IMPLANTABLE DEVICES FOR OPTICAL NEURAL INTERFACES

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ABSTRACT

Optical neural control requires light delivery techniques dependent on the experimental goal and biological model. Several light sources and neural interfaces have been implemented featuring one or more of the following criteria: deep illumination, specific and/or comprehensive access, spectral control, temporal precision, high resolution patterning. We've developed 3D needle-type waveguide arrays as potentially compact neural interfaces for light transmission of as much as 90% of input light to depths >1 mm in tissue; various experimental paradigms are easily accommodated as the arrays can be modified to project different illumination volumes at defined depths, wavelengths and patterns.

INTRODUCTION

Optical neural control has gained interest over traditional electrical-based strategies. One category is optogenetics, where light-gated ion channels from the microbial opsin family are targeted in specific cells. Examples of opsins include channelrodopsin-2 (ChR2; responsive to blue light for excitation), halorhodopsin (NpHR; responsive to yellow light for inhibition), channelrhodopsin from Volvox carteri (VChR; activated by green light), and various ChR2 chimeras [1]. Optical excitation without genetic manipulation is achieved via infrared (IR) neural stimulation, where absorbed IR energy leads to neural activity [2].

Here, we review some of the current optical neural stimulation light delivery strategies as well as present 3D penetrating waveguide arrays that are appropriate for a wide variety of applications.

LIGHT DELIVERY REQUIREMENTS

Input wavelength and power

Input wavelength and power depends on the channelrodopsin type for optogenetics [1] and the tissue absorption spectrum for infrared stimulation [2].

Depth of access

Many studies in neuroscience are based upon stimulation in the neocortex. In mammals, cortex consists of up to six layers; thickness ranges from 0.5 to 1 mm in rodents to $\sim$2 mm in primates. Neuroprosthesis requires comprehensive access to peripheral nerves. For instance, the sciatic nerve innervates most of the hind limb and ranges in diameter from about 0.5 to 2 mm in rodents and 4 mm in cats, to 2.5 cm in humans. However, light penetration in tissue is limited by intrinsic absorption and scattering; penetration depth varies from 0.1 to 1 mm in the blue to near-IR window.

Illumination volume

Required stimulation volumes vary. For example, blanket illumination of CA1/CA3 regions of the hippocampus is needed for epileptiform activity inhibition [3]. Narrow (microns) beams are used for highly-selective orderly recruitment in neural circuits [2], [4], [5]. Deep stimulation is desired in signaling of cholinergic axons in all layers of the neocortex [6]. Wide-field shallow illumination is required for isolating stimulation between cortical layers.

Spatiotemporal patterning

Multisite millisecond and microscale resolution light delivery is important for mimicking natural neuronal activity [4], [5].

LIGHT DELIVERY TECHNIQUES

Deep-tissue stimulation

Light has most commonly been delivered *in vivo* via single optical fibers (tapered or through cannulae) [7], [8]. Fibers or diodes glued to linear arrays of 4-8 silicon (Si) probes were also used [9], [10].

Patterned stimulation

High-resolution patterned light has been delivered with digital micro-mirror devices (DMD) [4], liquidcrystal spatial light modulators (LC-SLM) [11] and acousto-optic deflectors (AOD) [12] integrated with a microscope setup. Gallium nitride micro light-emitting diode (μLED) [5] and micro-electrocorticography (μECoG) [13] arrays were also used. Note that these techniques are limited to surface illumination.

Deep-tissue patterned stimulation

3D penetrating waveguide arrays with multisite light delivery capabilities extend spatiotemporal patterning deeper in tissue [14]–[16].

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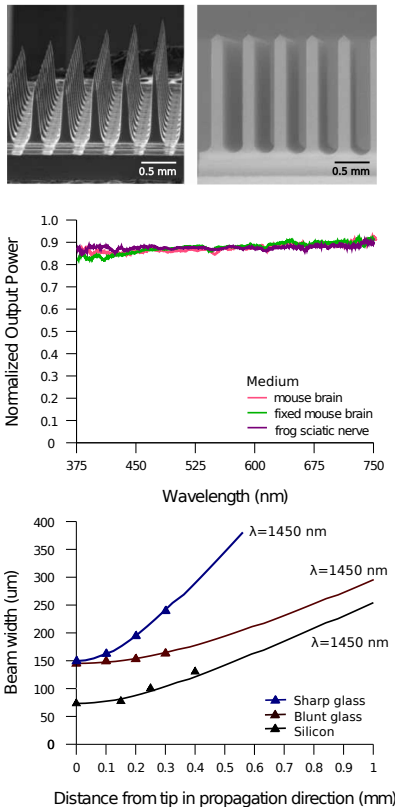

Fig. 1. Si (top left) and glass (top right) optrode arrays. ∼90% transmission through glass optrodes is almost independent of wavelength and tissue type (middle). Various output beam propagation profiles into mouse brain may be achieved to customize stimulation volumes (bottom); input is 1450 nm and optrodes are 1.5-mm long, blunt and sharp glass optrodes are 150-μm wide.

3D PENETRATING WAVEGUIDE ARRAYS

We have previously presented Si and glass waveguide (optrode) arrays based on the Utah Electrode Array (UEA) architectures [15]–[18]. Transmission efficiencies without in-coupling loss for 1.5-mm long Si and glass optrodes, shown in Figure 1, were as much as 39% and 90%, respectively. Optrodes are expected to operate under all modes of optical excitation, whether through visible, near infrared, or multi-photon excitation, where penetration depth is determined by optrode length. Figure 1 demonstrates that optrodes indeed provide high-efficiency light delivery in deep tissue regardless of wavelength or tissue type. Optrode manufacturing also allows changes in emission profile characteristics via changes in geometry to produce various stimulation volumes; examples are shown in Figure 1 for illumination in mouse brain. The optrode array is also adaptable for integration to any optical source including those with provisions for spatiotemporal (e.g., DMD, μLED) and multi-wavelength (e.g., blue and yellow light for simultaneous optogenetic excitation and inhibition) signaling, though the resolution achieved is limited by the number of optrodes.

CONCLUSION

The 3D optrode arrays introduce multiple transformative benefits relative to current optical approaches to tissue interactions in the contexts of fundamental neuroscience studies and neuroengineering applications. The optrode array architecture is perhaps the most flexible device in offering quasi-3D spatially-multiplexed optical stimulation, and it is based upon the UEA architectures that have been deployed successfully for decades in electrical stimulation and recording studies.

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