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Abstract: First order distributed feedback optofluidic dye lasers embedded in a 350 µm thick TOPAS® foil are demonstrated. They are designed in order to give high output pulse energies. Microfluidic channels and first order distributed feedback gratings are fabricated in parallel by thermal nanoimprint into a 100 µm foil. The channels are closed by thermal bonding with a 250 µm thick foil and filled with $5 \cdot 10^{-3}$ mol/l Pyrromethene 597 in benzyl alcohol. The fluid forms a liquid core single mode slab waveguide of 1.6 µm height on a nanostructured grating area of 0.5 × 0.5 mm^2. This results in a large gain volume. Two grating periods of 185 nm and 190 nm yield single mode laser light emission at 566 nm and 581 nm respectively. High emitted pulse energies of more than 1 µJ are reported. Stable operation for more than 25 min at 10 Hz pulse repetition rate is achieved.

OCIS codes: (140.2050) Dye Lasers; (140.3490) Lasers, distributed-feedback; (140.7300) Visible lasers; (130.3120) Integrated optics devices.

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1. Introduction

Since their first demonstration [1] optofluidic dye lasers based on distributed feedback (DFB) have gained interest as coherent visible light sources for lab-on-chip systems and integrated optics [2,3]. Typically, optofluidic dye lasers are optically pumped by frequency doubled Nd:YAG lasers. Such lasers, having high enough output pulse energies, could serve as visible coherent light sources for applications in spectroscopy, biosensing, e.g. excitation of fluorescent markers, or surface enhanced Raman spectroscopy (SERS).

Devices structured in SU8 by UV and electron beam lithography [4,5] and in PDMS by soft lithography [6,7] have been reported so far. First order DFB gratings are preferred because of no intrinsic scattering losses and only one existing resonance frequency. Here, also lowest threshold pump energies are expected [6]. Third order lasers have been reported by Gersborg-Hansen et al. [4]. Song et al. [6] have shown third, second, and first order lasers where second order lasers have shown the lowest threshold due to fabrication limitations in the case of first order gratings. Tunable lasers have been achieved by adjusting the grating period and the refractive index of the fluid [5,8], by mechanical stretching [9], and by an integrated pneumatic tuning air-gap etalon [10].

For bringing optofluidic lasers to markets fabrication technologies suitable for mass production must be used. In addition, a reduction of material costs is desired. Thermal nanoimprint and thermal bonding of all polymer devices is a promising approach to fulfill both requirements.

In this paper we demonstrate optofluidic first order distributed feedback liquid core dye lasers nanoimprinted in a TOPAS® foil with a liquid core of Pyrromethene 597 dissolved in benzyl alcohol. The lasers are designed in order to give high output pulse energies.

2. Design considerations

TOPAS® 6013 Cyclic Olefin Copolymer (COC) [11] foil was chosen as substrate and lid material as it can be structured by thermal nanoimprint [12] and is frequently used in mass production. Its refractive index for visible light is n_s ~1.53. Benzyl alcohol is a common solvent for laser dyes and has a refractive index of n_c = 1.538 at 25 °C and 589 nm [13]. Pyrromethene 597 [14] has been dissolved in it with a concentration of $5 \cdot 10^{-3}$ mol/l. Higher concentrations result in a drop of the quantum yield due to fluorescence quenching.

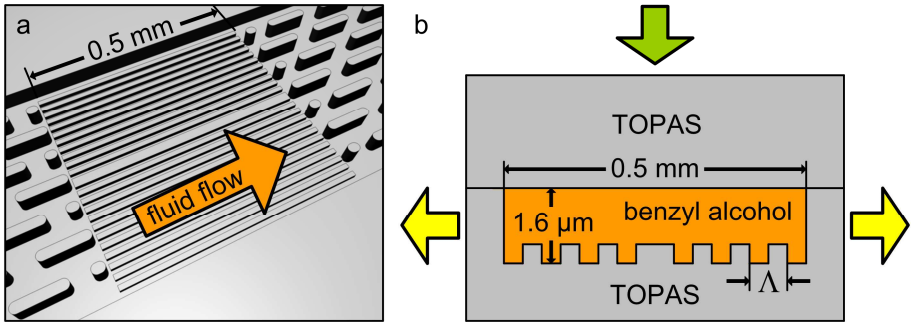

Fig. 1. (a) Illustration of an imprinted microchannel in a TOPAS® foil with support pillars and a phase shifted DFB grating in the center. (b) Scheme of the finished laser: A liquid core of Pyrromethene 597 dissolved in benzyl alcohol in the microchannel structured with the phase shifted DFB grating of period Λ. Arrows denote the direction of the pump light and the emission.

The benzyl alcohol should form a liquid core single mode slab waveguide. Apart from the weak perturbation from the grating the waveguide is symmetric and will thus always guide a fundamental mode. For single mode laser operation the waveguide must only support a single propagating mode. The cutoff height d_c for the second mode in a symmetrical slab waveguide is

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$$d_c = \frac{\lambda}{2\sqrt{n_c^2 - n_s^2}}, \quad (1)$$

where λ is the wavelength in vacuum. The cutoff height resulting from Eq. (1) for λ ~575 nm is d_c ~1.9 µm. A height of d = 1.6 µm was chosen to assure a single mode behavior and to achieve a strong enough feedback from ~140 nm deep grating lines. Taking into account the effective index n_{eff} = 1.537 (for λ ~575 nm and d = 1.6 µm) the grating period Λ_i determines the expected output wavelength λ_i to

$$\lambda_i = 2 n_{eff} \Lambda_i. \quad (2)$$

For grating periods of Λ_1 = 185 nm and Λ_2 = 190 nm Eq. (2) results in λ_1 = 584 nm and λ_2 = 569 nm respectively. In order to achieve lasers with high output energies a large gain volume is recommended. Thus a DFB grating area of 0.5 × 0.5 mm^2 was chosen for one laser, see Fig. 1(a). As the microchannel is very shallow, support pillars were introduced in it in order to increase the stability during bonding. They are designed to ensure maximum stability while only minimally affecting the fluidic flow. The microchannel is closed by another TOPAS® foil and filled with dye solution. Lasing is induced by pumping through the lid from above whereas the generated laser light is emitted into the plane of the foil, Fig. 1(b).

3. Fabrication

A stamp was fabricated on a four inch silicon wafer. DFB gratings were made by electron beam lithography, aluminum deposition, lift off and reactive ion etching (RIE). UV lithography on the same wafer was used for the fabrication of a resist mask for RIE of the microchannels. After cleaning, deposition of an antistiction coating finished the stamp.

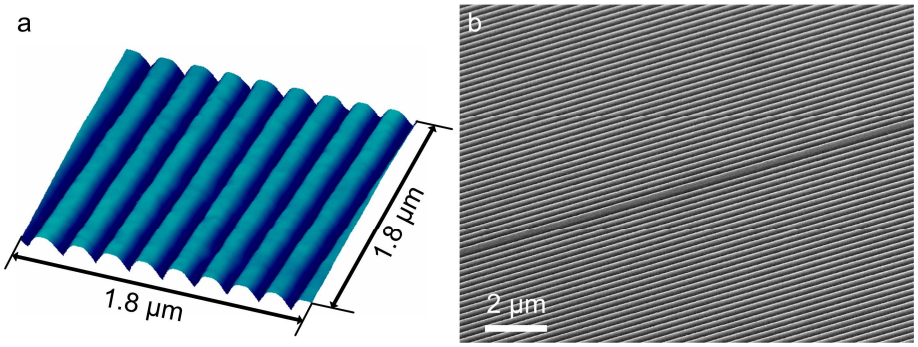

Fig. 2. (a) Atomic force micrograph illustrating the shape of imprinted grating lines. Here, the tip reached only 80 nm deep because of the narrow trenches but a depth of 140 nm has been measured on broader trenches on the same foil (b) Scanning electron micrograph taken under an angle of 30° of an imprinted grating with Λ/2 phase shift on a 100 µm thick TOPAS® foil.

This stamp was used for thermal nanoimprint into a 100 µm thick TOPAS® foil using an EVG 520 hot embosser. A pressure of 1.9 MPa was applied at 190 °C for 15 min. A scanning electron and an atomic force micrograph of resulting grating lines are shown in Fig. 2. The stamp is reusable. After imprinting, a 250 µm thick TOPAS® foil with prestructured inlets was bonded to the substrate foil (0.8 MPa at 110 °C for 20 min). Thereafter, a dicing saw was used to separate chips of 18 × 18 × 0.35 mm^3 size as shown in Fig. 3(a). Figure 3(b) shows a microscope image of a sealed channel before filling. A marginal bending of the lid above the grating can be seen from slightly different colors as a result of interference at the thin air layer. To test their robustness microchannels were filled with benzyl alcohol and pressurized. Pressures up to 400 kPa were applied causing no damage to the devices.

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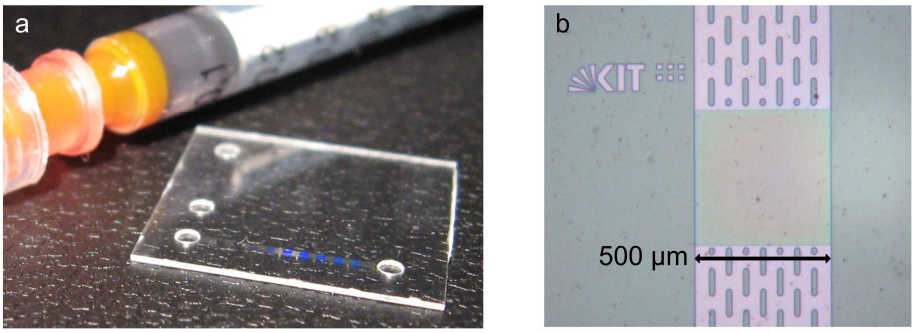

Fig. 3. (a) Photograph of a foil (size 18 × 18 × 0.35 mm^3) with two microchannels and 1 ml syringe filled with Pyrromethene 597 in benzyl alcohol in the background. Blue light is diffracted from the gratings on the right in the direction of the camera. (b) Microscope image of microchannel with pillars and distributed feedback grating in the center.

4. Optical characterization

The lasers were pumped from above [as indicated in Fig. 1(b)] with 15 ns pulses from a compact frequency doubled Nd:YAG laser. The microchannels were filled by capillary forces. Fluid flow was accomplished by a vacuum pump connected to one inlet where a low-pressure of 2 kPa was applied. This corresponds to a complete exchange of the exposed laser dye per second. Output spectra of two lasers with grating periods of Λ_1 = 185 nm and Λ_2 = 190 nm were measured, Fig. 4(a), 4(b). Using a Ocean Optics HR4000 spectrometer maxima were found at 565.8 nm and 581.2 nm with full widths at half maxima of 0.20 nm and 0.14 nm respectively. The wavelengths are slightly higher than expected which may be caused by the presence of the dye. However, as seen in Fig. 3(b) the lid of the microchannel is slightly bended. If the channel height decreases the effective index and thus also the expected wavelength decrease, compare Eq. (2).

Curves showing the output intensity as function of pump fluence are plotted in Fig. 4(c), 4(d). Thresholds of ~20 µJ/mm^2 and ~30 µJ/mm^2 result from these plots.

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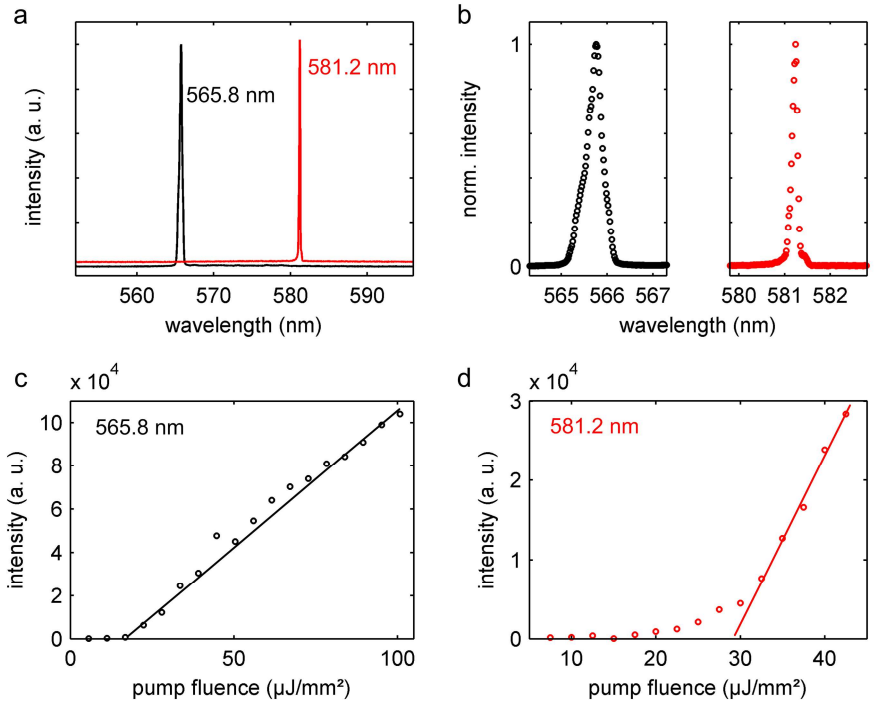

Fig. 4. Optical characteristics. (a, b) Output spectra of two lasers emitting at 565.8 nm and 581.2 nm. The full width at half maximum of the spectral peaks is 0.20 nm and 0.14 nm respectively. (c) Curve showing the output intensity as function of pump fluence for a laser emitting at 565.8 nm. The threshold is ~20 μJ/mm^2. A linear response is obtained for pump fluences above threshold. (d) Curve illustrating that the threshold at 581.2 nm is ~30 μJ/mm^2.

The TOPAS® foil resisted optical pump fluences of ~250 μJ/mm^2 without being damaged. To achieve high output pulse energies a laser emitting at 581.2 nm was pumped with a pump pulse energy of ~50 μJ hitting the entire laser area. On one side of the laser a maximum output pulse energy of 0.54 μJ was measured with an Ophir Optronics PE9-SH pulse powermeter. Taking into account that the device is symmetric an overall output energy of more than 1 μJ per pulse was achieved. The efficiency was thus approx. 2.1%. When pumping with a narrow spot of ~0.3 × 4 mm^2 a maximum output pulse energy of 0.40 μJ at 565.8 nm was observed on one side. With this smaller pump spot the laser gave a stable output spectrum and energy for more than 25 min at 10 Hz pulse repetition rate with steady fluid flow, see Fig. 5. Here, the average total output energy was 0.66 μJ per pulse with a standard deviation of 0.05 μJ.

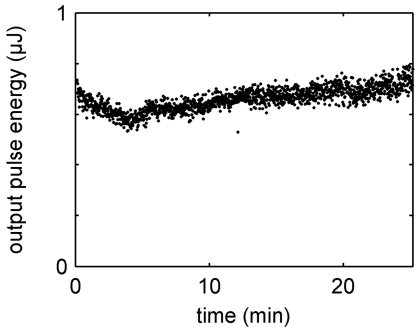

Fig. 5. Total output pulse energy of a laser emitting at 565.8 nm measured over a time of more than 25 min.

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5. Conclusions

We have demonstrated first order DFB liquid core optofluidic dye lasers embedded in a 350 µm thick TOPAS® foil. Light emission is reported at 566 nm and 581 nm. Emitted pulse energies of more than 1 µJ and stable operation for more than 25 min at 10 Hz pulse repetition rate make these lasers promising as tunable visible laser light sources for lab-on-chip systems and integrated optics. Due to high output energies the use as a free space light source in combination with appropriate pump sources is feasible as well. The lasers are fabricated utilizing a simple reproducible process out of only one solid material and one liquid. This makes them promising for mass production. A next step will be the fabrication of metal stamps according to [15] where a high number of replications is feasible. The process should even be transferable to roll-to-roll fabrication.

On-chip circulation of dye can be achieved by a meandering channel where fluid flow is accomplished by capillary forces [4]. Integrating the lasers into lab-on-foil photonic microsystems will e.g. allow for spectroscopy, attenuation measurements, excitation of fluorescent markers, and SERS.

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