way to non-invasive characterisation of aqueous droplet-based materials, such as hydrogel or cytoplasm for biological engineering applications. Sophisticated and high-performance electronic circuits will be built and integrated to develop functional fluidic manifolds, leading towards new capabilities and tools for life science studies as our future objectives.

CONCLUSION

This research demonstrates the potential of monolithic, 3D-printed microfluidic-microwave devices in detecting and analysing emulsions and aqueous droplets. Simulation was used to investigate novel ring geometries and aid in optimising conventional structures. Furthermore, analysis of field distribution has explained enhancements in Q and electric field leading to more sensitive resonant structures. These advancements offer for a non-invasive characterisation of droplet-based materials, which can be essential in biological engineering applications. The combination of 3D printing and microwave resonators holds promise for further advancements in diverse research areas, enabling innovative solutions for various scientific and technological challenges.

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Conflicts of interest
The authors declare no conflict of interest.

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