



TRANSFORMING FOOD ANALYSIS AND CONTROL:

NON-DESTRUCTIVE TECHNOLOGIES AND INNOVATIONS

K. Prasad, S. Shekhar, M. K. Paswan and R. Ahuja



Advancing Food Quality, Safety and Sustainability with
Smart, Innovative and Non-Destructive Technologies



Sant Longowal Institute of Engineering
and Technology, Longowal

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Edited by

**Kamlesh Prasad, PhD
Shubhra Shekhar, M. Tech.
Mani Kant Paswan, PhD
Rajeev Ahuja, PhD**



**Sant Longowal Institute of Engineering and Technology,
Longowal – 148106, Sangrur, Punjab, INDIA**

Editors

Prof. Kamlesh Prasad, SLIET, Longowal
Mr. Shubhra Shekhar, UNSW, Sydney
Prof. Manikant Paswan, Director, SLIET, Longowal
Prof. Rajeev Ahuja, Director, IIT, Ropar

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Microfluidic Half-Mode Substrate Integrated Waveguide Sensor Development for Non-Destructive Real-time Qualitative and Quantitative Evaluation of Liquid Foods and Beverages

Swapnil Shekhar 

Abstract. Quality evaluation involves the systematic assessment of product characteristics and is essential to ensuring compliance with predefined standards in meeting consumer expectations. The traditional approach to destructive quality evaluation destroys the sample and is thus unsuitable for future use. In contrast, non-destructive quality evaluation assesses attributes without compromising the sample's integrity, enabling real-time monitoring. Beverages are liquid consumables and may be alcoholic or non-alcoholic in nature. Determining the specific constituents of alcoholic and non-alcoholic beverages is of utmost importance for quality control, regulatory compliance, consumer safety, and consistency, all achieved through a low-cost approach to characterisation. Substrate-integrated waveguide (SIW) based sensors are precise and compact, with low loss and suitable for both contact and non-contact detection. SIW-based sensors offer a cost-effective and easily integrable solution for real-time quality evaluation. A novel half-mode SIW sensor, based on the material-perturbation cavity resonator approach, was designed for real-time assessment of its applicability in characterising liquid foods. Selection covers the range of most commercially available concentrations of water-soluble beverage components. The measured results show a significant shift in the resonant frequency, enabling quantitative estimation of the loaded sample under test. The findings suggest that the developed sensor can be successfully applied as a precision sensor in a real-time system.

Keywords: Cavity resonator, non-destructive evaluation, substrate-integrated waveguide, sensor, beverage, characterisation.

Swapnil Shekhar (✉)

Department of Electrical Engineering, Indian Institute of Technology Delhi (IIT D), New Delhi, 110016, India

email: scholarsshekhar@gmail.com

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1. Introduction

Concerns about food safety, authenticity, and quality assurance have created an increasing demand for non-destructive quality assessment techniques suitable for a varied range of food products. From pre-harvest to post-harvest processing, storage, transportation, and distribution need to be strengthened by developing an appropriate sensing system that provides alerts and guidance on the steps required to meet specific consumer needs. Liquid foods and beverages, alcoholic and non-alcoholic, are mainly susceptible to adulteration, microbial contamination, and spoilage. Since these quality changes directly impact consumer acceptance, food characteristics, and regulatory compliance, rapid assessment methods are becoming indispensable for food industries where subjective quality evaluation techniques are in force.

Traditional advanced analytical methods and conventional approaches, although they provide accurate compositional characteristics, require extensive sample preparation, sophisticated instrumentation, and skilled technicians, and are expensive and time-consuming. Also, most conventional techniques are destructive and unsuitable for real-time quality assessment. Subsequently, non-destructive testing (NDT) techniques have emerged as suitable alternatives, as they are rapid, reagent-free, repeatable, and enable in situ quality assessment without damaging the food products. In recent years, numerous non-destructive sensing approaches, including electronic nose systems, computer vision, machine vision, hyperspectral imaging, impedance spectroscopy, and microwave sensing, have been successfully investigated for agricultural commodities and processed food products. A comprehensive review further established the importance of non-destructive quality measurement for fruits and vegetables (Prasad, 2015a, b).

Recent advances in artificial intelligence, coupled with non-destructive assessment data, have significantly expanded the application of non-destructive food evaluation. Deep learning-based classification of ripening bananas (Kapri and Prasad, 2025) and quality assessment of mung beans using machine vision (Kaur et al., 2026) have been successfully applied, demonstrating that intelligent non-destructive sensing techniques are becoming reliable tools for rapid food quality evaluation. Nevertheless, optical techniques are primarily suitable for assessing food products based on their external features, thereby limiting their applicability to liquid foods and beverages, where quality is predominantly determined by internal physicochemical properties.

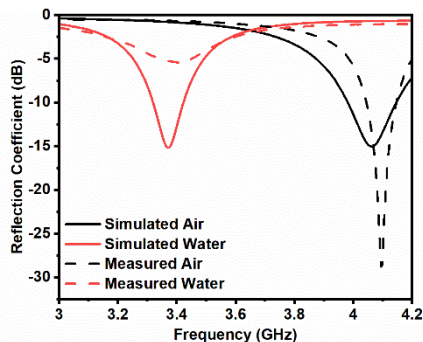


Fig. 12. Simulated and measured reflection coefficient for air and distilled water using the proposed sensor.

5. Conclusion

A dual-port microfluidic extended half-mode substrate integrated waveguide cavity resonator sensor is proposed for non-destructive complex permittivity measurement of liquid foods and beverages. The sensor incorporates a hole near the open edge of the modified cavity, where the electric field intensity reaches the maximum value. An open-ended PVC tube is inserted through this hole to facilitate the loading of liquid samples into the sensing region. To enhance the sensor sensitivity, a copper metal sheath is wrapped around the tube, resulting in stronger electromagnetic field confinement and improved interaction between the sample and the fields. A prototype of the optimised design was fabricated in the form of a sensor and experimentally validated for extreme sensing conditions for the sensing performance. The developed sensor thus can run in dual mode, namely single frequency mode and sweeping mode, for the complex permittivity characterisation of liquid foods in even real-time conditions.

Conflict of Interest

The authors have disclosed that there are no conflicts of interest to declare.

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