Optical Path Length, Temperature, and Wavelength Effects Simulation on Ozone Gas Absorption Cross Sections towards Green Communications

Michael David, Mohd Haniff Ibrahim, Sevia Mahdaliza Idrus, Nor Hafizah Ngajikin, Asrul Izam Azmi, and Tay Ching En Marcus

***Abstract*—Ozone is a green house gas. Ozone absorption cross sections have been reported with discrepancies and inconsistencies. In this paper, simultaneous effects of the optical path length and temperature variations on ozone gas absorption cross sections are investigated at different wavelengths. HITRAN 2012, the latest available line list on spectralcalc.com simulator, is used in this study to simulate ozone gas absorption cross sections in relation to the simultaneous effects of the optical path length and temperature at the wavelengths of 603 nm and 575 nm. Results obtained for gas cells with the optical path length from 10 cm to 120 cm show that the decrease in temperatures from 313 K to 103 K results in the increase in ozone gas absorption cross sections. At wavelengths of 603 nm and 575 nm, the percentage increase of ozone gas absorption cross sections is 1.22% and 0.71%, respectively. Results obtained in this study show that in the visible spectrum, at constant pressure, ozone gas absorption cross sections are dependent on the temperature and wavelength but do not depend on the optical path length. Analysis in this work addresses discrepancies in ozone gas absorption cross sections in relation to the temperature in the visible spectrum; thus, the results can be applied to get optimal configuration of high accuracy ozone gas sensors.**

***Index Terms*—Absorption cross sections, length, ozone, pressure, transmittance, visible spectrum.**

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M. David (corresponding author), M. H. Ibrahim, S. M. Idrus, N. H. Ngajikin, and A. I. Azmi are with the Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia (e-mail: mikeforheaven@futminna.edu.ng; hanif@fke.utm.my; sevia@fke.utm.my; nhafizah@fke.utm.my; asrul@fke.utm.my).

T. C. E. Marcus is with the Faculty of Engineering and Computing, First City University College, 47800 Petaling Jaya, Malaysia (e-mail: marcus.tay@firstcity.edu.my).

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1. Introduction

Green communications are the technology directed towards the sustainability of environment and economy[1]. Ozone is a primary green house gas. Green house gases are associated with the risk of causing climate changes which results in earth warming[2]. Thus, accurate and adequate monitoring of green house gases like ozone is necessary. The ozone gas absorption cross sections are crucial for the accurate measurement of ozone gas concentration[3]. However, inconsistencies and discrepancies have been associated with ozone gas absorption cross sections in [4] to [6]. Above 10% discrepancies in absorption cross sections of ozone gas have been reported in [7] and [8]. The dependence of ozone gas absorption cross sections on the temperature was recently investigated by Serdyuchenko *et al.*[4]. The authors observed that it is obvious that ozone absorption data is not consistent. Their work was in the wavelength range from 213 nm to 1100 nm and the temperature range from 193 K to 293 K. Results obtained by the authors in the visible spectrum, the wavelength range of 450 nm to 700 nm showed that the decrease in the temperature between 293 K and 193 K results in a small increment (about 1%) in the ozone gas absorption cross sections around 600 nm wavelength[4]. This result, however, contradicts the result of El Helou *et al.*, who showed 3% and 6.7% decreases in ozone gas absorption cross sections with the decrease in the temperature between 223 K and 144 K[6] in the wavelength range of 540.54 nm to 645.16 nm. In view of these discrepancies, further work on the temperature effect on ozone gas absorption cross sections is inevitable. Furthermore, different lengths of gas cells have been used in the measurement of ozone gas concentration in the visible spectrum: 10 cm, 25 cm, 50 cm[5], 70 cm[9], and 120 cm[10]. Differences in the length of gas cells will result in differences in the total volume of gas cells. According to Charle's Law, at constant pressure, the volume of a fixed mass of gas is proportional to its absolute temperature[11],[12]; thus, the optical path length variation is examined in the way it affects ozone absorption cross sections in the visible spectrum at different temperatures. In the literatures, accuracy[5], resolution, and sensitivity[13]-[20] have been shown to be dependent on the optical path length. The novelty in this work is to establish the relation between the optical path length and temperature with ozone gas absorption cross sections at different wavelengths. While the absorption spectroscopy is the focus of this manuscript, other spectroscopic techniques for gas detection such as intra-cavity spectroscopy were emphasized in [21].

This paper is organized into five sections. Section 1 is an introduction. This provides background information on which the study is built. Section 2 is a fundamental review to ozone gas absorption cross sections in the visible spectrum. Section 3 focuses on the methodology adopted in this study. In Section 4, results obtained are discussed and analysed. Finally, in Section 5, conclusions are drawn based on the findings in Section 4.

2. Review of Ozone Gas Absorption Cross Sections in Visible Spectrum

The relevance of ozone gas absorption cross sections is demonstrated by several research activities devoted towards obtaining the right value of ozone gas absorption cross sections in the visible spectrum[8],[13],[22]-[24]. Griggs[22] in 1968 found out that the value of ozone gas absorption cross sections he obtained for the visible spectrum were in excellent an agreement with Vigroux (5.18×10^{-25} m^2/molecule)[13],[23]. Thus, Griggs recommended the previous results obtained by Vigroux[23] for use in the Chappuis band[22]. Ozone gas has peak absorption in the visible spectrum; in 1988, Brion *et al.*[7] in their article reported that Amoruso *et al.*[25], Vigroux[23], and Inn and Tanaka[8] were in an agreement on the peak absorption of ozone gas in the visible spectrum at the wavelengths of 603 nm and 575 nm. Thus, simulation results in this work are compared with the peak absorption cross section at 603 nm and ozone gas absorption at 576.96 nm[7],[13]. This article investigates the relationship between the temperature and ozone gas absorption cross sections in the visible spectrum, thus, previous work on the temperature effect is also reviewed. Serdyuchenko *et al.*[4], El Helou *et al.*[6], Burrows *et al.*[26], and Burkholder and Talukdar[27] investigated the dependence of ozone gas absorption cross sections on the temperature in the Chappuis band. The work by Serdyuchenko *et al.*[4] and El Helou *et al.*[6] has been discussed in Section 1. Burrows *et al.* reported that ozone gas absorption cross sections decreased with decreasing temperatures at the wavelength range of 370 nm to 500 nm[26]. However, the authors observed an increase in ozone gas absorption cross sections as the temperature decreased at wavelengths of above 650 nm[26]. Burkholder and Talukdar in their work recorded a variation of less than 1% in ozone gas absorption cross sections between 550 nm and 650 nm wavelengths[27]. Measurements of ozone and other trace gases were dependent on the accurate value of absorption cross sections in [28].

3. Simulation Software and Methodology

The methodology adopted is online simulation via www.spectralcalc.com. The simulation is for high resolution spectral modelling. HITRAN 2012—the latest available line list on the spectralcalc.com simulator is used in this study to simulate ozone gas absorption cross sections in relation to the effects of varying the temperature and optical path length at the wavelengths of 603 nm and 575 nm. The ranges of the temperature and optical path length considered are between 103 K and 313 K and between 10 cm and 120 cm, respectively.

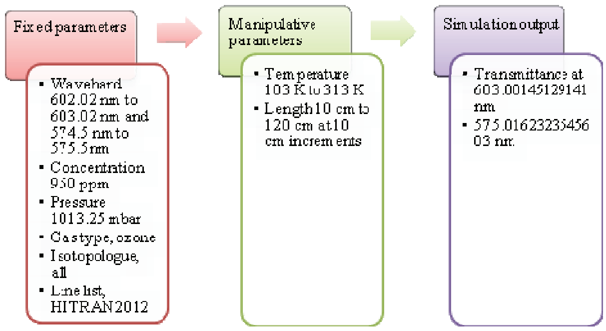


Fig. 1. Summary of spectralcalc.com simulation methodology.

The fixed parameters as shown in Fig. 1 include the wavelength ranges from 602.02 nm to 603.02 nm and 574.5 nm to 575.5 nm, concentration at 950 ppm, and one atmosphere pressure. Ozone gas is selected as the gas of choice. All isotopologues of ozone gas are considered. The output from the simulator is transmittance at 603 nm (actual value is 603.0105702572658 nm) and that at 575 nm (actual value is 575.0162323546030 nm). The methodology is summarized in Fig. 1. The ozone gas absorption cross section σ and deviation $\Delta\sigma$ are computed using (1) and (2) earlier[29],[30].

$$\sigma = -\frac{10^6 RT_p}{c_{\text{ppm}} N_A PL} \ln T \qquad (1)$$

where c_{ppm} is the ozone concentration in ppm. R is the ideal gas constant in atm·m^3·mol^{-1}·K^{-1}. T_p is the temperature in K. σ is the absorption cross section in m^2/molecule. N_A is Avogadro's constant in molecule/mol. P is the pressure in atmosphere atm. L is the optical path length. And T is the transmittance.

$$\Delta\sigma = \frac{\sigma - \sigma_w}{\sigma_w} \times 100\% \qquad (2)$$

where σ is the ozone absorption cross section at 603 nm. σ_w is the ozone absorption cross section obtained in this work.

4. Results and Discussion

Fig. 2 and Fig. 3 show the effects of the temperature and optical path length variations on transmittance for one atmosphere pressure at the wavelengths of 603 nm and 575 nm. The decrease in temperatures from 313 K to 103 K results in a decrease in the transmittance for each gas cell considered. At 603 nm, the decrease is 0.24% and 2.87% for the optical path length of 10 cm and 120 cm, respectively. Similarly, at 575 nm, the decrease is 0.22% for 10 cm and 2.63% for 120 cm, respectively. The longer the gas cell, the higher the decrease in the transmittance is with decreasing temperatures. Also, at a specific temperature, the light transmittance generally decreases with the increase in the optical path length. At 603 nm with the optical path length increased from 10 cm to 120 cm, the decrease in transmittance is 3.78% for the temperature of 103 K and 1.24% for 313 K, respectively. Similarly, at 575 nm with the optical path length increased from 10 cm to 120 cm, the decrease in transmittance is 3.47% for 103 K and 1.15% for 313 K, respectively.

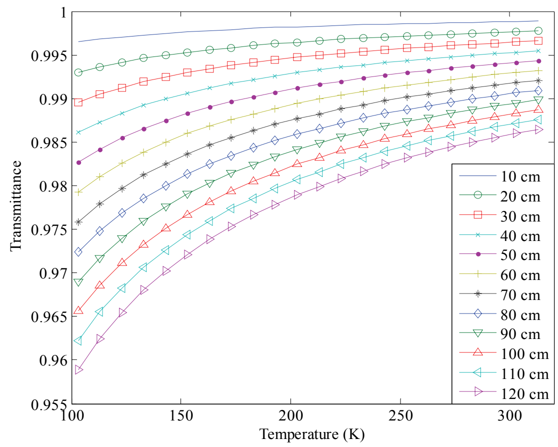


Fig. 2. Effects of the optical path length and temperature variations on transmittance at 603 nm.

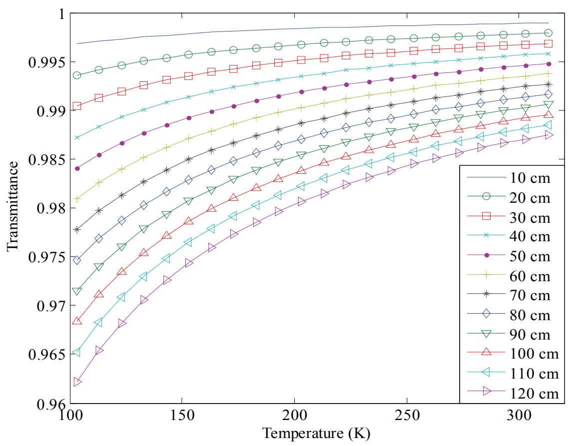


Fig. 3. Effects of the optical path length and temperature variations on transmittance at 575 nm.

Fig. 4 shows the temperature and optical path length effects on ozone gas absorption cross sections at the wavelengths of 603 nm and 575 nm. Increasing the optical path length from 10 cm to 120 cm has the same effect on ozone gas absorption cross sections. Hence, the effect of the optical path length for each gas cell is overlapping for wavelengths 603 nm and 575 nm, respectively. There are three different responses observed as the temperature is decreased from 313 K to 103 K. Between 313 K and 293 K, the absorption cross sections are a constant value of 5.1058×10^{-25} m^2/molecule at 603 nm and 4.7158×10^{-25} m^2/molecule at 575 nm, respectively. For the temperature range of 293 K to 203 K the absorption cross sections are increased from 5.1058×10^{-25} m^2/molecule to 5.1569×10^{-25} m^2/molecule at 603 nm and from 4.7158×10^{-25} m^2/molecule to 4.7468×10^{-25} m^2/molecule at 575 nm, respectively. For the temperature range of 203 K to 103 K, the absorption cross sections are increased from 5.1569×10^{-25} m^2/molecule to 5.1691×10^{-25} m^2/molecule at 603 nm and from 4.7468×10^{-25} m^2/molecule to 4.7495×10^{-25} m^2/molecule at 575 nm, respectively. For the temperature range of 193 K to 103 K, the absorption cross sections are a constant value of 5.1691×10^{-25} m^2/molecule at 603 nm and 4.7495×10^{-25} m^2/molecule at 575 nm, respectively.

The decrease in temperatures from 313 K to 103 K shows an increase in ozone gas absorption cross sections. At the wavelength of 603 nm, the increased percentage is 1.22%. At 575 nm, the increased percentage is 0.71%. A difference of 0.51% shows that the variation of absorption cross sections is wavelength dependent.

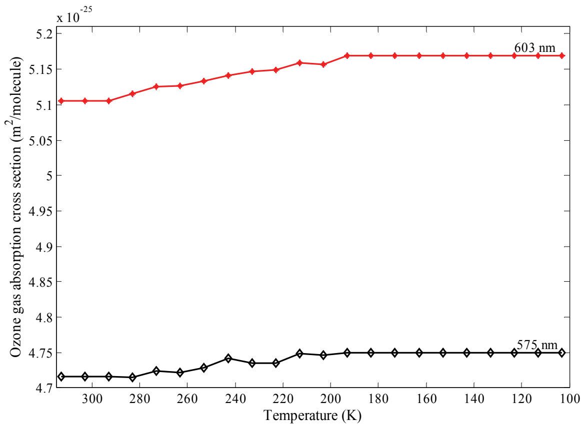


Fig. 4. Effects of the temperature and optical path length on ozone absorption cross sections.

In comparison with previous work, the results are in a good agreement with Serdyuchenko *et al.*[4], who obtained a similar increment of 1%. The increase in the ozone gas absorption cross sections is due to the temperature variation. The electronic ground state, vibrational and rotational distribution states change with temperatures[31]. Nonlinearity behaviour is more pronounced at 575 nm, which is observed at temperatures 263 K, 233 K, and 203 K. The peak absorption wavelength of 575 nm in comparison with 603 nm has lower absorption of ozone gas (approximately 8% lower).

The results obtained are further compared with the work of Brion *et al.* (5.23×10^{-25} m^2/molecule)[7] and Vigroux *et al.* (5.18×10^{-25} m^2/molecule)[13],[23] at 603 nm and with Brion *et al.* (4.766×10^{-25} m^2/molecule)[7] and Hearn (4.76×10^{-25} m^2/molecule)[32] at 575 nm. Fig. 5 and Fig. 6 show the deviation with the increase in temperatures from 103 K to 313 K.

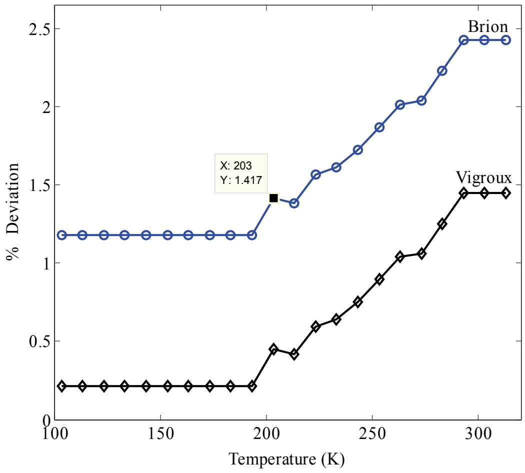


Fig. 5. Deviation of the absorption cross sections from 5.18×10^{-25} m^2/molecule and 5.23×10^{-25} m^2/ molecule at 603 nm.

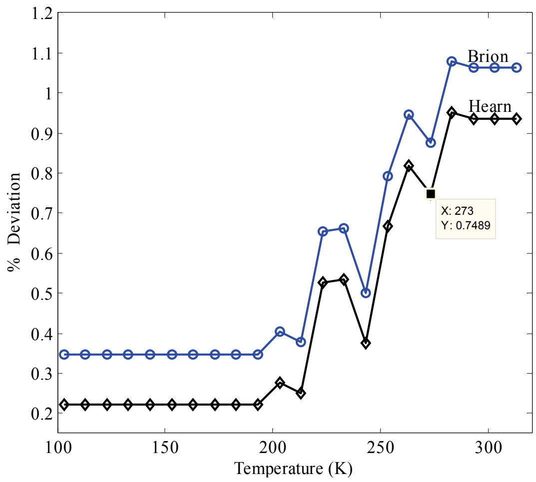


Fig. 6. Deviation from the absorption cross sections of 4.76×10^{-25} m^2/molecule and 4.766×10^{-25} m^2/ molecule at 575 nm.

In Fig. 5 the range of deviation at 603 nm is from 0.21% to 1.45% in comparison with that of Vigroux *et al.* and 1.18% to 2.43% in comparison with that of Brion *et al.* Similarly, in Fig. 6, the range of deviation is from 0.22% to 0.94% and 0.35% to 1.06% when compared with those of Hearn and Brion *et al.*, respectively.

In relation to green communications, the results in this study can be applied to enhance the accurate measurement of ozone gas, which will in turn, facilitate adequate monitoring of ozone gas impacts on the environment.

5. Conclusions

The temperature and optical path length effects on the ozone gas absorption cross sections were investigated in the visible spectrum at the wavelengths of 603 nm and 575 nm. The decrease in temperatures from 313 K to 103 K showed a decrease in transmittance for each gas cell considered. The longer the gas cell, the higher the decrease in transmittance was along with the decrease in temperatures. There was an increase in the absorption cross sections along with the decrease in temperatures. The decrease in the absorption cross sections was 1.22% at 603 nm and 0.71% at 575 nm, respectively, which shows the dependence on wavelengths. The increase in absorption was the same for all optical path lengths (10 cm to 120 cm) considered. Thus, the results obtained in this work show that at constant pressure, the ozone gas absorption cross sections are dependent on the temperature and wavelength, but are independent on the optical path length. The study addresses discrepancies that arise in the ozone gas measurement in relation to the temperature effect on the ozone gas absorption cross sections. These results will enhance the accurate measurement and monitoring of ozone gas as a green house gas. It is recommended that the results obtained need to be further verified through experiments.

References

[1] N. Nomikos, A. Nieto, P. Makris, *et al.*, "Relay selection for secure 5G green communications," *Telecommunication Systems*, vol. 59, no. 1, pp. 169-187, May 2015.

[2] W. Yu, L. Musavian, and Q. Ni, "Tradeoff analysis and joint optimization of link-layer energy efficiency and effective capacity toward green communications," *IEEE Trans. on Wireless Communications*, vol. 15, no. 5, pp. 3339-3353, 2016.

[3] J. Viallon, S. Lee, P. Moussay, K. Tworek, M. Petersen, and R. Wielgosz, "Accurate measurements of ozone absorption cross-sections in the hartley band," *Atmospheric Measurement Techniques*, vol. 8, no. 3, pp. 1245-1257, Mar. 2015.

[4] A. Serdyuchenko, V. Gorshelev, M. Weber, W. Chehade, and J. Burrows, "High spectral resolution ozone absorption cross-sections–part 2: Temperature dependence," *Atmospheric Measurement Techniques*, vol. 7, no. 2, pp. 625-636, Feb. 2014.

[5] K. Teranishi, Y. Shimada, N. Shimomura, and H. Itoh, "Investigation of ozone concentration measurement by visible photo absorption method," *Ozone: Science and Engineering*, vol. 35, no. 35, pp. 229-239, May 2013.

[6] Z. El Helou, S. Churassy, G. Wannous, R. Bacis, and E. Boursey, "Absolute cross sections of ozone at atmospheric temperatures for the wulf and the chappuis bands," *Journal of Chemical Physics*, vol. 122, pp. 244311:1-9, Jun. 2005.

[7] J. Brion, A. Chakir, J. Charbonnier, D. Daumont, C. Parisse, and J. Malicet, "Absorption spectra measurements for the ozone molecule in the 350-830 nm region," *Journal of Atmospheric Chemistry*, vol. 30, no. 2, pp. 291-299, 1998.

[8] E. C. Inn and Y. Tanaka, "Absorption coefficient of ozone in the ultraviolet and visible regions," *Journal of the Optical Society of America*, vol. 43, no. 10, pp. 870-872, 1953.

[9] S. Jodpimai, S. Boonduang, and P. Limsuwan, "Inline ozone

concentration measurement by a visible absorption method at wavelength 605 nm," *Sensors and Actuators B: Chemical*, vol. 222, pp. 8-14, Jan. 2016.

[10] S. Voigt, J. Orphal, K. Bogumil, and J. Burrows, "The temperature dependence (203-293 K) of the absorption cross sections of O_3 in the 230-850 nm region measured by fourier-transform spectroscopy," *Journal of Photochemistry and Photobiology A: Chemistry*, vol. 143, no. 1, pp. 1-9, Oct. 2001.

[11] R. Chang and J. Overby, *General Chemistry: The Essential Concepts*, 6th ed. New York: Mcgraw-Hill, 2011, ch. 5, pp. 145.

[12] H. P. Bloch, *A Practical Guide To Compressor Technology*, 2nd ed. New York: Wiley-Interscience, 2006, ch. 1, pp. 9.

[13] S. O'keeffe, C. Fitzpatrick, and E. Lewis, "An optical fibre based ultra violet and visible absorption spectroscopy system for ozone concentration monitoring," *Sensors and Actuators B: Chemical*, vol. 125, no. 2, pp. 372-378, Aug. 2007.

[14] S. W. Otto, *Fibre Optic Chemical Sensors and Biosensors Volume I*, London: CRC Press, 1991, pp. 2 & 26.

[15] M. Fowles and R. Wayne, "Ozone monitor using an LED source," *Journal of Physics E: Scientific Instruments*, vol. 14, no. 14, pp. 1143-1145, Oct. 1981.

[16] Y. Zhao, L. Bai, Y.-N. Zhang, W. Hou, and Q. Wang, "Review on structures and principles of gas cells in the absorption spectrum-based optical fiber gas sensor systems," *Instrumentation Science and Technology*, vol. 40, no. 5, pp. 385-401, Sep. 2012.

[17] A. Gomez and E. Rosen, "Fast response cavity enhanced ozone monitor," *Atmospheric Measurement Techniques*, vol. 6, no. 5, pp. 487-494, Feb. 2013.

[18] M. Degner, N. Damaschke, H. Ewald, and E. Lewis, "High resolution LED-spectroscopy for sensor application in harsh environment," in *Proc. of 2010 IEEE Intl. Instrumentation and Measurement Technology Conf.*, 2010, pp. 1382-1386.

[19] M. Degner, N. Damaschke, H. Ewald, S. O'keeffe, and E. Lewis, "UV LED-based fiber coupled optical sensor for detection of ozone in the ppm and ppb range," in *Proc. of 2009 IEEE Conf.* on *Sensors*, 2009, pp. 95-99.

[20] L. D. Maria and D. Bartalesi, "A fiber-optic multisensor system for predischarges detection on electrical equipment," *IEEE Sensors Journal*, vol. 12, no. 1, pp. 207-212, Jan. 2012.

[21] K. Liu, W.-C. Jing, G.-D. Peng, *et al*., "Intra-cavity absorption gas sensors using wavelength modulation and wavelength sweep," *Journal of Electronic Science and Technology of China*, vol. 6, no. 4, pp. 353-356, Dec. 2008.

[22] M. Griggs, "Absorption coefficients of ozone in the ultraviolet and visible regions," *The Journal of Chemical Physics*, vol. 49, no. 2, pp. 857-859, Jul. 1968.

[23] E. Vigroux, *Contribution À L'étude Expérimentale De L'absorption De L'ozone, Par Ernest Vigroux*, Masson, 1953.

[24] J. Brion, A. Chakir, D. Daumont, J. Malicet, and C. Parisse, "High-resolution laboratory absorption cross section of O_3. temperature effect," *Chemical Physics Letters*, vol. 213, no. 5-6, pp. 610-612, Oct. 1993.

[25] A. Amoruso, M. Cacciani, A. Di Sarra, and G. Fiocco, "Absorption cross sections of ozone in the 590 to 610 nm region at T=230 K and T=299 K," *Journal of Geophysical Research: Atmospheres 95(D12)*, vol. 95, no. D12, pp. 20565-20568, Nov. 1990.

[26] J. Burrows, A. Richter, A. Dehn, *et al*., "Atmospheric remote-sensing reference data from gome—2. temperature-dependent absorption cross sections of O_3 in the 231-794 nm range," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 61, no. 4, pp. 509-517, Mar. 1999.

[27] J. B. Burkholder and R. K. Talukdar, "Temperature dependence of the ozone absorption spectrum over the wavelength range 410 nm to 760 nm," *Geophysical Research Letters*, vol. 21, no. 7, pp. 581-584, Apr. 1994.

[28] K. Bogumil, J. Orphal, T. Homann, *et al.*, "Measurements of molecular absorption spectra with the sciamachy pre-flight model: Instrument characterization and reference data for atmospheric remote-sensing in the 230–2380 nm region," *Journal of Photochemistry and Photobiology A: Chemistry*, vol. 157, no. 2-3, pp. 167-184, May 2003.

[29] M. David, M. H. Ibrahim, and S. M. Idrus, "Sampling frequency effect on the absorption cross section of ozone in the visible spectrum," *Journal of Optoelectronics and Advanced Materials*, vol. 17, no. 3-4, pp. 403-408, 2015.

[30] T. C. E. Marcus, M. David, M. Yaacob, *et al*., "Pressure dependence of ozone absorption cross section," *Applied Mechanics and Materials*, vol. 735, pp. 260-264, Apr. 2015.

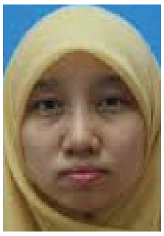
[31] K. Bogumil, J. Orphal, and J. P. Burrows, "Temperature dependent absorption cross sections of O_3, NO_2, and other atmospheric trace gases measured with the SCIAMACHY spectrometer," in *Proc. of Ers-Envisat-Symposium*, 2000, pp. 1-11.

[32] A. Hearn, "The absorption of ozone in the ultra-violet and visible regions of the spectrum," *Proc. of the Physical Society*, vol. 78, no. 5, pp. 932-940, Nov. 1961.

Michael David received his B.E. degree in electrical and computer engineering and M.E. degree in telecommunication engineering from Federal University of Technology, Minna, Nigeria in 2004 and 2010, respectively. The Ph.D. degree in electrical engineering was conferred on him by Universiti Teknologi Malaysia (UTM), Skudai Johor, Malaysia in 2016 for his work on visible absorption based ozone sensors. He currently is a member of the Lightwave Communication Research Group, UTM. His research focuses on absorption spectroscopy for gaseous ozone concentration measurement.

Mohd Haniff Ibrahim received his B.E. degree in telecommunications engineering from University of Malaya, Kuala Lumpur, Malaysia in 1999. He was awarded the Ph.D. degree by UTM in 2007 for his work on polymer based multimode interference devices. Now he is an associate professor and researcher with the Lightwave Communication Research Group, UTM. His research interests include simulation, fabrication, and characterization of polymer based optical devices and spectroscopic based sensors for environmental monitoring.

Sevia Mahdaliza Idrus received her B.E. degree in electrical engineering in 1998 and M.E. degree in engineering management in 1999, both from UTM. She obtained her Ph.D. degree in optical communication engineering from University of Warwick, Coventry, United Kingdom in 2004. Now she is a professor and researcher with the Lightwave Communication Research Group, UTM. Her research interests include optical communications systems and networks, optoelectronic design, and engineering management.



Nor Hafizah Ngajikin received her B.E. and M.E. degrees in electronic engineering from UTM 2001 and 2004, respectively. She was awarded the Ph.D. degree from UTM for her work on MEMS Fabry Perot optical tunable filters in 2011. Now she is a senior lecturer and researcher with the Lightwave Communication Research Group, UTM. Her research interests include analytical modeling of semiconductor-based Fabry Perot devices and sensors development for biomedical applications.

Asrul Izam Azmi received his B.E. and M.E. degrees in electrical engineering from UTM in 2001 and 2004, respectively. He received his Ph.D. degree from University of New South Wales, Sydney, Australia in 2012. His Ph.D. work was related to optical fiber sensors. Now he is a senior lecturer and the Head of the Lightwave Communication Research Group, UTM. His research interests include the development of fiber grating-based sensing techniques and applications of fiber grating sensing technology in engineering areas.

Tay Ching En Marcus received his B.E. degree in electrical and telecommunications engineering from UTM in 2012. The Ph.D. degree in electrical engineering was conferred on him by UTM in 2015 for his work on ultraviolet absorption based ozone sensors. He is a lecturer with the Faculty of Engineering and Computing, First City University College, Petaling Jaya, Malaysia. He is also a graduate engineer registered with the Board of Engineers Malaysia. His research focuses on ultraviolet absorption spectroscopy for gaseous ozone concentration measurement.