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Special Efficient Hydrogen FBG Sensor for Leakage Detection: Application in Propulsion System Fuel Tank of Aerospace Vehicle

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***Abstract*—In this paper special hydrogen Fiber Bragg Grating (FBG) sensor is presented. The design of this sensor is explained based on a new alliance of palladium-Silver (Pd-Ag) as hydrogen sensitive film with titanium (Ti) layer as adhesive layer. With this sensor, sensitive of 90pm/1% H_2 is easily reached and faster response time of 4-5 s is guarantee with very enhancement life time in 0.1%-4% H_2 range in volume ratio. Also, the sensor is applied using WDM in propulsion system fuel tank model of aerospace vehicle where we have good results for prevention against disaster aerospace due to hydrogen leakage.**

***Keywords*— Hydrogen Fiber Bragg Grating, palladium-Silver (Pd-Ag), faster response time, propulsion system fuel tank, prevention**

I. Introduction

Due to its promising properties and high specific energy content; hydrogen has become increasingly interesting for the aerospace industry (aircraft, rocket, etc.) [1]. For example liquid hydrogen (LH_2) is emerging as an alternative fuel for aircrafts. So aerospace vehicles are expected to provide sufficient capacity for flight durations; ranging from a few minutes to several days [2]. However use hydrogen system may be having a potential dangerous due to the presence of hydrogen leakage. Thus, it's requiring answers to the question: how to establish and demonstrate hydrogen leakage preventive system with sufficient safety. So it is understood the development of a safety prevention system for hydrogen leakage detection especially for long flight durations and in aging aerospace vehicles. In this paper we use the FBG technology as the safety prevention system for hydrogen leakage detection. We will do simulations, based on robust FBG sensor of length 4mm which is developed by our research group. In addition a new alliance of Pd-Ag (palladium-Silver) material (500nm) as hydrogen sensitive film is used with titanium (Ti) layer (35nm) as adhesive layer to enhance the strength between Pd-Ag layer and the optic cladding. We recall that this alliance is never proposed before as hydrogen sensitive film with FBG technology. It is presented only with Schottky Diode hydrogen sensor by NASA in 1995 [3]. The purpose of this alliance is to have more sensitivity, faster response time and further repeatability where locate the leakage position of hydrogen more quickly and accurately is very important to save people and equipments. In the first part of this paper we present this new sensor. In the second part we present the results that describe the sensor sensitivity, response time and repeatability to hydrogen. And in the thirds part, we apply our proposed sensor in real time way in propulsion system fuel tank of aerospace vehicle using WDM technique. Generally, the obtained results confirmed that the proposed sensor is very efficient hydrogen FBG sensor for leakage detection. All experiments will be made based on results in this paper should be with precaution for saving reasons.

II. Design of Special Hydrogen FBG Sensor

Numerous physical parameters can be varied in fiber Bragg grating (FBG) for achieving desired spectral characteristics, including effective refractive index modulation, effective refractive index, length, apodization, period chirp, and whether the grating supports counterpropagting or copropagating at a desired wavelength. And generally, the Bragg grating acts as a simple spectral filter that allow a part of the incident signal to be reflected, see Figure 1. The expression that enables and gives the central wavelength of the reflected part is [4]:

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

where λ_B is the central wavelength of the spectral band reflected by the Bragg grating, n_{eff} is the effective refractive index in the unperturbed parts of fiber Bragg grating length, and $\Lambda(z)$ is the grating period, naturally is a constant if we have uniform Bragg grating. In this paper is not the case because we use a special FBG where the grating period is expressed as:

$$\Lambda(z)=\begin{cases}\Lambda_0(1-c_p z)\,for\left[0\ldots\frac{z}{2}\right]\\ \Lambda'_0(1+c_p z)\,for\left[\frac{z}{2}\ldots z\right]\end{cases} \quad (2)$$

where Λ_0 and Λ'_0 are the nominal grating periods and c_p (nm/cm) is the linear chirp coefficient. In this context, and in previous work of our research group, we have shown the effectiveness of this special design of FBG where it gives robustness, acceptable sensitivities of strain and temperature with more stability [5]. Especially for length of 4mm, Λ_0 =0.53µm, Λ'_0 = 0.5284µm, c_p=1.5nm/cm, n_{eff} =1.456, and refractive index modulation equal to $2.5x10^{-4}$, we have λ_B =1.5414µm, 1pm/µε and 10pm/°C as strain and temperature sensitivities, and 100% reflectivity. These obtained results are very acceptable values if we compared with those published in scientific research [6]. In addition the proposed design is efficient where there is no need to apodized function for correction and to minimize sidelobs in the spectrum reflectivity. This is very important to increase the multiplexing solutions and enhance the used bandwidth.

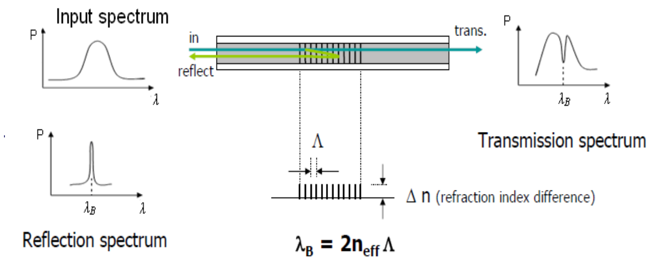

Fig. 1 Principle operation of FBG technology

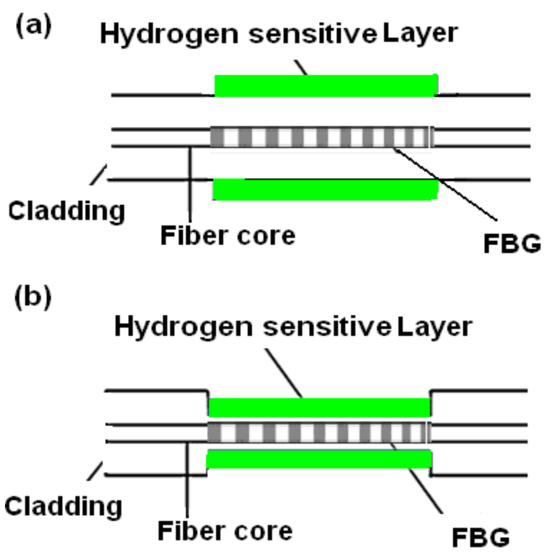

Fig. 2 Principle operation of hydrogen FBG sensor, (a) without etched cladding, (b) with etched cladding

Generally to have hydrogen FBG sensor we use hydrogen sensitive film round about FBG length, see Figure 2 (a). The best materials used are the palladium (Pd), platinum (Pt) [7], Pt-loaded WO_3 (tungsten trioxide) [8], etc. In another hand, in previous work in [9] of our research group, we have shown that the use of etched cladding technical increases the efficiency of a hydrogen FBG sensor; see Figure 2 (b). In this paper we well want to increase the published specification of hydrogen FBG sensors [7]: sensitivity, response time and life time. In addition, as we said before, the etched cladding increase the efficiency of sensor, this is why we have used in previous works an etched FBG sensor with palladium (Pd) as hydrogen sensitive film [5]-[9]. With these works we have a sensitive of 60pm/1% H_2, and faster response time, less than 9s but with shorter life time ie low repeatability of measurement. So we think to enhance these specifications to locate the leakage position of hydrogen more quickly and accurately to save people and equipments and to eliminate any tragedy to happen due to hydrogen leakage with further repeatability. For this we made a new design of hydrogen FBG sensor, see Figure 3. In this design, we use the alliance of Pd-Ag (500nm) as hydrogen sensitive film. The Ag material is used to enhance the sensitivity and life time of the hydrogen sensitive film of Pd. We recall that this alliance is never proposed before as hydrogen sensitive film with the technology of FBG. In addition, a titanium (Ti) layer (35nm) is used as adhesive layer to enhance the strength between Pd-Ag layer and the optic cladding. And to more enhance the sensitivity of the sensor, we inscribe two other Pd-Ag layers of length 4mm each in both sides of Bragg grating. With this way, the increased sensitivity is guaranteed like presented in [5].

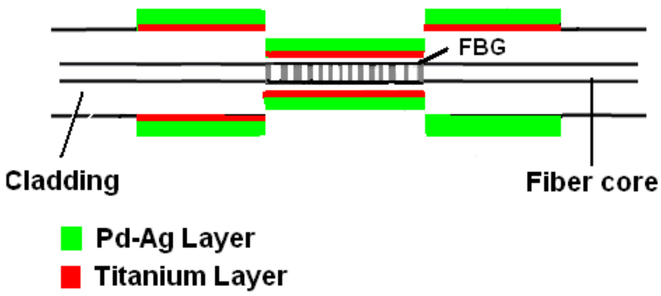

Fig. 3 Shape of proposed hydrogen FBG sensor

Practically, we can use a single-mode optical fiber of type SMF-28. The radius of the fiber core is equal to 4.6µm, that of the optic cladding is 62.5µm and that of the mechanical protective cladding is 125µm. In addition, a Lambda Physik excimer laser (COMPex-150T) operating at 248 nm can be used as UV light source to write FBG by phase mask method. Then if we have uniform FBG, we use carefully the stretch movement in the tow sides of FBG to have the shape mentioned above and according to the equation (2) in this paper. In addition our sensor is defined with etched cladding with 62µm, so the remainder of the cladding layer along FBG is 0.5µm. Thereafter above the remainder cladding, 0.5µm, the Pd-Ag layer (500nm) will be carried as shown Figure 3. The preparation of Pd-Ag layer can be realised with sol gel method. And to avoid Pd-Ag coating layer from being peeled off when we had a high gas hydrogen concentration, we used adhesive layer below the Pd-Ag layer. In our case, this adhesive layer is titanium (Ti) layer with low thickness (35 nm). Consequently, our hydrogen FBG sensor consist of fiber core, fiber cladding (0.5µm), titanium (Ti) layer (35 nm) and Pd-Ag layer (500 nm). On the other hand, both of the Pd-Ag layer and Ti layer can be also coated by using magnetron sputtering where Pd-Ag and Ti grains will be evenly distributed. So we can have high quality uniform metal layers in compared to the other classic coating technologies, which protect the FBG and improving also the sensor's sensitivity.

III. EXPERIENCE

A. Definition

We recall that the behaviour of FBG sensor remains the same using Pd-Ag coating technique with etched cladding if we have not a disruptive effect exerted on the FBG. In addition, the thick Pd-Ag layer used is the optimal thickness to achieve the performance characteristics. And our experiment model for examining our hydrogen sensor is shown in Figure 4. The gas test cell was a Teflon tube, having two ports of the gas to flow in and out. Hydrogen gas flow rate using air were measured and controlled separately by flow meter where the varying hydrogen concentration have provided by changing flowing rate of H_2. And in order to investigate the influence of different hydrogen concentrations to the shift of FBG wavelengths, FBG sensor array have inserted into the gas cell through a rubber cork and was fixed in a gas cell side. The FBG sensors array contained our FBG hydrogen sensor and temperature compensation FBG sensor. We remember that we use temperature compensation FBG sensor, can be achieved also by phase mask method, to eliminate the effect of temperature when calculating the shift of FBG hydrogen sensor. And as we have seen before, the center wavelength of hydrogen FBG sensor is 1.5414µm, whereas the center wavelength of the temperature compensation sensor set to 1.5463µm. In another hand, FBG sensors array is connected with 3 dB coupler to a LASER light source and to investigation system (ie optical spectrum analyzer (OSA)) to calculate the shift of wavelength. The investigation system consist of amplify system, band-pass filter and PC with LabVIEW program to analyze and process the system. The practical experiment of such system can be performed at room temperature of 25°C and at atmospheric pressure but should be with precaution for saving reasons.

B. Discussion

We remember that the thick Pd-Ag layer have used to absorb hydrogen, inducing strain change on the FBG. So shifts in wavelength are realised. These shifts of FBG wavelength are observed with different hydrogen concentrations: 0.1-4%. Figure 5 indicates these shifts responses after eliminating the temperature effect using data in LabVIEW program. We remember that our FBG have temperature sensitivity in the order of 10pm/°C at room temperature. From the curve, the wavelengths increase almost linearly as a function of hydrogen concentrations in the range of 0.1%–4% H_2. In addition, results showed highest sensitivity existed when we use our proposed sensor rather than those published up to now [5]-[10]. In 0.1%-2% H_2 range the sensitivity reached 90pm/1%H2 and in 2%-4% H_2 range this sensitivity is about 85pm/1% H_2. In addition, the response time is the faster also published up to now [5-7-8], see Figure 7. It is found about 4-5 s. Response time is calculated from the hydrogen flowing into gas room to FBG reaching the maximum shift wavelength. In another hand the recovery time is faster also as indicated the Figure 7. This recovery time is calculated from air flowing into gas room where FBG reaching maximum shift wavelength into initial FBG wavelength. In addition, from this figure, it is clear that the repeatability is very precise, and this is very important where we have enhancement in life time of the FBG sensor. This is due essentially to the presence of the Ag material in the hydrogen sensitive film.

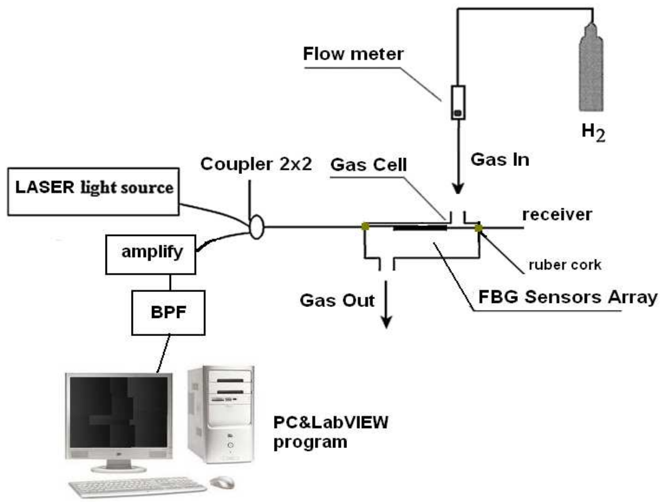

Fig. 4 Illustration of hydrogen sensing experiment model with special proposed FBG sensor

Considering the resolution of 1pm for the interrogation system, 0.012%H_2 can be detected in air by our special FBG sensor in range 0.1%-4% H_2 range. So it is reported from the simulation results that our FBG hydrogen sensor coated with Pd-Ag present the highest sensitivity with linear response and faster response time when the hydrogen concentration is below explosive limit (4% H_2 in volume ratio). On the other hand, practically the FBG hydrogen sensor can be a combustion source when hydrogen concentration is more than 4% H_2 where the temperature around FBG increases more than 100°C. Therefore to obtain FBG hydrogen sensor with intrinsic safety, the temperature increasing with H_2 around FBG should be controlled at a proper value [5]. Otherwise, in several cases the hydrogen concentration may be more than 4% in volume ratio. Figure 6 illustrates the response of our special FBG under higher hydrogen concentration by simulation using also data in LabVIEW program. From this figure, when the hydrogen concentration is increasing, FBG shifts to longer wavelength, but in a slow manner with a nonlinear response. And owing to structure of FBG, when the hydrogen increased to 50%, which is the highest value, published up to now, the Pd-Ag will be almost totally consumed and the central wavelength will be fixed. Despite this result the proposed FBG sensor is efficiency even under almost pure hydrogen atmosphere. Subsequently we hope that it can be used to monitor any hydrogen leakage.

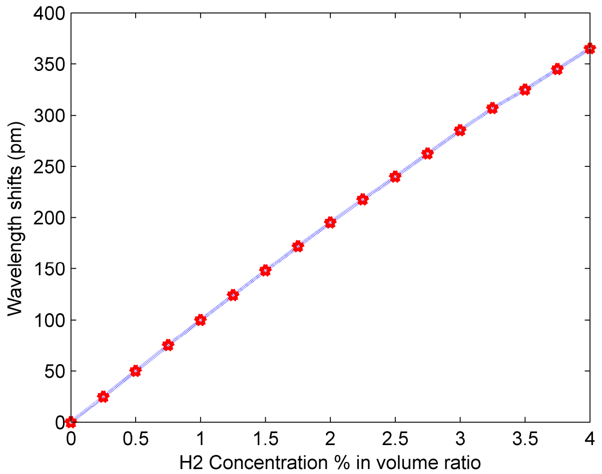

Fig. 5 Simulation results of wavelength shifts of the special proposed hydrogen FBG sensor in 0.1%-4% H_2 range in volume ratio using Data in LabVIEW program

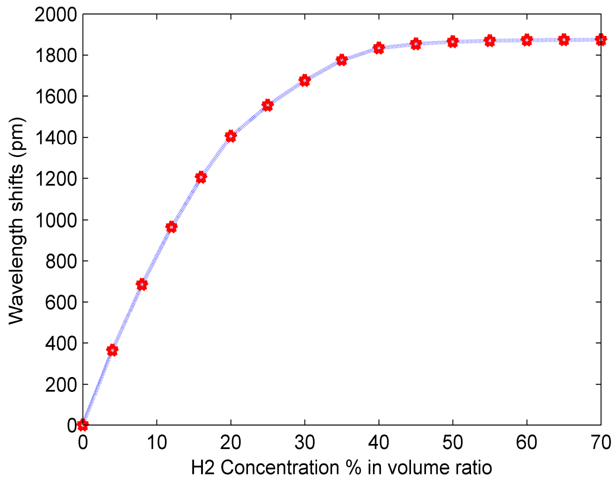

Fig. 6 Simulation results of wavelength shifts of the special proposed hydrogen FBG sensor under high hydrogen concentrations using Data in LabVIEW program

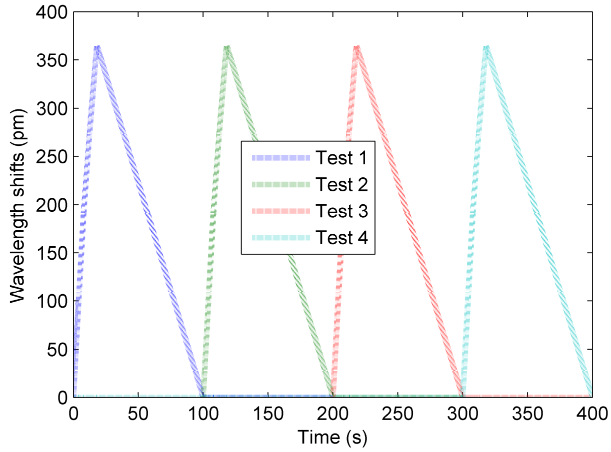

Fig. 7 Four tests of response time and recovery time of the special proposed hydrogen FBG sensor in hydrogen concentrations and in air

IV. Application in Propulsion System Fuel Tank of Aerospace Vehicle

The hydrogen FBG type of sensor is very promising for Disaster Aerospace Prevention where locate the leakage position of hydrogen more quickly and accurately is very important to save people and materials. In addition, in aerospace vehicle, using the WDM technique total body recover against hydrogen leakage is guarantee particularly in the components most sensitive to hydrogen as propulsion system fuel tanks, feed lines, engine elements and the location of traveler. And from the obtained results in the first part, we will apply 3 sensors of type our proposed hydrogen FBG sensor in aerospace vehicle body, especially in propulsion system fuel tank using the WDM technique. The wavelength centers are λ_B =1.5214μm λ_B =1.5414μm, and λ_B =1.5614μm, for the first sensor FBG1, second sensor FBG2 and the thirds sensor FBG3, respectively. In addition 3 temperature compensation FBG sensors were used to compensate the temperature effect in calculation of the wavelength shifts. Each temperature compensation FBG sensor is used with each FBG hydrogen sensor. The wavelength centers of the temperature compensation FBG sensors are λ_B =1.5443μm, λ_B =1.5463μm, and λ_B =1.5483μm, for the first sensor FBG4, second sensor FBG5, and the thirds sensor FBG6, respectively. And as there is not possibility to have reel propulsion system fuel tank of an aircraft or of aerospace vehicle, we used a parameters of a bottle in aluminum (Al) filled of 3% hydrogen and 97% nitrogen (N2). The use of aluminum material as wall material of the bottle has a high safety during storage of hydrogen at high pressure. In addition we can use austenitic steel or glass in place of the aluminum. Figure 8 illustrates the installation model of this proposed propulsion system fuel tank with the 3 hydrogen FBG sensors and the 3 temperature compensation FBG sensors. The first couple, FBG1 and FBG4, is installed in aft dome. The second couple, FBG2 and FBG5, is installed above the cylinder portion and the third couple, FBG3 and FBG6, is installed in forward dome.

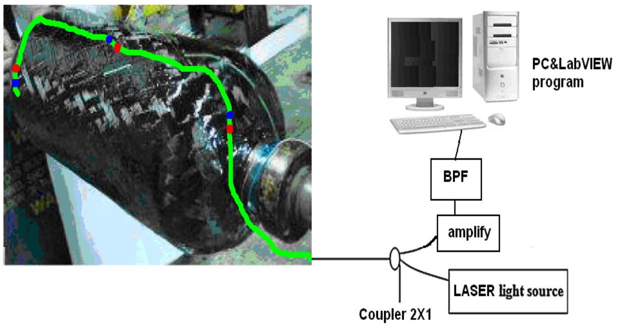

Fig. 8 Illustration of the proposed propulsion system fuel tank model with 3 FBG sensors of type our special proposed hydrogen FBG sensor and 3 temperature compensation FBG sensors as hydrogen preventive system

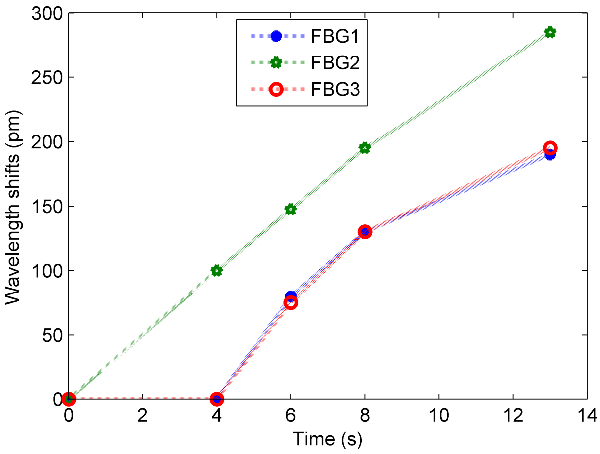

Fig. 9 Response of FBG1, FBG2 and FBG3 to hydrogen leak in propulsion system fuel tank of aerospace vehicle

From results, we investigate the response of sensors systems with real time monitoring. In the absence of any leakage hydrogen, the center wavelengths of the three hydrogen FBG sensors remain the same. And as there is not possibility of hydrogen leak due to an effect because our propulsion system fuel tank remains motionless and exist in place where the percentage of having a hydrogen leak in aluminum walls is very low. We are looking for way to have artificial hydrogen leaks. And at the realization of the leak in the cylinder portion, we have the curves shown in Figure 9. From these curves, FBG2 detect the hydrogen leakage in 4s, FBG1 and FBG3 detect the leakage in 6-7s. These result are very normal because the vanishing point is located next to the sensor FBG2, otherwise the other sensors are a bit far from this vanishing point. So the presence of the sensor near the vanishing point is very important to have faster response and localization. Consequently, our proposed system is efficiency to detect hydrogen leaks in propulsion system fuel tank of aerospace vehicle. In addition, to cover a total body of the most sensible components to hydrogen leaks of an aerospace vehicle, we use the same reasoning. Therefore our special proposed hydrogen FBG sensor can be used for disaster environment prevention where locate the fault position of hydrogen more quickly and accurately is very important than the conventional and is essential to save people and materials, especially in environmentally sensitive and in the environment where the hydrogen presents as nuclear centers power, aerospace vehicles, hydrogen dissolved in transformer gas as oil, etc. At present the fastest response of an FBG hydrogen sensor is based on Pt-loaded WO_3 coating, 10s [8]. Otherwise, we have demonstrated theoretically in this paper that our special FBG hydrogen sensor using etched cladding with Pd-Ag coating as hydrogen sensitive film gives a fast response time compared to those of Pt-loaded WO_3 with high sensitive especially in low hydrogen concentrations. This is due to the presence of the Ag material.

V. Conclusions

In this paper, new FBG hydrogen sensor with length 4mm based on alliance Pd-Ag material (500nm) as hydrogen sensitive film and Ti layer (35nm) as adhesive layer is developed. And its sensing characteristics have been investigated. From simulation results, better results are obtained especially in low concentration range of hydrogen where we have resolution reach 90pm/1%H_2 and faster response time in the order of 4-5s. Also the repeatability is guarantee. These better results are due especially to the presence of the Ag material in the hydrogen sensitive film. And with FBG demodulator resolution of 1pm, high precision to slight hydrogen concentration variation can be detected: 0.012% H_2. Also it is demonstrated that the sensor is safe even under higher hydrogen concentration. Therefore we hope that with Pd-Ag alliance we have more resistant to damage from exposure to high hydrogen concentration than Pd with very faster response times than all the solutions presented and published up to now in leakage hydrogen detection with FBG technology. Otherwise, this sensor is very promising for disaster aerospace prevention where locate the leakage position of hydrogen more quickly and accurately is very important to save people and equipments. In addition with WDM, body of propulsion system fuel tank of aerospace vehicle recover against hydrogen leakage with 3 FBG hydrogen sensors of type our proposed sensor is demonstrated. The results are investigated in real time and we hope that we have developed disaster aerospace prevention system against hydrogen leak using FBG technology to save people and aerospace vehicles especially in unmanned long-flight duration. In addition, the results mentioned above point to uses this detection technology toward applications in other areas such as in pipe walls or nuclear fuel cladding. So there is more scope for development.

Acknowledgment

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