Optical Fiber Sensors for Water Quality Monitoring (Summary)

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"A clear liquid, without colour or taste, that falls from the sky as rain and is necessary for animal and plant life" - **Cambridge Dictionary**

"A liquid without colour, smell or taste that falls as rain, is in lakes, rivers and seas, and is used for drinking, washing, etc." - **Oxford Dictionary**

These are the definitions of **water** according to the two main English language dictionaries, Cambridge and Oxford. Yet water in our lives is much more than that. Even though 75% of the Earth's surface is covered by water, only 3% of that water is the one which is used for our lives. In 2015 United Nations (UN) have prepared a list of 17 sustainable development goals to be achieved within 2030 and "Clean water and Sanitation" is the sixth in line. Actually, almost all the other 16 goals are somehow directly or indirectly related to water. For instance, *no. 2. Zero Hunger* and *no. 3. Good Health and Well-being* are directly related to the clean water situation on Earth.

It is clear that the world needs to develop in a sustainable way, as facts show that earth resources are not limitless, quite the opposite they are limited and require to be taken care of. Water is one of those resources, which, while for first world countries is almost taken for granted and quite often misused, for under-developed and developing countries it might even be considered a luxury. Indeed, ensuring availability and sustainable management of water and sanitation for all is the objective of the cited SDG6 (Sustainable Development Goal n.6). As a matter of fact 2.2 billion people lack access to safely managed drinking water services while over half of the global population - 4.2 billion people - lack safely managed sanitation services. Among these people 297,000 children under five die every year from diarrhoeal diseases due to poor sanitation, poor hygiene, or unsafe drinking water [4]. The numbers are outrageous and call for immediate action. Five years have already passed since the sustainable goals have been set and a lot of work has to be done in the next ten years in order for the SDG6 to be considered a success before the deadline.

Based on the above mentioned facts, lack of water is not the only problem people are facing. Most of them (more than half of the world population) lack water quality assurance. Quality is a relative parameter, which needs to be quantified according to the specific application. Definitely, when it comes to human consumption the quality is more important than for agricultural and industrial applications. Actually, when talking about industry and water, mainly the focus is put on the waste waters released by the industry in the environment and how they are impacting the global water management. Despite the importance of water, the use policies and the treatment and quality assurance processes are typically managed by local communities, as the administrative responsibility. In particular, much of water quality depends on the choices made by the local institutions, the communities and sometimes the final consumers at their houses. Moreover, industries have to take care of waste water treatment themselves before the release into the environment. As a result local institutions analyze water periodically but there exists no unique global agreement, likewise no database of the water quality and treatment worldwide. [3]. Actually, the World Health Organization (WHO) has released guidelines for the drinking water quality, but it is the responsibility of local authorities to follow such guidelines [2].

It is important at this point to briefly analyze how the water quality management process works. In order to assure the quality of the distributed water, responsible institutions sample the water in different parts of the distributing system periodically, transport it to the laboratory, perform the tests, analyze the data and report them. The sampling and transportation process are quite critical parts of the process as it must be guaranteed that the sample represents the water it was taken from, maintaining at least the specific properties that are supposed to be analyzed [3]. The most common tests that the samples undergo are chemical (heavy metal ion concentration, ammonia, chloride etc.), bacteriological tests, radiological and acceptability tests (odor, taste, color). How about Countries or cities where the water distribution system is not well established? Where there is no continuous water supply, or where the network has losses (leakage) and abusive intrusions? These kind of systems are characterized by unexpected events that might interrupt the water flow or contaminate it. In such cases the authorities can assure the quality of water only at some key points of the system, but it is impossible to guarantee the quality at the final consumer. Considering the random variations typical of discontinuous service cases, sampling and analyzing periodically does not help and the tragic numbers regarding the diseases and deaths caused by contaminated water reported above confirm the critical importance of assuring a constant water quality. The immediate solution to these problem could be to monitor the water quality in real time and in a distributed way to prevent people from consuming the water in case of unforeseen hazardous circumstances. This requires low cost devices suitable for being installed as close to the final consumer as possible, possibly at each household.

Refractive Index - Universal Parameter

At first sight it looks quite impossible to analyze the water in a distributed manner in real time. Of course it is not feasible if we aim to quantify the same amount of parameters as with their respective existing method. Nonetheless, in this dissertation we will discuss the first steps towards a real time water quality monitoring device based on the refractive index (RI) of water. Refractive index is a unitless parameter which defines the refraction of light when light hits a dielectric. In case of liquids the RI is a parameter which is prone to sense any chemical or physical modification in the composition. The first refractometer has been designed by Ernst Abbe and has been produced by Carl Zeiss in the end of 19th century and since then has found numerous applications in different application fields [1]. Nevertheless, most of the prism based refractometers nowadays exploit still the exact same principle (critical angle determination) as Abbe's refractometer.

In this work we will present an optical fiber based refractometer able to perform continuous real time monitoring. We believe that optical fibers' exceptional features can perfectly go along with the water analysis application. It is clear that one sensor regardless of how magnificent it can be it will hardly be able to substitute the long procedure of water quality assurance. Nevertheless we believe that a real time, high efficient refractometer can be a nice companion (non substitute) to the other existing tests (in developed countries), and a necessary low cost 'rising alert' instrument where other regular tests are impossible to be done (under developed countries). Optical Fibers have some really outstanding properties which make them favorable option when it comes to minimally invasive, real time and in harsh environment measurements. They are small size, made in silica glass, immune to electromagnetic disturbances, resistant to extreme temperatures, and moreover have a relatively low cost per unit.

We have chosen to exploit a fancy physical phenomenon called surface plasmon resonance (SPR) for our fiber base refractometer, as it promises high sensitivity and high resolution compared to other setups with similar purpose. Still the biggest part of this work is focused on the characterization of the SPR phenomenon in metrological terms. Along the chapters we will try to answer some questions we thought are really relevant in order to know better the system and possibly bring it one step closer to a commercial level. - Is the phenomenon really that sensitive as the theory suggests? - What are the factors that determine its detection limits? - How does the sensor behave in long terms? - Is it suitable to perform continuous real time measurements? - Which are the weak points that need to be overcome?

Temperature and Flow Rate

While studying the plasmonic OF refractometer we noticed the necessity of temperature compensation in such sensors. In order to keep the setup fully optical we have studied the alternatives for OF based thermometers, Apart from the compensation necessity of the plasmonic sensor, temperature is a very important parameter for the potable water. Long exposure to high temperatures favors micro-biological flora, creating optimal conditions for undesired bacteria, thus a real time temperature monitoring of the water is always welcomed. In this thesis we present an SMS (single mode - multi mode - single mode) OF sensor based on interference between first two fundamental modes of a MM fiber section which has a sensitivity five times higher than FBG (Fiber Bragg Gratings), the most common OF based temperature sensors. With slight modifications on the configuration setup we have shown the exploitability of this phenomenon to create a flow meter with working principle similar to a hot wire anemometer. Knowing the real time flow rate or velocity of the flowing water in the distribution system would be very appreciated as well, especially in the cases where the distribution system has undergone interventions, might have losses, or has interruptions. However the study of the flow sensor is limited to a proof of concept level. The sensor is tested in different temperature regimes analyzing its sensitivity and then tested at constant air flow to prove the anemometer concept.

Thesis Outline

This summary can be read also in the Introduction chapter of the final thesis. After the brief introduction focused on the motivation and the scope of this work, the dissertation continues with **Chapter 2**, covering a short theoretical background of the SPR phenomenon and how it is implemented in optical fiber setups discussing the most common configurations. It continues with the **Chapter 3** focused on the mathematical model of the SPR phenomenon and on the simulation of the plausible design configurations, analyzing the key quality parameters. The last section of this chapter discusses the possibility of adding an extra silica layer, which apart from playing a protective role, it also enhances the quality of the OFSPR sensors. **Chapter 4** describes the main aspects of experimental work which is carried out in the photonics laboratory and measurements laboratory of the Polytechnic University of Turin. The experiments are focused mainly in characterizing the OFPSR sensors in different configurations, making a cost-performance analysis. The fifth **Chapter 5** of this dissertation is dedicated to the work regarding the SMS (single mode - multi mode - single mode) optical fiber sensor exploited as an hot wire anemometer to measure the flow rate of fluids. The chapter covers the full topic, starting with a brief theoretical explanation of the phenomenon, continuing with the simulations done in Matlab and ends with the experimental work and results. The thesis concludes with the traditional chapter **Ch. 6 - Conclusions**, a short recap deducting the main aspects of this project and what the reader should keep in mind in case of interest to develop further the project.

In the appendices the reader can find valuable information about the sensor fabrication process (**Appendix A**) and the key aspects that need to be taken in consideration in case the procedure needs to be replicated or improved in the future; The fabricated sensors experimental characteristics and SPR curves (**Appendix B**); and the most important matlab codes exploited for the simulations of the OFSPRs (**Appendix C**).

References

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