FIBERLESS MULTICOLOR OPTOELECTRODES USING INJECTION LASER DIODES AND GRADIENT-INDEX LENS COUPLED OPTICAL WAVEGUIDES

K. Kampasi[1], J. Seymour[2], K. Na[2], K.D. Wise[1,2] and E. Yoon[1,2]
[1]Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA
[2]Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, USA

ABSTRACT

We present an integrated optoelectrode that can deliver multicolor light from a waveguide coupled to an optical mixer. Such a device can provide spatial precision and scalability needed to enable independent activation and silencing of local neural circuits, allowing study of brain activities such as memory consolidation networks in the hippocampus.

We have demonstrated successful implementation of fiber-less optoelectrodes in a highly compact form by achieving efficient end-fire coupling between a side-emitting injection laser diode (ILD) and a dielectric channel waveguide via a Gradient-index (GRIN) lens. Total optical efficiency achieved for 405nm and 635nm wavelengths through an optical mixer was 12.2% and 5.4%, respectively. This approach also provides robust thermal packaging by efficiently managing thermal power loss of ILDs.

KEYWORDS

Optogenetics, Optoelectrode, Gradient-index lens, Injection laser diode

INTRODUCTION

Optogenetics is based on the genetic transfection of specific cell types to express photosensitive proteins, whose spiking activities can then be precisely controlled by light pulses of specific wavelengths. These light-responsive proteins, called opsins, are used to selectively turn neurons on or off with specificity and precise temporal resolution. Several groups have developed optoelectrodes to deliver optical stimulation light to deep brain structures while simultaneously recording neurons [1]–[4]. However, light sources placed on the surface of brain [3] or large fibers placed in the brain parenchyma a few hundred microns away from the recording sites [2] inevitably require excessive power to illuminate the large area of the brain and activate many untargeted neurons. A complete multi-color optical stimulation and electrical recording system was demonstrated using diode-coupled optical fibers attached to commercial multi-shank silicon probes [4]. However, the manual attachment of fibers glued to portable light sources on probe shanks can be highly variable and labor-intensive. Recently, our group reported the monolithically integrated optical waveguide in a multi-electrode array silicon probe, precisely delivering light in the proximity of recording sites [5]. But here, the waveguide was connected to an on-bench solid-state laser source through optical fibers. Direct assembly of light sources on the silicon probe back-end was also introduced [6], but the issue of potential device heating, which can cause thermal damage to the surrounding brain tissue during device operation, needs to be addressed. Also, a reliable coupling scheme should be optimized for efficient optical coupling between the light source and the waveguide.

In this work, we report a novel optoelectrode design using highly compact Injection Laser Diodes (ILD) coupling to monolithic waveguides on the silicon probes through GRIN lenses (Fig. 1). Our design offers not only an efficient optical coupling but also good thermal isolation to minimize heating of the device. Our approach leverages the continual advancement of optoelectronic industries that nowadays offer highly efficient, compact and multicolor light sources, adequate for stimulating various opsins. The integrated GRIN lens offers several advantages over the conventional approaches for compact optoelectronic designs. The GRIN lens can collimate and focus in-coupled divergent laser beam. It has flat coupling ends to facilitate efficient parallel end-butt coupling and simple packaging. The GRIN characteristics like Numerical Aperture (N.A.), working distances and magnification can be designed and optimized for device specifications (Table 1). Moreover, it provides good thermal isolation between the light source and the silicon probe.

The resulting optoelectrode system is scalable and enables precise stimulation or inhibition of the targeted neurons in a cell-specific manner. We present our device design, fabrication, characterization, simulation models and experimental data.

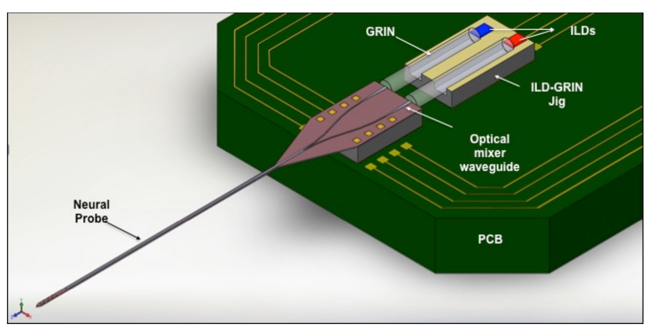

Figure 1: Schematic of the proposed optoelectrode.

DESIGN, FABRICATION AND ASSEMBLY

Optical design and ILD-GRIN coupling

The coupling efficiency between a divergent laser beam and a step-graded waveguide can be significantly enhanced by collimation-focusing lens mechanism, so called end-fire coupling. GRIN lenses form an ideal choice to implement end-fire coupling. Since the lens performance depends on a continuous change of the refractive index within the lens material, the light rays can be continuously bent within the lens until they are finally focused on a spot (Fig. 2). Flat optical end surfaces are used for better coupling and the lenses can be made down to 250µm in diameter. This simple geometry in a miniaturized size allows for a very elegant optical coupling and assembly solution for microscale optoelectronic devices. In addition, the option of varying the lens length/pitch offers an enormous flexibility to fit the lens parameters, such as focal length and working distances, to meet the design requirements.

We chose a full pitch GRIN of N.A. equal to 0.4. A full pitch GRIN gives a focused beam at the GRIN output because a beam travels exactly the full cycle of a sinusoidal period in that distance to achieve beam focusing on the other end. GRIN parameters, such as working distances (L1, L2) and mechanical length (Z), were optimized (Table 1) to match the aspect ratio of the device design.

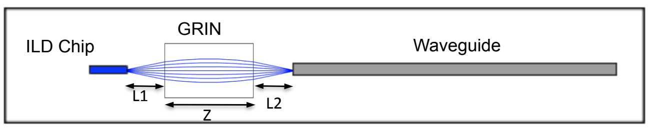

Figure 2: End-fire coupling between ILD and waveguide using a GRIN lens. GRIN lens gives an efficient coupling by sequential collimation and focusing of light rays within the lens.

GRIN Parameter	Equation
Length, Z	$2\pi P / \sqrt{A}$
Refractive index at radial distance r, N	$N_0 (1 - (A/2)\, r^2)$
Angular magnification, M	$n \cos(Z\sqrt{A}) - N_0 L1\sqrt{A}\sin(Z\sqrt{A})] / n$

Table 1: Analytical design equations for GRIN, where $\sqrt{A}$ is lens gradient, N_0 is lens index at the axis, P is lens pitch, and L1 is object distance.

Our ILD-GRIN coupled waveguide mixer design is based upon analytical optical equations and Zemax ray trace models. The parametric ray trace model was developed to explore the design space in full depth. Fig. 3(B) illustrates the optical system model, which consists of two ILDs (405nm and 635nm), coupled to the two arms of a 2mm-long optically optimized mixer via their respective GRIN lenses. The mixer arms are tapered down from a width of 50µm to 30µm and finally coupled to a 5 mm-long straight waveguide with 30µm x 7µm cross-section. The mixer geometry was optimized using analytical equations for dielectric optical bend waveguides to minimize radiation losses and mode conversion losses. The optical transmission properties of the optoelectrode were quantified by determining optical loss in each part of the system, that is, coupling losses at the ILD-GRIN and GRIN-waveguide coupling joints, respectively, radiation loss in the bends of the optical mixer, and scattering and absorption losses through the waveguide.

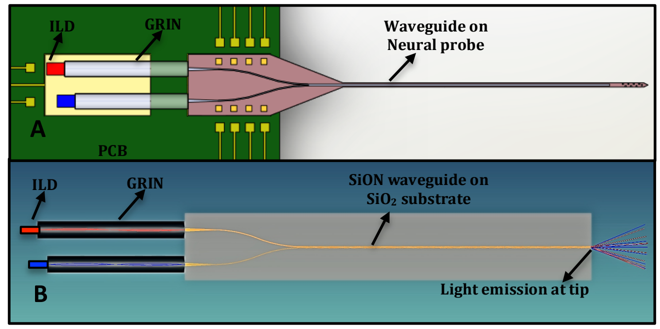

Figure 3: Top-down view: (A) Design schematic and (B) Zemax model of ILD-GRIN coupled optical mixer waveguide assembly.

Thermal heat transfer model

There are two requirements for successful device thermal design. First, the temperature increase of the tissue should be no more than 1°C to prevent thermal damage to the tissue. Second, the temperature of the ILD junction should be less than its thermal maximum (80°C) to prevent permanent diode damage.

We have chosen to use the ILDs with low optical power output (5mW) because of high system efficiency. This is critical when scaling an optoelectrode system up to 8 or 16 independent sources for multi-shank probes. Based on our simulation results from COMSOL Joule Heat Transfer model, we should generate at least 100µW optical power at 7µm x 30µm waveguide output to stimulate 200µm of tissue in depth. Our model indicates that we can easily achieve our light output goals while operating the ILDs at an average electrical power of 120mW. The model simulates the temperature rise at tissues around the neural probe (assuming any heat rise at silicon would rapidly dissipate into the tissue) and the results show that we can safely turn-on 4 ILDs at 20% duty cycle for 42 continuous seconds, which is more than adequate for various optogenetic applications [6]. The results also show that our design increases the continuous device operation time by at least 10 times as compared to conventional end butt-coupled ILD-waveguide design approach.

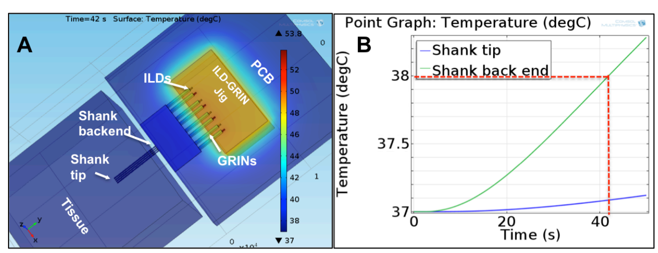

Figure 4: COMSOL Heat transfer model showing surface temperature rise of multi-shank optoelectrode components and tissue when 4 ILDs are operated at 20% duty cycle power for 42 continuous seconds. GRIN lenses help to thermally isolate light sources from the silicon probe.

Device fabrication

The fabrication process used here is similar to that of conventional Michigan probes [7]. The waveguide fabrication is extremely precise and customizable, which can be integrated onto a 22µm-thick neural probe for monolithic integration. The fabricated waveguide has a 7µm-thick and 30µm-wide a silicon oxynitride core (RI=1.52) with a 2µm-thick silicon dioxide cladding (RI=1.46), achieving a waveguide N.A. of 0.42. The stress of the dielectric waveguide films is compensated with an LPCVD-grown dielectric stack.

Silicon oxynitride is a very attractive material for integrated biomedical optics. It possesses excellent optical properties and is resistant to saline and enzymatic environments, providing negligible *in vivo* degradation. It can be deposited with refractive indices varying over a wide range (1.45-2) by tuning the reaction gas compositions during deposition. Fig. 5 shows the fabrication and assembly process of optoelectrodes.

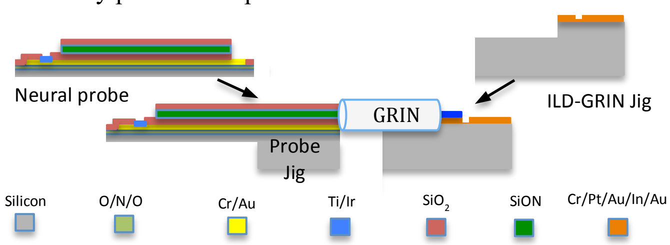

Figure 5: Fabrication of final device consisting of neural probe and ILD-GRIN jig coupled via a GRIN lens.

ILD packaging

An important element of laser diode packaging is the die bonding of the laser chip to a substrate. As ILDs generate large amount of heat fluxes that can adversely affect their performance and reliability, a thermally effective packaging solution is required to remove the excessive heat generated in the ILD to its surroundings as quickly and uniformly as possible. Thermal properties of laser diodes have critical effects on many device characteristics, affecting wavelength, maximum output power, threshold current, slope efficiency, and operating lifetime. Thus, development of ILD packaging forms an important technological challenge for achieving high performance and is a critical step for reliable high yield production.

We implemented In-Au eutectic bonding at 200^0C to achieve epi-down bonding of ILDs on ILD-GRIN jigs. In epi-down configuration, the diode is flip-chipped with anode side facing down, so that proximity of the heated active region is close to the heat sink surface. This allows for more rapid heat dissipation from the active region to the heat sink [8]. We chose indium for low-temperature diode bonding since it has a lower melting point of 156 °C (even lower than melting temperature of tin, 232 °C). Gold serves a good parent metal because it does not form native oxide and is therefore easily wet by molten indium without flux. This enables void-free bond-joint formation with high thermal conduction during diode operation.

Device assembly

Given the microscale nature of the devices, significant effort was directed towards efficient optical coupling, assembly and bench testing methods. The first step in constructing the optoelectrode assembly was to flip-chip ILDs on ILD-GRIN jigs (Fig. 6B). Then the GRIN lens were placed in a groove positioned in front of the ILDs, such that one end of the lens faces towards ILD emission point and another end of the lens faces towards distal end of the optical mixer waveguide. The light output from the ILD-GRIN assembly was directed and focused into the input arms of the waveguide mixer on the silicon probe. All optical coupling junctions were secured with a drop of index-matching epoxy to reduce Fresnel losses at the interfaces. In our GRIN design, fabrication techniques and assembly setup have been characterized to maximize alignment tolerance and minimize angle deviations.

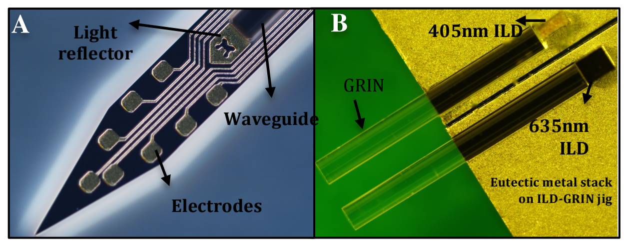

Figure 6: (A) Fabricated neural probe with a Buzsaki 8-electrode configuration (B) Fabricated jig (silicon heat sink with eutectic metal stack on top) with the assembled ILD and GRIN components.

RESULTS AND DISCUSSION

ILD characterization

We have achieved wall-plug efficiency of 11.8% (for 405nm) and 9.4% (for 635nm) for packaged ILDs via epi-side down flux-less In-Au eutectic bonding (Fig. 7). The measured diode efficiency is in agreement with the previous publication, which reported more than 20% improvement in optical power and 30% reduction in junction temperature and thermal resistance in epi-down mounted lasers compared to epi-up mounted lasers. [8]

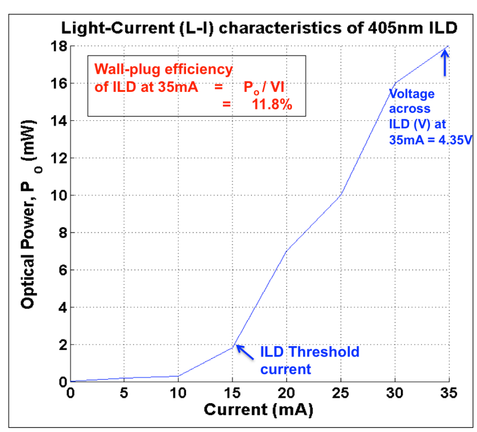

Figure 7: Light output power-current (L-I) graph for 405nm ILD.

Optical system characterization

Light propagation of the assembled optoelectrodes has been shown in Fig. 8. The target light intensity threshold for neural activation is 1 mW/mm^2 for Channelrhodopsin (ChR2) and 10 mW/mm^2 for Halorhodopsin (NpHR) for optogenetic studies [6]. We surpassed this target and measured the maximum optical irradiance of 10476 mW/mm^2 (12.2% efficiency) for 405nm and 690 mW/mm^2 (5.4% efficiency) for 635nm, respectively, at the maximum diode current ratings (Fig. 8).

Using optical modeling in Zemax, we also simulated alignment tolerances for ILD, GRIN and waveguide in detail. We can tolerate GRIN misalignment up to +/-25µm with only 10% optical loss in all three axes; and our measurements show a good agreement with simulations.

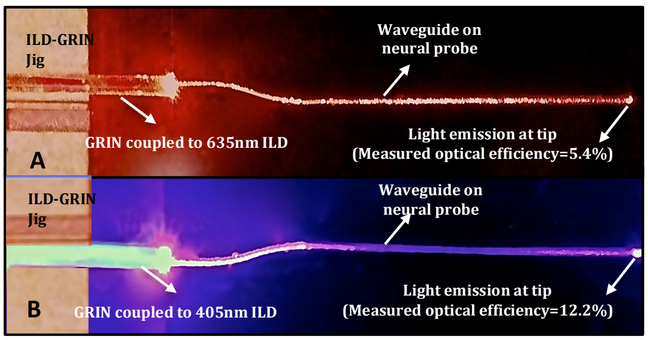

Figure 8: Actual prototyped system at (A) 635nm and (B) 405nm wavelength, respectively.

CONCLUSION

We have successfully fabricated, assembled, and characterized the first fiberless multicolor ILD-GRIN coupled optoelectrodes. Optimal thermal packaging was achieved by efficient ILD assembly and thermal isolation from GRIN lenses. The 7um-tall dielectric optical mixer waveguide, monolithically integrated onto Michigan probe, enabled light wavelength switching at a common waveguide port. The light intensities, 10476 mW/mm^2 for 405nm and 690 mW/mm^2 for 635nm, were sufficient to optically stimulate local populations of genetically targeted neurons.

The fabricated optoelectrodes can be utilized in a wide range of optogenetic experiments, not only illuminating different wavelengths at a given stimulation site but also synchronously stimulating multiple optical sites along the shank length. Such multiple wavelength stimulation capability allow for manipulating multi-opsin expressing local neural populations.

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CONTACT

*K. Kampasi, tel: +1-7347301787; kkomal@umich.edu