Chapter 6

MECHANICALLY TUNABLE OPTOFLUIDIC DISTRIBUTED FEEDBACK DYE LASER

6.1 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. Several groups have demonstrated such dye lasers using different materials and laser cavity designs [1-3]. Tunable output was also obtained using concentration or index tuning methods [3, 4]. Indeed, on-chip liquid dye lasers are examples of the new class of emerging optofluidic devices, in which the integration of microfluidics with the adaptive nature of liquids enables unique performance that is not obtainable within solid state materials [5]. Recently, an optofluidic distributed feedback (DFB) dye laser was demonstrated on a silicone elastomer chip [6]. Stable single-mode operation with narrow linewidth was obtained using a phase-shifted higher order Bragg grating embedded in a single mode microfluidic channel waveguide. In this chapter, by combining the mechanical flexibility of the elastomer materials and the reconfigurability of the liquid gain medium, we demonstrate the tunability of such single mode DFB liquid dye lasers.

6.2 Chip design

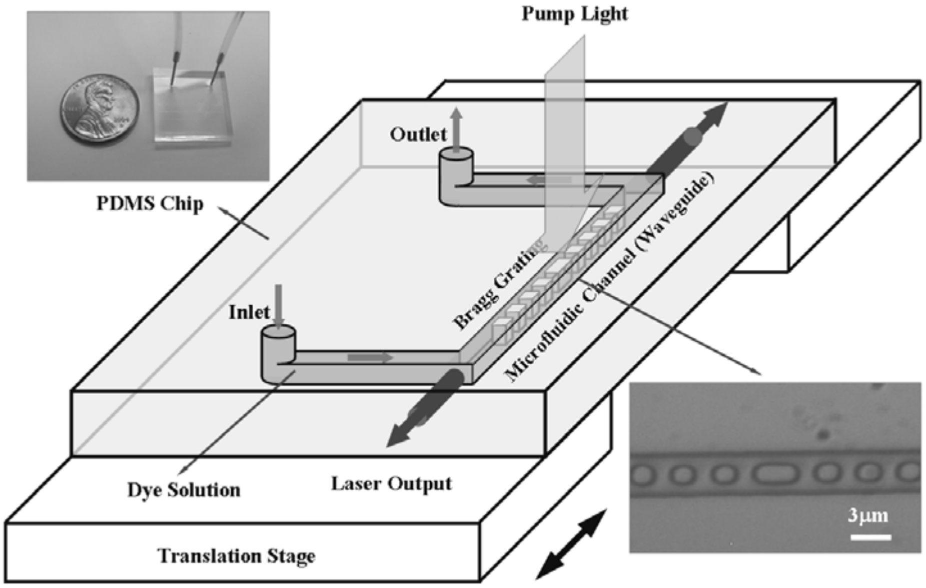

Figure 6.1. Schematic diagram of a mechanically tunable optofluidic DFB dye laser chip. The upper inset shows an actual monolithic PDMS laser chip. The lower inset is an optical micrograph of the central phase-shifted region of the laser cavity. A Bragg grating with 3080 nm period is embedded in a 3 μm wide microfluidic channel. The channel height is 2 μm. The size of the PDMS posts is about 1.28 μm×1.8 μm inferred from the optical micrograph. The central, larger PDMS post introduces an effective *π/2* phase shift to ensure single wavelength lasing. The movement of the translation stage deforms the chip, which causes the grating period to change.

As shown in Figure 6.1, the optofluidic DFB dye laser was fabricated on a monolithic PDMS chip using the replica molding soft lithography technique as described in [6]. 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 2 μm×3 μm 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 3080 nm period, which form a 1 cm long 15th order Bragg grating at wavelength around 570 nm. 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 [7]. The gain medium is a 2 mM solution of Rhodamine 6G (Rh6G) or Rhodamine 101 (Rh101) in a methanol and ethylene glycol mixture with refractive index of 1.409. The 6 ns Q-switched Nd:YAG laser pulses of 532 nm wavelength are focused by a cylindrical lens to a ~100 μm×1 cm wide stripe aligned with the microfluidic channel. The fabrication and operation of the laser chip is fully compatible with silicone elastomer-based microfluidics technology [8].

When a $\pi/2$ phase-shifted DFB structure is used to provide the optical feedback, the lasing wavelength is determined by the Bragg condition:

$$m\lambda_m = 2n_{eff}\Lambda \tag{6.1}$$

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. Given $\Lambda = 3080$ nm and $n_{eff} = 1.407$, the 15th resonant wavelength and the free spectral range (*FSR*) are 577.8 nm and 41.3 nm respectively. This large *FSR* ensures that at most two resonances can simultaneously appear inside the gain spectrum (typically 30–50 nm wide for dye molecules). Thus single frequency operation is obtained even at high pump levels due to gain discrimination. Figure 6.2 shows the simulated reflectivity spectrum of the overall structure using the Rouard’s method [9]. The parameters used are: $\Lambda = 1280$ nm + 1800 nm, grating length L = 1 cm, 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.

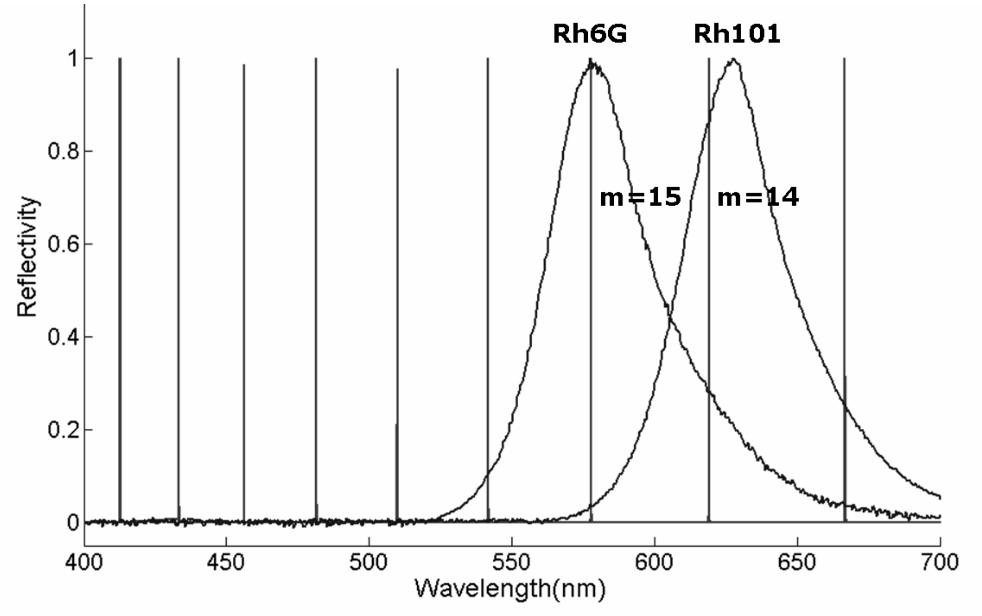

Figure 6.2. Simulated reflectivity spectrum of a *π/2* phase-shifted higher-order DFB structure. The parameters used are given in the main text. Also shown are the normalized measured fluorescence spectra of Rh6G and Rh101 solutions used in the lasing experiment.

6.3 Wavelength tuning

The lasing wavelength can be tuned by changing either n_{eff}, Λ, or m, as has been demonstrated in conventional DFB dye lasers [10]. 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 (~ 750 kPa) [11], the more straightforward tuning method is to change the grating period by simply stretching or compressing the chip along the waveguide direction. Finally, the grating order m can be chosen by using different dye molecules whose emission spectra cover different spectral regions. The last two methods were used in this work to achieve a nearly 60 nm tuning range from yellow to red. As can be seen from Figure 6.2, the potential tuning range for Rh6G and Rh101 is larger than 100 nm covering from 550 nm to beyond 650 nm. Actually, because of the multiple spectral resonances supported by the higher order grating, this laser can provide tunable output covering the whole available dye laser spectrum from 320 nm to 1200 nm [12] 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.

6.4 Results and discussion

To achieve the mechanical tuning, the laser chip was glued to two separate stages with the laser region suspended in the middle as shown in Figure 6.1. One of the stages is a high resolution micrometer with 1 μm 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 result of mechanical tuning is given in Figure 6.3. 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 565 nm to 594 nm and is from 613 nm to 638 nm for Rh101. When the length of the central suspended region is 1cm, the total chip deformations required to achieve the above tuning ranges are about 500 μm for Rh6G and 400 μm for Rh101, which correspond to 28 nm and 25 nm grating period changes respectively. Because of the extremely large allowed deformation of PDMS (> 120%), the ultimate tuning range is limited by the gain bandwidth. Only ~ 5% deformation was used to achieve the ~60 nm tuning range. We believe an even wider tuning range from 550 nm to 650 nm 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

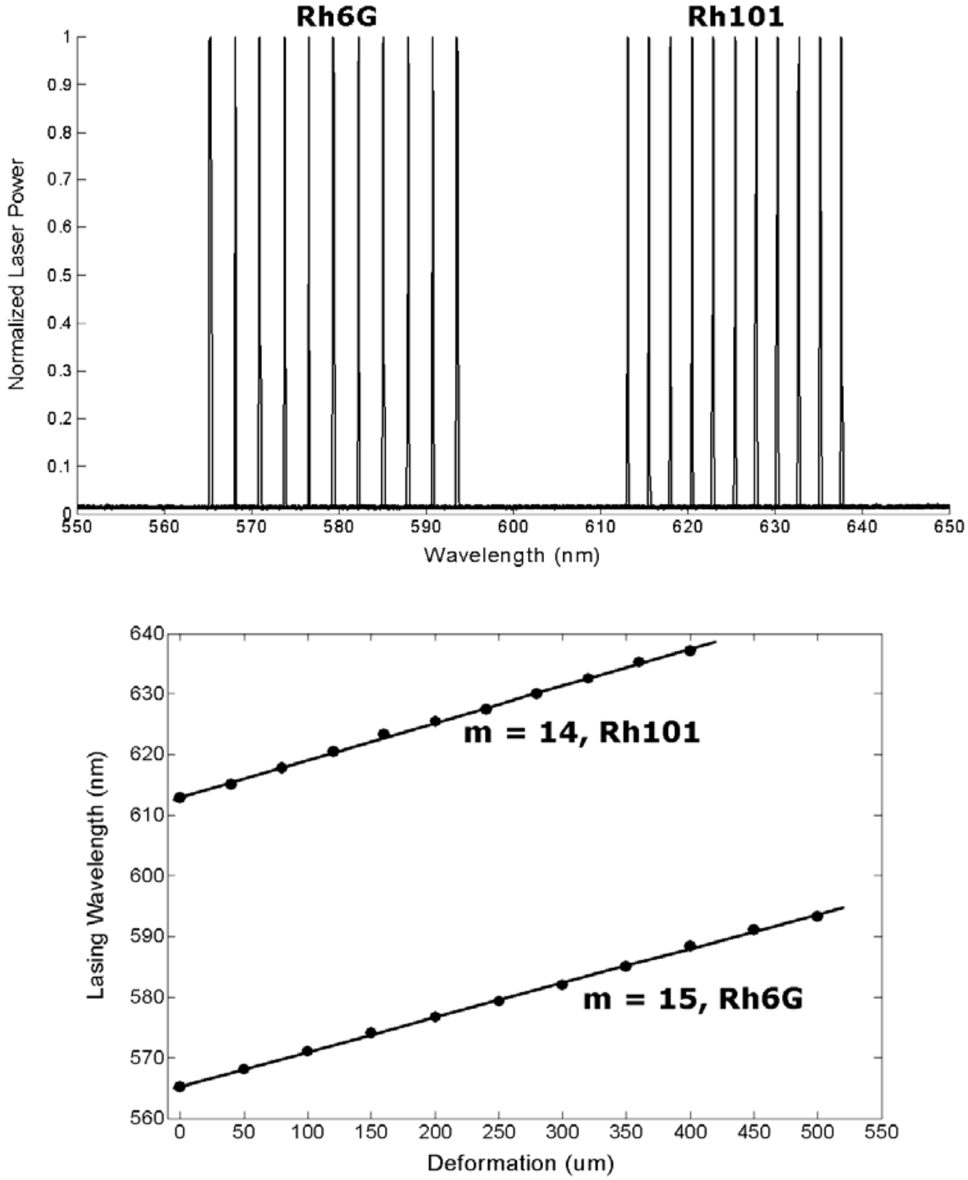

Figure 6.3. Upper: Normalized laser output of the mechanically tunable optofluidic DFB dye laser. Different peaks correspond to different grating periods. The measured laser linewidth is less than 0.1 nm throughout the tuning range. Lower: Lasing wavelength vs. the measured chip deformation. The points are the experimental data and the curve is the linear fit. The achieved single-mode tuning range for Rh6G is from 565 nm to 594 nm and is from 613 nm to 638 nm for Rh101.

operation was maintained with measured linewidth < 0.1 nm, resolution limited by the spectrometer (Ocean Optics HR4000). The absorbed pump thresholds are ~ 150 nJ and ~

200 nJ 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.

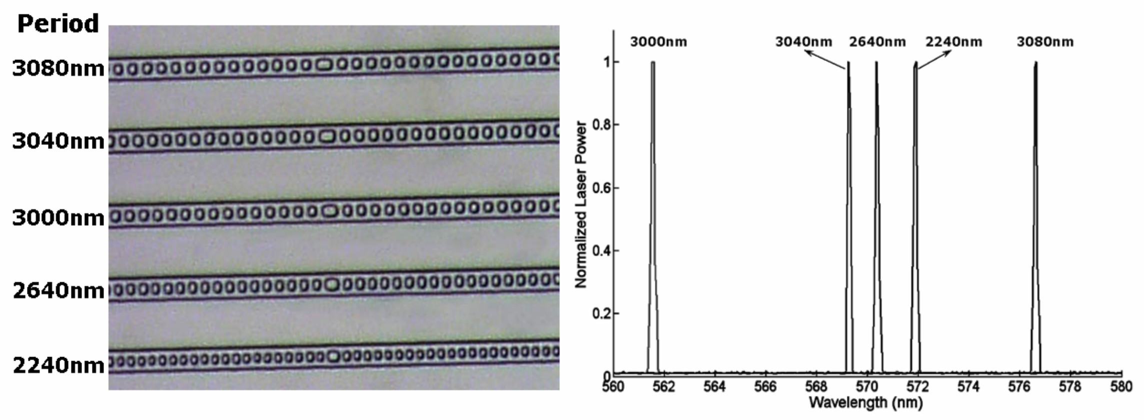

Figure 6.4. Left: Optical micrograph of an integrated array of five optofluidic DFB dye lasers. The grating period of each laser is given on the left. Right: Normalized laser output of the array using Rh6G dye solution as the gain medium

We also fabricated an array of five DFB dye lasers on a single PDMS chip. Figure 6.4 shows the lasing results using the Rh6G dye solution. Laser output spanning a ~ 15 nm range was achieved with different grating periods. The low pump threshold (< 1 uJ) 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 [13].

6.5 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 ~ 60 nm 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 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.

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