Combined optical water quality monitoring and sanitization system

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ABSTRACT

The paper presents the realization of a prototype of a compact, cost-effective, and real-time photonic system for the early detection of quality variations in flowing water and for its sanitization. The detection is based on a multi-functional fiber Surface Plasmon Resonance (SPR) sensor, while the disinfection is obtained with a combination of short-wavelength light in the UV-blue region.

Keywords: UV-C disinfection, Water quality monitoring, Plasmonic sensors, Germicidal action of light.

1. INTRODUCTION

Safe water for everybody is one the UN 2035 Sustainable Development Goals (SDGs), but still millions of people die every year due to waterborne diseases.[1,2] The situation is further aggravated by the ongoing climate change for which freshwater is becoming a scarce resource not only in areas known for their endemic scarcity, but practically everywhere in the world. Moreover, in many countries existing water sources are increasingly threatened by poorly treated industrial wastes and by the residues of fertilizers and pesticides. Quite a large number of initiatives has been undertaken to control the water quality, but their wide adoption is mainly hampered by installation and maintenance costs of available water quality monitoring systems and by the difficulty in their ubiquitous deployment.[3]

All this calls for the development of new cost-effective approaches for giving broader access to clean freshwater; in turn, among other things, this implies the availability of new continuous, real-time, and environment friendly methods to detect pathogenic conditions and counteract them. Indeed, today commonly used water treatment systems do not satisfy these requirements because the analysis is based on periodic sampling (hence not continuous) and long-lasting analysis processes (bringing of the samples to remote labs, hence not real-time) and the disinfection is through the addition of chemicals (hence not environment friendly).

Light, instead, constitutes a valid alternative for both actions. The paper presents the realization of a prototype of a compact, cost-effective, and real-time photonic system for the early detection of quality variations in flowing water and for its sanitization if necessary. The monitoring is based on multi-functional fiber Surface Plasmon Resonance (SPR) sensors that, when embedded into pipes, continuously measure some indicators of the water quality deterioration, most notably variations in the refractive index. The sensor interrogation uses a low-cost setup to allow the widespread use of the device and the disinfection is based on the combination of LEDs emitting in the UV-blue region. The use of UV, specifically UV-C, for sanitization is rapidly growing because it is effective without requiring the addition of chemical and generating harmful byproducts. The combination with blue light can further improve the outcome in some situations.

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2. MONITORING SYSTEM

Surface Plasmon Resonance (SPR) is well-known to be one of the elective optical phenomena that can be exploited to build high sensitivity devices for the detection of chemicals, which are used not only at the research level, but also in commercial lab instruments.[4–6] The challenge is to transfer this approach into a low-cost, affordable, and sensitive enough device to enable its wide deployment.

SPR is a phenomenon that occurs, for p-polarized light waves only, at the interface between two materials where the permittivity has opposite sign, like a dielectric and a thin metal deposited on it, and when the wave vector of the incident light is exactly equal to the wave vector of the surface plasmon mode at the metal-dielectric interface. The excited surface electromagnetic wave is characterized by a complex propagation constant that is very sensitive to the refractive index of the dielectric. This results in notch-like behavior, with a sharp dip in the transmission spectrum at wavelength that depends on the refractive index of the dielectric in contact with the metal, the analyte. Despite the most common implementation of such approach is with bulk components in the form of prisms, fiber sensors (the OFSPR) can be developed as well and many examples have been reported in the literature.[7,8] Considering an optical fiber (glass, $n_g \approx 1.45$) covered by a thin layer of gold surrounded by water ($n_d \approx 1.33$), the interaction point (i.e., the wavelength at which the reflectivity dip can be seen) is at 615 nm. Plain SPR-based sensors do not allow distinguishing the the cause of the refractive index variation; however, a specific selectivity can be obtained by properly functionalizing the metal surface.[9]

Working with OFSPR sensors brings several advantages, such as a higher mechanical stability and, most notably, the possibility of embedding the probe in pipes with a reduced invasive impact. Besides, it simplifies the use of both the wavelength interrogation method and the intensity interrogation method for the detection. Fig. 1 presents a graphical representation of these two interrogation methods.

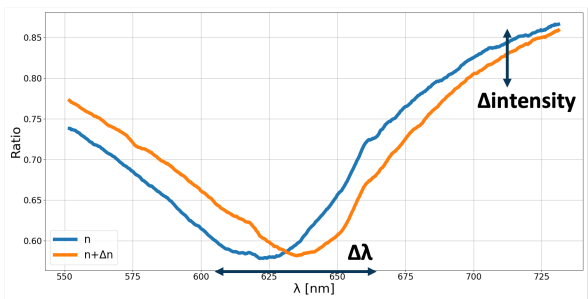

Figure 1. Typical SPR response for two different analytes with highlighted the principle exploited in intensity and wavelength interrogation methods.

The wavelength interrogation method is quite expensive (at least compared to electro-chemical sensors, which could be the closest competing alternative) because it requires a broadband (polychromatic) light source at one end of the fiber sensor and a spectrometer at the opposite end. The advantage of such a configuration is that the shift of the dip caused by a variation in the refractive index is recovered by fitting the entire spectral response and therefore it can be evaluated with high accuracy and pollutants with a lower than part-per-million (ppm) concentration can be measured.

The intensity interrogation method, instead, relies on the measure of a variation of the measured intensity at a suitable wavelength. Its implementation is simplified and more economic since it requires only a LED light source at a proper wavelength and a photodiode. The downside is that it is more sensitive to noise, source wavelength drifts, or any attenuation along the fiber. This limits the accuracy to some tens or even hundreds of ppm. A partial mitigation of the high sensitivity to noise can be obtained by using the readings obtained at two wavelengths.

In any case, regardless of the interrogation approach, SPR sensors require also a temperature compensation mechanism, because a change in the temperature can be erroneously read as a change in the refractive index of the analyte.[10] In a OFSPR sensor the temperature monitoring can be done either with an all-optical approach, such

as with Fiber Bragg Gratings (FBGs) or Single-Mode-Multimode (SMS) interferometer, or with electrical sensors, such as with thermistors.[11,12] The all-optical solution allows the fabrication of a fully dielectric probe, with the inherent advantages of such solution (for example, immunity to electromagnetic discharges or perturbations), but the interrogation system is more expensive, unless the OFSPR is interrogated using the wavelength interrogation method in which case the same spectrometer can be used both for sensors types. On the contrary, a thermistor can be the preferred choice in the case of the intensity interrogation method because it can be read by the same acquisition board also used for the photodiode.

Aiming at developing a low-cost system for a preliminary detection of possible generic pollutants into water, the sensor here presented is based on SPR without functionalizations. The sensor has been fabricated by depositing a titanium adhesion layer followed by a gold layer on the core of a 400 µm fiber.[13] The choice of a large fiber is to simplify the coupling with the source, which in this version is made by a single LED emitting at 660 nm. The sensor is coupled to a photodiode followed by a transimpedance amplifier so that a variation in the analyte refractive index is converted into a variation of a voltage according to the intensity interrogation method.

3. DISINFECTION

The sanitization of water is mainly obtained through chemicals, although this approach presents several drawbacks, such as the alteration of the odor and taste of the water and the generation of by-products that are sometimes toxic or carcinogenic to humans, not to mention the increasing bacterial resistance to disinfectants. Short-wavelength light can provide a more environmental friendly alternative. The sanitization effects of UV radiation, in particular of the so-called UVC (200 nm to 280 nm), have been known for decades. However, while until few years ago the UVC sources were practically only mercury vapor lamps, driven also by the revolution in the illumination, in recent years the elective sources have become the LEDs, with all the advantages in terms of flexibility of use and lower energy consumption. UVC are particularly effective for the disinfection because the wavelengths between 250 nm and 270 nm are highly absorbed by the nucleic acid of microbes.[14] Blue light has also disinfection properties, especially in the form of Antimicrobial Blue Light Therapy (aBLT), which is a specific type of Antimicrobial PhotoDynamic Therapy (aPDT).[?]

Aiming at developing a low-cost and flexible system, albeit highly effective in the disinfection, the sanitization tool chosen for it and here presented is based on the application of a combination of UVC and blue LEDs. The required power density depends not only on type of the pathogen, but also on the water flow. In the application considered in this paper only the case of *Escherichia Coli* has been considered; then assuming a water flow rate of about 10 m/ min, a typical value of common taps, this translates into the requirement of guaranteeing an energy density of 10 mJ/cm^2. This has been obtained with three LEDs arranged at 120° around the circumference of the pipe.

The effectivity of the disinfection action has been verified using specific contact slide made by a growth medium with selected nutrients specific for Enterobacteriaceae coated onto a plastic support. The number of colonies and the bacterial abatement between the control samples and the sanitized ones can be evaluated after incubation for a period of 24 hours at 37 degree.

4. RESULTS

The validation of the combined monitoring and sanitizing system has been done in two steps: first, the two sub-systems have been calibrated and assessed separately; then, the full system has been used in an experiment using the water taken from a lake in Italy.

The monitoring sub-system has been preliminary calibrated using water-alcohol solutions, comparing its reading with those of a commercial refractometer. After the calibration, some tests with water samples purposely contaminated with biological wastes containing *E. Coli* have been done to assess the capability to distinguish the contaminated and un-contaminated water samples. At the same time the contaminated water samples have been used to assess the disinfection capabilities of the sanitization sub-system.

The final experiment has been carried out with water samples from a lake in Piedmont, North-West of Italy. Fig. 2 reports the reading from the sensing sub-system in which the three curves have the following meaning:

- Control: 400 mL of water as taken from the lake;
- Diluted control: 400 mL of water as taken from the lake diluted in 1600 mL of tap water;
- Sanitized water: the "Diluted control" after disinfection with the sanitization device.

The voltage output value must be intended as arbitrary since it depends on the transimpedance amplifier gain, on the interrogator source power, and on the source-sensor-detector coupling losses.

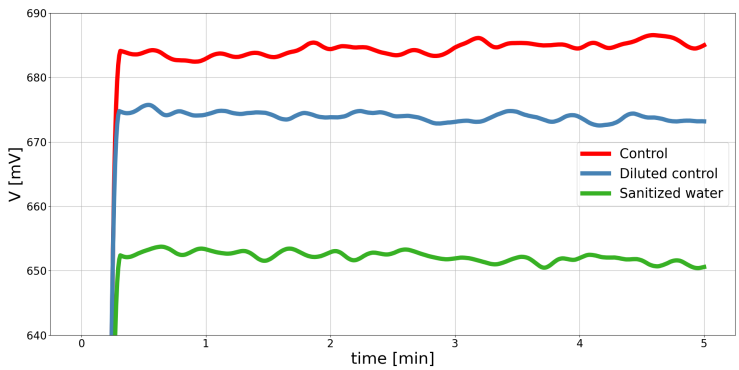

Figure 2. Readings from the water monitoring sub-system when exposed to water samples from a lake in the North-West of Italy before and after the sanitization.

Each acquisition lasted 5 min in which the sensor has been exposed to the same water sample. The acquisitions have been filtered by a FIR filter with a sample rate of = 50 and a cutoff frequency of 0.1 Hz. Then, since the developed sensor include a thermistor to compensate for the temperature induced errors, all the acquisitions reported in Fig. 2 are compensated in temperature. The importance of this compensation and the impact of the temperature can be better appreciated from the plot in Fig. 3 in which the variation in the output voltage with temperature for a constant refractive index solution is shown.

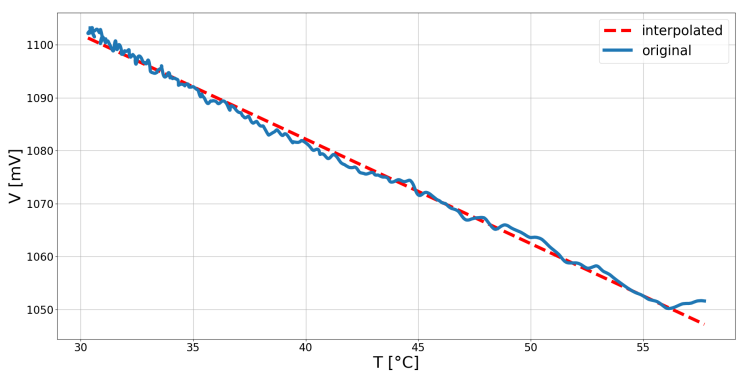

Figure 3. Sensor output voltage as a function of the temperature.

The three curves in Fig. 2 clearly show that the monitoring system is capable of distinguishing the three different conditions of the examined water samples. This result has to be complemented with those from the disinfection sub-system: the results of the contact slides after 24h of incubation are reported in Fig. 4 and demonstrate that a bacterial abatement of the sanitized sample with respect to the diluted control larger than 96% has been achieved.

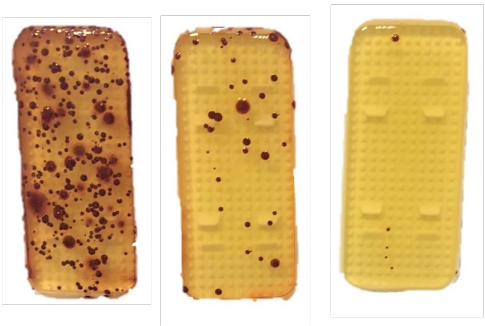

Figure 4. Contact slides exposed to the three water samples taken from a lake after 24h of incubation: from left to right, control, diluted control, and sanitized samples.

5. CONCLUSIONS

A combined water quality monitoring and sanitization system has been developed, characterized, and then validated in a real application with water samples taken from a lake. The sensing part exploit a fiber optic implementation of the SPR principle, interrogated with a low-cost setup; the obtained results show that, despite its simplicity, the obtained sensitivity is enough to distinguish the water before and after sanitization. The disinfection part relies on a combination of UVC and blue LEDs and has been designed to introduce an abatement larger that 90% in flowing water from a common tap found in domestic appliances. Its effectivity has been tested with contact slides so far specific for the *E. Coli* only; nevertheless this is a representative test because these bacteria are known for being quite resistant to light disinfection.

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