Single mode optofluidic distributed feedback dye laser

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

Department of Electrical Engineering, California Institute of Technology, Pasadena, California 91125
zhenyu@caltech.edu

Abstract: Single frequency lasing from organic dye solutions on a monolithic poly(dimethylsiloxane) (PDMS) elastomer chip is demonstrated. The laser cavity consists of a single mode liquid core/PDMS cladding channel waveguide and a phase shifted 15th order distributed feedback (DFB) structure. A 1mM solution of Rhodamine 6G in a methanol and ethylene glycol mixture was used as the gain medium. Using 6 nanosecond 532nm Nd:YAG laser pulses as the pump light, we achieved threshold pump fluence of ~0.8mJ/cm^2 and single-mode operation at pump levels up to ten times the threshold. This microfabricated dye laser provides a compact and inexpensive coherent light source for microfluidics and integrated optics covering from near UV to near IR spectral region.

OCIS codes: (140.2050) Dye lasers; (140.3490) Lasers, distributed-feedback; (140.3570) Lasers, single-mode; (230.4000) Microstructure fabrication; (230.7380) Waveguides, channeled; (130.0130) Integrated optics

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1. Introduction

Recently, several groups have demonstrated on-chip liquid dye lasers using different materials and laser cavity geometries [1, 2, 3]. Such lasers allow the integration of coherent light sources with other microfluidic and optical functionalities, and are of great interest for making fully functional ‘lab-on-a-chip’ systems. However, the lack of both transverse mode and longitudinal mode selection in the previous demonstrations led to multiple mode operation and wide emission linewidths (~5nm) that are hard to distinguish from amplified spontaneous emission (ASE). Balslev and Kristensen [4] recently demonstrated a microfluidic dye laser using a ~130th order Bragg grating imprinted on a glass substrate without transverse confinement. Approximately single spatial mode operation was observed due to the high losses of higher order spatial modes. In this paper we present a single mode optofluidic dye laser using a phase shifted 15th order distributed feedback (DFB) structure embedded in a single transverse mode channel waveguide. DFB cavities combined with 3D optical waveguides are very efficient structures for making single frequency microfabricated lasers [5]. Their implementation on a microfluidic chip will greatly improve the performance of microfabricated liquid dye lasers.

2. Chip design and fabrication

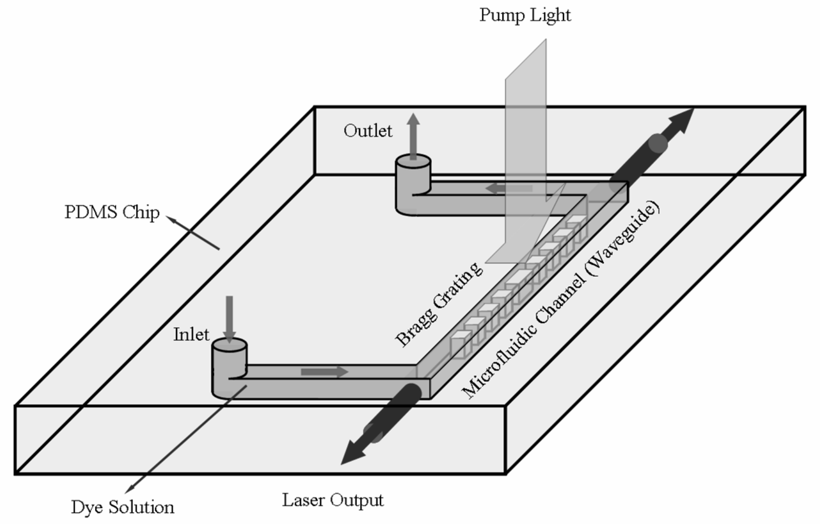

Fig. 1. Schematic diagram of a monolithic optofluidic DFB dye laser chip.

The schematic diagram of our device is shown in Fig. 1. The laser chip is entirely made of poly(dimethylsiloxane) (PDMS), a silicone elastomer which has become popular for microfluidics and nanofabrication [6, 7], and has good optical properties in the visible region. A sufficiently small microfluidic channel when filled with a dye solution of higher refractive index than that of PDMS ($n_{\mathrm{PDMS}} = 1.406$) acts as a single mode optical waveguide. The gain medium is a 1mM solution of Rhodamine 6G in a methanol and ethylene glycol mixture with refractive index of 1.409. The periodic PDMS posts inside the channel form a 4mm long 15th order Bragg grating which provides the optical feedback necessary for the laser action. In addition, a 15π phase shift is introduced at the center of the grating to ensure single frequency operation. The PDMS posts also provide support for the microfluidic channel.

The fabrication of the optofluidic DFB dye laser uses the same replica molding soft lithography technique which is widely used to make microfluidic devices [8, 9]. 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-

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on-glass mask. The mold was treated with tetramethylchlorosilane (Aldrich) for 3 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°C 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°C overnight. Figure 2 shows an optical micrograph of the central phase shifted region of the laser cavity.

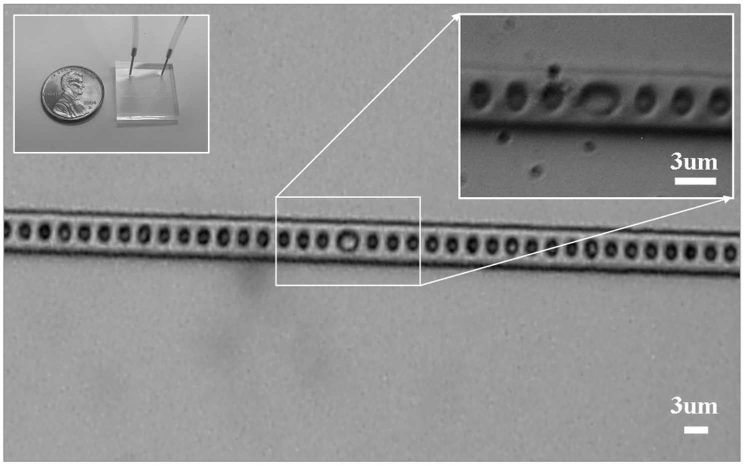

Fig. 2. Optical micrograph of a microfluidic channel with an embedded phase shifted 15th order DFB structure on a PDMS chip. The grating period is 3μm. The channel width is 5μm. The central larger PDMS post introduces a 15π phase shift. The upper left inset shows the picture of a actual optofluidic dye laser chip.

3. Longitudinal and transverse mode selection

To make a single mode laser, both the transverse mode and longitudinal mode selection need to be carefully designed. The waveguide dimensions (width 5μm; height 2μm) are chosen such that when filled with liquid of refractive index 1.409 it only supports the two fundamental E_{11} modes. If we define the x direction along the width and the y direction along the height, the E_{11}^{x} mode (transverse E field along x direction, TE-like) is more confined than the E_{11}^{y} mode, and thus is the preferred lasing mode. 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 per fill).

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 [5] and Λ is the grating period. The free spectral range (*FSR*) is given by:

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

Therefore for a DFB structure with Λ = 3μm (1.5μm + 1.5μm) and n_{eff} = 1.407, the 15th resonant wavelength and *FSR* are 563nm and 40.2nm respectively. In addition the even order resonances are absent when a 50% duty-cycle square-wave shaped grating is used. The resulting effective *FSR* of ~90nm ensures a single resonance 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 [10]. To break this degeneracy, a $14\pi + \pi$ phase shift is introduced at the center of the grating. Figure 3 shows the simulated reflectivity spectrum of the overall structure using Rouard's method [11]. The parameters used are: Λ = 1.5μm + 1.5μm, grating length L = 4mm, 15π phase shift at the center, core index n_{core} = 1.409, and cladding/post index n_{clad} = 1.406. It is clearly seen that only the 15th resonance falls in the gain spectrum of Rhodamine 6G. The inset of Fig. 3 shows the detailed 15th resonance, where the high-pass dip inside the stop band corresponds to the lasing mode.

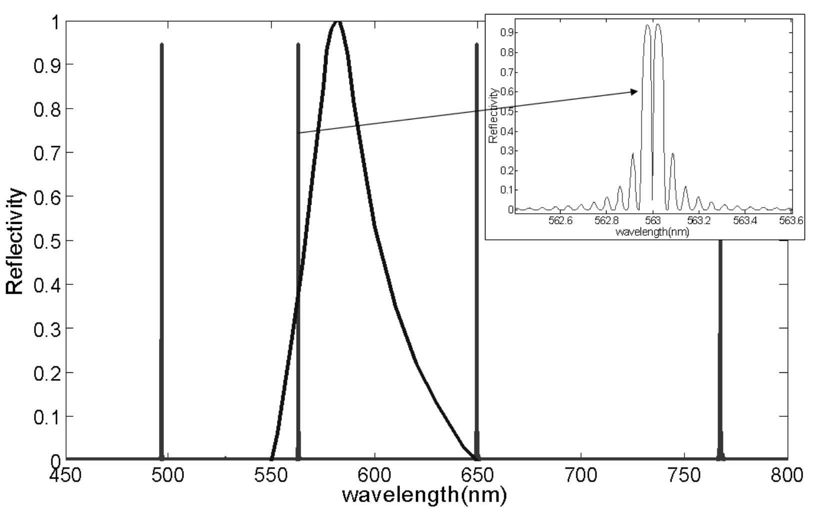

Fig. 3. Simulated reflectivity spectrum of a 15π phase shifted 15th order DFB structure. The curve spanning from 550nm to 650nm is the gain spectrum of Rhodamine 6G. The inset shows the enlarged plot the 15th resonance at 563nm.

An interesting property of the higher order DFB structure is that it enables multicolor lasing in the same cavity each at a single frequency. For example, Fig. 3 shows that the DFB structure employed in this work can support 497nm, 563nm and 650nm lasing as long as a suitable dye is chosen for each wavelength. This is a highly desired feature for applications where multi-wavelength laser sources are needed such as multi-color flow cytometry [12] and multiplex real time polymerase chain reaction (PCR). However, compared with the first order DFB structure, higher order DFB cavities are less efficient in terms of light confinement because the coupling coefficient is inversely proportional to the order of the Bragg scattering [13]. This can be compensated by increasing the cavity length to provide strong enough feedback.

4. Results and discussion

The dye solution was introduced into the microfluidic channel by applying 10psi pressure at the inlet port. We found, to operate the laser in the pulsed mode, it is not necessary to circulate the dye solution. The laser chip was optically pumped with 6ns Q-switched Nd:YAG laser pulses of 532nm wavelength, focused to a ~100μm wide stripe aligned with the microfluidic channel. A 10X microscope objective was used to collect the emission light from one edge of the chip and deliver it to a fiber coupled CCD-array based spectrometer with 0.1nm resolution (Ocean Optics HR4000). A typical single mode lasing spectrum is shown in Fig. 4 where the lasing wavelength is 567.3nm, very close to the predicted value 563nm. The measured linewidth is 0.21nm. A plot of laser output energy versus the absorbed pump energy is shown as the inset **B** of Fig. 4. The threshold pump fluence is estimated to be ~ 0.8mJ/cm^2, which gives a peak pump intensity around 150kW/cm^2. The laser remains single mode at pump levels as high as 8mJ/cm^2. At moderate pump intensities (~ 200kW/cm^2) and 10Hz repetition rate, stable laser output lasted longer than 20 minutes and the chip can be reused many times after proper cleaning with ethanol.

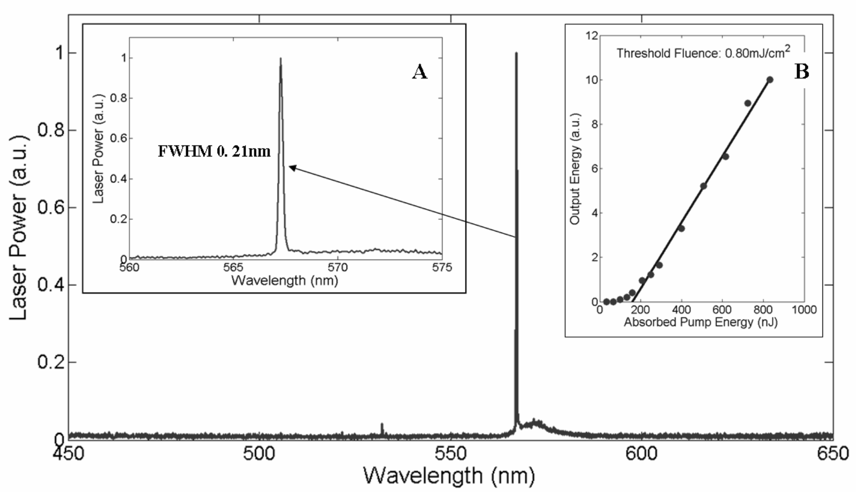

Fig. 4. Optofluidic DFB dye laser spectrum. The measured linewidth is 0.21nm. The inset **B** shows the output energy vs. the absorbed pump energy curve. The threshold pump fluence is ~ 0.8mJ/cm^2.

The elasticity of silicone elastomer and the microfluidics compatibility of the laser chip immediately suggest two wavelength tuning mechanisms. First, the grating period is easily tunable by stretching or compressing the whole chip due to the low Young's modulus of PDMS (~750kPa) [6]. Second, the refractive index of the dye solution can be tuned by mixing 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). Furthermore, different dye molecules can be used to cover an even larger spectral range. The mixing, switching and delivery of dye solutions can all be implemented on a silicone elastomer microfluidic chip using the recently developed mechanical micro valves and pumps [9].

5. Conclusions

In summary, we have proposed and demonstrated a phase shifted 15th order DFB structure as the optical cavity in an optofluidic dye laser system. Single mode operation was obtained with pump fluence from 0.8mJ/cm^2 to 8mJ/cm^2. The measured laser linewidth is 0.21nm. The fabrication and operation of the laser chip is fully compatible with silicone elastomer based microfluidics technology.

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