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Measurement of Turbidity Using an 850 nm Light-emitting Diode

Beom-Su Kim,[1] Sungkwan Youm,[2*] and Yong-Kab Kim[2**]

[1]SongBaek E&S, 20-23, Yakchon-ro 8-gil, Iksan-si, Jeollabuk-do 54630, South Korea
[2]Department of Information & Communication Engineering, Wonkwang University,
460, Iksan-daero, Iksan-si, Jeollabuk-do 54538, South Korea

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Evaluating and managing water quality have become increasingly important owing to industrialization and environmental degradation. Currently, Korean water laws and regulations stipulate that small particles should be at a low concentration of less than 0.5 nephelometric turbidity units (NTU) in process control; hence, control technology that utilizes infrared light-emitting diode (LED) sensors remains necessary. In this study, we used 470, 670, and 850 nm LEDs to measure the light absorbance and transmittance to evaluate turbidity. The light absorbance measured using the 850 nm LED was extremely reliable, with a determination coefficient (R^2) of 0.9997. The relationship between the reflected and transmitted lights at 90 and 180° was evaluated using an 850 nm light source and an 820 nm photointegrated circuit (IC) device. In addition, the effects of scattered light were determined by setting the distance between the height of the LED and the IC. From these results, we conclude that the 850 nm LED is optimal as the light source and that the effects of the horizontal distance between the LED and the IC are negligible.

1. Introduction

As environmental destruction accelerates owing to rapid industrialization, the associated problems are becoming increasingly severe; among these, reduced water quality due to pollution is threatening the survival of various species and reducing the quality of drinking, and even industrial water, thereby adversely affecting human health. To solve these problems, various wastewater treatment systems have been implemented, and regulations have been made more stringent. Personal water purifiers have become extremely popular for domestic use. These systems and regulations require the accurate measurement and management of water conditions and the degree of pollution for efficient use and implementation.

In a water supply system, the turbidity of raw water considerably affects the performance of flocculation treatment and filter papers. The turbidity of treated water is an important indicator of the efficiency of the water treatment process and any abnormality in the water supply and drainage facilities. Fine floating particles in treated water, which cause turbidity, are usually harmless but visually problematic. Occasionally, harmful substances may be present among

*Corresponding author: e-mail: skyoum@gmail.com
**Corresponding author: e-mail: ykim@wku.ac.kr
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the particles themselves or be adsorbed onto the suspended particles. Thus, turbidity is an important indicator for evaluating and managing the quality of purified water, tap water, and other types of water. As turbidity is an essential factor in water quality management, it should be measured accurately via precise, reasonable, and standardized methods.

Turbidity in a water purification plant is measured and used as an indicator to evaluate the settling operation function at the plant, as well as of filter papers, and to monitor the quality of purified and tap water. Korea's regulations on turbidity have been made more stringent and now permit only a low turbidity of less than 0.5 nephelometric turbidity units (NTU). A technology for controlling turbidity is essential, and a reliable continuous-operation sensor device for measuring turbidity is required for this purpose.[1–3] However, there is a lack of technology in Korea for measuring and monitoring turbidity in real time and for controlling it to the specified level; most automatic water quality turbidimeters operated in water purification plants and industry are imported from the United States or Japan.[4]

Turbidity is determined by measuring the amount of light scattered by particles in a sample by scanning light with an optical sensor. When the number of particles in the sample initially increases, the turbidity increases, and the amount of scattered light increases accordingly. However, if the number of particles in the sample continues to increase, the scattered light is then scattered by other particles, thereby making it impossible to predict the total amount of scattered light.[5–8] There are various methods for reducing the error in turbidity measurement, such as improving the light source, diluting the sample volume when the turbidity is high, or changing the position of measurement of the optical sensor. Unfortunately, the configurations of these methods are complicated, and the results are difficult to predict.[9–11] Therefore, in this study, the turbidity was measured on the basis of experimental results obtained using an infrared light source, and a regression analysis revealed that the reliability was high when turbidity measurements were performed using an 850 mm light source. In this paper, we present a study on the real-time measurement of turbidity of less than 1.0 NTU.

The remainder of this paper is organized as follows. In Sect. 2, we describe the light-emitting diodes (LEDs) used as light sources in this study, with wavelengths of 470, 650, and 850 nm, and the method of turbidity measurement. The experimental turbidity measurement results obtained using the 850 nm LED are discussed in Sect. 3. Section 4 presents conclusions based on the test results.

2. LED Light Source for Turbidity Measurement

2.1 Turbidity based on wavelength characteristics

To develop a turbidimeter, a light source with a specific spectrum that does not interfere with the sample should be selected, considering that the light characteristics depend on the wavelength. The most commonly used light source is an LED. A conventional tungsten lamp has a broad wavelength range of 400–600 nm but poor stability. Hence, an LED light source that delivers a single wavelength with general stability was used in this study. The International Standards Organization and the United States define turbidity in the regulations ISO7027 and

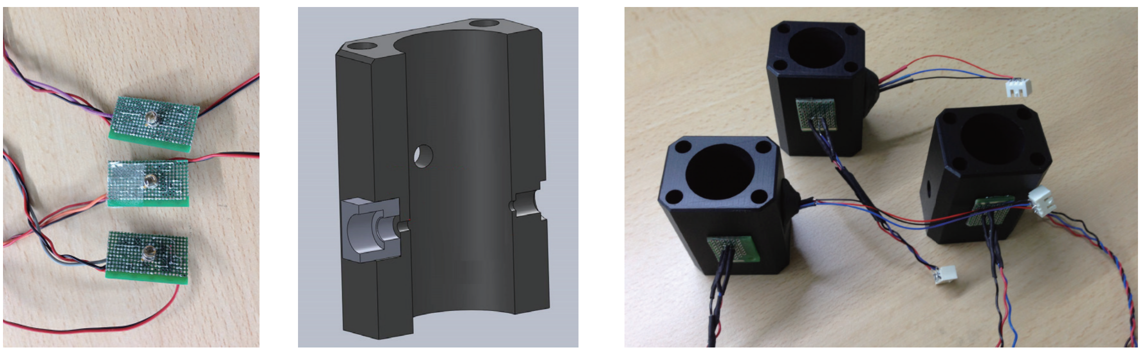
US EPA 180.1, respectively.(12) On the basis of these regulations, we attempted to estimate the error rate and accuracy with respect to the wavelength of the LED light source used in the turbidimeter.

ISO7027 defines the wavelength of the LED as 860 nm, and US EPA 180.1 specifies a 400–600 nm wavelength range. Turbidity sensors that use light with a wavelength of 400–600 nm require a separate filter, whereas an 800 nm band sensor incurs the problem of low scattering by small particles. However, as infrared LEDs in the 800 nm band are commonly used as light sources, the emitted and scattered lights in this band should be evaluated. In this study, the absorbance for each turbidity was measured using LED light sources with wavelengths of 470, 650, and 850 nm (ODTECH Co., Ltd.) on a holder, as shown in Fig. 1. The light-emitting and light-receiving elements shown in Fig. 1(a) were attached to the holder, manufactured in accordance with the model shown in Fig. 1(b), to produce the prototype optical measurement device shown in Fig. 1(c). Each water sample was a standard solution with turbidity ranging from 10 to 50 NTU, prepared by diluting 4000 NTU formazin (HACH Co., Ltd.) 80- to 400-fold with distilled water. The reference sample was distilled water with a turbidity of 0 NTU.(13)

Before the measurement, the cell containing the standard solution was agitated for 60 s using a Vortex-Genie mixer (Vortex, Inc.) and then measured for 120 s. For measurement consistency, the position of the cell was marked such that the light direction was the same in all tests.

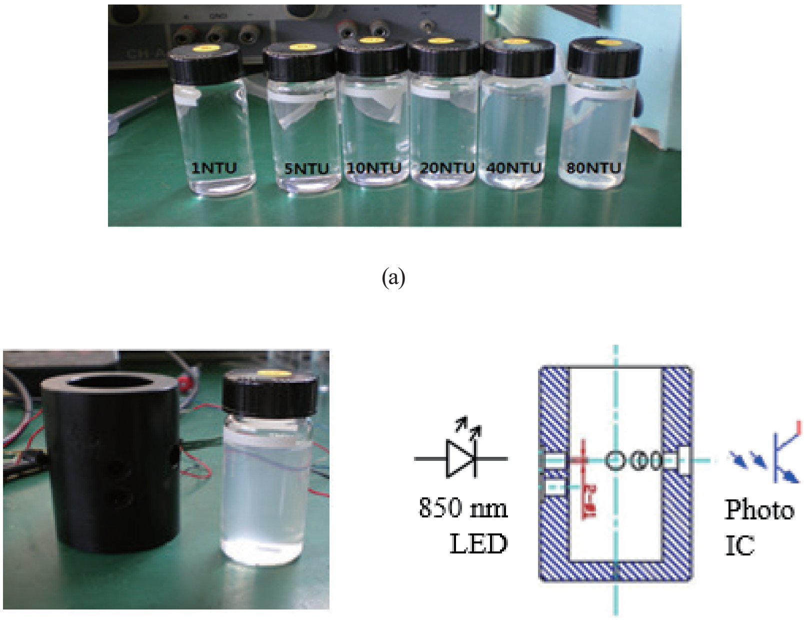
2.2 Light-receiving detector

The detector uses a TSL230 silicon light-to-voltage photodiode (Texas Instruments), which yields the maximum response at 820 nm.(14) Photointegrated circuits (ICs) are assembled with a can-shaped holder to produce various angles of light. The standard solutions shown in Fig. 2(a) were prepared by diluting distilled water with Formazin Turbidity Standard 4000 NTU (HACH),



(a) (b) (c)

Fig. 1. (Color online) Holder for measuring turbidity using wavelengths of 470, 670, and 850 nm: (a) LED light sources, (b) 3D model of holder, and (c) prototype holders.



(a)

(b) (c)

Fig. 2. (Color online) Holder for photo IC measurement: (a) standard solutions, (b) prototype of holder, and (c) holder and sensor.

e.g., a 40 NTU standard solution was prepared by diluting 100-fold the amount of distilled water in Formazin Turbidity Standard 4000 NTU (HACH). As shown in Fig. 2(b), the container of the standard solution is placed in the can-shaped holder to measure the absorbed and scattered lights, as shown schematically in Fig. 2(c). An LED and a photo IC are positioned on the left and right sides of the can-shaped holder, respectively, to measure the light absorbance. The scattered light can be measured at an angle of 90° through the hole in the middle of the can-shaped holder.

3. Experimental Method and Results

3.1 Relationship between absorbance and wavelength

Absorbance was measured for various voltages (mV) of the LED input to the photo IC. A linear regression analysis was performed to develop an appropriate linear model based on the experimental results. The determination coefficient is

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right). \tag{1}$$

This formula was used to validate the results, in which O_i and P_i are considered as the observed values on a scattered light and a transmitted light, respectively, while $\overline{O}$ and $\overline{P}$ are the predicted values calculated using a linear regression model on a scattered light and a transmitted light, respectively.

Figure 3 shows the transmitted light measured using an LED with a wavelength of 470 nm. The output voltage of the IC ranged from 0.04 to 0.251 mV, and R^2 was 0.9991. Figure 4 shows the transmitted light measured using an LED with a wavelength of 650 nm. The output voltage of the IC ranged from 0.021 to 0.125 mV, and R^2 was 0.9955. Figure 5 shows the transmitted light measured using an LED with a wavelength of 850 nm.

When low-turbidity samples are measured, using wavelengths in the range of 400–700 nm may cause a measurement error if organic materials are present because all organic molecules strongly absorb light at these wavelengths. Conversely, the advantage of reducing this error is obtained in the 800 nm wavelength region. At the time of low-turbidity measurement, it is advantageous to use an 850 nm LED with a low turbidity-vs-transmittance slope and an R^2 that is closer to 1, rather than an LED with a steep turbidity-vs-transmittance slope. Even though

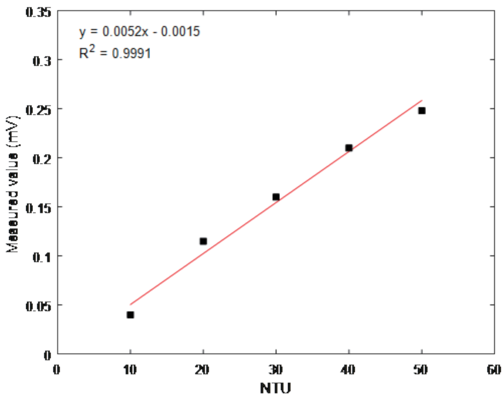


Fig. 3. (Color online) Transmitted light measured using an LED with a wavelength of 470 nm.

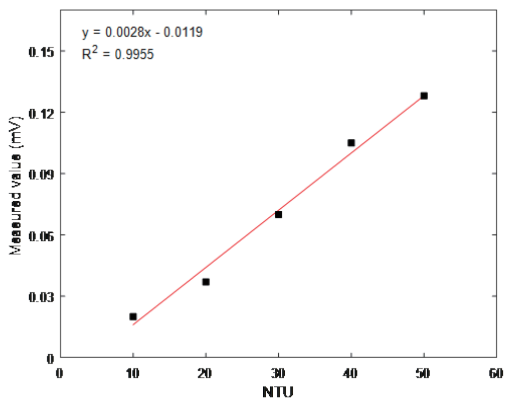


Fig. 4. (Color online) Transmitted light measured using an LED with a wavelength of 650 nm.

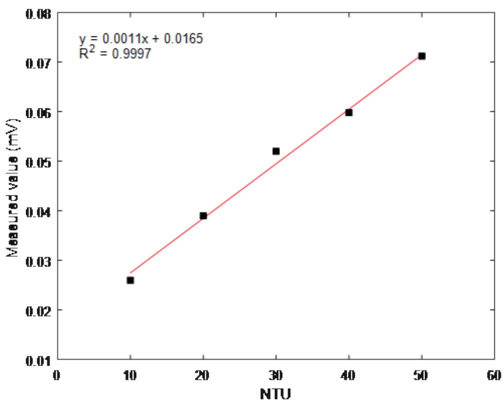


Fig. 5. (Color online) Transmitted light measured using an LED with a wavelength of 850 nm.

the 400–700 nm wavelength range is more sensitive as small particles absorb more light in this range, a wavelength of 850 nm is preferred owing to the high reliability, measured using R^2. According to the experimental results of R^2, an LED with a wavelength of 850 nm was used when applying a low-turbidity meter.[15,16]

3.2 Detector characteristics

A voltage of 3.5 V was supplied to the 850 nm LED, a 200 kΩ resistor was attached to the photo IC, and the output voltage was measured.[17] The scattered and transmitted lights were arranged on the same line from the LED, and a polarizing filter was attached to the permeation side to induce light attenuation; this was performed to obtain suitable values for the photo IC sensitivity and reduce the error range.

Table 1 shows the signal values of the photo IC relative to the reflected and transmitted lights in the NTU. In addition, Fig. 6 shows the values of the transmitted and reflected lights, with an R^2 of 0.9734. The points in the figure indicate the experimental values; these are at the approximate location of the straight line given by the formula.

Table 1
Reflectance and transmittance correlation with the NTU.

Unit	Instruments and sensors			
NTU	Permeation A, V	Reflection B, mV	B/A	B(B+A)
0.22	0.552	0.4156	0.7529	0.4295
0.28	0.547	0.4328	0.7912	0.4417
1.84	0.551	0.4609	0.8365	0.4555
1.95	0.548	0.4568	0.8336	0.4546
3.92	0.537	0.4777	0.8896	0.4708
3.96	0.529	0.5092	0.9626	0.4905
6.31	0.534	0.6057	1.1343	0.5315
7.56	0.533	0.6518	1.2229	0.5501
8.25	0.527	0.6915	1.3121	0.5675
9.12	0.521	0.6586	1.2641	0.5583

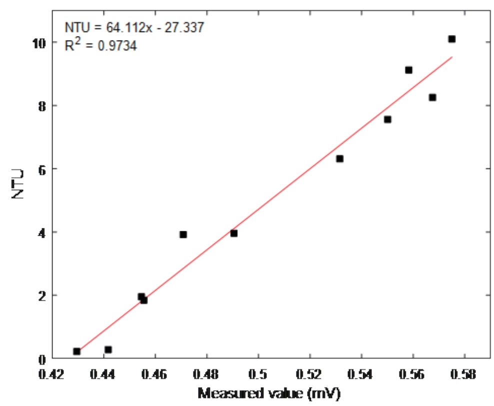


Fig. 6. (Color online) Relationship between the reflective light and the transmittance with IC.

3.3 Light scattering and absorbance characteristics

A photo IC with good light sensitivity and linearity was used to measure the scattered light at an angle of 90° and the transmitted light at an angle of 180°. The experimental results are presented in Table 2. The values in the table are the measured currents (mA) at the photo IC. The scattered light at an angle of 90° and the transmitted light at an angle of 180°, from the LED to the IC, are represented by '90°' and '180°' in the first row of the table, respectively. The current drawn into the LED is represented by '10 mA' and '20 mA' in the second row. In addition, the measurement was performed with a height difference between the LED and the photo IC. The '$^{-1}$' symbol in Table 2 indicates a vertical distance of 10 mm between the LED and the photo IC. The 10 mm gap at the 180° hole prevents the overexposure of light to the photo IC. Conversely, it was considered acceptable to measure the light even without a gap at 90° light exposure.

Figure 7 presents the results obtained at the photo IC at 90° and 10 mA, using an LED with a wavelength of 850 nm and powered by a 10 mA current source, according to a sensitivity of 1–80 NTU. R^2 was calculated as 0.9985. Figure 8 shows that R^2 was calculated as 0.9982 at a photo IC at 90° from an LED powered by a 20 mA current source.

Table 2
Measurements of the scattered and transmitted lights with different light direction angles and various source currents.

NTU	90°				180°	
	10 mA	20 mA	10 mA^{-1}	20 mA^{-1}	10 mA^{-1}	20 mA^{-1}
1	240	343	97	118	210	340
5	332	467	113	149	233	446
10	412	592	130	162	248	490
20	646	870	173	220	303	578
40	968	1378	227	305	440	654
80	1690	2285	396	540	532	786

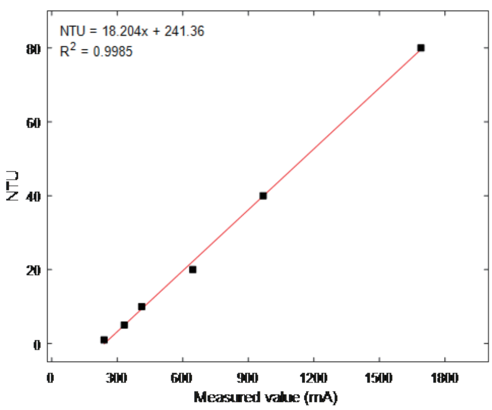


Fig. 7. (Color online) Scattered light measured at a photo IC located at angle of 90° from an LED powered by a 10 mA current source.

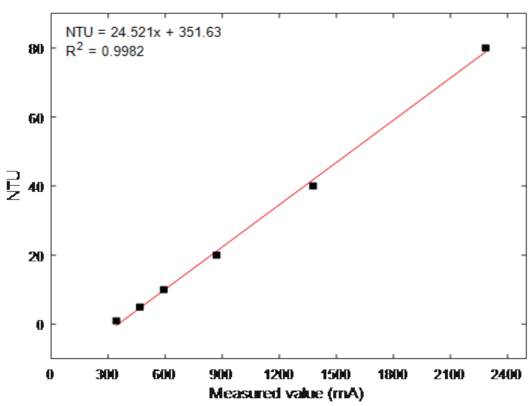


Fig. 8. (Color online) Scattered light measured at a photo IC located at angle of 90° from an LED powered by a 20 mA current source.

Figure 9 shows the output current of the scattered light measured at a photo IC located at an angle of 90° from an LED powered by a 10 mA current source at a vertical distance of 10 mm. R^2 was 0.9955. Figure 10 shows that R^2 was 0.9961 when the photo IC was 10 mm higher than the LED. The correlation coefficient was higher than that when the photo IC was located at an angle of 90° from the LED powered by a 10 mA^{-1} source current.

In Fig. 11, R^2 was 0.9558. The transmitted light is measured at a photo IC located at an angle of 180° from an LED powered by a 10 mA current source with a vertical distance of 10 mm. From the final experiment, R^2 in Fig. 12 was obtained as 0.8943 at 180° and 10 mA^{-1}. Among the measured R^2 values, that obtained at 90° and 10 mA was the best, and the signal value at the light receiver was the most stable at approximately 90°. However, as the sample cell is circular, the center of the sample was measured for optimal accuracy, considering that the light emitted from the LED causes the backscattering and front scattering of the cell.

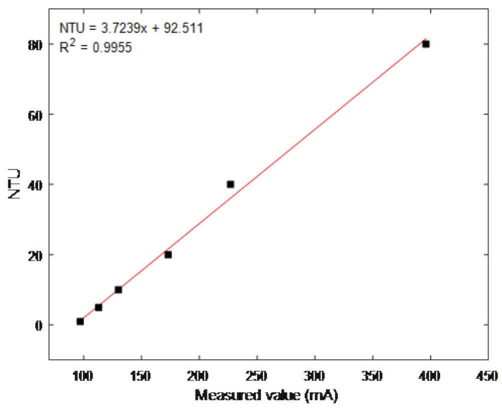


Fig. 9. (Color online) Scattered light measured at a photo IC located at an angle of 90° from an LED powered by a 10 mA current source, with a vertical distance of 10 mm.

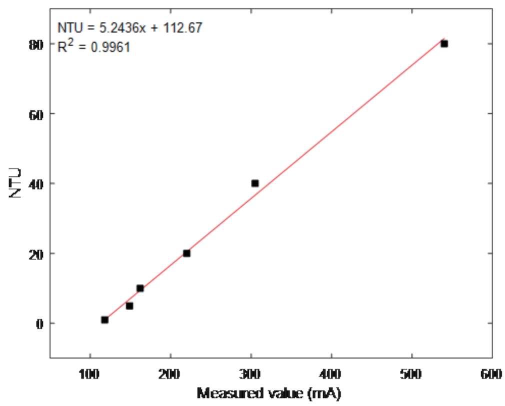


Fig. 10. (Color online) Scattered light measured at a photo IC located at an angle of 90° from an LED powered by a 20 mA current source, with a vertical distance of 10 mm.

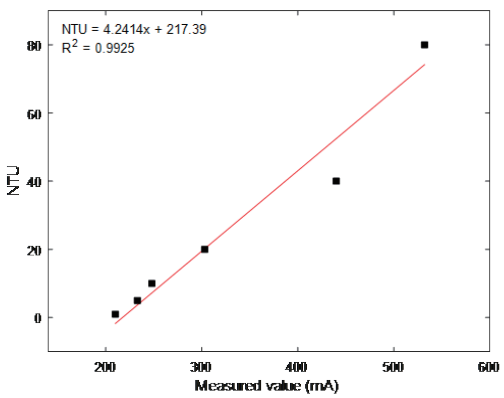


Fig. 11. (Color online) Transmitted light measured at a photo IC located at an angle of 180° from an LED powered by a 10 mA current source, with a vertical distance of 10 mm.

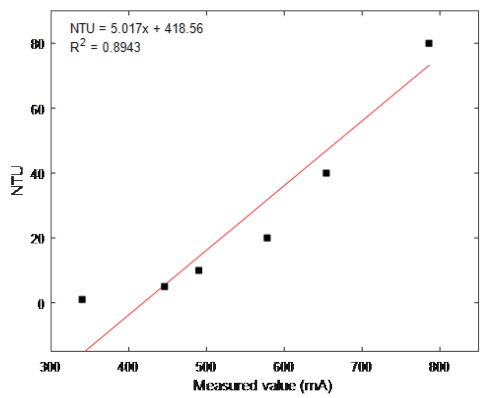


Fig. 12. (Color online) Transmitted light measured at a photo IC located at an angle of 180° from an LED powered by a 20 mA current source, with a vertical distance of 10 mm.

4. Conclusion

In this study, we experimentally determined the characteristics required for turbidity measurement. We analyzed the turbidity and presented the experimental results of light absorbance and transmittance, relative to standard NTU solutions, at three LED wavelengths of 470, 650, and 850 nm. The transmitted light measured using an LED with a wavelength of 850 nm was 0.025–0.065 mA at the photo IC, and R^2 was 0.9997, thereby indicating a reasonable certainty.

On the basis of the above results, we concluded that a wavelength of 850 nm is the optimal LED wavelength for the measurement of low turbidity; the determination coefficient R^2 between the light absorbance and the reflected light from the element receiving the light source was 0.9734. To reduce the measurement error with respect to the angles of the reflected and transmitted lights empirically, the holder was fixed, and experiments were conducted with scattered light at angles of 90 and 180°, and a height difference between the LED and the photo IC. The results of measuring the determination coefficient with the height difference indicated that the height difference had little effect on the determination coefficient. The R^2 obtained using the output current measured with the scattered light at the photo IC located at an angle of 90° from the LED powered by a 10 mA current source was excellent for adapting to the standard measurement method.

Acknowledgments

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About the Authors

Beom-Su Kim received his B.S. degree from the Business School of Wonkwang University in February 2015 and his master's degree from the Information and Communication Engineering Department of Wonkwang University in February 2017. He has been attending the Ph.D. program in the Information and Communication Engineering Department of Wonkwang University since October 2019. He is also serving as the CEO of Songbaek E&S. His areas of interest are information management, information and communications, LED lighting, and electrical and electronic materials.

Sungkwan Youm received his B.S. degree in control instrumentation engineering from Hankuk University of Foreign Studies, Yongin, Korea, in 1998, and his M.S. and Ph.D. degrees in electronics engineering from Korea University, Seoul, Korea, in 2001 and 2006, respectively. From March 2006 to February 2015, he was with the Telecommunication Systems Division at Samsung Electronics Co., Ltd., Suwon, Korea. From March 2015 to February 2018, he was an assistant professor at the Department of Information and Communication, Cheju Halla University. Since March 2018, he has been an associate professor at the Department of Information and Communication Engineering, Wonkwang University. His current research interests include network security and computer networks.

Yong-Kab Kim received his B.S. degree in electronics engineering from Ajou University and his M.S.E degree in electrical and computer engineering from the University of Alabama in Huntsville. He received his Ph.D. degree in electrical and computer engineering from North Carolina State University. He is currently a professor at the School of Information and Communication Engineering, Wonkwang University, Korea. His research interests include remote sensing for visible communication, optical fiber sensing, intelligent control, and advanced computational intelligence.