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A LIGHT GUIDE PLATE BASED FLEXIBLE OPTICAL CUFF FOR OPTOGENETIC STIMULATION OF MOTOR UNITS

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ABSTRACT

This paper reports a light guide plate based flexible optical cuff for optogenetic stimulation of motor units. We propose the optical cuff based on a single-sheet PDMS light guide plate (LGP). It has good flexibility, and can be improved the efficiency of the light source by distributing the light globally through the LGP. Moreover, the possibility of cell necrosis due to heat can help to reduce by preventing direct contact between the μ-LED and neurons.

KEYWORDS

Optogenetic stimulation, Optical cuff, motor nerve, Light plate guide

INTRODUCTION

Optogenetics technology has been actively studied since it enabled to precisely control neurons in response to brief pulses of light [1]. Conventional optical devices for optogenetic stimulation are mostly used optical fiber which was connected by an external laser source [2-7] and μ-LED array based on FPCB [1, 8-10]. However, optical fiber cannot be implanted inside a body due to a persistent connection to an external source. In case of μ-LED array, it is difficult to implant by partially rigid characteristics. Also, it generates a lot of heat which can damage to cells by high power dissipation of μ-LED. Studies on implantable device for motor nerve stimulation have not been widely progressed yet.

This paper reports a light guide plate based flexible optical cuff for optogenetic stimulation of motor units. We propose the optical cuff based on a single-sheet PDMS light guide plate. It has good flexibility, and can improve the efficiency of the light source by distributing the light globally through the LGP. Moreover, the possibility of cell necrosis due to heat can help to reduce by preventing direct contact between the μ-LED and nerve.

DESIGN AND METHOD

Design

A targeted photo-activatable protein for optogenetic stimulation is channelrhodopsin-2 (ChR2) from the alga *Chlamydomonas reinhardtii.* The minimum light intensity and wavelength required to activate ChR2 channels are 1mW·mm^{-2} and 470 nm [1, 3]. Therefore, optical cuff for optogenetic stimulation must meet the above conditions.

Figure 1 shows the conceptual view of the proposed optical cuff. The proposed optical cuff can make it possible to uniformly stimulate while wrapping the sciatic nerve as shown in figure 1 (a). The device was composed of a micro light-emitting diode (μ-LED), polydimethylsiloxane (PDMS) structure, and metal film. The LED (SMLP12BC7T, ROHM Co., Ltd.), the light wavelength is 470 nm, was chosen for optical source. The width, length, and height of the LED were 0.8mm, 1mm, 0.2mm. Three LEDs were connected in parallel on a PCB board with each width and length of 1mm and 3mm. The PDMS structure was attached onto the LED board. The PDMS structure had triangular-prism patterns in order to reflect the light and to emit the reflected light over. The total size of the PDMS light guide plate is width, length, and height of 3mm, 4mm, and 1mm as shown in figure 1 (b). The micro triangular-prism patterns were located on top of the PDMS structure. The width and height of the triangular-prism pattern were 100μm and 70μm. The spacing between each pattern is 50μm (Figure 1 (b) box). A metal film was laid under the PDMS structure. The metal film served to reflect the light from μ-LEDs. Figure 1 (c) shows the light trace of μ-LEDs in the single-sheet PDMS light guide plate. Lights from the side LEDs travel through the PDMS light guide plate by means of internal reflection and were emitted to upward direction.

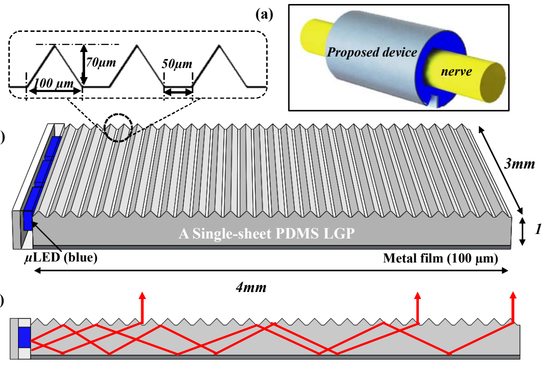

Figure 1: The conceptual view of the proposed optical cuff. (a) optogenetic excitation (photo-activatable protein: ChR2), (b) the triangular-prism patterned optical cuff, (c) light traces of μ-LEDs in the single-sheet PDMS light guide plate

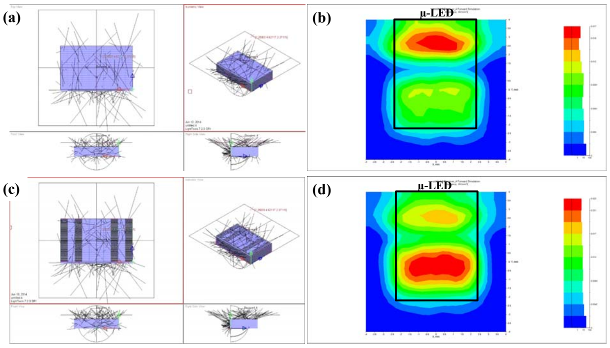

Figure 2: The simulation results of light traces and illumination of the optical cuff according to the presence or absence of the reflecting metal. (a, b) light traces and illumination without reflecting plate, (c, d) light traces and illumination with reflecting plate

Effect of the light guide plate

In order to determine the design of the PDMS light plate guide, a computation simulation was conducted using LightTools 7.2. Figure 2 shows the simulation results of light traces and illumination of the optical cuff according to the presence or absence of the reflecting metal film. Through the simulation result, it can be confirmed that light on the side of the μ-LED is effectively delivered to the upper portion. By adopting the reflecting layer, the optical efficiency of the cuff has been improved. However, it has the disadvantage that the thickness of the device is increased. We did not clearly marked power intensity of each point because the overall power intensity of the surface light source is important for the optical cuff.

The proposed optical cuff based on a single-sheet PDMS light guide plate has good flexibility, and can improve the efficiency of the light source by distributing the light globally through the light guide plate. Moreover, the possibility of cell necrosis due to heat can help to reduce by preventing direct contact between the μ-LED and nerve.

FABRICATION

Prism silicon mold

Figure 3 shows the simplified fabrication steps for silicon wafer mold. The fabrication began with the deposition of a silicon nitride layer as a protecting layer on a p-type silicon substrate, as shown in figure 3 (a). Then, a photoresist was spin-coated and patterned with Cr mask, as shown in figure 3 (b). After patterning, the resisted silicon nitride layer was removed by using dry etching process, as shown in figure 3 (c). The anisotropic wet etching process was used so as to define the shape of the silicon wafer using HF solution. An anisotropic wet etch on a silicon wafer creates a cavity with a triangular cross-section, as shown in figure 3(d). Finally, the nitride was removed by using dry etching process, as shown in figure 3 (e)

PDMS light guide plate

Figure 4 shows the simplified fabrication steps of the PDMS light plate guide plate with reflecting layer. At first, a PDMS solution (PDMS sylgard 184, Dow Corning, USA) was poured on the prism silicon mold and thermally cured for 1h at 100°C, as shown in figure 4 (a). After curing, a metal film with a thickness of 100μm was attached to the top of the cured PDMS, as shown in figure 4 (b). And then, in order to combine the PDMS structure with the metal film, the PDMS solution was poured on the top of the metal film again and baked at 100°C for 1h, as shown in figure 4 (c). By detaching the cured PDMS from the prism silicon mold, the PDMS light guide plate could be obtained, as shown in figure 4 (d). Finally, the fabricated PDMS light guide plate was attach to the PCB that was connected to the parallel μ-LEDs.

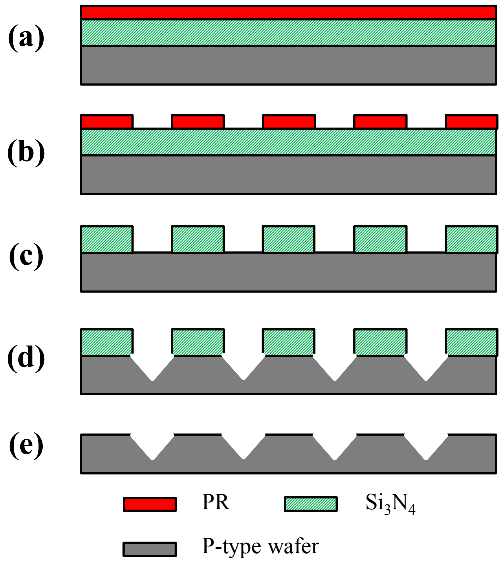

Figure 3: The simplified fabrication steps of the prism silicon wafer mold for PDMS light guide plate

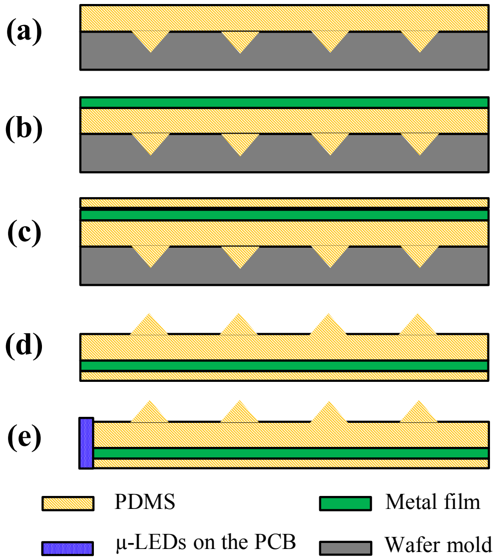

Figure 4: The simplified fabrication steps of the PDMS light plate guide plate with reflecting layer

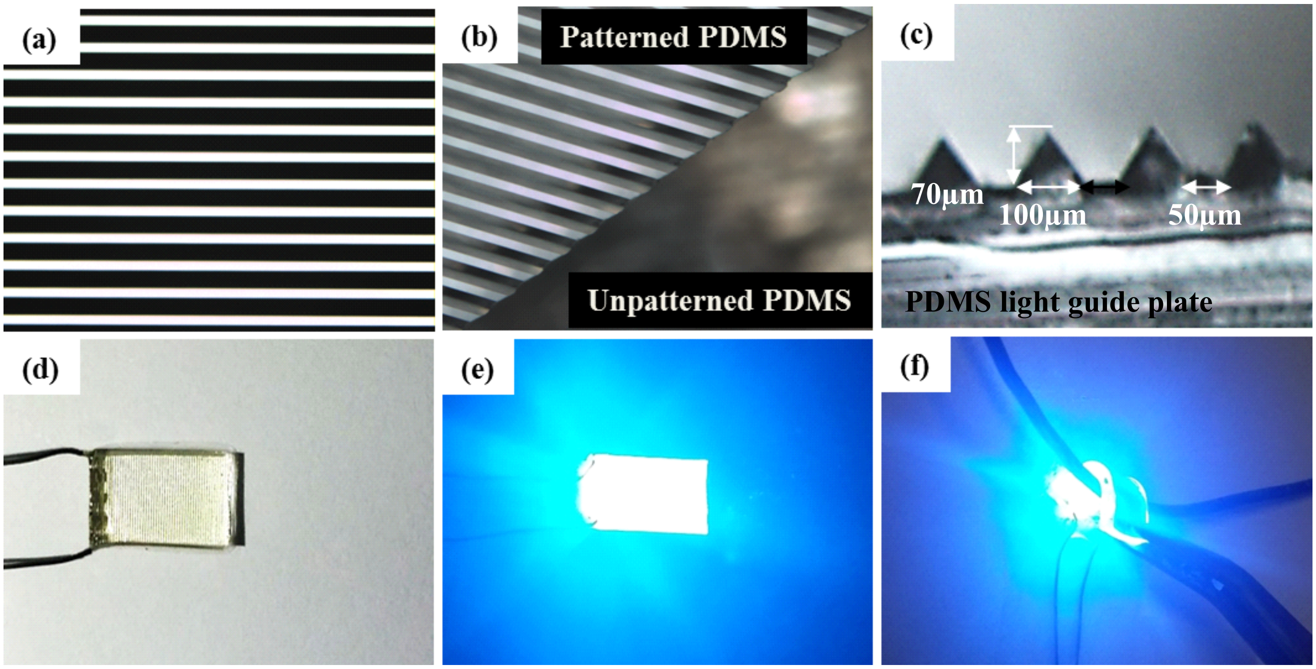

Figure 5: The optical photographs of the fabricated prism silicon mold (a), the patterned PDMS (b, c), the optical cuff (d, e), and illumination (f, g)

Figure 5 shows the optical photographs of the fabricated silicon mold and optical cuff.

EXPERIMENTS

Experimental setup

The output characteristic of the fabricated tactile sensor array was evaluated by an experimental setup as shown in figure 6. It consist of a DC power supply (U8002A, Agilent), a thermometer (TM-947SD, Lutron Electronics Co., Inc.) for measuring the temperature change, and digital optical power meter (PM120, Thorlabs) for measuring the optical cuff power intensity.

Thermal characteristic

The thermal characteristic of the fabricated optical cuff was evaluated through temperature change experiments. To compare the temperature change of the µ-LED and proposed optical cuff during the light emitting, we measured the temperature of center of each group. Figure 7 shows that temperature variation of the optical cuff is markedly smaller than that of the µ-LED.

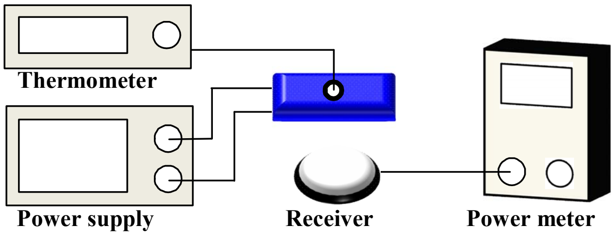

Figure 6: Schematic diagram of the experimental setup

Output optical power intensity

To evaluate the optical characteristic of fabricated optical cuffs, the optical power intensity was measured by digital optical power meter. Table 1 shows power intensity of fabricated optical cuffs according to the presence or absence of reflecting metal film. There was a large difference in the optical power intensity between two devices. The output optical power of the cuff without reflecting metal film was less than 1mW mW·mm^{-2}. On the other hands, The optical power intensity of the cuff with reflecting metal film, driven by 1mA current at 3 V, was 1.2mW·mm^{-2}, which was above ChR2 spiking threshold.

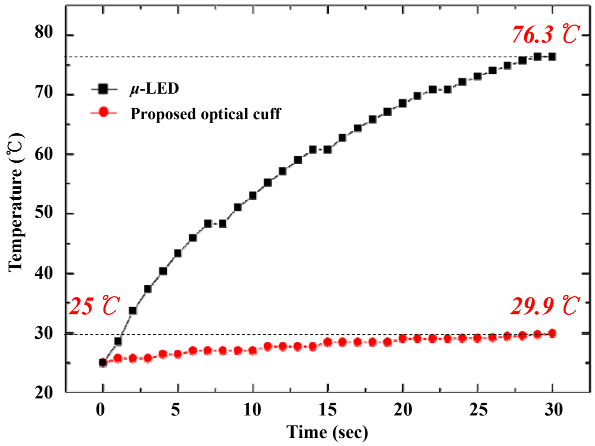

Figure 7: Temperature changes of the fabricated optical cuff and µ-LED

Table 1: Output power intensity of fabricated optical cuffs according to the reflecting plate.

	Reflecting plate	ChR2, minimal power intensity of light activation ($mW{\cdot}mm^{-2}$)	**Optical cuff power intensity ($mW{\cdot}mm^{-2}$)**
1	*X*	*1*	***0.7***
2	*O*		***1.2***

CONCLUSION

For stable motor nerve stimulation, optical device should be able to warp the nerve as a whole. In addition, to prevent neuronal damage due to heat generation of the light source, the light source should not be in contact with the nerve directly.

In this paper, we have proposed the light guide plate based flexible optical cuff for optogenetic stimulation of motor units. By applying PDMS light guide plate, the proposed optical cuff has good flexibility, and can improve the efficiency of the light source by distributing the light globally through the light guide plate. Also, the possibility of cell necrosis due to heat can reduce by preventing direct contact between the μ-LED and nerve. It was confirmed that the proposed optical cuff has heat stability due to heat generation of the light source through the experimental results. The optical power intensity of the cuff, driven by 1mA current at 3 V, was 1.2mW·mm^{-2}, which was above ChR2 spiking threshold. The proposed optical cuff is expected to secure stable optical stimulation for motor units.

ACKNOWLEDGEMENTS

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