View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Caltech Authors - Main

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Tunable optofluidic distributed feedback dye lasers

Zhenyu Li, Zhaoyu Zhang, Teresa Emery, Axel Scherer, Demetri Psaltis

Zhenyu Li, Zhaoyu Zhang, Teresa Emery, Axel Scherer, Demetri Psaltis, "Tunable optofluidic distributed feedback dye lasers," Proc. SPIE 6329, Optofluidics, 632903 (7 September 2006); doi: 10.1117/12.683343

SPIE.

Event: SPIE Optics + Photonics, 2006, San Diego, California, United States

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Tunable optofluidic distributed feedback dye lasers

Zhenyu Li*, Zhaoyu Zhang, Teresa Emery, Axel Scherer, Demetri Psaltis
California Institute of Technology, 1200 East California Boulevard, Pasadena, CA, USA 91125

ABSTRACT

We demonstrated a continuously tunable optofluidic distributed feedback (DFB) dye laser on a monolithic poly(dimethylsiloxane) (PDMS) elastomer chip. The optical feedback was provided by a phase-shifted higher order Bragg grating embedded in the liquid core of a single mode buried channel waveguide. We achieved nearly 60nm continuously tunable output by mechanically varying the grating period with two dye molecules Rhodamine 6G (Rh6G) and Rhodamine 101 (Rh101). Single-mode operation was obtained with <0.1nm linewidth. Because of the higher order grating, a single laser, when operated with different dye solutions, can provide tunable output covering from near UV to near IR spectral region. The low pump threshold (< 1uJ) makes it possible to use a single high energy pulsed laser to pump hundreds of such lasers on a chip. An integrated array of five DFB dye lasers with different lasing wavelengths was also demonstrated. Such laser arrays make it possible to build highly parallel optical sensors on a chip. The laser chip is fully compatible with PDMS based soft microfluidics.

Keywords: Optofluidics, optofluidic dye lasers, distributed feedback dye lasers, tunable dye lasers, single mode dye lasers, microfluidics, laser arrays

1. INTRODUCTION

On-chip liquid dye lasers are promising coherent light sources for 'lab-on-a-chip' systems in that they allow the integration of laser sources with other microfluidic and optical functionalities. Also, microfabricated liquid dye lasers have many advantages over conventional dye lasers such as easier and safer to handle, compact and inexpensive. And compared to solid state dye lasers, microfabricated liquid dye lasers don't suffer from the photobleaching problem because the dye solution can be continuously replaced. Several groups have demonstrated such on chip dye lasers using different materials and laser cavities [1,2,3]. Tunable output was also obtained using concentration or index tuning methods [3,4]. Such on-chip liquid dye lasers are an example of the newly emerging optofluidic devices [5], in which the integration with microfluidics and the adaptive nature of liquid materials enable unique features that are not obtainable with solid state materials. Recently, an optofluidic DFB dye laser was demonstrated on a monolithic PDMS elastomer chip [6]. Stable single-mode operation with narrow linewidth was obtained using a phase-shifted higher order Bragg gating embedded in a single mode liquid core optical waveguide. In this paper, by combining the mechanical flexibility of the elastomer materials and the reconfigurability of the liquid gain medium we demonstrate the ultra-wide tunability of such single mode DFB liquid dye lasers. Also due to the low pump threshold, we explore the possibility of building an array of large number of such lasers on a chip pumped by a single external light source.

2. SINGLE MODE OPTOFLUIDIC DFB DYE LASER

2.1. Chip design and fabrication

The schematic diagram of the optofluidic DFB dye laser is shown in Figure 1. The laser chip is entirely made of poly(dimethylsiloxane) (PDMS), a silicone elastomer which has become popular for microfluidics and nanofabrication [7,8], and has good optical properties in the visible region. A microfluidic channel when filled with liquid of higher refractive index than that of PDMS (1.406, GE RTV615) acts as a buried channel waveguide. The channel dimensions are 2μm×3μm and the index contrast is less than 0.003 so that the waveguide supports only the fundamental TE_{00} and TM_{00} modes. The distributed feedback is provided by the periodic PDMS posts inside the channel with 3080nm period,

* Zhenyu Li: E-mail: zhenyu@caltech.edu, Telephone: 1 626 395 3889

Optofluidics, edited by Demetri Psaltis, Yeshaiahu Fainman, Proc. of SPIE Vol. 6329,
632903, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.683343

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

which form a 1cm long 15th-order Bragg grating at wavelength around 570nm. The PDMS posts also provide mechanical support for the microfluidic channel. An effective $\pi/2$ phase shift is introduced at the center of the grating to ensure single frequency operation at the Bragg wavelength [9]. The gain medium is a 2mM solution of Rhodamine 6G (Rh6G) or Rhodamine 101 (Rh101) in a methanol and ethylene glycol mixture with refractive index of 1.409. The 6ns Q-switched Nd:YAG laser pulses of 532nm wavelength are focused by a cylindrical lens to a ~100μm×1cm stripe aligned with the microfluidic channel. The fabrication and operation of the laser chip is fully compatible with silicone elastomer based microfluidics technology [10].

The fabrication of the optofluidic DFB dye laser uses the same replica molding soft lithography technique which is widely used to make microfluidic devices [10,11]. Briefly, a master mold was fabricated using conventional photolithography. 2um thick SU8-2002 negative photoresist (MicroChem) was spin-coated on a silicon wafer and patterned with a Cr-on-glass mask. The mold was treated with tetramethylchlorosilane (Aldrich) vapor for 5 min before use to facilitate the release of PDMS. Then 5:1 part A:B PDMS prepolymer (GE RTV 615) was poured onto the mold and baked at 80^oC for 30 min. The partially cured PDMS was peeled from the master and the liquid inlet and outlet ports were punched through the whole layer using a 23-gauge luer-stub adapter. This patterned PDMS, containing the laser structure, was then treated with oxygen plasma and bonded to another featureless PDMS to form a monolithic device. Finally, the resulting device was cut to size and baked at 80^oC overnight. The lower inset of Figure 1 shows an optical micrograph of the central phase shifted region of the laser cavity. Two issues need to be considered for replica molding in PDMS. First, due to the shrinking effect of PDMS upon curing, the feature size needs to be enlarged by 0.2% on the master mold. Second, the softness of PDMS limits the aspect ratios of the microfluidic channels to be between 0.2 and 2. A too high aspect ratio leads to pairing of adjacent features and a too low aspect ratio causes the channel to collapse especially after the oxygen plasma treatment.

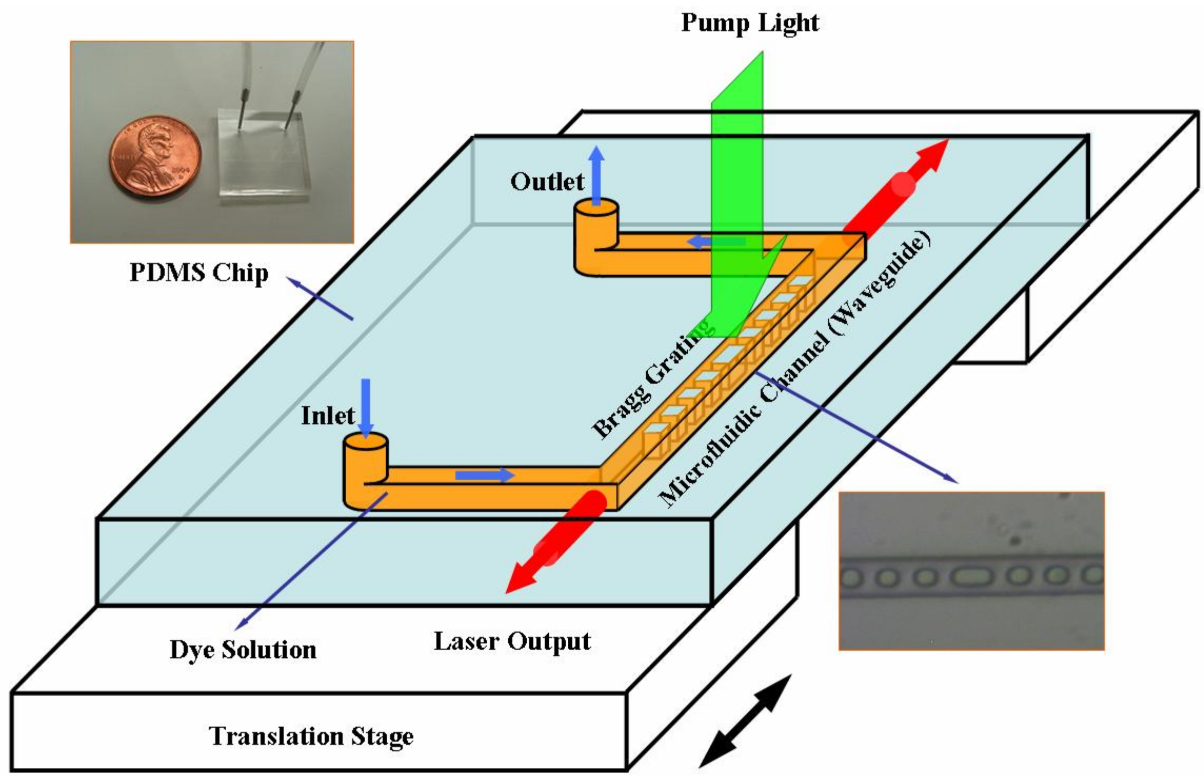

Figure 1. Schematic diagram of a mechanically tunable optofluidic DFB dye laser chip. The upper inset shows an actual monolithic PDMS laser chip. The lower inset is an optical micrograph of the central phase-shifted region of the laser cavity. A Bragg grating with 3080nm period is embedded in a 3μm wide microfluidic channel. The channel height is 2μm. The size of the PDMS posts is about 1.28μm×1.8μm inferred from the optical micrograph. The central larger PDMS post introduces an effective $\pi/2$ phase shift to ensure single wavelength lasing. The movement of the translation stage deforms the chip which causes the grating period to change.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

2.2. Transverse and longitudinal mode control

To make a single mode laser, both the transverse mode and longitudinal mode selection need to be considered. The number of transverse mode and the level of optical confinement are determined by the cross sectional dimensions of the waveguide and the index contrast between the core and the cladding. The waveguide dimensions (width 3μm; height 2μm) are chosen such that when filled with liquid of refractive index 1.409 it only supports the two fundamental modes. The small cross-section area not only reduces the required pump power to achieve the lasing threshold but also results in an extremely small consumption of dye solution (less than 40 picoliter per channel).

To obtain stable single frequency operation, the free spectral range of the employed cavity structure has to be larger than the gain spectral bandwidth. Organic dye molecules are well known to have very broad gain spectra with a typical bandwidth of 30nm to 50nm (full width at half maximum FWHM). This forces the characteristic length of the resonant structure to be shorter than 4μm. When a DFB structure is used to provide the optical feedback, the lasing wavelength is determined by the Bragg condition:

$$m\lambda_m = 2n_{eff}\Lambda \tag{1}$$

where λ_m is the mth order resonant wavelength, n_{eff} is the effective index of the guided mode and Λ is the grating period. The free spectral range (*FSR*) is given by (neglect dispersion):

$$FSR = \frac{\lambda_m}{m-1}, \quad (or\ \ \Delta\nu = \frac{c}{2n_{eff}\Lambda}) \tag{2}$$

Therefore for a DFB structure with Λ = 3.08μm (1280nm + 1800nm) and n_{eff} = 1.407, the 15th resonant wavelength and *FSR* are 577.8nm and 41.3nm respectively. This large *FSR* ensures at most two resonances fall inside the gain spectrum of Rhodamine 6G which spans from 550nm to 650nm. However, within each resonance, there are still side modes due to the finite length of the grating. It's well known that a DFB laser with a uniform grating operates not at the Bragg wavelength but instead at the two degenerate wavelengths situated symmetrically on either side of the Bragg wavelength [9]. To break this degeneracy, a $7\pi + \pi/2$ phase shift is introduced at the center of the grating. Thus single frequency operation is obtained even at high pump levels due to gain discrimination. Figure 2 shows the simulated reflectivity spectrum of the overall structure using the Rouard's method [12]. The parameters used are: Λ = 1280nm + 1800nm, grating length L = 1cm, effective $\pi/2$ phase shift at the center, core index n_{core} = 1.409, and cladding/post index n_{clad} = 1.406. Also shown are the normalized measured fluorescence spectra of Rh6G and Rh101 solutions used in the lasing experiment.

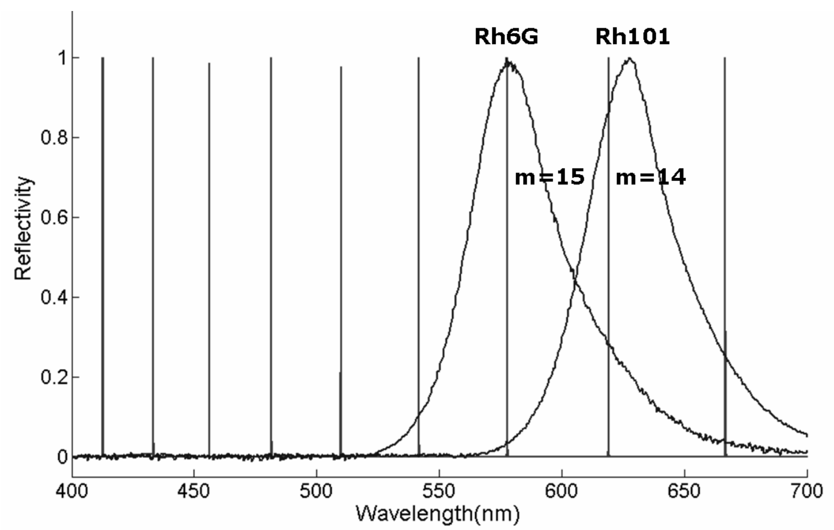

Figure 2. Simulated reflectivity spectrum of a $\pi/2$ phase shifted higher order DFB structure. The parameters used are given in the main text. Also shown are the normalized measured fluorescence spectra of Rh6G and Rh101 solutions used in the lasing experiment.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

3. WAVELENGTH TUNING METHODS

The lasing wavelength can be tuned by changing either n_{eff}, Λ or m as have been demonstrated in conventional DFB dye lasers [13]. The effective index n_{eff} can be varied by changing the core index or the cross sectional dimensions of the waveguide. However, due to the low Young's modulus of PDMS (~750kPa) [7], the most straight forward tuning method is to change the grating period by simply stretching or compressing the chip along the waveguide direction. The grating order m can be chosen by using different dye molecules whose emission spectra cover different spectral regions. The last two methods were combined in this work to achieve a nearly 60nm tuning range from yellow to red using Rh6G and Rh101 dye solutions. As can be seen from Figure 2, the potential tuning range for Rh6G and Rh101 is larger than 100nm covering from 550nm to beyond 650nm. Actually, because of the multiple spectral resonances supported by the higher order Bragg grating, a single laser can provide tunable output covering the whole available dye laser spectrum from 320nm to 1200nm [14] when suitable dye molecules and pump light are used. With a mixture of several dye molecules, simultaneous multiple color lasing from the same cavity is also possible.

To change the refractive index of the dye solution, one can mix two solvents with different refractive indices. For example, using methanol and dimethylsulfoxide (DMSO), the achievable refractive index change can be as large as 0.148 (1.33 for methanol versus 1.478 for DMSO). The choices of solvents are limited because PDMS swells in most of them [15]. Compatible solvents which are also used in dye lasers include water, methanol, ethanol, ethylene glycol, glycerol and DMSO. The mixing, switching and transport of dye solutions can all be implemented on a silicone elastomer microfluidic chip using the recently developed mechanical micro valves and pumps [10]. This compatibility with PDMS based soft microfluidics should allow us to build not only powerful on chip optical sensing and imaging systems but also novel adaptive optofluidic devices.

4. RESULTS AND DISSCUSION

4.1. Mechanical wavelength tuning results

To achieve the mechanical tuning, the laser chip was clued to two separate stages with the laser region suspended in the middle as shown in Figure 1. The glue is the same PDMS prepolymer used for the device fabrication. To form a strong bonding, the glue was cured at 80°C for an hour. One of the stages is a high resolution micrometer with 1μm sensitivity which provides accurate control and quantitative measurement of the deformation of the chip. This allows us to both stretch and compress the chip along the channel direction. The experimental results of mechanical tuning are given in Figure 3. The points on the figure are experimental data and the curves are the linear fit. The achieved single mode tuning range for Rh6G is from 565nm to 594nm and is from 613nm to 638nm for Rh101. Linear relationship between the lasing wavelength and the chip deformation was found as shown in Figure 3.**B**. When the length of the central suspended region is 1cm, the total chip deformations required to achieve the above tuning ranges are about 500μm for Rh6G and 400μm for Rh101, which correspond to 28nm and 25nm grating period changes respectively. Because of the extremely large allowed deformation of PDMS (>120%), the ultimate tuning range is limited only by the gain bandwidth. Only about 5% deformation was used to achieve the ~60nm tuning range. We believe an even wider tuning range from 550nm to 650nm is obtainable with a better cavity design and a more uniform mechanical load. The tuning is continuous and completely reversible due to the elastomer nature of PDMS. No noticeable degradation of the chip was observed during a 5-cycle full range tuning test. Throughout the tuning range, stable single-mode operation was maintained with measured linewidth <0.1nm, resolution limited by the spectrometer (Ocean Optics HR4000). The absorbed pump thresholds are ~150nJ and ~200nJ for Rh6G and Rh101 respectively. As expected, we observed the decrease of laser output power as the lasing wavelength moved away from the gain spectrum peak in either direction. The deformation along the channel causes its transverse dimensions to change also, which changes the effective index of the guided mode. However, given that the Poisson's ratio of PDMS is ~0.5, the estimated effective index change is only about 1.5×10^{-5} and its effect on the lasing wavelength is negligible.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

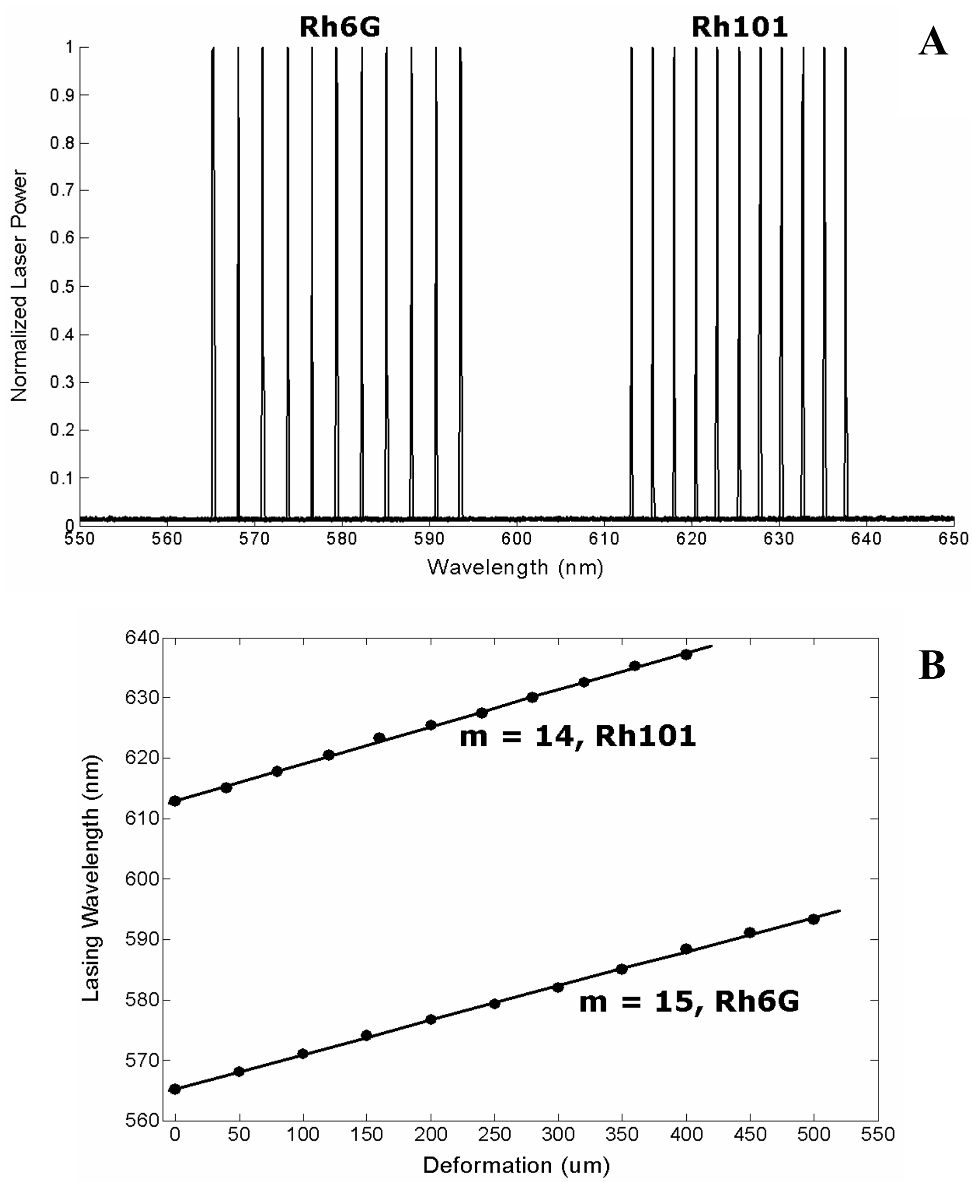

Figure 3. **A**: normalized laser output of the mechanically tunable optofluidic DFB dye laser. Different peaks correspond to different grating periods. The measured laser linewidth is less than 0.1nm throughout the tuning range. **B**: lasing wavelength versus the measured chip deformation. The points are the experimental data and the curve is the linear fit. The achieved single-mode tuning range for Rh6G is from 565nm to 594nm and is from 613nm to 638nm for Rh101.

4.2. Fluidic wavelength tuning results

We also studied the index tuning method because it is amenable to microfluidic implementation using the recently developed mechanical micro valves and pumps [10]. However, in the current design the relative large dimensions of the waveguide cause multiple transverse mode operation when the index contrast is increased to above 0.003. Figure 4 shows a measured lasing spectrum when a high refractive index dye solution is used. In this case, the gain medium is a solution of 2mM Rh6G in dimethylsulfoxide(DMSO) which has a refractive index of 1.478. In this experiment, the waveguide dimensions were 2μm×5μm and the grating period was 3μm. More than 20 lasing lines were observed in the spectrum. Finite element analysis (FEMLAB 3.2, Comsol) shows the waveguide supports totally 48 transverse modes.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

The measured longest lasing wavelength was 587nm, close to the predicted 588nm for the lowest TE_{00} mode, which had moved by ~25nm to longer wavelength compared with the case when the core index is 1.409. To avoid multiple transverse mode operation, a smaller channel has to be used. For example, a waveguide of transverse dimensions 880nm×880nm remains single mode throughout the index range from 1.406 to 1.478, which gives a 15nm single mode tuning range. Although this is a quite large tuning range using direct index tuning, it is still considerably smaller than the gain bandwidth of Rh6G. Techniques such as Vernier tuning can be used to fully utilize the wide gain bandwidth of dye molecules. Fabrication of such small scale channels in the soft PDMS material represents a technical challenge. We are currently working on building a fully integrated microfluidic tunable DFB dye laser based on multilayer soft lithography enabled valves and pumps[10].

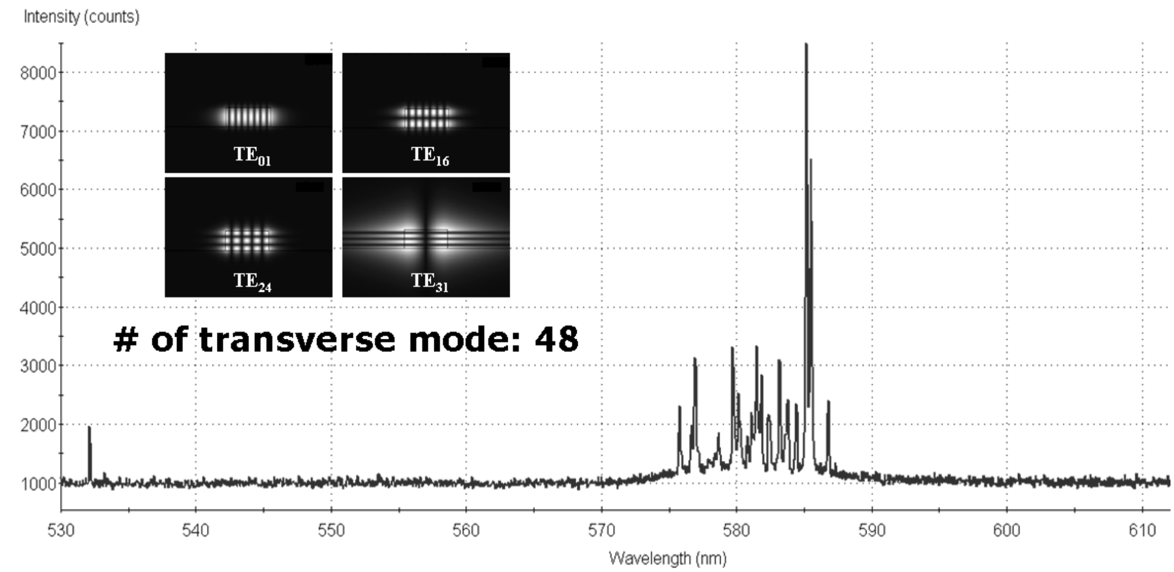

Figure 4. Typical lasing spectrum of the optofluidic DFB dye laser with high index contrast between the liquid core and the PDMS cladding. The waveguide dimensions are 2μm×5μm. The grating period is 3μm. The refractive index of the Rh6G dye solution is 1.478. More than 20 lasing modes were observed. The inset shows four simulated TE-like transverse mode profiles.

4.3. Integrated laser array

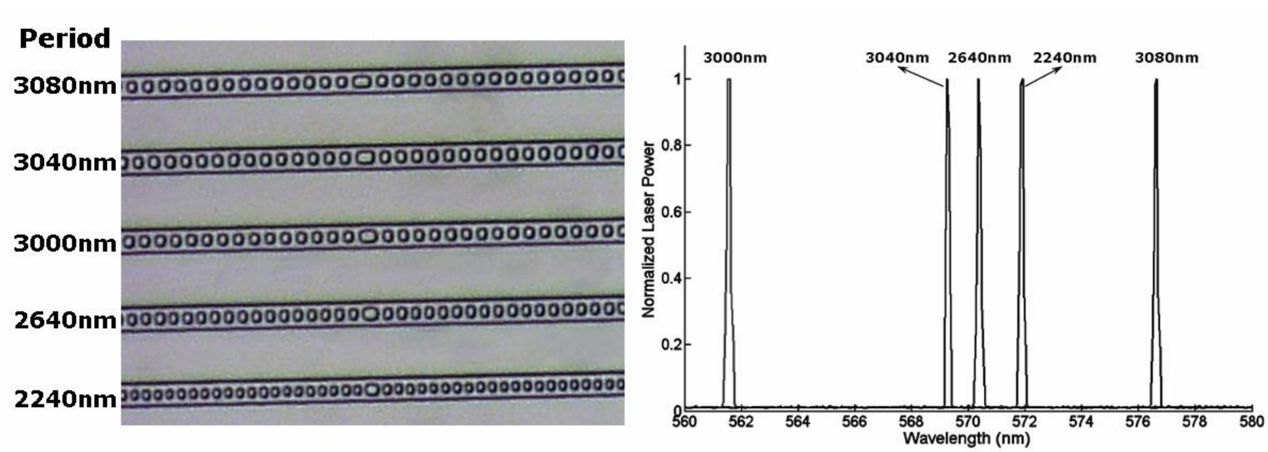

Figure 5. Left: optical micrograph of an integrated array of five optofluidic DFB dye lasers. The grating period of each laser is given on the left. Right: normalized laser output of the array using Rh6G dye solution as the gain medium.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

We also fabricated an array of five DFB dye lasers on a single PDMS chip. Figure 5 shows the array lasing results using the Rh6G dye solution. Laser output spanning a ~ 15nm range was achieved with different grating periods. The low pump threshold (< 1uJ) of each optofluidic DFB dye laser makes it possible to use a single high energy pulsed laser to pump hundreds of such lasers on a chip. This opens up the possibility of building highly parallel multiplexed biosensors on a chip such as multiple-color flow cytometers and surface plasmon resonance based sensors. This also provides an alternative to tunable lasers for making compact and inexpensive wavelength scanning-less spectrometers on a chip [16]. Also the low pump threshold allows the use of visible semiconductor laser diodes as the pump source to build compact portable devices.

5. CONCLUSION

We have demonstrated a continuously tunable optofluidic DFB dye laser on a monolithic PDMS chip using a simple mechanical deformation method. Single-mode operation was maintained throughout the achieved ~60nm tuning range. Due to the higher order of the DFB structure, a single laser is capable of generating tunable output covering from near UV to near IR spectral region when a UV pump light is used. An integrated array of five such lasers was also demonstrated. Such laser arrays can be used to make highly parallel multiplexed biosensors and scanning-less spectrometers on a chip. Finally, we want to point out that these lasers are still not stand-alone devices because both the gas pressure source for the microfluidic valves and the pump laser are outside the chip. The gas pressure source can be eliminated by using electrokinetically driven flows. However, an external pump light is necessary for all dye lasers. For portable devices, visible semiconductor lasers can be used as the pump source.

ACKNOWLEDGMENTS

This research was supported by the DARPA center for optofluidic integration at California Institute of Technology.

REFERENCES

1. G. B. Helbo, A. Kristensen, and A. Menon, “A micro-cavity fluidic dye laser”, J. Micromech. Microeng. 13(2), 307-311 (2003).

2. G. D.V. Vezenov, B.T. Mayers, R.S. Conroy, G.M. Witesides, P.T. Snee, Y. Chan, D.G. Nocera, and M.G. Bawendi, “A low-threshold, high-efficiency microfluidic waveguide laser”, J. AM. Chem. Soc. 127(25), 8952-8953 (2005).

3. J.C. Galas, J. Torres, M. Belotti, Q. Kou and Y. Chen, “Microfluidic tunable dye laser with integrated mixer and ring resonator”, App. Phys. Lett. 86, 264101 (2005).

4. B. Bilenberg, B. Helbo, J.P. Kutter and A. Kristensen, “Tunable Microfluidic Dye Laser”, Proceedings of the 12th Int. Conf. on Solid-State Sensors, Actuators and Microsystems, Transducers, 206-209 (2003).

5. http://optofluidics.caltech.edu. DARPA Center for Optofluidic Integration.

6. Z. Li, Z. Zhang, T. Emery, A. Scherer and D. Psaltis, “Single mode optofluidic distributed feedback dye laser”, Optics Express, **14**, 696-701 (2006). http://www.opticsinfobase.org/abstract.cfm?URI=oe-14-2-696

7. J. C. McDonald and G. M. Whitesides, “Poly(dimethylsiloxane) as a material for fabricating microfluidic devices,” Acc. Chem. Res. **35**, 491-499 (2002).

8. S. R. Quake and A. Scherer, “From micro- to nanofabrication with soft materials,” Science **290**, 1536-1540 (2000).

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

9. A. Yariv, *Optical Electronics in Modern Communications* (Oxford, New York, 1997).

10. M.A. Unger, H.P. Chou, T. Thorsen, A. Scherer, S.R. Quake, "Monolithic microfabricated valves and pumps by multilayer soft lithography", Science, 288, 113-116 (2000).

11. Y. N. Xia and G. M. Whitesides, "Soft lithography," Annu. Rev. Mater. Sci. **28**, 153-184 (1998).

12. L. A. Wellerbrophy and D. G. Hall, "Analysis of wave-guide gratings - application of Rouard's method," J. Opt. Soc. Am. A **2,** 863-871 (1985).

13. C.V. Shank, J.E. Bjorkholm and H. Kogelnik, "Tunable distributed-feedback dye laser", App. Phys. Lett. 18, 395-396 (1971).

14. W.T. Silfvast, *Laser Fundamentals* (Cambridge, Cambridge, 2004).

15. J. N. Lee, C. Park.; G. M. Whitesides, "Solvent Compatibility of Poly(dimethylsiloxane)-Based Microfluidic Devices" *Anal. Chem. 75*, 6544-6554 (2003).

16. Y. Oki, S. Miyamoto, M. Maeda and N. J. Vasa, "Multiwavelength distributed-feedback dye laser array and its application to spectroscopy", Opt. Lett. 27(14), 1220-1222 (2002).

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 7/6/2018
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use