Novel multipass absorption cell for carbon dioxide detection

Olga M. Conde, Sergio García, Roberto García, Adolfo Cobo, José M. López-Higuera
Grupo de Ingeniería Fotónica; Dept. T.E.I.S.A.
Universidad de Cantabria, Avda.Los Castros s/n, 39005 Santander, S pain

ABSTRACT

Infrared Spectroscopy has been confirmed as an interesting technique in the process of environmental pollution monitoring. This detection technique is related to the absorption coefficient of each hazardous gaseous compound. When this coefficient is low, as in the case of carbon dioxide, or else, when the gas concentration is small, the transducer has to be designed in order to maximize the interaction between the gaseous compound and the light beam. In addition, the gas cell must be portable, low-size and cost effective. The multipass absorption cell presented in this communication satisfies both requirements, compact physical size and large interaction length. The design is based on a cylindrical cell with a reflective configuration. The dimensions of this cell are carefully adjusted in order to have a completely closed optical path around the contaminant. With this structure, an optical path about 313 cm. could be achieved with a physical size of 20 cm. In this communication, theoretical simulation and preliminary results will be presented to demonstrate the functionality and versatility of the developed gas cell.

Keywords: Gas cell, multipass cell, gas sensor.

1. INTRODUCTION

Nowadays, environmental safety have gained a great impact, especially all topics related with the measurement and control of emissions of gaseous pollutants (methane and carbon monoxide or dioxide) to the atmosphere from cars, factories, dumps, etc. The necessity of knowing the presence and concentration of these pollutants compel us to design sensor systems very accurate and very sensitive. One of the multiple techniques to measure concentrations is the absorption spectroscopy which allows to monitor a large number of atmospheric trace gases. This method is based on the gases property of absorbing light at an specific wavelengths. Most of the time, this absorption is very weak, so it is needed a great sensibility in the equipments to detect it.

The transmission of laser light through an absorbing gas can be expressed by the Lambert –Beer's law as:

$$I = I_0 \exp\left(-\alpha\, C\, L\right) \tag{1}$$

where I is the transmitted intensity, I_0 the incident intensity, C the gas concentration that needs to be measured, α its absorption coefficient and finally, L is the interaction length between light and gas. Reach a better sensibility implies to keep the sample and the light more time in contact, i.e. obtain an interaction length as long as possible. When environmental monitoring with a portable equipment must be done, the achievement of such a long length can suppose a problem. The solution for this problem is the use of multipass optical systems as the one presented in this paper.

Multipass cells allow large lengths in small volumes which is the optimum condition for absorption experiments in field conditions. There are different types of multipass systems with optical path lengths much larger than the longitudinal dimension of the sensor. Traditionally, the more well-known are the White [1] and the Herriott cells [2] . The first one makes use of three spherical concave mirrors (A, B, C) with the same radius of curvature, its design is showed in Figure 1. It's a confocal system and the light enters and goes out through different holes.

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

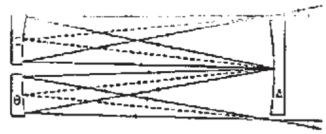

Figure 1: Scheme of the White cell.

About the Herriott cell, two possibilities can be found, the conventional Herriott cell [2] and the astigmatic one [7]. The first one utilizes two spherical and identical mirrors separated by a distance between *f* and *2f*, being *f* the focal length of the mirrors. Apart from this, the light enters and goes out through an unique port. In the astigmatic case, the mirrors have different curvature radius. An example of these cells is depicted in Figure 2. All the theoretical development about these cells can be found in [3, 4, 5, 6, 7].

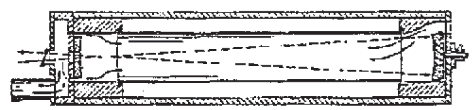

Figure 2: Scheme of the Herriot cell.

The cell presented in this paper is also a multipass cell having two ports to enter and extract the light beam. Figure 3 gives a schematic idea about the ray tracing inside this cylindrical cell. The beam travels thesurface of the cylinder in a periodic form, keeping the same arc among neighboring spots, except the first and the last arcs.

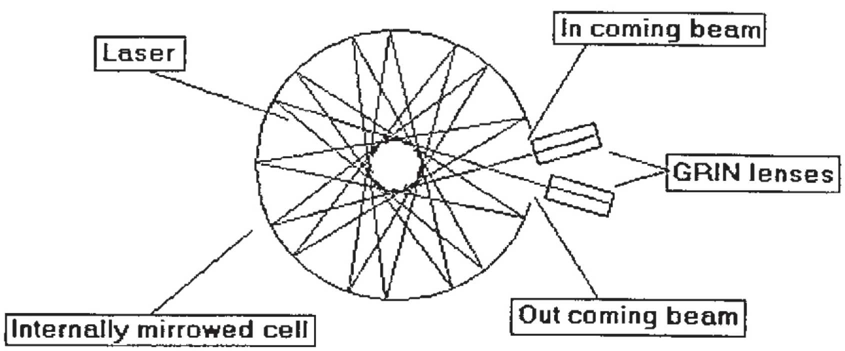

Figure 3: Lateral view of a cylindrical cell with a schematic ray tracing.

This kind of cell, similar to the one used in [8] for current sensing, let us improve the interaction path or the time in which the laser beam is in contact with the gas object of the analysis.

2. CELL DESCRIPTION

The design of this multireflective optical system is relatively simple and needs three elements: the cylindrical surface and its coating, the lenses and the laser source as Figure 4 shows. The laser beam is collimated by the lens before it goes into the cell. Afterwards, it passes through a little hole in the surface. Obviously, this hole should be large enough to avoid any possible vignette effects that would increase the diffraction effects and would reduce the laser beam intensity.

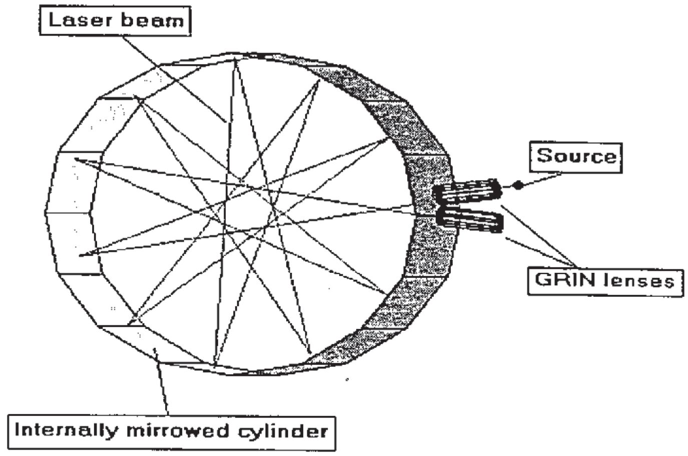

Figure 4: Elements of the cylindrical cell.

Figure 5 presents more realistic aspect of the multipass gas cell.

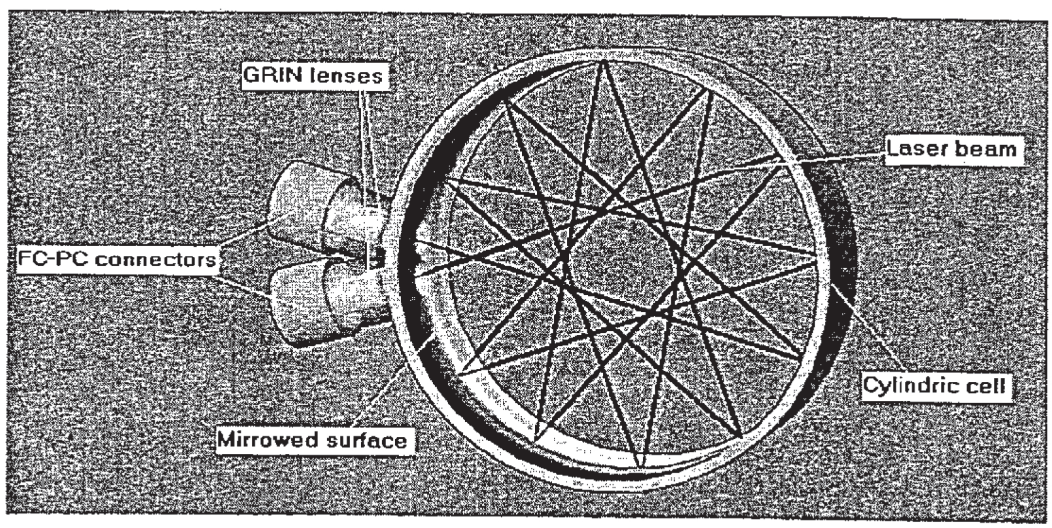

Figure 5: Cell design.

This last multipass model presents three constituent elements:

- A metallic component where the emission and reception systems will be connected. This component will include the fiber connectors and the two lenses which will collimate the light sent by the source and collect the laser beam returned by the cell.
- The optical fiber will be connected through a FC-PC connector with a displacement mechanism to adjust the optical system source-lens.
- The third part is the cylindrical cavity. Gold coating has been chosen in spite of silver because its best behavior in harsh environments [9], [10], gold is more resistant than silver in corrosive atmospheres where the sensor is supposed to work. The reflection coefficients of different coatings are shown, for the infrared area of the spectrum, in Figure 6.

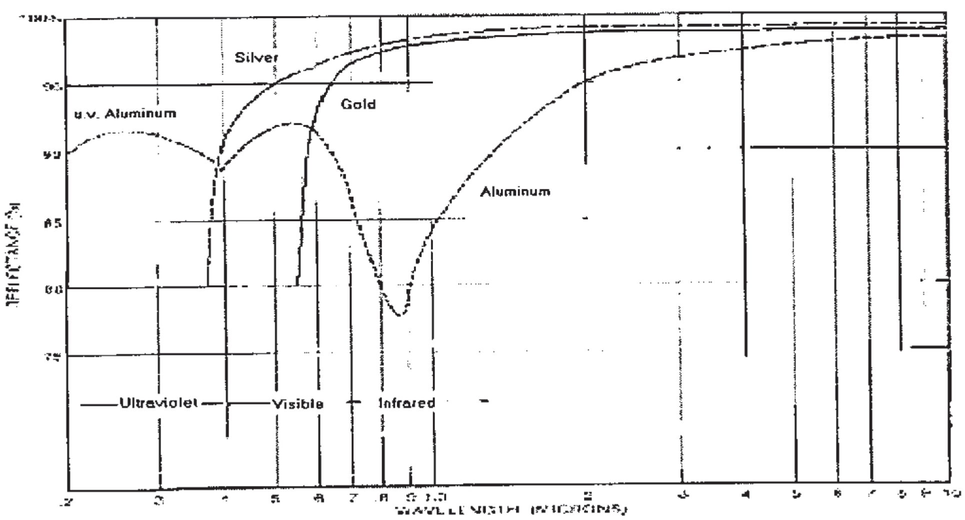

Figure 6: Reflectance of different metals.

The analysis of the designed cell has been carried out with the optical software ZEMAX [11]. The lenses are two GRIN ones of 0.25 pitch designed by Nippon Sheet Glass for a wavelength of 1670 nm. This is one of the best systems to collimate the divergent output beam of the fiber. Finally, the two lenses have a little tilt respect to the main axis to achieve the right ray tracing inside the cell. This tilt will control the number of reflections and, with it, the optical path travel by the light inside the cylindrical gas cell.

With all these characteristics and elements, the simulation with the ZEMAX software arises the ray tracing showed in Figure 7. In this figure, the laser beam has only one ray, the main one, for visualization reasons. With more rays, would be very difficult to differentiate the ray tracing. With the present configuration, it can be seen that the laser makes fifteen reflections increasing therefore the optical path.

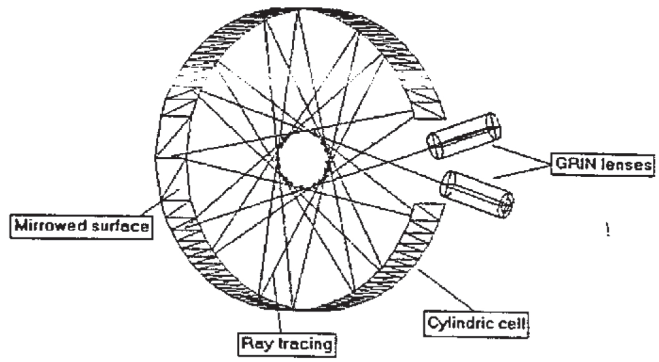

Figure 7: Ray tracing inside the cell.

3. THEORETICAL ANALYSIS

All the theoretical development of this multipass cell is based upon a first assumption, the curvature radius of the curved surface is much bigger than the laser spots diameter. So, when the laser hits the reflective surface, this last one works as if it were a flat mirror. Therefore, all the rays of the beam are reflected with the same angle and the divergence becomes inappreciable.

With this assumption in mind, if the collimated beam comes into the cell from the **A** point, separated a distance **Ro** from the cell center and with an incident angle β, it will hit the reflective surface in point **B** making an angle α with the normal, i.e. with the radius of the circumference. This raytracing is represented in Figure 8.a.

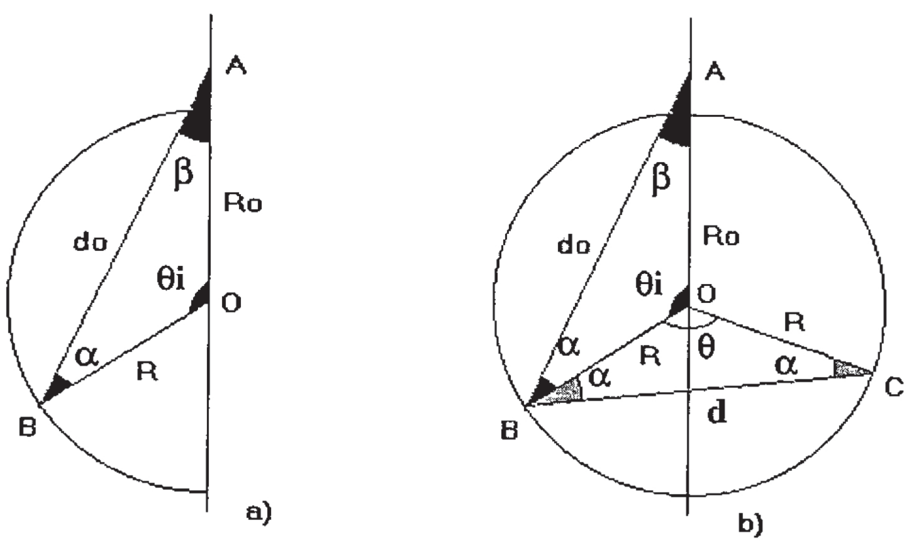

Figure 8: Involved trigonometry.

Following Snell's law, the next ray will be reflected from the **B** point with the same angle **α** (Figure 8. b.) and the ray will travel this way until it comes out of the cell, passing again through the point A, after hitting n times the reflective surface and running an optical path $\mathbf{d_T}$.

It is useful to distinguish between the first and the n-th reflection, *main* reflections, and all the other ones, from now on called *secondary* reflections, because they have different geometrical characteristics. The path length between two secondary reflection points is always the same, **d**, and it differs from the distance, $\mathbf{d_0}$, between the point A and the first or last reflection points. The distance $\mathbf{d_0}$, Figure 8.a., comes from the expression:

$$d_0^2 = R^2 + R_0^2 - 2RR_0\cos\theta_i \Rightarrow d_0 = \sqrt{R^2 + R_0^2 - 2RR_0\cos\theta_i} \qquad (2)$$

obtained after application of the Cosine Law, where $\boldsymbol{\theta_i}$ is the aperture angle from the entrance point to the first reflection. This aperture angle is the same that the one for the last reflection point but differs from the angles **θ** formed by two successive secondary reflections. This angle **θ** provide the angular advance among the consecutive secondary reflections and it is always the same.

The **n-th** angle, run by the light in its travel around the cell, will be:

$$\theta_n = \theta_i + (n-1)\theta \qquad (3)$$

The distance **d** between consecutive secondary reflection points, Figure 8.b, is obtained applying the Sine Law:

$$\frac{d}{\sin\theta} = \frac{R}{\sin\alpha} \Rightarrow d = \frac{R\sin\theta}{\sin\alpha} \quad \text{where} \quad \theta = \pi - 2\alpha \qquad (4)$$

therefore,

$$d = \frac{R\sin\theta}{\sin\alpha} = \frac{R\sin(\pi - 2\alpha)}{\sin\alpha} = \frac{R[\sin\pi\cos 2\alpha - \cos\pi\sin 2\alpha]}{\sin\alpha} = \frac{R\sin 2\alpha}{\sin\alpha} \qquad (5)$$

and finally, the distance **d** will be:

$$d = 2R\cos\alpha \qquad (6)$$

So, the complete optical path $\mathbf{d_T}$ will be:

$$d_T = 2d_0 + nd \qquad (7)$$

where **n** is the number of secondary reflections made over the reflective surface.

Expanding the total optical path (7) making use of (2) and (6):

$$d_T = 2\sqrt{R^2 + R_0^2 - 2RR_0\cos\theta_i} + 2nR\cos\alpha \qquad (8)$$

writing $\cos\alpha$ as a function of θ_i , Figure 8.a., applying the Sine law again:

$$\frac{R_0}{\sin\alpha} = \frac{d_0}{\sin\theta_i} \Rightarrow \sin\alpha = \frac{R_0 \sin\theta_i}{d_0} \Rightarrow \cos\alpha = \sqrt{1 - \frac{R_0^2 \sin^2\theta_i}{d_0^2}} \quad (9)$$

and then, putting d_0 and $\cos\alpha$ as a function of θ_i, it's possible to express d_T as funtion of θ_i too:

$$d_T = 2\sqrt{R^2 + R_0^2 - 2RR_0 \cos\theta_i} + 2nR\sqrt{1 - \frac{R_0^2 \sin^2\theta_i}{R^2 + R_0^2 2RR_0 \cos\theta_i}} \quad (10)$$

The raytracing of the light inside the cavity depends of the β angle because modifying this angle we are modifying θi, α and with them, the number of possible reflections. So, with one only parameter, the travel of light and the interaction length can be controlled.

Finally, taking the origin of turns on the segment OA the closure condition to take out the laser beam is:

$$2\theta_i + n\theta = 2m\pi \quad (11)$$

where **n** and **m** are integers and represent the number of reflections and the number of complete turns fulfilled by the light respectively.

4. CONCLUSIONS

A new multipass optical system for the detection of hazardous gaseous pollutants has been designed. The main advantage of the new cell is the large interaction length achieved in a small volume. The transducer has an optimun interaction path-volumen ratio so it can be a good option for the spectroscopy on field test due to its great portability.

Another important characteristic of this new cell is the facility to make the transducer and to control its performance. Changing the tilt of the incident ray, it is possible to modify the interaction length and the sensibility of the transducer. Of course, working with reflective surfaces there are always diffuse reflections [12, 13, 14, 15] which would produce noise in the signal but, in this case, the effect can be neglected attending to the properties of the cell.

The main problem of this cell is the dirtiness that can to modify the reflectance of the reflective surface making the performance of the system gets worse. This problem could be avoided covering the both sides of the cylinder. These covers should have holes on the surface to let the gas flow through the cavity. At the moment, the present system is in simulation process, it will be incorporated as soon as possible to a new spectroscopic optical system being developed in the University of Cantabria.

ACKNOWLEDGEMENTS

Authors thank the European Union and the Spanish Government for its support through the TIC'98-0397-C03-02 and 1FD97-2257 (SOGAM) Projects.