Optical Fiber Technology 38 (2017) 136–141

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

Fluoride contamination sensor based on optical fiber grating technology

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ARTICLE INFO

Keywords:
Fiber Bragg grating (FBG)
Fluoride
Optical fiber sensor

ABSTRACT

A number of distinct advantages of the optical fiber technology in the field of sensors and communications which leads to enormous applications. Fiber Bragg grating (FBG) developed from the fabrication of photosensitive fiber through phase mask technique is used in the present report. The designed fiber sensor used for the detection and determination of contaminants in drinking water at ppm & ppb level and it is considered as a special type of concentration sensor. The test samples of drinking water have been collected from different regions. In this paper we have calibrated the FBG sensor to detect Flouride concentration in drinking water in the range of 0.05–8 ppm. According to WHO, the normal range of fluoride content in drinking water is about 0.7 ppm to 1.5 ppm. The results for resultant spectral shifts for test samples are closely agree with standard values.

1. Introduction

Recent years have witnessed an increase in the development of sensors in health monitoring systems [1,2]. One of the main reasons for this increase is adulteration in foodstuff and drinking water that can cause serious health implications. The fiber optic sensor technology is an emerging technique to detect and determine the adulterants or the contaminants in different food items due to its potential applications. Earlier reports have elaborated the application of fiber Bragg grating (FBG) used as chemical sensors, temperature sensors, strain sensors, gas sensors [3–8]. FBG is an excellent sensing element in various applications, as it is highly sensitive due to its inbuilt grating, easy to manufacture with low cost, smaller in dimension and ability to multiplex fiber optic sensors [9–12].

Over one billion of people across the world have less access to safe drinking water. Bottled water and tap water are expected to contain small amounts of some contaminants like arsenic, lead, zinc, chlorine, cadmium and fluoride [13–15]. Moreover, geogenic contamination which is mainly due to the inorganic pollutants like fluoride and arsenic has a negative health effect on humans. Arsenic problems report only 3136 habitations, but fluoride is endemic in 36,988 habitations [16]. The survey suggests that among 25 nations, over 200 million people are under the dreadful fate of florists. India and China are the worst affected countries due to drinking of contaminated water [17,18]. In the present report author concentrates on fluoride contaminant in drinking water.

1.1. Optical fiber grating theory

FBG works on two basic theories (i) Coupled mode theory (ii) Phase matching condition. Coupled mode theory is for quantitative information about the diffraction efficiency and spectral dependence of optical fiber grating.

For the coupled modes, the phase mismatch factor

$$\Delta\beta = \beta_i \pm \beta_d - \frac{2\pi}{\Lambda_g} N\cos\theta \tag{1}$$

where, β_i and β_d are the propagation constants for the incident and diffracted modes respectively. Λ_g is the period of the grating, θ is the grating tilt angle and N represents an integer. It is noteworthy that the " $\pm$ " sign in the above equation describes the case wherein the mode propagates in $\mp z$ direction. Further, it is divided into forward mode coupling and backward mode coupling. In case of backward coupling, the Bragg wavelength of core mode is given by

$$\lambda_B = 2n_{eff}\Lambda \qquad \text{at } \theta = 0 \text{(for normal FBG)} \tag{2}$$

n_{eff} – effective index of mode propagating in the fiber.

Abbreviations: FBG, Fiber Bragg grating; WHO, World Health Organization; EPA, Environmental Protection Agency; ppm, parts per million

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http://dx.doi.org/10.1016/j.yofte.2017.09.014
Received 20 January 2017; Received in revised form 6 September 2017; Accepted 14 September 2017
1068-5200/

Λ – grating period of the refractive index modulation with a form.

$$n(z) = n_{co} + \delta n\{1 + \cos(2\pi z/\Lambda)\} \quad (3)$$

n_{co} – Unexposed core refractive index
δn – Amplitude of the photo-induced index excursion.

Certain structures allow reflection of light, to be coupled from the forward-propagating core mode into backward propagating core mode [19]. In most cases, the FBG acts as a notch filter to block certain wavelengths or as a wavelength-specific reflector. Due to the arrangement of grating or grating formation of fiber, only the light wave satisfying Bragg condition is reflected and the rest is transmitted [20–22]. Generally, FBG is sensitive to variation in the refractive index of its surrounding medium. However, the formation of grating on its core makes it more sensitive and can be used as a sensor to detect even at low concentrations. Bragg grating is formed by the illumination of the core, where the spatial pattern is formed by intense UV light or other light source. The pattern can be formed by different techniques like phase mask, amplitude mask and point by point. The pattern formed on the fiber with respect to the periodic arrangement (grating period) along reflected and transmitted spectrum is as shown in Fig. 1. Earlier, fiber optic sensors for chemical sensing application were extensively developed and reported in the literature. FBG sensor shown more sensitive compare to other existing methods for detection of Zinc, Manganese, Nitrate [23]. FBG as a chemical sensor has a long lifetime, good reproducibility and high sensitivity.

1.2. Fluoride

Fluoride naturally occurs in rocks in many geological environments. Fluorine is an element that does not usually occur in the elemental state in nature because of its high reactivity but occurs as fluoride ion with the oxidation state of −1 [24]. Fluoride account for about 0.3 g/kg of the Earth's crust and are essentially found in minerals, of which fluorspar, cryolite and fluorapatite are the most common. Its higher concentrations may occur in ground water, in areas with granitic, acid volcanic, sodium-rich (alkaline) igneous rocks and in some sedimentary and metamorphic terrains [25]. In areas rich in fluoride-containing minerals, well water may contain about 10 mg of fluoride per litre. Fluorides may also enter rivers because of Industrial discharges [26]. In groundwater, fluoride concentrations vary with the type of rock through which the water flows, but usually do not exceed 10 mg/litre [27–30]. In the river Rhine in Netherlands, levels are below 0.2 mg/litre. Fluoride is one of the most important chemical contaminants that must be considered, as its presence in drinking water becomes a major source of adverse human health effects around the world. Widespread dental mottling is a health indicator which shows that water contains high concentrations of fluoride. Reports have shown that fluoride can penetrate the blood-brain barrier and accumulate in cerebral tissue before birth. India is affected by many water quality problems due to prolific contaminants mainly of geogenic origin and fluoride stands first among them. Fluorosis turns out the most widespread disease in India, affecting nearly 66 million people including 6 million children less than 14 years age. Children below 9 years are not supposed to drink water that contains 2 mg/L of fluoride. In the Meuse, concentration study concludes that high levels of fluorine in human body affect human health causing dental effects, accumulation of fluoride in bone leading to depletion in muscle energy. Apart from dental and bone problems exposure of soft tissues, organs and other parts of the body to fluoride lead to non-skeletal fluorosis. Therefore the concentration of flouride in drinking water must be monitored to make it suitable for drinking. In this paper we have designed an FBG sensor to find the concentration of flouride in drinking water samples.

2. Materials and methods

2.1. Materials used

Sodium fluoride [(NaF) a colorless white solid which is moderately soluble in water], specific reagents, distilled water, water samples, Photosensitive fiber, Optical spectrum analyzer (JDSU-MTS, 8000), Broadband source (C-band ASE light source), Hydrofluoric acid (40%), Wax container (candle- for etching) and sample container.

2.2. Fabrication of FBG

For the fabrication of fiber gratings by UV laser the modified construable methods were discovered by Meltz et al. [31]. The phase-mask technique, based on near-contact UV-beam is one of the most effective techniques for reproducible FBG inscription [32]. The grating written by phase mask technique has a period of

$$\Lambda = \frac{\lambda_{UV}}{2Sin\theta_m} = \frac{\Lambda_{PM}}{2} \quad (4)$$

where, Λ_{PM} is the period of the phase mask.

Formation of phase grating leads to band rejection filter wherein, the induced wavelengths that are not in resonance with FBG grating are rejected and only the wavelengths that satisfy the Bragg condition are being reflected effectively. Writing of grating on the photosensitive fiber at C-band is done using developed 255 nm UV radiation from the second harmonic of the copper vapor laser. This photosensitivity occurs as electronic absorptions in silica materials are in this UV regime. This effect is enhanced with Ge-doping through Ge sub-oxide defect production. The Kramer-Kronig relation has been used by Hand and Russel to explain the photosensitivity of Ge-doped fibers. The photosensitivity of a fiber is its capability to change locally its refractive index, when a UV light irradiates it. The copper vapor laser source is used for the fabrication due to its high intensity beam diameter of 10 mm, Spatial Coherence of 10 mm, Average power 220 mW and energy density of 0.0016 J/cm^2. Grating formed on the photosensitive fiber with period of about 1060 nm is as shown in Fig. 2. Maximum transmission dip of 30 dB is observed in the Bragg wavelength of 1540 nm. Hence, fabricated fiber is used for the sensing purpose in different detection mechanisms and FBG shows response in both reflected and transmitted spectrum with respect to incident intensity. Altering the period of grating on photosensitive fiber results change in amplitude bandwidth, strength of refractive index, magnitude (Fig. 3).

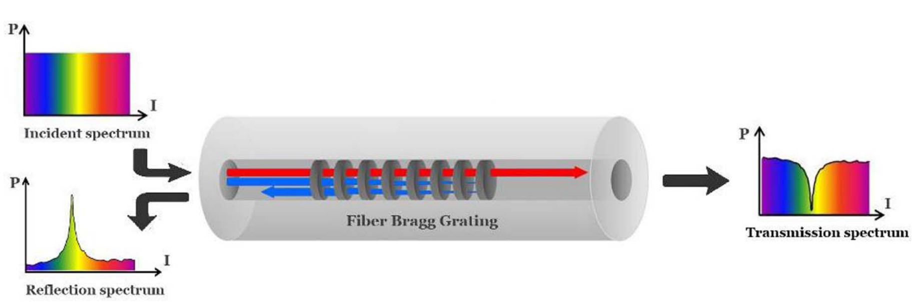

Fig. 1. Working principle of optical fiber (FBG): Transmission and reflected spectra from FBG.