Production of a microfluidic random laser using ultrashort laser pulses

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***Abstract*— A random rhodamine laser system is produced on board of a femtosecond laser machined microfluidic system. When pumped by a nanosecond pulsed laser beam at 532 nm, laser emission at 610 nm is observed together with the linewidth narrowing typical of random lasers. The system can be easily integrated as an optofluidic component into microfluidic circuits for assessment of optical parameters on board of the lab-on-chip.**

Keywords—microfluidics, lab-on-chip, random lasers

I. INTRODUCTION

Optofluidics is the combination of optical components and microfluidic devices on a single platform with the purpose of creating an integrated device capable of executing all necessary functions for biosensors, molecular imaging tools, energy production, lab-on-chips, and many more. The optics part is responsible for assessment and quantification of optical parameters of chemical and physical reactions such as process speed and temperature. Many of these optical assessment methods require directional light beams to cross microfluidic channels and reservoirs in order to collect the necessary optical parameters. Traditionally these light sources are handheld LEDs or semiconductor lasers and are external to the microfluidic device, such as the ones already used in odontological applications [1], [2]. However, ideally these light beams are generated by on-board sources and are portable and sufficiently cheap to be incorporated into disposable devices for sanitary reasons. Such on-board directional light beams can be generated e.g. by waveguide lasers which would require high-end fabrication methods and ultrapure materials to create the high-quality optical finish necessary (e.g. mirrors). Random lasers on the other hand work by receiving feedback from scattering centers and are cheap and disposable.

On the other hand, random lasers suffer from low optical efficiency and omnidirectional emission with very low spatial coherence. Therefore, potential applications of random lasers in lab-on-chip applications require optimization of their optical properties.

Our group has developed several strategies to separately increase optical efficiency and decrease laser threshold and beam divergence. In a recent work we achieved a random laser with 68 mrad beam divergence (M2~10) and one percent optical efficiency [3]. In another publication we achieved 50% slope efficiency and 40% optical efficiency [4] or random laser tunability [5]. In yet another publication we achieved threshold of laser oscillation with 1 μJ of pump laser energy [6]. For each application we may therefore direct the optimization of the random laser towards its specific purpose whilst maintaining its attractive feature of having a simple, injectable on-board light source.

Similar to reference [3], in this work we employ samples operating in the ballistic or weakly scattering regime, given that the transport mean free path is bigger than the absorption length of the sample, meaning that within the active volume the photons have little chance of scattering, whereas outside the active volume they may become absorbed.

In its final version, this microfluidic circuit will be used in enzyme-linked immunosorbent assays (ELISA).

II. FABRICATION OF THE MICROFLUIDIC DEVICE

A random laser system was produced on the surface of a BK7 optical glass plate by machining with a beam of ultra-short laser pulses. This machined plate with channels and reservoir for storage of the active laser medium was mounted in the form of a microfluidic circuit as shown in figure 1.

The machining of the random laser was done with the use of a Ti:Sapphire laser system, model "PRO 400" from Femtolasers Produktions GmbH, amplified by the "Femtopower Double 10 kHz" system, also from Femtolasers. The output laser beam is polarized, with emission centered at 800 nm, pulse length of 30 fs, maximum energy per pulse of 200 μJ and 10 kHz of repetition rate. For the machining process, the laser beam is injected into the workstation model "PRJ0221" from Lasea Laser Engineering Applications, which guides the beam to the focusing lens.

In our system, the focal point remains stationary and the sample is moved by a three-axis translator stage of the Aerotech ANT130 series with accuracy of ± 10 nm. The programming of movements is done through the software Mastercam 2018 - Mill with post processor dedicated to the laser system. To focus the laser beam, a doublet lens with focal length f = 20 mm was used, which produced a focal point with a calculated diameter of 3.6 μm.

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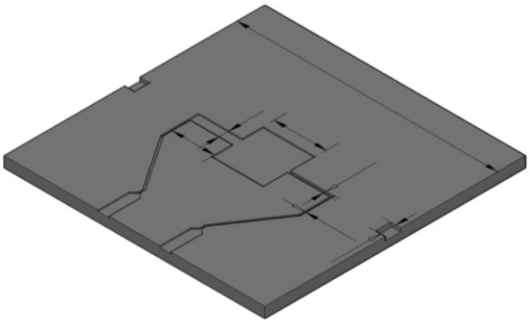

Fig. 1. Schematic of the random laser machined on a glass plate.

The machining of the glass surface was done from a 2D drawing of the desired structure shown in figure 1. A program cadcam - MasterCam 2018 was used in the excavation mode to machine and deepen the structure with the desired dimensions and optimized process conditions. The 3.6 µm diameter focal point swept the surface of the interior of the drawing in parallel lines until it was completely filled. This requires choosing the energy and repetition rate of the laser pulses, and programming the effective diameter of the tool, the speed of this focal point, and the distance between the machined lines. The choice of these parameters is made in order to obtain the highest efficiency in the extraction of the material, with high quality of finishing of the lateral surfaces and the bottom of the structures. High energies ablate more material per shot, but cause defects in the bottom of the machined surface, such as microcracks, melting and spalling. Thus, the highest energy that still does not cause these damages is used during the procedure.

Once the process energy is chosen, the diameter of the crater formed by a laser pulse is measured and used as the effective diameter of the machining tool, which is an important parameter in the cadcam program. With this diameter, the process speed is chosen for which a 4-pulse overlap is obtained at the maximum laser system rate, that is, 10 kHz.

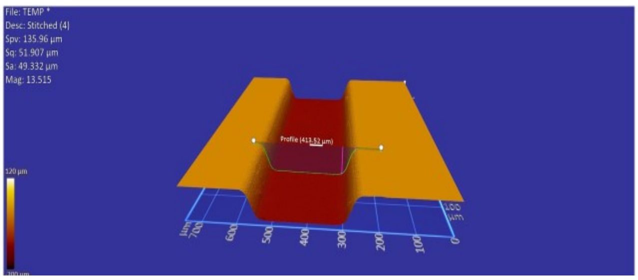

Fig. 2. Optical profilometry of a 300 µm wide and 120 µm deep channel machined in BK7 with ultrashort pulse laser.

All these parameters were developed in previous works of the group [7] and led to a very good edge definition with the bottom surface and no defects. Measured roughness is Ra ~ 0,2 µm. The desired depth is obtained through successive machining of layers. The depth of the layers is measured experimentally in an optical profilometer (Zygo model Zgage) and is repeated as many times as necessary to reach the desired depth. This parameter also feeds the cadcam program, which corrects the positioning of the focal plane each time a new layer is started. An optical profilometry of a typical microchannel is shown in figure 2.

The structure of the machined system consists of a central reservoir of 5.0 x 5.0 mm^2 and 120 µm depth, a channel of 4 mm in length and 300 in width on one side and another channel of also 4 mm in length and 1.0 mm in width on the other side; both channels are 120 µm deep. This structure is sealed by a 300 µm thick flexible sheet of the PDMS polymer (polydimethylsiloxane) which is pressed by another BK7 glass plate using a metal structure as shown in figure 3. Smaller channels are used for coupling the system to external syringes where the liquid of the active medium and connectors are located.

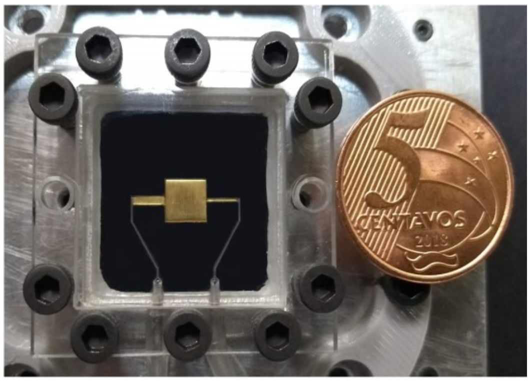

Fig. 3. Mounted microfluidic random laser circuit

Prior to assembly, the machined surface of the reservoir and channels were coated with a gold layer of 170 nm thickness. This process was done in a ACE200 model Leica sputtering system.

After sealing, the reservoir and channels are filled with the active laser medium, which in this case was a 1 mMol rhodamine B46 solution in ethanol. Scattering center concentration (TiO_2 of 250 nm diameter) is 1x10^{10} cm^{-3}, causing a scattering mean free path of the order of 1 mm.

III. PUMP LASER SET-UP

The central reservoir of the microfluidic device is pumped from the top at 532 nm by an optical parametric oscillator with a repetition rate of 10 Hz, a pulse duration of 9 ns and a beam size of 3 mm diameter. Using a cylindrical lens of 150 mm focal length placed in the beam's path, a beam waist was formed in the form of a stripe with a width of approximately 300 µm and a length of 3.2 mm. This stripe of pump light was placed, by means of a plane steering mirror that directed the laser beam downwards into the device and along the horizontal axis of the reservoir shown in figure 3 and aligned with the channels. In this way, the directional laser emission, which is preferentially along the stripe direction, was effectively collected by the channels that acted as waveguides collimating the emission into a laser beam. For optimum output power the pump stripe was partly overlaid with the output channels of the reservoir in a manner that about half of the pump laser focus was inside the reservoir and the other half in the channel. The amount of overlay with the channels depends on the concentration of scatterers in the solution. The more scatterers the closer the pump focus needs to be to the laser output in order to not become dispersed.

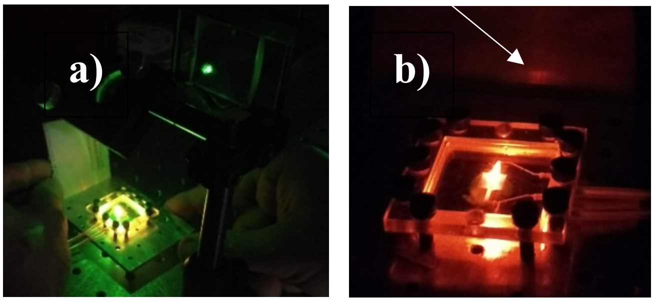

Fig. 4. Photos of the random laser under operating conditions. Left photo: 532 nm pump beam hitting the random laser. Right photo: laser emission captured using a cut off filter for the green wavelength.

IV. Results

In figure 4 we can observe the emitted laser light of the optofluidic device. The arrow in figure 4b shows the laser beam captured at a distance of 8 cm from the microfluidic device. There exists some dispersion in the observed laser beam because the lateral wedges of the glass plate that contained the microfluidic circuit are not polished and quite rough.

For laser analysis a fiber optic cable was positioned at location of the laser beam indicated by the arrow in figure 4b. The output power spectrum was analyzed in terms of its width at FWHM and its peak output power. The results are shown in figure 5. A clear laser threshold can be observed at about 0.45 mJ of pump energy accompanied by laser linewidth narrowing down to 4 nm.

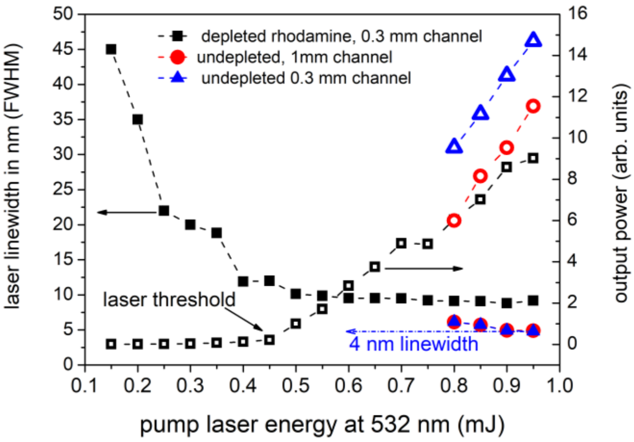

Fig. 5. Laser linewidth (left axis) narrowing as a function of pump power (full markers) and output power (right axis) as a function of output power (open markers) are shown for the case of depleted and undepleted rhodamine. Triangles: 1mm channel output. Spheres: 0.3 mm channel output.

Figure 5 demonstrates the usefulness of a microfluidic random laser. After several minutes (10 – 15 min) of operation, the rhodamine becomes depleted at high pump powers and decreases in output power. At the same time the linewidth becomes larger. This is easily compensated for by a small flux of new, undepleted rhodamine through the microfluidic channels and the output power increases again (open triangles).

When comparing the 0.3 mm wide channel with the 1 mm wide channel, a higher output power is observed for the smaller channel whereas linewidth narrowing remains the same, decreasing from 45 nm at low pump powers to 4 nm at high pump powers. The higher output power of the smaller channel may be explained by the better collimation of the smaller channel. Figure 6 demonstrates the emission spectra below threshold (0.3 mJ of pump power) and linewidth narrowing above threshold (0.7 mJ of pump power).

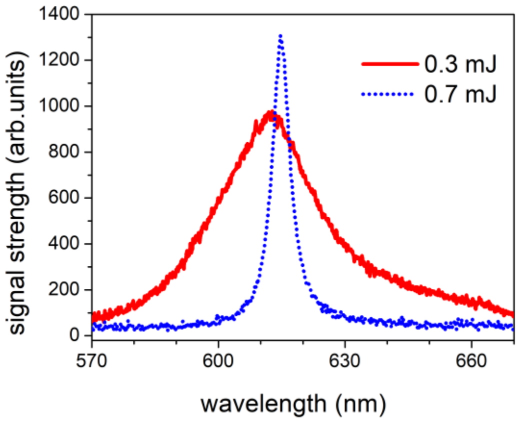

Fig. 6. Emission spectra of the microfluidic random laser below (0.3 mJ) and above (0.7 mJ) threshold.

V. Conclusions

We demonstrate an optofluidic random laser based on a femtosecond laser machined microfluidic system capable of generating a collimated output beam which can be used for the assessment of physical and chemical parameters of integrated devices such as lab-on-chips. The random laser shows the traditional laser characteristics of laser linewidth narrowing and laser threshold indicating a high participation of stimulated photons (~50%) and a good degree of coherence of the output beam.

As demonstrated, degradation of the dye is resolved by a small flux of new dye in order to recover original output power. The mechanics to provide for such a flux should pose no additional problems because, in general, microfluidic devices already need to be surrounded by pumps and circulators in order to keep on-board reactions and processes going.

Finally, microfluidic random lasers are cheap and easily integrated into disposable devices made of glass or plastics, which allows for true point-of-care applications.

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