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Optofluidic microring dye laser embedded in polydimenthylsiloxane with reduced threshold

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We demonstrate an integrated optofluidic microring dye laser with a relatively low threshold on a polydimenthylsiloxane (PDMS) chip. The chip was fabricated through conventional soft lithography. It consists of a liquid waveguide with microring structure providing the feedback. A reduced threshold is realized due to the unique design of the bus waveguide across the center of the microring structure, which results in a great reduction in the cavity losses. Laser dye rhodamine 6G (R6G) dissolved in benzyl alcohol was injected into the microfluidic channel as the gain medium. When the dye laser was pumped with a pulsed laser at 532 nm, the dye laser oscillation was achieved with a threshold of only 4−5 μJ mm^{-2}. The convenience in fabrication and operation makes the optofluidic microring dye laser a promising underlying photonic component in the integrated optofluidic systems.

optofluidics, optofluidic microring dye laser, integrated optofluidic systems

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1 Introduction

Optofluidic dye lasers have drawn much attention in the past decade due to their great potential as photonic laser sources in integration with micro total analysis systems (μ-TAS) for lab-on-a-chip applications [1−5]. To date, optofluidic dye lasers have shown unique capabilities in biosensing applications by synergizing optofluidics and laser technology [6−9]. Since optofluidic dye lasers exhibit the advantages of low cost, compact and portability, various kinds of feedback cavities including Fabry-Perot resonators [10−12], distributed feedback (DFB) gratings [13−16], optofluidic ring resonators (OFRRs) [17−19] and microdroplet cavities [20, 21] have been exploited, leading to significant advancements such as large wavelength tunability [15, 22], single mode operation [16, 17] and fast-switching [21, 23] in optofluidic dye lasers. Optofluidic microring dye laser, first reported by Li et al. [24], has a great advantage compared with OFRR laser because it can be readily implemented on a microfluidic chip to make fully integrated and multifunctional device without worrying about the evaporation of the liquid dye. Bonding the microring structure with a flat PDMS slice ensures the long-term operation of the optofluidic microring laser, thus providing an attractive platform for integration with other microfluidic networks. However, on the other hand, the relatively low quality factor and large lasing threshold caused by the microring cavity losses limit the performance of the optofluidic microring dye laser.

In this work, we present an optofluidic microring dye laser with a unique structure by designing the bus waveguide across the center of the microring architecture. Compared with the previous optofluidic microring dye laser with the

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*Corresponding author (email: xfchen@sjtu.edu.cn) bus waveguide, our design exhibits good optical confinement in the contact region between bus waveguide and the microring (see Figure 1), which leads to a relatively low lasing threshold. We show that the microring laser emission can be obtained with a lasing threshold on the order of a few μJ mm^{-2}. Furthermore, the chip was fabricated via conventional soft lithography [25, 26] and can easily lead to mass production of the optofluidic microring dye laser.

2 Experiment

Figure 1(a) presents a schematic of the optofluidic microring dye laser consisting of a liquid-filled waveguide with an inlet and an outlet across the center of a microring resonator. Our design (Figure 1(b)) shows its unique feature of good light confinement in the contact region between the liquid waveguide and the microring compared with the previous research (Figure 1(c)). Two optofluidic dye lasers with different microring sizes were fabricated in this experiment. One is a microring with an outer diameter of 160 μm, the outer diameter of the other is 360 μm. The waveguides are 30 μm in width and all features are 20 μm in depth as shown in Figures 2(a) and 2(b). During the experiment, laser dye rhodamine 6G (R6G) dissolved in benzyl alcohol with a concentration of 2 mmol L^{-1} was injected into the waveguides using a syringe pump (PHD 2000, Harvard Apparatus) as depicted in Figures 2(c) and (d). Due to the larger refractive index (*RI*) of the benzyl alcohol (*RI* = 1.54) compared with that of the polydimenthylsiloxane (PDMS) (*RI* = 1.41), light can be well confined in the liquid microring waveguide.

The optofluidic micoring laser was pumped by a Nd:YAG laser (532 nm center wavelength, 6 ns pulse width and 10 Hz repetition rate). A convex lens with a focal length of 10 cm was employed to focus the light. In order to prevent the PDMS chip from damage by the extreme energy intensity at the focal point, the distance between the PDMS chip and the convex lens was fixed at 7 cm. The chip was placed on a three-dimensional adjustment of racks and lifts so that the pump light could be accurately coupled onto the microring structure. The emitted laser light was collected by another convex lens from one edge of the chip as shown in Figure 2(c) and then transmitted to a high resolution spectrometer (AVaSpec 2048-FT, Avantes, spectral resolution = 0.1 nm).

3 Results and discussion

For a microring laser, a stable oscillation in the cavity can be formed when the phase change for the light going a roundtrip in the microring is an integer multiple of 2π. The light waves are strengthened due to the interference, so the resonant wavelength of a microring is determined by the condition

$$m\lambda=2\pi n_{\mathrm{eff}}R,\quad m=1,2,3\cdots,\tag{1}$$

where λ is the resonant wavelength, n_{eff} represents the effective index and R is the outer radius of the microring. By derivation of both sides of eq. (1), we can get

$$\Delta\lambda=\lambda^2/2\pi n_{\mathrm{eff}}R,\tag{2}$$

where $\Delta\lambda$ is the free spectral range (FSR), which is defined as the wavelength difference between two neighbour modes. Figure 3(a) shows the output spectrum of the optofluidic microring dye laser with an outer diameter of 160 μm at different pump energies. The measured FSR (0.42 nm) was exactly the same as the theoretical one calculated from eq. (2). The lasing threshold was measured to be 5.5 μJ mm^{-2} as depicted in Figure 3(b). Figure 3(c) presents the lasing spectrum of another optofluidic microring dye laser with an outer diameter of 360 μm. It has a similar lasing threshold of 4.0 μJ mm^{-2}. In addition, the measured FSR (0.18 nm) was also well agreed with the theoretical calculation according to eq. (2) (0.19 nm).

In our future work, single mode optofluidic microring dye laser will be developed by using the Vernier effect.

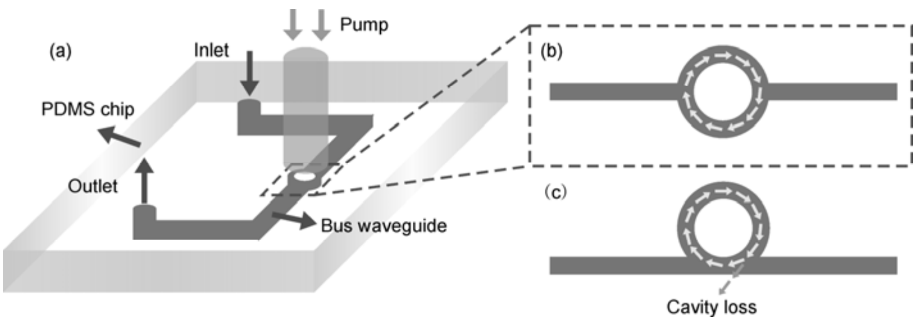

Figure 1 (a) Schematic diagram of the optofluidic microring dye laser; (b) optofluidic microring dye laser with the bus waveguide across the centre of the microring structure; (c) previous design of the optofluidic microring architecture by Li et al. in ref. [24], laser mode leak is more likely to happen in the contact region between the microring structure and the bottom liquid waveguide. The white arrows inside the microring resonator indicate the direction of the light propagation.

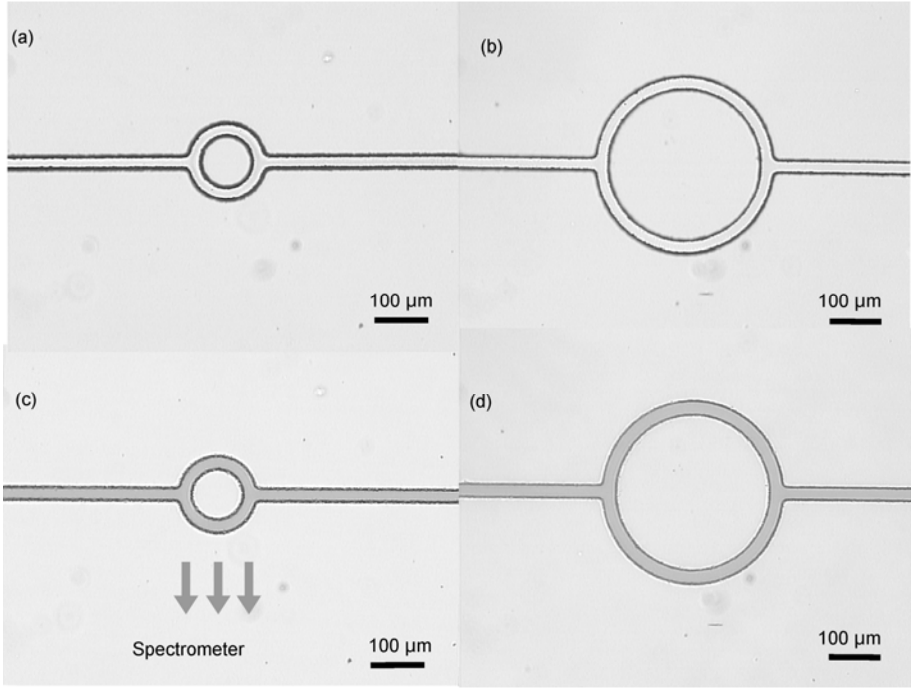

Figure 2 Microscope image of the optofluidic microring dye laser with an outer diameter of (a) 160 μm and (b) 360 μm. Microscope image of the microring filled with laser dye R6G dissolved in benzyl alcohol with an outer diameter of (c) 160 μm and (d) 360 μm.

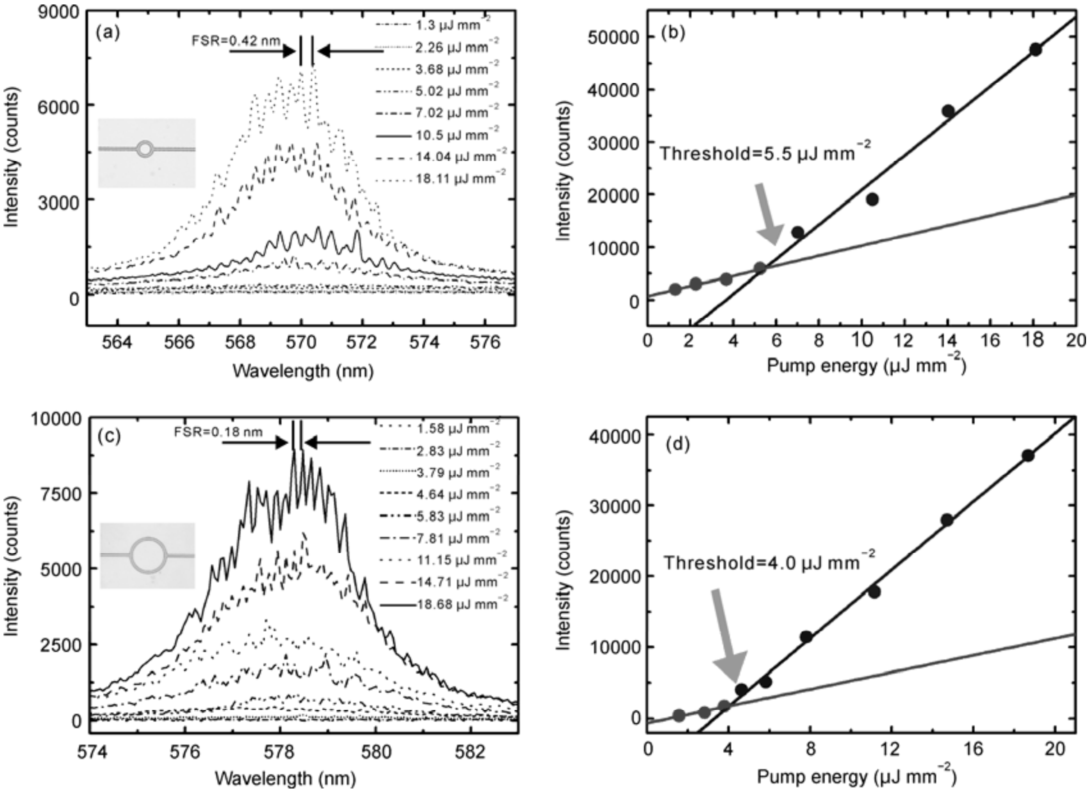

Figure 3 (a),(c) Emission spectra of the microring laser versus pump energy density with an outer diameter of 160/360 μm. Inset: microscope images of the corresponding microrings; (b),(d) output intensity of the microring laser as a function of the absorbed pump energy with an outer diameter of 160/360 μm.

Two microrings with slightly different diameters can be vertically coupled but physically disconnected via multilayer soft lithography techniques [27]. Real-time tunability in emission wavelength could be realized by changing the refractive index of the dye solution with the help of syringe pumps, which also makes the optofluidic microring dye laser an attractive platform in biosensor applications.

4 Conclusions

In summary, we demonstrate a novel optofluidic microring dye laser with reduced lasing threshold by designing the bus waveguide across the center of the microring structure, which results in a great reduction in cavity losses and thus enhances the performance of the optofluidic microring dye laser. A lasing threshold of 4–5 μJ mm^{-2} was achieved. Such a low threshold also shows strong competitiveness compared with other kinds of optofluidic dye lasers. Furthermore, bonding the microring structure piece with a flat PDMS slice and the convenience in fabrication not only pave the way for stable long-term on-chip laser operation, but also open the door to integration with other microfluidic networks to create more functionalities.

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