Microwave Sensors for Real-Time Nutrients Detection in Water

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Abstract. Current wastewater monitoring techniques rely on the use of nutrients detection as the result of some chemical reaction, which is undesirable for long-term use in real-time applications. In addition, new legislation may render such systems obsolete if they cannot reliably determine the amount of nutrients in wastewater relative to allowable levels. This chapter attempts to address this issue by considering the use of microwave sensing techniques as an alternative real-time approach that has the potential to monitor wastewater nutrients such as phosphate and nitrate. The method utilizes a broad range of microwave frequencies (1-15 GHz) and is demonstrated with two different types of structure for this purpose, namely a traditional resonant cavity and a flexible interdigitated electrode structure. A variety of experimental results are shown that validate the applicability of the microwave sensing for detecting phosphates and nitrates in the solutions. LabView software used for analysis of captured data and for easy user interpretation of this data is also demonstrated. Future work to be undertaken is discussed in relation to improving the performance of the sensor further, as well as adding the capability to automatically determine both the type and concentration of nutrients in water solutions.

Keywords: Water quality monitoring, wastewater, nitrate, phosphate, microwave sensor, interdigitated electrode, flexible sensor.

1 Introduction

Urban wastewater is defined by the Council of the European Communities [1] as "*Domestic wastewater or mixture of domestic wastewater with industrial wastewater and/or run-off rain water*". Domestic wastewater is defined as "*Wastewater from residential settlements and services which originates predominantly from the human metabolism and from household activities*". On the other hand, industrial wastewater is "*Any wastewater which is discharged from premises used for carrying on any trade or industry, other than domestic wastewater and run-off rain water*". Therefore we can say that wastewater refers to a broad spectrum of contaminated water.

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In order to maintain a healthy environment and to control the spread of disease, wastewater has to be collected and treated prior to discharge back to the environment. UK directives have been implemented through the urban wastewater treatment regulations since 1994 [2]. The collection and treatment of wastewater plays a vital part in the protection of public health, water resources and wildlife; directives set the standards to be used for its collection and treatment. As part of these standards, a sewerage system is provided for all urban areas above a specified population size, and the collected sewage receives at least secondary (biological) treatment before it is discharged to the environment. Discharges from the sewerage systems are only allowed under storm conditions. Areas where sewage requires extra treatment before discharge are identified by the Council of the European Communities as "sensitive areas" [1]. One example is the atrophic waters, where additional nutrients, mainly nitrogen or phosphorus, stimulate the growth of algae and other plants, damaging the natural environment. In these areas, larger sewage discharges must be treated to reduce their load of nutrients.

Wastewater treatment plants (WWTP) and industrial sites that discharge more than 1 m^3 of effluent on a daily basis have to provide periodic reports for the quality and quantity of their effluent before discharging. They also need to pay fines for pollution events. Charges could be reduced if continuous monitoring is available to control and solve problems before discharging. As mentioned before, wastewater treatment involves removing nutrients from wastewater before it is discharged to the water course (e.g. canals and rivers). Many technologies have been developed for this purpose, such as the activated sludge system EBPR (enhanced biological phosphorus removal). These technologies made the detection of such nutrients more difficult because it reduces the nutrient levels significantly compared with previous practice. To solve these difficulties, many types of sensor and analyzer systems have been developed to detect and monitor the wastewater treatment process. However, most of these analyzers are based on off-line measurements which imply low frequency data sampling and significant delays between sampling and availability of results.

Effective monitoring for the quality of effluent can be achieved by obtaining representative samples for lab analysis, or by installing an on-line analyzer. Current on-line technologies for monitoring the limits have a high capital cost, are unreliable and incur high maintenance costs.

2 The Wastewater Treatment Process

Wastewater, also known as sewage, contains more than 99% water and is characterized by volume or rate of flow, physical condition, chemical constituents and the bacteriological organisms that it contains. In general it contains pathogens such as bacteria, viruses, and parasitic worms, as well as organic particles such as plant material, humus, and paper fiber. The soluble organic material that also can be found in sewage could come from urea, fruit sugar and soluble proteins. Sand, grits and metal particles are considered as inorganic particles, and sewage also contains soluble inorganic material such as ammonia, road salt and hydrogen sulphide. In the UK, over

350,000 kilometers of sewers collect over 11 billion liters of wastewater a day, and this is treated at about 9000 sewage treatment works [3] before the treated effluent is discharged to inland water, estuaries and the sea. Wastewater treatment is an important component in the water cycle [4], as it ensures that the environmental impact of human usage of water is significantly reduced.

WWTPs use a series of treatment stages to clean up the contaminated water so that it is safely released into lakes, rivers, or streams. Wastewater treatment consists of several processes (physical, biological and chemical) that aim to reduce nitrogen, phosphorous, organic matter and suspended solids content. To reduce the amount of these substances, WWTPs consist of (in general) five treatment stages: (1) a mechanical pre-treatment stage, (2) a primary treatment stage, (3) a secondary treatment stage, (4) a tertiary treatment stage and (5) a final sedimentation stage. Note that not all of these stages can be found in every wastewater treatment plant, depending on the size of the plant and where the treated wastewater is discharged. Fig. 1 shows the five treatment stages in a typical WWTP [5].

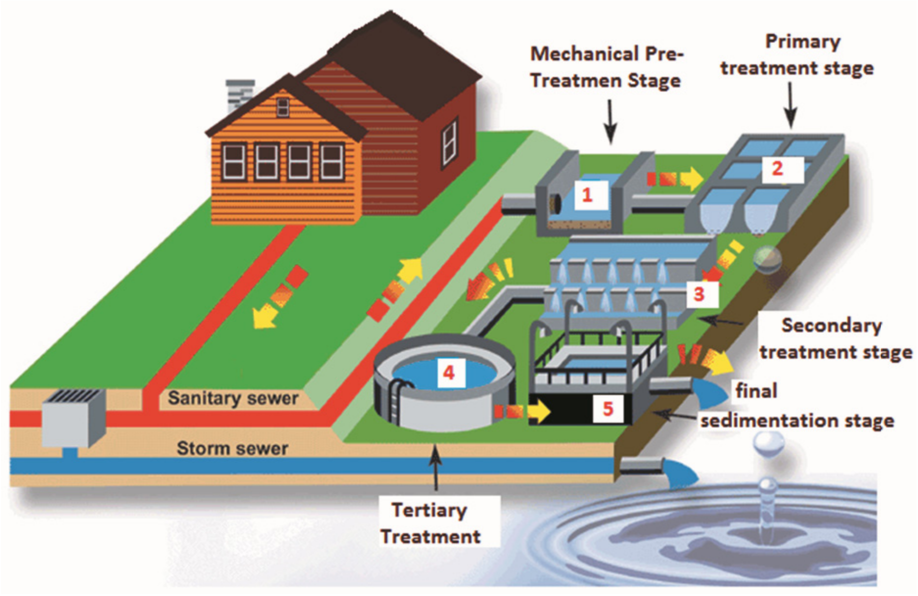


Fig. 1. A simplified overview of the wastewater treatment process

The mechanical pre-treatment stage is essential to remove different types of suspended solids from the incoming wastewater. It also adjusts the pH level to avoid damage to equipment, underwater sewer pipes, and microorganisms used as part of the treatment process [6]. This physical treatment is meant to protect the next stages from different types of grits and larger particles. Practically, this stage consists of multiple screening grids that remove larger objects found in wastewater, an aerated sand filter that removes sand, and a sedimentation unit that reduces the content of suspended solids by means of sedimentation. Since October 2007, the non-hazardous

UK waste produced by the pre-treatment stage such as sewage screenings and grits must be treated before it can be land filled [7].

The primary treatment stage consists of a large settling tank, and aims to settle down the suspended solid and grits that are still in wastewater after the pre-treatment stage. The settled matter (sediment), known as sludge, is pushed into hoppers and carried out to be treated. Also the settling tank will allow the grease and oil to float on the surface so that it can be skimmed off. The primary treatment stage reduces the amount of solids by 50%, and also BOD (Biochemical Oxygen Demand) by at least 20% before it is discharged [8].

Once all noticeable solids have been removed, a biological treatment that targets the organic matter takes place during the secondary treatment stage. The most common type of biological treatment is called 'Activated sludge' where WW is mixed with air to provide oxygen for bacteria to grow and then consume the organic matter. Turbines and surface aerators can be used as air diffusers. Microorganisms degrade the content of the organic matter in the WW aerobically, i.e. when air is supplied to the biological reactor.

The biological treatment stage has originally been solely to remove organic matter. However, many wastewater treatment plants today are also designed for the biological removal of nitrogen and phosphorous. A unique type of microorganism called Polyphosphate Accumulating Organisms (PAO) are enriched into the activated sludge tank for phosphorus removal in EBPR process The role of these organisms is to consume phosphate by accumulating it within their cells. PAO can incorporate up to 0.38 mg/L phosphorous and remove 15-20% of it in many municipal wastewaters [9].

Organic nitrogen is converted to ammonium through a process called hydrolysis while travelling through sewer pipes. In the activated sludge tank, a biological nitrification process is used for ammonium removal. In this process, ammonium ions (NH_4^+) are converted or oxidized to nitrite ions (NO_2^-) and then to nitrate ions (NO_3^-) [10], with the nitrifying organisms (*nitrosomonas* and *nitrobacter* bacteria) adding oxygen to the ions during the oxidation process.

Tertiary treatment involves chemical removal of any soluble phosphorus or nitrogen that remains after the biological removal to enhance the quality of the effluent before discharging. Phosphorus precipitation can be achieved by adding some metal salts such as Calcium (Ca^{2+}), iron (either Fe^{2+} or Fe^{3+}), or aluminum ($Al_2(SO_4)_3$) [11]. The chemical process for nitrogen removal is called ammonia stripping, where pH is raised to convert the ammonium ion into ammonia, which can be stripped from the water by passing large quantities of air through the water [12]. Also, Chlorine could be added to oxidize ammonia-nitrogen into nitrogen gas; 9-10 mg/L of chlorine is required for every 1 mg/L of ammonia-nitrogen [13].

At the end of the treatment process, a secondary settling tank is used to settle down the remaining precipitates that resulted from either the biological or the chemical nutrients removal in the activated sludge stage. The final settled sludge is then carried out to be treated. Sludge can be recycled to produce an organic-based fertilizer and soil conditioner for use in agriculture. It also may be used for energy generation, large tanks called digesters are used to transform the organic solids of the sludge into gaseous end products with the absence of oxygen in a process called anaerobic digestion. The final effluent is discharged into ship canals or coastal waters, and it is here that initially this work is aimed; i.e. to detect nutrients remaining in water after treatment. Such information is important in many cases, but particularly (for example) in cases where water is discharged into coastal waters close to shellfish habitats, since contaminated coastal waters impact negatively on both the marine life and agriculture, which in turn harms people in the area of wastewater discharge. Ultimately however it is envisaged that the technique proposed in this work could be utilized at many stages during the treatment process in order to determine the effectiveness of the process and give some real-time alert when nutrient levels unexpectedly vary.

3 Microwave Sensing

Microwave analysis (or microwave spectroscopy) can be applied to suit a broad range of requirements [14-19] and has a number of advantages over competing technologies for wastewater sensing applications, some of which were highlighted by the current authors in a prior paper [20]. The primary advantages in this case are twofold:

(1) **True real-time sensing**, the analyte material flows past or through the sensor and an instantaneous measurement is acquired without the need for significant pre-processing.
(2) **Direct sample measurement**, a feature which is currently unavailable in many competing technologies which rely on some chemical reaction to induce a change (most commonly a color change) in the analyte material.

Further work by the authors considers a variety of sensing techniques and compares them to that of microwave sensors [21]. The microwave sensor (or cavity) is constructed from closed sections of metallic materials, such as aluminum or copper, which are often selected due to their excellent conductive properties. A microwave sensor may have multiple inputs and outputs, which are commonly referred to as *ports*. In this work no more than two-ports are utilized for the sake of simplicity. Fig. 2 illustrates a schematic overview of a two-port device.

Microwave analysis can provide unique signal spectrum signatures which consist of a reflected signal, S_{11}, and/or a transmitted signal, S_{21}, based on parameters such as conductivity and permittivity [22]. Conductivity is a measure of a material's ability to conduct an electric current. Permittivity is a measure of how an electric field is

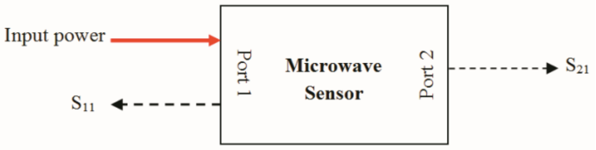


Fig. 2. Illustration of a microwave structure, showing where measurements of S_{11} and S_{21} may be acquired

affected by a dielectric medium, which is determined by the ability of a material to polarize in response to the field, and reduce the total electric field inside the material. Therefore, permittivity relates to a material's ability to transmit an electric field and is a complex value which varies with frequency, and accounts for both the energy stored by a material (ε') as well as any losses of energy (ε") which might occur. The dielectric properties of materials are closely related to their molecular structure. As a result, any change in these structures can be detected by means of a microwave sensor provided that the microwave response directly depends on the permittivity of the material with which the electromagnetic waves interact [23].

For much of the work conducted so far, a cylindrical cavity has been utilized. When one excites a cylindrical cavity with microwave energy, at certain frequencies predictable arrangements of the electric and magnetic fields will form inside, typically referred to as *resonant modes*. These modes are based upon such parameters as the relative permeability (μ_r), the relative permittivity (ε_r), the radius (a) of the cavity and also its depth (d). Using work detailed by Pozar [24], it is possible to predict the frequencies at which these modes will occur from (1).

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \left[\left(\frac{p_{nm}}{a} \right)^2 + \left(\frac{l\pi}{d} \right)^2 \right]^{1/2} \tag{1}$$

here c is the speed of light and p_{nm} is the m^{th} root of the of Bessel function of the n^{th} order for TM modes or the m^{th} root of the first derivative of Bessel function of the n^{th} order for TE modes. It is also possible to visualize these modes using 3D modeling software such as the Ansys High Frequency Structure Simulation (HFSS) package [25]. For the cavity shown in Fig. 3, a number of resonant modes are shown in Fig. 4 by way of example.

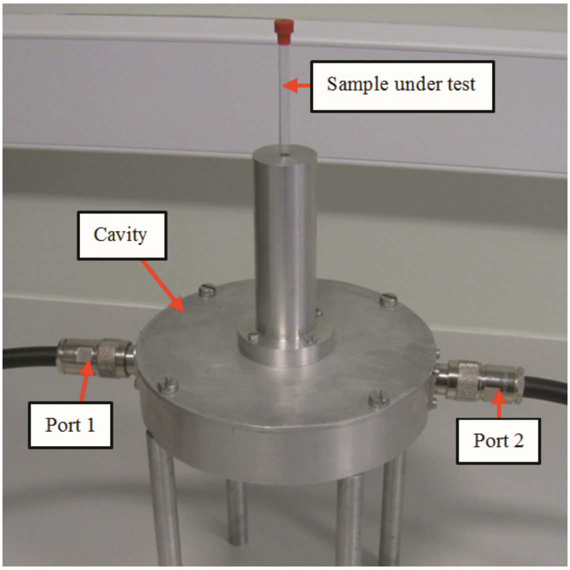


Fig. 3. Example of a cylindrical microwave cavity used by authors in other works [26-28]

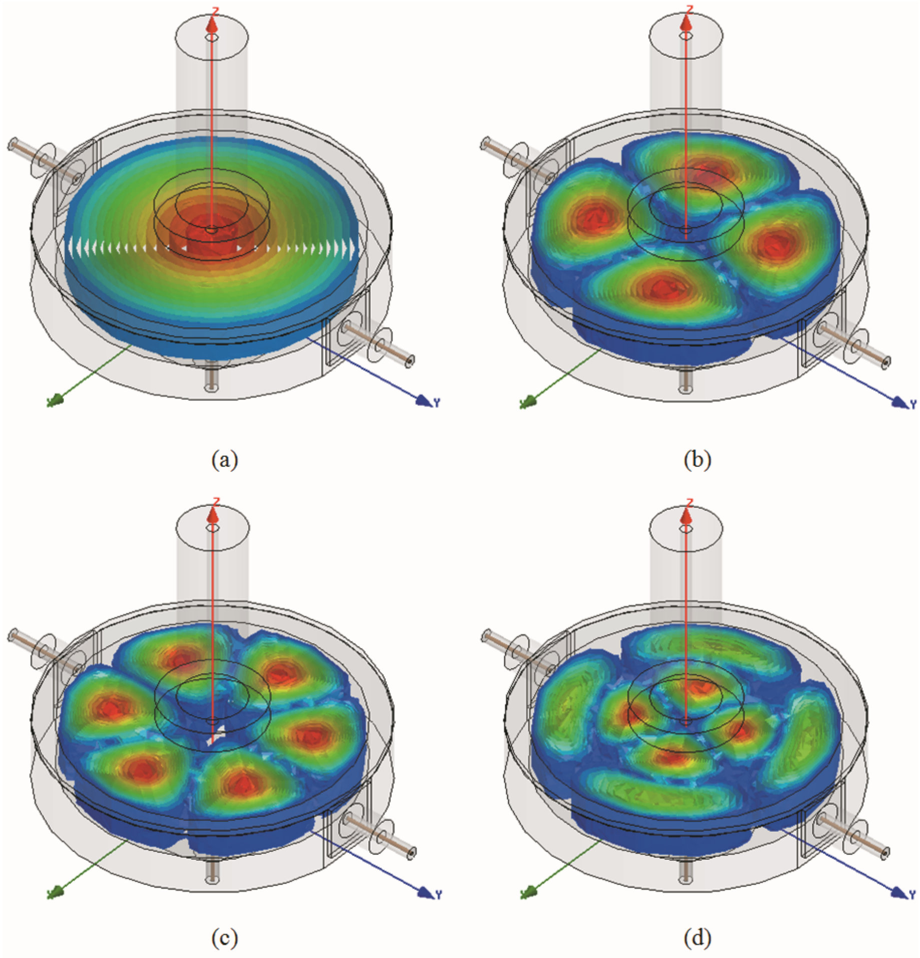


Fig. 4. An example of the electromagnetic fields formed inside the cavity shown in Fig. 3. at increasing frequencies, namely showing the modes (a) TM_{010}, (b) TM_{210}, (c) TM_{310} and (d) TM_{220}

This work considers, for the moment, *narrow band analysis* to enable primarily the optimization of system sensitivity to nutrients in wastewater. This means that the work is dominantly based around the response which occurs at the TM_{010} mode of a cylindrical cavity when different analytes (i.e. phosphates and nitrates at varying concentrations) are placed within the cavity. The multi-parameter nature of broadband microwave analysis is discussed as a topic for future work toward the end of this paper, and is the mechanism by which the issue of nutrient *specificity* will be explored.

4 Experimental Setup

4.1 Equipment Used

The microwave resonant cavity used in this work is pictured in Fig. 5. The cavity is designed such that its fundamental mode of operation (i.e. TM_{010}) occurs at approximately 2.5 GHz [29] when the central PTFE pipe is water filled. This is based upon internal dimensions where $a = 36$ mm and $d = 30$ mm. When the water is evacuated, the operating mode shifts to approximately 3 GHz. This behavior is explained generally by (1). Fig. 6. shows a comparison of the modeled and real-world response of the cavity in the frequency range 1-6 GHz.

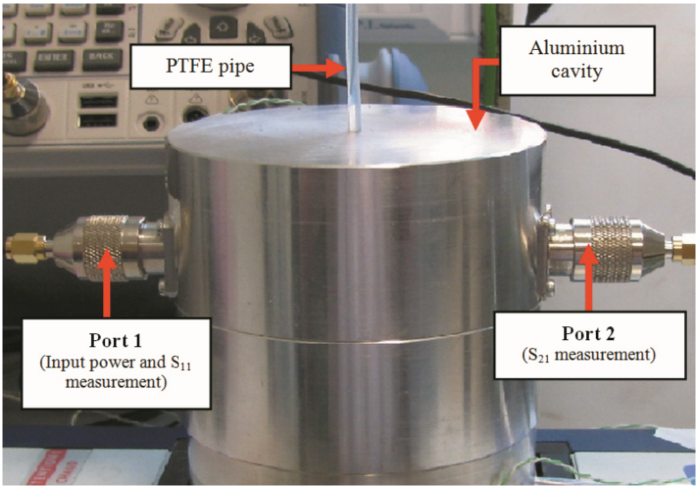


Fig. 5. The 2-port microwave resonant cavity sensor utilized for this work, showing the PTFE tubing passing through the center of the aluminum construction thus allowing nutrient concentration measurements via interaction with the electric field formed inside the cavity

The experimental system, shown in Fig. 7, is constructed from a number of components which are briefly detailed as follows:

(1) **Four Port HLPC Pump.** This allows sample material (i.e. synthetic wastewater) to be mixed and passed through the sensor to characterize and determine its response to differing nutrients and nutrient concentrations.

(2) **Vector Network Analyzer.** This device is responsible for providing input power to the microwave cavity in addition to measuring the S_{11} and S_{21} response to differing nutrients and nutrient concentrations. The analyzer is a Rohde and Schwarz ZVL6 unit, and is calibrated prior to measurements in order to ensure negligible external impact on measurements which is particularly important considering the length of cable required for this experimental work (i.e. 0.5 m).

(3) **Heating Element.** The permittivity of water is known to be affected heavily by temperature [30]; if temperature increases then the permittivity decreases [22, 31].

Therefore the system is designed to alleviate ambient temperature changes by heating the nutrients to a fixed temperature.

(4) **Microwave Cavity Sensor.** As described earlier, this is the device which responds to the changing nutrient type and concentration.

(5) **Synthetic Wastewater (SWW).** A synthetic wastewater is created in this case from a simple combination of deionized water and either KH_2PO_4 (Potassium Phosphate) or KNO_3 (Potassium Nitrate).

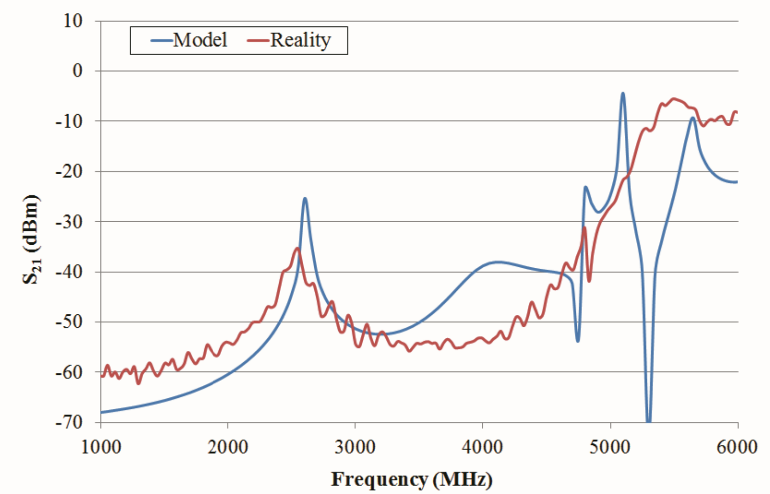


Fig. 6. Shows the microwave cavity S_{21} response during simulated and real world measurements

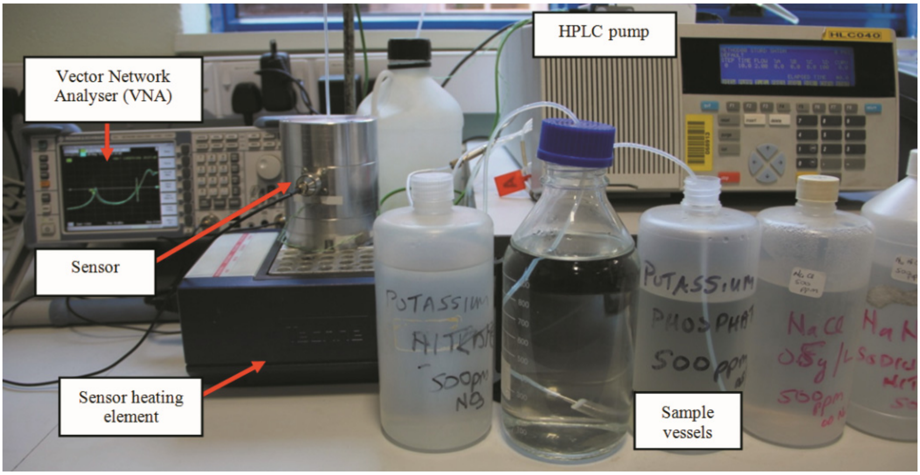


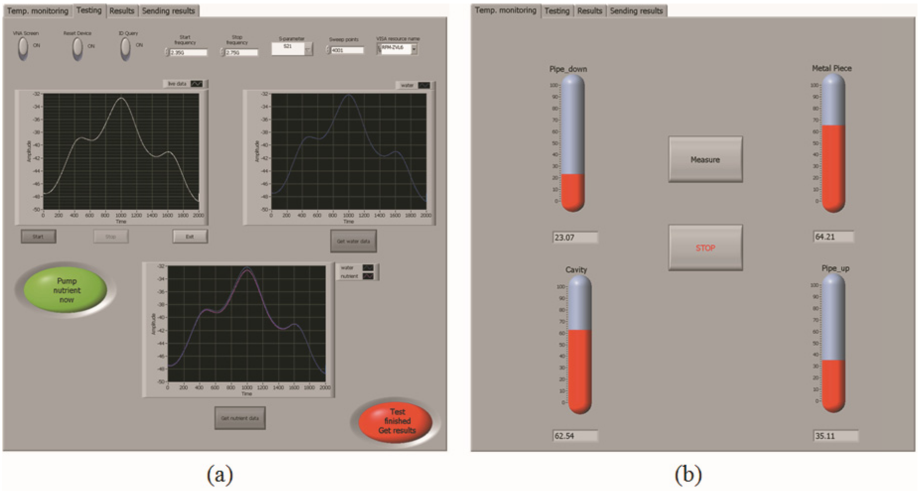
Fig. 7. Shows the experimental setup used for this work, with heating elements being employed to negate ambient temperature variation

4.2 Experimental Procedure

Beginning with the SWW, this is created to emulate a simplistic wastewater, and is envisaged to be similar to the final effluent of a wastewater treatment plant (i.e. relatively free of solids). This removes the need to incorporate filtration into the system, and allows better assessment of the sensor performance in relation to water soluble nutrients.

Two varieties of SWW were prepared, one utilizing Potassium Phosphate (KH_2PO_4) and the other Potassium Nitrate (KNO_3) – both are used as agricultural fertilizer and are therefore one of the main sources for such nutrients being present in actual wastewater. The phosphate solution was prepared by diluting 2.2 g of KH_2PO_4 salt in 1L of deionized water to obtain 500 mg/L of PO_4-P (or 1535 mg/L of PO_4). The nitrate was prepared by diluting 3.6 g of KNO_3 salt in 1L of deionized water to obtain 500 mg/L of NO_3-N (or 2200 mg/L of NO_3).

Using the 500 mg/L solutions, it is possible to have numerous concentration levels mixed by the HLPC pump in real-time ready for introduction to the sensor. For this preliminary study, concentrations of 500 mg/L down to 0 mg/L of PO_4-P and NO_3-N are considered in 100 mg/L intervals. This is intended to consider the limitations of the current design, and suggest improvements which will lead to a more fine-grained approach to testing and characterization in the future.



Start frequency 2.35G
Stop frequency 2.75G
S-parameter S21
Sweep points 4001
VISA resource name RPM-ZVL6

Pipe_down 23.07
Metal Piece 64.21
Cavity 62.54
Pipe_up 35.11

(a) (b)

Fig. 8. LabView front panel window for capturing data from (a) the Rohde and Schwarz VNA and (b) the thermocouple probes used to monitor sample testing during the measurement process. Note that the front panels shown here are all integrated into a single application, and the above images represent different "tabs" within the application.

The output of the HPLC pump is connected to the PTFE piping that runs through the center of the sensor and feeds to a waste vessel – samples are not recirculated to prevent algae build up in the piping and also to prevent unwanted sample contamination or dilution. A heating block heats the cavity to approximately 63°C, which heats the SWW to a maximum of 35°C when it leaves the cavity. The stability of the cavity and SWW is monitored via thermal couple measurements which are incorporated into to a LabView interface (see Fig. 8) for monitoring.

Measurements from the system are acquired in two stages. In the first stage water only is pumped through the sensor to provide a reference level, and the LabView interface acquires an average of the stabilized microwave spectrum between 2480 and 2620 MHz over the course of a 1 minute period. Secondly, the SWW is pumped through the system and a similar procedure is applied. Between each stage sufficient time is allowed for the water or SWW sample to propagate through the tubing. When pumping at 10 ml/min, this waiting time is approximately 45 seconds.

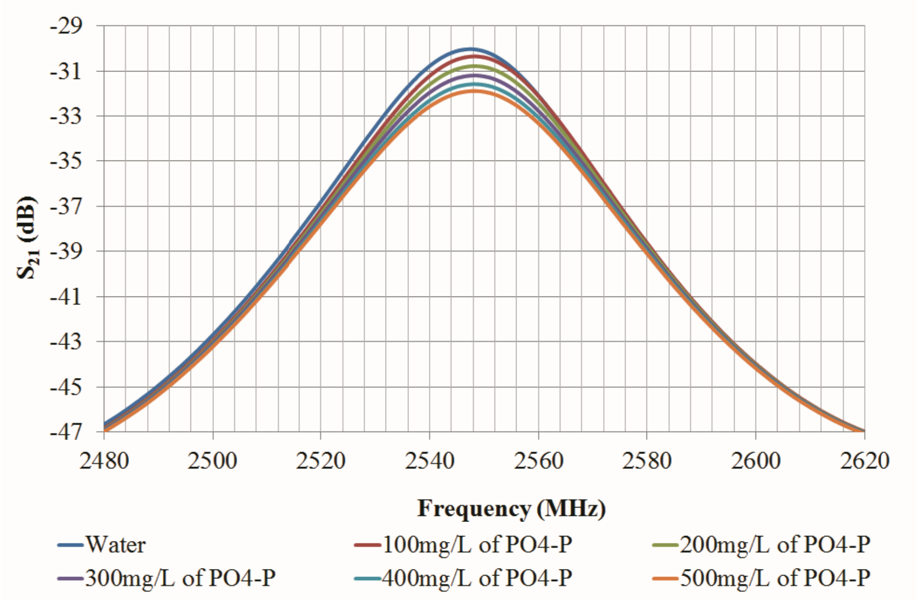
The method used here for acquiring data has proven to give considerable measurement reliability, and along with the heating block, helps to further negate external impacts on measurements to ensure that the system provides both short-term and long-term repeatability. This is particularly important when the system is used as a predictive tool, as discussed later in this chapter.

5 Results

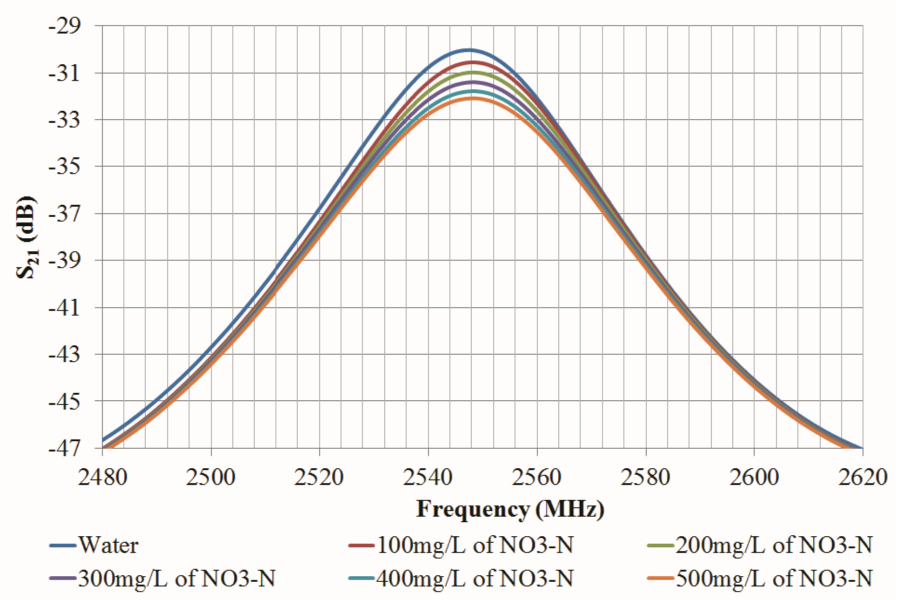
Data acquired for phosphate and nitrate concentrations are shown in Fig. 9. Table 1 notes the prominent features of the results – i.e. resonant peak amplitude and frequency – for each nutrient. This data is also represented in Fig. 10, showing clearly the linear relationship between nutrient concentration and peak amplitude. The linearity of the peak frequency is not quite so clear, although there is a general trend of increasing frequency with increasing nutrient concentration.

Table 1. Peak amplitude and frequency data for PO_4-P and NO_3-N concentrations, as shown in Fig. 9 and 10

Concentration (mg/L)	Peak Amplitude (dBm)		Peak Frequency (MHz)	
	PO_4-P	**NO_3-N**	**PO_4-P**	**NO_3-N**
0	-30.04	-30.04	2547.4	2547.41
100	-30.36	-30.56	2547.83	2547.83
200	-30.77	-30.99	2548.11	2548.11
300	-31.20	-31.40	2548.11	2548.11
400	-31.59	-31.79	2548.25	2548.25
500	-31.89	-32.09	2548.39	2548.39

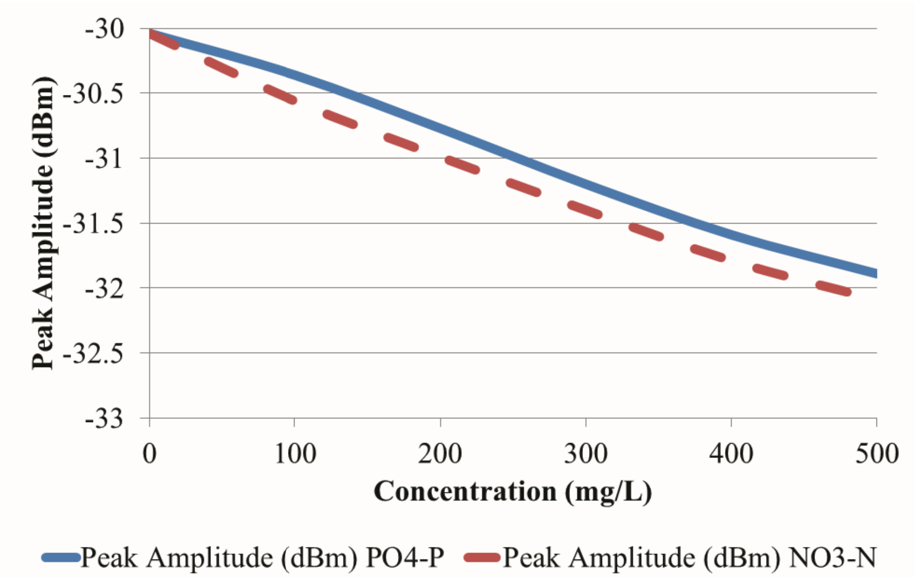


(a)

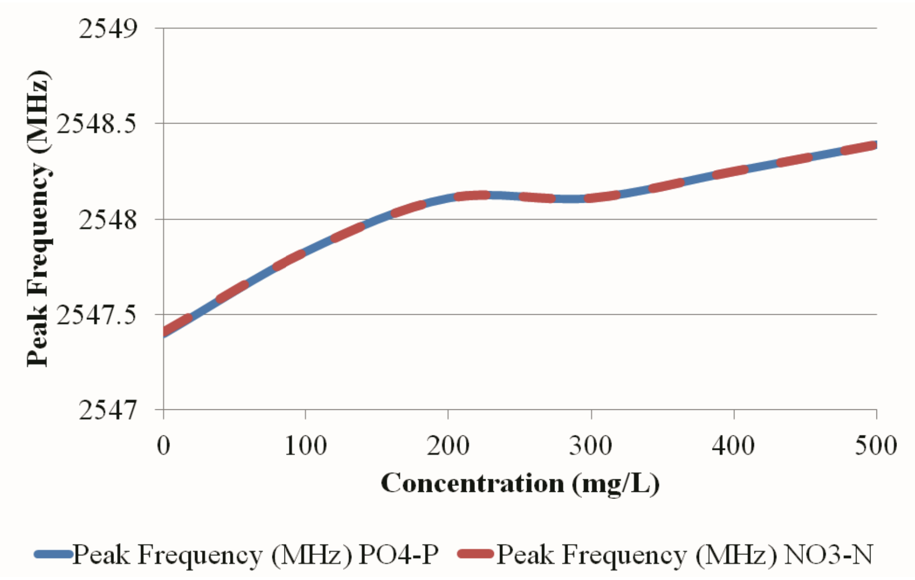


(b)

Fig. 9. S_{21} results for (a) PO_4-P and (b) NO_3-N concentrations from 0-500 mg/L in the frequency range 2480 – 2620 MHz



(a)



(b)

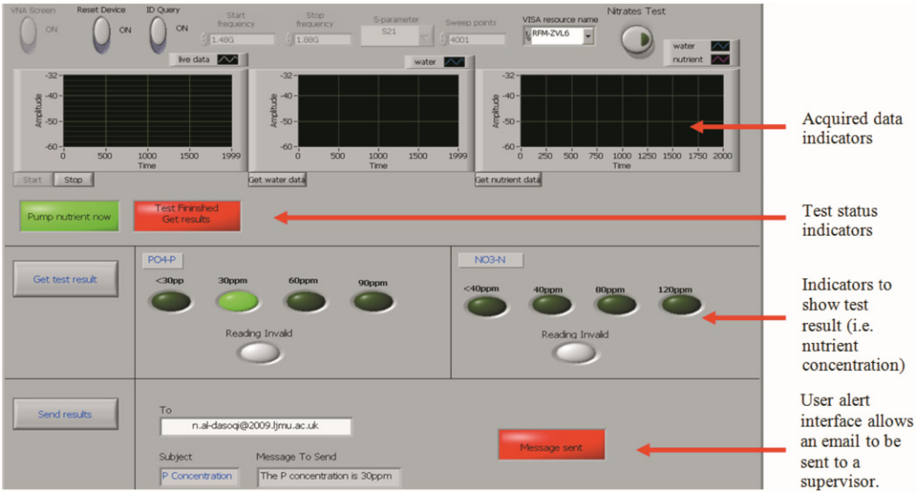
Fig. 10. Indicators of linearity for the sensor peak (a) amplitude and (b) frequency

From the results displayed it is possible to determine the concentration of PO_4-P and NO_3-N in a SWW solution. Since these results show a great deal of repeatability, it has been possible to develop a semi-automated user interface for the sensor which can reliably determine the concentration of PO_4-P or NO_3-N in water, although currently the user must specify which nutrient will be present.

This user interface has been developed using National Instrumental LabView software, which is capable of interfacing directly with the Rohde and Schwarz VNA. Using this interface, a database of expected data for each nutrient has been compiled. This database contains differential variance values for each nutrient concentration in the range of 0-500 mg/L. In order to calculate the differential variance, first the variance of the two captured spectra (i.e. water and SWW) is calculated using (2).

$$\sigma^2 = \frac{1}{N}\sum_{i}^{N}(x_i - \mu)^2 \tag{2}$$

Where N is the number of data points acquired in each spectra and μ is the population mean. Upon calculating the variance for water (σ^2_{W}) and the SWW (σ^2_{SWW}), the difference between them (i.e. $\sigma^2_{SWW} - \sigma^2_{W}$) is calculated and utilized for future predictions. The LabView interface for achieving this prediction is shown in Fig. 11.



Start frequency 1.48G
Stop frequency 1.88G
S-parameter S21
Sweep points 4001
VISA resource name RFM-ZVL6
To n.al-dasoqi@2009.ljmu.ac.uk
Subject P Concentration
Message To Send The P concentration is 30ppm

Acquired data indicators

Test status indicators

Indicators to show test result (i.e. nutrient concentration)

User alert interface allows an email to be sent to a supervisor.

Fig. 11. The LabView user interface which provides a decision to the user regarding the nutrient content of the synthetic waste water sample presented to the sensor

6 Discussion and Future Progression

This work has shown great promise of the microwave technique in detecting nutrients such as phosphate and nitrates in wastewater. However, microwave sensing is not limited to the use of cavity structures, which are seen by many as bulky and expensive due to the use of reasonably expensive high conductivity metals (e.g. aluminum or copper). Thus the authors have been considering new ways in which to achieve the benefits of microwave sensor capability but in a variety of formats. The use of microstrip printed antennas operating as microwave sensors in the GHz frequency range with a Ag planar pattern printed on flexible substrate was recently reported [32]. These sensors are conformable to planar and non-planar surfaces, simple and cost-effective to manufacture using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, and when the particular patch shape and mode are selected they are very versatile in terms of resonant frequency, polarization and impedance.

As an example, an interdigitated electrode (IDE) structure shown in Fig. 12 operating at microwave frequencies was chosen for its versatile design that combines ease of manufacturing with desired functionality [32]. A distinct feature of IDE type sensors is their superior sensitivity to change close to the sensor surface, with this sensitivity decaying rapidly with distance away from the surface. This is advantageous as it reduces significantly the chance of undesirable factors influencing sensor response. Thin flexible substrate provides not only structural benefits for a wide range of applications, but also plays a pivotal role in controlling the strength of a microwave signal fed into the sensor. Thicker substrates are known to be prone to the following effect: as the height increases, surface waves are introduced which usually is not desirable because they extract power from the total available for interaction with the analyte material. The surface waves travel within the substrate and they are scattered at bends and surface discontinuities and degrade the antenna pattern and polarization characteristics [33].

Silver was used as a metal material for both the bottom layer, which acted as a ground plane, and top IDE pattern to maintain chemical neutrality when the device is placed in contact with water. Fig. 13 (a) illustrates optical images of the manufactured prototype microwave sensor, which is bent to illustrate the flexibility of the substrate.

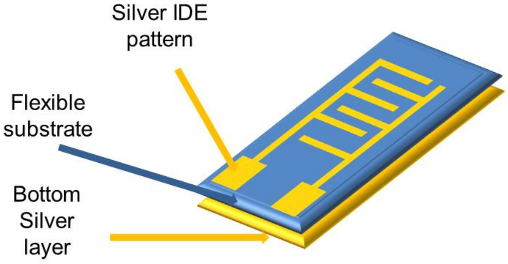


Fig. 12. Schematic of a microwave sensor with interdigitated electrodes

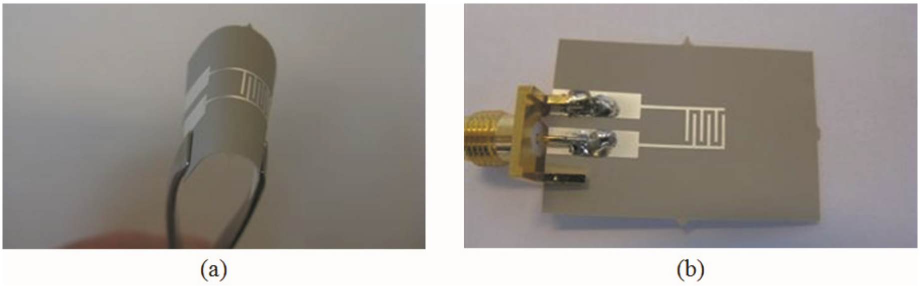
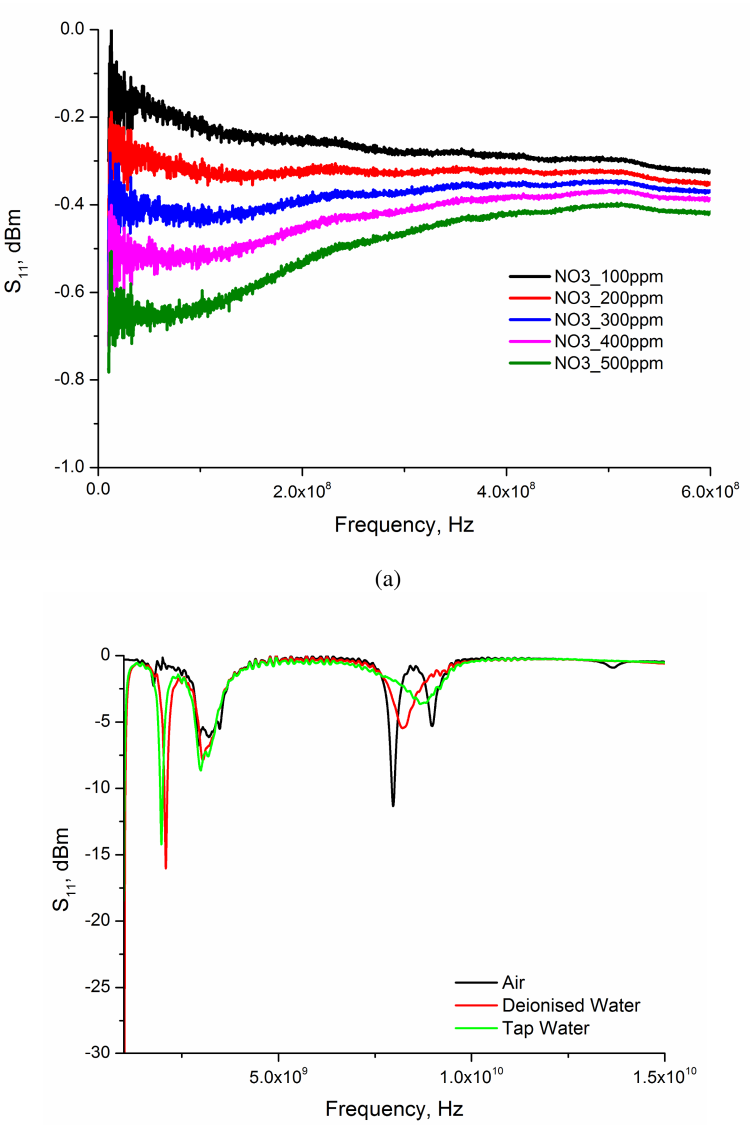

(a) (b)

Fig. 13. Images of the microwave sensor: (a) sensor bent to illustrate the flexibility of the substrate and (b) sensor with SMA connector soldered [32]

To give a feeling of the performance of sensors such as that shown in Fig. 13, preliminary S_{11} measurements where obtained using a VNA (as described in Section 4). These results are shown for 0-500 ppm NO_3 in Fig. 14 (a). There is a clear distinction between the samples, and similar principles can also be applied to smaller concentrations. In terms of sensitivity, the design of the sensor, particularly its geometry, plays a crucial role and the authors are currently investigating a variety of structures which provide enhanced sensitivity. While current legislation requires detection of mg/L quantities of nutrients such as nitrates, in the future it is likely that this will be pushed lower and thus will require sensors which can detect µg/L levels.

Also under investigation is the notion of *selectivity*, such that the sensor will respond in a different manner to the variety of nutrients that might be present in water or wastewater. Although other works suggest the use of coatings (e.g. polymers [34-36], sol-gels [37-39] or metal oxides [40-42]), it is also noteworthy that broadband microwave analysis provides us with a unique spectrum for different analytes [28] and in some cases this may be sufficient to determine the analyte present in some media. Fig. 14 (b) demonstrates this with different media by way of an example.

Fig. 14 (b) illustrates the power S_{11} distribution measured with the flexible microwave sensor in the range 1-15 GHz when in contact with air, deionized water and tap water samples. One may note the significant number of resonant peaks available with the IDE sensor, which indicates that the various sensing elements each influence the obtained spectrum. It is believed that this will give significant advantages in terms of identifying the presence of water contaminants with greater sensitivity, selectivity and high resolution. Focusing on 1-4 GHz and 7-10 GHz ranges, one may notice distinctive shifts in the resonant frequencies of the spectra, corresponding to the sample properties under test. Thus, there is no peak for the sensor response when not in contact with water at around 2 GHz, whereas once the deionized water was placed onto the sensing pattern, a well-pronounced peak occurred at 2.11 GHz and it has shifted to 1.93 GHz when in contact with the water sample taken from the tap. Similarly, at higher frequencies there is a change in the resonant peaks for all the samples and, having maintained all other experimental parameters constant, the only explanation to these shifts is that they are connected with the properties of the water, namely its composition. This particular feature makes the developed microwave sensor an attractive option for real-time monitoring of water purity.



(a)

(b)

Fig. 14. Illustrating the response of planar microwave structures to (a) different concentrations of NO_3 and (b) to different analyte materials; air, deionized water and tap water [32]

7 Conclusion

This research was driven by the industrial need for a novel real-time monitoring method of water purity that would be able to meet strict regulatory demands and yet be versatile, sensitive and cost-efficient. It has been demonstrated that the method can provide adequate sensitivity for measurement of different nutrients which would be found in wastewater, namely phosphate (PO_4) and nitrate (NO_3). There is still work to be done in enhancing this sensitivity further, however this area is still under active investigation by the authors and the subject of a number on-going industrially focused research projects. It is envisaged that the technique, once fully developed, could be used for a wide variety of applications, and at numerous stages in the wastewater treatment process as was briefly outlined in Section 2 of this chapter.

It is notable that the work has demonstrated both traditional resonant cavity methods in addition to novel IDE structures which provide a cost effective and flexible means by which to apply the suggested technique. This highlights one of the key benefits of using microwave sensors; they can take many different forms depending on the application and its requirements. It is believed that the small flexible sensor shown in Section 6 would provide for long-term usage since this configuration is less prone to failure due to mechanical damage than perhaps a rigid substrate planar device. The sensor response was tested using a VNA in 1-15 GHz frequency range. It was clearly seen that the resonant peaks have shifted once deionized and tap water samples were placed in contact with the antenna pattern. Notably, the sensor's response returned to its original position, namely the air spectrum, after each water sample measurement, confirming that the developed microwave sensor is reliable, re-usable and thus a sustainable solution for water monitoring.

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