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Core-cladding mode resonances of long period fiber grating in concentration sensor

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Abstract: *Long period fiber grating (LPFG) is photoinduced fiber device that facilitates the coupling of core mode to different cladding modes resulting into series of transmission dips in the transmission spectrum. Here we present LPFG chemical sensor to determine the concentration of Manganese in water at ppm level. We fabricated LPFG of period 600μm in single mode communication fiber using 12W carbon dioxide laser applying point by point method. The fabricated LPFG is directly used as chemical sensor since cladding modes coupled to core mode directly come in contact with surrounding chemicals. Concentration of manganese in our collected sample is found to be 0.0329ppm. The result is verified with sophisticated Atomic Absorption Spectrometer (AAS).*

Key words: *Cladding mode, Core mode, Coupling, Long Period Fiber Grating (LPFG), Manganese.*

I. Introduction

Long period fiber grating (LPFG) fabricated in single mode fiber has refractive index modulation of period greater than 100μm, couples core mode to different cladding modes resulting into series of transmission dips in the transmission spectrum. The study of the transmission spectrum of LPFG and behavior of transmission dips with change in various physical parameters broadened the optical fiber field both in communication as well as sensing. LPFG has many applications due to its sensitivity to temperature, strain, bend, refractive index etc [1-4]. Their resonance wavelengths are very much dependent on the core-cladding differential effective refractive index. The refractive index induced shift on the resonance wavelength is used to monitor the contents of the fluid in which the grating is immersed. The shift is experimentally measured by changing the concentration of fluid contents.

Manganese is one of the most abundant metals on the earth's surface, constituting approximately 0.1% of the earth's crust. Manganese is not found naturally in its pure (elemental) form, but in a form of component of over 100 minerals. Manganese is naturally occurring in many surface and ground water sources due to erosion of soil. However, human activities are also responsible for much of the manganese contamination in water in some areas [5].

Manganese is essential to the proper functioning of both humans and other animals as it is required by many cellular enzymes [6]. Even though manganese is an essential nutrient at low doses, chronic exposure to high doses may be harmful. Most amount of Mn supplied to the body is through food. It also enters the body through water. Generally, in water manganese is present in the form of manganous ion (Mn^{2+}). Ground has excellent mechanism of filtering out dissolved chemicals and gases. Still they can occur in large enough concentrations to cause problems. In low concentrations Mn produces extremely objectionable stains due to oxidation on everything with which it comes in contact. Deposits collected in pipelines, and tap water may contain black sediment and turbidity due to precipitated manganese. Adverse neurological effects (decreased performance in school and in neurobehavioural) were reported in 11- to 13-year-old children who were exposed to excess manganese through ingestion of contaminated water and from wheat fertilized with sewage water [7-10]. Long term studies concluded that progressive increase in the manganese concentration in drinking-water is associated with a higher prevalence of neurological problems of chronic manganese poisoning [11]. It is found from research on animals that the higher concentration of manganese input (via food or water) brings about many complications such as neurotoxicity, reproductive problems etc. World Health Organization and many countries recommend a limit of 0.05mg/l manganese in consumer usable water.

There are many methods to analyze the amount of manganese present in water such as atomic absorption spectrometry (AAS), inductively coupled plasma method (ICP), flow injection analysis (FIA), spectrofluorimetry. Here we are presenting simple, highly sensitive and precise method to analyze the concentration of manganese in water based on optical fiber grating technology using our fabricated LPFG.

II. Long Period Fiber Gratings

Fiber grating consists of a periodic perturbation of the refractive index along the confined length of fiber core. Fiber gratings are classified into two types depending upon the period of grating - short period fiber grating or fiber Bragg grating (FBG) and long period fiber grating. FBGs have a sub micron period and couple light from the forward propagating core mode of the optical fiber to a backward propagating modes. While LPFG has a period typically in the range 100µm to 1mm and couple light between propagating core mode and co-propagating cladding modes. Transmission spectrum of LPG consists of series of attenuation bands as shown in Fig. 1.

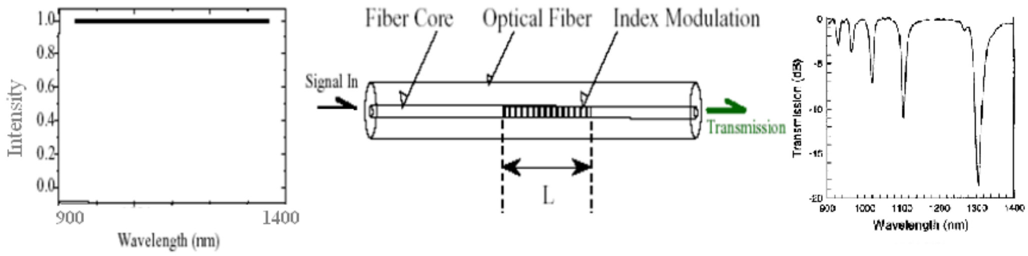

Figure 1. Transmission spectrum of input signal through LPG.

LPFG in single mode fiber facilitates coupling between the propagating core mode and co-propagating cladding modes as shown in Fig. 2. Optical power coupled to the cladding modes are strongly affected by imperfections in fiber, micro and macro bending, and boundary conditions at the cladding-external medium interface. As light travels through the grating region, the light coupled from core mode to different cladding modes leaks out of the fiber resulting in the transmission spectrum of the fiber containing a series of attenuation bands centered at discrete wavelengths. Phase matching between the mode propagating in the core of the fiber and a co-propagating cladding mode is achieved at the wavelength λ_m given by [12, 13]

$$\lambda_m = (n_{co}^{01} - n_{cl}^{1m})\Lambda \tag{1}$$

where, λ_m is the peak wavelength of the resonance band. n_{co}^{01} and n_{cl}^{1m} are the effective refractive indices of the core mode and of the m^{th} order cladding mode respectively. Λ is period of the LPG. In the above equation, '01' refers to LP_{01} mode and '1*m*' refers to HE_{1m} axially symmetric modes. Period of grating determines the wavelength of interaction and the strength of coupling is determined by the modal overlap given by coupling coefficient. The minimum transmission of the attenuation bands is determined by the expression [13]

$$T_i = 1 - \sin^2(\kappa_m L) \tag{2}$$

where L is the length of the LPG and κ_m is the coupling coefficient for the m^{th} cladding mode. Coupling coefficient is determined by the overlap integral of the core and cladding mode and amplitude of periodic modulation of the mode propagating constants.

$$\kappa_m = \frac{w\varepsilon_0}{4}\int_0^{2\pi} d\phi \int_0^{\infty} r dr \psi_1^* \Delta n \psi_2 \tag{3}$$

where ψ_1 and ψ_2 are the transverse field distributions of core and cladding modes. Δn is peak change in the refractive index.

T. Erdogan[14] showed by theoretical analysis that efficient coupling is possible only between core and cladding modes that have a large overlap integral, i.e. modes that have similar electric field profiles. Thus coupling is observed between the core and circularly symmetric cladding modes of odd order. Electric field profile of the even-order modes have low field amplitude within the core, whereas the electric field profiles of the odd modes have a peak located within the core. Resonant peaks position, amplitudes and intermode spaces are dependent on the fiber core and cladding diameters, core and cladding material refractive index difference, the total length of grating and refractive index modulation depth. The centre wavelengths of the attenuation bands are sensitive to the surrounding environment such as temperature, strain, bend radius and to the refractive index of the medium surrounding the fiber. This sensitivity of LPFG spectrum and attenuation bands to the external refractive index can be used to design it as chemical sensors.

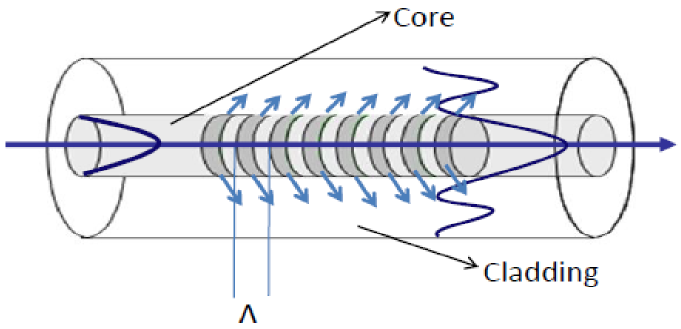

Figure 2. Operating principle of LPG.

III. Chemical Sensing Principle of LPG

The chemical sensitivity of LPFG can be explained interms of refractive index (RI). LPFG's sensitivity to the refractive index of the material surrounding the cladding in the grating region can be employed to develop it as chemical sensor. The position and strength of attenuation band depends on effective refractive index of the cladding modes, which in turn depends on the refractive index of the surrounding environment. It enables the use of LPFG's as index sensors based on the change in wavelength and/or attenuation of the LPFG bands [15].

LPFG is very useful as a sensor when the refractive index of the external medium changes. The change in ambient index changes the effective index of the cladding mode and will lead to wavelength shifts of the resonance dips in the LPFG transmission spectrum.

The grating period remains unchanged under the effect of a change in ambient refractive index (n_s) and assuming that the effective refractive index of the core mode is unaltered, we obtain an expression by differentiating "equation 1" with respect to n_s for mth cladding mode

$$\left(\frac{d\lambda}{dn_s}\right)_m = \left(\frac{d\lambda}{d\delta n_{eff}}\right)_m \left(\frac{d\delta n_{eff}}{dn_s}\right)_m \quad (4)$$

where

$$\delta n_{eff,m} = n_{co}^{01} - n_{cl}^{1m} \quad (5)$$

For each cladding mode, the term $(d\delta n_{eff}/dn_s)_m$is distinct and hence an LPFG is expected to have a strong dependence on the order of the coupled cladding mode [15, 16].

The behavior of transmission spectrum of LPFG as chemical sensor can be explained in terms of surrounding refractive index (SRI) of medium. If the SRI is lower than the refractive index of the cladding ($n_{sur}< n_{cl}$), mode guidance can be explained using total internal reflection. In this case, typically strong resonance peaks are observed and the attenuation dips shift towards shorter wavelengths when the external medium refractive index increases up to that of the fiber cladding. As the refractive index of the external medium approaches the cladding RI, sensitivity increases, which leads to larger wavelength shift of resonance wavelength. When the SRI matches with that of the cladding, the cladding layer acts as an infinitely extended medium and thus supports no discrete cladding modes. In this case, a broadband radiation mode coupling occurs with no distinct attenuation bands. In short, when the external RI becomes equal to that of silica, rejection bands disappear, and the transmission spectrum gets flattened. Once the SRI is higher than the refractive index of the cladding ($n_{sur} > n_{clad}$), the cladding modes no longer experience total internal reflection and Fresnel reflection can be used to explain mode structure. In this case the resonance peaks reappear at slightly longer wavelengths compared to those measured with air as the surrounding medium. In such cases the wavelength shift is very small with change in SRI, but changes in the amplitude of resonance dips are large [15].

IV. Experiment

4.1 Fabrication of LPFG

Many methods were demonstrated for fabrication of LPFG – amplitude mask method and holographic method using excimer laser, point by point method using excimer lasers / CO_2 lasers / electrical discharge of optical fiber splicer, introducing mechanical stress etc [13]. Point by point method using CO_2 laser is flexible method as it can be applied to any kind of glass fibers. In this paper we present LPFG fabrication in single mode communication grade fiber (SMF-28). The schematic diagram of fabrication of LPFG is as in Fig. 3. Fiber acrylate coating of 3cm is stripped off at the center of long length fiber (2m), ends of which were connected to white light source and OSA. The acrylate removed part of fiber was fixed infront of CO_2 laser at distance 1.5meter. Details of CO_2 laser are given in Table 1. The fiber was mounted on fiber holder which keeps fiber in position by holding it tightly at two points. This fiber holder was fixed on motor controlled translation stage. The fiber was irradiated with CO_2 laser for less than one second. Then displacement of 600µm was given to fiber along its axis. Again fiber was exposed to laser output for less than one second. The same steps were repeated to complete 60 exposures. The formation of grating was monitored online by observing transmission spectrum of the grating using optical spectrum analyzer. The transmission spectrum is given in Fig. 4, which shows two low resonant dips at 1.446µm and 1.522µm with transmission loss -5.98dB and -10.02dB respectively.

Table 1: CO_2 Laser details

Wavelength	10.6µm
Output Power	12W
Beam diameter	2.4mm
Divergence angle	5.5mrad
Make	Access Laser Company Model: LASY -12

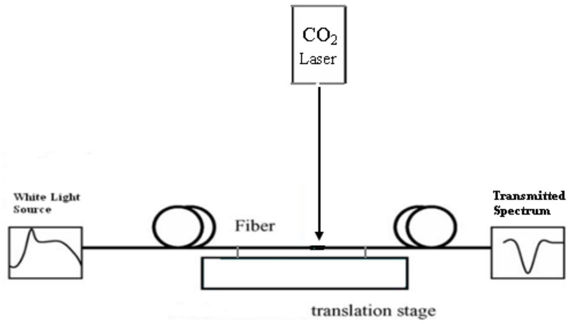

Figure 3. Schematic diagram of fabrication of LPG

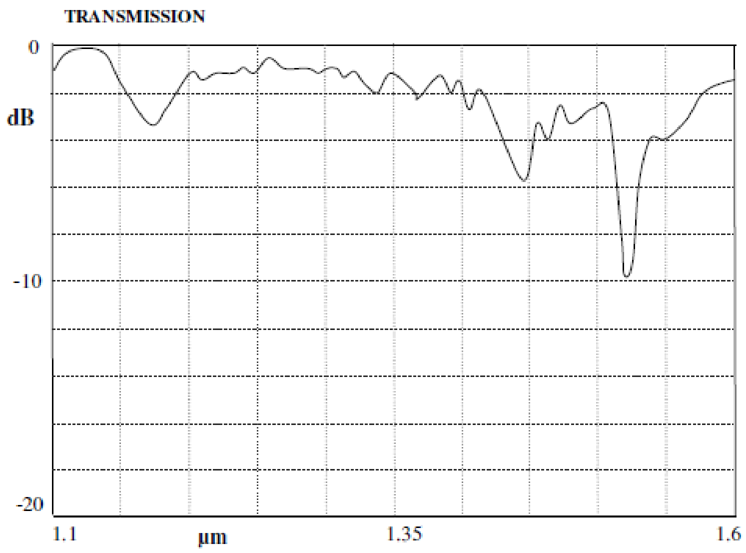

Fig. 4. Transmission spectrum of fabricated LPG

4.2. Design of Concentration Sensor

The fabricated LPFG is used to design manganese concentration sensor. Standard solutions of manganese varying from 0.01ppm to 0.04ppm were prepared by dissolving manganese chloride in distilled water. To each concentrations of particular volume, reagents N,N-dimethylaformamide and potassium cyanide were added to extract Mn in the solution. Glass cell containing LPFG (fixed in it) was filled with standard solution of Mn with reagents and transmission spectrum of LPFG was recorded for all standard solutions. The same procedure was repeated for our test sample. Transmission spectrum of LPFG in each case is recorded and Fig. 5. shows the spectral behavior of LPG for solutions of different concentration.

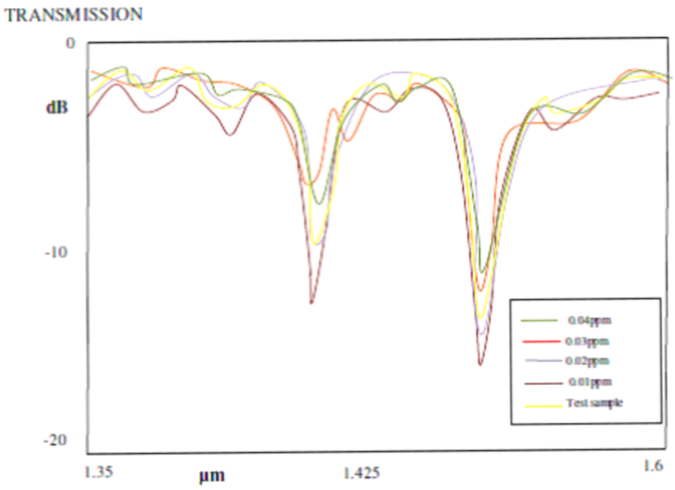

Figure 5. Spectral behavior of LPFG for manganese solution of different concentrations.

V. Results and Discussion

When medium surrounding the LPFG changes, the response was observed in the transmission spectrum. Because of change in chemical composition of surrounding liquid, there was change in refractive index of the medium surrounding LPFG which further effects coupling scheme of core and cladding modes resulting in variation in transmission dips of resonance wavelengths. As the concentration of surrounding medium varies, coupling strength of cladding mode is affected since cladding is in direct contact with the solution. Both resonance wavelengths are sensitive to surrounding solution. The resonance wavelength centered at 1.522µm showed the linear response in transmission dip with the surrounding liquid, which is not observed with resonance wavelength centered at 1.446µm. There was no considerable change in resonance wavelength, because the RI of medium surrounding LPFG is greater than the cladding, the shift in wavelength of the attenuation bands is very small but amplitude of resonance dip is considerable as explained by Patrick et. al. [15]. The linear response of the amplitude of transmission dip of attenuated wavelength centered at 1.522µm is observed in Fig. 6. The linear least-square fit with experimental data gives correlation factor of 0.997 and standard deviation 0.138.

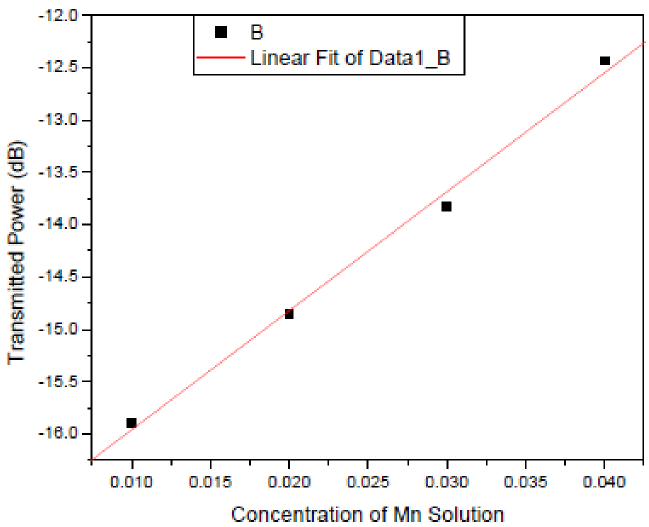

Figure 6. Amplitude of Transmission dip Vs Solution Concentration

Using linear fit graph to the experimental data, (Fig. 6) we can determine the concentration of Mn in our test sample which is found to be 0.0329ppm. The result is verified with sophisticated instruments like Atomic Absorption Spectrometer (AAS) and Inductive Coupled Plasma (ICP) method. We have also determined the concentration of manganese in the same sample using FBG and both results are comparable[17]. The results obtained using different methods are tabulated in Table 2.

Table 2. Concentration of Manganese in sample using different methods

Chemical Species	FBG Sensor (ppm)	LPG Sensor (ppm)	@Atomic absorption Spectrometer (ppm)	*Inductive coupled plasma Method (ppm)	WHO Standard (ppm)
Manganese	0.0303	0.0329	0.048	<0.05	0.05

@Measurements were made in USIC (University Scientific Instrument Center, Karnatak University, Dharwad, India).
*Measurements were made at Met–Chem Laboratories, Bangalore (India Pvt. Ltd.).

VI. Conclusion

LPFG is highly sensitive to concentration of the solution surrounding it. Hence, fiber grating can be a potential tool in determining the concentration of dissolved compounds in water and many other industrially important organic liquids. Advantage of such sensors lies in simplicity of construction and ease of use.

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