Transactions on Engineering and Computing Sciences - Vol. 12, No. 1
Publication Date: February 25, 2024
DOI:10.14738/tecs.121.16170.
Kurihara, A., Osada, Y., & Bao, Y. (2024). Making and Evaluating Visible Light Splitters Using Polyethylene Kitchen Wrap. Transactions on Engineering and Computing Sciences, 12(1). 130-152.

Making and Evaluating Visible Light Splitters Using Polyethylene Kitchen Wrap

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ABSTRACT

We propose a method of creating an inexpensive visible light range wave plate using a birefringent material—kitchen wrap—and an evaluation method using a camera and projector. By stacking the appropriate number of kitchen wraps, any wave plate corresponding to any color can be created. The light of the projector is photographed using a camera through a kitchen wrap sandwiched between polarizing plates arranged in the crossed-Nicols condition. First, by rotating the kitchen wrap, the optical axis was obtained based on the change in luminance. Next, by increasing the number of kitchen wraps, the wavelength deviation per sheet was measured based on the change in luminance. The experimental results confirmed that polyethylene wrap is suitable as the material of the wave plate, and the optical axis is tilted by 45° with respect to the cut surface.

Keywords: Polarization, polyethylene, polarizing plates, crossed-Nicols, kitchen wraps.

INTRODUCTION

Polarization is an important optical characteristic. It is widely applied in our daily life in products including polarized glasses, liquid crystal displays, and 3D movies [1-2]. It is also widely used in the industrial field for researching material strength, calculating the density of organic solutions, and in medical equipment for diagnosis of eye-related pathologies [1-2]. However, understanding the properties of polarization is challenging because it is difficult to interpret the properties intuitively [3].

A previous study [1] reported the results of a post-class interview with Croatian high school students (18–19 years old) on their understanding of polarization of light and the model of light itself. Students often remembered the general schema of polarization. However, they often misunderstood it or showed fragmentary knowledge [1]. In addition, reports have suggested that polarization tends to be neglected in higher education [2][4]. In Japanese education on polarization, only contents of linear polarization by polarizing plates are described up to high

school, and no deep knowledge is provided [4]. For example, polarization is not limited to the field of physics; it forms a part of optical rotation (rotation of linear polarization) in the field of chemistry, insects with eyes that capture polarization in the field of biology, and polarizing microscopes in the field of geology. However, there is no description of topics such as circular polarization or elliptical polarization, which is important for understanding these fields, and the topic is expressed vaguely [4]. In addition, as an optical teaching material, an "Optics Suitcase" was developed by the OSA Rochester Section (OSA-RS). This package is designed to introduce the interesting concept of light to junior high school students. There are three experiments which involve investigating the colors that make up white light with respect to diffraction (The Rainbow Peephole), polarization (Magic Stripes), and selective reflection (Magic Patch) and are designed to appeal to students [5]. A previous report [6] provided results regarding the experience of introducing Optics Suitcase to high school students according to the experimental curriculum in the field of telecommunications. Practical work was emphasized during the demonstration of diffraction, polarization, and liquid crystals; the study reported that the test results succeeded in increasing the students' interest in physics and optics [6]. However, in the explanation of polarization, it is recommended to ignore the explanation of circular polarization for the sake of simplicity [7]. There is consensus for including Quantum mechanics in the high school curriculum [8]. In a previous report [8], the authors designed and implemented a course of active learning education for secondary school students including content for polarization. It included content of birefringence as part of the rationale that it is impossible to give a locus to a photon (to a quantum system). Moreover, a rotating-analyzer ellipsometer rotates the analyzer synchronously to detect the polarization state after reflection on the surface of the object [9]. An experiment using the rotating analyzer method has been used for student experiments to deepen the understanding of polarization in the upper grades of university [3].

Knowledge of polarization is important in education, and the corresponding teaching materials must be developed [4]. The use of a circular polarizing element can be considered as one of the teaching materials. However, circular polarizing elements are expensive (1,000 Yen to tens of thousands of Yen per sheet), and it is difficult to introduce them to educational sites [4][10]. In this study, we aim to establish a method for making and evaluating inexpensive wave plates.

CONVENTIONAL METHODS

Polarized light is light whose vibration direction is biased in a specific direction. Polarization that oscillates in one plane is called linear polarization. As shown in Fig. 1 (a), a polarizer such as a polarizing plate extracts linearly polarized light from natural light. When light is incident on two polarizing plates, the intensity of the transmitted light changes depending on the angular relationship between the polarizing plates. As shown in Fig. 1 (b), when the transmission axes are parallel (parallel Nicol), the linearly polarized light that has passed through the first polarizing plate also passes through the second. In contrast, as shown in Fig. 1 (c), when the second polarizer is rotated 90° (orthogonal Nicol), the light rays are blocked [11-12].

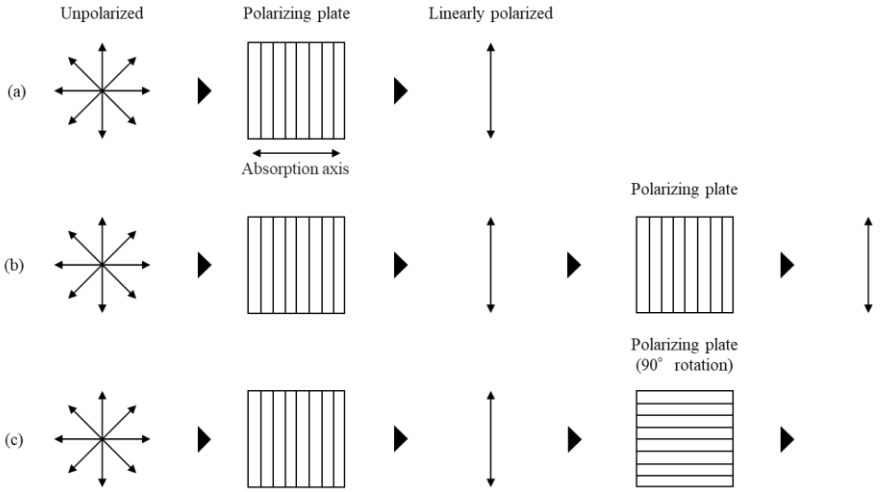


Fig. 1: Linearly polarized light

Birefringence (optical anisotropy) is a property in which the refractive index differs depending on the direction. Light is transmitted by arranging the birefringent substance at an appropriate angle between polarizing plates in the orthogonal Nicol state. As shown in Fig. 2, linearly polarized light with a vibrating surface rotated by 45° from the x-axis is incident on a birefringent substance having different refractive indexes on the x- and y-axes. Because the light transmitted through this substance has a phase difference between the x-axis component and the y-axis component, it becomes polarized different from the linear polarization at the time of incidence. Because the refractive index depends on the wavelength of light, the phase difference also differs depending on the wavelength. As shown in Fig. 2 (a), when elliptically polarized light is obtained in this substance, only the transmission axis component of the polarizing plate is extracted. As shown in Fig. 2 (b), when the phase difference is an odd multiple of a half wavelength, the polarized light transmitted through the substance is linearly polarized light parallel to the transmission axis of the polarizer. Therefore, it is not shielded. In addition, as shown in Fig. 2 (c), when the phase difference is an integral multiple of the wavelength, polarized light transmitted through the substance is shielded because it is orthogonal to the transmission axis of the polarizer [11-12].

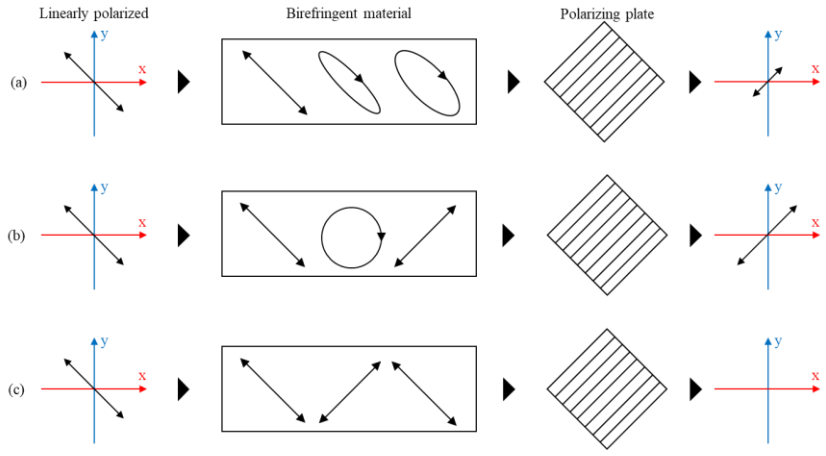


Fig. 2: Birefringence

As educational equipment that refers to the wave plate, a polarization-related classroom demonstration experiment system using the polarization axis finder (PAF)—a tool in which many linearly polarized light components are arranged concentrically—has been proposed. Using this equipment, the direction of the polarization axis of the linearly polarized light can be intuitively understood. In addition, it is possible to confirm that there is no fixed polarization axis in the circular polarization by the 1/4 wave plate and to observe the strain distribution of the lens. The study also describes observations of LCD, polarized dark glass, and sky polarization [13].

Cellophane tape has been used as an inexpensive 1/4 wave plate [4]. Cellophane is made of long chains of aligned glucose molecules. Electromagnetic waves with polarization orthogonal to the molecule propagate through this material at a different velocity than waves with polarization parallel to the chain. Therefore, cellophane is a birefringent substance, and it can be used as a wave plate by stacking an appropriate number of cellophane sheets. In addition, polarized stained glass has been made by pasting cellophane in various directions between the polarizing plates in the orthogonal Nicol state. This is a famous experiment conducted in science experiment classrooms [11,12][14]. Not limited to cellophane, numerous materials that show optical anisotropy have been reported, and familiar ones include quartz and liquid crystals used in televisions and personal computers [12, 14]. In addition, thin films such as oriented polypropylene, plastics subjected to mechanical stress, and polyvinyl alcohol are also birefringent [2, 15]. Such a phenomenon is called photoelasticity and occurs because the refractive index slightly changes in the direction when an external force is applied to a transparent object made of the same substance [14]. A study has reported the production of inexpensive large aperture infrared (IR) polarizers by stretching a film using polyethylene kitchen wrap [16]. However, these studies are costly because expensive equipment such as spectrophotometers and IR spectrometers are used. In addition, a previous report [16] suggested that using a film-stretching jig and a laser for evaluation is not cost-effective. Furthermore, studies on using an acrylic plate as a 1/4 wave plate have been reported [10]. This plate is fabricated by measuring the size of the birefringence of a commercially available acrylic plate in which the directions of the molecules are aligned through the stretching treatment and then polishing the acrylic plate in layers as necessary. However, a single-wavelength laser and a device for measuring its intensity are required.

PROPOSED METHODS

We propose a method for making and evaluating an inexpensive visible light splitter using kitchen wrap. This method has the following advantages:

1. Special equipment such as spectroscopic analyzers or lasers are not used so that experiments in educational facilities can be carried out at low cost.
2. It is possible to create a wave plate of any wavelength to understand circular polarization and elliptically polarized light.
3. A wave plate corresponding to any color can be created to understand that the performance of the wave plate depends on the wavelength of light.

Specifically, the luminance is calculated by taking a picture of the light of the projector through a kitchen wrap sandwiched between polarizing plates arranged in orthogonal Nicols using a

camera and performing image processing. First, the kitchen wrap is rotated, and the optical axis is obtained by changing the luminance. Next, kitchen wraps are stacked to increase the number of sheets, and the wavelength deviation per sheet is measured from the change in luminance. Fig. 3 shows the flow chart of image processing. For color cameras such as smartphones and single-lens cameras, the average value of the pixel values of one channel is set as the luminance by grayscale with Eq. (1) based on the color vision characteristics of the human eye [17]. In case of a monochrome camera, the average value of the pixel values of one channel is used as the luminance. These values are normalized to 0 to 1 for ease of comparison. In addition, to confirm the effectiveness of the proposed method, measurement by a spectroscopic analyzer is performed in advance.

$$Y = (0.298912 \times R + 0.586611 \times G + 0.114478 \times B) \quad (1)$$

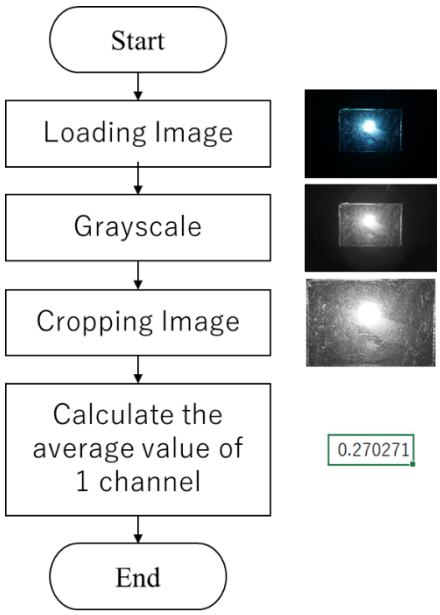


Fig. 3: Image processing flowchart to calculate luminance

EXPERIMENTS AND RESULTS

To confirm the effectiveness of the proposed method, the following three experiments were conducted.

Experiment 1: Preparatory Experiment

The preparatory experiment including the following four steps:

- Step 1: A spectroscopic analyzer was used, and a wrap of suitable material was selected for use in the wave plate.
- Step 2: To obtain a criterion for experimentally judging the effectiveness of the proposed method, the polarization performance of the wrap of the selected material was measured and obtained using a spectroscopic analyzer.
- Step 3: At the same time as measuring the optical axis of the kitchen wrap, we checked whether the performance of the wrap with the same product name changes depending on the size and production lot.

- Step 4: The changes in polarization characteristics are checked depending on the location of the kitchen wrap.

Experiment 2: Polarization Performance Measurement Experiment

The polarization performance measurement experiment included the following two steps.

- Step 1: Checking the polarization axis of the projector to prepare a linearly polarized light source.
- Step 2: Measuring the polarization performance using the proposed method.

Experiment 3: Transmittance Comparison Experiment Between a Wave Plate Created Using the Proposed Method and A Commercially Available Wave Plate

Preparatory Experiment

Selecting a Wrap of Suitable Material Using a Spectroscopic Analyzer:

Experiment Method:

To select a kitchen wrap material that can be used as a wave plate, we confirmed the presence or absence of polarization characteristics and the optical axis using a polarizing plate and a spectroscopic analyzer, respectively. As shown in Fig. 4, three types of wraps were used: (A) polyethylene, (B) polyvinylidene chloride, and (C) vinyl chloride. Table 1 to Table 3 show the details of the wraps.



Fig. 4: Used kitchen wraps. (A) Polyethylene. (B) Polyvinylidene chloride. (C) Vinyl chloride.

Table 1: (A) Polyethylene wrap

Product name	ADDITIVE-FREE FOOD WRAP
Size	22 [cm] x 50 [m]
Heatproof temperature	110 [℃]
Cold resistant temperature	-60 [℃]
Selling agency	Global Co., Ltd.

Table 2: (B) Polyvinylidene chloride wrap

Product name	Saran Wrap
Size	30 [cm] x 50 [m]
Additive	Fatty acid derivative (Softener)

	Epoxidized vegetable oil (Stabilizers)
Heatproof temperature	140 [℃]
Cold resistant temperature	-60 [℃]
Business name	Asahi Kasei home products Co., Ltd.

Table 3: (C) Vinyl chloride wrap

Product name	RIKEN WRAP
Size	22 [cm] x 50 [m]
Additive	Fatty acid derivative (Softener) Epoxidized vegetable oil (Stabilizers) Calcium compounds (Stabilizers)
Heatproof temperature	130 [℃]
Cold resistant temperature	-60 [℃]
Business name	RIKEN FABRO Co., Ltd.

Table 4 shows the specifications of the polarizing plate, and Table 5 shows the details of the spectroscopic analyzer.

Table 4: Polarizing plate

Polarization rate	99% or more
Transmittance	40%
Material	Plastic

Table 5: Spectrophotometer

Manufacturer	HITACHI
Model number	U-4100

As shown in Fig. 5, the kitchen wrap is sandwiched between the polarizing plates in the orthogonal Nicol state, and θ is rotated from 0 to 90° every 10° to measure the transmittance. The arrangement of each film in Fig. 5 is in the direction viewed from the sensor side.

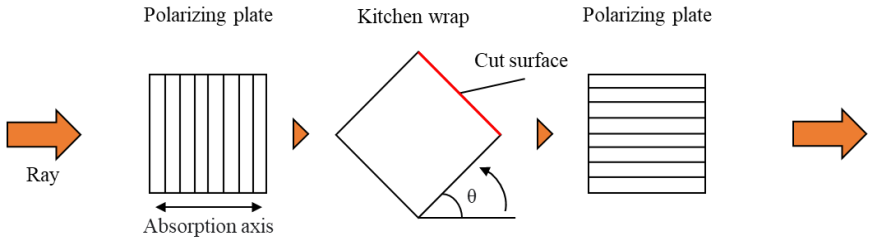


Fig. 5: Sample placement for the selection of materials using a spectroscopic analyzer

Experimental Results:

Fig. 6 shows the measurement results of the transmittance of the polarizing plate in the orthogonal Nicol state. Fig. 7 shows the measurement results of the transmittance of the polyethylene wrap (A). Fig. 8 shows the measurement result of the transmittance of the polyvinylidene chloride wrap (B). Fig. 9 shows the measurement result of the transmittance of

the vinyl chloride wrap (C). In this study, we consider the wave plate in visible light. Therefore, the wavelength range is 350 to 750 nm.

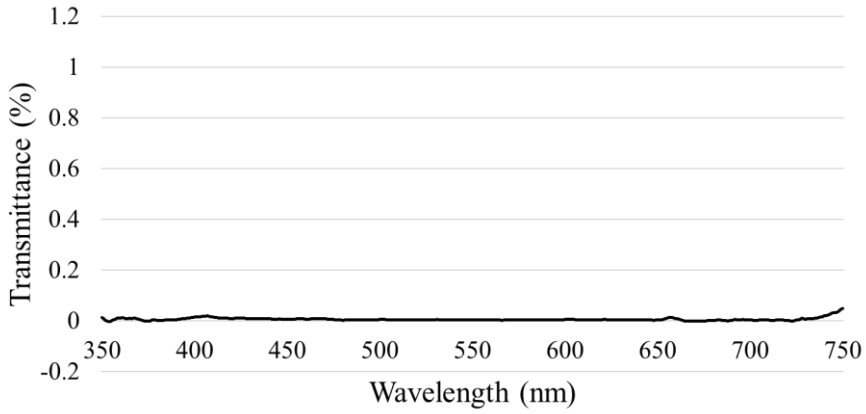


Fig. 6: Transmittance of the polarizing plate in the orthogonal Nicol state

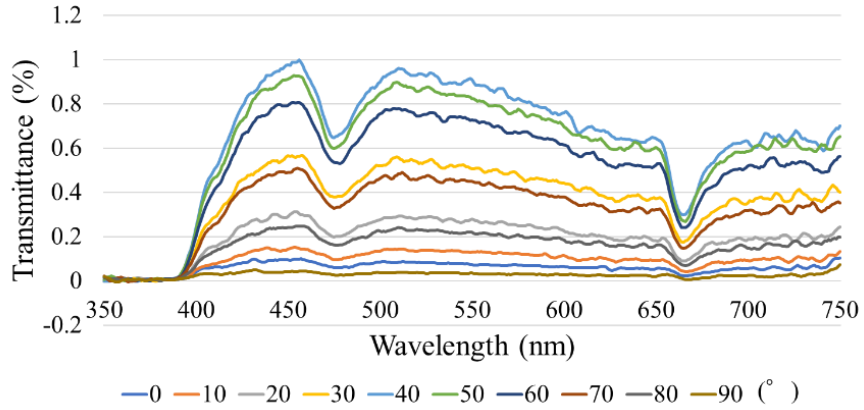


Fig. 7: Transmittance of the polyethylene wrap (A)

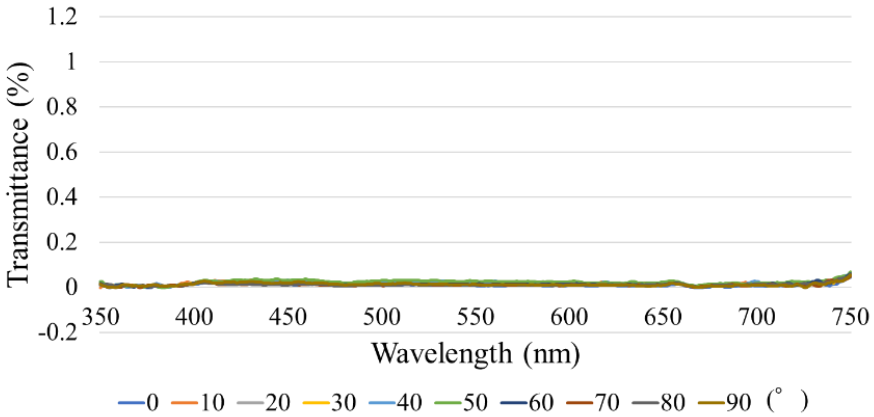


Fig. 8: Transmittance of the polyvinylidene chloride wrap (B)

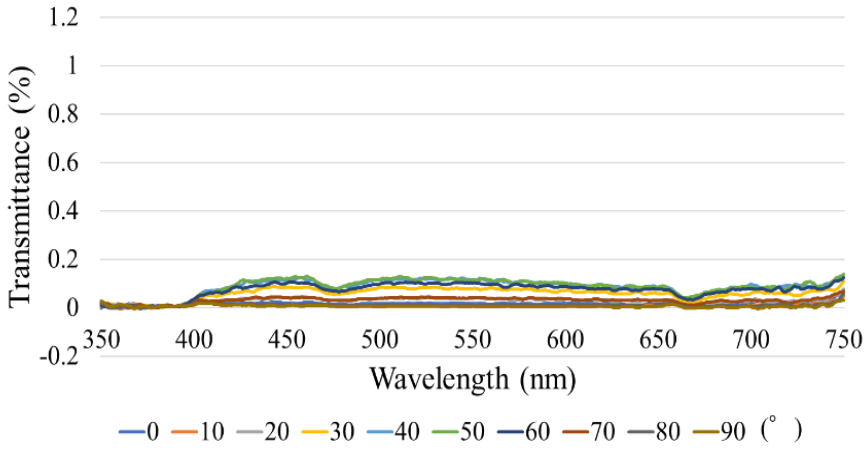


Fig. 9: Transmittance of the vinyl chloride wrap (C)

Consideration:

Fig. 6 shows that the light is blocked by the polarizing plate with the orthogonal Nicol arrangement. Fig. 7 to Fig. 9 show that the transmittance of polyethylene wrap changes when the angle is changed, but that of polyvinylidene chloride wrap and vinyl chloride wrap hardly change. In addition, polyethylene wrap has low transmittance when θ is 0° and 90°. Therefore, polyethylene wrap is suitable as a material of the wave plate, and the optical axis is tilted by 45° with respect to the cut surface. Polyethylene wrap is used in the following experiments.

Measurement of Polarization Performance of the Polyethylene Wrap Using a Spectroscopic Analyzer:

Experimental Method:

We aimed to identify the length of the wave plate for which one polyethylene wrap can be used. Fig 10 shows the sample arrangement. Between the polarizing plates in the orthogonal Nicol state, a polyethylene wrap tilted 45° from the absorption axis is sandwiched. The transmittance was measured by changing the number of wraps from 0 to 24.

Experimental Results:

Fig. 10 shows the measurement results of the relationship between the number of wraps and the transmittance. Focusing on 550 nm, which is the standard for commercially available wave plates, Fig. 11 shows the relationship between the number of wraps and transmittance at 550 nm.

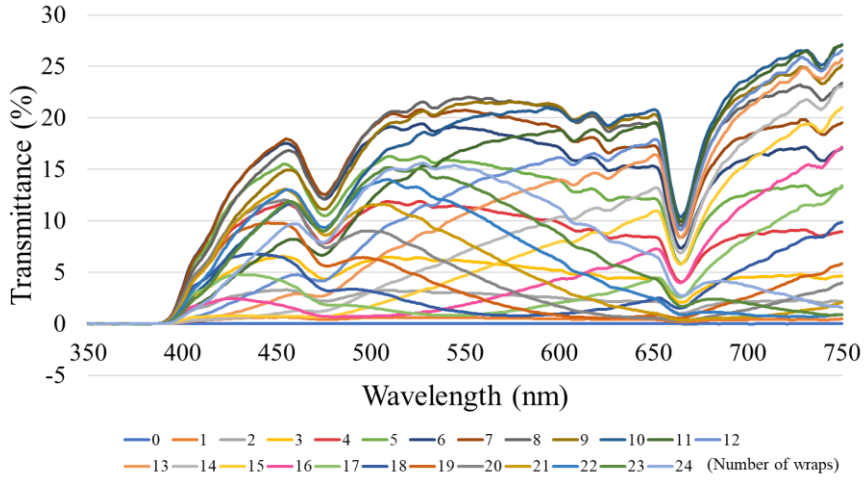


Fig. 10: Relationship between the number of wraps (A) and transmittance

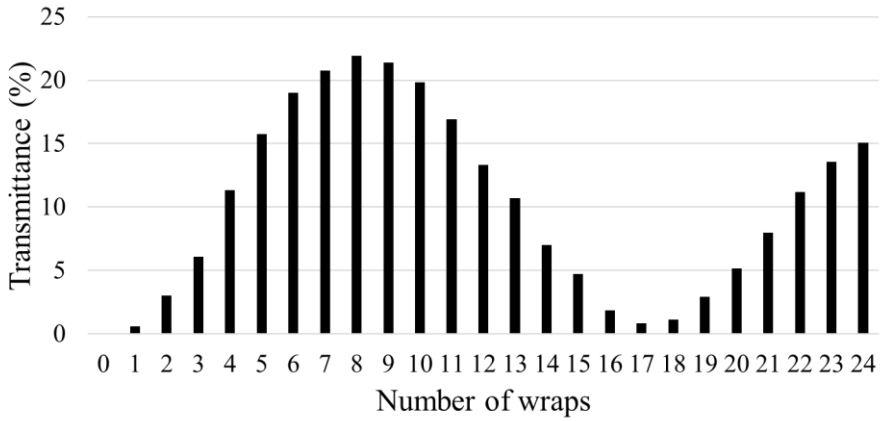


Fig. 11: Relationship between the number of wraps (A) and transmittance at 550 nm

Consideration:

Focusing on 550 nm from Fig. 12, we confirmed that the transmittance is the highest when eight sheets are used. Therefore, eight wraps can be used as a 1/2 wave plate for 550 nm light. Furthermore, Fig. 12 shows that four wraps can be used as a 1/4 wave plate because the transmittance of four sheets is ~52% that of eight sheets. When there are 12 sheets, the transmittance is ~61% when there are eight sheets. This is because the angle of the optical axis shifts due to the manual stacking of the wraps, and the thickness changes due to the pulling force when pasting, resulting in elliptically polarized light instead of circularly polarized light, which reduces the transmittance.

Measuring the Optical Axis of the Kitchen Wrap:

Experimental Method:

We performed the same experiment as the material selection experiment in Section 4.1.1 using a camera. As shown in Fig. 12, a projector with a polarizing plate and a camera were placed to take a picture. The illuminometer was placed in the same position as the camera in Fig. 12. The kitchen wrap is arranged on the back side of polarizing plate 2 and in the direction shown in

Fig. 13. The projector light is photographed through these, and θ is rotated by 10° from 0 to 90°. The arrangement of each film in Fig. 13 is the direction viewed from the sensor side. Luminance was calculated using the proposed image processing method.

Table 6 to Table 10 show the details of the experimental equipment. A smartphone (SAMSUNG Galaxy S10), a single-lens camera (SONY a6000), and an industrial camera (VCXU-32M) were used as cameras. The reason for using different cameras is to compare the effects of hardware on the proposed method. Shooting was performed in a dark room. Table 11 shows the camera settings. All subsequent experiments other than 4.2.1 will be performed with this setting. In addition, to investigate the difference in polarization characteristics between polyethylene wraps of the same product wrap (A), this measurement was performed for the four wraps in Table 12. A-1 to A-3 is 22 cm wide and A-4 is 30 cm wide to allow comparison of the polarization performances when the product name is the same but sizes differ. Because A-1 to A-3 were all purchased at different stores, and A-1 and others were purchased on different days, we will compare whether there is a difference between shipping lots.

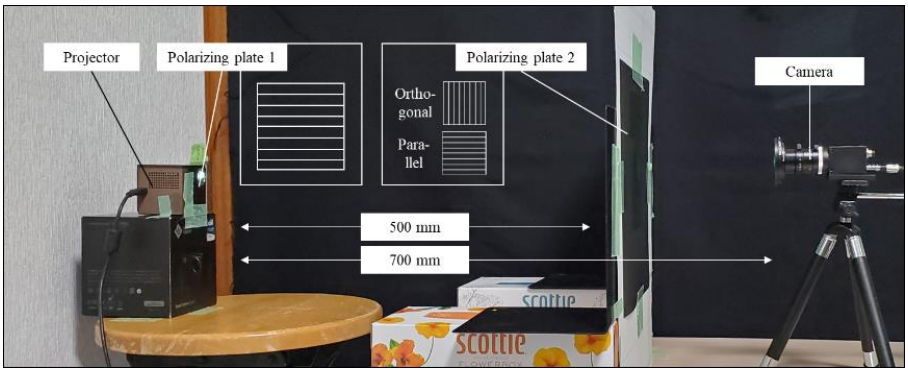


Fig. 12: Experimental environment for measuring the optical axis of kitchen wrap

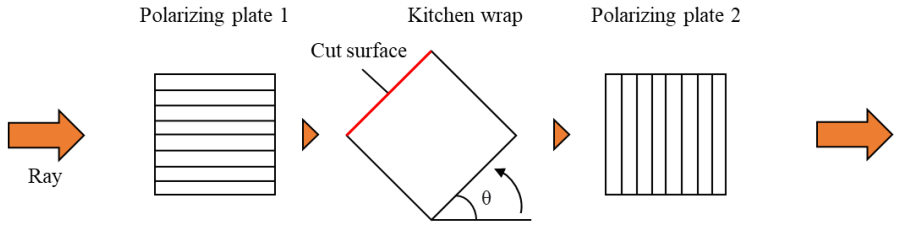


Fig. 13: Sample placement for measuring the optical axis of kitchen wrap

Table 6: Projector

Manufacturer	SK telecom Co., Ltd.
Product name	Smart Beam Laser
Model number	LB-UH6CB
Brightness	100 [lm]
Projection method	Laser driven LCOS
Laser safety standards	IEC60825-1

Table 7: Illuminance meter

Manufacturer	Sanwa Electric Instrument Co., Ltd.
Product name	ILLUMINANCE METER LX2
Range of measurement	0.1 [lx] ~ 399.9[klx]

Table 8: Smartphone

Manufacturer	Samsung Electronics Co. Ltd.
Product name	Galaxy S10
Number of pixels	About 12 million pixels

Table 9: DSLR camera

Manufacturer	Sony Corporation
Product name	α6000
Total number of pixels	About 24.7 million pixels
Lens	E 30mm F3.5 Macro

Table 10: Industrial camera

Manufacturer	Baumer Optronic GmbH
Product name	VCXU-32M
Total number of pixels	3 million pixels

Table 11: Camera settings

Camera	f -number	Shutter speed	ISO
Galaxy S10	f/2.4	1/30 [s]	50
a6000	f/3.5	1/30 [s]	100
	f -number	Exposure Time	Gain
VCXU-32M	f/1.8	10000.00 [μs]	1.00 [db]

Table 12: Polyethylene wrap (A-1—4)

	A-1	A-2	A-3	A-4
Size	22 [cm] × 50 [m]	22 [cm] × 50 [m]	22 [cm] × 50[m]	30 [cm] × 50 [m]
Store	Matsumoto Kiyoshi (233-0013, 3-1-7, Maruyamadai, Konan, Yokohama City, Kanagawa Prefecture)	Cocokarafine (158-0086, 3-22-7, Oyamadai, Setagaya-ku, Tokyo)	Cocokarafine (152-0035, 2-11-16, Jiyugaoka, Meguro-ku, Tokyo)	Cocokarafine (152-0035, 2-11-16, Jiyugaoka, Meguro-ku, Tokyo)
Purchase date	2021-6-28	2021-8-27	2021-8-27	2021-8-27

Experimental Results:

Fig. 15 shows the measurement results of the illuminometer. The luminance calculation results of each camera are shown in Fig. 16 to Fig. 18.

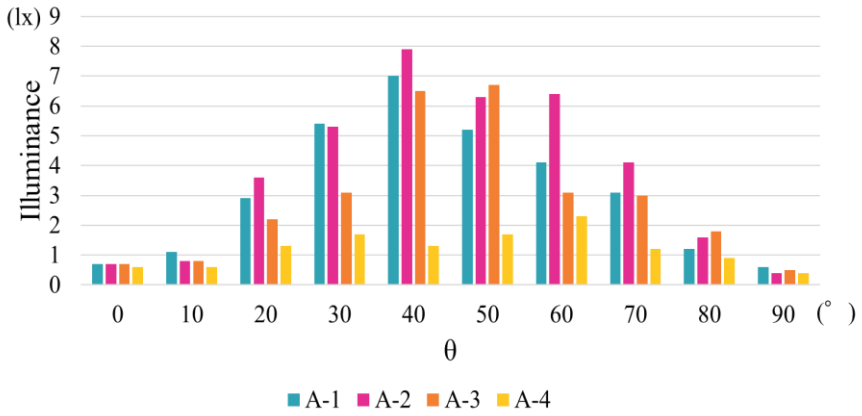


Fig. 14: Illuminance measurement results for measuring the optical axis of the kitchen wrap

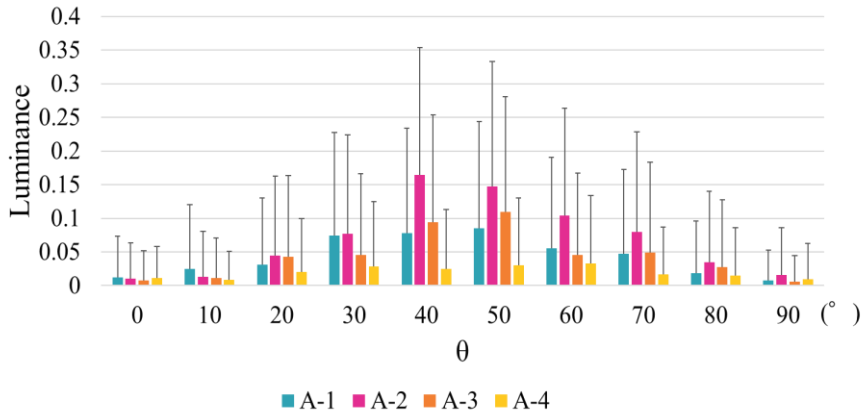


Fig. 15: Luminance measurement results for measuring the optical axis of the kitchen wrap using a Galaxy S10

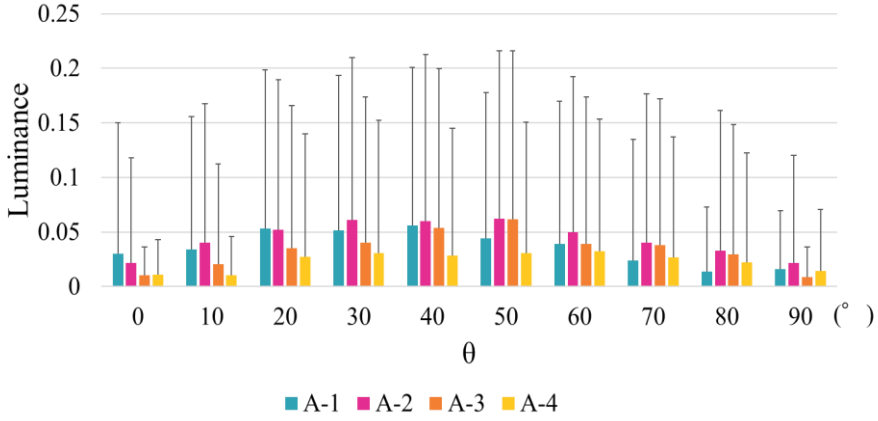


Fig. 16: Luminance measurement results for measuring the optical axis of the kitchen wrap using an a6000

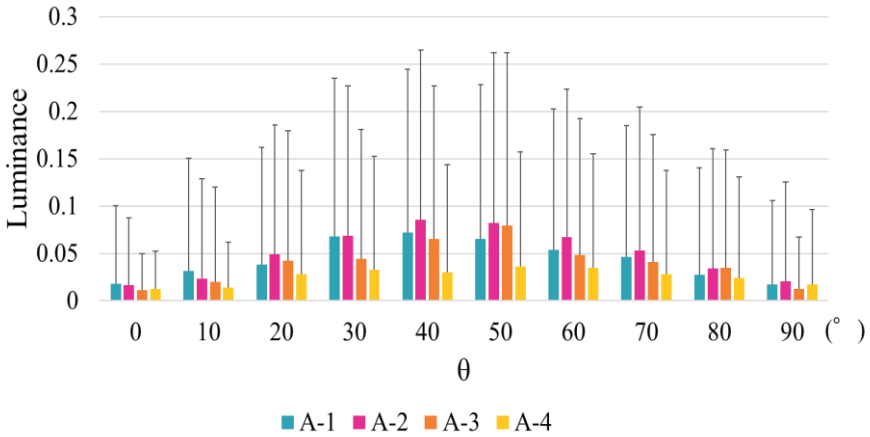


Fig. 17: Luminance measurement results for measuring the optical axis of the kitchen wrap using a VCXU-32M

Consideration:

With the illuminometer and all cameras, a peak exists from 40° to 50° in A-1 to A-3. However, there is not considerable change in A-4. This experimental result shows that the same product with the same size can be used as the same wave plate, but the birefringence of the wave plate differs with different sizes. It is presumed that this is because the stretching force differs during the manufacturing process. In addition, because the brightness is the lowest at 0° and 90°, it can be considered that the optic axis is tilted 45° with respect to the cut surface.

Checking for Changes in Polarization Characteristics Depending on the Location:

Experimental method:

To measure the difference in polarization characteristics at the position of one kitchen wrap, 10 different locations of A-1 were photographed in the experimental environment shown in Fig. 18, and the luminance was calculated.

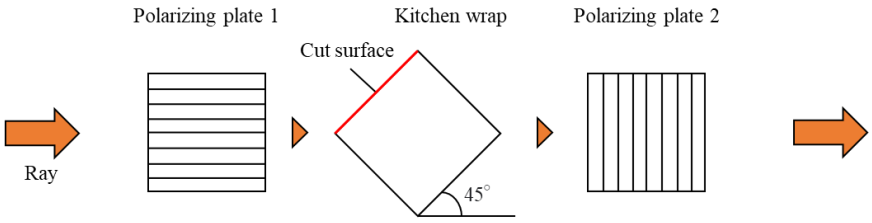


Fig. 18: Sample placement for evaluating the variations in polarization characteristics

Experimental Results:

Fig. 19 shows the measurement results of the illuminometer. The results of luminance were calculated using each camera, as shown in Fig. 20 to Fig. 22.

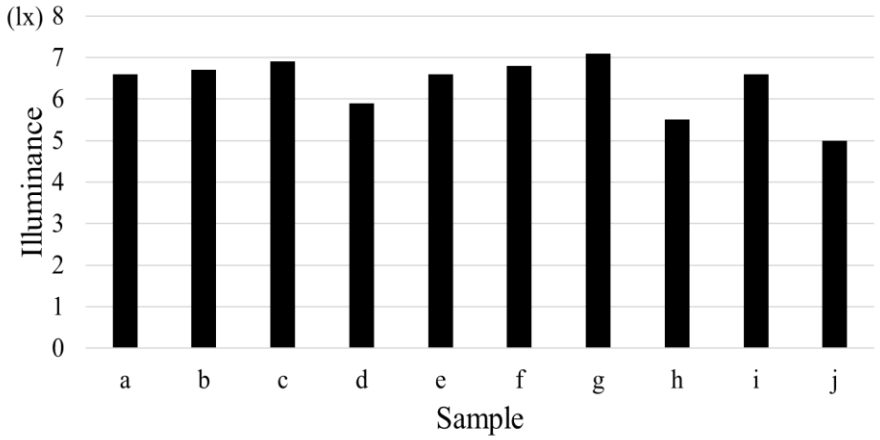


Fig. 19: Illuminance measurement results for evaluating variations in polarization characteristics

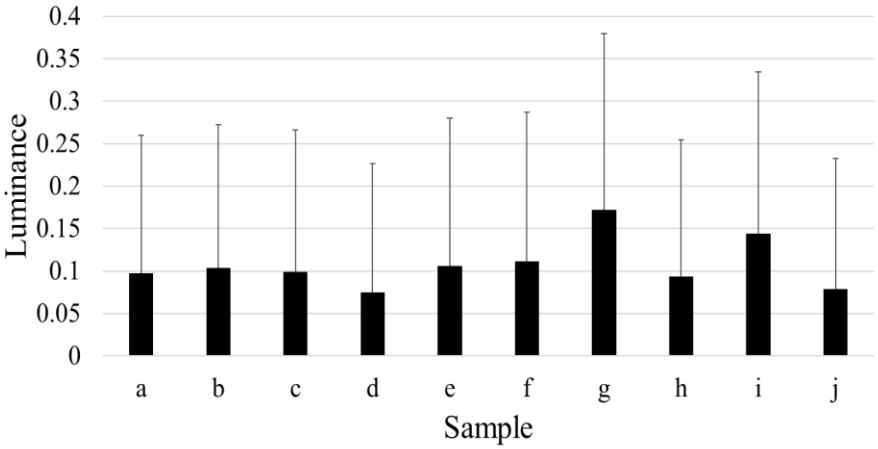


Fig. 20: Luminance measurement results for evaluating variations in polarization characteristics using a Galaxy S10

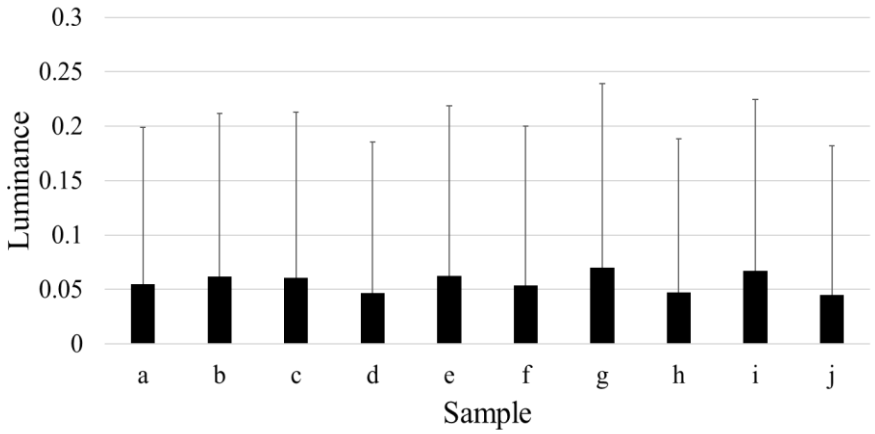


Fig. 21: Luminance measurement results for evaluating variations in polarization characteristics using a6000

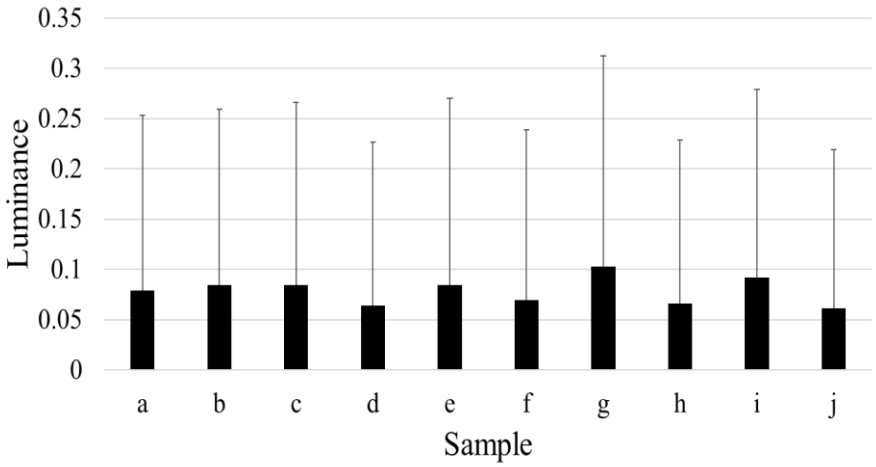


Fig. 22: Luminance measurement results for evaluating variations in polarization characteristics using VCXU-32M

Consideration:

Table 13 shows the results of the average brightness and standard deviation calculated using each device. The standard deviation was less than 1 lx on the illuminometer and ~3% or less as a result of calculating the brightness of each camera. Therefore, the wrap can have constant polarization characteristics regardless of the location.

Table 13: Average and standard deviation of experiments for evaluating variations in polarization characteristics

	LX2	Galaxy S10	a6000	VCXU-32M
Average	6.4	0.10790099	0.05710205	0.078789109
Standard deviation	0.64	0.027797758	0.008329514	0.012760907

Polarization Performance Measurement Experiment

Checking the Polarization Axis of the Projector:

Experimental Method:

Because the projector used as a light source in this study is a liquid crystal projector using liquid crystal on silicon (LCOS), the light rays are polarized.

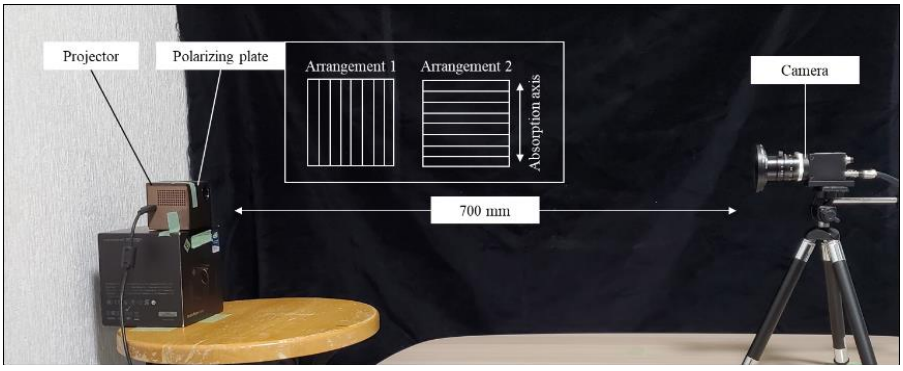


Fig. 23: Experimental environment for measuring the polarization axis of the projector

A linearly polarized light source must be prepared for the wave plate evaluation experiment described later; therefore, the polarization axis of the projector was confirmed in this experiment. Fig. 23 shows the experimental environment. The illuminometer was placed in the same position as the camera in Fig. 23. Table 14 shows the camera settings. Shooting was performed in a dark room.

Table 14: Camera settings for measuring the polarization axis of the projector

Camera	f -number	Shutter speed	ISO
Galaxy S10	f/2.4	1/30 [s]	50
a6000	f/3.5	1/30 [s]	100
	f -number	Exposure Time	Gain
VCXU-32M	f/1.8	1000.00 [μs]	1.00 [db]

Experimental Results:

Table 15 shows the measurement results of the illuminometer. Table 16 shows the luminance calculated by the image processing of the proposed method from the photographs taken by each camera.

Table 15: Illuminance measurement results for measuring the polarization axis of the projector

Arrangement 1	1.3 [lx]
Arrangement 2	190.3 [lx]

Table 16: Luminance calculation results for measuring the polarization axis of the projector

	Arrangement 1		Arrangement 2	
Camera	Average	Standard deviation	Average	Standard deviation
Galaxy S10	0.0127075	0.0899516	0.381697	0.248999
a6000	0.00414627	0.0544871	0.0158924	0.0744987
VCXU-32M	0.003928913	0.048475946	0.037545788	0.130675458

Consideration:

In Table 15 and Table 16, because arrangement 2 is brighter than arrangement 1 in both cases, the projector is linearly polarized in the same direction as the polarization axis of arrangement 2. In the following experiment, the polarizing plate of placement 2 is installed in the projector. This is because the polarization axis of the projector is not always horizontal or vertical.

Calculation of the Polarization Performance of the Polyethylene Wrap by a Camera with the Proposed Method:

Experimental Method:

This experiment measures how long wavelengths of one polyethylene wrap can be used as a wave plate using a camera. Fig. 24 shows the sample arrangement. A polyethylene wrap tilted 45° from the absorption axis is sandwiched between the polarizing plates in the orthogonal Nicol state. The changes in the brightness of the wrap from 0 to 24 sheets were calculated.

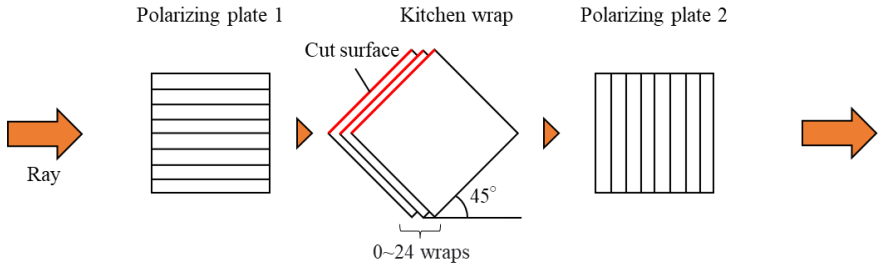


Fig. 24: Sample placement for evaluation of polarization performance of polyethylene wrap

Experimental Results:

Fig. 25 shows the measurement results of the illuminometer. The results of luminance were calculated using each camera and are shown in Fig. 26 to Fig. 28.

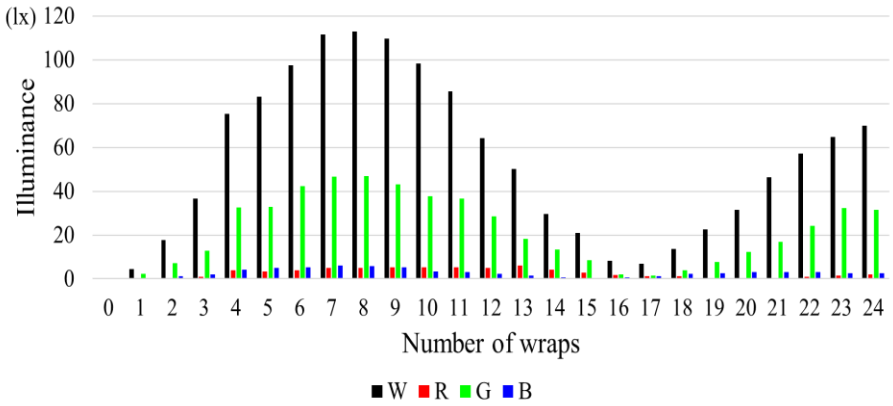


Fig. 25: Illuminance measurement results for evaluation of the polarization performance of the polyethylene wrap

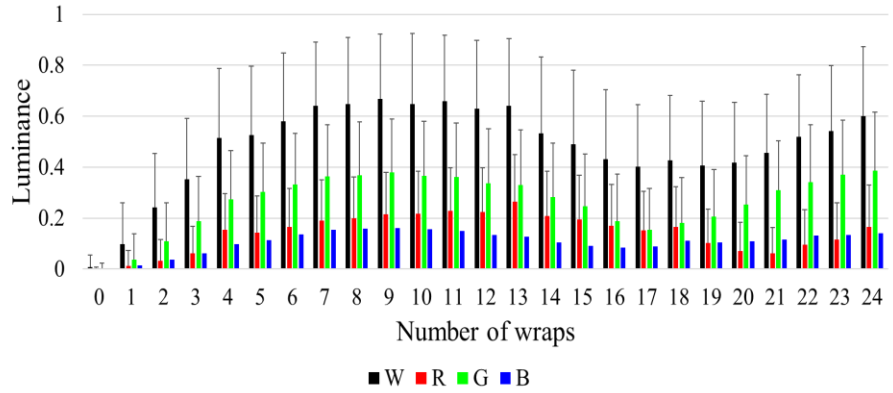


Fig. 26: Luminance measurement results for the evaluation of the polarization performance of the polyethylene wrap using the Galaxy S10

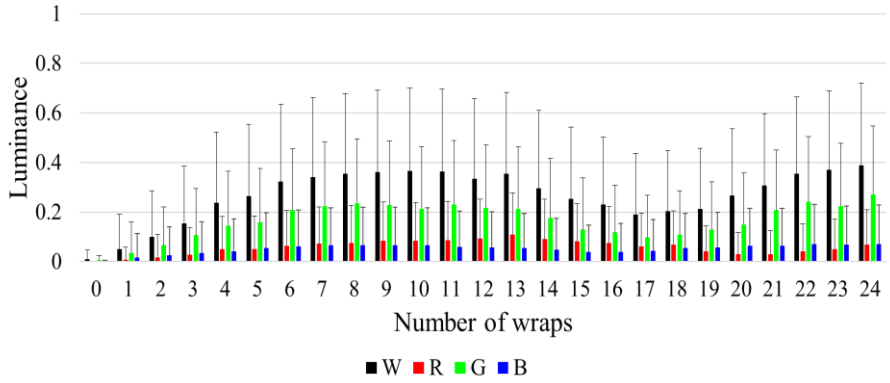


Fig. 27: Luminance measurement results for the evaluation of the polarization performance of the polyethylene wrap using a6000

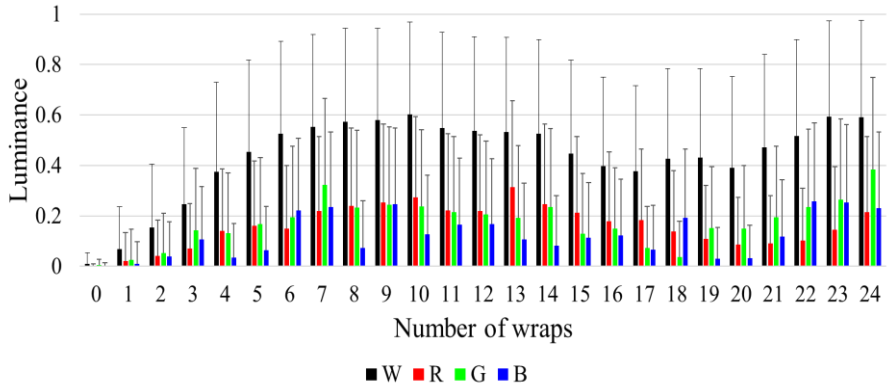


Fig. 28: Luminance measurement results for evaluation of the polarization performance of the polyethylene wrap using VCXU-32M

Consideration:

Because we focused on a 550 nm with a spectroscopic analyzer, we consider G (green) in this experiment as well. Fig. 25 shows that the illuminance is the highest when the number of sheets is eight in the measurement by the illuminance meter. Therefore, eight wraps can be used as a 1/2 wave plate for green light. This is consistent with the results of the spectroscopic analyzer. However, the illuminance of four sheets is ~70% of that of eight sheets, which is different from the result of the spectroscopic analyzer, which is ~52%. In addition, in the case of 12 sheets, both the illuminometer and the spectroscopic analyzer have a value of ~61% in the case of eight sheets, which is the same. Therefore, we believe that the angle of the sensor, the angle of the optic axis, and the thickness due to the pulling force at the time of sticking changed at the time of measuring four sheets. Fig. 26 shows the measurement with a smartphone (Galaxy S10); the luminance is the highest when there are nine wraps. In addition, the luminance of four sheets is ~72% of 9 sheets, and that of five sheets is ~80%. With 13 sheets, it is 87% that with nine sheets, and with 14 sheets, it is ~74%. Fig. 27 shows that the luminance is the highest when the number of wraps is eight in the measurement with a single-lens camera (a6000). In addition, the luminance of four sheets is ~62% of eight sheets, and that of 12 sheets is 92% of eight sheets. With a single-lens camera (a6000), the number of sheets with the maximum brightness matches that of the spectrophotometer. Fig. 28 shows that the luminance is the highest when

the number of wraps is seven, as measured by the industrial camera (VCXU-32M). Compared with the luminance of seven sheets, the luminance of three sheets is ~44%, that of four sheets is ~41%, that of 10 sheets is ~74%, and that of 11 sheets is ~67%. In addition, because the industrial camera does not have a color filter, it is considered that the luminance of BGR has a similar transition. The following causes can be considered as the reason for the variation in the number of sheets that maximize the brightness. Eight wraps were the maximum for spectrophotometers and illuminometers; however, the captured images were affected by the fact that the light was scattered by the wraps. Alternatively, the brightness cannot be measured accurately because there is overexposure at the position of the light source in the captured image.

Transmittance Comparison Experiment Between a Wave Plate Created Using the Proposed Method and a Commercially Available Wave Plate

Experimental Method:

This experiment compares the transmittance of the polyethylene wrap and 1/4 wave plate. In the experiment, the arrangement is the same as that in Fig. 12, polarizing plates 1 and 2 are removed, and the film (wraps and 1/4 wave plate) is placed in the place of the polarizing plate 2. The film is arranged so that θ in Fig. 13 becomes 0. The experimental results show that the number of wraps that can be used as a 1/4 wave plate is 4; thus, the number was changed from 1 to 4 sheets for measurement. Table 17 shows the details of the 1/4 wave plate used.

Table 17: 1/4 wavelength plate

Thickness	70 [μm]
Phase difference value	140 [nm] at 550 [nm]

Experimental Results:

Fig. 29 shows the measurement results of the illuminometer. The results of the luminance calculated using each camera are shown in Fig. 30 to Fig. 32.

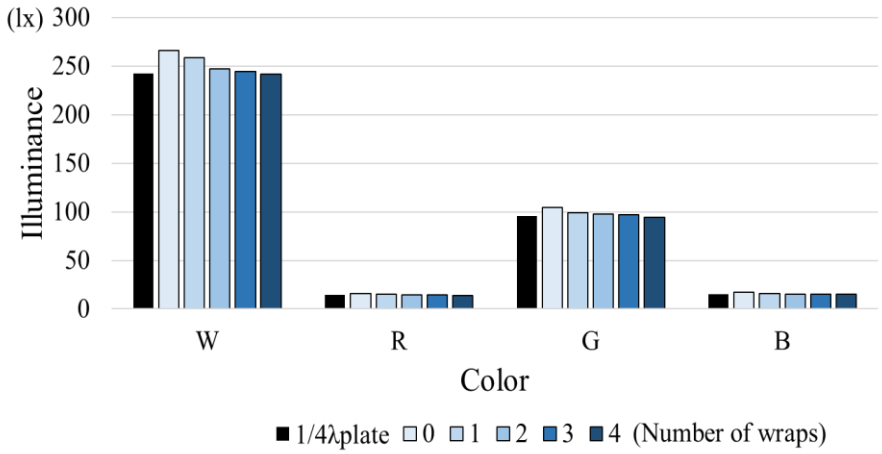


Fig. 29: Illuminance measurement results for comparison of the transmittance between the polyethylene wrap and the 1/4 wave plate

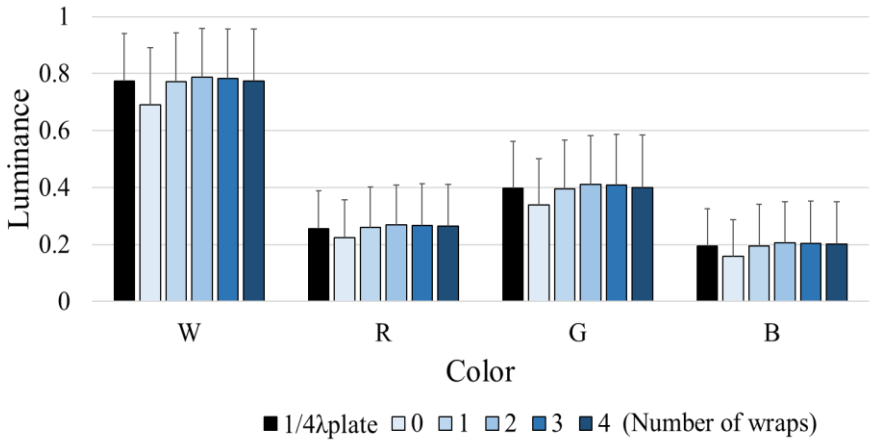


Fig. 30: Luminance measurement results for comparison of the transmittance between the polyethylene wrap and the 1/4 wave plate using a Galaxy S10

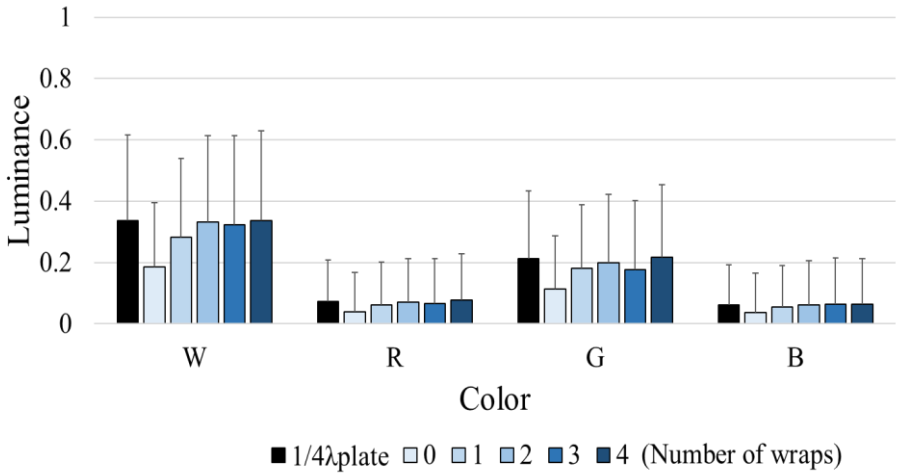


Fig. 31 : measurement results for comparison of the transmittance between the polyethylene wrap and 1/4 wave plate using a6000

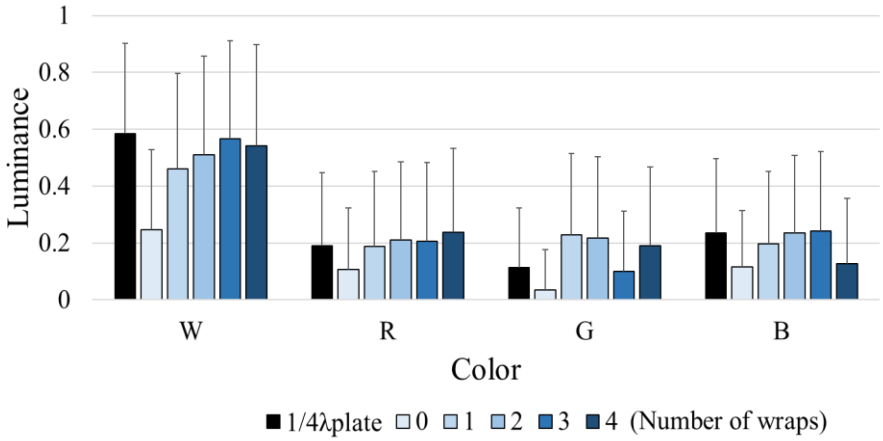


Fig. 32: Luminance measurement results for comparison of transmittance between the polyethylene wrap and 1/4 wave plate using VCXU-32M

Consideration:

W (white) is noted for consideration. Fig. 29 shows the measurement with the illuminometer, which indicates that the 1/4 wave plate is 242.5 lx and the four wraps are 241.5 lx. These are almost the same. Fig. 30 shows the measurement with the smartphone, which indicates that the luminance of the 1/4 wave plate is 77.4 and that of the four wraps is 77.4. These showed the same values. In addition, because the second and subsequent sheets are stretched by hand, a high luminance may have been calculated because of the influence of wrinkles. Fig. 31 shows the measurement with a single-lens camera, which indicates that the luminance of 1/4 wave plate is 33.7 and that of four wraps is 33.7. These showed the same value. Fig. 32 shows that in the measurement with the industrial camera, the luminance of the 1/4 wave plate is 58.4 and that of four wraps is 54.2, which are almost the same. Therefore, the four wraps have almost the same transmittance as a commercially available 1/4 wave plate.

CONCLUSION

In this study, as an experiment to be employed in an educational facility, we proposed a method for creating an inexpensive visible light range wave plate using a birefringent material—a kitchen wrap—and an evaluation method using a camera and a projector. The proposed method has the following features.

1. Education that leads to the understanding of circular polarization and elliptical polarization can be easily imparted by creating a wave plate of any wavelength using inexpensive materials that are familiar to us.
2. Education that leads to the understanding of the wavelength dependence of the performance of the wave plate can be easily imparted by creating a wave plate corresponding to any color using inexpensive materials that are familiar to us.
3. Practical education on polarization characteristics can be imparted without using expensive equipment such as spectroscopic analyzers and lasers.

DISCLOSURES

The authors declare no conflicts of interest associated with this manuscript.

ACKNOWLEDGMENTS

This work was partly supported by Tokyo City University Interdisciplinary Research Center for Nano Science and Technology for instrumental analysis. We would like to thank Editage (www.editage.com) for English language editing.

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