A coupled cavity micro-fluidic dye ring laser

M. Gersborg-Hansen *, S. Balslev, N.A. Mortensen, A. Kristensen

MIC – Department of Micro and Nanotechnology, Technical University of Denmark (DTU), Building 345 East, Ørsteds Plads, Kongens Lyngby, DK-2800, Kongens Lyngby, Denmark

Available online 4 January 2005

Abstract

We present a laterally emitting, coupled cavity micro-fluidic dye ring laser, suitable for integration into lab-on-a-chip micro-systems. The micro-fluidic laser has been successfully designed, fabricated, characterized and modelled. The resonator is formed by a micro-fluidic channel bounded by two isosceles triangle mirrors. The micro-fluidic laser structure is defined using photo lithography in 10 μm thick SU-8 polymer on a glass substrate. The micro-fluidic channel is sealed by a glass lid, using PMMA adhesive bonding. The laser is characterized using the laser dye Rhodamine 6G dissolved in ethanol or ethylene glycol as the active gain medium, which is pumped through the micro-fluidic channel and laser resonator. The dye laser is optically pumped normal to the chip plane at 532 nm by a pulsed, frequency doubled Nd:YAG laser and lasing is observed with a threshold pump pulse energy flux of around 55 μJ/mm². The lasing is multi-mode, and the laser has switchable output coupling into an integrated polymer planar waveguide. Tuning of the lasing wavelength is feasible by changing the dye/solvent properties.

Keywords: Micro-fluidic dye laser; Rhodamine 6G; SU-8; PMMA

1. Introduction

Integrable lab-on-a-chip light sources are essential for on-chip spectral analysis of chemical samples [1]. For these applications dye lasers are of particular interest due to the possibility of tuning the wavelength in the visible range. Micro-fluidic dye lasers have recently been demonstrated by glass [2] and polymer [3] micro-fabrication and tunability has also been reported [4]. Polymer-based laterally emitting single-mode dye-lasers were reported recently [5]. The latter implementation is advantageous due to the direct integrability with lab-on-a-chip systems without additional hybridization steps [6].

In this paper, we present a new type of polymer-based laterally emitting micro-fluidic dye laser utilizing coupled cavities. Lasing is achieved with a new cavity design (see Fig. 1) relying on total internal reflection at the interface between the polymer
SU-8 with refractive index \( n_1 = 1.59 \) and the surrounding air at an incidence angle of 45°. Bleaching of the dye is avoided by a regenerating flow through the micro-fluidic channel. In this way, the dye may also be dynamically changed, enabling real-time tunability of the laser. Furthermore, the output coupling is switchable.

In the following sections, we describe the resonator structure, the fabrication, and the optical characterization. We also address the cavity mode spacing by a simple model and finally conclusions are given.

### 2. The resonator structure

The laser resonator, see Fig. 1, resembles a classical Fabry–Perot resonator. A 100 \( \mu \)m wide 10 \( \mu \)m deep micro-fluidic channel is bounded by two isosceles triangle mirrors formed in SU-8, giving rise to the laterally emitting ring laser cavity. This optical resonator relies on total internal reflection at the vertical sidewalls (a), (b), and (c) of the triangles, see Fig. 1. The laser dye gain medium is located in the micro-fluidic channel passing through the cavity.

Out-coupling of the laser light is achieved by a second micro-fluidic channel filled with ethanol, thereby removing the total internal reflection at the side (d) in the cavity. The out-coupled light is collected through an integrated planar ‘output waveguide’ (also in Fig. 1). The output coupling is switchable by alternating the content of the second fluidic channel between ethanol and air. A metal mask with a transparent window at the resonator serves to localize the optical pumping light to the resonator and diminish unwanted fluorescence.

### 3. Fabrication

The fabrication sequence is schematically shown in Fig. 2. The process consists of two parts: step 1–3 is a lift-off process to deposit the metal mask, 50 nm Cr and 250 nm Au, on a glass substrate, and step 4–8 is the forming of the micro-structures in SU-8, drilling, and bonding a glass lid on top.

In step 4 the micro-fluidic laser structure, the integrated waveguide, and the micro-fluidic channels (shown in Fig. 1) are defined by UV lithography on the substrate in a 10 \( \mu \)m thick layer of SU-8 photo resist [7]. Subsequent to development (step 5), the substrate is placed on a 150 °C hotplate for 2×60 s which has the effect of healing the cracks in the SU-8 (step 6). After drilling the holes for the fluid inlets and outlets (step 7) the micro-fluidic channels are sealed in step 8 by bonding a glass lid on top by means of a 5 \( \mu \)m thick PMMA film [8]. The bonding is carried out at a temperature of 120 °C with a bonding force of 2 kN on a 4 inch wafer pair with a duration of 10 min.

### 4. Optical characterization

The laser structure is characterized using the laser dye Rhodamine 6G (Rh6G) dissolved in...
(i) ethanol and (ii) ethylene glycol as the active gain medium, which is infused at 50 \( \mu \)L/h through the micro-fluidic channel and laser resonator. The dye laser is optically pumped normal to the chip plane through the window (see Fig. 1) at 532 nm by a pulsed, frequency doubled Nd:YAG laser. The repetition rate is 10 Hz and the pulses have a duration of 5 ns.

The upper panels in Figs. 3 and 4 show typical output spectra with the dye dissolved in ethanol and ethylene glycol, respectively. The concentration is in both cases \( 2 \times 10^{-2} \) mol/L. By increasing the pump pulse energy we observe an increase in the output intensity. The lower panels show the output power (numerically integrated output intensity) vs. the pump pulse energy flux and the observed change of slope in the curves around 55 \( \mu \)J/mm\(^2\) is a clear signature of the onset of lasing for both solvents.

As shown in Fig. 5, the change of solvent introduces an over-all shift of the output spectra of approximately 2 nm. The red shift of the spectra measured using the ethylene glycol solution may be explained by a lower cavity-loss or a higher dye quantum efficiency using this solvent [9]. Since the dye/solvent properties can be changed dynamically this enables real-time tuning of the central lasing wavelength [4].

The output coupling from the structure is switched on by filling the second fluid channel (see Fig. 1) with ethanol, and it is switched off again by blowing air into the second channel or providing an under-pressure with a syringe, thereby sucking air through the second channel.

5. The cavity modes

The cavity mode spectrum has been modelled by a scattering matrix approach and Fig. 6
illustrates the ‘unfolded’ structure. Formally, the scattering matrix of the ‘unfolded’ structure is calculated and periodic boundary conditions are applied. In other words the ring resonator is formed by ‘joining’ the two ends of the unfolded structure. This allows for calculation of the spectral position of the cavity modes. For the experimentally relevant parameters a mode spacing of approximately 0.13 nm is found.

Comparing to the experimental output spectra in Figs. 3 and 4, we might speculate that the sub-nanometer modulation of the overall peak resembles the longitudinal mode spacing. However, since the spectrometer resolution is around 0.15 nm the mode-spacing is not resolved experimentally. Compared to the estimated mode-spacing the over-all width of the output spectra suggests that the lasing is longitudinally multimode.
6. Conclusion

We have demonstrated a laterally emitting coupled cavity micro-fluidic dye ring laser. The laser is fabricated with polymer technology using a total internal reflection based cavity formed by two triangle mirrors. The light-source is straightforward to integrate with polymer planar waveguides for use in lab-on-a-chip devices. The dependence of the lasing wavelength on the dye solution may enable tunability. Using a simple modeling approach we estimated the mode-spacing of the order 0.13 nm which however cannot be fully verified experimentally due to limited spectrometer resolution. We have shown the possibility of switching the output coupling which can be highly useful also in other applications.

Acknowledgements

The first author gratefully acknowledges financial support by Otto Mønsteds Fond and Geheimestatsminister Greve Joachim Godske Moltkes Legat from Bregentved Gods. The work was supported by the Danish Technical Research Council (STVF, grant numbers: 26-02-0064, 26-03-0073).

References