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Wearable pupil position detection system utilizing dye-sensitized photovoltaic devices

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Abstract

Detection of the line-of-sight (LOS) has a variety of applications, such as communication tools for elderly or disabled people, assisting drivers, and effective location of traffic signs. To realize such promising applications, there is strong demand for an LOS detection system that does not restrict users' activities and inflicts no mental stress. The LOS can be obtained by combining the directions of the face and eyes, respectively, where the detection of location and motion of the pupils is a critical technology. In this paper, we propose a novel wearable pupil position detection system, featuring minimum disturbance to users, both physically and mentally, via the use of dye-sensitized photovoltaic devices. These latter are transparent and generate voltage according to the incident light intensity. Arraying the devices on wearable eyeglasses, this system detects the difference in the reflection light from the pupil and the white of the eye and hence determines the position of the pupil. It is wearable as an eyeglass, meaning it does not disturb users' activities or eyesight. More importantly, it involves minimal physical and psychological stress. We fabricated the photovoltaic device and demonstrated their feasibility to determine the location of the pupil. We found it possible to meet the required reaction time of 100 ms by reducing the size of the device and to improve the accuracy of pupil location detection by arraying the devices.

Keywords: MEMS; Human interface; Line-of-sight; Wearable; Dye-sensitized photovoltaic device

1. Introduction

A wide variety of applications featuring line-of-sight (LOS) detection systems are expected, such as human–computer interfaces [1,2], diagnoses of patients affected by neurological or mental disease [3,4], communication tools for elderly or disabled people, driver aids and effectively locating traffic signs. The LOS information can be utilized either for pointing or monitoring human behavior. In early studies, using an external camera to detect the location and motion of the pupil is the mainstream method of detecting LOS, with fixed eye cameras utilized to gauge the movement of the pupil and thus deduce the LOS [5–8]. Head-mounted eye cameras are also utilized [4,9,10]. However, these methods involve several problems in that they restrict users' activities and expose them to physical and mental stress [11]. With this in mind, a solution to enhance the practicality of the promising LOS detection applications, with systems that do not impose any restriction on users' activities nor expose them to any stress, is strongly demanded. In this study, we propose a novel wearable LOS detection system that affects the users minimally, both physically and mentally, using dye-sensitized photovoltaic devices fabricated on an eyeglass, as illustrated in Fig. 1. The photovoltaic devices are transparent and generate voltage according to the incident light intensity. In this system, the devices are used as transparent photo sensors. Arraying the devices on wearable eyeglasses, this system detects the difference in the light reflected from the pupil and the whites of the eyes and thus derives the position of the pupils. Fig. 2 illustrates the LOS detection using the proposed pupil position detection system. The pupil positions are detected by the device as depicted in Fig. 2(b). A small CCD camera mounted on the eyeglasses acquires an image in front of the user, in which the LOS is deduced from the pupil position as shown in Fig. 2(c). Calibration is conducted in advance by using the LOS targets whose relative positions to the devices are known to derive the relationship among the LOS, the pupil position, and the acquired image. Since this system is wearable and transparent, it neither limits users' activities nor blocks their eyesight. Wearable like

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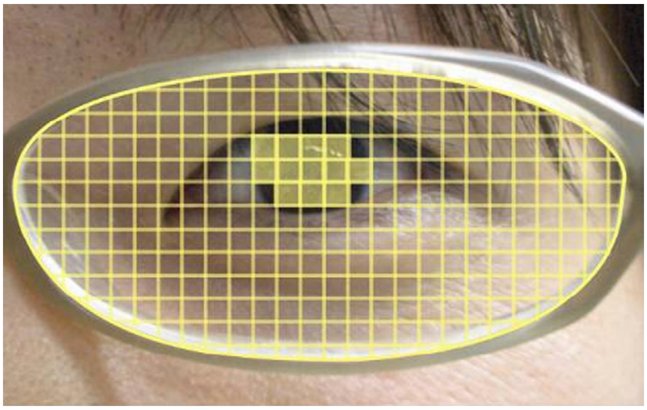

Fig. 1. A conceptual image of the wearable LOS detection system using transparent dye-sensitized photovoltaic devices.

an eyeglass, in particular, it exposes users to the bare minimum of physical and psychological stress. In this paper, we demonstrate fabrication and characterization of the photovoltaic device arrays and their feasibility of detecting the pupil location.

2. Dye-sensitized photovoltaic device

2.1. Structure

Dye-sensitized photovoltaic devices are currently attracting widespread scientific and technological interests as high efficiency and low-cost alternatives to inorganic solar cells [12]. Fig. 3 presents the structure and the operating principal of the device, which consists of two electrodes and an iodide (I^-)- and triiodide ion ($I_3{}^-$)-containing electrolyte. The cathode has a highly porous nano-crystalline semi-conductive titanium dioxide (TiO_2) layer, deposited on a transparent electrically conductive glass. Since TiO_2 absorbs only UV light, dyes are adsorbed on the TiO_2 layer to utilize the light with a wider range

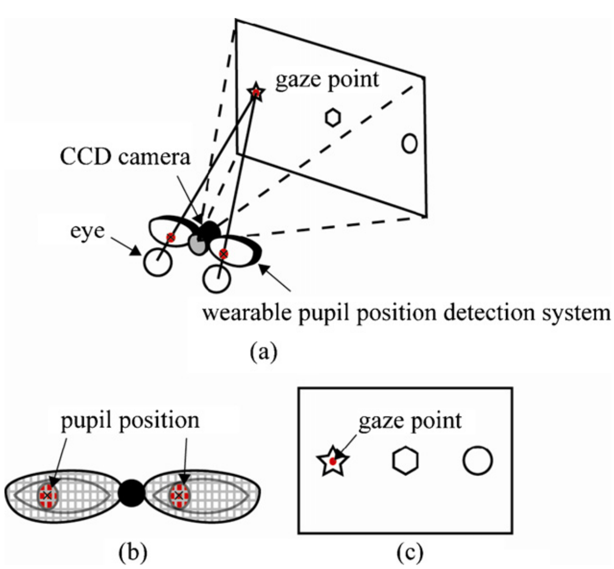

Fig. 2. LOS detection using the proposed devices. (a) Schematic view of the LOS detection. (b) Front view of the wearable pupil position detection system. (c) Acquired CCD image and the LOS.

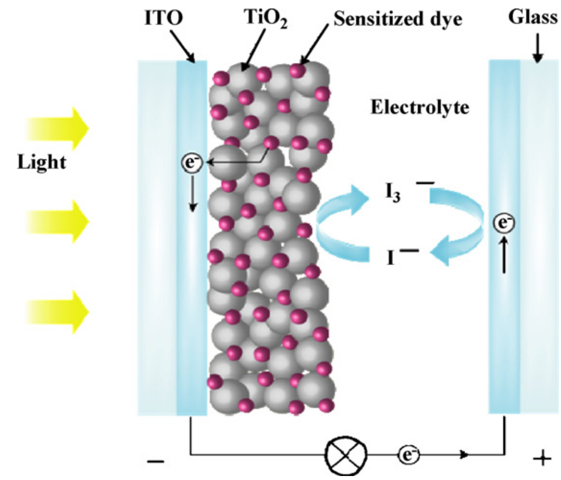

Fig. 3. The structure and operating principle of the dye-sensitized photovoltaic device.

of frequency and enhance the device performance. The counter electrode that functions as the anode, meanwhile, is a transparent electrically conductive glass. The device is transparent in the dye's color.

2.2. Operating principle

When light passes through a conductive glass, the dyes are excited and transfer an electron to the semi-conducting TiO_2 layer via electron injection. The electron is subsequently transported through the porous TiO_2 layer and collected by the conductive layer on the glass, whereupon within the electrolyte, mediators I^- and $I_3{}^-$ undergo oxidation and regeneration. The electrons lost by the dyes to the TiO_2 are replaced by the I^- and $I_3{}^-$, generating I or I_3, which, in turn, obtains electrons at the counter electrode, culminating in current flows through the electrical load. This is how the device receives light energy and emits electricity [13]. This device also incorporates an interesting feature in that it reacts strongly to incident light from the TiO_2 layer side. Therefore, when the TiO_2 layer electrode faces to the eyes, it is capable of detecting only the light reflecting from the pupil and white of the eye, without being affected by incident light from the surrounding environment.

2.3. Fabrication

Fig. 4 illustrates the fabrication processes of a single photovoltaic cell. First, a conductive glass (12 Ω/sq Asahi Glass Fabritech, SnO_2-coated glass, A11DU80) is rinsed using ethanol. The TiO_2 layers are fabricated from TiO_2 coating solution containing TiO_2 nano-particles (Tayka TKC-303, TiO_2 size 6 nm). In manufacturing a rather large single cell, scotch (3 M) adhesive tape is applied to the four sides of a conductive glass plate to form a mold into which the TiO_2 solution can flow, where a photoresist is used in fabricating arrays of the small cells. The TiO_2 solution is distributed uniformly on the glass and the layer is then air-dried. After the tapes are removed, the device is further annealed in the air at 450 °C for 30 min. Subse-

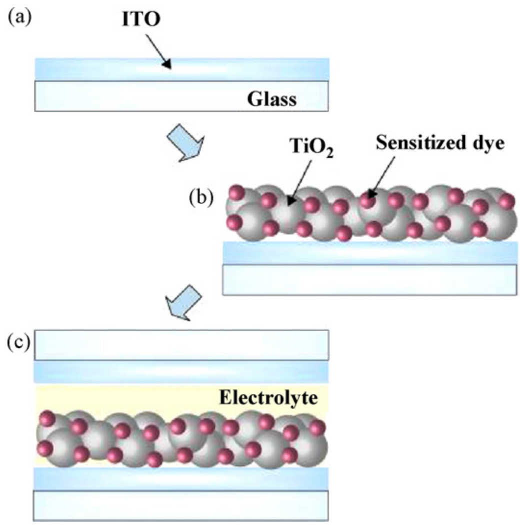

Fig. 4. Fabrication processes of the dye-sensitized photovoltaic device.

quently, it is dipped in herb tea with rosehip and hibiscus flowers (Pompadour) for 30 min to ensure the dyes adsorb into the TiO_2 layer. The electrolyte (0.5 M potassium iodide and 0.05 M iodine in water-free ethylene glycol) is dripped onto the stained TiO_2 layer and carbon is deposited on the counter electrode plate, which works as a catalyst. The counter electrode is placed on the top with a lateral offset.

3. Experiment

3.1. Proof-of-concept experiment

We conducted proof-of-concept experiments of the pupil detection using the device. We fabricated a 15 mm × 20 mm device and placed the device in front of the eye, with the TiO_2 electrode facing the pupil, as shown in Fig. 5. The distance between the pupil and devices was set at 10 mm, which is approximately the distance between the eyes and eyeglasses in common. We measured the output voltage when the pupil moves iteratively in the lateral direction, with the result shown in Fig. 6. When the white was in front of the device, the measured voltages

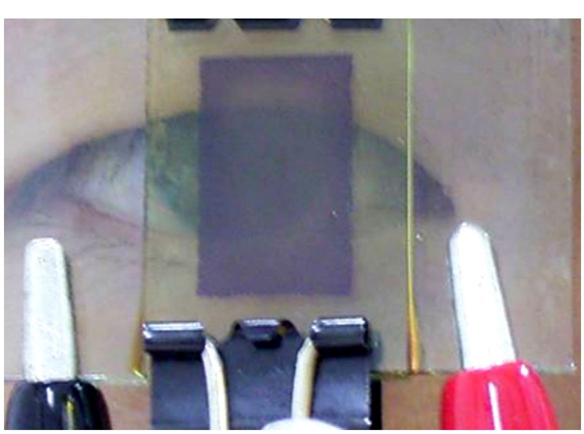

Fig. 5. An image of the experiments to detect the pupil and white of the eye using the fabricated photovoltaic device.

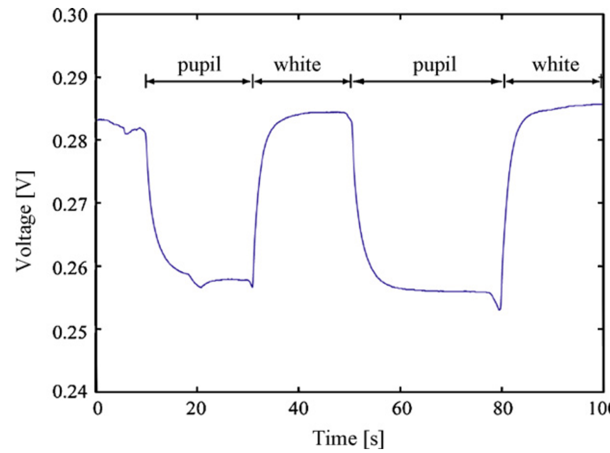

Fig. 6. The output voltage of the device detecting the pupil and white of the eye.

were 280–290 mV, while facing the pupil, the device generated voltages of 250–260 mV. These results verified the feasibility of using the device to detect pupil location. Arraying the devices is also considered to have the potential to enhance the spatial resolution of detection.

3.2. Reaction time

We evaluated the reaction time of the devices with respect to the size, with the former measured photo transistor (Toshiba, TPS603A, reaction time 2 μs) as a benchmark. Fig. 7 illustrates the experimental set-up. The photovoltaic device was positioned adjacent to the photo transistor and the incident light was turned on and off by the shutter. The data were acquired via a card-type PC date sampling system (Keyence NR-110) and we measured the reaction times of 20-mm-, 10-mm-, 5-mm- and 3-mm-square devices, respectively. Fig. 8 shows the reaction time of the fabricated photovoltaic device ranging in size from 3 mm to 20 mm square in size. The evaluated reaction time of the 20 mm^2 device was 190–210 ms, while that of the 3-mm-square-device was 80–120 ms. This result indicated that the reaction time diminishes as the device becomes more compact, which is attributable to the short diffusion time of the electrons in the small devices. It is thus possible to meet the required reaction time of 100 ms [14] by reducing the size of the device.

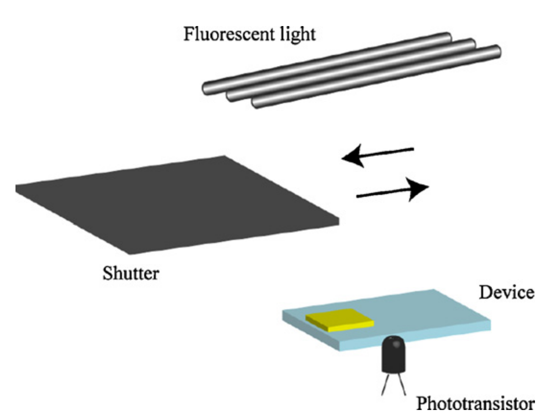

Fig. 7. The experimental set-up to evaluate the reaction time of the device.

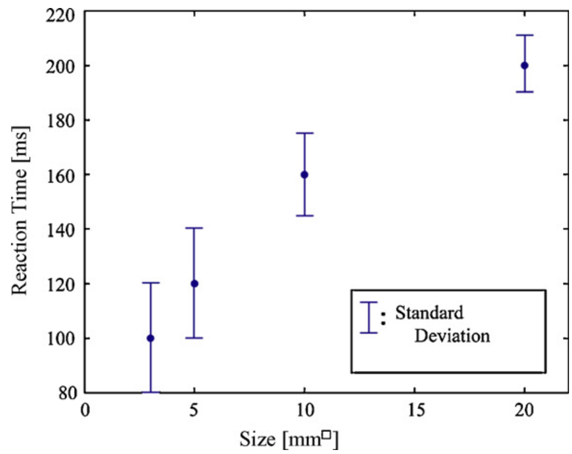

Fig. 8. The measured reaction time with respect to the size of the devices.

3.3. Fabrication of the device array

To enhance the pupil detection performance, the devices must be arrayed. We thus fabricated a 3 × 1 array of the device, each of which had a 3-mm-square active area. The succinct fabrication processes are illustrated in Fig. 9. First, we patterned the conductive layer (SnO_2) on the glass substrates for both electrodes via photolithography, whereby a positive photoresist (AZ) film was utilized as a protective mask and the SnO_2 layer was chemically etched using a mixture of hydrochloric acid (80 ml) and ferric chloride solution (67 ml). We then placed zinc powders on the SnO_2 layer, which worked as catalysts, and subsequently dipped it into the etchant for 20 min. AZ was used as a mold to pattern the TiO_2 layer as well. The TiO_2 nano-particles solution was then channeled into the mold on the glass and air-dried at 100 °C for 10 min, before the AZ mold was removed by the following UV exposure and development. Subsequently, the device was annealed in the air at 450 °C for 30 min and dipped in herb tea with rosehip and hibiscus flowers for 30 min to ensure the dyes adsorbed into the TiO_2 layer. polydimethylsiloxane (PDMS), which is a thermosetting polymer, is molded to form a casing to contain as well as seal the electrolyte. The PDMS casing was molded by a patterned SU-8 structure, a thick photosensitive polymer. It was treated by the oxygen plasma for 0.5 s at 50 W and then bonded to the glass. The electrolyte was dripped onto the TiO_2 layer with a micropipette, while the counter electrode is placed on the top of the TiO_2 electrode via the PDMS casing. Fig. 10 shows a photo of the 3 × 1 array of the devices.

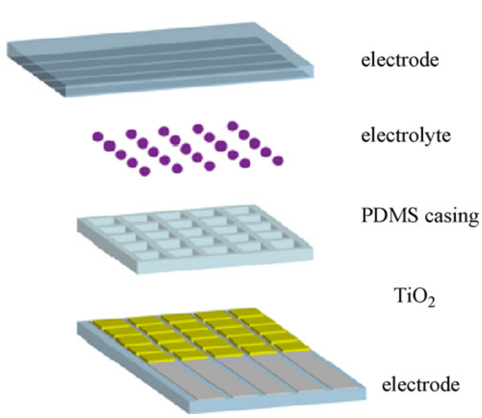

Fig. 9. The schematic fabrication processes of the photovoltaic device array.

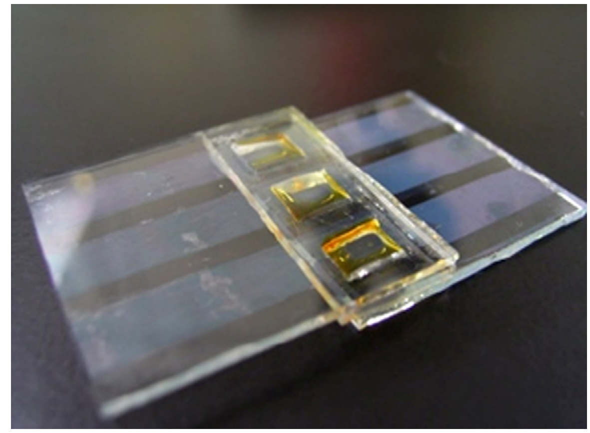

Fig. 10. The 3 × 1 array of the devices.

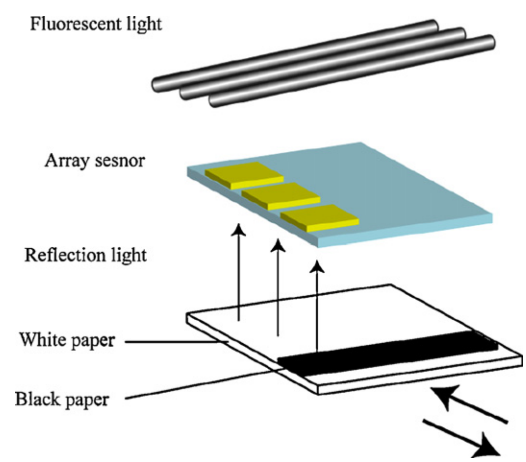

Fig. 11. The experimental set-up involving the black and white regions being detected by the 3 × 1 devices array.

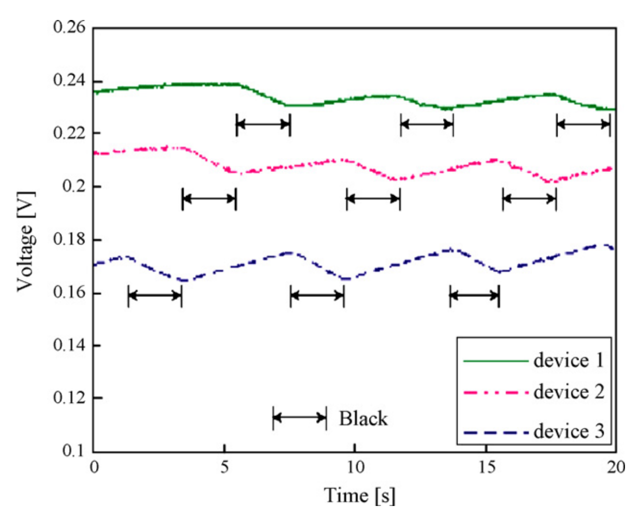

Fig. 12. The output voltages from the array. Based on the difference in voltages, the movement of the black region can be derived.

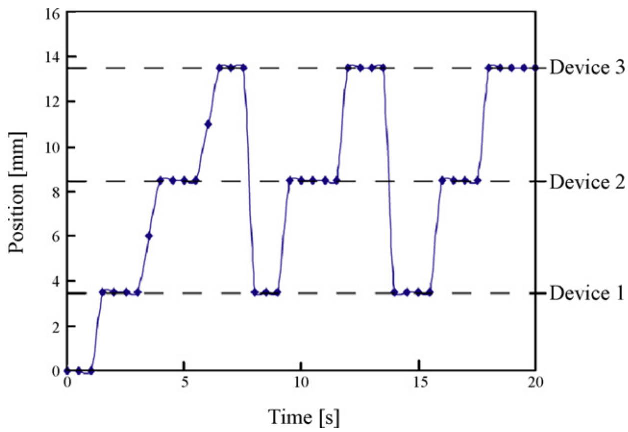

Fig. 13. Estimated location of the black region by the 3 × 1 device.

3.4. Experimental of the arrayed device

We conducted experiments to evaluate the fabricated arrayed device and Fig. 11 illustrates the schematic experimental set-up. The device was located over a white paper with a black stripe that simulates the pupil and a fluorescent light was applied from above. We measured the output voltages from the arrayed devices when the paper was moved laterally at constant speed. The data were acquired via the date sampling system with a sampling frequency of 50 Hz and the output voltages of the three devices vary associated with the movement of the paper as shown in Fig. 12. This result indicates that the photovoltaic devices array can detect the black and white region and hence the position and movement of the pupil. Fig. 13 depicts the estimated position of the black region, as calculated from the output voltages of the devices. The results indicated the “stop-and-go” movement of the black region, which is due to the relatively large area of each cell and the gap between them. This error can be fixed by refining the manufacturing processes and miniaturizing the cells.

3.5. 3 × 3 device array

We fabricated an array of 3 × 3 devices, each of which has an active area of 5 mm^2, while the gaps between the adjacent

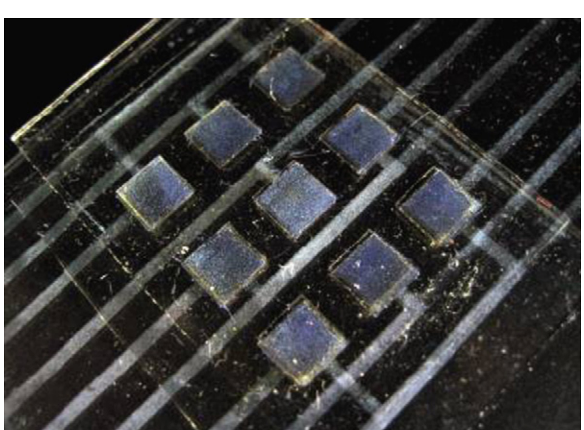

Fig. 14. The 3 × 3 array of the device.

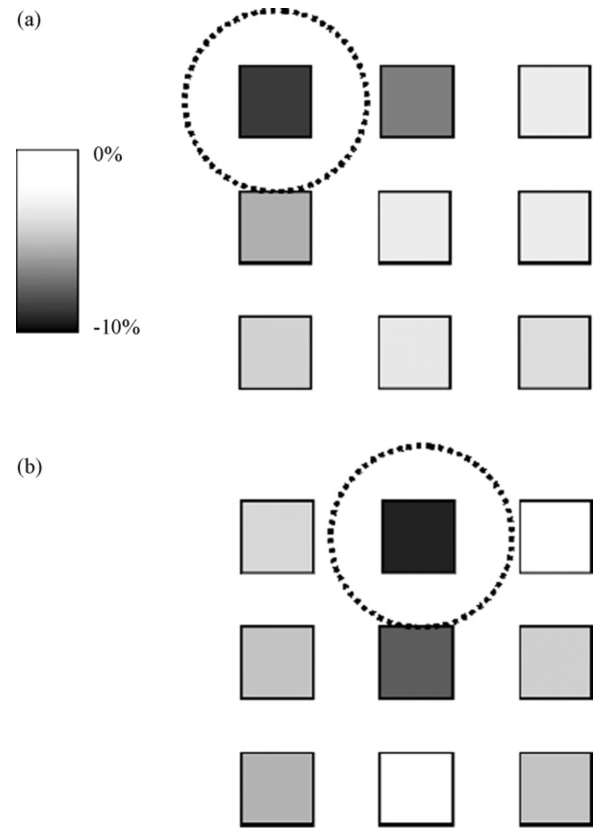

Fig. 15. Experimental results with the 3 × 3 array of the device. (a) The simulated pupil is located below the upper-left cell and (b) the upper-middle cell.

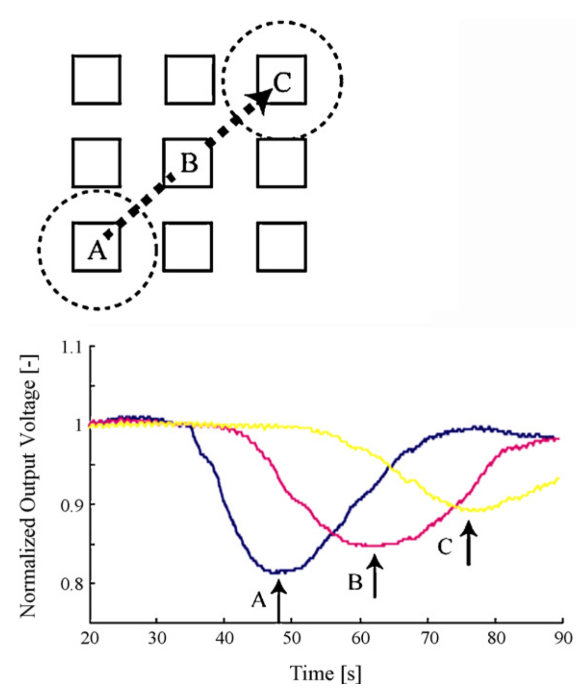

Fig. 16. Normalized output voltages of the devices A, B and C when the simulated pupil was moved from A to C.

device are 3.5 mm in a vertical direction and 4.5 horizontally. Fig. 14 shows a photo of the 3×3 devices array. Here, we used a black circle 12.5 mm in diameter to simulate a pupil, which represents the approximate average pupil size. Fig. 15 depicts the output voltages of each device when the simulated pupil is located below (a) the upper-left device and (b) the upper-middle device. The gray scale of the illustrations represents a reduction in output voltage, where −10% of the output voltage corresponds to black. The greatest reduction in output voltage, meanwhile, was observed in the device above the simulated pupil, while the output voltages of the adjacent devices also declined. The experiments indicated that the arrayed device provides a more precise location of the pupil than the single device. Fig. 16 illustrates the output voltages of three devices (A–C in the figure) when the simulated pupil moved across the array, where the voltage of each device was normalized by the average voltage when the device is not above the simulated pupil. The reduction in output voltage of the devices was obtained associated with the movement of the pupil, which indicates successful detection of the movement of the pupil by the devices array.

4. Conclusions

The transparent photovoltaic devices could detect the eye movement based on the difference in the light reflected from the pupil and the white of the eye, which verified our concepts of the wearable pupil position detection system. MEMS technology can miniaturize the cells and increase their number, which, in turn, can augment the time and spatial resolution of the detection. The reaction time of the devices was found to diminish in line with decreasing device size and it is possible to meet the required reaction time of 100 ms for the LOS application by reducing the size of the device. The fabricated 3×3 arrayed device successfully detected the location and movement of the pupil. The fabrication processes involved can be applied to manufacture the device array on eyeglasses, which achieves a practical and wearable LOS system free from both physical and mental stress.

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Biographies

Takeshi Shigeoka is presently a graduate student of Faculty of Science and Technology at Keio University, Kanagawa, Japan. His research focuses on the design, fabrication and testing of wearable LOS detection system using dye-sensitized photovoltaic devices. From 2006 to 2007, he joined Vulcanus in Europe Program, which consists of an international internship and language training, run by the Ministry of Economy, Trade and Industry of Japan and the EU Commission. He was with LMS International in the internship program, where he worked on modal analysis.

Takeshi Ninomiya is a graduate student of Faculty of Science and Technology at Keio University. As an undergraduate, he was in charge of a quantitative analysis of human and robot hand movements. Currently his research focuses on the design and fabrication of MEMS-based human interface devices.

Takayuki Muro is currently a senior student of Department of Mechanical Engineering at Keio University. His research focuses on manufacturing and testing of wearable pupil position detection system using dye-sensitized photovoltaic devices.

Norihisa Miki received his BE, ME and PhD degrees in mechanical engineering from the University of Tokyo in 1996, 1998 and 2001, respectively. From 2001 to 2004 he was a postdoctroal associate and then a research engineer in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology, where he worked on the development of a button-size silicon microgas turbine engine. In 2004 he joined the Department of Mechanical Engineering at Keio University, Kanagawa, Japan, as an associate professor/lecturer. His principal fields of interests include MEMS-based human interface, microfabrication technology, microTAS, bio and chemical sensors, and power MEMS. Prof. Miki is a member of IEEE.