Microwave Technology: The Missing Piece of the Puzzle

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Abstract. At present, water quality control is still dominated by laboratory analysis of grab samples. Sensors are only available for a very limited number of parameters and frequently do not entirely meet the needs of the users. Even a brief overview of the state-of-the-art in the real time water monitoring reveals that it is not possible to achieve adequate detection of water parameters by using only one type of sensor. Accordingly, the solution is to merge various technologies into a single system that would employ the best available methods for the detection of specific water contaminants, so as to provide overall superior sensitivity, selectivity and long-term stability, while enabling real-time wireless data collection for enhanced cost-effectiveness. Namely, multi-sensor platforms that utilise the best available methods combined into a single monitoring process are seen as the only way to achieve the holistic monitoring capabilities. It is suggested that a special role in this development is reserved for microwave technology based sensors – a missing piece in the puzzle to potentially solve the issue of real-time water quality control. This paper reviews the capabilities of microwave sensors for real-time water quality monitoring as compared to other alternative methods, namely standard UV-VIS optical methods; fibre optic sensors; amperometric sensors, biosensors, specifically-sensitive microelectrodes and lab-on-chip sensing systems.

Introduction

Water quality assessments are based on the analysis of the physical, chemical and bacteriological parameters and require customised apparatus and trained staff. In daily use there are up to 70,000 known [1] and emerging [2, 3] chemicals that might be present in various water resources, including for drinking water production. Physical, chemical, biological and radioactive variables vary widely in all types of water and some high concentrations may be difficult to reduce during the treatment process. To this end, water supply companies have developed quality management systems and monitoring strategies using well-established but laboratory based techniques that are becoming of limited scope and usefulness. For this reason, a continuous online water quality monitoring platform is essential for preserving potable water resources.

Phosphate and Nitrate as a main pollutants that need novel monitoring platform

In 2004, Amine and Palleschi [4] urged scientists to put more effort into the development of phosphate, nitrate, and sulfate biosensors, as these were the least developed types at that time. Since then, the water treatment industries still struggle in the search for cost-effective real-time monitoring equipment, especially to detect phosphate, nitrate and nitrite in water.

Various detection strategies for phosphate include phosphate ion selective electrodes based on potentiometric techniques, indirect voltammetric detection based on the reaction of phosphate with various metals and associated complexes, and sensors exploiting enzymatic reactions [5]. Nitrate is a key element in the nitrogen cycle as it is the link between the nitrification and denitrification processes. As nitrate fertilisers are increasingly used in agriculture, the quantity of nitrate leaching from fields into rivers and ground waters is increasing cumulatively.

State-of-the-art in the real time monitoring of nitrates and phosphates

Optical methods of detection. The main method for phosphorus detection is using a photo sensor which measures the wavelength of a distinct colour (e.g. blue or yellow) that results from a chemical reaction between phosphorus and special reagent [6]. The concentration of the resultant dye indicates the concentration of phosphorus in the sample. Examples of commercially available systems are Hach Lange; EnviroTech Instruments (AutoLAB 4); TresCon on-line water analysis systems, ChemScan UV-6100 Analyser and so forth [7].

Fibre optic sensors are used in combination with the UV-Vis methods of detection and normally are suitably doped to produce luminescence when exposed to an excitation light source. Glass fibres are either doped with a rare earth metal or activated with a transition metal. Polymeric fibres are doped with a dye. Notably, the coating of the fibre determines the sensitivity and selectivity of the sensor and research is continuing to develop novel materials that would suit the need of a particular sensing task [8, 9]. The fibres have fast response and decay times and can achieve high efficiency through the design of appropriate delivery optics. Fibre optic systems are particularly suitable for harsh and difficult to reach places.

Potentiometric sensing including amperometric and conductometric is widely used in the measurement of pollution in water. These sensors change their properties as a result of interaction with the component being measured. The species of interest are either oxidised or reduced at the working electrode causing a transfer of electrons, thus generating a measureable signal. This change can be recorded as a change in the output signal, i.e. output voltage, current, change in conductivity, capacitance or dielectric constant – whatever parameter gives the most pronounced sensor response [10]. Various potentiometric approaches for monitoring of nitrates and phosphates typically fall within one of five main categories [5], as illustrated in Fig. 1.

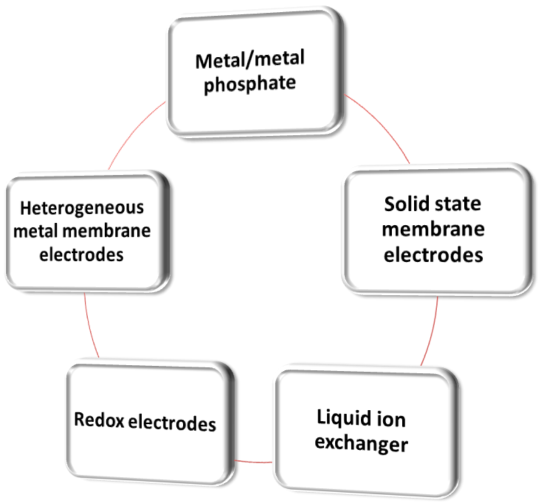

Fig. 1. Potentiometric detection methods.

Biosensors for the determination of phosphate are normally based on mono- or multi-enzymatic reactions where phosphate acts as an inhibitor or substrate [4]. For example, an amperometric phosphate biosensor, based on a cobalt phthalocyanine screen-printed carbon electrode (CoPC-SPCE) was recently reported [11] with a linear range of 2.5–130 μM and detection limit of 2 μM, exhibiting a response time of ~13 s.

Micro-Electro Mechanical (MEMs) Microelectrode Array Sensors: the major advantages of these systems include the ability to penetrate samples to perform measurements, small tip size for in situ measurements, array structure for higher robustness, and possibility of multi-analyte detection. For example, a cobalt-based MEMs microelectrode array sensors for direct measurement of phosphate in small environmental samples, such as microbial aggregates, has been reported in [12]. These microelectrodes performed linearly and exhibited high sensitivity toward the phosphate ions in the range $10^{-5.0}$ to 10^{-25} M KH_2PO_4 solution at pH 7.5.

Lab-on-chip and electrochemical sensing-based portable monitoring systems appear well suited to complement standard analytical methods for a number of environmental monitoring applications, including the water quality monitoring. The concept of a lab-on-chip type systems started from the integration of the various chemical operations involved in conventional analytical processes in a laboratory, such as sampling, preparation, mixing, reaction, and separation into a single unified system, requiring only a tiny volume of chemicals and sample and only a fraction of the time needed for the conventional approach.

Novel approach: microwave technology based sensors

Microwave sensing is a developing technology which has been successfully used as a sensing method for various industrial applications including water solution concentrations [13] and water level measurements [14], material moisture content [15, 16], for continuous process monitoring for biogas plants and in the healthcare industry.

Microwave sensors in the form of cavity resonators operate based upon the interaction of the electromagnetic waves and the material, i.e. water sample, being tested. Due to this interaction, the permittivity of the material changes and it manifests itself as a frequency change, attenuation or reflection of the signal.

By considering how transmitted (S_{21}) and reflected (S_{11}) microwave powers vary at discrete frequency intervals, the change in the signal can be linked to the composition of the object under test. Fig. 2 shows the 2-port microwave resonant cavity sensor with PTFE tubing passing through the centre of the aluminium construction thus allowing nutrient concentration measurements via interaction with the electric field formed inside the cavity.

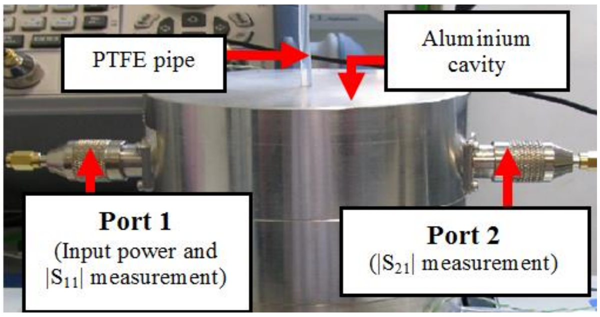

Fig. 2. Microwave resonant cavity sensor.

Multi-sensor real-time monitoring system

Even a brief overview of the state-of-the-art in the real time water monitoring given above reveals that it is not possible to achieve adequate detection of water parameters by using only one type of sensor. Accordingly, the solution is to merge various technologies into a single system (Fig. 3) that would employ the best available methods for the detection of specific water contaminants, so as to provide overall superior sensitivity, selectivity and long-term stability, while at the same time enabling real-time wireless data collection for enhanced cost-effectiveness. The feasible monitoring system might consist of a network of sensors deployed at key locations, capable of autonomous operation in the field for a year or more [17].

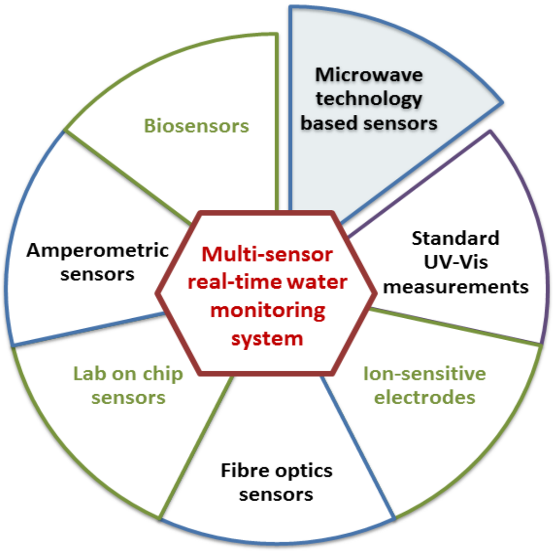

Fig. 3. Components of an ideal multi-sensor real-time water monitoring system.

Such a system should be portable and would have to satisfy a broad range of requirements, including robustness and cost-effectiveness of the sensors; long battery life, which will depend on the sensors type and monitoring frequency; data should be gathered in real-time from remote locations to a central server, where they will be processed, presented and communicated instantly, even by e-mail or SMS [17], if for example a set threshold of any water pollutant is exceeded. This will also help with mapping the spatial and temporal distribution of pollutants and may be of particular importance in identifying sources of water contamination.

Summary

Currently it is not possible to achieve adequate simultaneous detection of different water parameters by using only one type of sensor. The proposed solution is to merge various technologies into a single system that would employ the best available methods for the real-time detection of specific water contaminants, providing overall superior sensitivity, selectivity and long-term stability. Importantly, a special role is reserved for microwave technology based sensors – a missing piece in the puzzle to potentially solve the issue of real-time water quality control.

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