Wavelength-codified fiber laser hydrogen detector

A. Ortigosa-Blanch,[a] A. Díez, A. González-Segura, J. L. Cruz, and M. V. Andrés
Departamento de Física Aplicada-ICMUV, Universidad de Valencia, Dr. Moliner 50, 46100 Burjasot, Spain

(Received 28 April 2005; accepted 20 September 2005; published online 8 November 2005)

We report a scheme for an optical hydrogen detector that codifies the information in wavelength. The system is based on an erbium-doped fiber laser with two coupled cavities and a Palladium-coated tapered fiber within one of the laser cavities. The tapered fiber acts as the hydrogen-sensing element. When the sensing element is exposed to a hydrogen atmosphere, its attenuation decreases changing the cavity losses. This change leads the system to switch lasing from the wavelength of the auxiliary cavity to the characteristic wavelength of the cavity which contains the sensing element. The detection level can be shifted by adjusting the reflective elements of the cavity containing the sensing element. © *2005 American Institute of Physics*.
[DOI: 10.1063/1.2130531]

Over the last few years there has been an increasing interest to facilitate and accelerate the development and deployment of cost-competitive fuel cell based energy systems and component technologies for applications in transport, stationary, and portable power, aiming for a sustainable hydrogen economy. Hydrogen is the lightest chemical element and offers the best energy-to-weight ratio of any fuel. Hydrogen is colorless, odorless, and its only by-product is water. Nevertheless, research needs to be carried out to make hydrogen safe when it is used as a fuel. It is highly flammable and has a high explosive range in air.

At the same time, great efforts have been made in the development of hydrogen sensors and detectors. Several technologies have been explored, including fiber optic based sensors.[1–6] Sensing techniques based in optical fibers allow light based detection systems. These systems do not represent a hazard in explosive environments as their electric counterparts do, where a spark could ignite the hydrogen reservoir.

There are different types of optical fiber based hydrogen sensors that use Palladium (Pd) as the transductor element. Some of these sensors consist on a tapered fiber region on which a thin Pd film is deposited.[4,5,7] The hydrogen detection is based on the attenuation of the light propagating along the fiber. These sensors are amplitude codified and present several problems, two of the most important being aging of the optical source and low signal to noise level.

Some other sensors exploit the possibility of writing a Bragg grating in the core of an optical fiber and then coating that fiber region with Pd.[3] In this case hydrogen detection relays on the change of the Pd coating lattice parameters due to hydration resulting on a tensioning of the grating. Therefore, the wavelength reflected by the Bragg grating will change and the detection is codified by the relative wavelength change of the output of the sensor. However, this approach requires a thick film of Pd which makes the time response of the sensor quite slow and, in addition, wavelength changes of the order of 10 pm are obtained.

There is a third type of hydrogen sensors which codified their output in the time domain. Sensing techniques translating the measurement to the time domain offer the possibility to acquire and process the information very easily and accurately using reliable, low-cost electronics. One example is the cavity ringdown technique that has been extensively used in chemical spectroscopy, in which the magnitude is achieved in the time domain by measurement of ringdown time.[3,6] Recently we have demonstrated a new hydrogen sensor codified in the time domain where the detection is based on the build-up time of the laser transient.[8]

In this paper we present an original configuration for a wavelength codified hydrogen detector. The detector consists on two coupled fiber laser cavities, emitting at different wavelengths, and a sensing element within one of them. The detector changes its wavelength of emission depending on the losses inserted by the sensing element in one of the cavities. When the sensing element is exposed to hydrogen, its losses decrease and the detector switches from emitting at the characteristic wavelength of the auxiliary cavity to the wavelength of the main cavity with contains the sensing element. This new approach presents several advantages with respect to others mentioned above. The sensor overtakes the limitations of amplitude codified sensors and, although wavelength codified, the output wavelength shift is large and, therefore, it is easily discriminated.

A diagram of the hydrogen detector is shown in Fig. 1. An 8 m piece of a standard single-mode erbium-doped fiber [Er_2O_3-concentration 300 ppm (mol)], with a numerical aperture of 0.23 and a cut-off wavelength of 965 nm, was used as laser active medium. A Faraday rotator mirror (FRM) and two different fiber Bragg gratings (FBG) centered at different wavelengths define the main and the auxiliary Fabry-Perot laser cavities. FBG1 is centered at 1539.67 nm with a reflectivity of 85% and defines the auxiliary cavity, while FBG2 is centered at 1549.29 nm with a reflectivity of 98% and de-

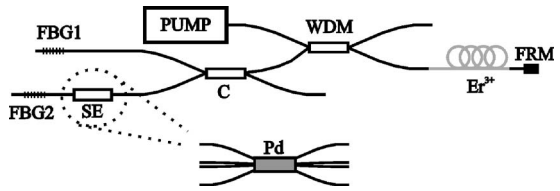

FIG. 1. Diagram of the set up of the detector. FBG: fiber Bragg grating, FRM: Faraday rotator mirror, C: 10/90 coupler and SE: sensing element.

[a]Present address: Optical Communications Group, iTEAM Research Institute, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain; electronic mail: aortigos@iteam.upv.es

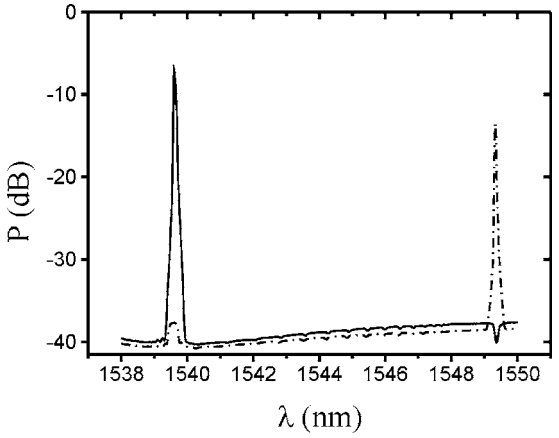

FIG. 2. Response of the detector showing the spectra when the hydrogen concentration is below the threshold (solid line) and when it is above the threshold (dashed line).

fines the main cavity. The active fiber was pumped at 980 nm through a WDM. The sensing element introduced within the main laser cavity consisted of a Pd-coated tapered fiber. The taper had a uniform waist of 25 μm in diameter and 8 mm in length, which was Pd-coated with a 10 nm thick layer. The taper transmission losses in air due to light absorption in the Pd layer were about 10 dB at a wavelength of 1.55 μm. When it was exposed to a 4% hydrogen concentration, the transmission losses decreased by 30% with a time response of around 90 s, at room temperature.

The response of the detector is shown in Fig. 2. When the sensing element is in air the losses in the main cavity are higher than the losses in the auxiliary cavity and the detector is lasing at the characteristic wavelength of the auxiliary cavity (solid line). Once the hydrogen concentration increases, the Pd coating starts reacting with the hydrogen and the losses of the sensing element decrease. When the threshold of the cavity with the sensing element in it is reached, the detector starts lasing at the wavelength of the main cavity (dashed line). Thus, the response of the detector is codified in wavelength. Unlike other sensing elements based on optical fibers, where the detection translates into small changes on the emission wavelength,[3] our detection system shows two well differentiated wavelengths (approximately 10 nm apart). The detection system then acts as an alarm system and implies the selective detection of a distinctive wavelength and not its relative change.

Once the functioning principle of the detector was tested, we investigated the response of the detector, i.e., the power emission of the main cavity at 1549 nm, for different pump powers as well as the detector's response for different H_2 concentrations. Figure 3 shows the response of the detector for three different pump powers and for two different main cavity conditions. Figure 3(a) shows the detector response for 41 mW (circles), 31 mW (squares), and 22 mW (triangles) pump powers. It is seen how the response of the detector is independent of the pump power and how the H_2 concentration has a threshold at which losses changes make

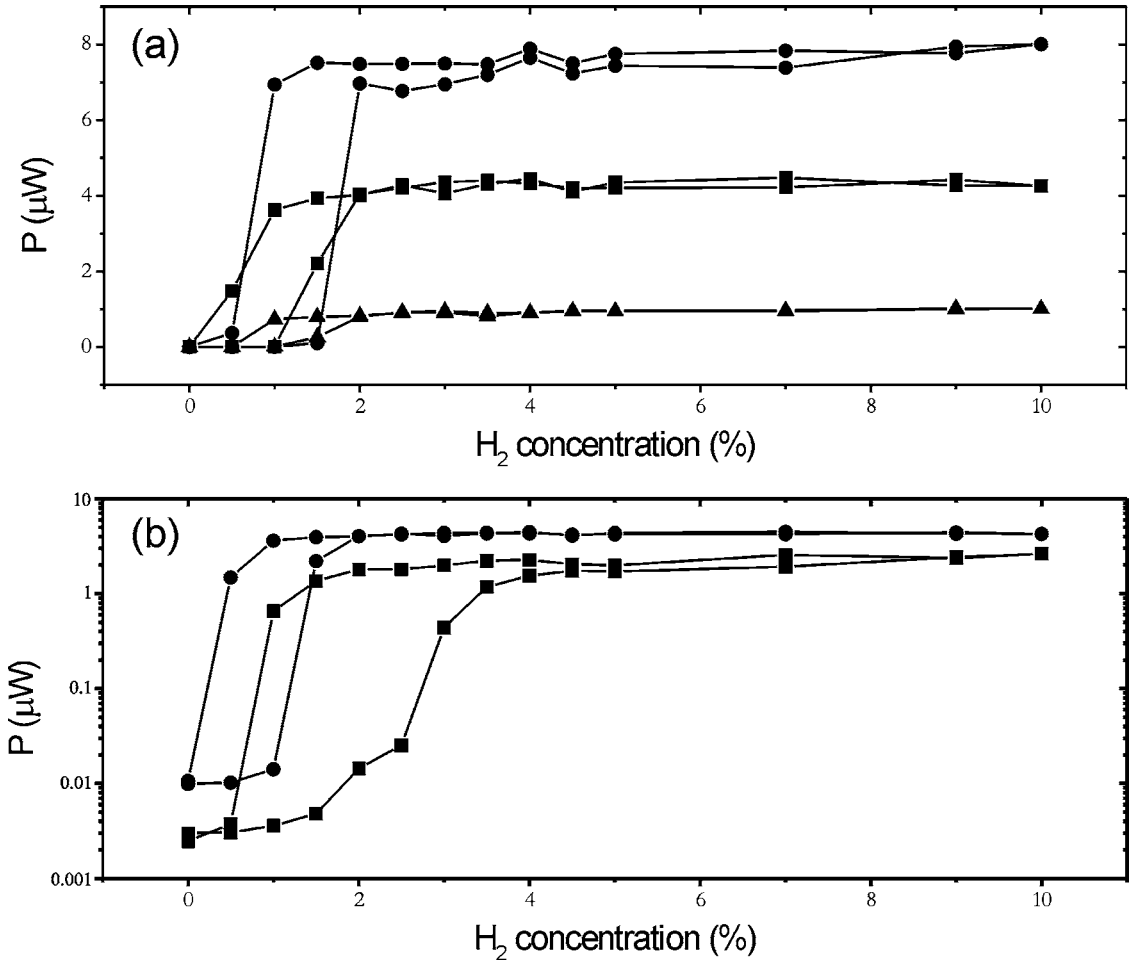

FIG. 3. Response of the detector for (a) three different pump values and (b) two different main cavity conditions.

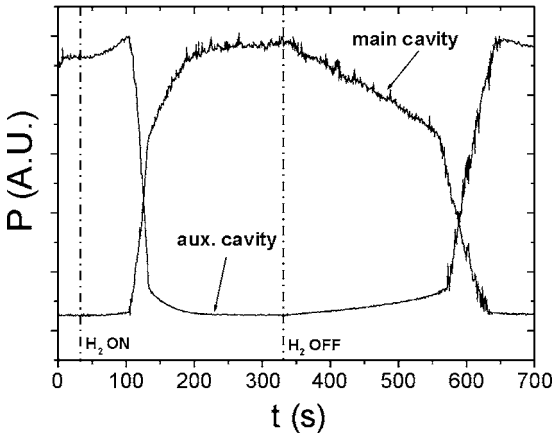

FIG. 4. Time response of the detector when exposed to 4% hydrogen concentration showing the power emitted by both cavities.

the system switch from the auxiliary cavity to the main cavity. This concentration threshold in all three cases remains the same (around 2% hydrogen concentration). Figure 3(b) shows the response of the detector for a pump power of 31 mW for two different main cavity conditions. When the losses of the main cavity are increased (squares) the concentration threshold of the detector shifts to higher values. Therefore, adjusting the reflecting elements of the cavity which contains the sensing element, the threshold of the detector can be tuned.

The response of the detector also clearly shows the hysteresis behavior of the system. This hysteresis is quite convenient for an alarm system in order to achieve stable functioning in the vicinity of the threshold. In this case, the competition between both cavities gives us the chance to stabilize the detection.

Figure 4 shows the typical time response of the detector when the sensing element was exposed to 4% hydrogen concentration and for a pump power of 31 mW. It takes about 150 s to reach 90% of the overall power change, while the recovery time after the hydrogen flow shutdown was larger, about 300 s. This result is somewhat different to others previously reported, when using Pd-coated tapered fiber hydrogen sensors.[7] Although the dynamic behavior of the sensing element when exposed to hydrogen is much slower than the dynamics of the laser, the response of the detector is governed by the competition between both laser cavities. When the hydrogen concentration increases above the detector's threshold, the auxiliary cavity tends to keep on lasing and, therefore, the time response of the detector is greater than that of the sensing element itself (around 90 s). On the contrary, when the main cavity is lasing and the hydrogen concentration decreases below the detection level, the recovery time is lower than that of the sensing element. As the hydrogen concentration decreases, the losses of the sensing element increase and therefore the quality of the main cavity decreases. Before the sensor reaches its typical recovery time (around 450 s), the threshold condition of the auxiliary cavity is reached and therefore the main cavity power decreases sharply and the auxiliary cavity starts lasing.

Although the overall power change takes 150 s, the presence of hydrogen can be pointed out as soon as the light emission from the main cavity begins, which in our system happens 80 s after the hydrogen flow was open. This is probably too long for some practical applications. The time response of commercially available hydrogen sensors based on electric means of detection that operate in the range from 0% to the 4%, is typically of the order of 10 s. Nevertheless, we believe that the time response of our detector can be shortened significantly: (1) By optimizing the design of the laser cavities, for example, making the round-trip losses of both cavities closer, and (2) by shortening the time response of the sensor head itself. In this sense, Xu *et al.*,[9] have reported recently a new technique, which could be potentially applied to our sensor head, that reduces the time response of resistive-type palladium hydrogen sensors down to few tens of milliseconds.

We have presented an original scheme for a hydrogen detector system based on an erbium-doped fiber laser with two coupled cavities and a Pd-coated tapered fiber acting as the hydrogen sensing element within one of the laser cavities. When the sensing element is exposed to a hydrogen atmosphere, its attenuation decreases changing the cavity losses, which leads the system to switch lasing from the wavelength of the auxiliary cavity to the wavelength of the cavity that contains the sensing element. The detector shows hysteresis and the output is codified with two well differentiated wavelengths. The detection level can be adjusted by changing the reflective elements of the cavity containing the sensing element. Our results could be extended to detect different physical and chemical parameters by changing the sensing element.

This work has been supported by the Ministerio de Ciencia y Tecnología of Spain (TIC2002-04527-C02-01) and the Generalitat Valenciana (Grupos 03/227).

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