Optical wireless power transmission characteristics of surface appearance controlled solar cells using visible colour filters

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Abstract
Optical wireless power transmission (OWPT) systems are attractive photonic systems based on light sources and solar cells. To improve the visual design of practical consumer applications, we applied visible colour filters to change the normal black appearance of solar cells. Different colours made by multilayer-type filters on solar cells were investigated for control of visible colour with maintained power transmission efficiency. The surface colours seen by the eyes and standard cameras were controlled by the filter as expected from the filter spectral response. The electrical output characteristics of the solar cell covered with the filter were experimentally measured in order to confirm the OWPT performance. The results showed that the OWPT system can change colour appearance with an acceptable slight deterioration of performance.

1 INTRODUCTION
An optical wireless power transmission (OWPT) system is an attractive photonic system that uses a beam light source and solar cells [1]. In this study, the term solar cell is used as a light-receiving device of OWPT. The OWPT system can transmit power over long distances by beam light. It is also compact and lightweight because it is composed of mature semiconductor devices. In addition, beam light sources of several milli-watts to more than several 100 watts can supply the required electrical power [2–4]. Although there are some reports such as OWPT to drones [4], charging mobile devices [5], and demonstration of commercial-level OWPT using a light source installed on the ceiling [6], the OWPT has not been sufficiently investigated.

Almost conventional solar cells including the above demonstrations are designed for sunlight. In these devices, the surface is almost black to absorb wide wavelengths of sunlight. Although devices designed for optical power transmission have also been researched [7–9], these are also black. Such surface appearance of solar cells can cause a lack of design in the appearance of consumer equipment used in our daily lives. For extension of applications of the OWPT, this property will become an obstacle. There were researches on the coloured solar cell [10, 11]; however, they considered only the visible wavelength range which was related with both power generation using sunlight and visible colour.

In an OWPT system, the light source is not sunlight that has a broad spectrum but monochromatic light of laser or light-emitting diode (LED) to achieve a high-power conversion efficiency of the solar cell [1]. Near-infrared (NIR) range is the optimum wavelength for mature Si or GaAs (Gallium Arsenide) solar cells in an OWPT system [8, 9]. Since NIR wavelength longer than 0.7 µm cannot be seen by the human eye [12], the visible wavelength light can be utilised for other characteristics of non-primary function of OWPT, such as appearance.

In this study, power transmission characteristics are investigated under a controlled appearance of the solar cell surface of the OWPT using colour filters. Although conventional wavelength filter for most applications has been designed primarily for appearance, light transmission, or reflection characteristics of single wavelength range, this study focuses on two wavelength ranges for two independent functions of visible colour and power transmission. A part of the results shown in this study was presented in the 1st Optical Wireless Power Transmission Conference (OWPT2019) [13]. In this study, the detail of experimental conditions, characterisation of additional samples, fabrication and demonstration of a solar cell module are additionally discussed.

2 WAVELENGTH OF LIGHT IN OWPT SYSTEMS
In the OWPT system, the power transmission efficiency is very important from the viewpoint of the primary function of this system. Transmission efficiency depends on several properties...
of the system and device configuration parameters, and the power conversion efficiency of the solar cell is one of the important characteristics. The power conversion efficiency of the solar cell depends on the relationship between the bandgap energy of the solar cell and the wavelength of the light (photon energy). Ideally, irradiation of monochromatic light with a slightly shorter wavelength from the bandgap wavelength is the best for high efficiency [14]. Although solar cells are made from various materials, the performances of the commercially available Si and GaAs solar cells are excellent and cost-effective because these materials are well developed. The reason for selection of these materials is that the bandgap energies of Si (1.1 eV) and GaAs (1.42 eV) are close to the ideal ones for absorbing sunlight spectrum. In order to absorb a wider range of sunlight spectrum of shorter than the bandgap wavelength, almost visible wavelengths are absorbed, and therefore, in general, the surface of most solar cells including Si and GaAs becomes black or dark. Some solar cell materials, such as organic solar cells, have colour due to the limited range of absorption wavelength [15], but their conversion efficiency is less than that of Si or GaAs solar cell.

In most OWPT systems, the light source is not sunlight but monochromatic light of lasers or LEDs. Thus, the bandgap energy of the solar cell can be selected independently of the sunlight spectrum if a light source having that wavelength can be provided. However, currently, commercialised solar cell materials will be optimal for OWPT due to their excellent performance. A monochromatic NIR wavelength of 850–1000 nm is appropriate for Si solar cells and 700–850 nm for GaAs. In view of this situation, the combination of Si solar cell and NIR light source was tested in this study.

As the light source, semiconductor lasers are candidates because of monochromatic light, high efficiency, and compact devices. The maximum power conversion efficiency of NIR of 750–1000 nm range have been as high as about 60%–70% [16–18]. Even commercialised typical semiconductor lasers have efficiencies of over 40%. In this study, 850 nm laser is prepared.

On the other hand, there is lighting or sunlight in daily life. The visible wavelength range from 450 to 650 nm is important for colours of the material. In this study, a typical fluorescent light was prepared as ambient light. The human eye or standard camera recognises the colour of the material under this ambient light.

3 | VISIBLE COLOUR CHARACTERISTICS OF SOLAR CELL

3.1 | Selection of colour filters and their characteristics

The appearance of colour depends not only on the reflected light spectrum from the object but also on its light-scattering characteristics. In this initial study, the case of non-scattering has been investigated. Planar reflectors that have the function of colour filters were set on the solar cell. Commercially available filters of SIGMAKOKI Co. Ltd. were prepared [19–20], and the model numbers of the filters used in the experiment are DIM-GRE, DIF-YEL, DIF-MAG, and DIF-RED. Transmission spectra of selected filters are shown in Figure 1. The types of filters tested are as follows: (a) A visible dichroic mirror (DIM), and (b) a visible dichroic filter (DIF). These filters are made of non-absorbent multilayer structure. The DIM and DIF have essentially the same device structure, however, DIM is designed for reflection to be used at an incident angle of 45 degrees. The DIF is designed for transmission at an incident angle of 0 degrees. These filters are designed for the visible-light range, especially for the typical red, green, and blue. DIM-GRE is designed for reflection of green (500–590 nm) at 45 degrees (reflection of 400–430 nm and 560–660 nm at 0 degrees), the DIF-YEL for transmission of yellow (> 510 nm) at 0 degrees (reflection of 400–480 nm at 45 degrees), the DIF-MAG for transmission of blue and red (400–500 nm and > 600 nm) at 0 degrees (reflection of 450–550 nm at 45 degrees), DIF-RED for transmission of red (> 600 nm) at 0 degrees (reflection of 550 nm at 45 degrees). The reflection wavelength range of the DIM and DIF is changed by the light incidence angle [21]. Although these approximate wavelength ranges are enough to discuss basic colours, detailed transmission spectra can be obtained from the provider’s specification.

The transmittance of the prevent wavelength range is almost 0%, and that of the transmission wavelength range of NIR of 750–900 nm is 85%–95%. The reduction from 100% at NIR is mainly due to surface residual reflections on the backside of the filter substrates because the anti-reflection (AR) coating
TABLE 1  Predicted and measured colour of filters. The colour of transmitted light (A), the colour of reflected light from the surface of filter (B), the colour of reflected light from filter backside or solar cell surface (C).

|            | DIM-GRE | DIF-YEL | DIF-MAG | DIF-RED |
|------------|---------|---------|---------|---------|
| A)         | cyan    | yellow  | magenta | red     |
| B)         | light   | magenta | blue    | green   | cyan |
| 0 deg      | cyan    | yellow  | magenta | red     |
| B)+C)      | light   | orange  | blue    | green   | cyan |
| Measured   | orange  | blue    | green   | cyan    |

|            | DIM-GRE | DIF-YEL | DIF-MAG | DIF-RED |
|------------|---------|---------|---------|---------|
| A)         | magenta | light   | yellow  | white   | yellow |
| B)         | green   | blue    | cyan    | cyan    |
| 45 deg     | magenta | light   | yellow  | white   | yellow |
| B)+C)      | light   | green   | light cyan | cyan |
| Measured   | green   | blue    | cyan    | cyan    |

is not applied. In addition, the transmittance or reflectance at NIR range that is the non-target wavelength of the DIM and DIF may be sometimes large depending on the fabrication error of the multilayer because of interference of light by multilayer. These reflections in the NIR range affect the deterioration of the transmission power of the OWPT system.

3.2  Visible colour of surface of solar cell module

Table 1 shows predicted colours in consideration of the filter spectrum and measured results of filters from the light incident side. The photographs were taken under a white fluorescent light typically used for home. In the photograph, the filter device is a rectangular area in the centre, and the surrounding area is a coloured printing material prepared for simulating a coloured surface of the equipment. Photographs were observed from directions approximately perpendicular (0 degrees) and oblique (45 degrees) to the filter surface. Although the detailed spectrum of appearance colour was not measured in this experiment, it was confirmed that settings of several typical colours were possible as shown in Table 1.

The table contains several predicted colours classified as shown in Figure 2. The surface colour of these filters also changes due to the reflection of transmitted light caused not only by the backside of the filter but also by a solar cell in the case of an OWPT module. These are colour (A) of filter-transmitted light, colour (B) of reflected light from the filter surface, and colour (C) of reflected light of once transmitted light. Although case (A) is a designed colour of the DIM and DIF, in the case of the OWPT, the transmitted side has a solar cell, and the transmitted colour (A) has no meaning. Case (B) is the designed colour of the DIM and DIF. Case (C) is an unexpected light behaviour of the filter device in a practical configuration. The solar cell under the filter does not absorb all transmitted light, and there is some reflected light due to the residual reflection of the solar cell and the reflection from the surface electrode pattern. In addition, in this experiment, each filter has light (C) due to reflection from the back of the filter substrate because of no AR coating, and reflectivity of around 4% exist. Both lights of (B) and (C) are observed simultaneously in a practical situation. Therefore, some of the predicted colours in (B) are different from the colours that can be seen in the photographs; however, they will be correct by considering the condition of (B) + (C). In the case of the DIM and DIF, such weak reflections of transmitted light may have little influence on colour appearance of almost filters because there is a high-intensity reflected light for designed wavelength. However, for the detailed control of the colour, such unexpected light should be taken care of. In the case of OWPT system, the optimum design of filter will be a problem because the light for power transmission should be taken cared as well as visible light.

4  CHARACTERISATION OF POWER TRANSMISSION

4.1  Light transmission characteristics

This experiment was carried out to confirm the transmittance of the NIR wavelength that is not the target wavelength of the colour filter. At first, the transmitted light power transmitted through the filter was measured using a light power meter (Coherent Inc., PM150-50C). A power meter was set under the filter and light was irradiated from the upper side as shown in Figure 3. Although the maximum rated power of the 850 nm vertical-cavity surface-emitting laser (VCSEL) array light source used in the experiment was 4 W, 1 W output was used in the
The beam size at the filter distance is about 2 cm in diameter. The size of the filter is 5 × 5 cm square, and the diameter of the power metre is 5 cm. Therefore, most of the output light irradiated the filter and received by the power metre.

The measured transmission efficiency is shown in Table 2. When the VCSEL light passed through the filter, the power was reduced slightly. For example, if 1 W of light passed through the DIF-RED, the power became 0.91 W. These results show that one filter reduces the light power by 5%–10%. Some DIM and DIF filters showed a larger reduction than 4% that is expected as reflections on non-AR backside. The reason is the transmission spectrum fluctuation in the NIR range as discussed in Section 3.

### Table 2

| Applied filter | Transmission efficiency |
|----------------|-------------------------|
| DIM-GRE        | 0.90                    |
| DIF-YEL        | 0.95                    |
| DIF-MAG        | 0.93                    |
| DIF-RED        | 0.91                    |

The experiment of the OWPT was carried out using solar cell and laser light. The block diagram is shown in Figure 3(a) and the setup is (B). The light source is an 850 nm VCSEL array, and the solar cell module with the size of 6×7 cm is a 2-series connected polycrystalline-Si type (∼10%@1sun). The surface of the solar cell is directly covered with a filter. The transmission distance from the VCSEL without a lens was set to 22.5 cm in order to irradiate the 5×5 cm filter. Since the filter was set in a 5 × 5 cm through holes made of opaque material, leakage light outside the filter cannot enter the solar cell.

The current–voltage (I–V) characteristics and electrical output power of the solar cell were measured as shown in Figures 4 and 5. From Figure 4, a short-circuit current of about 170 mA and an open-circuit voltage of about 1.1 V are confirmed. As with the characteristics of ordinary solar cells, the maximum output point is within the short-circuit current point and the open-circuit voltage point in the I–V characteristic. As shown in Figure 5, the voltage corresponding to the maximum output points in this experiment was in the range of 0.90 to 0.91 V depending on the amount of transmitted light power of the filter. If the whole output light from VCSEL is absorbed by the solar cell and it ideally causes a current, short-circuit current of 686 mA is expected from the number of output and absorbed photons. The measured short-circuit current was only 25% of the expected current. There were some reasons for the low
current because of the following. In order to irradiate a solar cell uniformly, the light beam size was set slightly larger than the filter. Solar cell modules were also slightly larger than filters and holes. Therefore, a part of the output light from the VCSEL cannot enter the solar cell even without using a filter. Reflection at the surface of the solar cell was also one of the reasons. In addition, from the specification characteristics of the solar cell module, slightly low efficiency under sunlight is another reason for the small short-circuit current. In the below, the current is quantified. The specification of Si solar cell with 31.25 mm × 62.5 mm × 2 cells under 1sun is 500 mA. By assuming of short-circuit current of 410 A/m² of high-quality Si solar cell, current (quantum) efficiency of the applied cell is calculated to be 0.624. By considering the photon energy of 1.459 eV for 850-nm wavelength, output current under monochromatic light is calculated as 195 mA. The ratio between the experimental value and the calculated current was 0.398. This ratio is considered due to light leakage outside the solar cell as discussed above.

Since the transmittance of the filter is not 100%, the output power and current of the solar cells under the filter are slightly lower than those of the solar cells without the filter. The measured results are summarised in Table 3. For example, the solar cell without filter under 1 W of VCSEL illumination has a short-circuit current of 170.4 mA and maximum output power of 156.1 mW. When the solar cell is covered with the dichroic filter DIF-RED, the short-circuit current is 149.0 mA and maximum output power is 134.5 mW. Even with the other filters, the output power was 134–144 mW. Although the output power was approximately 14% of output light power, the power conversion efficiency was much larger than the specification value of 10% under the sunlight. This is because the monochromatic light was used in the OWPT measurement and it is an advantage of OWPT. However, even in the case of monochromatic light, external quantum efficiency of the solar cell should be large at the applied monochromatic wavelength [14].

From these experiments, relatively high efficiency of power transmission was confirmed under different colours of the surface appearance of the solar cell or equipment. If there is an appropriate AR coating on the filter, slightly higher output power can be expected. In addition, light irradiation without invalid light increases the output power and efficiency.

### 4.3 OWPT light receiver module with colour filter

For demonstration of appearance control assuming actual equipment, a light power-receiving module using a 3D printer was fabricated using a five-series connected flexible-type GaAs solar cell module. The spec efficiency of the solar cell is 26% under 1sun. The size of the solar cell was 5 × 9 cm. Two colour filters are set in the module to cover the solar cell as shown in Figure 6. The types of filters in GaAs solar cell module are DIM-GRE and DIF-RED. An impressive colour appearance was obtained. Two different colours are due to setting of different colour filters. On the other hand, there are several wires under the filter, which are electrical wires connected between the solar cell and the connector device. The wires are not black, and it reflects some of the light that transmitted the filters. Such an appearance of an unexpected or non-black object would not be appropriate for equipment. Therefore, the reduction of reflection in the module should be considered. The output of the solar cell is obtained through the USB (Universal Serial Bus) connec-
tor. By irradiation of the NIR laser light from 50 cm distance, charging mode of a smartphone was confirmed as shown in Figure 7. In order to charge this smartphone, we increased the output power of VCSEL array to about 3.5 W. However, because the shape of irradiation is bigger than the area of GaAs solar cell module, the output power of the solar cell is just about 2.5 W when charging this smartphone.

5 CONCLUSIONS

To improve the visual design of practical consumer applications of OWPT systems, we applied visible colour filters to change the typical black appearance of solar cells. By applying commercially available transmission-type colour filters, the colour appearance of the solar cell side of OWPT system can be controlled. By experiments of NIR light irradiation to filters on a solar cell, I–V characteristics and output power of solar cell in an OWPT system with a colour filter were characterised. As a result, it is possible to change the surface appearance of the solar cell to some extent without large deterioration of the OWPT performance. The deterioration is mainly due to the reflection of the filter back that has no AR coating. In this report, a planar filter was applied, however, light scattering is important in visible appearance. The control of light scattering and characterisation of the effect of scattering on the OWPT will be investigated.

ACKNOWLEDGEMENTS

This work was partly supported by Tsurugi-Photonics Foundation and by NEDO “Technical survey of optical wireless power transmission for mobility”.

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