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Analysis of Improved Low Cost Transmissive Formaldehyde (CH_2O) Ultraviolet Gas Sensor

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Abstract: The Ultraviolet gas sensor specifically designed for Formaldehyde (CH_2O) which consists of low cost components has been simulated using ZEMAX®12. The transmissive gas cell design used aluminum material that is robust and inert material to increase its performance. CAF_2 lens has been replaced with CAF_2 window to reduce the construction cost. Therefore, to collimate the light, compound parabolic concentrator (CPC) structure attached at both ends of the gas cell. The simulated results show the improved gas cell with CAF_2 windows and truncated CPC structure yields the initial power efficiency of 60.72%. However, when the optical path length of the gas sensor being adjusted and reduced down to 25 mm, the power efficiency increases to 66.82% with peak irradiance and output power of 0.2511 W/cm^2 and 0.2673 mW respectively.

Keywords: CH_2O, Transmissive Gas Sensor, Ultraviolet, Efficiency, Compound Parabolic Concentrator, ZEMAX®12.

1. INTRODUCTION

Spectroscopy based sensor has been developed because of several advantages over conventional sensor such as fluorometric, piesoresistive, conductive or amperometric method based. Some of the advantages of spectroscopic sensor are compact size, straightforward operation, fast respond, lower power consumption and also potential for low-cost mass production [1]. All sensor may have specific sensing properties such as it can only use to detect specific type of gas and can detect a specific range of concentration. One gas that researchers has been studied and developed it sensing mechanism is formaldehyde (CH_2O). This gas has many applications such as adhesive in manufacturing industry, house hold production industry for reagent such as paints, wallpapers, antimicrobial hair shampoo and conditioners, industrial chemical and also pharmaceutical. Laboratory and mortuaries used this chemical as disinfectant and tissue preservatives.

It is beneficial and very useful to develop a low cost and highly efficient formaldehyde gas sensor. This is because this gas is considered to be carcinogenic and harmful towards human if one exposed for a certain amount of time with certain amount of concentration. Occupational Safety and Health Administration (OSHA) set a standard of 100 ppm to be immediately dangerous to life and health (ILDH) [2] and for The National Institute for Occupational Safety and Health (NIOSH) the concentration is conspired as ILDH if one being exposed to 20 ppm of formaldehyde. The gas sensor has been developed using ZEMAX®12 software simulation and its performance being analyzed. The gas cell configuration consists of few optical components including Calcium Fluoride (CaF_2) lens, CaF_2 window, aluminum gas chamber, UV light source and photodiode detector. After few simulation and analysis, the sensor is no longer use CaF_2 lens but being replace with CaF_2 window to reduce the fabrication cost.

The objective of this design is to observe the power detected at the photodiode detector for efficiency analysis and also as mentioned before to reduce the fabrication cost. Simulation have been done with few configurations to see the effect of varying parameter such as the optical path length (gas cell length) and the use of compound parabolic concentrator (CPC) structure at both end of the gas cell to observed the level of power detected and the ability of the sensor if such parameter being modified.

A low cost with high efficiency formaldehyde gas sensor have been successfully constructed and analyzed. The gas sensor still can be further improved and used for other gases which have the absorption in UV-Vis (ultraviolet-visible) range from 200 nm to 800 nm [3]. Few modifications still need to be done for the use of other gases such as the light source and the detector need to replace with suitable light source that can emit light at the specific wavelength or simply used tunable light source and the detector also can detect it.

2. UV-VIS COMPONENTS

Few UV-Vis optical components used in this design which distinguish this sensor with other spectroscopy sensor for other spectral range such as IR spectroscopy.

2.1 UV Light Source

Specific gas for this work is formaldehyde (CH_2O) which has peak absorbance at 340 nm wavelength [3]. Therefore, to get the best result for the sensor is highly recommended to use a light source at this particular wavelength. In this work, UV light source that has been used is UVTOP335TO39FW LED from Sensor Electronic Technology Inca [4]. The reason for choosing this type of light source is because it suits the requirement for this work which is compact, robust, low voltage, no hazardous waste. The maximum forward voltage, optical power, viewing angle ($2\theta_{1/2}$), maximum forward current and full width at half maximum (FWHM) is 6.2V, 0.4 mW, 120°, 30 mA and 20 nm respectively. To use UV LED instead of using halogen tungsten light source can be a great agreement to reduce the cost but the tradeoff is halogen tungsten light source is more reliable for longer period of usage.

2.2 Photodiode Detector

The detector used for this low-cost design is OSD5.7-8Q Series 7 Silicon photodiode detector from Centronic Inc [5]. It detects light from 194 nm to 400 nm with operating temperature range -55°C to 70°C. The active region is 5.8 mm^{-2} (2.4x2.4 mm) therefore the after light being collimate inside the gas chamber, it needs to be focused at this exact region for increasing its efficiency and sensitivity. At 340 nm, the responsivity is 0.18 (A/W) at maximum illumination intensity of 100 W/cm^2. Other work tends to use spectrometer at the receiver or detection point because spectrometer can provide a stable and good reading but due to expensive and relatively bulk in size photodiode detector can a replacement. This is due to it has cheaper price and more compact size.

2.3 CaF_2 Lens and Window

Bi-convex CAF_2 lens is the most suitable and have excellent UV transmittance with high refractive index homogeneity, n=1.448381 at wavelength of 0.33490 nm [6]. The purpose for CAF_2 lens in transmissive spectroscopy sensor is to collimate light and focus it back to the detector to increase transmission and signal-to-noise ratio (SNR) [7]. This can be done by allocate the light source and detector at the specific focal point. This focal point can be calculated using equation as follow:

$$\frac{1}{F} = (n-1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad (1)$$

where F is the focal point, r_1 and r_2 is the radius for the lens. After allocate the light source at the focal point the light will collimate inside the gas chamber and then place the detector at focal point to once again focusing the light. On the other hand, this work replaces the use of expensive CAF_2 lens with low cost CAF_2 window. In order to replace with the window, the design must be improved so that the light can collimate and converge back similar with using bi-convex lens. Therefore, after run few simulation processes using ZEMAX®12 software, the additional compound parabolic concentrator (CPC) structure has been implemented in the design to serve the same purpose as the lens. This CAF_2 window has similar refractive index as previous lens thus providing similar transmissive properties as before.

2.4 Compound Parabolic Concentrator (CPC) Structure

After replacing the bi-convex CAF_2 lens with CAF_2 window, the light cannot be collimated inside the gas chamber and converged back to the active region of the detector. Compound parabolic concentrator (CPC) structure is needed to increase the sensor efficiency by imitate bi-convex lens function to collimate and converge the UV light as shown in Figure 1.

This CPC has the ability to accept a greater amount of light and needs less accurate tracking because CPC has acceptance angle and light which enter the CPC at greater angle than the acceptance angle will not be collected at the other side of this structure. If light enter at the input aperture, it will collimate through exit aperture.

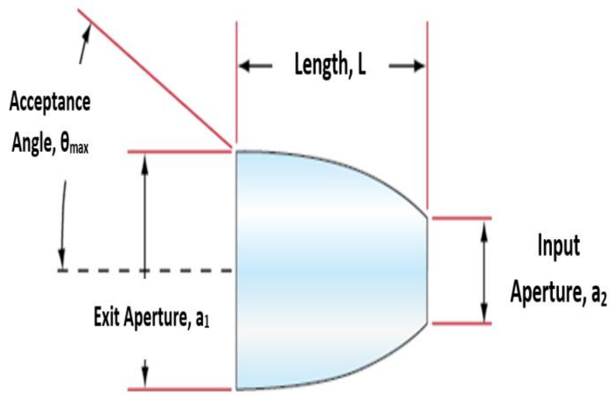

Figure 1. Traditional CPC

Traditional CPC according to the principle of non-imaging optics, has maximum angle for exit aperture to receive light ray using equation [8]

$$\sin\theta_{max} = \frac{a_1}{a_2} \quad (2)$$

Where a_1 is the exit semi-diameter and a_2 is the entrance semi-diameter aperture of the CPC. In this work, a_2 is set to be 2 mm which is suitable for both UVTOP335TO39FW and OSD5.8-7Q light source and emitter size [4-5]. Using (2), the maximum angle θ_{max} is 11.537°. The length of CPC is calculated using equation [8]

$$L = \frac{a_1 + a_2}{\tan\theta_{max}} \quad (3)$$

Using (3), the length is 58.788 mm. The structure has been studied and simulated using ZEMAX®12. The profile of the traditional CPC as shown in Figure 2.

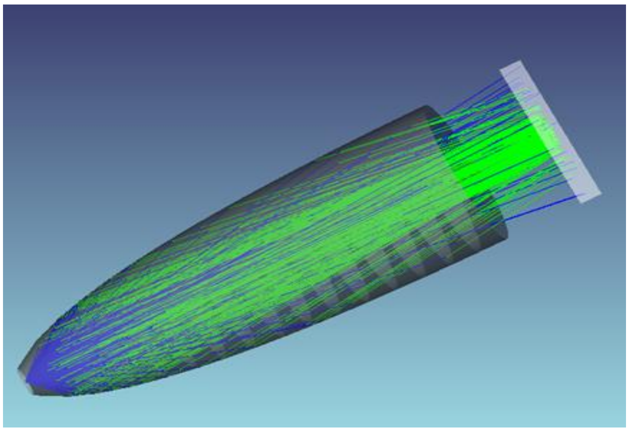

Figure 2. Profile of CPC in ZEMAX®12.

Table 1. Efficiency of varying CPC length

CPC Length (mm)	Peak Irradiance (W/cm^2)	Output Power (W)	Efficiency
10	$3.9472x10^{-4}$	$2.1333x10^{-4}$	53.33%
20	$2.8951x10^{-1}$	$3.1901x10^{-4}$	79.75%
30	$3.0063x10^{-1}$	$3.4563x10^{-4}$	86.41%
40	$3.8485x10^{-1}$	$3.6062x10^{-4}$	90.16%
50	$5.9239x10^{-1}$	$3.6790x10^{-4}$	91.92%

Although the efficiency of the traditional CPC is high, but the structure is not suit the sensor requirement and it is too bulky. So, a truncated CPC is designed to meet this work specification [8]. The parameter has set in ZEMAX®12 such as the new maximum angle, θ_{max} and new length, L, which 4.5° and 20 mm respectively. The entrance aperture 2 mm and output aperture 10 mm is kept constant.

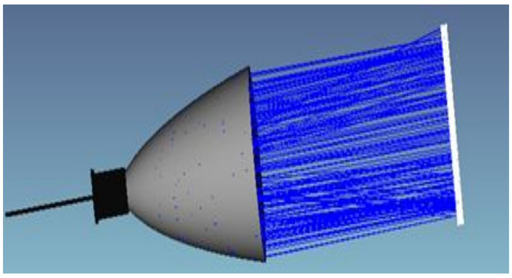

Figure 3. Profile of truncated CPC in ZEMAX®12.

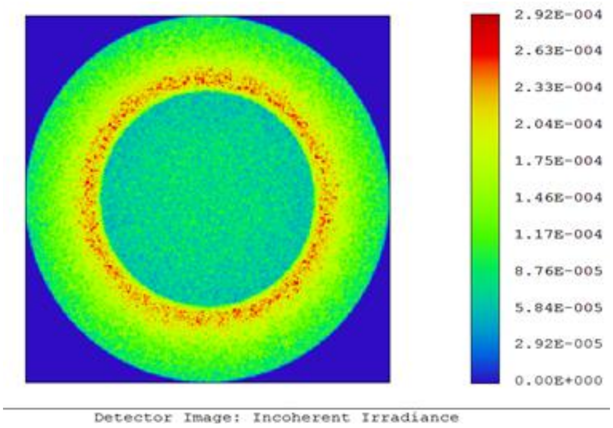

Figure 4. Incoherent Irradiance of truncated CPC

With new truncated CPC design as shown in Figure 3, the light can be collimated inside the gas chamber thus this structure may be used to replace the expensive CAF_2 lens function. The output power from the CPC is $3.1901x10^{-4}$ W and the efficiency for the truncated CPC is 79.75%. Refer to the Figure 4, it can be seen that the light is collimated through the truncated CPC. This can be a good agreement that the light can interact well with the mesurand gas inside the gas chamber.

3. GAS SENSOR DESIGN

The design of improved low-cost sensor as shown in Figure 5. The transmissive type may have advantage over reflective type which is in long term usage, the light may be deposited on the reflective surface and degrade the performance and sensitivity of the sensor [10] but the drawback of transmissive type is that optical path is shorter compared to double length in reflective type with similar size. This will reduce the sensitivity and detection limit of the sensor because according to Beer's Law increase in optical path length, the higher the detection limit. The optical path length of the gas chamber for this work is set to be 200 mm and the diameter is 20 mm. The diameter is set smaller because smaller diameter of 20 mm has higher sensitivity and response time compared to bigger diameter for example 200 mm [11]. Plus, reducing the diameter will make the sensor more compact. The suggested material used for the gas chamber is aluminum because it is inert towards chemical reaction, resist to UV degradation, inexpensive, robust and high resistive to temperature.

The design is constructed in SOLIDWORKS software using exact dimension from ZEMAX®12. After export the gas chamber structure and the truncated CPC structure, the final design is completed by adding few structure as shown in Figure 5. Additional vessel has been added at the top of the gas sensor for the purpose of flowing formaldehyde gas inside gas chamber. The UV light source and photodiode detector also being constructed as specification stated in datasheet [4-5].

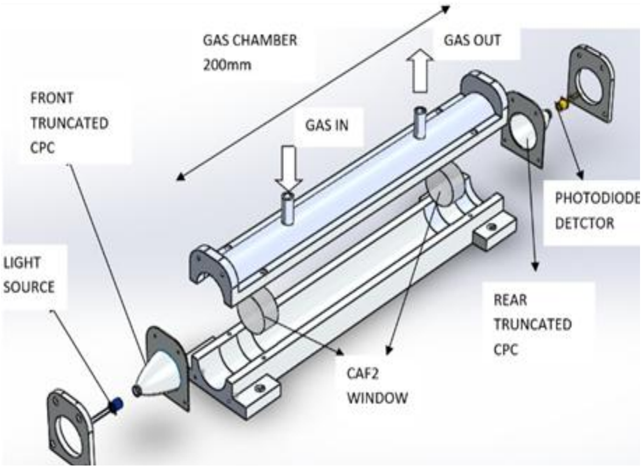

Figure 5. Exploded view of 200 mm transmissive CH_2O gas sensor constructed in SOLIDWORKS

The light will be collimated by truncated CPC and pass through CAF_2 window and interact with the formaldehyde gas inside 200 mm gas chamber before being converged back with similar truncated CPC structure to photodiode detector. In ZEMAX®12 software, non-sequential ray tracing analysis as shown in Figure 6 is being carried out using $1x10^6$ ray light and the power detected being analyzed. After complete studied and computing the best parameter for the truncated CPC structure, the final design of the gas sensor which using CAF_2 window instead of CAF_2 lens and truncated CPC structure is placed at both end of the gas sensor has been successfully constructed.

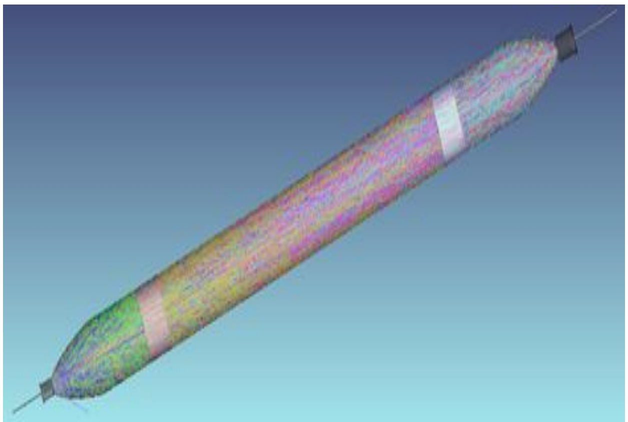

Figure 6. Ray tracing analysis using non-sequential layout.

4. RESULT AND ANALYSIS

The design started with replacing CAF_2 lens with CAF_2 window without the use of CPC structure. Simulation has been done to see the power efficiency of that design. Using (5), the power efficiency is 31.86% with power received by detector is $1.2745x10^{-4}$ W/cm^2. This design has very poor efficiency and need to be improved. CPC structure is said to be the best alternative to increase the efficiency because CPC can collimate light and converge it back almost similar to CAF_2 lens but with small degrade efficiency. Because of traditional CPC is too bulky to be implemented in this design, truncated CPC is being introduced.

At rear end of the gas sensor, similar truncated CPC structure is used but the function is to converge back the light toward the active area of the OSD5.7-8Q photodiode detector. The thickness of the CAF_2 window is 10 mm, gas chamber length is 200 mm and truncated CPC structure length is 20 mm that make the total length of this gas sensor is 240 mm. Before the CAF_2 window is being used, the design using the CAF_2 lens also being carried out using ray tracing analysis in ZEMAX®12. Because the UV light source already emit light at certain angle, analysis is being carried out to set the best angle to yield the highest efficiency. Using focal length value from (1), which is 27.871 mm, the best emitting angle for highest efficiency is 19.738° based on Pythagoras theorem

$$\tan\theta = {}^{opposite}\!/_{adjacent} \qquad (4)$$

Few angles also being simulated to observe the efficiency. Therefore, it is suggested to get the best and highest efficiency for the gas sensor, the light source should be selected to emit light ray at the specific angle which in this work emitting angle is approximately 20°. Table 2 shows the efficiency and the output power from different emitting angle.

Table 2. Efficiency of different emitting angle

Angle (°)	Peak Irradiance (W/cm^2)	Output Power (W)	Efficiency
10	$6.011x10^{-2}$	$3.5790\ x10^{-4}$	89.48%
20	$6.6009x10^{-1}$	$3.5588\ x10^{-4}$	88.97%
30	$5.3007x10^{-1}$	$3.1784\ x10^{-4}$	79.46%
40	$3.4761x10^{-1}$	$2.4871\ x10^{-4}$	62.18%
50	$2.511x10^{-1}$	$2.0331\ x10^{-4}$	50.83%

The efficiency of the sensor is analyzed by the power received at detector. Power efficiency is calculated using the following equation:

$$P_{(eff)}(\%) = {}^{P_{out}}\!/_{P_{in}} \times 100\% \qquad (5)$$

After getting the data from the final design as shown in Figure 5, the simulation is further done by decreasing the optical path length of the gas chamber. Optical path length can be considered as the gas chamber length as the gas is react with the light inside this gas chamber. The purpose of this simulation is done because theoretically the efficiency will increase as the detector is placed closer to the light source. Thus, sample data is collected from 150 mm, 100 mm, 50 mm and 25 mm optical path length.

Table 3. Efficiency of decreasing the optical path length

Optical Length (mm)	Peak Irradiance (W/cm^2)	Output Power (W)	Efficiency
200 mm	$3.2327x10^{-1}$	$2.4288x10^{-4}$	60.72%
150 mm	$3.4114x10^{-2}$	$2.4876x10^{-4}$	62.19%
100 mm	$4.3450x10^{-2}$	$2.5409\ x10^{-4}$	63.52%
50 mm	$2.6763x10^{-1}$	$2.6282\ x10^{-4}$	65.71%
25 mm	$1.4961x10^{-1}$	$2.6728x10^{-4}$	66.82%

From Table 3, the efficiency increases as the optical path length decreases. The data prove the theory as mentioned before. But the increase in power efficiency is very small. Bear in mind that the longer the optical path length, the lower detection limit according to Beer Lambert's Law [7]. Therefore, reducing the optical path length, the sensor will be less sensitive and cannot detect a very low concentration. Therefore, the best design should consider detection limit for the gas sensor so that it can detect the lowest concentration compared to shorter optical path length.

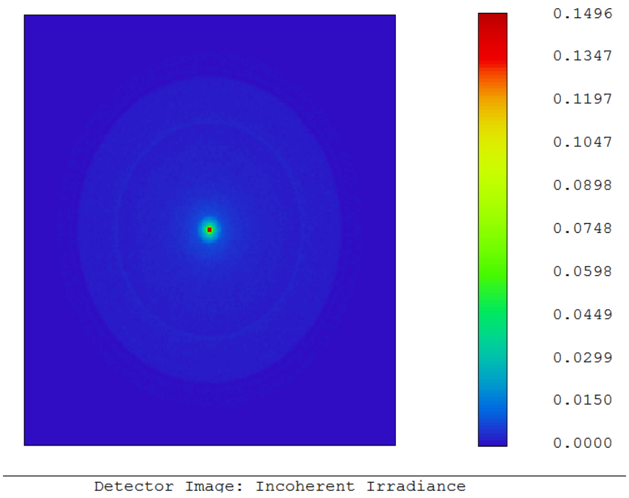

Figure 7. Incoherent Irradiance for 25 mm optical path length.

Figure 7 shows that the irradiance at 25 mm is converged at the middle of the detector. This data similar to the data taken from previous analysis which use the CAF_2 lens instead of using CAF_2 window as shown in Figure 9. Thus, it proves that by replacing the expensive CAF_2 lens with truncated CPC structure in the final design, the results show similar pattern. The only different in term of power efficiency. Using CAF_2 lens and emitting angle 20° (highest efficiency for CAF_2 lens) and using truncated CPC at both end and optical path length is 25 mm (highest efficiency for truncated CPC) the efficiency is 88.96% and 66.82% respectively. Although the efficiency is degraded from using truncated CPC, the advantages is in term of costing because CAF_2 window will cost lower than CAF_2 lens.

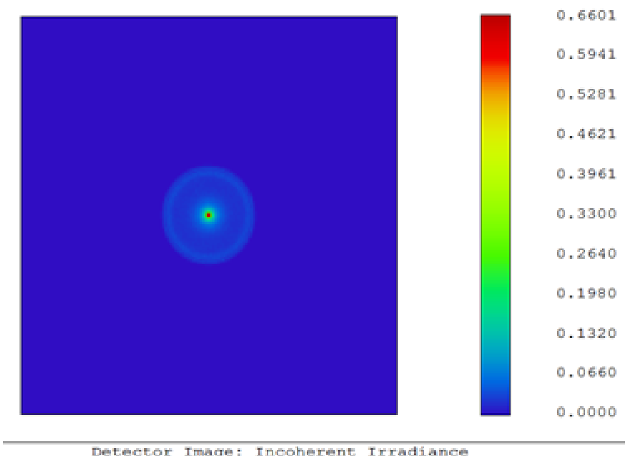

Figure 8. Incoherent irradiance for 20° emitting angle using CAF_2 lens.

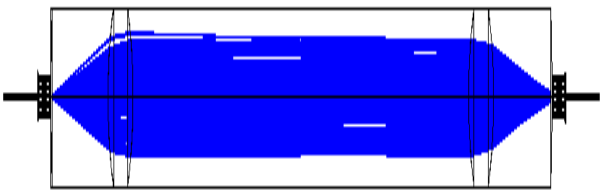

Figure 9. Ray tracing for 20° emitting angle using CAF_2 lens

5. CONCLUSION

An improved and low cost transmissive formaldehyde gas sensor has been successfully designed. This new transmissive design replaces the use of expensive CAF_2 lens with low cost CAF_2 window and other optical components such as the UV light source which replaced by UV LED from using halogen tungsten and also photodiode detector is used instead of using an expensive and bulky spectrometer. Although the replacement might affect the sensitivity and the performance of the gas sensor, still it is a good agreement to have reasonably cheap and compact sensor for practical use. The highly sensitive gas sensor is more convenient to be used in the laboratory for study and research purpose.

To get the highest efficiency for the CAF_2 lens, the light source must emit light at the angle of 20° ± 10. This can be proven from Pythagoras theorem and using right angle triangle model to calculate the suitable angle and use the length from the focal length and the height is equal to the radius of the gas chamber.

Simulation and data collection are completed using ZEMAX®12. Using non-sequential type, ray tracing analysis can be a good and effective data analysis. The final design using truncated CPC structure at both end enable the light from light source collimated and interact with the gas inside the gas chamber and then converged and focused back to the active area of the photodiode detector for power efficient analysis. Using the CAF_2 lens, the highest efficiency is 88.96% if the light source emits at the angle of 20°. However, then the truncated CPC structure being introduced, the highest efficiency decreases to 66.82% with the optical length of 25 mm. Although the efficiency might degrade 22.14%, the design is still considered to be successful and excellent design as the truncated CPC structure provides the same capability as the lens for light collimation with good efficiency.

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