Design and Electromagnetic Characterisation of a Dual-Resonant SRR-Based Biosensor for Multi-Class Cancer Cell Differentiation in the Sub-6 GHz Band

***Abstract*—*CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

Microwave biosensing leverages the interaction between electromagnetic fields and biological materials to enable label-free, non-invasive characterisation of biological samples [1]. It is suitable for identifying and differentiating cancer cells based on their electrical properties. This is because this type of biosensor exploits the sensitivity of resonant structures to variations in the dielectric properties of MUT. The dielectric properties of biological tissues—specifically permittivity and conductivity—vary significantly between healthy and malignant cells, providing a measurable basis for cancer detection and classification [2]. Metamaterial-based resonators, such as split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs), are widely used sensing elements due to their small size, strong field confinement, and compact fabrication layouts [3], [4]. Sensors made of these composites also display high sensitivity and Q-factor, label-free detection, and real-time sensing capabilities [3]. These structures generate localised electromagnetic fields which are highly sensitive to dielectric perturbations in their vicinity, enabling enhanced detection performance. Their small size, simple geometry, and ease of fabrication have led to applications in gas sensing [5], [6], chemical detection [7], [8], and biological sensing [9], [10]. Fundamental research has established that cancer cell lines exhibit distinct dielectric properties across microwave frequencies. Researchers in [11] characterised the permittivity and conductivity of MCF7, MDA-MB-231, HS578T, and T47D breast cancer cell lines between 200 MHz and 13.6 GHz using the open-ended coaxial cable technique. Their measurements revealed that the complex permittivities of the cells have an inverse relationship with frequency, while the conductivities are directly proportional. Their study noted that cancer cells cause significant microwave scattering due to their high dielectric constants. Similarly, [12] extended this work by measuring the complex permittivity of multiple cancer cell lines, including Cervical (HeLa), Prostate (PC3), Breast (MDA231), and Uveal melanoma at microwave frequencies. In [13], dielectric microwave spectroscopy was employed. An open-ended coaxial probe within the 1-8 GHz range was utilised to differentiate ductal carcinoma, lobular carcinoma, mucinous carcinoma, and fibroadenoma based on permittivity and conductivity measurements. Finally, [14] measured the dielectric behaviour of breast cancer tissues up to 50 GHz and confirmed that their properties change noticeably with frequency. Several implementations of SRR-based biosensors have demonstrated sensitivity to biological samples. An SRR-based sensor on FR-4 was fabricated in [15] and tested with four breast cancer cell lines: HS578, MCF-7, MDA-MB-231, and MDA-2. They modelled each cell as a 1 mm hemispherical sample placed in the resonator gap and assigned dielectric values from earlier measurements [11]. The sensor responded differently to each cell type, with sensitivities ranging from about 1% to 10% relative to air. The study in [10] demonstrated an antenna-coupled SRR for biosensing applications, while [9] developed an asymmetric SRR-based biosensor for label-free stress biomarker detection. [16] proposed a differential microwave sensor by loading a microstrip line with two identical uncoupled SRR on a 0.762 mm thick Rogers RO4350 substrate, demonstrating improved sensitivity for minor dielectric changes in solid dielectric samples through the generation of two transmission zeros due to asymmetric perturbation. [17] developed dual-notch microwave sensors based on complementary metamaterial resonators, while [4] investigated the electrical characteristics of complementary metamaterial resonators for sensing applications. In most reported studies, flame-retardant 4 (FR-4) has been used as a dielectric substrate [18]. However, various other dielectric substrates, such as RT/Duroid [19], metallophthalocyanines, and metal oxide substrates [20], are also employed to achieve enhanced performance [3]. The choice of substrate material significantly influences sensor performance characteristics, including resonance frequency, quality factor, and sensitivity. Most SRR-based sensors still rely on a single resonance, which limits their capability to detect the presence of a sample and struggle to separate multiple cell types on the same platform. Many designs still use FR-4, which does not deliver the best performance. Issues such as environmental drift and coupling between nearby resonators are also not fully addressed in the current work. Existing SRR-based biosensors operate in single-resonant modes. This approach makes it difficult to distinguish among multiple cancer cell types on a single platform. Additionally, many reported sensors utilise FR-4 substrates [15][15], which, while cost-effective, may not provide optimal performance characteristics. Environmental cross-sensitivity and mutual coupling between resonator elements remain inadequately addressed in current designs. Furthermore, the application of resonator-based differentiation techniques specifically within the Sub-6 GHz band—a frequency range offering favourable propagation characteristics and reduced tissue attenuation—remains underdeveloped despite its practical advantages for biomedical sensing applications. To overcome these limitations, this work introduces a dual-resonant SRR-based biosensor that generates two independent resonance frequencies, thereby enabling multi-class cancer cell differentiation through enhanced spectral information. This configuration provides multiple data points for classification, thereby improving discrimination compared to single-resonant designs. The structure is optimised to minimise mutual coupling between resonator elements while maintaining high sensitivity to dielectric perturbations. Operating within the Sub-6 GHz band, the proposed sensor leverages favourable electromagnetic propagation characteristics for biological tissue interaction while maintaining compatibility with standard measurement instrumentation.

II. METHODOLOGY

A. Theoretical Framework

B. Experimental Setup

III. RESULTS & DISCUSSION

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Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, ac, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

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- The subscript for the permeability of vacuum μ_0, and other common scientific constants, is zero with subscript formatting, not a lowercase letter "o".
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TABLE I
TABLE TYPE STYLES

Table Head	**Table Column Head**		
	Table column subhead	***Subhead***	***Subhead***
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[a]Sample of a Table footnote.

Fig. 1. Example of a figure caption.

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IV. CONCLUSION

ACKNOWLEDGMENT

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