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On-chip tunable optofluidic dye laser

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Abstract. We demonstrate a chip-scale tunable optofluidic dye laser with Au-coated fibers as microcavity. The chip is fabricated by soft lithography. When the active region is pumped, a relatively low threshold of 6.7 μJ/mm^2 is realized with multimode emission due to good confinement of the cavity mirrors, long active region, as well as total reflectivity. It is easy to tune the lasing emission wavelength by changing the solvent of laser dye. In addition, the various intensity ratios of multicolor lasing can be achieved by controlling flow rates of two fluid streams carried with different dye molecules. Furthermore, the convenience in fabrication and directional lasing emission outcoupled by the fiber make the tunable optofluidic dye laser a promising underlying coherent light source in the integrated optofluidic systems. [DOI: 10.1117/1.OE.55.11.116117]

Keywords: dye lasers; microcavity devices; lasers; tunable; optical confinement and manipulation.

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1 Introduction

Optofluidic dye lasers have drawn much attention in the past decade due to the advantages of less dye consumption, low threshold, compactness, and portability.[1–3] As the essential component to the photonic laser sources in integration with micrototal analysis systems for lab-on-chip applications, various kinds of feedback cavities have been explored to enhance the confinement, including Fabry–Pérot (F–P) cavities,[4–6] embedded distributed feedback (DFB) gratings,[7–9] optofluidic ring resonators (OFRRs),[10–13] microdroplet cavities,[14–16] and random laser cavities.[17–19] In these lasers, the gain medium used widely is a dye mixed within a solvent. An important advantage of the gain medium in fluid form resides in its capability of controlling lasing characteristics by simply replacing one fluid with another,[20]combining different dye molecules in a solvent,[21] manipulating the liquid flow rate of liquid core and cladding,[6] and so on. Meanwhile, the tunable optofluidic laser has also been demonstrated by taking advantage of the high elasticity of polydimethylsiloxane (PDMS) in order to tune the periodicity of a Bragg grating.[22] In addition, researchers have achieved lasers with single-mode operation,[7,10] multicolor emission,[21,23] as well as fast switching.[14] Among those microcavities, F-P cavities show the advantages in ease of implementation and good compatibility. For example, single-mode emission has been demonstrated by utilizing a short F-P cavity,[24] which avoided the precise Bragg gratings design in DFB systems.[7] On-chip F-P cavity laser was used to measure the refractive index (RI) of single living cells.[25] Recently, wavelength tunable dye laser was also achieved by changing the translation stage with Au-coated end face of single-mode fiber easily.[26]

In this paper, we present an on-chip optofluidic dye laser with a 5-mm-long path length F-P cavity formed by two Au-coated end faces of commercial multimode fibers. The chip is fabricated by soft lithography[27,28] with PDMS. When the active region filled with dye solution is pumped, it exhibits multimode emission with a narrow linewidth and relatively low threshold. The main advantages of the fiber based on optofluidic dye laser are as follows. First, the linewidth of our device is reduced to less than 1 nm for single longitudinal mode when the pump intensity is slightly larger than threshold. However, the previous F-P microcavity lasers[4,21] have larger linewidth, around 4 to 6 nm. Second, due to good parallelism of the cavity mirrors, long active region, as well as total reflectivity, the relatively low threshold of 6.7 μJ/mm^2 is achieved with a flow rate of 2 μL/min to avoid dye bleaching and heating problems. Third, the output wavelength could be tuned by changing the solvent of laser dye and the various output intensity ratios of multicolor lasing are realized by controlling flow rates of two fluid streams carried with different dye molecules. More importantly, it is simple to fabricate and can be easily integrated in lab-on-a-chip systems by using the fiber to achieve directional lasing output.

2 Fabrication Processes and Experimental Setup

Figure 1(a) shows the schematic picture of the tunable optofluidic dye laser chip. It consists of a 5-mm-long active region, which is terminated at both ends with T-junctions, for dye to flow and two fiber ports to hold the Au-coated fibers acting as the resonator mirrors. To avoid the Au-coated fiber being hydrophobic, the fiber ports are designed to be 30 μm away from the T-junctions to separate the end faces of fibers from the flowing dye. As the microscope image shows, the coated fiber in the fiber port has a cleaved end face and is very close to the T junction. The width of the fiber forts is designed to be 125 μm, the same as the outer diameter of coated fibers, which makes sure that the cavity mirrors are paralleled in alignment. And the waveguide is 100 μm in width and all features are 125 μm in height.

To fabricate the optofuidic channels and fiber ports, PDMS is chosen as basic material and conventional soft lithography is used. To construct the fiber-based F-P microcavity, a thin

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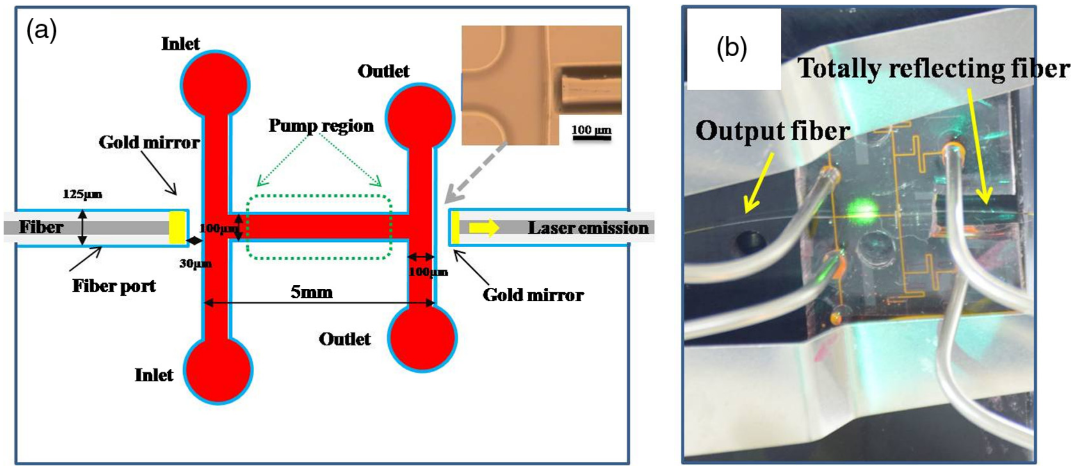

Fig. 1 (a) Top-view digram of the tunable opotofluidic dye laser based on F-P cavity. The dimensions of the active region are 125 μm × 125 μm × 5 mm (height × width × length). Inset image: The microscope image of a coated fiber in the fiber port. (b) A tunable microcavity dye laser chip used in the experiment. The laser emission is coupled out through fiber to be detected.

layer of Ti/Au is coated to the end faces of two bunches of multimode fibers using the physical vapor deposition method. The thicknesses of Ti/Au are coated to be 30/150 nm (reflectivity about 85%) for one bunch of fibers and 5/40 nm (reflectivity about 61%)[29] for the other acting as the output fibers by controlling the vapor time, respectively. The material Ti here is to enhance the adhesive between silicon and Au. At last, the on-chip optofluidic dye laser based on F-P cavity is formed by inserting the well-coated fibers into the prepared PDMS chip carefully.

For experiment setup, Fig. 1(b) shows a tunable microcavity dye laser chip used in the experiment. The laser emission is coupled out through fiber to be detected. Considering the 5-mm-long active region is slightly larger than 4 mm diameter of the pump spot, the chip is directly pumped by a Nd:YAG laser (532-nm center wavelength, 6-ns pulse width, and 10-Hz repetition rate) without a lens, which also simplifies the experiment and protects the PDMS chip from damage. The chip is fixed on a one-dimensional adjustment of lifts so that the pump light could be easily coupled onto the active region in the direction of being perpendicular to the microchannel. The laser emission which is coupled out through fiber contacted in the chip is analyzed by a high resolution spectrometer (AVaSpec 2048-FT, Avantes, spectral resolution = 0.09 nm).

3 Results and Discussion

In contrast to OFRRs, F-P cavity laser has no requirement for RI of the dye solution. For initial characterization, the laser dye R6G dissolved in alcohol (RI = 1.36) with a concentration of 6 mM is injected into the waveguide channel by utilizing a syringe pump (PHD 2000, Harvard Apparatus) through one inlet. The flow rate is chosen to be 2 μL/min, which provides a sufficient replacement of dye molecules in the laser cavity to avoid problems in heating or dye bleaching. Figure 2(a) shows the typical emission spectra of fiber-based optofluidic dye laser at various pump pulse intensity from a long distance which aims at the removal of strong fluorescence. The fiber-based F-P cavity offers good confinement of light. When the pump energy is low, the F-P cavity cannot support efficient optical feedback, leading to a broad spontaneous emission. As the pump intensity

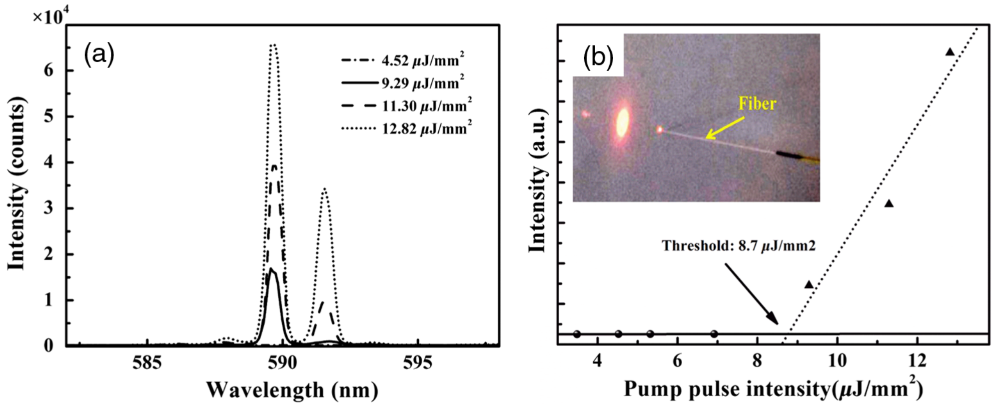

Fig. 2 (a) Typical emission spectra of tunable optofluidic dye laser at various pump pulse intensity with R6G dissolved in alcohol. (b) Output intensity of the tunable optofluidic dye laser as a function of the incident pump pulse intensity with R6G dissolved in alcohol. Inset image: the photograph of lasing spot outcoupled by multimode fiber.

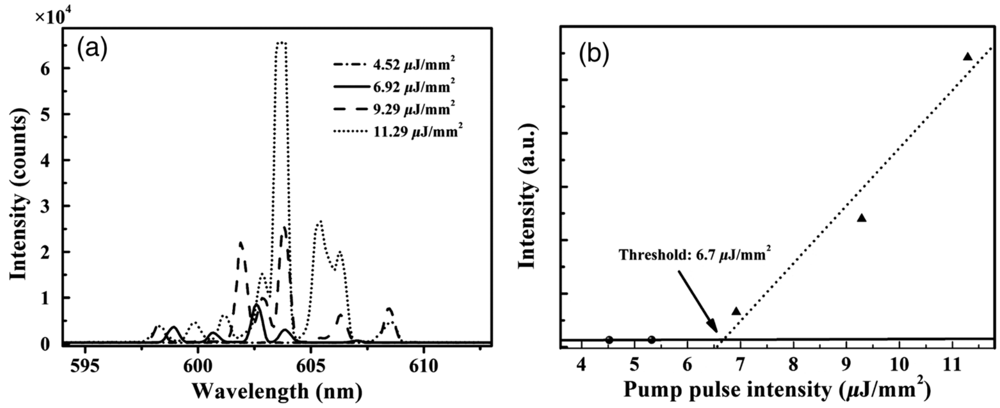

Fig. 3 (a) Typical emission spectra of tunable optofluidic laser at various pump pulse intensity with R6G dissolved in benzyl alcohol. (b) Output intensity of the tunable optofluidic laser as a function of the incident pump pulse intensity with R6G dissolved in benzyl alcohol.

increases, multimode laser emission is observed with multiple sharp peaks ranging from 589 to 592 nm. Typically, such a set of sharp spectral features indicates that the microcavity offers coherent optical feedback. The inset image of Fig. 2(b) shows the photograph of lasing spot outcoupled by multimode fiber at relatively low pump pulse intensity. In addition, as Fig. 2(b) shows, the nonlinear relationship between the output intensity and pump pulse intensity indicates a lasing threshold of 8.7 $\mu\mathrm{J/mm}^2$. It is worth noting that when the pump pulse intensity is slightly larger than the threshold, the linewidth reduces to less than 1 nm immediately.

We could further improve the properties of the tunable laser by adjusting the RI contrast between the liquid core and PDMS via injecting 6-mM R6G in benzyl alcohol (RI = 1.54) into the active region. Due to the larger RI of the benzyl alcohol compared with that of the PDMS, light can be further confined in the waveguide, resulting from the residual reflectivity at the interfaces between the liquid core and PDMS. As the typical emission spectra show in Fig. 3(a), more longitudinal modes emerge with a wider range from 597 to 610 nm. Since the distance between two longitudinal modes is estimated to be about 0.04 nm within a 5-mm-long laser cavity. There exist more longitudinal modes that the spectrometer could not detect because of the limitation of resolution. Figure 3(b) plots the output intensity at various pump pulse intensity. It has a lower lasing threshold of 6.7 $\mu\mathrm{J/mm}^2$, indicating a strong confinement in this way. Compared with alcohol as the gain medium, such low threshold benefits from not only the good parallelism of the cavity mirrors and long active region but also the total reflectivity. In addition, the wavelength of the light output for dye R6G dissolved in benzyl alcohol has been shifted about 10 nm. The wavelength could be tuned continuously by adjusting the composition of a mixture of alcohol and benzyl alcohol.

To further explore the versatility, we demonstrate two laminar streams of 6-mM R6G and LDS722 both dissolved into separate benzyl alcohol in the microwave guide and achieve the tuning of output lasing intensity by manipulating the flow rates of the two dye solutions. The microscope images show the laminar flows corresponding to their left flow rates, respectively. The flow rate of R6G is fixed at 10 $\mu\mathrm{L/min}$ and the flow rate of LDS722 varies from 2 to 15 $\mu\mathrm{L/min}$. When the active region with two laminar fluid streams is pumped, the overlapped multicolor lasing emission intensity is tunable via the dynamic controlling of the optical and geometrical properties of the laminar fluid by changing the flow rates of two laser dye solutions. As shown in Fig. 4, various intensity ratios of multicolor lasing emission have been achieved, which opens a way to achieve white lasing emission even rainbow lasing emission using a mixture of many dye molecules without worrying about the chemical interaction. Because there is no chance for different dye molecules to interact, due to the property of laminar, the only mixing is the result of diffusion of molecules across the interface between the fluids. The curves are vertically shifted for clarity and the pump pulse energy density is 15.40 $\mu\mathrm{J/mm}^2$ for all curves.

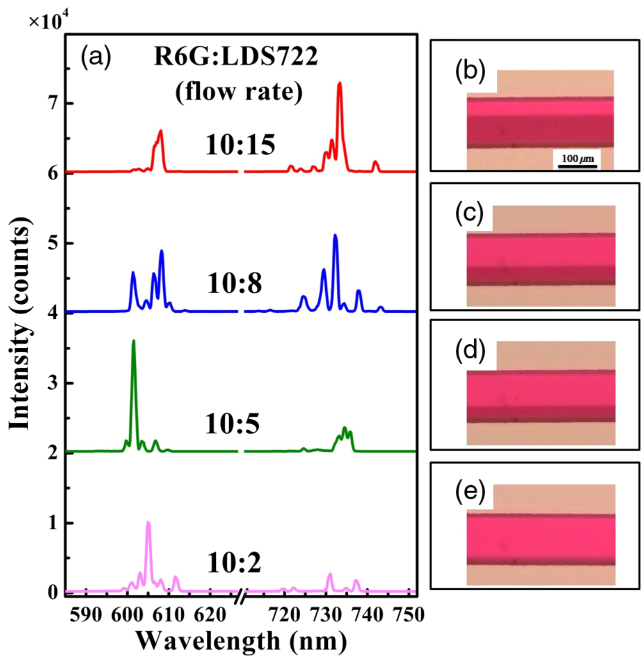

Fig. 4 (a) Lasing spectra from various ratios of laminar flow between R6G and LDS722 with a concentration of 6 mM dissolved in benzyl alcohol, respectively. (b–e) The corresponding microscope image of laminar flow.

4 Conclusion

In summary, we demonstrate a fiber-based long-path microcavity optofluidic dye laser with a relative low lasing threshold of 6.7 $\mu J/mm^2$, due to the good confinement of F-P cavity, long-path active region, and total reflection. Such a low threshold also shows strong competitiveness compared with other kinds of optofluidic dye lasers. The narrow linewidth less than 1 nm is achieved in a long-path microcavity for the first time. In addition, the emission wavelength can be tuned by varying the solvent composition of one dye molecule. The output intensities are changed by manipulating flow rates of two fluid streams carried with different dye molecules, which can be associated in arrays or cascades to generate integrated broadband light sources. Furthermore, the convenience in fabrication and the directional output by using the fiber also pave the way for integration with other optofluidic networks.

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