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Estimation of Gas Concentration using Energy Absorption of Non-dispersive Infrared Gas Sensors with three optical paths

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***Abstract*—In this paper, we designed, simulated and analyzed a non-dispersive infrared gas sensor which can replace gas sensors of the catalytic combustion, electromechanical and semiconductor types. We also proposed commercial sensors to be used in fields of the gas industry. The proposed non-dispersive infrared gas sensor is structured with three ellipsoidal waveguides. Three waveguides share one light source. A non-dispersive infrared sensor is equipped at the end of each waveguide. We designed the proposed CO2 sensor with three waveguides, verified its sensor by using a 3D modeling program (Solid-works), and manufactured its sensor. To simulate its sensor, we supplied power to the light source and measured the maximum emitting energy at absorption wavelength bands of the ethanol and carbon dioxide. Energy absorbed by the gas sensors mounted on the end of the three elliptical waveguides was calculated by a computer simulation program (Trace-Pro). As the results, every power absorbed by three sensors was about 1% of power supplied to a light source. Gas concentration can be measured at three sensors applied 1% of original power. Other two waveguides was 65% of the peak energy of a center waveguides. Experiment is performed that concentration is measured with output voltage of proposed sensor while standard carbon dioxide gases with 6 type CO2 concentrations are slowly injected into a closed chamber. It is derived of the calibration equation using the result of experiments and compared output characteristics of the proposed sensor with a manufactured sensor. It is verified that errors are ±16% at 0~500 ppm and ±4% at 500~ 2000 ppm. When the maximum and minimum values were excluded, the error is estimated to less than ± 1.5% at 100~2000ppm. It is showed the proposed optical CO2 sensor is similar to performance of commercial gas sensor.**

***Keywords* - blackbody Infrared source, three ellipsoidal paths, thermopile, NDIR gas sensor, estimating concentration.**

I. INTRODUCTION

Recently, various sensors are made by MEMS (micro-electromechanical Systems) technology for making a miniature and for intelligence of household appliances and vehicle components. A drunk-meter using catalytic combustion gas sensor is manufactured by MEMS technology and is issuing a great interest in the emerging market [1]. However, catalytic combustion gas sensor has two limitations against inaccuracy and slow response time on sides of concentration measurement. An electrochemical sensor has a lot of problem along with variable environments [2]. The first is that the sensor is not made a normal function at some low temperatures. The second is that the warm-up time is long at the start time. The third is periodic calibration is required because term stable reliability is bad. Therefore, in order to reduce the number of accidents and deaths caused by drunken driving, many researchers have been conducted for preventing their starting automobiles since about 2005. There is an increased demand for a small-sized gas sensor module that has excellent long-term reliability and accuracy to replace an electro-chemical sensor. So, an infrared sensor has been intensively studied [3]-[4]. An Infrared gas sensor consists of a light source, an optical path, one or two filters and an infrared detector. There are light sources such as a laser, an infrared lamp and a blackbody infrared emitter made by MEMS technology [5]-[6]. IR sensors of various optical structures are marketed with property rights at global area. To convert from light or thermal to electric energy infrared sensors, thermopile and pyro-electric devices are used [7]-[12]. Infrared gas sensors mainly use an infrared lamp as a light source and a thermopile as a detector. In the part of automobiles, because a number of continuous vibrations are existed, black body light sources and thermopile infrared detectors are suitable.

In this study, a blackbody light source, a thermopile infrared detector, and a proprietary optical waveguide were modeled to develop some creative non-dispersive infrared gas sensor. In addition, we analyzed a part of absorbed energy reached at an infrared sensor according to the changes of the supplied power and a wavelength band of a narrow band filter. We estimated gaseous concentration through analyzing and comparing our proposed simulation results and the output voltages measured from CO_2 commercial gas sensors in our experiments.

II. SIMULATION TARGET AND CONDITION

In order to improve the applicability of the non-dispersive infrared gas sensor, the light source, the infrared sensor, and the optical waveguide were designed and simulated. Three-dimensional modeling of each component was performed by Solid-works. Optical characteristics analysis was performed by Trace-Pro and output characteristics by applied power for optical gas sensors were investigated.

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A. A modeled Light source

A commercial light source and a three-dimensional modeled sensor of the light source are as shown in Fig. 1. The infrared rays are emitted at the center of the light source at the size of 1.7×1.7㎟. The emitted infrared rays were modeled on the basis of data described in the manufacturer datasheet of the light source.

Fig. 1. A 3-D shape to model blackbody infrared source(MIRL17-900)

The supplied powers of the black body are three kinds of 600mW, 700mW and 800mW. A parabolic reflector is attached to the infrared light source. Infrared light rays are emitted in the range of ±20 degrees around the optical axis. The continuous light of 0 to 10 micrometer band was set to be emitted. The infrared light source is used as a black body source, MILR 17-900(Importec, Italy) made by MEMS technology. The Relative emission energy in the black body is in by referring to the manufacturer's specifications. Those characteristics are shown in Fig. 2.

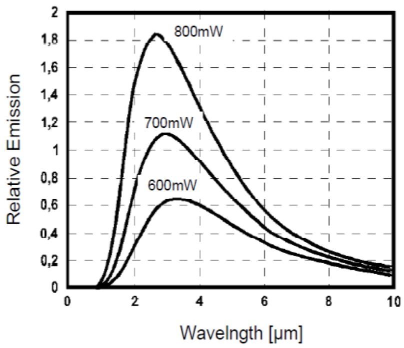

Fig. 2. Relative emission against wavelengths(MIRL17-900)

B. A modeled infrared gas sensor

When modeling an infrared sensor, we designed activation area of the infrared thermopile, 1.2×1.2㎟ in the center, as shown in Fig. 3. It is assumed that a thermopile material absorbs all input rays. The supplied power absorbed into its square is calculated by computer simulation. It has been modeled by commercial gas sensor, A21 F4.26 G5600 (Heimann Sensor GmbH, Germany), integrated thermopile sensor. Our researchers used Heimann's infrared sensors for measuring carbon dioxide and alcohol. It is defaulted with small signal amplification circuits and a temperature sensor.

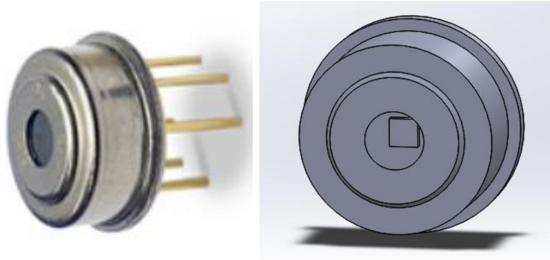

Fig. 3. The sensor shape to model heimann sensor

C. Modeled three-dimensional optical waveguides

Optical waveguide, a part of an infrared gas sensor, has unique characteristic by each manufacturer. In this study, we proposed and designed 3D ellipsoidal optical paths. In order to measure three gases simultaneously, we designed and modeled optical paths under the following conditions. (1) The basic ellipsoid is assumed that the length of a long axis is 150mm and a length of short axis is 20mm, and focal lengths are -74.3mm and +73.3mm from the center of a long axis to the terminals as shown in Fig. 4. (2) Three basic ellipsoids were concentrated to the first focus to use a common optical source at the top, middle and bottom. Three elliptical paths are combined with differences of angles of 10 degrees. The shape of optical paths is modeled with 3D as shown in Fig. 5. Because an infrared light source is not a point light source but a surface light source of area 1.7×1.7 ㎟, one light source chip was divided into three paths like Fig. 6a. A three-dimensional optical waveguide was formed by locating the first focus of three ellipsoids to each central point. The optical characteristics were simulated by placing the infrared sensor at the second focal point of each three-dimensional ellipsoid as shown in Fig. 6b. (4) In simulation analysis, inner materials of each ellipsoid were set as a standard mirror. A standard mirror is with absorptivity 0.05 and reflectance 0.95.

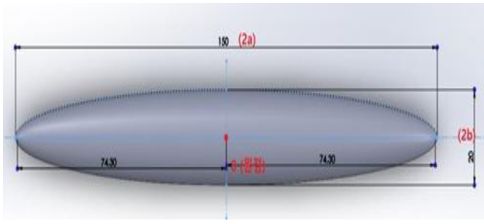

Fig. 3. An optical paths 3-D modeled with ellipsoidal structure.

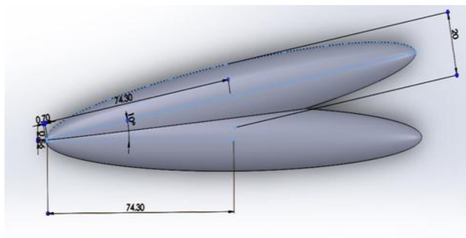

Fig. 4. The shape of everlapped by two ellipsoids

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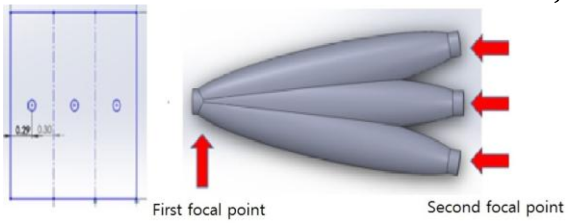

(a) (b)

(a) The first common focal point , (b) The secondary three points.

Fig. 5. Modeled optical paths with three waveguides

III. SIMULATION RESULTS AND DISCUSSION

A. Light source

1) Through the simulation test, wavelength of the peak light energy was measured at each supplied power such as 600mW, 700mW and 800mW. The results are shown in Table 1. Trace-pro was used for simulation analysis. In the program, we use the light source editor to set up the energy based on referring to the manufacturer's data sheet. The maximum energy was obtained by increasing the wavelength from 0 to 10 in 0.01 unit. The result showed the largest energy at 600mW at 3.51㎛, 700mW at 2.90㎛ and 800mW at 2.89 ㎛

2) The infrared sensor used for the simulation analysis passes through only a specific wavelength band. Depending on the power applied to the light source, the energy has a different value in the range of 0 ~10㎛ according to Planks' law [13]. Therefore, in this study considered the use of narrowband filters on the central wavelengths of reference infrared sensors (3.91 ㎛), ethanol (3.45㎛), and carbon dioxide (4.26㎛). The results are shown in Table 2. When the supplied power is 700mW, the amount of light emitted at the center wavelength of 3.45㎛ is 0.032W (4.59%) of the total 0.7W, and 0.013W (1.86%) and 0.023W (3.38%) at 3.91 ㎛ and 4.26 ㎛, respectively. Considering the characteristics of the central wavelength and the cut-off wavelength, the infrared gas sensor uses less than about 5% of the energy emitted from the infrared light source. Therefore, the optical structure which can effectively use the light energy is important for the infrared gas sensor.

B. Three Ellipsoid and infrared sensors

(1) The simulated results of the absorbed energy into the active region of the infrared sensor located at three elliptical waveguides are shown in Fig. 7 and Table 3. As shown in Table 3, the absorbed energy ratio at the top and bottom is 65% at the center. It has a constant value even if the supplied power changes.

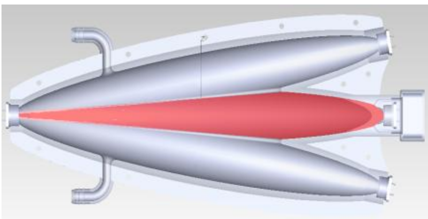

Fig. 6. Inner shapes of optical waveguide with three ellipsoidal paths

(2) As can be seen in Fig. 8, the infrared rays absorbed in the active area of the infrared sensor shows a circular shape with a radius of 2 mm or less. Therefore, the energy density per unit area is improved. The absorbed energy at infrared sensor mounted at three-elliptic optical waveguide is less than 5% of the supplied power. It is shown as Table 2. The results of the ratio of the energy absorbed by the infrared sensor at the transmission wavelength range according to the supplied power are shown in Table 4. When the supplied power is 600mW, the energy of the ethanol gas sensor mounted at top and bottom is 61~62% of the middle part. It can be seen that the energy ratio of the top part and the bottom part to the middle part in the carbon dioxide gas wavelength range is 60.9% and 56.1%, respectively. That is, regardless of whether or not the target gas is selected, absorbed energy of the top and bottom have a ratio of about 56% to 62%, compared with the middle part. If the infrared sensor of the same infrared gas sensor is located at the center, top or bottom, it will have the different output voltage of each gas sensor. However, a sensor module has similar reaction characteristics.

Table 1. Peak fluxs and wavelengths according to the applied power to blackbody

600mW		700mW		800mW	
Wavelength(㎛)	**Flux(W)**	**Wavelength(㎛)**	**Flux(W)**	**Wavelength(㎛)**	**Flux(W)**
3.49	0.14996	2.88	0.1745	2.88	0.2002
3.5	0.15004	2.89	0.1750	2.89	0.2003
3.51	0.15009	2.90	0.1752	2.90	0.2000
3.52	0.14990	2.91	0.1751	2.91	0.1994

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Table 2 Transmission Fluxs after passing bandpass filters by supplied powers

Supplied power / wavelength		600mW		700mW		800mW	
From(μm)	To(μm)	Flux(W)	%	Flux(W)	%	Flux(W)	%
3.35	3.55	0.0263	4.39	0.0321	4.59	0.0367	4.59
3.865	3.955	0.0113	1.88	0.0130	1.86	0.0149	1.86
4.17	4.35	0.0210	3.51	0.0236	3.38	0.0270	3.38

Table 3. Absorged energy and rations by supplied powers

Power (mW)	600mW		700mW		800mW	
	Absorbed energy(mW)	Ratio (%)	Absorbed energy(mW)	Ratio (%)	Absorbed energy(mW)	Ratio (%)
600	73.4	12.2	111.7	18.6	72.0	12.0
700	85.7	12.2	130.4	18.6	84.0	12.0
800	98.0	12.2	149.0	18.6	96.1	12.0

Table 4 Absorption energies at three ellipsoids(Top, Middle, Bottom)

	Top			Middle			Bottom		
	3.350~ 3.550μm	3.865~ 3.955μm	4.170~ 4.350μm	3.350~ 3.550μm	3.865~ 3.955μm	4.170~ 4.350μm	3.350~ 3.550μm	3.865~ 3.955μm	4.170~ 4.350μm
600 mW	3.1	1.3	2.5	5.0	2.1	4.1	3.1	1.4	2.3
700 mW	3.8	1.5	2.6	5.8	2.6	4.4	3.9	1.3	2.7
800 mW	4.3	1.7	3.0	6.6	3.0	5.1	4.5	1.5	3.1

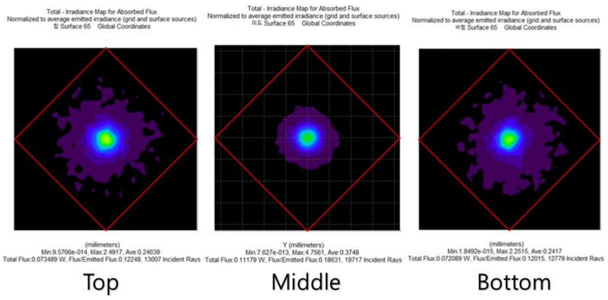

Fig. 7 Simulation results of absorbed energy pattern at three regions in the ellipsoidal structure

C. Estimation of concentration according to simulation test result

Based on the simulated results of the 3 ellipsoid and the experimental results measured on the 2 ellipsoidal structures, we assumed the following. The applied power of the light source was 700mW. A CO_2 detector was located at the top and center, and a reference detector was located at the bottom. Based on the voltage output characteristics according to the concentration of CO_2 obtained from the center part of three ellipsoidal structures, Fig. 9 shows the output voltage of the second CO_2 gas sensor at the top and the reference infrared sensor at the bottom. As can be seen Table 4. Among the energy radiated from the light source, the wavelength band absorbed by the CO_2 infrared sensor is 4.17~4.35μm, and the energy absorbed in the activation region of the infrared sensor at the top part and the middle part is 2.6mW and 4.4mW. Therefore, when the absorption energy at the middle is set at 100%, the absorption energy at the top is about 59%. When the output voltage of the top part CO_2 gas sensor is set to 59% of the output voltage of the middle part, it appears as an output voltage at the top. The voltage trend for the actual concentration measured in the middle part can be expressed by the following equation (1) using the Sigma-Plot program [14].

$$V_{OUT}=V_{BPF}+V_{4.26\mu m}\cdot \exp(-\beta x) \quad (1)$$

Where x is the gas concentration and V is the voltage measured through the narrowband filter in the specified band including the center wavelength of the gas to be

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measured and y is the initial voltage. Through this formula, when the same CO_2 infrared sensor is mounted to estimate the output voltage on the top and middle, two concentrations are obtained through the actual voltage and simulation voltage. Accordingly, it is possible to calculate the two estimated concentrations. That is, the theoretical two concentrations are calculated by multiplying and dividing the two gas concentrations actually measured and the theoretical output voltage ratio. A total of four estimated concentration averages are shown in Fig. 10. Fig. 10 shows the results of the comparison between the two output voltages of the actual gas concentration measured in the actual sensor module and the estimated gas concentration results. As a result, the estimated concentration in the low concentration range at 110 ppm was calculated as 128 ppm. The error was about 16%. At the concentration of 500ppm or more, the average error range can be predicted to be less than 4%. However, when the maximum and minimum values were excluded, the maximum error is measured about 6% at less than 100 ppm and 1.5% at more than 100ppm.

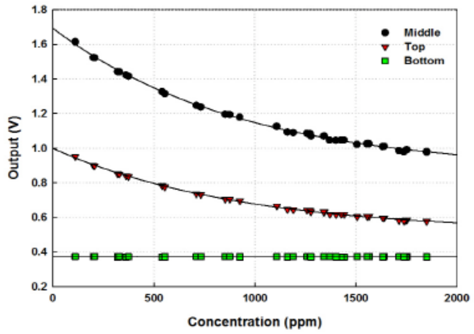

Fig. 8 Output voltages of infrared sensors located at three focal points in ellipsoidal structure

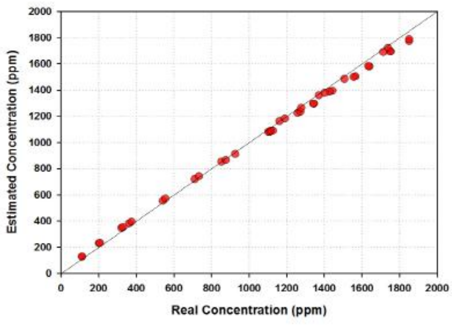

Fig. 9 Estimated concentrations vs. real concentrations of CO2 gas

IV. CONCLUSION

In this paper, we proposed a structure of a common optical source and optical paths with three ellipsoids to develop an infrared gas sensor module. In order to implement, first we designed and virtually modeled an optical light source and am infrared gas detector in compared with real IR gas sensor through computer simulations. Our proposed IR sensor is manufactured by calculating size, rays, intensity of beam, filters, voltages and currents as a commercial gas sensor. A created IR sensor with three elliptical paths is advantage of high accuracy because calculation is performed three times at three optical paths such as top, middle and bottom. Twice signal compensation is achieved at top and bottom paths with weak signals for a middle path with strong signals. In here, we demonstrated high accuracy of proposed infrared gas sensors through measuring experiments. Averaged error of gas concentration is within ±1.5% against standard gases. In the near future, an additional study need to measure intensity of infrared beam at three optical paths to induce the best calibration equation at the middle path and to compensate signal of a middle waveguide. It is hopeful that our sensor is commercialized and is helped at gas safety management fields.

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