Design and implementation of a sensor for environmental control based on fiber optics

Yamelys Navarro Becerra, Cesar Orlando Torres, Francisco J Giacometto
Laboratorio de Óptica e Informática, Universidad Popular del Cesar,
Sede balneario Hurtado, Valledupar, Cesar – Colombia

E-mail: cesartorres@unicesar.edu.co

Abstract. In this paper, we developed and implemented experimentally a prototype sensor, with application to environmental monitoring. The prototype sensor is constituted by a capillary in which the gaseous fluid is set to move (gas or pollutant) and using the intensity of light transmitted through an optical fiber, we could obtain measurements of light intensity according to the presence of the pollutant, in our case correlated measures or levels of intensity of SO2 with the intensity of light that the sensor designed was able to measure, the sensor had two indicators of pollution lighting a red color when levels exceed the regulations (Resolution 909 of 2008) and green when everything is in its normal, the signal was issued electronically by a phototransistor fdt317 reference. With intensity meter Newport. And respectively a detector upon detection of the presence of the contaminant to infrared light showed an amount proportional to the rate of contamination.

1. Introduction
One of the most important concerns of our time is the environmental quality of the ecosystem. As is well known in the past 150 years, Earth has changed the natural structure of its atmosphere and hydrosphere especially for the activities already undertaken by humans. For this reason the adequate protection and conservation of the environment represents one of the most important challenges facing humanity.

Refractive index measurements were performed for a long time through refractometers, such as Abbe, Jamin, Pulfrich, Rayleigh, Hilgen-Chance, and others [1]. Many of these devices are based on critical angle method and others use interferometric techniques. Recently a new class of refractometers had appeared, these are based on microfluidics, the science of confined fluids on a micrometer scale. Some new refractometers work with microcavities, Fabry-Perot type [2], diffraction gratings [3], optical waveguides [4], photonic crystals microcavities [5], nanowire evanescent field interaction [6] and micro-ring resonators [7]. Refractometers that use diffraction gratings are arranged parallel channels 50 μm wide, completely filled with fluid. The optical waveguides simultaneously confine light and the substance to be measured at the core of the waveguide.

Two-dimensional photonic crystal microcavities enable the phase shift of resonant wavelength. The interaction of nanowires is done when a tapered fiber, immersed in a transparent and soft polymer interacts through an evanescent field with a fluid in a microchannel, this miniaturized photonic device.

1 To whom any correspondence should be addressed.
which can be integrated in optical elements single chip, may revolutionize chemical analysis. The manufacture of these new kinds of refractometers require exclusive use of expensive manufacturing technology, developed and optimized for different applications in the field of research such as microelectronics.

This article proposes a simple method to identify the refractive index of gaseous pollutants, which flow through a capillary and two fibers assembled in a polymer matrix. Section 2 describes and analyzes the physical principle of operation of proposed refractometer sensor. Section 3 shows the materials and equipment used in its optical configuration. Section 4 describes the calibration of the refractometer method and finally in Section 5 make comments and conclusions on the device developed and shows some data on the status of the pollution emitted by stationary sources in the city of Valledupar, using the prototype sensor, which also contribute to the conservation of the environment.

2. Physical Principle

The equation of lensmaker expresses a relation between the radius of curvature of the lens \( r_1 \) y \( r_2 \), the index of refraction of the lens \( n_1 \) and the medium \( n_m \), where he is immersed, and the focal length \( f \).

The equation for the manufacturer of lenses for thin lenses is defined by the following equation [8]:

\[
\frac{1}{f} = (n_1 - n_m) \left[ \frac{1}{r_1} - \frac{1}{r_2} \right]
\]

This relationship defines an optical element knowing only the radius and refractive indices. When the lens is immersed in air \( n_m = 1 \).

Today you can find optical elements that can change its focal distance. These dynamic elements [9-12] that have sizes and ranges ranging from a few centimeters to large segmented telescope mirrors. Active optical elements usually small compressed piezoelectric actuators that modulate the surface of a mirror. Therefore changing the radio a dynamic element is obtained, yet another way to implement a dynamic element is to change the refractive index \( n_1 \).

![Figure 1. Performance of the focal length as a function of refractive index of the lens. we have assumed that the lens is immersed in a medium with a refractive index of 1.4126.](image-url)
In Figure 1 the behavior of the focal length as a function of refractive index of the lens is shown. This behavior was calculated as in (1) assuming $n_m = 1.4126$, $r_2 = 0.615 \text{ mm}$, $r_1 = -0.615 \text{ mm}$. In the figure is interesting that when the refractive index of the lens is smaller than the environment that surrounds the lens is a negative element. Then when the refractive index of the lens and the means are equal, the focal length is very large, and when the refractive index $n_1$ is larger than $n_m$, the lens is a plus element.

![Figure 2](image.jpg)

**Figure 2.** Diagrams obtained by an optical design program, a capillary lens focusing collimated light.

The situation described by the equation of lensmaker is difficult to achieve when using liquid lenses. Typically a container is required to confine the liquid. This container has walls that have a thickness. In Figure 2, a series of schemes, are made using an optical design program, showing the physical situation when a collimated beam of light is sent to a capillary lens ($r_2 = 0.615 \text{ mm}$, $r_1 = -0.615 \text{ mm}$) immersed in a polymer matrix with a refractive index of 1.4126. The inner diameter of the lens is on the order of 939 μm and outer diameter of 1230 μm. The parameters in the diagrams correspond to the refractive indices of the fluid filled lenses. The capillary walls are built of silica glass with a refractive index of 1.45851. One can show that the lens acts as a negative lens for some values of refractive indices as a positive lens and for other values of refractive indices. It should be noted that if a detector is located very close to the second surface, i.e. after the light exits the lens, the detector receives more energy. This is the physical basis of the proposed Capillary refractometer. It should be mentioned that Figure 2 shows the behavior of light only in the plane of the page. A capillary lens acts as a cylindrical lens, so the spatial distribution of light after the capillary has an elliptical cross section geometry. The size of the ellipse change when different liquids are introduced into the capillary.

### 3. Making Refractometer

To implement the ideas proposed in Section 2, design the optical configuration shown in Figure 3. The light source for Capillary refractometer was a laser stabilized He-Ne ($\lambda = 632.8 \text{ nm}$). The beam intensity shows a Gaussian-type cross section. The fiber was chosen to confine the light and send it was brand multimode fiber Newport (NA = 0.29). This fiber is designed to work under multimode laser red light. The light passing through the capillary showed a elliptical cross section, as mentioned above. The intensity at the axis of the ellipse is more dispersed than in the minor axis, the distribution of light shows that have no rotational symmetry.

As mentioned above Newport fiber used to illuminate the capillary, despite working in multimodal system that wavelength can be used exclusively for the single mode regime, that is established by the experimental setup done, so as to avoid getting other modes obtained by the value defined by the
parameters of the fiber, as these higher modes have nodes in the spatial distribution of light, therefore impossible refractive index measurements in this case the gas flows and acts as a lens dynamics. Figure 2 shows that an elliptical light cone at the outlet of capillary diameter changes as change the gas flowing through the capillary allowing information about the characteristics of the gas. Trying to simulate a configuration in which light coming from the physical infinity, place the capillary containing the light beam at a distance sufficiently far from the capillary tube that carries the gas to be evaluated. With this configuration and using the Fresnel diffraction, the light that reaches the capillary gas will approach a wavefront plane, but its intensity will decrease significantly because most of the light is dispersed and the capillary lens focus only a portion of its beam properly, to try and reduce this situation should optimize the optical design to find the right distance so that the light emitted from the capillary fiber is focused by the capillary tube containing the gas, this can be done using a program optical design or through the experimental setup. Ensuring a good position which corresponds to approximately 1.98 mm of the capillary. In this position the light illuminates the central part of the capillary containing the gas and no further loss of light.

4. Sensor Calibration
Only when the capillary refractometer is constructed, the calibration curve is obtained using for this the following methodology. Light from a He-Ne laser was sent to the refractometer through the fiber Newport. The output side of the 100-125 um fiber was coupled to the Newport detector Model 1815-C, ref. 818 - SL. To levels of stable light intensity He-Ne laser.

Table 1. Meter Specifications intensity of the Newport

| PARAMETER   | CHARACTERISTICS     |
|-------------|---------------------|
| Dimensions  | 3.2X6.0X6.25 inches |
| Weight      | 1.5Lb               |
| Coating        | ABS Plastic         |
|---------------|---------------------|
| Connectors    | BNC input           |
| power         | 6x1.5 volt/amps     |
| Battery Life  | 130-1880 Hours      |
| Display       | LCD 3.5 digits      |
| Compatible detectors | long power except 818 - F - SL, 818-F-IR |
| Environmental ranges | ≤90%                |
| Swicht Range  | gain per decade of 6 positions |
| Range         | 2.5                 |

Also comparisons were made between the device designed and one for commercial use known as gas analyzer reference Quintox KM9106 (see Figure 5) produced by Kane International signatures. This device measures the concentrations of carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), molecular oxygen (O2) and hydrocarbons (HC), ambient temperature, stream temperature. It has an oxygen sensor, particle filter, a filter Zufre, an internal battery, a connection of a water trap, accessories storage spaces, printer, particle filter, a 285 mm standard shaft, a connection probe with water trap, internal specialized sensors that allow display measures of each parameter driven. It is important to note that the comparison was performed only on measurements of $SO_2$.

Figure 5. Gas analyzer reference mark Quintox KM9106.
5. Measurements
The complete and calibrated device was used for measurements of industrial application in order to ensure monitoring of environmental pollution in environments of this nature, see Figure 6.

Through direct visits to stationary sources was achieved by identifying the most relevant contamination, using as criterion the location, size and volume of production, and once identified three of them were selected, which were analyzed in aspects such as the different processes that go on, the type of fuel used for each source, the frequency with which they perform activities that generate emissions, the technical specifications of the chimneys, and all studies that have been made prior to about air pollution at these facilities and reviewed the relevant permits must be processed to make such broadcasts.

Given that the population under study was the city of Valledupar, which is located in the foothills of the slope suboriental of the Sierra Nevada de Santa Marta in the rich and wide valley formed by rivers Cesar and Guatapuri, which crosses the city and between the Sierra Nevada to the west and east Perija mountain range, which can be seen from the city. Bordered on the north by the municipalities of San Juan del Cesar and Guajira Dibulla, northeast to La Paz, Cesar and Guajira Urumita; Pueblo Bello northwest to cease, on the south by El Paso, Cesar; the southwest and Bosconia Copey, Cesar and the southeast with the Paz Cesar. Valledupar this to 169 m.s.n.m. and the city's average temperature is 28 ºC. the municipality presents from the warm thermal layers to the snow. The Sierra Nevada de Santa Marta, which shares the department of Cesar and Guajira, Magdalena, is the most important mountain system and excel in the municipality of Valledupar Codazzi, the Guardian, Ojeda and Queen. Its hydrographic system is made up of the rivers originating in the Sierra Nevada including Ariguani, Badillo, Boilers, Rio dry. The municipality of Valledupar in its 4493 km2 houses 348,990 inhabitants according to the census conducted by DANE in 2005, is divided into 6 communes, 175 districts includes 25 districts and 140 villages in rural areas. Today 5 industries with approximately 90% devoted to dairy and meat sector remaining.
So in this first phase employed a qualitative approach, based on information leading to knowledge and selection of industries such as Dairy Spring, Fridge Coolesar, Enterprise DPA. (Dairy Partners Americas). Once observed parameters described above are We observed that 2 of these companies have no periodic demands on monitoring and analysis of gas emissions in chimneys with carrying out their work, only carry out research for knowledge management and internal even more focused on the performance, therefore there is no concern for the development of studies contributing to the environment. Once the literature review was achieved in a cautious manner to determine the direct relationship between human health, environment and pollution, to all the conditions caused by the combustion gases and now has joined deaths in the nationally and globally. Taking as a measure pollutants $\text{SO}_2$ and $\text{NO}_2$.

Once the sampling took place with the prototype sensor developed in this research, when applied to one of the industries was identified that the greater the intensity of the presence of the contaminant the infrared light intensity decreased, the result obtained by the intensity meter of Newport, and identifying the hours during which the $\text{SO}_2$ was considered on the allowable limits, the correlation was performed with the control measures with the results shown in Table 2.

Table 2. Results of application of the prototype sensor for environmental monitoring.

| SAMPLING | MEASURE |
|----------|---------|
| 7        | 0.145   |
| 8        | 0.143   |
| 9        | 0.143   |
| 10       | 0.141   |
| 11       | 0.760   |
| 12       | 0.680   |
| 1        | 0.520   |
| 2        | 0.320   |
| 3        | 0.210   |
| 4        | 0.820   |
| 5        | 0.820   |

Decrease is noticeable by 40 and 50% of light in the hours that pollution levels rise.

6. Conclusions
After the investigation we determine the importance of knowing the state of pollution from stationary sources in the city of Valledupar, an issue little studied and required by the competent authorities, just as episodes like this are now allowed the concern to develop a system in this case a prototype sensor for industrial applications to gain control of such pollution.

Pollution is evident by the pollutant $\text{SO}_2$; considered a conventional pollutant (carbon monoxide, particulate matter, sulfur oxides and hydrocarbons) and that once this reaches the atmosphere can be oxidized to $\text{SO}_3$ by different media and react with moisture in the environment to produce sulfuric acid particles are dispersed in the atmosphere as rain, fog, rain, snow or dew, giving rise to a process of acidification of land and water bodies, high concentrations of this pollutant can cause difficulties associated with respiratory and cardiovascular system and even death, depending on the awareness of
each individual, however given that the existence of these industries exceed 10 to 20 years of production and they work at least environmental requirements for emissions of combustion gases.

It is also advantageous that high peaks of NO2 emissions were present throughout the morning, a day in which there is an increased demand for steam from the production processes, but still not determined the limits on resolution 909 by 2008. And the level achieved by the SO2 pollution were located in the hours between 11 noon and 2 pm.

Correlates with the prototype sensor developed the relationship between pollution and the emission of red light is inversely proportional to the levels of contamination, and if it is possible to measure intensity of pollution. The same sensor may have other applications in the chemical industry for example, for measures of degrees brix or sugar content of foods.

Therefore should be required to control these emissions, since if we look at the fuel addressing global warming, a closely related criterion is the temperature, but a tackle emissions analysis according to the most polluting fuels and it became clear that the natural gas temperature at the exit of the chimney gases was 320 - 350 °C, while with coal as fuel was 120 - 180 °C, therefore there is less pollution by using natural gas but higher exit temperature of flue gas that contributes to global warming.

7. References

[1] Sergio Calixto, Martha Rosete-Aguilar, David Monzon-Hernandez, and Vladimir P. Minkovich, “Capillary refractometer integrated in a microfluidic configuration,” Appl. Opt. 47, 843–848 (2008).
[2] Sergio Calixto, Martha Rosete-Aguilar, Francisco J. Sanchez-Marín, and Lizbeth Castañeda-Escobar, “Rod and spherical silica microlenses fabricated by CO2 laser melting Pyramid sensor for segmented mirror alignment,” Appl. Opt. 44, 4547–4556 (2005).
[3] R. S. Longhurst, Geometrical and Physical Optics (Longman, 1973).
[4] P. Domachuk, I. C. M. Littler, M. Cronin-Golomb, and B. J. Eggleton, “Compact resonant integrated microfluidic refractometer,” Appl. Phys. Lett. 88, 093513 (2006).
[5] O. J. A. Schueller, D. C. Duffy, J. A. Rogers, S. T. Brittain, and G. M. Whitesides, “Reconfigurable diffraction gratings based on elastomeric microfluidic devices,” Sens. Actuators, A 78, 149–150 (1999).
[6] S. Campopiano, R. Bernini, L. Zeni, and P. M. Sarro, “Microfluidic sensor based on integrated optical hollow waveguides,” Opt. Lett. 29, 1894–1896 (2004).
[7] E. Chow, A. Grot, L. W. Mirkarimi, M. Sigalas, and G. Girolami, “Ultracompact biochemical sensor built with two-dimensional photonic crystal microcavity,” Opt. Lett. 29, 1093–1095 (2004).
[8] P. Polynkin, A. Polynkin, N. Peyghambarian, and M. Mansuripur, “Evanescent field-based optical fiber sensing device for measuring the refractive index of liquids in microfluidic channels,” Opt. Lett. 30, 1273–1275 (2005).
[9] F. Xu, P. Horak, and G. Brambilla, “Optical microfiber coil resonator refractometric sensor,” Opt. Express 15, 7888–7893 (2007).
[10] M. Born and E. Wolf, Principles of Optics (Pergamon Press, 1975).
[11] G. Vdovin, S. Middelhoek, and P. M. Sarro, “Technology and applications of micromachined silicon adaptive mirrors,” Opt. Eng. 36, 1382–1390 (1997).
[12] www.varioptic.com. They describe a liquid lens based on electrowetting phenomenon.
[13] S. Esposito, E. Pinna, A. Puglisi, A. Tosi, and P. Stefanini, “Pyramid sensor for segmented mirror alignment,” Opt. Lett. 30, 2572–2574 (2005).
[14] R. Duarte-Quiroga and S. Calixto, “Dynamical optical microelements on dye sensitized gels,” Appl. Opt. 39, 3948–3954 (2000).
[15] S. Calixto, “Relief gratings and microlenses fabricated with silicone, Appl. Opt. 46, 5204–5209 (2007).