

## A NON-SPECIFIC MICROWAVE SENSOR FOR WATER QUALITY MONITORING

G. Gennarelli, F. Soldovieri

*Institute for Electromagnetic Sensing of the Environment, National Research Council of Italy,  
Via Diocleziano, 328-80124 Napoli, Italy.*

*E-mail: [gennarelli.g@irea.cnr.it](mailto:gennarelli.g@irea.cnr.it)*

### ABSTRACT

*This paper deals with a microwave measurement system for the real-time monitoring of water quality. The sensor is a compact cavity resonator tuned at 1.91 GHz which has been designed by a Finite Element Method code to maximize the Q-factor. The sensing principle relies on the changes of the device response in terms of the transmitted power, resonance frequency, and 3-dB bandwidth. These variations are caused by the change of the permittivity and conductivity of the water sample under test induced by the presence of pollutants. Experiments are carried out in laboratory conditions on water solutions contaminated with different substances. As shown, the system is capable to reliably detect the presence of nitrates and sulfites dissolved in water in concentrations above 10 mg/L. The proposed set-up is portable and thus particularly tailored for its deployment on-field. Moreover, it has reduced cost since it does not necessitate expensive instrumentation such as network analyzers.*

**Keywords:** microwave sensor, nitrates, sulfites, water pollution analysis.

### 1. INTRODUCTION

Water pollution concerns any chemical, physical or biological variation in the quality of water which exceeds some reference values and may cause health problems. The most evident ones are the result of microbial (bacteriological, viral, protozoan or other biological) contamination usually arising in presence of untreated waste and sewage discharges. Nevertheless, an appreciable number of serious health problems may also occur as a result of chemical contamination. Chemical pollutants are typically classified into organic and inorganic materials. They may be products expelled from factories, e.g. industrial solvents, heavy metals, plastics, fertilizers and pesticides which are harmful to humans and also to all plants and animals in water.

Nowadays, the quality of water intended for human consumption is usually high when it leaves the purification plant, but it can deteriorate on its way to the consumers for the presence of chemical substances or because of stagnation in reservoir which may facilitate the growth of algae and bacteria. As a result, water monitoring is of primary concern for most health and security authorities. In this framework, the European Directive 98/93/EC [1] has set quality standards of drinking water on the basis of the guidelines from the World Health Organization (the most recent guidelines can be found in [2]). In particular, it has fixed the maximum allowed concentrations of several chemical and microbiological substances based on their maximum daily consumption over long period of times, their nature and their potential toxicity.

Water quality sensors exploiting different technologies (e.g. chemical, optical, acoustic, etc.) have been presented in the literature [3]-[9]. Moreover, many commercial solutions are currently available on the market and commonly adopted to analyze specific parameters of interest such as PH, conductivity, free and residual chlorine concentration, dissolved oxygen, turbidity, etc. Sometimes

these features can be even monitored by a single multi parameter sonde which provides much more flexibility at the expense of a major complexity and cost.

However, real-time monitoring of drinking water can involve the presence of several sensors deployed along the distribution network. In this scenario, it may be convenient to use non-specific devices, possibly low-cost, which are sensitive to several impurities instead of many specific sensors each sensitive to a single substance. For instance, to reduce the complexity and the cost of the overall monitoring system, it may be sufficient at an early stage to measure only the variations, with respect to some nominal conditions, of some typical sensor parameters. Only when significant variations are recorded, detailed analyses with specific sensors are carried out.

It must be noted that among the different types of sensor technologies today available, the one based on dielectric spectroscopy (e.g. see [10]-[12]) represents a promising and cost-effective solution for detecting water contaminants.

The aim of this paper is to demonstrate the feasibility to detect water contaminants by exploiting microwave technology. The sensing device here considered is a rectangular cavity resonator working at 1.91 GHz in the fundamental  $TE_{101}$  mode. The basic idea is to introduce a water sample inside the cavity by means of a low loss capillary. As well-known, the presence of pollutants in water alters the complex permittivity of the solution (i.e. the dielectric permittivity and conductivity) [13] thus modifying the cavity response in terms transmitted power, resonance frequency and 3-dB bandwidth. As a consequence, it is possible to detect the pollutants by monitoring these parameters in real-time. It must be stressed that the sensor is non-specific, i.e. it is not capable to discriminate the type of contaminants and their respective concentrations without a-priori information on the solution composition and the availability of proper calibration curves. This point is easily understood since the same permittivity and/or conductivity variations could be for instance induced by different substances or different combinations of substances.

Cavity perturbation methods have been widely investigated in the past years for characterizing the dielectric behavior of materials at microwave frequencies [13]. Moreover, their application to water pollution analysis has been considered in [14] and [15]. With respect to previous works, here we propose a different design and portable measurement system suitable for on field applications. Moreover, the novel contribution is the appraisal of the achievable sensing performance in terms sensitivity and lowest detectable concentrations.

The paper is organized as follows. Section 2 provides the description of the sensor, its working principle and design parameters. The measurement system and the characterization of several polluted waters are presented in Section 3. Conclusions follow in Section 4.

## 2. THE CAVITY SENSOR

A drawing of the rectangular cavity-based sensor also comprising the elements for signal coupling is depicted in Fig. 1. The structure is made of aluminum and has dimensions  $a$ ,  $b$ , and  $l$  along the  $x$ ,  $y$ , and  $z$  axis, respectively. Such dimensions are fixed to  $a=l=11.065$  cm and  $b=5.45$  cm thus giving a fundamental resonant  $TE_{101}$  mode at the frequency 1.9158 GHz. The structure is coupled to the external circuit via coaxial probes connected to 50 Ohm cables. The probes are inserted in the cavity via holes drilled in the bottom wall. Their geometrical features have been optimized by using a Finite Element (FEM) code in order to maximize the  $Q$ -factor, i.e., frequency selectivity. Based on this optimization, a resonant frequency of 1.915 GHz and a  $Q$ -factor of 3800 have been experimentally determined. These values are in good agreement with the simulation results (errors less than 1 %). More details on the design of the cavity and the characterization of its operation are available in a recent paper [16] dealing with the usage of this device as concentration sensor for binary liquid mixtures.

As shown in Fig. 1, a cylindrical capillary with radius  $r_c$  passes through the cavity at its center where the electric field is maximum to allow the water flow. The water sample to be analyzed is modeled as a dielectric material characterized by the complex relative permittivity  $\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta)$ , where  $\varepsilon'$  and  $\varepsilon''$  are the real and imaginary parts and  $\tan\delta$  is the loss tangent.

According to resonant perturbation theory [13], the presence of a water solution inside the capillary gives rise to a shift of the resonant frequency and an increase of the 3-dB bandwidth (reduction of the  $Q$ -factor) with respect to the empty cavity case. Of course, the amount of these perturbations depends on sample volume as well as on its dielectric properties, i.e. its chemical composition.

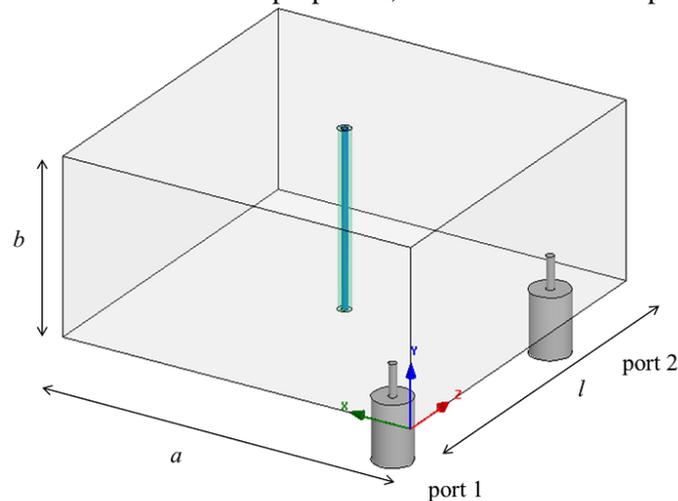


Fig. 1: Sketch of the rectangular cavity and its coupling elements.

Based on this principle, a variation of the electromagnetic properties of water caused by contaminants is expected to produce a change of the resonance frequency and of the 3-dB bandwidth. Moreover, the reflected and transmitted powers at the ports of the cavity (ports 1 and 2 in Fig. 1) also vary.

In order to get insight into the physical behavior of the sensor when it is filled with water samples, numerical simulations are carried out with the FEM method. An example showing the transmission coefficient  $S_{21}$  of the cavity is reported in Fig. 2. The effect of the capillary radius as well as of the complex permittivity is investigated (see caption of Fig. 2 for further details). Once  $\varepsilon'$  and  $\varepsilon''$  ( $\tan\delta$ ) are fixed, increasing  $r_c$  yields a higher resonant frequency shift and a broadening of the 3-dB bandwidth. Moreover, increasing the sample radius yields a higher sensitivity with respect to complex permittivity changes (see in particular the curves relevant to  $r_c = 1.5$  mm). Figure 2 also reveals that the transmission peak of the  $S_{21}$  coefficient lowers with the sample volume. In a similar way, the reflection coefficient at the input port (not shown) is strongly influenced by the sample volume and the mismatch increases with  $r_c$ . Accordingly, depending on the type of liquid to be characterized, a limitation on the maximum sample volume is expected in practice. Note that the accuracy of the resonant frequency evaluation is directly related to the  $Q$ -factor and to the signal-to-noise ratio on measured data [17].

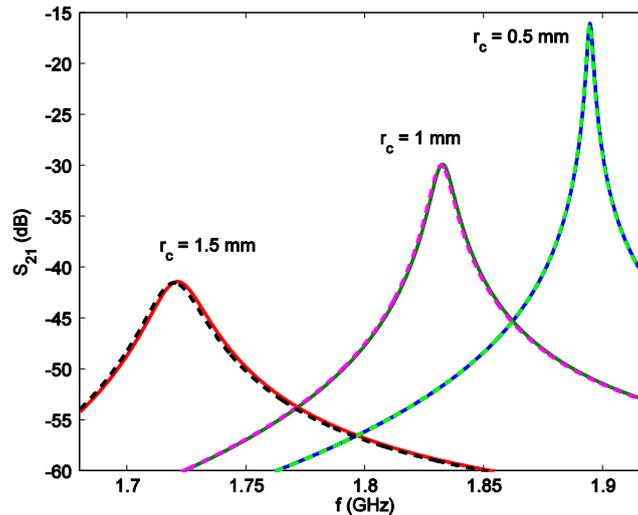


Fig. 2: Simulated transmission coefficient for different sample radii and dielectric constants. The solid curves refer to  $\epsilon' = 74$  whereas the dashed lines are related to  $\epsilon' = 75$ . The dielectric loss tangent is equal to 0.05.

### 3. EXPERIMENTAL ANALYSIS

In this Section, the results of laboratory tests carried out in controlled conditions at IREA-CNR are reported. A photo of the measurement set-up is shown in Fig. 3. The cavity-based sensor is fed at the input port by a synthesized RF signal generator (mod. SSG-4000LH manufactured by Mini Circuits) and the power transmitted at the output port is measured by a power meter (mod. PWR-4RMS produced by Mini Circuits). Both devices are programmable and communicate via USB with a laptop which represents the control unit. The RF generator transmits CW signals over the frequency range [1815, 1840] MHz with a step of 200 KHz and acquires each resonance curve in about 20 seconds. Then, the resonance frequency and the 3-dB bandwidth are extracted from each measured curve by a Lorentzian fitting method [17]. A software has been developed to easily configure measurement parameters, acquire the data, process them and display the results in real-time.

The water solutions are introduced in the cavity via a thermoplastic capillary of inner radius equal to 1 mm and thickness of 1 mm. In particular, the capillary is connected to an external pump via tube fittings so that a continuous water flow is created and no air bubbles are formed in the capillary. The temperature of the liquid under test is kept constant at 25°C using a thermostatic bath (mod. Lauda M12). As will be shown, temperature variations represent a key point that must be taken into account. As a matter of fact, they can alter the electromagnetic properties of the solution under test thus lowering the sensor capability to detect pollutants.

The water contaminants considered for the experiments are potassium-nitrate ( $\text{KNO}_3$ ) and potassium-sulfite ( $\text{K}_2\text{S}_2\text{O}_5$ ). Nitrates are generally not extremely toxic but their reduction to nitrites can lead to a generalized lack of oxygen in organ tissue and a dangerous condition called methemoglobinemia [2]. Their allowed maximum concentration is fixed by law to 50 mg/L. As regards the potassium-sulfite ( $\text{K}_2\text{S}_2\text{O}_5$ ), it is commonly employed as an additive for food conservation and can cause allergies. However, no guidelines values are available for it.

Several water- $\text{KNO}_3$  and water- $\text{K}_2\text{S}_2\text{O}_5$  samples are prepared with growing solute concentrations in the range [0, 500] mg/L. For each concentration value, ten measurements are collected in order to perform an estimate of measurement errors. The sensor response is evaluated only in terms of transmitted power at resonant frequency and 3-dB bandwidth since the resonance frequency changes are less detectable for the considered solutions.

This point is clearly highlighted by the results shown in Fig. 4 concerning the measured power versus frequency in the case of water-KNO<sub>3</sub> solutions. Note that increasing the nitrate concentration mainly lowers the peak power and increases the bandwidth due to the higher conduction losses.

Starting from the measured curves, the variation of the mean value of the transmitted power at the resonance frequency and of the 3-dB bandwidth are computed and plotted versus KNO<sub>3</sub> concentration in Figs. 5 a and b, respectively. As can be seen, these quantities well agree with a linear model. Moreover, the sensitivity to peak power variation is 0.0013 (dBm/(mg/L)), whereas that related to the 3-dB bandwidth variation is equal to 2.6 (KHz/(mg/L)).

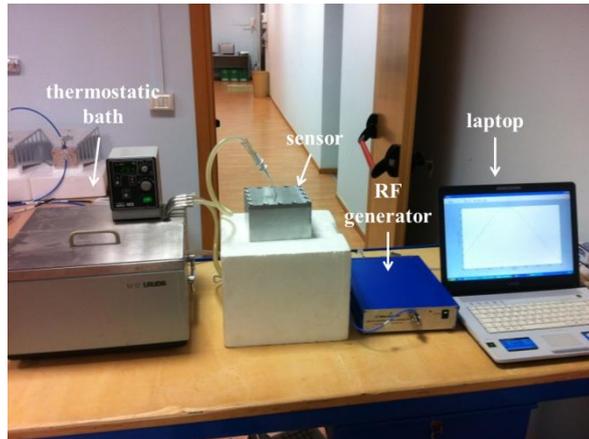


Fig. 3: A photograph of the measurement system.

After, we analyze the water-K<sub>2</sub>S<sub>2</sub>O<sub>5</sub> samples for the same concentrations of solute. The results obtained in this case, plotted in Figs. 6 a and b, reveal similar trends as for the water-KNO<sub>3</sub> solutions, and the main difference is a reduction of the sensor sensitivities (0.001 dBm/(mg/L) and 2.1 KHz/(mg/L)).

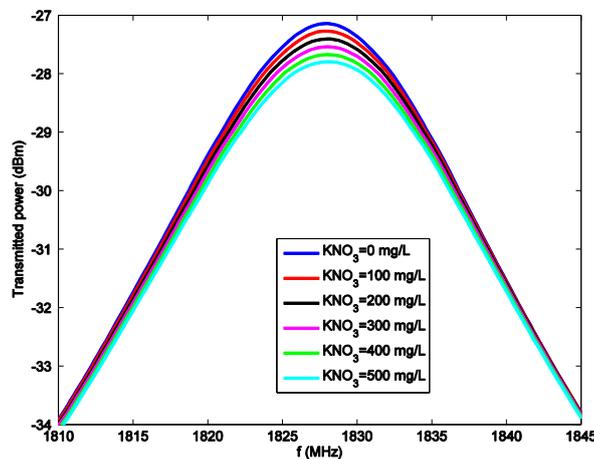


Fig. 4: Transmitted power versus frequency for different water-KNO<sub>3</sub> solutions. Only one measurement is shown for each concentration value to improve readability.

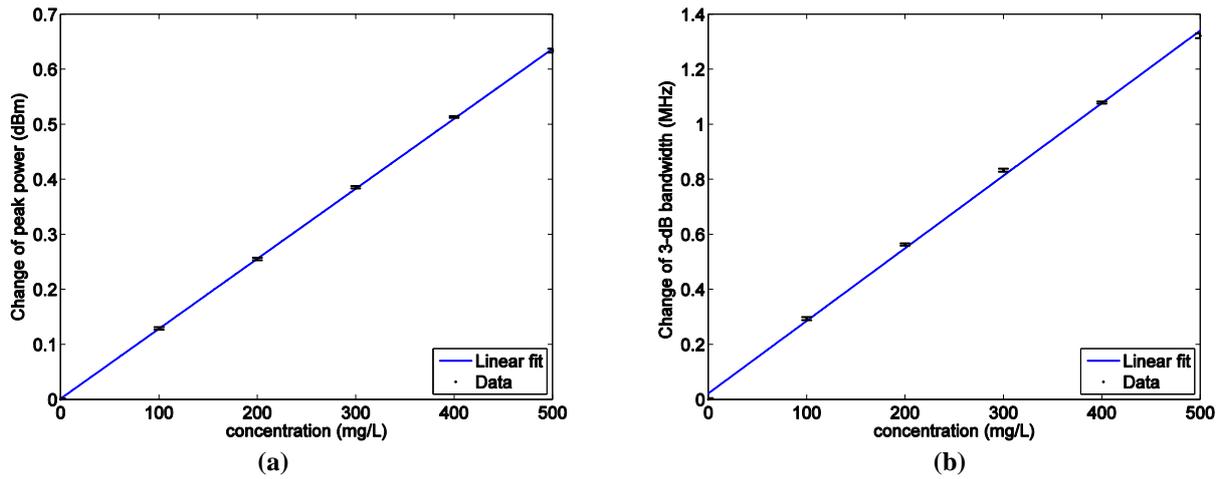


Fig. 5: Measurement results (mean values and error bars) and the linear fit curve for water-KNO<sub>3</sub> solutions. (a) Variation (modulus) of the peak power. (b) Variation of the 3-dB bandwidth.

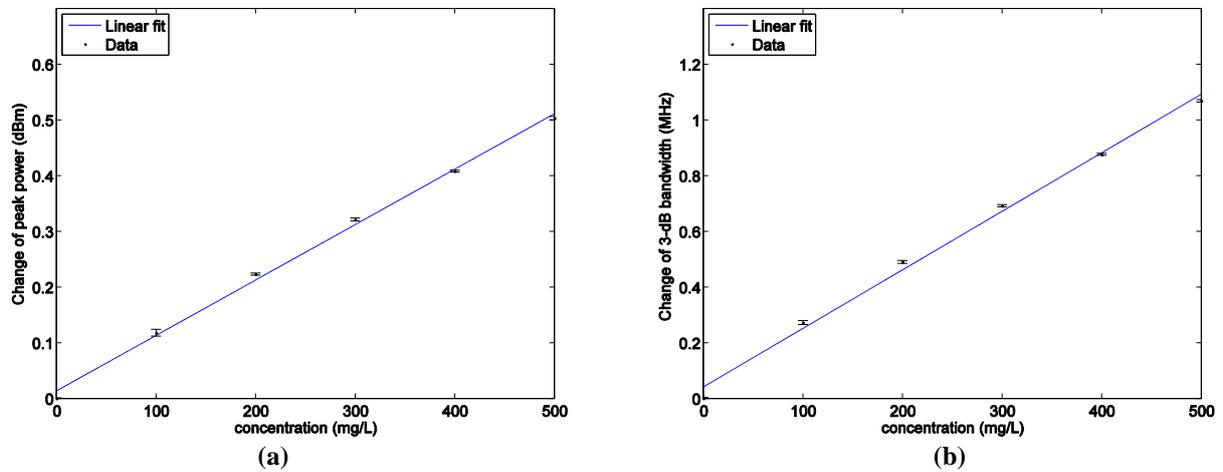


Fig. 6: Measurement results (mean values and error bars) and the linear fit curve for water-K<sub>2</sub>S<sub>2</sub>O<sub>5</sub> solutions. (a) Variation (modulus) of the peak power. (b) Variation of the 3-dB bandwidth.

Based on the above results, we perform an estimation of the Limit of Detection (LoD), i.e., the minimum detectable concentration for a given pollutant. To this end, the standard deviations of the sensor response have been evaluated on a water sample. The achieved sensor performance are summarized in Tab. 1 and, as can be noted, they confirm the feasibility to detect pollutant concentrations in excess of 10 mg/L.

Finally, we investigate the effects on the sensor response caused by temperature variations intentionally induced with the thermostatic bath. This analysis is accomplished to estimate the temperature sensitivities which may aid to compensate unwanted temperature changes arising when the sensor is needed to operate on field. In particular, the temperature of a water solution is progressively increased by steps of 1 °C in the interval [20, 25] °C. The variations of the transmitted power, resonance frequency, and 3-dB bandwidth versus temperature are plotted in Figs. 7a, b, and c. In this case, increasing the temperature lowers the permittivity and conductivity of the solution with a resulting increase of the peak power, of the resonant frequency, and reduction of the bandwidth. Moreover, the trends are linear and the sensitivity of power variation is equal to 0.2 dBm/°C, the sensitivity of resonant frequency is 400 KHz/°C, and that relevant to bandwidth is equal to 380 KHz/°C.

Table 1. Sensor performance at 25 °C

Solution	Power sensitivity (dB/(mg/L))	Bandwidth sensitivity (KHz/(mg/L))	Power LoD (mg/L)	Bandwidth LoD (mg/L)
Water-KNO <sub>3</sub>	0.0013	2.6	8	9
Water-K <sub>2</sub> S <sub>2</sub> O <sub>5</sub>	0.001	2.1	9	7

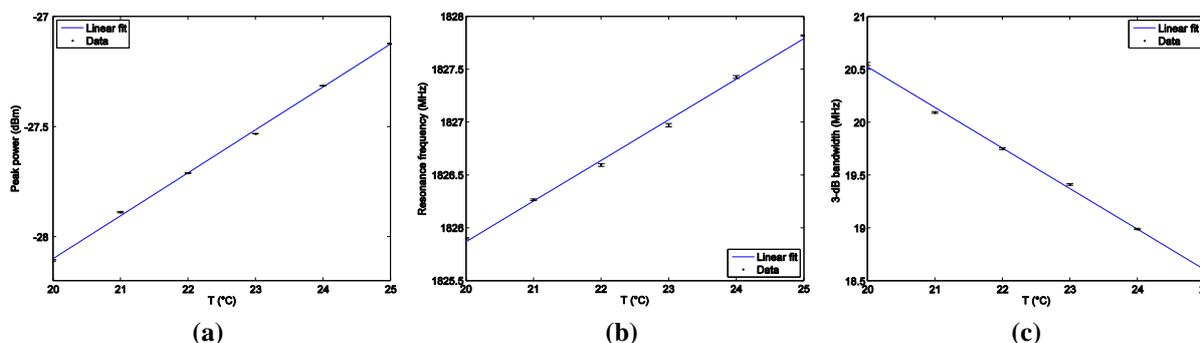


Fig. 7: Measurement results (mean values and error bars) and the linear fit curve for water versus temperature in the range [20, 25] °C. (a) Transmitted peak power. (b) Resonance frequency (c) 3-dB bandwidth.

#### 4. CONCLUSIONS

A non-specific microwave cavity sensor has been proposed as a useful tool for real-time water pollution analysis. The measurement system here considered is portable and has a relative low cost with respect to more expensive solutions based on network analyzers. Experimental tests have confirmed that the sensor is capable to detect pollutants such as nitrates and sulfites dissolved in water at concentrations above 10 mg/L regardless of the parameter measured. These results turn out to be very promising and suggest that, if temperature variations of the liquid under test are properly monitored and compensated, it is possible to detect the presence of several pollutants of practical interest.

#### ACKNOWLEDGMENTS

This research has received funding from the Italian Ministero dello Sviluppo Economico, under Grant Agreement "Industria 2015 - New Technologies for the Made In Italy", No. MIOI 00223 (project ACQUASENSE).

#### REFERENCES

- [1]. Council directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption, L 330/32 EN, Official Journal of the European Communities.
- [2]. *Guidelines for drinking-water quality 4<sup>th</sup> edition*, World Health Organization, 2011.
- [3]. J. Wang, R. K. Bhada, J. Lu, D. MacDonald, Remote electrochemical sensor for monitoring TNT in natural waters, *Analytica Chimica Acta*, vol. 361, pp. 85-91, 1998.
- [4]. J. W. Gardner, H. W. Shin, E. L. Hines, C. S. Dow, An electronic nose system for monitoring the quality of potable water, *Sensors and Actuators B*, vol. 69, pp. 336-341, 2000.

- [5]. W. Bourgeois, P. Hogben, A. Pike, R. M. Stuetz, Development of a sensor array based measurement system for continuous monitoring of water and wastewater, *Sensors and Actuators B*, vol. 88, pp. 312-319, 2003.
- [6]. E. M. Nolan and S. J. Lippard, A "Turn-On" fluorescent sensor for the selective detection of mercuric ion in aqueous media, *J. Am. Chem. Soc.*, vol. 125, pp. 14270-14271, 2003.
- [7]. E. S. Forzani, H. Zhang, W. Chen, and N. Tao, Detection of heavy metal ions in drinking water using a high-resolution differential surface plasmon resonance sensor, *Environ. Sci. Technol.*, vol. 39, pp. 1257-1262, 2005.
- [8]. M. I. S. Verissimo, M. T. S. R. Gomes, The quality of our drinking water: aluminium determination with an acoustic wave sensor, *Analytica Chimica Acta*, vol. 617, pp. 162-166, 2008.
- [9]. O. Korostynska, A. Mason, A. Al-Shamma'a, Monitoring of nitrates and phosphates in wastewater: current technologies and further challenges, *International Journal on Smart Sensing and Intelligent Systems*, vol. 5, no. 1, pp. 149-176, 2012.
- [10]. V. Saltas, F. Vallianatos and D. Triantis, Dielectric properties of non-swelling bentonite: the effect of temperature and water saturation, *Journal of Non-Crystalline Solids*, vol. 354, pp. 5533-5541, 2008.
- [11]. V. Saltas, D. Triantis, T. Manios, F. Vallianatos, Biomonitoring of environmental pollution using dielectric properties of tree leaves, *Environmental Monitoring and Assessment*, vol. 133, pp. 69-78, 2007.
- [12]. V. Saltas, F. Vallianatos, P. Soupios, J. Makris, D. Triantis, Dielectric and conductivity measurements as proxy method to monitor contamination in sandstone, *Journal of Hazardous Materials*, vol. 142, pp. 520-525, 2007.
- [13]. L. Chen, C. Ong, C. Neo, V. V. Varadan, and V. K. Varadan, *Microwave electronics: Measurement and materials characterization*, John Wiley and Sons, New-York, 2004.
- [14]. H. J. C. Blume, Measurement of dielectric properties and determination of microwave emissivity of polluted waters, *IEEE Trans. Instrum. Measur.*, vol. 29, no. 4, pp. 289-291, 1980.
- [15]. U. Raveendranath, and K. T. Mathew, Microwave technique for water pollution study, *Journal Microwave Power and Electromagnetic Energy*, vol. 30, no. 3, pp. 188-194, 1995.
- [16]. G. Gennarelli, S. Romeo, M. S. Scarfi, F. Soldovieri, A microwave resonant sensor for concentration measurements of liquid solutions, *IEEE Sensors Journal*, vol. 13, no. 5, pp. 1857-1864, 2013.
- [17]. R. Inoue et al., Data analysis of the extraction of dielectric properties from insulating substrates utilizing the evanescent perturbation method, *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 2, pp. 522-532, 2006.