

# Fiber Bragg Grating Multifunctional pH Sensor for Monitoring the rain in Cultural Heritage

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**Abstract** – A new era of pollution requires an important focus on the conservation of archaeological sites and monuments. During the last decades, there has been a rising interest in the development of sensors based on optical fibers for several applications, including chemical sensing [1]. An innovative new fiber optic sensor that combines Fiber Bragg Gratings (FBG) coated with pH responsive polymers for monitoring the pH of the rains on critical and prestigious monuments is proposed. In this study the setup arrangement of the optical sensor is modeled by our own FEM code. Monitoring the pH of the water can be used by experts to predict and control the corrosion phenomenon of specific materials, especially limestone and marble, and thus scheduling the timely restoration.

## I. INTRODUCTION

Over the years, the “acid rains” damage monuments and other ancient artworks, destroying the historical and cultural heritage of many countries much faster. Acid rains favor metal corrosion and the destruction of monuments resulting in loss of mechanical strength and compactness, causing a partial dissolution of the materials themselves. The corrosion of different materials cannot be prevented without a continuous monitoring of the rain’s pH. Nowadays the catastrophic effects of the polluted rain are addressed merely with restoration after visible damages. With an innovative monitoring procedure of the pH of the water, maintenance and restoration programs can easily be set depending on the chemical features of the rains over the years. Monitoring the pH can also help to forecast the possible predictable damages for the different materials in order to preserve the original status of the artworks.

The main enemy for the artworks is the acidity of the acid rain. Normal rain is not neutral like pure water but is slightly acidic at around 5.6 pH or lower. Industrial areas have registered acidity of the rain below a pH value of 2.4. Rainwater becomes weakly acidic because carbon

dioxide gas in the atmosphere reacts with water to form carbonic acid. Then the rainwater increases the acidity even more, mixing with sulfur oxide and nitrogen oxide molecules, as result of industrial pollution and automobile exhaust.

Fiber Bragg Grating sensors coated with pH sensitive Hydrogel have been studied, providing a linear response in pH range of 5 to 7 with a sensitivity of 0.114 nm/pH unit [2,3]. Optical pH sensors have advantages compared to the conventional pH sensors being free from electromagnetic interference, wide bandwidth, feasibility of miniaturization, real-time measurement and possibility of remote sensing [4-6].

The outstanding innovation of this paper is to monitor the pH of the water for the artworks point by point in real time. The actual pH of the water, resulting from the mixing of calcium carbonate and calcium-based compounds, coming from limestone and marble, with acid rain can be discovered.

The acidity of the water that attacks the statues and ancient buildings is surely worse than the normal rain causing enormous damages without control. This technique allows monitoring small and critical areas like an elbow or an inner thigh of a statue.

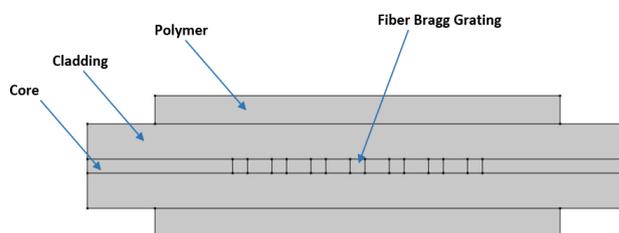


Fig. 1. Schematic drawing of polymer-coated Fiber Bragg Grating pH sensor.

The pH sensor suffers from some limitations due to temperature and bending cross-sensitivities [7] that will

be assumed to be constant and negligible respectively. This assumption does not seem to be too heavy, as there is a wide variety of compensation techniques for such variables. The accuracy of the sensor is also affected by the multiple resonance peaks and the vast transmission resonance [7]. One of the main advantages of the Fiber Bragg Grating coated with Hydrogel is that the sensed information is encoded directly into wavelength, providing an outcome independent of the intensity of the input light and the loss along the optical system [7].

The device can be split into two sensors, one using a pH sensitive polymer with an acidic group and the other with a polymer with a basic group. In contact with certain pH values, the polymers acquire a charge, become ionized, causing a modification for the length of the Fiber Bragg Grating. The configuration of the device could be composed of two Fiber Bragg Grating sensors to detect the variations both acidic and basic.

A further strength of the device is the dimension. The developed sensor has a length of 10 mm. The small size allows the sensor to be located on almost unreachable artwork elements for pH monitoring.

## II. MATERIALS AND METHODS

The fiber optic sensor is formed by layers of alternating materials with different refractive indices as shown in the schematic in Figure 1. Each layer boundary causes a partial reflection of the incident optical wave. The pH responsive polymers respond to the changes in the pH of the surrounding water by having a volumetric variation. The expansion of the polymer coating causes a strain on the fiber modifying the Bragg Grating period that results in a shift in resonant Bragg wavelength and thus in the sensor response. Peak reflectance is achieved with a design wavelength  $\lambda_0$  when the configuration of Bragg Grating provides constructive interference between reflections. This is reached when the Bragg condition is satisfied:

$$\lambda_0 = 2 n_{eff} \Lambda \quad (1)$$

where  $n_{eff}$  is the effective refractive index of the optical fiber and  $\Lambda$  is the grating period. The Bragg wavelength is set to 550 nm, because average wavelength of the visible spectrum. Achieving the Bragg condition requires layer thicknesses of:

$$t_i = \lambda_0 / 4n_i \quad (2)$$

where  $n_i$  is the refractive index of the i-th layer.

The model is studied with 5, 11 and 21 layers of the distributed Bragg Grating, showing the different response of the sensor. The Fiber Bragg Grating is constituted by two different dielectric materials, chosen in this study with 2.32 and 1.38 as refractive index; air and substrate form the core of the sensor outside the FBG with

refractive index 1 and 1.5 respectively. The polymer is assumed to coat the sensor for the length of 10 mm. The change in pH determines a mechanical expansion of the Hydrogel that stretches the dimension of the alternating material layers. The change of the layer's thicknesses creates a shift in the Bragg wavelength. The pH range between 4 and 7.1 is considered to show the performance of the sensor. The percentage reflectance and the wavelength shift are analyzed to provide estimation of efficiency and sensitivity in the measuring range.

In the study both a 2-D and a 3-D geometry were analyzed. The planar technology has been chosen to adapt the FBG to the examined surfaces for the synthesis of the device. The cladding material and the Bragg grating will be deposited by using the standard micro-electronic processes on two different polymer substrates, making two identical samples; finally, the two surfaces will be bonded achieving the final structure.

## III. RESULTS

In order to validate the measurement system, we have conducted simulations with our own code based on FEM (Finite Element Method). The grating period  $\Lambda$  is around 158.9 nm and the Bragg wavelength is around 550 nm.

In Figure 2, the simulation results show an evident shift of the wavelength as a function of pH variation in a time period of 0.05 ns. The chart is based on the assumption of having the original length of the sensor for a pH value equal to 4.

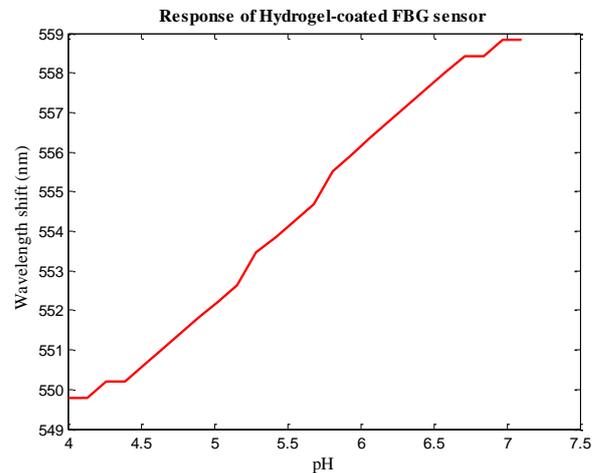


Fig. 2. Response of a Fiber Bragg Grating coated with Hydrogel as a function of pH.

It is observed that the shift in the wavelength presents a growing behaviour, approximately linear, when the pH increases from 4 up to 7.1.

As expected, the wavelength shift showed in Figure 2 is identical for the three scenarios with number of layers of 5, 11 and 21 for FBG. The shift in the peak of

the wavelength is independent of the number of layers in the model.

In Figure 3 is depicted the peak of the percentage reflection in the range of pH, 4–7.1. Increasing the number of layers from 5 to 21 results in an increase of the reflectance of the initial light intensity, while maintaining the same pattern. As shown in Figure 3 the reflectance peak of the sensor when 21 layers are considered is higher than 99.99%, reaching almost the total reflection.

As is depicted in Figure 3 the higher is the number of layers in the sensor and the narrower is the range of the reflectance where the peak values will fall.

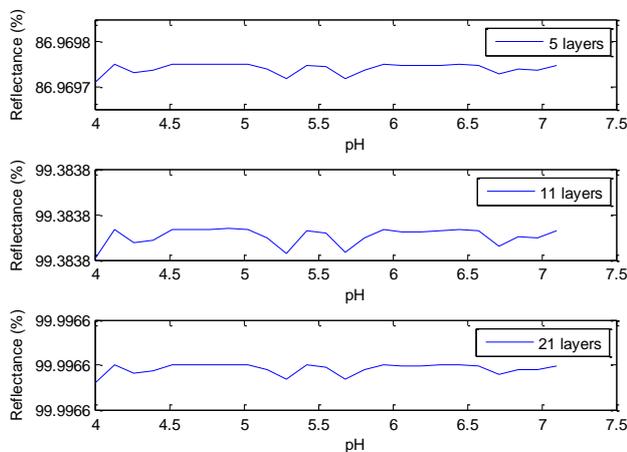


Fig. 3. Trend of the peak of percentage reflectance of the distributed Bragg Grating in the range of pH 4 – 7.1 for number of layers 5, 11 and 21.

In the Figure 4 is depicted the response of the distributed Bragg Grating for the different number of layers 5, 11 and 21, for the pH values under study. In the three scenarios, a beam reflectance is achieved because the response of the Bragg Grating for different strain of hydrogel is showed. The beam shape for the curves is the result of the wavelength shift in the pH range, where the increase of pH shifts the wavelength to higher values.

Figure 4 illustrates that the response of the distributed Bragg Grating in the pH range 4-7.1 shows a narrower reflectance range with higher number of layers in the FBG for vacuum wavelength.

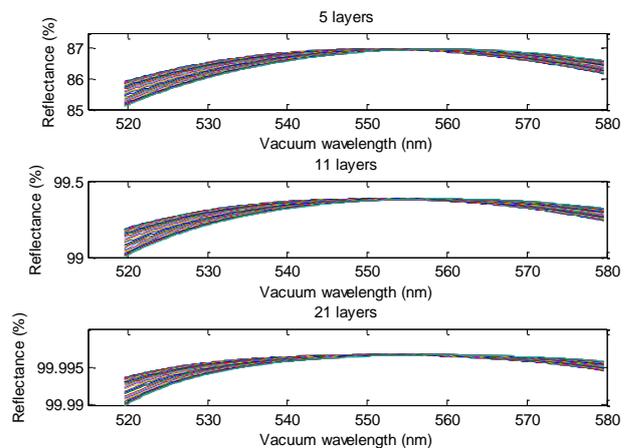


Fig. 4. Response of the distributed Bragg Grating for all the strain of the Hydrogel in the range of pH 4–7.1 for number of layers 5, 11 and 21.

Concluding, the FBG pH sensor coated with hydrogel has been devised exploiting the hydrogel swelling as a result of the change of surrounding pH in a time interval and its mechanical effect on the FBG.

#### IV. DISCUSSION

In this work, an innovative system has been presented in order to determine the pH value of the rain. The advantage of forecasting the corrosion of monuments is putting optimal restoration programs in place. These are also depending on the materials under analysis and can have an important impact in terms of cost reduction and higher maintenance efficiency.

The parameter temperature will also be taken into account for the next generation of FBG pH sensors.

Moreover this sensor for the future developments will be integrated with the optical ring resonator in order to improve its performances.

#### V. CONCLUSION

As conclusions, modeling the hydrogel coated FBG pH sensor for monitoring the rain in archaeology and in cultural heritage provided innovative results in terms of high sensitivity and small dimensions of the device. The sensitivity of the sensor as can be confirmed in Figure 2 is around 2.91 nm/pH.

#### REFERENCES

- [1] M. Debligny, J.-M. Renoirt, C. Caucheteur, P. Mégret, and M.-G. Olivier, "pH sensor based on tilted fiber Bragg gratings covered by a sol-gel," IMCS 2012 – The 14th International Meeting on Chemical Sensors, 2012.
- [2] I. Yulianti, A.S.M. Supa'at, S.M. Idrus, N.M.

- Kassim, and A.M. Al-hetar, "Fiber Bragg grating based pH sensor," *Enabling Science and Nanotechnology (ESciNano), International Conference on*, 2010.
- [3] I. Yulianti, A.S.M. Supa'at, and S.M. Idrus, "Characterization of fiber Bragg grating sensor for pH measurement," *Advanced Intelligent Mechatronics (AIM), IEEE/ASME International Conference on*, 2014.
- [4] V.N.K. Pabbiseti and S.S. Madhuvarasu, "Hydrogel-coated fiber Bragg grating sensor for pH monitoring," *Optical Engineering*, Vol. 55, No. 6, 2016.
- [5] M.F. Md Jaafar, H.M. Saman, M.N.M. Sidek, "Simultaneous Monitoring on Corrosion-pH-Temperature using Multiplexed Fiber Bragg Grating Sensors Techniques in New RC Structure: A Review," *International Journal of Civil Engineering and Geo-Environmental*, 2013.
- [6] L.Y. Shao, M.J. Yin, H.Y. Tam, and J. Albert, "Fiber Optic pH Sensor with Self-Assembled Polymer Multilayer Nanocoatings," *Sensors*, Vol. 13, pp. 1425-1434, 2013.
- [7] I. Yulianti, A.S.M. Supa'at, S.M. Idrus, O. Kurdi, and M.R.S. Anwar, "Modeling of Hydrogel Coated Fiber Bragg Grating pH Sensor," *International Journal of Information and Electronics Engineering*, Vol. 3, No. 3, 2013.