New optical cell design for pollutant detection

Olga M. Conde, Sergio García, Jesús M. Mirapeix, Juan Echevarría, Francisco J. Madruga,
José M. López-Higuera
Grupo de Ingeniería Fotónica; Dept. T.E.I.S.A.
Universidad de Cantabria, Avda.Los Castros s/n, 39005 Santander, Spain

ABSTRACT

A new and simple optical gas cell, developed to perform as the transducer for a methane fiber optic sensor, is presented. Its main advantage lies in the fact that, employing low-cost components and an easy alignment process, the path where the light beam is in contact with the pollutant becomes maximized to as much as four times the physical length of the optical cell. This increment in optical length is directly related to the optimization of the fiber optic sensor since low levels of methane concentration can be measured as stated by Beer-Lambert's law. One of the main advantages of this design lies in the simplicity of the optic cell, which makes it very interesting when one has to deal with the manufacturing process. The cell is mounted on a reflective configuration which improves the connection as only one optical fiber is employed. The main elements of the cell are an optical fiber, a mirror of high reflectivity and a converging lens arranged in an appropriate fashion to obtain the desired result. With this relatively reduced and low cost set of devices the insertion losses achieved are in the range of the 4-5 dB's.

Keywords: Gas cell, multipass cell, gas sensor.

1. INTRODUCTION

Detection of pollutant compounds has become an important application field to carry out tasks related with air quality monitoring of urban and industrial environments, not only for reasons of occupational safety but also for public health motivation. Detection of combustible gases through the employment of optical methods has revealed as an efficient approach achieving generally lower detection limits than alternative techniques[1] such as electrochemical, catalytic, solid-state, etc. The optical absorption process of an specific compound is accomplished as stated by the well-known Beer-Lambert's law:

$$I = I_0 \, 10^{-\alpha(\lambda)\, C\, L} \qquad (1)$$

where I_0 is the intensity of incident energy; I is the intensity of transmitted light; $\alpha(\lambda)$ is the absorption coefficient of the gaseous compound that depends on the wavelength emitted by the light source, λ; at the center of the corresponding absorption line of the compound , λ_0, this coefficient becomes maximum reaching a value of α_0; C is the gas concentration and, finally, L is the pathlength where the gas interacts with the luminous beam.

After a careful observation of Beer-Lambert's law, one can deduce that the sensitivity of the system, limited by the ability of detection of intensity of transmitted light I, will be improved by:

- having a channel and transducer system with insertion losses as low as possible
- minimizing the noise inherent in all electro-optical system: source, detector, etc.

olga.conde@unican.es; Phone: + 34 924 201539; Fax: +34 942 200877; http://www.teisa.unican.es/gif; Photonic Engineering Group, Dep. TEISA, University of Cantabria, Avda. Los Castros s/n, 39005 Santander, SPAIN

Obviously, in the design process of a gas cell, the accomplishment of both conditions will determine the excellence of the sensor.

When WMS (Wavelength Modulation Spectroscopy)[2] is applied as detection technique, a highly coherent source light, typically a DFB laser diode, is employed to be able to sweep the absorption line of the gas. The laser driving current is modulated sinusoidally with a signal of frequency *f*. Under certain modulation conditions, at the reception end, the detection of the harmonics of this modulation frequency provides information about the concentration of the gas. The ratiometric detection of the two first harmonics has the value:

$$\frac{I_{2f}}{I_f} = \frac{-2\,k\,\alpha_0\,C\,L}{\eta} \tag{2}$$

where k is a constant value that depends on the half-width of the absorption line and the amplitude of the modulation and η is the intensity modulation index.

From Equation (2), a cell with a large pathlength L will allow an improvement in sensitivity to the gas concentration. This is the operation principle underlying the design of large volume multipass cells[3,4]. But, when one has to face field operative conditions, it is important to have rugged and robust gas cells, able to operate in a harsh environment, where the bulky multipass cells are difficult to manage and the careful alignment process required by them complex to be achieved.

The main motivation of this work is to design a new gas cell with a reduced volume and a significant improvement in pathlength. Between the existing 'compact' gas cells, two configurations can be distinguished:

- *Transmissive* [5,6] : typically based on a collimation scheme between the two fibers that constitute the transmission channel. Light coupling is done through a lens system and the space between lenses is open to the gas.
- *Reflective* [7] : the transmission channel is conformed by only one optical fiber allowing a reduction in cost of the final system. Light is coupled into the cell and afterwards reflected by a mirror located at the other extreme of the cell, the information about the gas absorption comes on the reflected intensity. Just only by construction, this kind of cells have double pathlength than those equivalent with a transmission scheme.

The design scheme adopted for the present cell follows the line of reflective configuration but with its elements arranged in such a manner that the pathlength of the resultant cell is not twice its physical size, but four times increasing therefore the sensitivity of the detection. Even more, the structure of the optical system allows a certain degree of misalignment given rise to a robust field transducer.

2. CELL DESCRIPTION

The elements that conform the 4-pass gas cell are the following:

- *Metallic ferrule:* this is one of the key elements that makes the cell able to implement the four passes inside it. The ceramic ferrule of a standard FC/PC connector has been metalized with gold following a process of vacuum deposition.
- *Lens:* this element has the purpose of collimating the light beam coming from the single mode fiber into the cell. It must also focalize the reentrant beam, after the four passes, into the fiber core. The type of lens selected is a biconvex one made of BK7 material and has a physical diameter of 10 mm. and a focal distance of 10 mm.
- *Mirror*: situated at the distant end of the cell. Studies have been carried out in order to choose the best coating for this mirror. Finally, a gold coating has been selected because, at the operation wavelength of 1666 nm. (line Q6 of methane), presents a reflection coefficient of 98% much better than the silver coating that presents a coefficient of 95%. A better reflection coefficient will result in a lower insertion loss. Taking into account that 3 reflections will arise from the 4-pass cell, an effort in the reduction of the reflection coefficient will improve the behavior of the gas cell and will enhance the sensitivity of the global system.
- *Cylindrical body*: this element of the gas cell will play the role of being the gas inlet and outlet as the cylinder is periodically perforated to allow the flux of the gaseous compound. It has been made of stainless steel to prevent any kind of corrosion. In order to get rid of any unwanted reflections, the internal surface of the cylinder has been covered with black paint.

The aspect of the gas cell, as well as its maximum dimension, is shown in Figure 1.

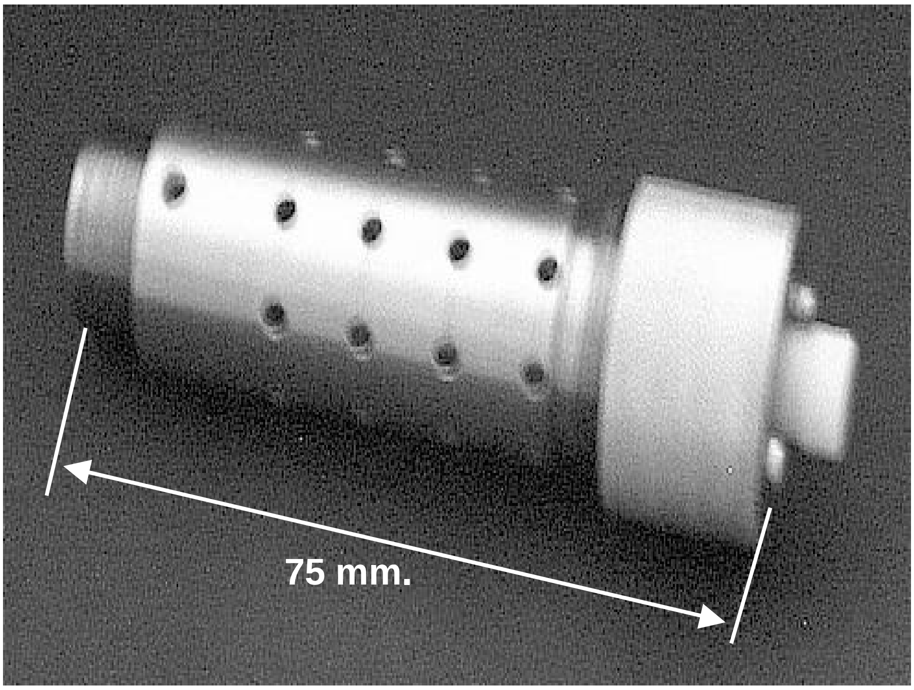

Figure 1: Front view of the gas transducer with its associated dimension.

The mirror is placed on a stepped circular structure designed for the diameter of the mirror, the external surface of this structure is threaded and inserted into the cylindrical body. A different degree of insertion will lead to a different optical pathlength, this element can be viewed on the left side of Figure 1. Also, this figure shows that the access to the gas cell is done by means of a FC/PC connector that has been previously should be metalized with gold. For the sake of completeness, Figure 2 shows a photograph with all the elements that conform the gas cell.

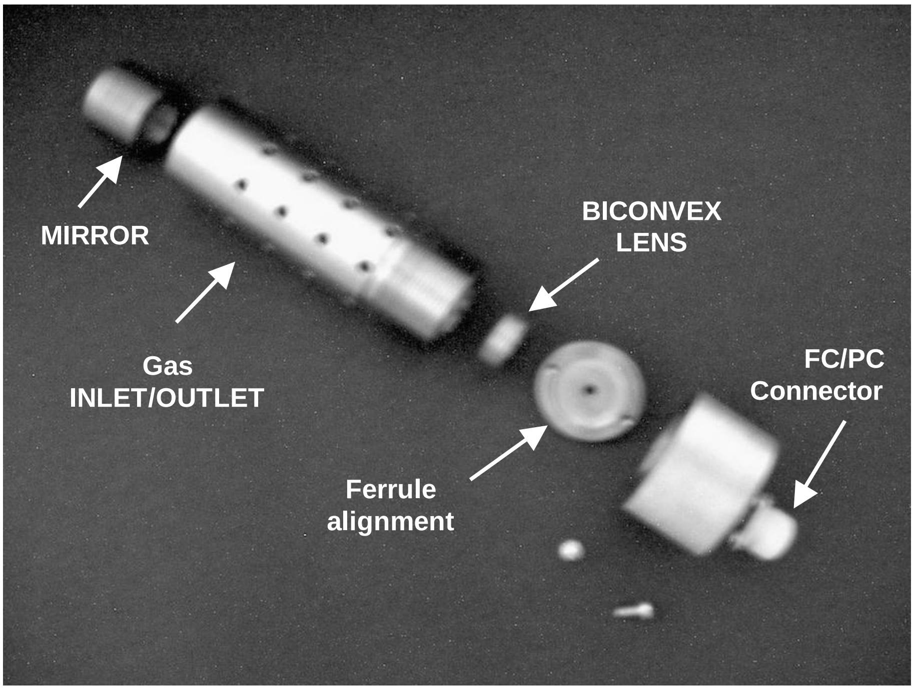

Figure 2: Gas cell elements.

2. THEORETICAL ANALYSIS

The mechanism that allows the four passes and the recovery of the reflected beam is as follows: the incident beam from the fiber core is collimated by the lens and launched to the mirror; afterwards, it is reflected into the metallic ferrule where it is again reflected and redirected to the mirror; there, the third reflection is produced and the light beam reach the fiber core after a final pass through the biconvex lens. The basis of the gas cell performance is centered on the fact that the fiber core and the reflection point on the metallic ferrule are *conjugated points* with respect to the lens-mirror system [8] and therefore, the reciprocity principle is achieved, favoring the reentrant condition of the light beam into the fiber core independently on the mirror tilt. This optical set-up is also independent on the longitudinal translations giving rise to the possibility of analysis of different optical pathlengths without the necessity of an strict alignment process.

In an early simulation step, previous to the manufacture one, the gas cell behavior has been analyzed employing the optical software ZEMAX® (Focus Software Inc.) [9]. Figure 3 shows the ray-tracing resultant for the present gas cell. In this figure, the main elements of the transducer can be identified as well as the four passes path. Apart from the basic cell performance, several studies have been carried out in order to prevent, as much as possible, the effects of the different errors involved in the manufacture process: mirror tilt, focal point longitudinal displacement, focal point lateral displacement, etc. As result of these studies, different mechanical elements have been designed in order to be as independent as possible on this manufacturing tolerances.

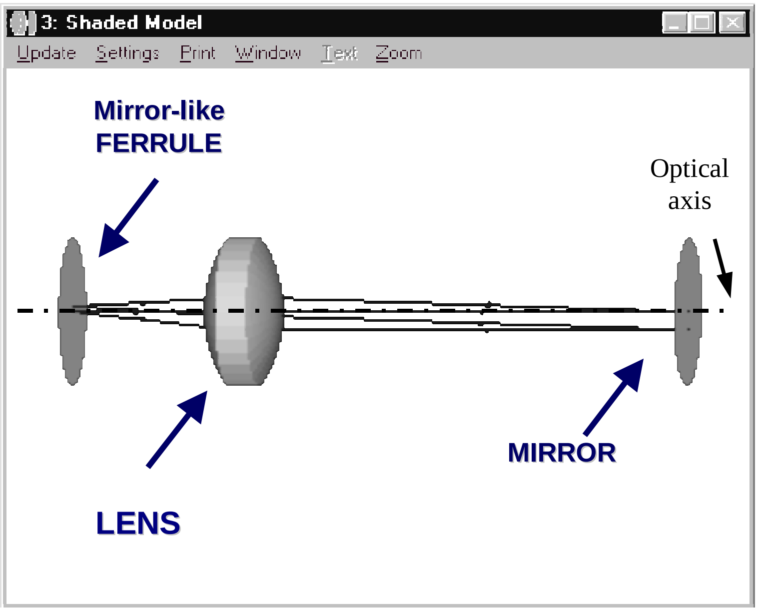

Figure 3: Ray-tracing into the transducer.

- *Mirror tilt*: Figure 4 represents the IL (Insertion Losses) evolution as a function of the tilt angle of the distant mirror. The 4-pass cell IL are compared with the IL of a traditional collimating transmissive gas cell of 35 mm. of pathlength realized with GRIN lenses of 0.25 pitch, in this last case, the tilt is introduced in one lens respect to the other. As said in the previous section, the 4-pass cell is more tolerant to tilt angles and can support until 0.8º without a significant degradation of IL. Furthermore, Figure 4 also reflects the best behavior of the gold coating respect to the silver one.

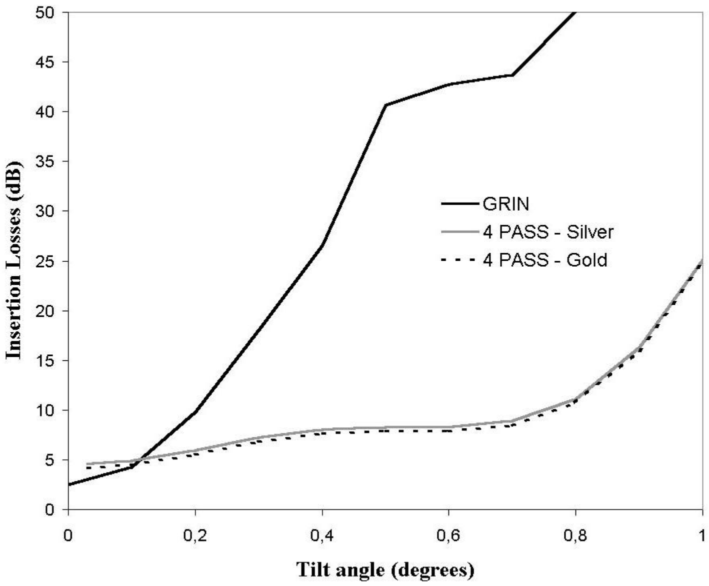

Figure 4: Insertion Loss evaluation as a function of the tilt angle of the elements from the optical axis.

- *Focal longitudinal displacement*: Figure 5 represents the IL evolution as the ferrule is separated from the lens, i.e. which is the effect of putting the ferrule away from the focal point of the biconvex lens. It can be observed that there is a minimum for the IL. This research results in a change of the cell design putting the lens in a fixed position, inside the cylindrical body, an the ferrule access in a mobile element easily matched during the calibration process.

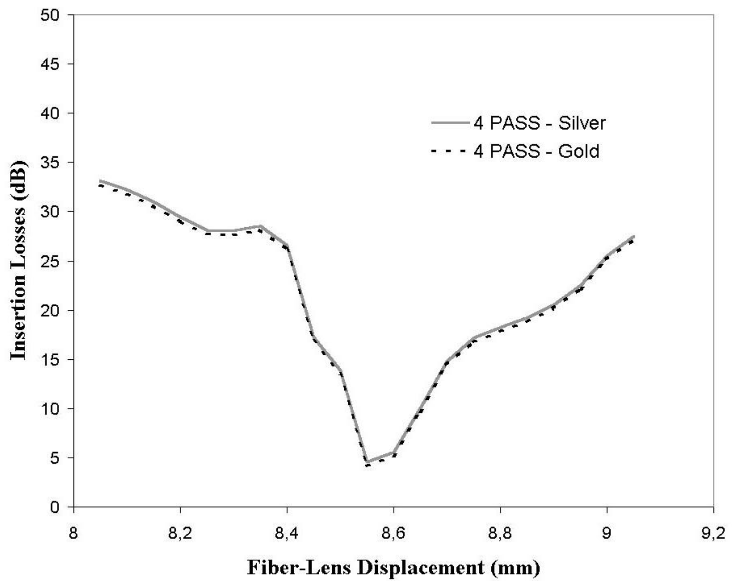

Figure 5: Insertion Losses as function of the displacement of the ferrule from the lens focal point.

- *Focal longitudinal displacement*: Figure 6 represents the IL of the 4-pass cell as the ferrule is separate from the optical axis. To assure a ferrule position aligned to the optical axis, a brass element was introduced inside the cell, this last element can be easily identified in Figure 2.

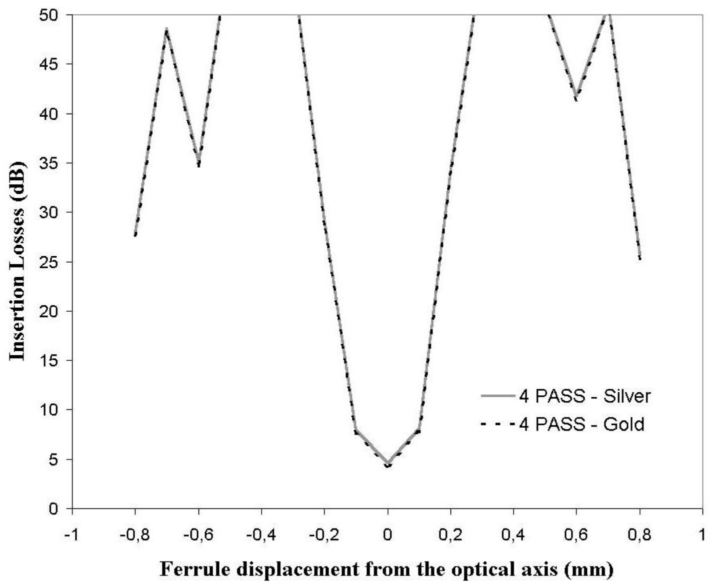

Figure 6: Insertion Losses as function of the lateral displacement of the ferrule from the optical axis.

3. EXPERIMENTAL CHARACTERIZATION

After the simulation process, the gas cell construction result in the transducer shown in Figures 1 and 2. The first step in order to undertake the experimental characterization was the measurement of the real insertion losses produced for the gas cell. To this end, the laboratory set-up depicted in Figure 7 was arranged. As the configuration of the gas cell was reflective, an element as an optical coupler or an optical circulator must be included in the set-up.

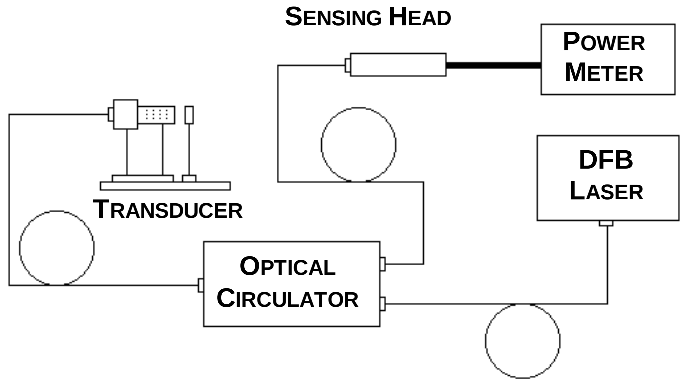

Figure 7: Laboratory set-up for the evaluation of the insertion losses.

The measured insertion losses were about 5.46 dB that, according to Figure 4, are in the order of the predicted ones. These losses were the corresponding for an optical pathlength of 220 mm. resulting from the four passes over a physical longitude of 55 mm. When compared with traditional GRIN collimating fiber-lenses, and for an optical, these insertion losses are not too large and even better that some commercial systems that offer insertion losses of 10 dB for 25 cm. open-air path. Apart from this, it has to be taken into account that this optical path is achieved with a very compact gas cell of only 70-75 mm. long. The received optical power, when the center wavelength of the DFB laser is changed by means of temperature control, is shown in Figure 8.

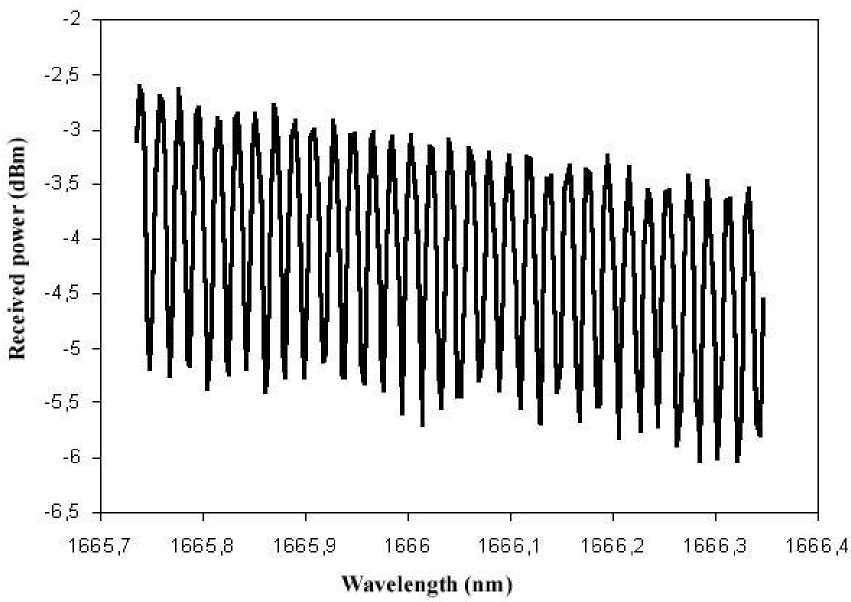

Figure 8: Interferometric noise in the 4-pass gas cell when a high coherent light is applied.

If WMS is applied as detection technique, another viewpoint of the gas cell performance is how it behaves in terms of interferometric noise. The interferometric noise appears as the coherence of the light source is high. In Figure 8, it can be appreciated that a Fabry-Perot etalon is present in the measurement. After the process of painting of the internal surface of the cylindrical body, this noise has been reduced nearly 2 dB. Obviously, if a less coherent source would be applied, the effect of the interferometric noise would become minimized. Works in this sense are in course with good expected results.

4. CONCLUSIONS

This work has been focused in the design of a gas cell for an optical sensor system dedicated to the measurement of gaseous compounds. Parameters as insertion losses, independence of optical misalignments and interference effects have been thoroughly analyzed. The new cell, designed with low-cost elements, is able to achieve an optical path of four times its physical size allowing the detection of lower concentrations of contaminant. The scope of application of the gas cell will be larger due to its relative low insertion losses, large optical path, easy alignment process and low cost. The gas cell has been constructed and measured in the laboratory achieving insertion losses close to the predicted ones in the simulation step of the design process. As the cell is based on a reflective configuration, it presents large interferometric noise levels [2] when it is employed for a detection system based on WMS and using coherent light. To decrease this noise levels, works are in progress using incoherent interrogation light.

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