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Low-cost Ozone Measurement Device in the Chappuis Band

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Abstract

Ground level ozone in the atmosphere is an air pollutant. This is formed in the atmosphere through a complex reaction of the chemical substances emitted from the vehicles, plants and many other sources. Its presence close to the earth is harmful to humans, animals, plants and non-living things. Different countries have different permissible level of concentration of ozone in the atmosphere. The Central Pollution Control Board of India has set the permissible limit for ozone concentration at 100 μg/m^3 over 8 hours. Hence, it is very essential to know the concentration of ozone in the atmosphere for healthy living. There are various types of ozone measurement devices. Optical absorption based UVC-type ozone measurement devices are costly and there is necessity to replace ozone scrubbers used in those devices at regular intervals. Mercury lamps used in these optical absorption based ozone measurement devices produce harmful UVC rays. Mercury lamps also have a shorter life period. To overcome these shortcomings, a low cost LED based Ozone measurement device has been developed and concentration of ozone can be measured by this device. In this investigation, Yellow-Green, Diffused Yellow, DIP Yellow, Amber, and Orange LEDs have been used to generate incident light sources from 573 nm to 605 nm wavelengths. In the detector stage, available 565 nm and 580 nm peak sensitivity photodiodes have been used to measure the reduced intensity using the Beer-Lambert Law. It is found that DIP and Diffused yellow LEDs show better results among these LEDs when tested by 565 nm and 580 nm photodiodes. The use of LEDs and Photodiodes makes this system low-cost in comparison to other available ozone-measuring systems.

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Introduction

Ozone in Atmosphere

Ground level ozone concentration is detected in the atmosphere in varying amounts. Ozone concentration in nature varies with season, altitude, etc.[1] Lightning and sunlight also create ozone in nature by breaking oxygen molecules. Naturally, a very small amount of ozone is created in the atmosphere. A significant amount of man-made ozone is created in the lower level of atmosphere due to various processes. Increased ozone concentration in the atmosphere affects our nervous system, lungs, eyes, nose, throat, skin, etc.[2] Ozone can also affect DNA's normal structure. As per guidelines of the World Health Organization (WHO), the safe limit of ozone concentration in the atmosphere is 100 µg/m^3 as the maximum daily 8-hour mean and 60 µg/m^3 in the peak season (average of daily maximum 8-hour mean concentration in the six consecutive months with the highest six-month running average O_3 concentration).[3]

Historical Overview

Ozone gas was first identified by the German Scientist C.F. Schönbein in 1867 in the atmosphere.[4] Oxford University Professor, G.M.B. Dobson made a Photographic Spectrometer in 1926 and later on, with the availability of electronic components, Professor Dobson made standard Spectrophotometer using the photomultiplier tube at the detector stage for the measurement of ozone in 1931.[5,6] Dobson Spectrophotometer uses two different UV wavelengths of light. The shorter wavelength of light is absorbed more than the longer wavelength of light by the ozone molecules. Due to this dissimilar absorption, two light beams of varying intensity are generated and fall on a photomultiplier tube alternately. By computing the difference in intensity of two light beams, the concentration of ozone is calculated.[7] The World Meteorological Organization still uses the Dobson Spectrophotometer by incorporating additional features. Nowadays, Dobson Spectrophotometers have been automated for the measurement of concentration of atmospheric ozone.[8] Alan Brewer who was an associate of Dobson also developed Spectrophotometer in 1982 to monitor the concentration of ozone in the atmosphere.[9] The Brewer Spectrophotometer was upgraded to measure U.V. Radiation and there are various versions of the Brewer Spectrophotometer like Mark-II, Mark-III, Mark-IV, Mark-V, etc. The Dobson and Brewer Instruments are used at various stations throughout the world for the measurement of ozone concentration in the atmosphere.

Measurement Technologies

Molecules can absorb light energy of specific wavelengths when the light passes through the target molecules of the species. Different species absorb photon energy at different wavelengths and also may absorb several wavelengths from the UV to IR regions.[10] An ozone molecule has three oxygen atoms and the molecular weight of the ozone molecule is 47.9982 g/mol. Atoms have strong and sharp energy levels but the molecules have widespread energy levels and these widespread energy levels belong from the UV regions to the IR regions.[11] Scientists and researchers have shown that ozone molecules absorb light energy from 200 nm to 1100 nm wavelength region.[12] These wavelength regions are called the Hartley Band, Huggins Band, Chappuis Band, and Wulf Band respectively.

James Chappuis in 1880 stated that ozone absorbed light in the visible range from 515 nm to 650 nm and within this absorption region there were two maxima at 575 nm and 603 nm wavelengths.[13,14] This absorption band in the visible range is the weak absorption band of ozone but is safe for human health.

W. N. Hartley in 1881 stated that ozone had a strong absorption band in the UVC region from 233 nm to 285 nm wavelength and the strongest absorption occurred at 256 nm wavelength.[15,16] Later on, scientists and researchers established that the strongest absorption of ozone occurred at 253.65 nm wavelength. This absorption band of ozone at 253.65 nm is harmful to living organisms as well as detrimental to non-living things. To generate a light source at about 253.65 nm wavelength, usually mercury lamps are used whose life span is less than the life span of LED. The photodetectors used for the measurement of 254 nm wavelength of light are costly and are not easily available. The wavelength region of the Huggins band belongs to the UVB-UVA region and is approximately 300 nm to 350 nm wavelength. The wavelength region of the Wulf band belongs to the IR region and its range is beyond 700 nm wavelength.[17] The concentration of ozone can be measured according to the light absorption capacity of ozone of specific wavelength and Beer-Lambert Law can be implemented for this purpose.

There are also other methods like the Electrochemical method and Metal Oxide Semiconductor method to measure the concentration of atmospheric ozone.[18] In the Electrochemical method, an electrochemical sensor interacts with the surrounding ozone gas, and according to the strength of the surrounding ozone gas, the output of the sensor changes. The disadvantage of the electrochemical method is that the life span of sensor used is limited to 1 year to 2 years. In the Metal Oxide Semiconductor method, when the heated metal oxide surface reacts with the surrounding ozone gas, its sensitivity changes.[19,20] The disadvantage of the Metal Oxide Semiconductor-based method is its high power consumption and long warm-up time. The aim of this research is to develop an indigenous cost-effective ozone measuring device based on absorption of visible light using easily available components. In this research low cost visible range LED has been used to generate light source whose life span is long. The absorption of visible light is detected at the other end of the gas measurement chamber with the help of a visible range photodiode and concentration of ozone can be calculated using Beer-Lambert Law. These ozone measuring devices can be used individually in personal capacity and cost will be a few thousand only. In real world scenarios the imported equipment is used in Environment Monitoring Stations. The size of the equipment is also large and cost is many millions of rupees.

Materials and Methods Adopted for the Experiments

Materials

The ozone measurement chamber is built with a 21 mm diameter and 25 cm long aluminum tube. Aluminum tube has been used here since aluminum is soft and easy to process. The 21 mm diameter aluminum tube is chosen to match with the available 21 mm diameter plano convex lens required for the experiment.

Major Components

The basic electronic components used are LEDs and photodiodes. The photodiodes are encapsulated in a separate small tube to fix properly with the set-up for the measurement of light intensity. The 12 Volt air pumping motor is used for the air flow inside the gas measurement chamber. The air flow rate inside the gas chamber is 2L/minute.

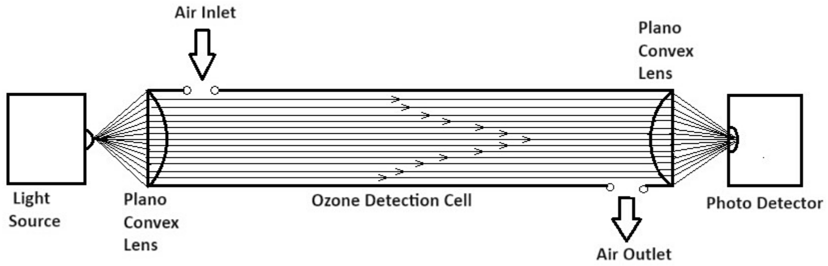

Fig. 1: Block Diagram of Ozone Measurement Device

Brief Description of the Block Diagram

Light Source

Here the light of visible range wavelength is generated from the LED for the purpose of propagation through the ozone measurement cell.

Plano Convex Lens

The left side plano convex lens has been used to make radiated light parallel and pass through the maximum ozone molecules. The right side plano convex lens has been used to make radiated light concentrate to a point at the other end of the ozone measurement cell. The reduced intensity of the concentrated light is measured by a photodiode.

Ozone Detection Cell

Atmospheric air passes through the ozone detection cell which is also described as ozone measurement chamber. The ozone detection cell is made up of aluminum tube and depending upon the concentration of ozone molecules in the ozone detection cell, the radiated visible light will be absorbed in the ozone detection cell.

Photodetector

Here photodiode whose peak sensitivity is near the wavelength of generated light source is used. The photodiode is fixed at the other end of the ozone gas detection cell to measure the intensity of radiated light.

Experimental Procedure

The length of aluminum tube has been chosen as 25 cm. In Beer-Lambert Law, σ is constant and the concentration of ozone $c = [(1/\sigma l) \ln (I_0/I)]$ depends upon the length as well as the reduced intensity of light I. When the length is increased, the value of I decreases and when the length is decreased, the value of I increases due to the change in absorption of light. In this experiment the length of aluminum tube is selected as 25 cm to measure the reduced intensity (I) of visible light source properly at the other end of the aluminum tube.

The accuracy of experimental result of these experiments mainly depends upon

1. The generation of visible light source of required wavelength and intensity.
2. The absorption cross section of ozone molecules to a specific wavelength of light.
3. The proper measurement of reduced light at the other end of the experimental set-up by using a photodetector whose peak sensitivity is near the wavelength of generated light source.

Here the investigation has been carried out to determine the concentration of ozone using Green, Yellow-Green, Yellow, Amber, and Orange LEDs as the incident light sources. The Yellow-Green LED used in this experiment has 573 nm dominant wavelength. Yellow LED usually generates 589 nm dominant wavelength and Amber LED usually generates 595 nm dominant wavelength and Orange LED generates 605 nm dominant wavelength. The molecules absorb light of specific wavelengths and the extent of absorption depends upon the absorption cross section per molecule.[21,22] The strongest absorption cross-section of ozone (per molecule) occurs in the UVC range at 253.65 nm wavelength and in the visible range, the amount of absorption cross-section of ozone at 603 nm wavelength becomes more than the absorption cross-section of ozone at 575 nm. So, the design of a low-cost device for the detection of ozone in the visible range of light depends upon the light source of 603 nm wavelength as well as the photodetector whose wavelength of peak sensitivity is 603 nm. The photodetector of the peak sensitivity wavelength 565 nm (BPW21R) and 580 nm (VTB 8440BH) is available and here experiments have been conducted using 565 nm and 580 nm peak sensitivity photodiode. The range of spectral bandwidth of BPW21R photodiode is 420 nm to 675 nm and highest sensitivity occurs at 565 nm. The range of spectral bandwidth of VTB 8440BH photodiode is 330 nm to 720 nm and highest sensitivity occurs at 580 nm. In a photodiode the incident light of specific wavelength falls on the window of the photodiode, then photodiode absorbs incident light and generates electron-hole pair. The specific wavelength region is determined by the absorption coefficient of the semiconductor. The measurement accuracy enhances when the wavelength of the incoming light approaches the peak sensitivity wavelength of the photodiodes.

In the experiment, the incident light source from the LED passes through the 25 cm long aluminum tube and at the end of the aluminum tube, a photodiode is placed to measure the intensity of light. For the measurement of the concentration of ozone, Beer-Lambert Law has been used.[23,24] The Beer-Lambert Law is

$$I = I_0 . e^{-\sigma l c}$$

Here I_0 is the initial intensity of light, I is the reduced intensity of light, σ is the absorption cross-section of gas, l is the optical path length of the cell and c is the concentration of gas.

$$\sigma l c = \log_e (I_0/I)$$

$$c = (1/\sigma l) \ln (I_0/I)$$

σ is the absorption cross section of gas and its value is constant. The concentration of atmospheric ozone level is in the $\mu g/m^3$ or in the parts per billion (ppb) range. In this experiment the value σ has been taken as $1.15 * 10^{-17}$ cm^2/molecule and the optical path length in this experiment l is 25 cm.

The average value of I and I_0 has been calculated from morning 7.30 A.M to night 11.30 P.M and after averaging, the hourly value of ozone concentration has been calculated.

Results

The experimental data obtained on 3rd May 2024 inside a residential building at Center Sinthi of North Kolkata is shown in Table 1. To measure indoor ozone concentration, 10 mm diffused yellow LED and 10 mm DIP yellow LED have been used with 565 nm (BPW 21R) peak sensitivity photodiode.

National Ambient Air Quality Standards has prescribed that for 8 hours sampling the average value of ozone should be within 100 µg/m3 and for 1 hour sampling the average value of ozone should be within 180 µg/m^3.

Table 1: Experimental data dated 03 May 2024

Indoor Ozone Concentration values at Center Sinthi of North Kolkata on 03 May 2024 (values in µg/m^3)

Time	10 mm Diffused Yellow LED	10 mm DIP Yellow LED
8.00	64.09	38.41
9.00	73.15	40.31
10.00	77.50	41.80
11.00	80.56	42.55
12.00	82.93	43.29
13.00	84.79	44.47
14.00	86.09	45.40
15.00	87.76	46.31
16.00	88.34	46.33
17.00	88.14	45.97
18.00	87.94	45.71
19.00	85.35	43.68
20.00	83.38	42.11
21.00	81.05	40.24
22.00	79.17	39.34
23.00	78.35	39.13

Two waveforms from the initial experiment carried out at Center Sinthi of North Kolkata dated 03 May 2024 have been shown in Fig. 2. It is found that the two waveforms have almost same nature. The minor difference in nature is due to different category of LEDs. The difference in amplitude can be adjusted by changing the resistances used in the biasing of LED and Photodiode. In the experimental set-up variable resistance has been used with the cathode of the LED and by varying this resistance, the intensity of the generated light source can be varied. Depending upon the intensity of this light source output amplitude of the photodiode will vary. Output amplitude of the photodiode will also vary depending upon the value of the resistance used with the cathode of the photodiode. Here the photodiode has been used in the reverse biased mode. So, the amplitude scale of the two waveforms can be adjusted during the calibration of the set-up but the nature of the waveform will remain same.

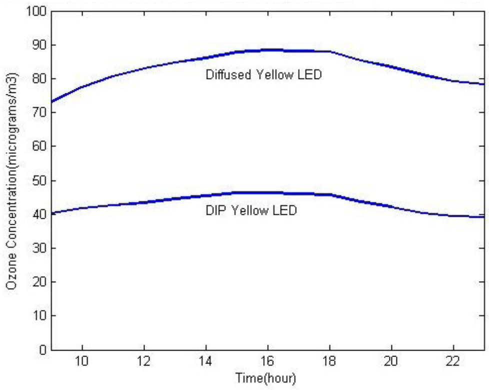

Fig. 2: Indoor ozone levels at Center Sinthi on 03 May 2024

Table 2: Experimental data dated 31 May 2024

Indoor Ozone Concentration values at Center Sinthi of North Kolkata on 31 May 2024 (values in µg/m^3)

Time	5 mm 573 nm yellow -green LED
8.00	53.80
9.00	54.03
10.00	55.25
11.00	57.76
12.00	59.02
13.00	54.23
14.00	50.03
15.00	48.27
16.00	50.25
17.00	53.18
18.00	54.75
19.00	52.89
20.00	48.77
21.00	48.71
22.00	49.18
23.00	45.46

The other investigation was done by the Experimental Set-up using 5 mm 573 nm yellow-green LED with 565 nm peak sensitivity photodiode (BPW 21R) dated 31 May 2024 at Center Sinthi of North Kolkata. The ozone values have been measured inside the building. The experimental data are shown in Table 2.

The indoor ozone levels from the experimental data of 5 mm 573 nm yellow-green LED have been shown in Fig. 3. The experiment was done inside a building at Center Sinthi of North Kolkata dated 31 May 2024.

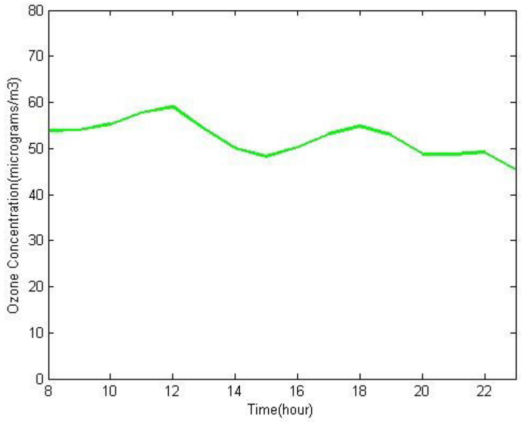

Fig. 3: Indoor ozone levels at Center Sinthi on 31 May 2024

The another investigation was done by the experimental set-up using 5 mm 589 nm yellow LED, 5 mm amber LED, and 3 mm 605 nm orange LED with 580 nm peak sensitivity photodiode (VTB 8440BH) inside a building at Center Sinthi of North Kolkata dated 14 June 2024. The experimental data are shown in Table 3.

The indoor ozone levels from the experimental data of 5 mm 589 nm yellow LED, 5 mm amber LED, and 3 mm 605 nm orange LED have been shown in Fig. 4. The experiment was done inside a building at Center Sinthi of North Kolkata dated 14 June 2024. It is found that there is a major deviation of waveform of the orange LED. The reason is the non availability of required photodiode and the photodiode used here does not match with the wavelength of orange LED.

Table 3: Experimental data dated 14 June 2024

Indoor Ozone Concentration values at Center Sinthi of North Kolkata dated 14 June 2024 (values in μg/m³)

Time	5 mm Yellow LED	5 mm Amber LED	3 mm Orange LED
8.00	55.22	58.02	63.29
9.00	57.63	62.24	64.04
10.00	60.49	64.61	65.10
11.00	64.95	68.29	66.21
12.00	67.79	70.99	67.15
13.00	70.79	73.30	68.27
14.00	73.26	75.37	69.45
15.00	74.03	76.40	70.27
16.00	73.10	76.19	70.52
17.00	72.22	75.78	69.98
18.00	71.90	75.57	69.59
19.00	72.50	75.82	69.27
20.00	72.42	75.45	69.38
21.00	71.90	74.92	69.31
22.00	73.26	75.20	69.55
23.00	74.55	75.94	70.09

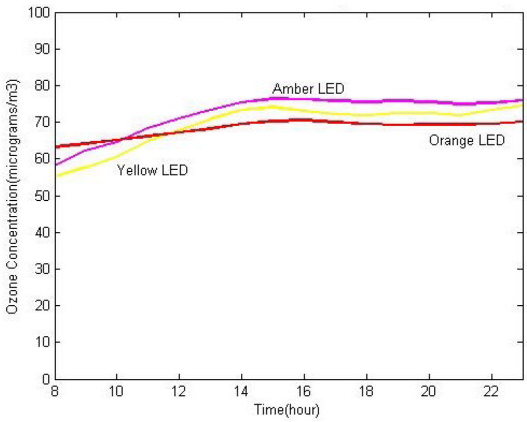

Fig. 4: Indoor Ozone Levels at Center Sinthi on 14 June 2024

Here mean value of concentration of 5 mm yellow LED is 69.125625 and standard deviation is 6.1792502. The mean value of concentration of 5 mm amber LED is 72.130625 and standard deviation is 5.7596441.

Further investigation has been carried out to measure indoor ozone by the experimental set-up using 10 mm diffused yellow LED and 10 mm DIP yellow LED with 580 nm peak sensitivity photodiode (VTB 8440BH) inside a building at Center Sinthi of North Kolkata dated 20 June 2024. The experimental data are shown in Table 4.

Table 4: Experimental data dated 20 June 2024

Indoor Ozone Concentration values at Center Sinthi of North Kolkata dated 20 June 2024 (values in μg/m³)

Time	10 mm Diffused Yellow LED	10 mm DIP Yellow LED
8.00	54.88	53.33
9.00	63.79	58.19
10.00	63.33	55.38
11.00	63.45	54.69
12.00	67.09	56.77
13.00	71.56	59.47
14.00	72.19	58.17
15.00	66.13	53.36
16.00	63.79	53.88
17.00	58.87	51.45
18.00	63.64	53.72
19.00	59.89	50.71
20.00	61.02	51.65
21.00	64.85	52.56
22.00	67.29	52.79
23.00	68.99	51.97

The indoor ozone levels from the experimental data of 10 mm Diffused and DIP yellow LED dated 20 June 2024 have been shown in Fig. 5. The experiment was done inside a building at Center Sinthi of North Kolkata dated 20 June 2024. The indoor ozone concentration was initially measured on 3rd May 2024 by using photodiode of 565 nm peak sensitivity wavelength (BPW 21R) and in the experiment done on 20 June 2024, photodiode of 580 nm peak sensitivity wavelength (VTB 8440BH) has been used.

Here mean value of concentration of 10 mm diffused yellow LED is 64.4225 and standard deviation is 4.5323. The mean value of concentration of 10 mm DIP yellow LED is 54.2556 and standard deviation is 2.64994.

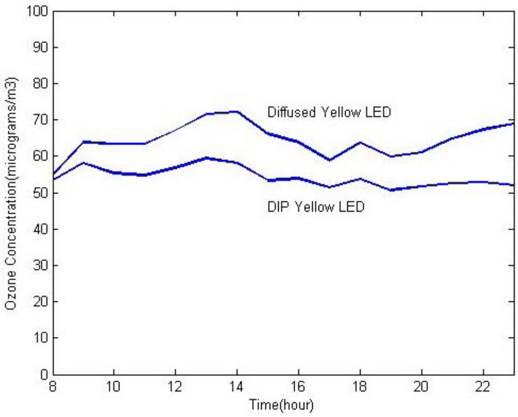

Fig. 5: Indoor Ozone Levels at Center Sinthi on 20 June 2024

Discussion

The objective of this research was to design a low cost ground level ozone measurement device. The design of a low cost ozone measurement device using visible range of light in the Chappuis band is challenging and still in the research level. In this research, the experiments have been conducted several days by changing LEDs, photodiodes and biasing resistances to measure ozone concentration. The value of ground level ozone in the atmosphere remains in the range of parts per billion (ppb) and it is also represented by micrograms per cubic meter (μg/m³).

The ozone concentration was initially measured on 3rd May 2024 by using 10 mm DIP yellow LED and 10 mm Diffused yellow LED with photodiode of 565 nm peak sensitivity wavelength (BPW 21R). The similar experiment has also been conducted on 20 June 2024 by using 10 mm DIP yellow LED and 10 mm Diffused yellow LED but with a photodiode of 580 nm peak sensitivity wavelength (VTB 8440BH). It is found that the result by using photodiode VTB 8440BH as shown in Fig. 5 gives more appropriate values than the values of other experimental results.

Conclusion

Experiments have been conducted by using the available 573 nm wavelength yellow-green LED, 589 nm wavelength DIP & Diffused yellow LED, amber LED of approximately 595 nm wavelength, and 605 nm wavelength orange LED. Available photodiodes of 565 nm and 580 nm peak sensitivity have been used as the photodetector. Here detection level of photodiode wavelength and yellow LED wavelength are close to the visible range absorption spectrum of ozone. So, it is found that data obtained from the yellow LED shows better results than the results obtained from other LEDs. The present limitation to develop an indigenous and low-cost ozone measuring device using visible light is that photodiode of 605 nm wavelength is not easily available.

Future Scope of Work

Measuring the concentration of ground level ozone using a standard ozone generator inside a chamber which will help to provide the accuracy in measuring the ozone concentration.

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Conflict of Interest

The author(s) do not have any conflict of interest.

Data Availability Statement

All the data shown in the tables have been generated by the experiments and no outside data has been used in this article.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

First author has made experiment and drafted manuscript under the guidance of co-author. Co-author has reviewed the manuscript and approved the manuscript after correction.

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