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ELECTROMAGNETIC BIOSENSING: A COMPREHENSIVE REVIEW ON MICROWAVE AND TERAHERTZ ANTENNAS FOR BACTERIAL AND MICROBIAL DETECTION

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Abstract

Clinically, highly sensitive and specific detection of bacterial and other microbial contamination is necessary for diagnostic purposes, as well as for safety control in food processing, water quality monitoring and environmental monitoring and research. Conventional culture and nucleic-acid methods are still required reference techniques, but can be labor intensive including enrichment, sample preparation, use of laboratory equipment, and trained personnel. A complementary approach is represented by microwave and terahertz (THz) electromagnetic biosensors, where the loading, binding and/or biochemical composition of the microbe affects the complex electromagnetic response of a resonant structure. The physical sensing mechanism, resonator architectures, surface-recognition strategies, microfluidic integration, and engineering limitations of microbial detection are reviewed. Special attention is given to experimentally proven microwave resonator platforms for Escherichia coli and to novel THz metasensors, and to the different types of analytical selectivity and intrinsic electromagnetic sensitivity. Other significant translation obstacles (aqueous dielectric loss, non-specific adsorption, matrix effects, temperature drift, calibration transfer, and the necessity for real sample validation) are also highlighted, along with potential differential measurement, phase-based sensing, microfluidic pre-concentration, and data-driven spectral analysis

Keywords: Electromagnetic biosensors; bacterial detection; microwave resonators; terahertz metasurfaces; split-ring resonators; microfluidics; biofunctionalization; label-free sensing; Escherichia coli

1. Introduction

Bacterial contamination is an ever-present problem in the clinic, food, water and environment, and there is a need for analytical technique that is rapid and yet has a good degree of sensitivity and specificity. Culture based assays still play an important role in aiding to provide viable counts and allow for isolation of organisms, however the flow of the assay can be labor intensive and may require enrichment and incubation for a result to be obtained. While the analytical phase can be significantly reduced with the use of molecular techniques like PCR, these typically involve the preparation or extraction of nucleic acids, the use of amplification reagents, the need for thermal control, and the need for specialized instrumentation. Therefore, electromagnetic biosensors are not intended as a replacement for existing microbiological methods, but should rather be considered as additional screening platforms that could offer a fast screening, or near real time monitoring. In the case of microwave sensors, the changes in effective permittivity and dielectric loss due to the sample and to captured cells are exploited, while, in the case of THz systems, frequency-dependent absorption and resonant interactions that are affected by hydration and molecular composition are exploited. Recent experimental research has shown that microwave resonators, differential resonator arrays, capacitive matrices, and phase-sensitive step-impedance resonators can be used to detect E. coli with a planar technology, and THz metasensors have been used to identify a number of selected bacterial species without the need for labeling. The central engineering challenge is thus not only to have the highest resonance sensitivity but also to achieve a reproducible analytical response, even in the presence of water, non-target biomolecules, temperature changes, and complex sample matrices. [16], [1]

Table 1: Comparison of Conventional Diagnostic Methods vs. Antenna-Based EM Biosensors

Diagnostic Platform	Detection Time	Sensitivity / LOD	Reagent Required	Label-Free	PoC Suitability
Culture-Based Assay	24 – 72 Hours	10^0 CFU/mL	Nutrient Agar / Media	No	Very Low
PCR Analysis	2 – 6 Hours	10^1–10^2 CFU/mL	Primers, Enzymes, Dyes	No	Low to Moderate
ELISA Assay	3 – 8 Hours	10^4–10^5 CFU/mL	Antibodies, Chromogens	No	Moderate
Microwave Antenna Sensor	1 – 15 Minutes	10^2–10^4 CFU/mL	None (or SAM layer)	Yes	High
THz Metasurface Array	Real-Time (<5 min)	10^1–10^2 CFU/mL	None / Aptamers	Yes	Very High

Note: Detection time and sensitivity/LOD values are highly assay-dependent. The ranges in Table 1 are presented as indicative comparisons, not universal specifications; published electromagnetic studies use different sample matrices, volumes, calibration procedures, and definitions of detection limit.

2. Electromagnetic Principles & Microbial Dielectric Properties

Microbial cells are electromagnetically nonhomogeneous and consist of an aqueous cytoplasm, ions, proteins, membranes and cell-wall components. When the frequency is in the microwave range, the response measured depends on the effective complex permittivity of the whole volume of the sample, not on a single intrinsic dielectric constant of an isolated cell. A convenient representation is $\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$ with the $\tan\delta = \varepsilon''/\varepsilon'$ the loss tangent. When cells are trapped in a high field part of a resonator, the presence of cells affects the effective capacitance and loss of the sensing structure, and can thus alter the resonant frequency, amplitude or phase response. For a resonant LC equivalent circuit, the frequency of the resonant frequency is $f0=1/(2\pi\sqrt{LC})$ and for a small perturbation ΔC of the capacitance, the resonant frequency changes approximately to $\Delta f/f0 \approx -(1/2)\Delta C/C$. This relation underlines the reason why focusing the electric field in a small sensing volume can enhance the observation. The strength and even direction of an experimental shift, however, will depend on the frequency, the hydration, the cell concentration, the geometry, and losses in the surrounding medium. Thus, the numerical values for the dielectric ranges listed in Table 2 are only illustrative and cannot be considered as material constants in general; characterization for the detection has to be done under the same frequency, temperature and hydration conditions as used in sensor design. [1], [2], [10]

Table 2: Complex Dielectric Properties & Structural Characteristics of Target Microbes

Microorganism Class	Representative Pathogen	Cell Wall Structure	Dielectric Constant (ε')	Loss Tangent (tan δ)
Gram-Negative Bacteria	Escherichia coli	Thin peptidoglycan (2-3nm), Outer Lipopolysaccharide	30 – 45 (Hydrated)	0.25 – 0.40
Gram-Positive Bacteria	Staphylococcus aureus	Thick peptidoglycan (20-80nm), No Outer Membrane	40 – 55 (Hydrated)	0.30 – 0.50
Fungal Spores	Candida albicans	Chitin and Glucan Rigid Matrix	15 – 25 (Hydrated)	0.15 – 0.25
Bacterial Endospores	Bacillus subtilis	Dehydrated Core, Dipicolinic Acid Coat	3 – 8 (Dry State)	0.05 – 0.10

Analytical identification is to be distinguished from interpretation of dielectric perturbation. A resonator can be very sensitive to any variation in permittivity or conductivity, without being able to differentiate the target microorganism from other cells, proteins, salts, or suspended particles. Specificity is then added by the

biochemical interface, e.g., antibodies or aptamers or bacteriophages or any other recognition layer or by a multidimensional electromagnetic signature that is sufficiently discriminatory. This distinction is corroborated by experimental microwave studies, which demonstrate the ability to measure concentration changes of E. coli, while selective identification can be achieved by functionalizing the sensor with a biofunctionalization agent or by using additional spectral features. Similarly, THz measurements reveal that there can be different absorption responses from different species and physiological state of bacteria, while the spectra are highly sensitive to hydration. Thus, a thorough review of EM microbial sensing should separate sensitivity, selectivity, dynamic range, repeatability and matrix performance from a low frequency shift or low nominal detection threshold to illustrate species-specific detection. [2], [4], [7], [10]

Note: Microbial dielectric properties are frequency-, hydration-, temperature-, and measurement-method dependent. The ranges given are representative and not necessarily the intrinsic constant for particular organisms.

3. Antenna Biosensor Topologies

The topology of the resonator will have a significant influence on the strength of the interaction between the electromagnetic field and the sample, the volume of the sample being sensed and the ease of resolution of small perturbations. SRR and CSRR structures are attractive due to the ability to localize strong electric fields in the capacitive gap or localized fields of the structures near the biofunctionalized surface. Further, differential and multi-resonant architectures include a reference response or multiple spectral observations to help reduce common-mode drift and discrimination. But it is possible to use tighter field confinement, and SIW or other guided structures can be beneficial for microfluidic integration if necessary, although with consideration for fabrication complexity and dielectric loading. Metasurfaces can demonstrate resonant or interference effects to increase light–matter interaction at THz frequencies, but significant practical difficulties are water uptake and sample preparation. It is convenient to characterize the sharpness of the spectra by the Q factor, which is approximately equal to $f0/\Delta f3dB$, but a high value of Q does not necessarily mean a low value of analytical detection limit; a high Q can also lead to high sensitivity to temperature, fabrication tolerances and fluid loading. It is therefore important to consider the entire measurement chain rather than just the Q factor when choosing a topology, that is: field localization, sample delivery, readout noise, reference compensation, biochemical capture.

Table 3: Comprehensive Comparison of Resonant Antenna Sensor Topologies

Antenna Geometry	Operating Band	Field Concentration Mechanism	Q-Factor Range	Target Application
Split-Ring Resonator (SRR)	1 – 6 GHz	Intense E-field in capacitive gap	50 – 150	Label-free bacterial cell binding
Complementary SRR (CSRR)	2 – 10 GHz	Substrate ground-plane cavity mode	100 – 300	Microfluidic flow-through monitoring
Substrate Integrated Waveguide (SIW)	10 – 30 GHz	Substrate metallic via confinement	300 – 800	High-precision liquid biological sensing
THz Plasmonic Metasurface	0.1 – 3 THz	Localized Surface Plasmon Resonance (LSPR)	10 – 50 (Ultra-sensitive)	Molecular fingerprinting & single-cell sensing
Flexible Patch Antenna	2.4 / 60 GHz	Planar patch fringing fields	20 – 60	Conformal, wearable wound infection monitoring

The following are some examples of the wide range of possible microwave architectures based on recent experimental evidence. In the realm of single point detection, planar resonator systems have been used for the detection of E. coli at a concentration of ~103 CFU/mL, while a microwave capacitive matrix has been used to achieve multipoint detection at a comparable concentration, and a biofunctionalized LTCC differential resonator array has shown selective detection through multiple resonances. Lately, a weakly coupled step impedance resonator phase-sensitive sensor has been demonstrated for detecting 100CFU/mL of controlled E. coli suspensions. Although these results are promising, the quoted limits are platform- and protocol-dependent and should not be regarded as general limits on the performance of microwave biosensors. Comparisons are especially sensitive to sample volume, the time of incubation or binding, reference conditions, the viability of the bacteria, and the buffer composition, as well as the type of experiment: purified suspensions or in complex real-world matrices. [4 - 9]

Note: The Q-factor ranges are design dependent and are added to provide a sense of the relative architectural behavior, not to set hard limits on antenna classes.

4. Surface Bio-Functionalization Protocols

A modification in the metal or dielectric surface in the electromagnetic sensing region is a common method of introducing selective microbial capture. Antibodies are direct demonstration in microwave resonators for E. coli detection that provide a high level of target recognition and aptamers have advantages in chemical stability, synthesis and storage and are now being investigated in bacterial biosensing. While the binding properties of antimicrobial peptides can be broad, bacteriophages can offer strain-level recognition in appropriate applications without compromising of specificity. The immobilization chemistry should maintain the activity of the receptors, while at the same time avoiding unwanted changes in the resonator impedance. In cases where gold surfaces are used, thiolated SAMs are a convenient means of attachment, while EDC/NHS chemistry can be employed for carboxyl- and amine-functionalized surfaces. However, as well as this, it is also important that the blocking strategy used is one that is highly selective, as a highly selective receptor will not be able to

compensate for the strong non-specific protein and debris binding from the sample matrix. Thus, surface chemistry must be assessed in conjunction with negative controls, non-target species, matrix blanks, recovery or storage performance and replicate analyses. [7], [9], [12 - 15]

Table 4: Surface Recognition Elements for Selective Pathogen Capture

Bioreceptor Type	Immobilization Strategy	Selectivity	Thermal / Chemical Stability	Cost / Shelf Life
Monoclonal Antibodies	EDC/NHS on Alkanethiol SAM	Extremely High	Low (Requires Refrigeration)	High Cost / Limited Shelf Life
DNA / RNA Aptamers	Thiolated Aptamers on Au Patch	High to Very High	High (Thermal Reversible)	Moderate Cost / Long Shelf Life
Antimicrobial Peptides (AMPs)	Cysteine-tag Direct Binding	Moderate (Broad Class)	High Stability	Low Cost / Robust
Bacteriophages	Covalent Amide Linkage	Species/Strain Specific	Moderate	Low Production Cost

The problem of purely dielectric sensing is transformed into an integrated biointerface–electromagnetics system through recognition chemistry. The capture layer increases the thickness, permittivity and losses in the sensing region, and the binding kinetics determine how quickly the electromagnetic response reaches a measurable level. Therefore the apparent detection time should be carefully specified: a short electrical readout does not always imply a short total assay if there is a need for sample preparation, transport, washing, incubation and/or regeneration of the receptor. Useful statements for scientifically useful performances should include the total time taken to get the results, the sample matrix, the concentration of the bacteria, the number of replicates, the calibration procedure and whether or not the concentration was measured using an independent reference procedure. [7], [9], [12]–[14]

5. Technical problems and Engineering solutions

There are several coupled effects which dominate the practical implementation. First, the dielectric properties of water are considerable at microwave and particularly THz frequencies, causing resonances to be broadened, damped and the sensing volume to be reduced. Second, a non-specific adsorption may result in a frequency, amplitude or/or phase shift that is indistinguishable from target binding unless appropriate blocking and/or reference assays are used. Third, the perturbation caused by the few cells can be similar to the instrumental noise and environmental drift. Fourth, the temperature and ionic strength of the sample in the water changes the dielectric properties of water and change the baseline without any dependence on the bacterial concentration. Last but not least, sensor-to-sensor fabrication tolerances may change the resonance frequency and coupling, making the transfer of calibration more difficult. Solutions for the engineering aspects are differential reference channels, phase based readout, localised microfluidics, controlled sample volume, temperature compensation, surface anti-fouling layers, pre-concentration when the target concentration is below the practical electrical detection threshold. It is essential that these strategies are confirmed with blind or independently prepared samples and realistic matrices and not just idealized buffer suspensions. [1], [3], [5], [9]–[11]

Table 5: Major Technical Bottlenecks and Engineered Mitigation Strategies

Technical Bottleneck	Physical Origin	Impact on Sensor Signal	Engineered Mitigation Strategy
Aqueous Attenuation	High dielectric loss of liquid water ($\varepsilon'' \approx 20–80$)	Severe resonance damping & lower Q-factor	Microfluidic channel narrowing, localized cell drying, differential dual-port topologies
Non-Specific Binding	Adsorption of non-target proteins and debris	False positive frequency shifts (Δf)	PEGylated self-assembled monolayers (SAMs) & BSA surface blocking
Limit of Detection (LOD)	Small volume dielectric perturbation	Insufficient signal-to-noise ratio at $<10^3$ CFU/mL	Functionalized magnetic nanoparticle (MNP) pre-concentration & Fano resonances
Temperature Fluctuations	Temperature coefficient of permittivity	Drift in baseline resonant frequency	Integrated temperature sensors & differential reference channels

6. Critical Discussion and Research Gaps

In the literature, there is a clear correlation between sensitivity, selectivity and practical robustness of microwave biosensors. While small dielectric changes can be resolved on the resonant structures, so can unwanted changes in water content, ionic strength, temperature, and non-specific adsorption. The problem is at least partially alleviated by differential designs, which compare a sensing element to a reference element, as well as by using phase-sensitive operation to get a large measurable change from a small permittivity change. However, the best examples are still found in largely controlled laboratory experiments. Systematic assessment of recovery, matrix interference, cross-reactivity, sensor to sensor variation, and long-term stability are required for the translation to food, wastewater, serum, or other complicated matrices. [2]–[11]

Inconsistency of performance reporting is another key missing piece. Published data may be reported in terms of detection limits (CFU/mL, optical density, frequency shift, amplitude shift or phase shift) and may be based on different sample volume and/or assay lengths. These numbers are not directly comparable without a common protocol for measurement. Future studies should include report of calibration model, confidence intervals, number of replicates, calculation of limit of detection, limit of quantification, dynamic range, false-positive and false-negative rates and performance against non-target organisms. If a clinical or food-safety translation task is performed, a comparison with an accepted reference method is also needed. [1], [2], [6]–[11]

In cases where the sensor generates multiple frequency spectra, and not just a scalar resonance change, AI and machine learning might be beneficial. Classification models can discover the fine spectral differences of organisms, and regression models can estimate the concentrations. Data-driven performance needs to be tested on independent test sets and samples collected on separate days or chips, however, as otherwise the generalization can be overestimated if the measurements used for training and test sets are highly correlated due to random splitting. The most realistic future architecture is thus the combination of selective surface capture, differential or

multi-resonant electromagnetic front end, controlled microfluidics, environmental compensation and statistically validated spectral analytics. [1], [8], [11], [15].

Table 6: Representative experimentally demonstrated microwave and THz microbial sensing platforms

Study	Technology	Target	Frequency / Band	Reported experimental performance	Reference
Mohammadi et al. (2019)	Planar microwave resonator + microfluidic chip	E. coli	2.5–2.6 GHz	Frequency sensitivity −56 kHz/log(OD600); amplitude sensitivity −0.01231 dB/log(OD600)	[2]
Mohammadi et al. (2020)	Differential planar SRRs	E. coli growth	1.95 / 2.11 GHz	Measured Q >200; growth monitored through S21 response over 48–96 h	[3]
Piekarz et al. (2020)	Microwave capacitive matrix	E. coli	1–3 GHz	Multipoint label-free detection; ~10^3 CFU/mL reported	[4]
Jain et al. (2021)	Passive microstrip ring resonator	E. coli growth	1.76 GHz	Real-time monitoring of subsurface bacterial growth in LB agar	[5]
Piekarz et al. (2022)	Planar single/dual resonant microwave biosensor	E. coli	Microwave resonator	Detection down to ~10^3 CFU/mL reported	[6]
Piekarz et al. (2023)	Biofunctionalized LTCC differential resonator array	E. coli	4–6 GHz	Five resonances; selective response evaluated against L. rhamnosus	[7]
Piekarz et al. (2025)	CPW weakly coupled step-impedance resonators	E. coli	K-band	100 CFU/mL reported; phase sensitivity 3.24° per concentration decade	[8]
Cui et al. (2025)	Antibody-functionalized microwave SRR	E. coli O157:H7	Microwave	Rapid reagent-free detection in water samples; controlled-sample validation	[9]
Yang et al. (2016)	THz time-domain spectroscopy	Multiple bacteria	THz	Species-dependent absorption; differences also observed between living and dead cells	[10]

Ma et al. (2023)	THz metasensor	E. coli and S. aureus	THz	Experimental lowest detectable concentration ~10^4 CFU/mL	[11]

Note: Reported limits and sensitivities are study-specific and should not be interpreted as directly comparable universal detection limits because sample matrices, volumes, assay times, readout metrics, and calibration procedures differ.

7. Conclusion and Future Trends

Moving forward with electromagnetic microbial sensing, integration will likely become the next key focus, instead of single improvements in resonator sensitivity. Differential and phase-based architectures, low-cost single use substrates, and microfluidic sample handling are becoming the trends of the day for microwave platforms, while metasurfaces and spectral fingerprinting are the focus of THz research for species discrimination. In a practical point-of-care system, delivery of the samples needs to be controlled, selective biofunctionalization is needed, environmental compensation is required, and the calibration needs to be easy to reproduce, while the measurement protocol must be repeatable across sensor chips. For multi-frequency signatures, AI-assisted analysis might be helpful if the model validation is performed on independent samples and no data leakage occurs. In general, the microwave and THz antenna biosensors have shown to be promising for quick testing of the microbes, but the validity of any future claims would better be supported by experimentally determined limits of detection, realistic matrices, reproducibility, and comparisons with appropriate reference methods. These requirements are necessary to advance from the proof-of-concept electromagnetic sensing to clinical, food-safety, and environmental applications. [1], [8 - 15]

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***Authors' contributions*:** SKK conducted the literature search, drafted the initial manuscript, and prepared the tables. BFA conceptualized the review framework, structured the technical content regarding microwave and terahertz antennas, and critically revised the manuscript for intellectual content. Both authors read and approved the final manuscript.

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