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Highly sensitive fiber grating chemical sensors: An effective alternative to atomic absorption spectroscopy

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ABSTRACT

Accuracy in quantitative determination of trace elements like Zinc, present in drinking water in ppm level, is a big challenge and optical fiber gratings as chemical sensors may provide a promising solution to overcome the same. This paper presents design of two simple chemical sensors based on the principle of shift in characteristic wavelength of gratings with change in their effective refractive index, to measure the concentration of Zinc in drinking water using etched short period grating (FBG) and Long period grating (LPG) respectively. Three samples of drinking water from different places have been examined for presence of Zinc. Further, the results obtained by our sensors have also been verified with the results obtained by a standard method, Atomic absorption spectroscopy (AAS). The whole experiment has been performed by fixing the fibers in a horizontal position with the sensor regions at the center of the fibers, making it less prone to disturbance and breaking. The sensitivity of LPG sensor is about 205 times that of the FBG sensor. A few advantages of Fiber grating sensors, besides their regular features, over AAS have also been discussed, that make our sensors potential alternatives for existing techniques in determination of trace elements in drinking water.

1. Introduction

Zinc (Zn) is an important dietary component in human beings and animals. Human beings obtain the required amount of Zn through food and water. Natural water contains very small concentration of Zn but domestic water supply may get contaminated due to Zn entering into it from deterioration of galvanized iron and dezincification of brass [1,2]. Industrial and household waste containing Zn, through leakages in sewage systems, discharge into water sources and cause severe pollution in surface and underground water [3]. Due to leaching of Zn from piping and fittings, tap water has shown higher concentration of Zn [4,5] and in certain circumstances, found to have 10% contribution to the overall Zn intake in humans [6,7] . Wells also have been reported to have high concentration of Zn [5,6]. Although not considered hazardous, overdose of Zinc may cause nausea, vomiting, dizziness, colics, feverand diarrhea in human beings and if it exceeds a certain limit it may also prove to be toxic. Drinking water containing Zn at levels above 3 mg/litre tends to be opalescent, develops a greasy film when boiled, and has an undesirable astringent taste [5,8]. According to WHO and United States Environmental Protection Agency the maximum permissible concentration of Zn in drinking water is 3–5 ppm [5,9]. Thus, examining concentration of Zinc in drinking water accurately is essential to make it potable.

The most widely used methods of Zinc determination in drinking water are Atomic absorption spectroscopy (AAS) and inductively coupled plasma(ICP) methods. Some other methods used are Dithizone method I and the zincon method. However, all these methods are spectroscopic methods requiring costly and huge equipments and need proper sampling and storage [10]. They also have their limitations when concentration to be measured is in ppm level. Optical Fiber grating(OFG) sensors may provide a good option as highly sensitive chemical sensors in determining the concentration of trace elements in water.

OFGs are of two types, Short period Fiber Bragg Gratings (FBG) and Long period Gratings (LPG). Both FBG and LPG sensors have already made a mark in the field of research for measurement of parameters like strain, pressure and temperature. There are a few research papers that report the use of etched FBGs and LPGs in the

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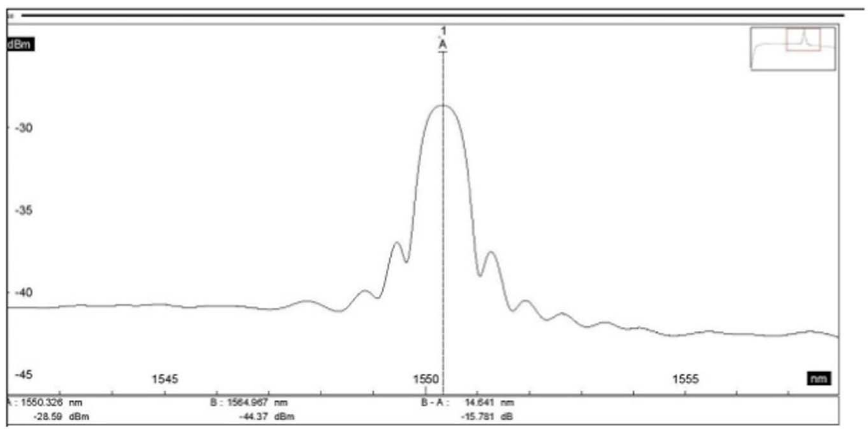

Fig. 1. FBG characteristic wavelength in air (Fiber trace viewer).

measurement of refractive index of liquids and also as chemical sensors [11–13]. Measurements of concentrations of Cadmium and Chloride ions in water have been reported using FBG and LPG respectively [12,14]. A large number of advantages of OFGs over traditional sensors like their small size, immunity to electromagnetic radiations, higher sensitivity and possibility of on line observation at remote places make Optical Fiber Gratings a suitable and favorable candidate as a chemical sensor [13,15].

In this paper, we have designed an FBG and an LPG chemical sensor to determine Zinc concentration at ppm level in drinking water samples. A comparative study has been made regarding their performances and sensitivities. Further, the results of our designed sensors have been compared with the results of AAS, a standard method for the purpose.

1.1. Principle of FBG, LPG techniques

FBG and LPG are intrinsic fiber optic devices which have a periodic modulation in their refractive index (RI) in the fiber core. These gratings are photo-induced on the core of a photosensitive single mode fiber by exposing it to UV light. Most widely used methods for fabrication of gratings are phase mask method and point by point method for FBG and LPG respectively. The periodicity of RI modulation in FBG is less than 100 µm. In FBG, coupling occurs between modes traveling in opposite direction [15,16]. When light consisting of several wavelengths is passed into the FBG, it reflects only a narrow band of wavelengths with a characteristic central wavelength, called the Bragg wavelength which is given by

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where, n_{eff} is the effective refractive index of the fiber core and Λ is the grating pitch. The FBG is made sensitive to the external environment by etching its cladding partially or completely so that the core mode of propagation interacts with the surrounding medium. In an etched FBG, Λ is independent of the external surrounding medium [17,18]. If the concentration of medium surrounding the etched cladding is varied, only the effective refractive index varies, resulting in shift in the Bragg wavelength according to Eq. (1). In LPG, periodicity of RI modulation is greater and in the range 100 µm-1 mm. Here, coupling occurs between fundamental mode propagating in the core and forward propagating cladding modes which produces a series of attenuation bands in the fiber transmission spectrum due to the rapid attenuation of the cladding mode in the fiber, when the following phase matching condition is satisfied [14,19].

$$\beta_o - \beta_{cl}^i = \frac{2\pi}{\Lambda}. \qquad (2)$$

Where $\boldsymbol{\beta_o}$ and β_{cl}^i are propagation constants of fundamental core mode and the i^{th} cladding mode of the fiber respectively and Λ is the pitch of the grating. The central wavelength of each attenuation band is given by

$$\lambda_i = (n_{co} - n_{cl}^i)\Lambda \qquad (3)$$

Where $\boldsymbol{\lambda_i}$ is the peak wavelength of the resonance band due to coupling of the core mode and i^{th} cladding mode, n_{co} and n_{cl}^i are the effective refractive indices of the core mode and i^{th} cladding mode respectively. When the RI of the surrounding medium changes, only n_{cl}^i changes which results in the shift in the central wavelength of the attenuation band according to Eq. (3). This shift can be related to the concentration of the solution under test surrounding the cladding region since RI is a function of concentration. For small concentrations of the measurand, effective refractive index changes linearly with concentration [20]. Therefore, resonant wavelength $\boldsymbol{\lambda_i}$ in LPG and Bragg wavelength λ_B in FBG vary linearly with concentration. Thus, the principle of etched FBG and LPG lies in the measurement of shift in wavelength by immersing them in solutions of known concentration of element under study and then using the linear relation between wavelength and concentration, in determination of unknown concentration of the element in drinking water samples.

2. Experimental procedure

2.1. Design of FBG sensor and sensor test

FBG used for the experiment was bought from S.A. Technica. The grating, fabricated on SMF-28 fiber has a Bragg wavelength of 1550 nm and a reflectivity of more than 85%. The length of the grating is 10 mm. Fig. 1 shows the reflected spectrum of the FBG used in air. The FBG was etched to remove a part of the cladding region using HF solution. The experimental set-up for etching is shown in Fig. 2. Light from Broadband source (ASE, C-band) was made to pass through FBG and its reflected spectrum was recorded using Optical Spectrum Analyzer (OSA, JDSU-MTS 8000) throughout the etching process. The FBG was mounted horizontally in the narrow groove inscribed in a candle by removing the wax along its length. At the center a deeper groove was

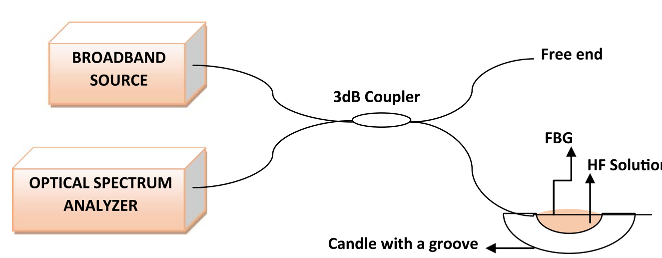

Fig. 2. Experimental setup for FBG etching/Sensor.