Microelectronic Engineering 192 (2018) 88–95

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Research paper

Laser micromachining of tapered optical fibers for spatially selective control of neural activity

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ARTICLE INFO

Article history:
Received 21 October 2017
Received in revised form 6 February 2018
Accepted 8 February 2018
Available online 09 February 2018

Keywords:
Direct laser writing
Tapered fiber
Coupling angle
Ablation
Laser micromachining

ABSTRACT

Tapered and micro-structured optical fibers (TFs) recently emerged as a versatile tool to obtain dynamically addressable light delivery for optogenetic control of neural activity in the mammalian brain. Small apertures along a metal-coated and low-angle taper allow for controlling light delivery sites in the neural tissue by acting on the coupling angle of the light launched into the fiber. However, their realization is typically based on focused ion beam (FIB) milling, a high-resolution but time-consuming technique. In this work we describe a laser micromachining approach to pattern TFs edge in a faster, more versatile and cost-effective fashion. A four-axis piezoelectric stage is implemented to move and rotate the fiber during processing to realize micropatterns all-around the taper, enabling for complex light emission geometries with TFs.

1. Introduction

The advent of optogenetics to trigger neural activity in vivo [1] has generated a new class of hardware technologies to better interface with the brain [2–6]. Most of these methods aim at overcoming the limitations given by light delivery based on flat-cleaved optical fibers, i.e. producing severe implant damage and illumination of a small and fixed brain volume. Promising approaches to reduce invasiveness and to dynamically switch illumination between several regions of the brain are represented by multiple micro light emitting diodes (μLEDs) [7–9], holographic illumination via head-mounted objectives [10] GRIN lenses [11] and tapered optical fibers (TFs) [12–14].

TFs are advantageous because they can generate both wide-volume light delivery and site-selective optical control of neural activity [15,16]. Also, the photonic properties of the fiber taper can be exploited to engineer minimally invasive multipoint emitting tapered fibers (MPFs) that can switch illumination between different, localized regions of the brain [13–15]. This has been obtained by coating the tapered region with a reflective metal layer and then opening micrometer-sized apertures with Focused Ion Beam (FIB) milling to define several light-emitting windows [13]. Being placed at specific sections of the taper, each of these windows can be independently activated by exploiting mode division de-multiplexing [14]. This, in turn, results in a single device that provides for reconfigurable light-delivery in multiple brain regions [14].

However, the fabrication process to obtain MPFs presents a critical step: the realization of optical windows on the non-planar, small curvature radius surface of the taper. Focused Ion Beam (FIB) milling has been previously employed as it allows fabrication with a resolution of a tens of nanometers [13], much lower than the taper's radius of curvature where the patterning is usually performed (~5 μm) [13,14,17]. However, FIB milling becomes not practical for the realization of structures exceeding a few hundreds of micrometers, due to (i) the long processing time and (ii) the need to stitch geometries exceeding the available field of view. While this latter induces unavoidable imperfections in the milled geometry, the time required to mill large patterns limits the overall throughput. Indeed, the realization of a $20 \times 20 \mu m^2$ optical window can require up to 0.5 h of continuous milling, while a 3.5 h processing time is required for realizing a taper with 7 windows arranged over a 1 mm length [13]. These drawbacks, in combination with the high cost of the equipment to implement FIB milling, represented an obstacle to the potential diffusion of the MPF technology.

This work proposes laser micromachining as an alternative to FIB milling for faster, more versatile and cost-effective realization of micro-patterns on the highly-curved surface of TFs' edge. With respect to other Direct Laser Writing (DLW) systems used to realize patterns on non-tapered optical fibers [18], a 4-axis (x-y-z-Φ) piezoelectric stage is implemented to have the fiber rotating around its axis during

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https://doi.org/10.1016/j.mee.2018.02.010

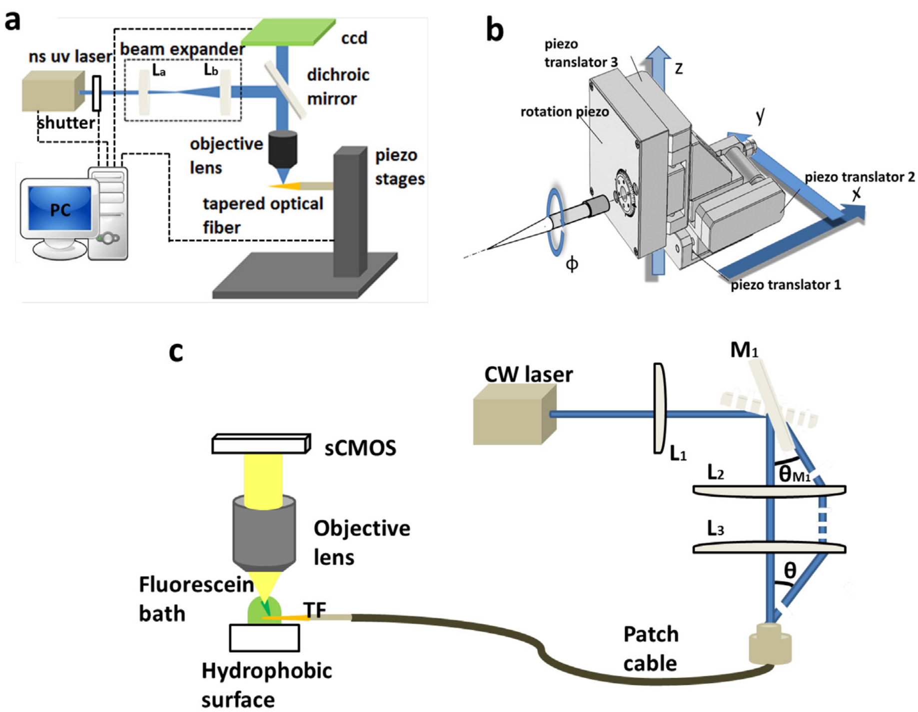

Fig. 1. (a) Diagram of the DLW system. A UV ns pulsed laser is expanded by lenses L_a (focal length f1 = 60 mm) and L_b (f2 = 250 mm), reflected by a dichroic mirror and focused by a microscope objective on the taper edge. A CCD camera captured a live view of the TF mounted on a computer-controlled x-y-z-φ piezoelectric (see axis definition in Fig. 1b) (b) Schematic of the piezoelectric stage. Three single-axis translation stages were combined with a rotational stage to control the movement of the TF that was mounted coaxially to the rotation stage. (c) Optical setup used to change light injection angle θ while observing emission from the taper in a PBS: Fluorescein solution with a sCMOS camera.

exposure to a UV ablation beam. This approach enables the realization of complex geometries all around the taper, extending the possible light emission patterns that can be generated with TFs.

2. Materials and methods

TFs were provided by OptogeniX (www.optogenix.com) and were realized starting from 0.39 NA optical fibers with 200/225 core/cladding diameters. To coat the TFs with a ~600 nm-thick aluminum (Al) or gold (Au) layer, the chamber of a thermal evaporation system was modified by introducing a stepper motor and a custom holder to have several fibers rotating during the evaporation process (see scheme in Fig. S1) [17].

Patterns on the metal coating were obtained with the setup displayed in Fig. 1a, using a 10 ns-pulsed laser (Spectra Physics Explorer, $\lambda = 349$ nm, tunable repetition rate in the range 1 Hz–4 MHz) at $\lambda = 349$ nm, which was expanded with two converging lenses (L_a and L_b with focal length $f_a = 60$ mm and $f_b = 250$ mm, Thorlabs LA1401-A and LA1301-A, respectively). The laser beam was focused on the sample by a 0.90NA microscope objective (Olympus, Uapo340, 40×) with a theoretical waist of ~485 nm. The TF was connected to a four-axis piezo mover (PI GmbH, Q-545.140 and U-628.03) by a custom fiber holder, allowing for translation along x, y and z and rotation around the taper axis (see Fig. 1b). The overall system was controlled by LabView.

Light emission from the patterned TFs was tested with the optical setup depicted in Fig. 1c: a 2 mW $\lambda_0 = 473$ nm beam (Laser Quantum Ciel 473) passes through lens L_1 (focal length $f_1 = 100$ mm, Thorlabs LA1050-A) and is focalized on the surface of a galvanometric mirror M_1 (Sutter RESSCAN-MOM); light reflected from M_1 is then collimated by lens L_2 ($f_2 = 100$ mm, Thorlabs AL50100-A). The laser beam is focused by lens L_3 ($f_3 = 32$ mm, Thorlabs AL4532-A) into the fiber with an input coupling angle $\theta = \tan^{-1}(f_2 \cdot f_3^{-1} \cdot \tan\theta_{M1})$ depending on the deflection θ_{M1} induced on the beam by the galvanometric mirror inclination. TFs were connected to the setup by a ferrule-to-ferrule butt coupling and immersed in a PBS:fluorescein bath. The fluorescence images were collected by an optical microscope (Scientifica Slicescope) equipped with a 4× objective lens (Olympus XLFluor 4×/340) and a sCMOS sensor (Hamamatsu ORCA-Flash4.0 v2). Emission profiles were evaluated over a line placed next to the taper. The extinction ratio was defined as the ratio between light intensity emitted from the active window divided by the light intensity emitted from a non-active window.

3. Results

3.1. Direct laser writing on a tapered optical fiber

The DLW experimental setup developed in this work is summarized in Fig.1a. The pulsed $\lambda = 349$ nm laser was directed to the back aperture of the 0.90 NA objective, which focuses the radiation on the TF and locally ablates the metal coating. A software-driven shutter was used to control exposure time. The x-y-z-Φ piezoelectric stage moves the tapered fiber with respect to the objective's focal spot (Fig. 1b). Control on Φ allows to realize patterns all around the tapered fiber and to precisely move the taper surface following the designed patterns. Eccentric fiber rotations can be compensated by fine adjustment of the y-z position, therefore assuring an accurate alignment between the point to be ablated and the objective focal spot, apart from the small angle in the x-z plane introduced by the waveguide narrowing. Both Au and Al metal coatings were tested. Al was chosen by virtue of its high reflectivity at both $\lambda = 473$ nm and $\lambda = 593$ nm, two wavelengths commonly used to excite or inhibit action potential generation [19], although it is not suitable for chronic implants since it induces neurotoxicity by accelerating oxidative damage to biomolecules [20]. Au can instead be used by virtue of its higher biocompatibility, although it has a lower reflectivity at 473 nm and a higher cost of the raw material.

To estimate the minimum feature size that the system can ablate on the fiber edge, single-point exposure was performed as a function of