Carbon Nanotube-Based Molecularly Imprinted Polymer Antenna Sensor for Ambient Methanol Vapour Detection

Kabir Hossain, *Graduate Student Member, IEEE*, Todd Cowen, Sotirios Grammatikos, and Michael Cheffena

***Abstract*—This study introduces a novel antenna sensor that incorporates molecularly imprinted polymers (MIPs) to selectively detect methanol vapour under room temperature conditions, thereby eliminating the requirement for pre-heating the analyte. The selection of methanol as the target analyte was based on its dual significance, serving as both a prevalent industrial hazard and a relatively non-toxic model for volatile pollutants. A conductive polymer composite consisting of MIPs modified with carbon nanotubes (CNTs), with a high affinity for methanol was drop-cast onto a resonant patch antenna operating at a frequency of 3.490 GHz. The resulting copper-layered antenna, integrated with the MIP-CNT composite, demonstrated exceptional sensitivity and selectivity for methanol vapour detection under ambient conditions. Real-time sensing was enabled to continuously monitor the antenna's reflection coefficient (S_{11}) within a controlled chamber exposed to methanol vapour. Notably, our MIP-CNT composite exhibited selectivity by discriminating against common interferents, including other alcohols. We achieved a limit of detection of 0.5 mmol dm^{-3}, with consistent and reliable responses up to 6 mmol dm^{-3}. This research underscores the significant potential of MIPs in antenna-based gas sensors and contributes to the advancement of selective and sensitive pollutant monitoring technologies.**

***Index Terms*—Antenna sensor, microwave sensor, molecularly imprinted polymer, carbon nanotubes, volatile organic compounds, methanol sensor, gas sensor.**

I. Introduction

MONITORING hazardous gases in ambient conditions has become imperative due to the prevalence of air pollution in indoor and outdoor settings. Consequently, the development of gas sensing technology and sensors has become indispensable [1]–[3]. In recent years, there has been a notable upsurge in the utilisation of microwave sensors [4], [5]. This surge can be attributed to their capacity for real-time sensing and their self-sufficiency in energy, particularly in the context of analyte absorption and desorption. Microwave sensors function by utilising the transmission and reception of electromagnetic (EM) waves within a specified frequency spectrum [6]–[8]. Nanomaterials, including MXene, graphene, carbon nanotubes (CNTs) (and their derivatives) and nanohybrids, play a pivotal role in advancing sensor technology. Nonetheless, it is imperative to prioritise advancements in sensor performance, material design, and fabrication techniques to attain superior levels of sensitivity, selectivity, and reliability [9]–[12].

The integration of nanomaterials into microwave resonator-based sensors has resulted in improved selectivity for specific analytes [13], [14]. Furthermore, there have been recent advancements in the field of gas-sensing applications with the development of microwave sensors utilising nanomaterials [15]–[17]. Singh and coworkers [15], [16] employed resonator-based microwave sensors, leveraging the use of nanomaterials for the detection of methanol and ammonia gases. In their investigation of methanol gas sensing [15], they utilised CNT-coated carbon fibres incorporated with a split-ring-resonator (SRR), while in their study of ammonia gas analysis [16], they used ZnO/N-doped graphene nano-hybrids integrated with a complementary-split-ring-resonator (CSRR) for the sensor development. Bailly *et al.* [18] showcased the successful application of nanomaterial deposition on a microstrip interdigital capacitor, creating an ammonia gas sensor. Instead of employing a resonator to fabricate microwave sensors, it has also been shown possible to design a microstrip patch antenna with the inherent ability to function as a sensor. A vital advantage of this technology lies in its ability to simultaneously transmit and receive signals, thereby offering the potential for seamless integration into a sensor network [19], [20]. Nonetheless, the issue of selectivity remains a significant challenge in the domain of gas sensors utilising nanomaterials. Additionally, achieving high affinity for the target analyte, typically necessitates post-synthesis surface modification of these nanomaterials, requiring further expense of time and resources [13], [21]. Consequently, researchers have turned to the utilisation of molecularly imprinted polymers (MIPs) to enhance the selectivity of gas sensors, as evidenced by previous works [22], [23].

MIPs exhibit a remarkable selectivity characterised by their robust binding affinity for specific target analytes, making them promising candidates for advancing sensor technology

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[24]–[26]. This selectivity is achieved through a unique manufacturing process involving the presence of the target molecule during polymer synthesis. The subsequent removal of this molecule leaves behind a distinct molecular imprint, which exhibits a pronounced tendency for rebinding the specific analyte. While MIPs have gained significant recognition in the analysis of liquid samples, there is a growing emphasis on their application in detecting gaseous analytes, including ethanol, methanol, and acetone. Nevertheless, it is crucial to integrate them with transducer devices that are compatible to enable the capture of distinguishable responses. Although antenna sensors are widely recognised for their ability to provide real-time sensing capabilities, there is a lack of comprehensive research on developing antenna sensors based on MIPs. Adams *et al*. [20] presented a study in which they developed a specialised antenna sensor based on MIPs with high selectivity for detecting methyl salicylate. The selected volatile organic compound (VOC) in their study, however, was a fairly large molecule, functionalised in a manner analogous to common drug analytes targeted by aqueous MIP sensors [27], [28]. In order to establish the fundamental framework for the development of the MIP-based antenna sensor, we selected methanol as the target analyte due to its dual relevance as a prevalent industrial hazard and a relatively benign surrogate for volatile pollutants. Methanol is classified as a highly toxic gas capable of causing irreversible tissue damage when introduced into the body through ingestion, inhalation, or dermal absorption [29], [30]. However, methanol is commonly used as a solvent in laboratory and chemical plant settings, posing a significant hazard due to potential exposure to hazardous levels of methanol vapour [31]–[33]. Finally, methanol was chosen for its higher volatility, which signifies a lower intrinsic affinity, and its reduced chemical distinctiveness [32]. Subsequently, we employed the developed MIP onto a 3.490 GHz patch antenna using the drop-coating technique during the sensor preparation process.

Herein, we present a pioneering antenna sensor designed for the sensitive and selective detection of methanol, using carbon nanotubes embedded within a molecularly imprinted polymer. To the best of our knowledge, this work marks the inaugural instance of such a sensor. The functionality of this sensor relies on radio frequency signals and operates seamlessly under ambient conditions, specifically at room temperature. It offers continuous detection capabilities by monitoring reflection coefficient of the antenna sensor. We demonstrate the effectiveness of MIP-based antenna gas sensors in the domain of selective and sensitive air pollutant monitoring.

II. Materials and Methods

A. Materials and Equipment

Double-sided 35 μm thick copper clad FR4 board with a thickness of 1.5 mm, dielectric constant of 4.1, and a loss tangent of 0.02 was obtained from Solectro Fastighets AB (Lomma, Sweden). Polyvinyl alcohol (PVA, M_w 9,000–10,000, 80% hydrolysed), glutaraldehyde solution (50wt% in water), methanol ($\geq$99.9%), ethanol (96%), 2-propanol ($\geq$99.5%), and 1-propanol ($\geq$99.5%) were obtained from Sigma-Aldrich (Merck Group, Darmstadt, Germany). Multi-walled CNTs with an average diameter of 9.5 nm and length of 1.5 μm (NC7000$^{\text{TM}}$), produced via catalytic chemical vapour deposition were supplied by Nanocyl SA (Sambreville, Belgium). Distilled water was obtained using a purification system (Merit® W4000 water still, Radnor, Pennsylvania, USA). Radio frequency (RF) signal measurements were performed using a Vector Network Analyzer (VNA, ZVA 67) by Rohde & Schwarz (Munich, Germany). Antenna prototype modelling was performed using the Computer Simulation Technology (CST) Microwave Studio Suite (MWS) EM simulation solvers by the SIMULIA (Dassault Systèmes, GmbH, Germany). An airtight chamber (10.5 $\pm$ 0.05 dm^3 EM-Tec Save-Storr inert gas container) for the measurement was obtained from Micro to Nano (Haarlem, Netherlands).

B. Device Fabrication

The device fabrication procedure consisted of a well-defined sequence of three essential steps. The three essential stages are: 1) the development of an antenna prototype, 2) the synthesis of the CNT-based MIP-composite, and 3) the precise deposition of the MIP-composite onto the antenna's surface.

During the first step, the antenna prototype was comprehensively modelled and simulated using the CST MWS with a time-domain solver. The simulation covered a frequency range of 2 GHz to 5 GHz. The square-shaped radiating patch antenna was carefully modelled to function at a central frequency of 3.50 GHz. The overall dimension of the antenna prototype is $60 \times 65 \times 1.6$ mm^3 ($0.7\lambda_0 \times 0.758\lambda_0 \times 0.019\lambda_0$, where λ_0 is the free space wavelength at 3.50 GHz).

The second step involved the creation of a highly selective and sensitive MIP-CNT composite tailored for the detection of methanol vapour as the analyte. To prepare the composite, 50 mg of PVA was dispersed in 10 mL of distilled water using a heated ultrasonic processor water bath at 60 °C for 20 min. Simultaneously, a 1 mg/mL suspension of CNTs in 1-methyl-2-pyrrolidinone was prepared by continuous sonication at 60 °C. 100 μL of an aqueous 79 μL/mL methanol solution was added to the PVA dispersion and sonicated for an additional 2 min. The flask was placed in a 45 °C water bath with gentle stirring for 60 min. 50 μL of glutaraldehyde solution (50wt.% in water) was added dropwise and allowed to react for 3 h. The polymer suspension was then divided into 5 mL aliquots, with the final product formed by combination with 4 mL of 1 mg/mL suspension of CNTs. This was stirred for 20 h before being transferred to an evaporation dish and concentrated to approximately 2.5 mL under continuous stirring.

In the third stage, the MIP-carbon nanotube composite sensing layer was deposited onto the patch antenna surface. To ensure an uncontaminated surface, the antenna was cleaned using an ultrasonic cleaner for 5 min and washed with high purity solvents. Once the antenna surface was thoroughly dried, 2×130 μL of the MIP-carbon nanotube composite was drop-cast onto the antenna surface, drying following each addition in an oven at 60 °C. As depicted in Fig. 1, the resulting MIP-based antenna sensor featured a MIP sensing layer positioned on the radiating surface of the antenna prototype.

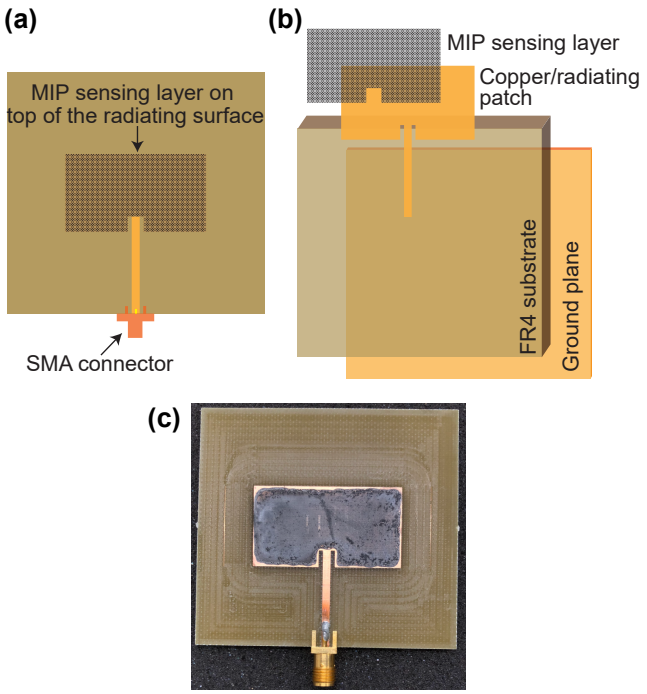

Fig. 1. (a) The developed MIP-antenna sensor consisting of a MIP sensing layer positioned on the top of the radiating surface of the antenna. (b) A visual depiction of the antenna sensor's layered structure. (c) Photograph of the fabricated antenna sensor prototype coated with MIP-CNT composites.

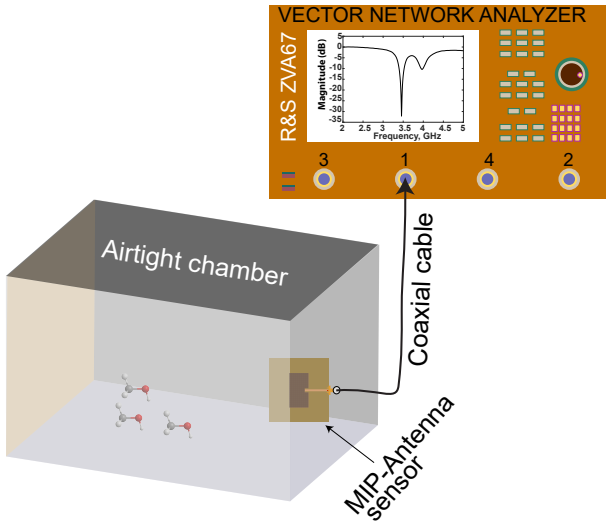

Fig. 2. A visual representation of the experimental configuration.

C. Experimental Setup

Fig. 2 depicts the experimental approach and set-up employed in this work. In our measurement setup, the sensor was sealed inside this chamber with a known volume of liquid methanol—which was allowed to evaporate at room temperature. The sensor's reflection coefficient (S_{11}) was measured using a VNA. A 50-ohm coaxial cable linked the sensor to the VNA. The VNA was further connected to a workstation via a Local Area Network (LAN) cable. The measurement process was automated and regulated through the utilisation of MATLAB software, enabling the capture of data without causing any interruption to the ongoing experimental procedure. In addition, our experimental setup incorporated EM absorbers, a standard component used to shield the Radio Frequency (RF) equipment from external environmental factors. EM absorbers were employed to mitigate undesired reflection, transmission, and interference, ensuring our measurements' accuracy and consistency. A comprehensive 1-port short-open-load-thru (SOLT) calibration procedure was performed manually using the Rohde & Schwarz ZV-Z129 calibration kit before conducting measurements. The calibration process involved configuring the frequency range within 2 – 5 GHz, setting the number of sweep points to 501, and maintaining the VNA's default output power at –10 dBm, equivalent to 0.1 mW. Additionally, all other parameters of the VNA were kept at their default settings.

In order to obtain precise measurements, the sensor was enclosed within an airtight chamber for background data acquisition. The background measurements were acquired by repeatedly collecting S_{11} data sets at intervals to ensure data consistency, with a minimum of 15 sets taken. Subsequently, the target analyte gas was introduced into the chamber in liquid form using a micropipette—after which the chamber was securely resealed. Throughout the experimental process, the rate of analyte evaporation was continuously monitored, and S_{11} data were consistently recorded at regular 1 min intervals during the analyte's evaporation phase. A maximum amplitude of S_{11} reading at 3.458 GHz was recorded when the S_{11} values exhibited stability, corresponding to the analyte having reached its highest concentration within the chamber—which also considered as the peak response. Following this stability phase, data collection continued for a minimum of 15 min to confirm that the final concentration had been achieved. All experiments were conducted under the routine conditions of the laboratory, specifically in an environment with a temperature of approximately 20 °C and a humidity level of 50%. While minor impurities associated with the local environment were present, their influence on the experimental results was not evident.

D. Sensing Mechanism

Molecularly imprinted polymer is a key component of the proposed sensor's successful performance. When the sensor is subjected to its operational surroundings, it engages with a range of molecules that extend beyond the intended analyte, bringing intricacy into the process of detection. Nevertheless, upon the interaction of the designated target compound (methanol) with the imprinted site of the molecularly imprinted polymer layer, substantial alterations in physical properties are induced. The occurrence of this binding event leads to an increase in loss tangent of the material in the composite overlaying the transduction layer, which, in our case is composed of a layer of copper. Recent electrochemical studies involving similar materials suggests a catalytic oxidation of the methanol analyte, resulting in a change of current [34]. Analyte oxidation is less likely in the antenna device due to the absence of an external energy supply, though this may

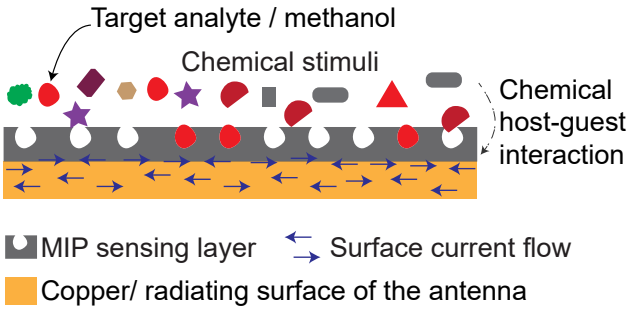

Fig. 3. A schematic representation of the MIP-antenna sensor. Current flow through the copper layer of the antenna, upon which is a MIP-based composite which selectively binds the target analyte.

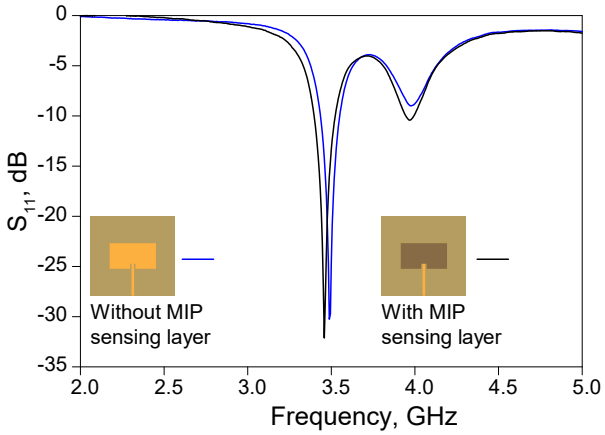

Fig. 4. A comparison of the antenna's measured reflection coefficient before and after MIP-CNT deposition.

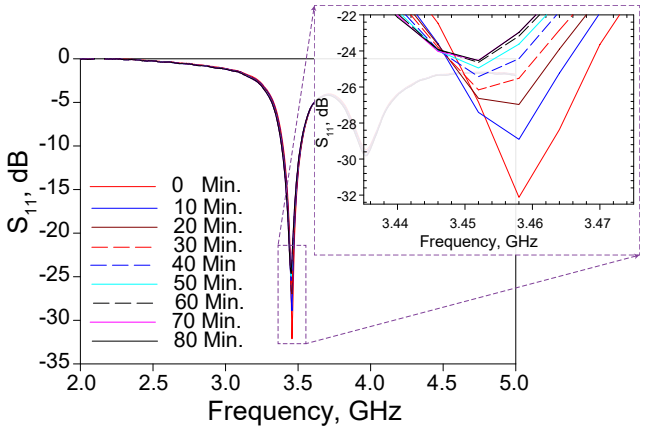

Fig. 5. Impact of 6 mmol dm^{-3} of methanol at various time intervals (from 0 to 80 min) at 3.458 GHz in the vacuum chamber.

contribute to the response. The response observed with the antenna is more likely due to selective absorption of methanol, resulting in swelling. Swelling of the composite film separates the conductive components of the composite, increasing the loss tangent of the material in proportion to film expansion, which itself is a function of methanol concentration.

This loss tangent of the material function, resulting from the interaction between the MIP layer and the target analyte, also leads to alterations in the distribution of surface current over the antenna surface. Fig. 3 presents a graphical depiction of the sensing mechanism. The variations in the conductivity of the radiating element of the antenna and the distribution of surface current are critical aspects that impact adjustments in the impedance values, which is a measure of the ratio between the output and reflected signals. Hence, the sensing capabilities of the proposed device is achieved through the differences in impedance, which directly correspond to the changes seen in our MIP-antenna sensor's detecting capabilities, as depicted in Fig. 3.

III. Results

A. Device Fabrication and Characterisation

Antenna's reflection coefficient was measured before and after the MIP-CNT composite was deposited, as shown in Fig. 4. Before the MIP-CNT composite was deposited onto the antenna's surface, the unaltered antenna's resonant frequency was measured at 3.490 GHz with a resonant amplitude of –30.258 dB. After addition of the composite, the resonant frequency changed to 3.458 GHz with a resonant amplitude of –32.122 dB. The inclusion of the MIP-CNT sensing layer induced modifications in both the antenna's conductivity and the surface current's orientation, leading to a subtle variation in the resonant frequency and its corresponding resonant amplitude.

In order to evaluate the efficacy of the MIP-CNT based antenna sensor, a time-dependent study was carried out, wherein S_{11} readings were recorded as depicted in Fig. 5. The antenna sensor was studied in its response to the evaporation of a volume of methanol ultimately giving a concentration in the chamber of 6 mmol dm^{-3}. The results indicate that the sensor rapidly responds to relatively subtle variation in environmental methanol vapour. Specifically, we saw an approximate 3.8 dB alteration in a span of only 10 min. Following a duration of 65 min, the response levels reached a stable state of approximately 24 dB, corresponding to total methanol evaporation. Fig. 6 shows the time dependent response of the sensor, tracking the evaporation of the methanol over the observed period. Fig. 6 therefore demonstrates the real-time response of the impedance values of the antenna, to methanol vapour concentration. Importantly, our sensor operated effectively under typical ambient conditions, yielding a robust S_{11} response of approximately 858 μmol dm^{-3} dB^{-1} on average. Therefore, the aforementioned device exhibits considerable potential for gas-sensing applications, highlighting its strong performance in typical environmental circumstances.

B. Sensitivity

Our studies found that the sensor's response to methanol concentrations of 6 mmol dm^{-3} and 5 mmol dm^{-3} resulted in resonant frequency shifts of 5.5 MHz and 4.1 MHz, respectively. However, at concentrations below 5 mmol dm^{-3}, the sensor showed no frequency shift. Nonetheless, noticeable deviations in amplitude were always recorded. Therefore, to establish a robust foundation for the sensing system, we have considered the data on relative amplitude variations over time

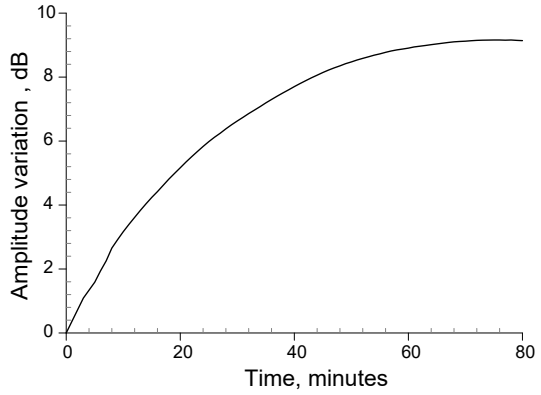

Fig. 6. The mean response of the proposed sensor over an 80-min period at 3.458 GHz in terms of amplitude variation of S_{11} data versus concentration variations of methanol vapour up to 6 mmol dm^{-3} (corresponding to the results presented in Fig. 5).

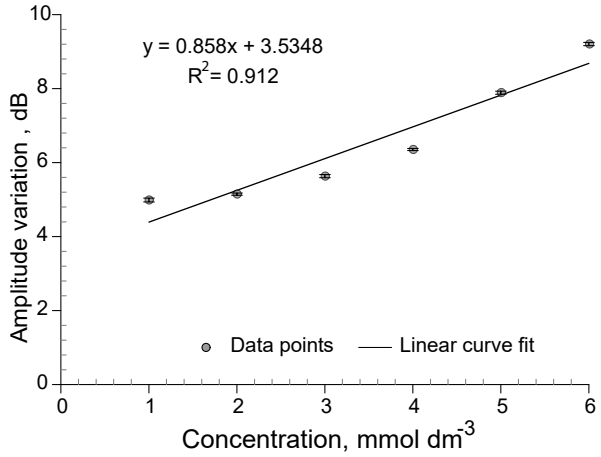

Fig. 7. The peak response of the corresponding S_{11} amplitude fluctuations to various concentrations of methanol vapour was measured at room temperature with laboratory air. The standard deviation and data points are calculated based on 11 measurements.

in the presence of an analyte of interest as the primary metric for sensing. Hence, in this study, we established a quantitative relationship between the concentration of methanol vapour and the observed peak response of amplitude variations in the reflection coefficient from our antenna sensor. Fig. 7 presents a graphical representation of the results obtained. These measurements were conducted under ambient conditions—including room temperature, atmospheric humidity, and potential interferents. The background response of our sensor was measured using the VNA, and the results showed an average value of -32.121 dB with a standard deviation of 0.07 dB. Following the measurement and exposure to ambient air, the response of the sensor returned to this baseline value.

We employed a linear fitting approach to analyse the data collected at methanol concentrations varying from 1 to 6 mmol dm^{-3} within the sealed chamber. The choice of a linear fit was motivated by the desire to effectively capture deviations from linearity in the dataset. Data points that closely align with the linear fit indicate a robust correlation between the sensor's peak response and varying methanol concentrations. Following this linear fit, data interpolation suggested the potential for a remarkably low detection limit.

Experiments were conducted to validate the sensor's response at methanol concentrations of 0.5 mmol dm^{-3} and below. The recorded response for the 0.5 mmol dm^{-3} concentrations exhibited a peak response of 1.997 ± 0.076 dB. No significant measurement could be made at concentrations below 0.5 mmol dm^{-3}, establishing the practical limit of detection as 0.5 mmol dm^{-3}.

Given the linear response of the sensor to concentrations above the experimental limit of detection, the theoretical limit of detection is however much lower than 0.5 mmol dm^{-3}. This could plausibly be a result of the static gas analysis protocol, which results in adsorption of methanol to the analytical chamber walls. Assuming a simple adsorption model, the observed effect from the sensor would be an approximately linear response to higher concentrations with a relatively sharp decline near the concentration required to form a monolayer on the walls. Future studies will be required with a dynamic, continuous flow methodology to verify this assumption and accurately measure the limit of detection.

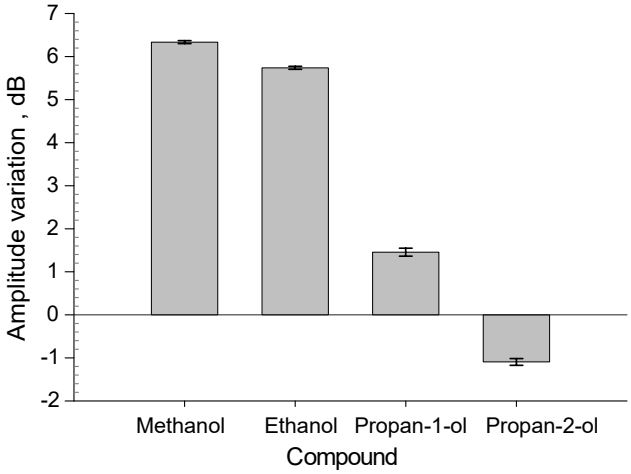

Fig. 8. The selectivity of the MIP-CNT based antenna sensor towards methanol was evaluated by comparing its response to other volatile organic compounds in the gas phase, all at a concentration of 4 mmol dm^{-3}. The median and standard deviations were derived from the set of 11 measurements.

C. Selectivity

This study investigated the sensor's selectivity for methanol by exposing it to various volatile organic compounds at a concentration of 4 mmol dm^{-3} (Fig. 8). As expected, ethanol exhibited a notable response due to its chemical similarity to methanol. To optimise the functionality of this composite material, it would be helpful to design a supplementary sensor specifically designed for ethanol detection. This array has the potential to provide a direct comparison of the responses to methanol and ethanol.

Furthermore, the responses to propanol-1-ol and propanol-2-ol were essentially negligible. The choice of a moderate concentration (4 mmol dm^{-3}) in this analysis was deliberate to minimise potential issues related to pressure and ensure the reliability of the results. Throughout the sensor's development,

TABLE I
COMPARISON OF THIS STUDY WITH OTHER RELATED MICROWAVE GAS SENSORS

Ref	Sensor type	Sensing material	Target analyte	Primary sensing principle	Sensitive	Selective
[15]	SRR	CNT-coated carbon fibres	Methanol	Frequency shift of S_{21}	Yes	Yes
[16]	CSRR	ZnO/N-doped graphene nano-hybrids	Ammonia	Frequency shift of S_{21}	Yes	Yes
[17]	SRR	PEDOT:PSS	Ammonia	Amplitude deviations of S_{21}	Yes	Yes
[20]	Antenna	Graphene (transduction layer) with MIP–graphene	Methyl salicylate	Amplitude deviations of S_{11}	Yes	Yes
[35]	SIW cavity resonators	Graphene	Ammonia	Frequency shift of S_{11}	Yes	No
[36]	Antenna	CNT	Ammonia	Frequency shift of S_{11}	Yes	No
This Work	Antenna	MIP–CNT composites	Methanol	Amplitude deviations of S_{11}	Yes	Yes

SRR = split ring resonator; CSRR = complementary split ring resonator; SIW = substrate integrated waveguide; S_{11} = reflection coefficient; S_{21} = transmission coefficient

propan-2-ol was employed on multiple occasions to expedite the return to baseline levels. The precise mechanism underlying propan-2-ol's neutralising effect on surface current flow and the associated S_{11} response remains uncertain. However, it is plausible that propan-2-ol aids in clearing any residual methanol vapour from the composite, contributing to the observed effect.

By presenting these findings, we highlight the sensor's potential for selective methanol detection and its distinctive ability to differentiate methanol from other VOCs. This work opens possibilities for advanced environmental and industrial monitoring with the proposed sensor technology.

IV. DISCUSSION

This investigation introduces a groundbreaking methanol vapour sensor that seamlessly merges two distinct scientific disciplines: RF/microwave engineering (antenna technology) and chemical engineering (carbon nanotube-based MIP composites). The primary objective of this sensor is highly sensitive and selective detection of methanol vapour under typical ambient conditions, emphasising cost-effectiveness and reliability. A direct comparison of this study with other studies is not straightforward, since the sensing materials employed in those studies differ, and the target analytes are mostly not the same. However, Table I provides a comparison of this study with related research on microwave gas sensors, primarily highlighting other state-of-the-art studies within the domain of microwave gas sensing. In this context, the molecularly imprinted polymer sensing layer in this study demonstrates remarkable selectivity and sensitivity, showcasing its effectiveness in operation within standard laboratory environmental conditions. Since we used an engineered antenna to work as a gas sensor, this holds the advantage over other resonator-type microwave sensors due to its inherent capabilities of simultaneously transmitting and receiving signals, thereby offering the potential for seamless integration into a sensor network. The sensing layer is coupled with the printed circuit board (PCB) antenna to facilitate this process.

The materials and chemicals employed in the sensor fabrication are readily accessible and cost-effective. For the antenna prototype, we utilised low-cost FR4 PCBs, and distilled water served as the primary solvent through the composite synthesis. The molecularly imprinted polymer was primarily synthesised using polyvinyl alcohol, a polymer well-known for its biocompatibility and biodegradability. This polymer can be synthesised from bio-based sources, acetic acid and ethylene. Achieving a 100% atom economy, the synthesis process produces negligible waste, emphasising its advantages [37].

Preliminary investigations revealed that for imprinted polymers of this nature, a 12.5% (m/m) template-to-polymer ratio during synthesis produced the most effective sensors. Hence, the MIP-to-carbon nanotubes ratio was optimised in accordance with the sensor's sensitivity towards methanol vapour. During the synthesis procedure, low temperatures were maintained during the glutaraldehyde cross-linking to avoid disrupting the molecularly imprinted polymer formation. According to recent research findings, efficient cross-linking with glutaraldehyde can be realised at a relatively low temperature of 40 °C [38]. While the process may necessitate more time for achieving comparable cross-linking, it is evident that the rate is mostly influenced by the concentration of glutaraldehyde [39], [40]. The final MIP sensing layer, functioning as an affinity composite, was able to achieve effective discrimination among various alcohols. This was accomplished by placing it on top of the copper-layered antenna, which worked in conjunction to create a highly responsive and specific antenna sensor operating at room temperature.

Synthesis of molecularly imprinted polymer under aqueous conditions is presumed to follow a similar mechanism to that described in the literature [41], [42]. Maximal polyvinyl alcohol dispersion is first achieved via sonication at elevate temperatures in water. Ceasing the sonication, reduction of the temperature, and the commencement of cross-linking result in a destabilisation of the polymer from the aqueous phase. The methanol template then acts as a nucleation site around which the imprinted polymer develops. This template-centred structure is further solidified by further cross-linking, and finally by removal of supporting solvent.

The potential for further enhancing the sensitivity of our

MIP-CNT based antenna sensors lies in continued optimisation. One promising avenue is integrating advanced conductive materials like MXene, which may significantly augment the sensor's sensitivity and thereby contribute to developing more efficient RF-based antenna sensors. However, it is essential to note that these innovative nanomaterials often exhibit a degree of instability, which may necessitate more frequent sensor replacements as opposed to those employing more stable products [43]. MXene and many similar materials are also relatively difficult to produce, and consequently expensive to purchase or fabricate. Conversely, we can explore improvements in the antenna design to enhance the signal response. This involves the incorporation of robust design elements, including the use of low-loss dielectric materials and the exploration of different operating frequencies. These design enhancements promise to advance our sensor's performance and can serve as a compelling foundation for future research endeavours.

The sensor developed in this study exhibits significant promise for deployment in industrial applications, particularly in the domain of air quality monitoring. However, it is imperative to acknowledge certain limitations encountered in this study. As previously mentioned, the static gas protocol may be undermining our analysis at lower concentrations due to adsorption of the analyte on the chamber walls. Furthermore, it is essential to emphasise the need for further investigation to assess the performance of our sensors under extreme conditions, particularly at elevated levels of air humidity and temperatures approaching 0 °C. Under such conditions, the MIP component may exhibit phenomena related to swelling and shrinking. It is worth noting that the antenna is expected to maintain its functionality despite these variations in the MIP. However, it is prudent to advocate for a comprehensive analysis before considering practical deployment to ensure the reliability and stability of the system in diverse environmental conditions.

Accuracy and repeatability are critical in measurements, yet results obtained using a VNA are inherently subject to measurement uncertainty. This uncertainty defines the expected statistical deviation of the measured values from their true value [44]. In our study, we conducted multiple S_{11} measurements inside a vacuum chamber (without introducing VOCs) to assess the correlation between VNA calibration uncertainties and observed variations, which proved to be minimal (with a standard deviation of 0.07 dB). Nevertheless, measurement repeatability can be affected by environmental factors such as temperature and pressure changes; however, conducting a new calibration can significantly reduce these errors. Additionally, the measured S-parameters may contain inaccuracies due to limitations of the measuring instrument (for example, VNA) and the limited precision of calibration kits employed during the calibration process. These systematic errors are reproducible and can be corrected through computational techniques, for instance, using VNA Tools developed by the Swiss Federal Institute of Metrology (METAS) [45]. Despite these efforts, complete error correction is unattainable due to random fluctuations superimposed on the measurement results. Owing to our meticulous experimental approach, the measurement errors observed were negligible. Moving forward, we plan to incorporate VNA Tools by METAS in our future research endeavours.

In this proof-of-concept demonstration, we have introduced a sensor designed for the specific detection of methanol. This innovative technology holds the promise of expanding its applicability to the detection of other volatile pollutants. In a broader context, our sensor showcases the potential of integrating RF technology to address longstanding challenges in chemical sensing, particularly distinguishing analytes within the same chemical family. Nonetheless, it is imperative to emphasise the need for further research to comprehensively evaluate the sensor's selectivity towards various volatile organic compounds, establish its precise limit of detection, and optimise an efficient sensor recovery method. Also, Further investigation using variations of the resonance frequency and the quality factor should be carried out to increase the measurement accuracy. Our preliminary results demonstrate the sensitivity of the developed sensor, particularly in generating an easily measured response in proportion to ambient methanol concentration. This sensitivity highlights its potential as a promising instrument for upcoming pollution monitoring initiatives. Furthermore, this technological advancement opens new avenues for evolving gas-sensing technologies that leverage RF/microwave (antenna) based systems.

V. Conclusion

We have proposed a novel MIP-CNT composite-based antenna sensor designed for cost-efficiency and room temperature operation. Specifically designed for the real-time detection of methanol vapour, the sensor exhibits remarkable sensitivity at low concentrations while maintaining selectivity. Our results highlight the promising potential of antenna-based gas sensors, exemplified by the proposed model, within RF-based electronic systems. This suggests the possibility of deploying sensor networks, enabling comprehensive environmental monitoring. The versatility of this design extends to its applicability in both sensing and communication domains, positioning it as a key element in sensor networks. While further research is required, the results presented in this study provide a promising foundation for the realisation of dual functional antenna-sensor devices. Thus, the proposed sensor represents a significant step towards advanced environmental and industrial pollutant monitoring capabilities.

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