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ScienceDirect

Procedia Engineering 87 (2014) 1537 – 1540

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

Optrode for multimodal deep-brain infrared stimulation

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Abstract

In recent years, optical stimulation in neuroscience has emerged as an alternative to electrical stimulation. In this work, we present the concept and optical simulation of an optrode capable of delivering focused infrared light to brain tissue, while simultaneously recording electrical signals from the surrounding area. The system combines the advantages of silicon microfabrication and silicon's transparency in the near-infrared. For efficient coupling into the probe and controlling the illuminated volume in the brain, silicon microlenses were simulated using MATLAB. The lens system can focus light in 2-D, with configurable focal length and spot size.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

*Keywords:*optrode; neural probe; infrared neural stimulation; deep reactive ion etching; MEMS; silicon; electrophysiology; MEA

1. Introduction

Electrical stimulation is the gold standard for neural stimulation, however it has several drawbacks: external electromagnetic interference, artefacts in the recorded signals [1] and poor spatial selectivity due to the sparsely distributed activated neurons [2]. Nowadays, new methods are emerging for neural stimulation, most prominently optical stimulation.

Infrared neural stimulation has a number of advantages compared to electric stimulation. INS does not produce recording artefacts (cross-talk) in the electrical signal, allowing recording close to the stimulation in both space and time. The stimulated volume is controlled by the outcoupled intensity profile, which is a design parameter of a stimulation system. Compared to optogenetics, this method lacks of the sensitising step, which is both an advantage

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Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.592

and disadvantage in terms of experimental difficulty with respect to the greater control of optogenetic stimulation. The interest in this stimulation method is increasing, demonstrated by the various applications of INS [3,4].

A system which can integrate stimulation and recording capabilities can increase reproducibility and ease-of-use of experiments. Several solutions have been published so far [5,6], among that of Abaya et. al [7], where a multielectrode array capable of configurable optrode setup was demonstrated.

Infrared neural stimulation (INS) was discovered by Jonathon Wells and his team in 2005 [8]. The stimulation employed a pulsed infrared beam of varied wavelength and intensity to evoke action potentials. Later studies revealed that there is a wavelength-dependent radiant exposure range where action potentials are evoked without cell damage [9].

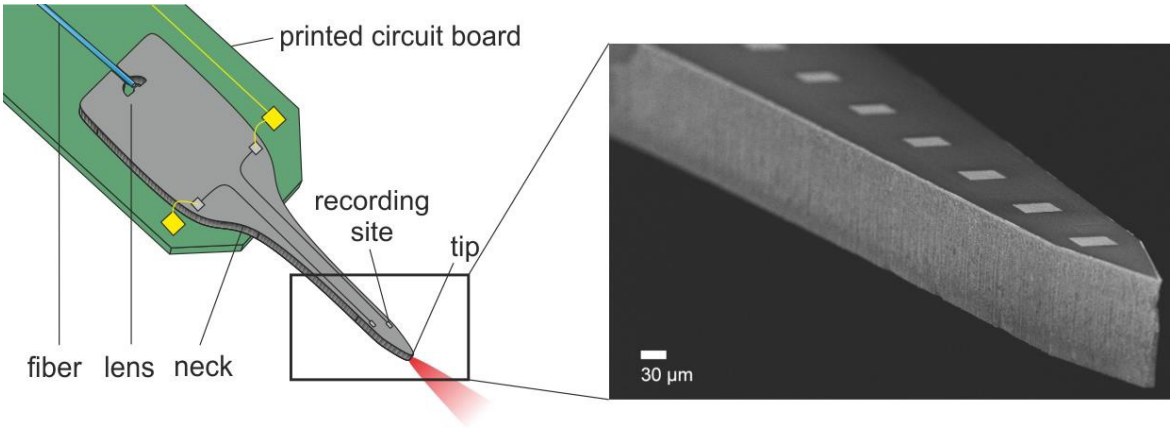

Fig. 1. Concept of the stimulation/recording system. Inset: SEM micrograph of the tip of the Si microelectrode.

The aim of this paper is to present a tunable optrode capable of integrated optical stimulation and electric recording. The optical stimulation parameters can be chosen in a wide range due to the use of lenses to shape the profile of the outcoupled light. The probe is realised using silicon microtechnology utilising deep reactive ion etching. This allows the fabrication of very precise shapes via lithography, which can be used to create microlenses. The probe fabrication process is detailed in a separate paper [10].

2. Methods

In order to design the optical parameters of the stimulation system, a custom ray tracing simulation was created in MATLAB, since the simulated volume is too large to simulate using meshing methods (finite element, finite difference). On the other hand, the applied wavelengths are small with respect to the probe geometry, so ray tracing is still a suitable approximation. A 2-D simulation is used, since the probe depth profile can be considered constant and thus there is no coupling between the (x, y) and z dimensions. In order to speed up the design, interactive lens placement and configuration was implemented to find a rough solution, and was locally optimised afterwards.

The optical system which can be created using deep reactive ion etching is similar to conventional lens systems, however the lenses are comprised of a single refracting surface. Since the main source of inefficiency in the system occurs when rays travel from the probe's silicon to the surrounding media (due to the large refractive index difference), only the contour of probe is utilised, no refractive surfaces are realised inside the probe.

The realised lens system has two purposes: efficient coupling from an optical fiber to the shaft of the probe and coupling out from the shaft. When coupling in, the lens-fiber distance is determined, so that the rays are approximately parallel and the spot on the tip is the smallest. Since there is some aberration due to the fiber being a line source in 2-D, a single mode fiber is used. The fiber – lens distance is kept small enough to exploit the whole cone hitting the probe. For coupling out, a parabolic mirror is used to direct the light in the vicinity of the shaft, stimulating sufficiently close to the recording sites.

3. Results

When evaluating the results of for the simulation, the main problem is the sensitivity to the placement of the fiber. While the parabolic mirror focuses the rays to the same point, the coupled out beam's angle changes to a large extent even in case of small difference in fiber position (Fig 2a). Since the critical angle is large, this implies that coupling out through a flat surface has a very limited acceptance angle.

Table 1. Examples of designed systems

Design note	Parabolic mirror focal point, vertex [µm]	Supplementary lens position, radius [µm]	Beam divergence half angle	Focus distance [µm]
No supplementary lens	(-300, 15000), (-300, 15150)	N/A	45°	N/A
Increased stability	(-300, 15000), (-300, 15150)	(-280, 15000), -20	10°	N/A
Increased beam divergence	(-260, 15000), (-260, 15120)	(-280, 15000). -20	30°	N/A
Focus near probe	(-285, 15000), (-285, 15130)	(-325, 15000), 50	7°	5
Focus far from probe	(-325, 15000), (-325, 15150)	(-325, 15000), 50	8°	45

To overcome these limitations, an additional lens is placed opposite to the parabolic mirror. This lens can be configured to act as a supplementary optical element.

A lens surface of negative radius can be used to greatly decrease sensitivity of the out-coupled rays to the position of the optical fiber. The lens transforms a large angle difference to a small position difference (Fig. 2b). By moving the lens further away from the parabolic focus point, the beam can be enlarged to illuminate a larger volume.

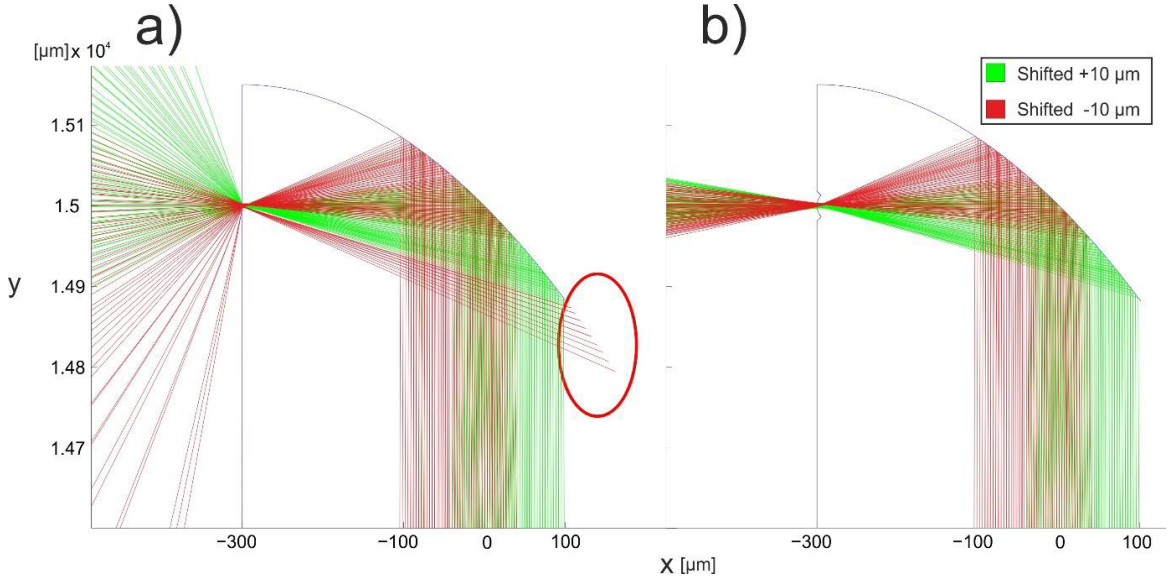

Fig. 2. Decreasing the sensitivity of the optical system: a) no supplementary lens; b) negative supplementary lens. Highlighted: rays reflected because of the small acceptance angle

A surface of positive radius can be used to create a configuration, where light is focused inside the tissue. Since the parabolic mirror introduces coma, the light is focused in to a small area rather than a point. This solution offers the opportunity to tune optical power to maintain stimulation threshold in the focused area. Changing radii of lenses can be used to set the position of area in focus (Fig. 3).

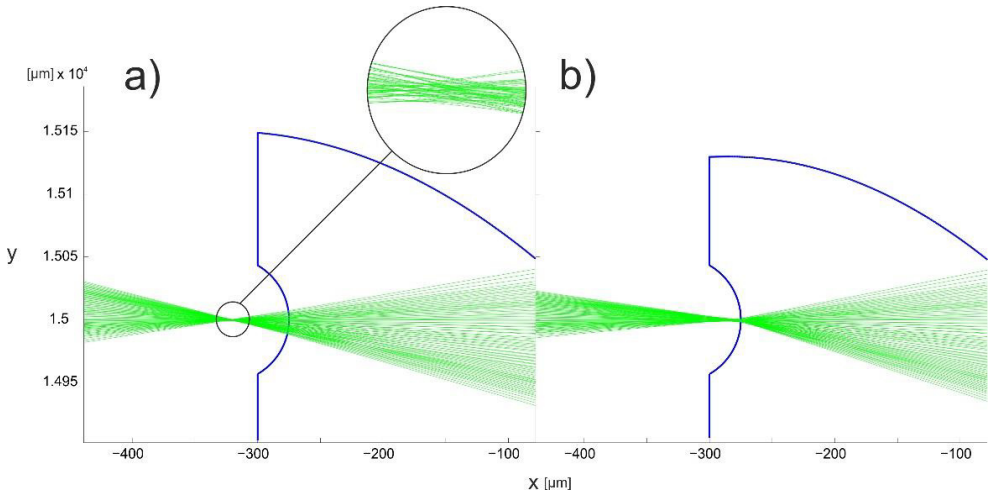

Fig. 3. Supplementary lens used to control focus distance from probe. a) 45 µm from probe b) 5 µm from probe. Inset: rays near focused area, showing aberration

4. Conclusion

In this paper we have shown the concept and simulation of a monolithically integrated lens system optrode. The parameters of the illuminated volume can be controlled in a wide range, making it suitable for a wide variety of experimental setups. The system is capable of focusing light inside brain tissue, achieving better spatial selectivity than conventional optrodes.

Acknowledgements

The authors are grateful to the supportive staff of MEMS Lab, Research Centre for Natural Sciences. Z. Fekete is thankful to the Postdoctoral Research Programme granted by HAS.

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