Development of Lightning Simulator

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Abstract

In this work we have developed a lightning simulator. Reproducing the light of lightning, we adopted seven waveforms that contains two light waveforms and five current waveforms of lightning. Furthermore, the lightning simulator can calibrate the color of the simulated light output based on a correlated color temperature (CCT). The CCT of the simulated light can range over from 4269 K to 15042 K. The lightning simulator is useful for the test light source of the optical/image sensor of the lightning observation. Also for science education (e.g. physics education and/or earth science education etc.), the lightning simulator is available. In particular, the temporal change can be slowly seen by expanding the time scale from microsecond to second.

Keywords: Lightning, Lightning Simulator, Correlated color temperature, Integrating sphere

1. Introduction

Measurement of lightning is difficult. It is well known that lightning is very high-speed natural phenomena. We also cannot forecast the location occurring lightning events. For the above reason, the direct measurement of lightning is very difficult and lightning is, in general, observed indirectly.

The analysis of light emitted from a lightning channel is indirect measurements. It is considered that the light emitted from a lightning channel contains many interior information. This encourages to develop the optical sensor for lightning. In development of the optical sensor, the accurate test light source is needed. Thus in this work we have developed the test light source and we refer this as the lightning simulator.

We have developed the lightning simulator which consists of a waveform generating unit, an amplifying unit, and a light-emitting unit. In the develop-
opment, we used electronic parts realizing high-speed operation. We adopted seven waveforms of lightning and confirmed that the lightning simulator emitted the simulated light preserving waveforms of lightning. While the lightning simulator was developed for the test light source of the optical/image sensor, the application for science education or a lightning projector of a planetarium to simulate lightning can also be considered.

2. Instruments

We have developed a lightning simulator shown in Fig. 1. The lightning simulator consists of the waveform generating unit, the amplifying unit, and the light-emitting unit as shown in Fig. 1. The generation of the simulated light of lightning is as follows: creating a lightning waveform in the waveform generating unit, regulating the lightning waveform to appropriate value in the amplifying unit, and emitting the light preserving the simulated waveform in the light-emitting unit. In the light-emitting unit, although several LEDs are used, the light is uniformized in the integrating sphere.

![Figure 1: Schematic illustration of the lightning simulator. The lightning simulator consists of three units, the waveform generating unit, the amplifying unit, and the light-emitting unit. The integrating sphere is used in the light-emitting unit.](image)

The details of the units above are shown in Fig. 2. Reproducing high-speed lightning waveforms, we used electronic parts (e.g. operational amplifier (Op-Amp), n-channel enhancement MOS FETs, and LEDs) having nanosecond response speed. In the waveform generating unit (Fig. 2 (a)), binary signals of the simulated waveform of lightning are created by a microcontroller (BeagleBorn Black, Rev A5A) in which Debian/Gnu Linux 7 (kernel 3.8.13 - bone 28) for the operating system and gcc ver.4.6.3 (debian 4.6.3-14) for the C compiler are adopted. Since, the 10/90 rise time is inconstant for each lightning, we set appropriate value in $1.0\mu s \leq \Delta t \leq 2.4 \mu s$ to $\Delta t$ at the first step. At the other steps, $\Delta t = 2.4\mu s$. We show the pseudocode...
Figure 2: Circuits of the (a) waveform generating, (b) amplifying, and (c) light-emitting unit. The external voltage reference VDD of the DAC is 9.8 V. The reference voltage VREF of the DAC is 5 V. The supply voltage for the Op-Amp is ±9.8 V. The output waveforms of the amplifying unit is transferred to the input, INPUT, of the light-emitting unit.

of the waveform generation algorithm to Algorithm I. Then by the 12 bit res-
olution digital-to-analog converter (DAC), AD7574AKN, the binary signals are converted to an analog waveform. Fig. 2(b) shows the amplifying unit. The output (simulated waveform) created by the waveform generating unit (Fig. 2(a)) is regulated to appropriate value by the amplifying unit. The variable resistor $R_4$ is to regulate the amplification degree. The capacitor $C_2$ is the compensation capacitor. The light-emitting unit (Fig. 2(c)) contains a high-power white LED (typ. 103250 mcd), three high-brightness blue LEDs (typ. 12000 mcd), and ten high-brightness yellow LEDs (typ. 4000 mcd). The brightness of the blue and yellow LEDs are adaptable by regulating the variable resistor $R_9$ (10 kΩ). Regulating the brightness of the blue and yellow LEDs we can calibrate the CCT of the light output. The brightness of
Algorithm 1 Pseudocode of the waveform generation algorithm.

// (Variable Declaration)
// GPIOPin: I/O pin on the microcontroller (BeagleBone Black)
// TimeStep: Time step $\Delta t$ (µs).
// Waveform[]: array containing the waveform data.
// $t_{max}$: Maximum number of the array of the waveform data.

Initializing $\text{GPIOPin}$

\[
\text{for } Time \leq t_{max} \; \text{do} \\
\text{Time} \leftarrow \text{Time} + \text{TimeStep} \\
\text{GPIOPin} \leftarrow \text{Waveform}(\text{Time}) \\
\text{Output(GPIOPin)} \\
\text{end for}
\]

the white LED is not adaptable, namely, constant. The variable resistors $R_5$, $R_7$, and $R_{10}$ in Fig. 2(c) are to prevent oscillation. In the light-emitting unit, uniforming the light emitted from the white, blue, and yellow LEDs the integrating sphere is used. The diffuse reflectance of the diffuse reflectance material coated in the integrating sphere are shown in Fig. 3[1]. From Fig. 3[1].

![Figure 3](image_url)

Figure 3: Diffuse reflectance of the diffuse reflectance materials of the integrating sphere. The data was provided by Tokyo Metropolitan Industrial Technology Research Institute [1].
it is seen that in the visible light range, the diffuse reflectance is 80 – 86% without deep blue region. Fig. 4 shows the side view of the integrating sphere. The diameters of the integrating sphere and the exit port are 300 and 70 mm, respectively.

3. Methods

3.1. Performance test of the integrating sphere

We have evaluated the performance of the integrating sphere. Fig. 5 shows the schematic illustration for the experimental setup to evaluate the performance of the lightning simulator. The distance between the lightning simulator and the digital still camera is 1.0 m.

Figure 5: Experimental setup to test the uniformity of the integrating sphere and the CCT of the simulated light. The distance between the lightning simulator and the digital still camera is 1.0 m.
settings are as follows: file type is “NEF (Nikon NEF raw image)”, compression is “Uncompressed”, F number is “5.6”, ISO is “800”, color space is “sRGB”. Under the photographing condition above, we measured the uniformity of the integrating sphere and the CCT of the simulated light.

3.1.1. Uniformity of the light emitted from the integrating sphere

We analyzed the uniformity of the integrating sphere. Fig. 6 shows the exit port of the integrating sphere. The dashed line in Fig. 6 is to check the uniformity of light emitted from the integrating sphere. For the measurement of the uniformity, only the high-power white LED driven by the constant current was used and the blue and yellow LEDs did not be used. The driving current of the high-power white LED was set to 338.6 mA. Under these condition, we analyzed the variation of the grayscale pixel value (256 levels) on the test line shown by the dashed line in Fig. 6.

Figure 6: Front view of the integrating sphere. The dashed line acrossing the exit port is the test line to check the uniformity of light.

3.1.2. CCT of the lightning simulator

We analyzed the CCT of the lightning simulator. All LEDs in the light-emitting unit were driven by the constant current. As mentioned in the previous section, the luminous intensity of the blue and yellow LEDs are
adaptable by regulating the variable resistor $R_9$. Thus, the CCT of the lightning simulator was calibrated regulating the variable resistor $R_9$. For the evaluation of the CCT, all LEDs were driven by the five test conditions TC1 – TC5 shown in Table 1. Usually, the CCT is discussed on the CIE 1931 $xy$-chromaticity diagram shown in Fig. 7. Thus we analyze the CCT of the light emitted from the lightning simulator by plotting to the $xy$-chromaticity diagram.

### Table 1: Five test conditions. The current values are defined for each test conditions TC1 – TC5.

| Condition ID | LED driving current (mA) |
|--------------|--------------------------|
|              | white | blue | yellow |
| TC1          | 338.6 | 0.296 | 29.800 |
| TC2          | 338.6 | 0.299 | 15.000 |
| TC3          | 338.6 | 0.588 | 0.585  |
| TC4          | 338.6 | 15.000 | 0.299  |
| TC5          | 338.6 | 29.800 | 0.296  |

3.2. Test of the simulated light output of the lightning simulator

Reproducing the simulated light of the lightning, we adopted seven lightning waveforms shown in Table 2. Since it is suggested that there are the strong positive correlation between the light intensity and the channel current of lightning 3–6, in this work we proactively used the waveforms of the channel current as the waveforms of the simulated light of the lightning simulator. Table 2 shows the waveform information used in the lightning simulator. The WF1 7 and WF7 10 in Table 2 are the waveforms of the light signal of lightning and the WF2 – WF6 7 – 10 in Table 2 are the current waveforms of lightning.

Using these waveforms, we carried out the test of the simulated light output of the lightning simulator. The light emitted from the lightning simulator was measured by using the photodetector as shown in Fig. 8. The distance between the photodetector and the exit port is 50 mm. Under the photographing setup above, the test of the lightning simulator was carried out.
Figure 7: CIE 1931 $xy$-chromaticity diagram. The sRGB color triangle and the black-body locus are drawn. The thin lines crossing the black-body locus are the isotemperature lines. The thin lines along the black-body locus are the $\Delta uv$ lines of $\pm 0.02\Delta uv$.

Figure 8: Schematic illustration for measurement of the light output. The distance between the lightning simulator and the photodetector are 50 mm.
Table 2: Waveforms used in the lightning simulator. The ID, WF1 and WF7, are the light signal waveforms and WF2 – WF6 are the lightning current waveforms. The 10/90 rise time and the duration of wave tail of WF7 were indeterminable since the waveform of WF7 is very complex. The “Type” indicates the waveform type either a light signal or a lightning current.

| ID  | Duration (µs) | Type       | Fugire number | Reference |
|-----|---------------|------------|---------------|-----------|
|     | 10/90 rise    | wave tail  | Light/Current |           |
| WF1 | 0.9           | 4.0        | Light         | Fig. 2    | Ref. [5]  |
| WF2 | 1.8           | 18.0       | Current       | Fig. 2 (RS 1) | Ref. [7] |
| WF3 | 8.1           | 109.1      | Current       | Fig. 12   | Ref. [8]  |
| WF4 | 1.07          | 45.2       | Current       | Fig. 13   | Ref. [8]  |
| WF5 | 7.25          | 134.9      | Current       | Fig. 2 a  | Ref. [9]  |
| WF6 | 18.75         | 94.8       | Current       | Fig. 1 a  | Ref. [10] |
| WF7 | –             | –          | Light         | Fig. 6    | Ref. [10] |

4. Results

4.1. Performance test of the integrating sphere

Fig. 9 shows the variation of the grayscale pixel value (256 levels) on the dashed line in Fig. 6. We can see that the pixel values on the exit port is holding the constant value approximately. This means that the light emitted from the lightning simulator is uniform.

Fig. 10 shows the magnified figure of the xy-chromaticity diagram on which the simulated lights for the five test conditions (see Table 1) are plotted. The points a – e on Fig. 10 were obtained under the test condition TC1 – TC5. We confirmed that the CCT of the simulated light ranges over from 4269 K to 15042 K with regulating the variable resistor $R_9$. From Fig. 10, it is seen that the CCT a – e of the lightning simulator are 15042, 7578, 6597, 4618 and 4269 K under the test condition TC1 – TC5. From above, we can find that the CCT of the simulated light changes on the line segment a – e as regulating the variable resistor $R_9$.

4.2. Test of the simulated light output of the lightning simulator

Fig. 11 shows the input waveforms of the light-emitting unit and the simulated light waveforms detected by the photodetector. The 10/90 rise
time and the duration of wave tail are summarized in Table 3. Fig. 11 indicate that the simulated light can reproduce the drastic change.

Table 3: Duration of the 10/90 rise time and wave tail of the results in Fig. 11.

| Figure  | 10/90 rise time (µs) | wave tail (µs) |
|---------|----------------------|----------------|
|         | Input voltage | Light signal | Input voltage | Light signal |
| Fig. 11 (a) | 1.1                | 1.2           | 3.7          | 3.9           |
| Fig. 11 (b) | 1.0                | 2.0           | 20.0         | 21.0          |
| Fig. 11 (c) | 10.4               | 10.2          | 100.8        | 115.2         |
| Fig. 11 (d) | 1.6                | 1.2           | 92.4         | 108.4         |
| Fig. 11 (e) | 6.4                | 6.2           | 139.6        | 154.0         |
| Fig. 11 (f) | 6.8                | 6.2           | 82.25        | 96.2          |
| Fig. 11 (g) | –                  | –             | –            | –             |

5. Discussion

We have developed the lightning simulator that emit the uniform light. The color of the light emitted from the lightning simulator can calibrate based on the CCT. It is already reported that the lightning opacity is thin, namely not the blackbody radiation. However, we obtained results (Aoyama
and Shimoji, 2013, unpublished data) that when we plot the image pixels of two lightning images to the CIE1931 \(xy\)-chromaticity diagram, the points distribute mainly in the \(\pm 0.02\Delta uv\) lines. This suggests that the color of lightning can be defined by the CCT. Thus, we designed the lightning simulator which is adaptable the color based on the CCT, since the CCT can define the color quantitatively.

It was also confirmed that the lightning simulator reproduce the original lightning waveforms. Idone and Orville\(^3\), Gomes and Cooray\(^4\), Wang et al.\(^5\), and Zhou et al.\(^6\) suggest that there exists a strong positive correlation between the current and light signal of lightning channel. Therefore we used the current waveforms of lightning as the light waveform.

The lightning simulator is useful for the test light source to develop the optical/image sensor. Hereafter, it will be considered that a ground-based observation of lightning and/or space-based observation of planetary lightning increase. Accordingly, high-speed optical/image sensors will be developed. A accurate test light source reproducing the lightning waveform is necessary for evaluating the optical/image sensor. We consider that the lightning simulator developed in this work will be used as the test light source. It is also considered that the lightning simulator can be used for science education.
Figure 11: Waveforms of both the input voltage of the light-emitting unit and the simulated light emitted from the lightning simulator. The INPUT voltage indicate the input of the light-emitting unit. The light signal indicate the waveform detected by the photodetector.
waveform can be expanded from the microsecond order to the second order. Therefore we can visually observe the slow change of the simulated light. Thus the lightning simulator is useful for science education (especially physics education and earth science education).

6. Conclusion

We have developed the lightning simulator. The CCT of the light emitted from the lightning simulator can be calibrated from 4269 K to 15042 K. The lightning simulator in this work can simulate seven waveforms. It is considered that the lightning simulator is useful for the test light source for the image/optical sensor of the lightning observation. Furthermore, we consider that expanding the time scale from microsecond order to second order, the lightning simulator can be used for science education.

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