Single mode coupled optofluidic ring resonator dye lasers

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The authors demonstrate the single mode dye laser from a coupled optofluidic ring resonator that consists of a cylindrical ring resonator fused onto the inner surface of a thin-walled capillary ring resonator. The whispering gallery modes in each ring resonator interact strongly and utilize the Vernier effect to generate single mode laser emission. The lasing threshold is 3.0 $\mu J/mm^2$. The light can be coupled out through an optical taper in contact with the capillary. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3156861]

Optofluidic dye lasers are being investigated because of their broad applications in compact laser light sources and micrototal analysis systems for biochemical sensing.[1,2] Currently, three types of optical resonators are employed in optofluidic lasers: Fabry–Pérot (FP) resonators,[3–6] distributed-feedback (DFB) gratings,[7–10] and ring resonators. While tunable and single mode operation lasers have been realized using FP and DFB, the low Q-factors of these lasers ($\sim 10^3$) result in a relatively high lasing threshold.[3–10] In contrast, ring resonators, such as microdroplets,[11–13] microspheres,[14] microcylinders,[15] and microcapillaries[16–20] provide whispering gallery modes (WGMs) with much higher Q-factors ($>10^6$) to achieve low lasing threshold. Among various ring resonators, the optofluidic ring resonator lasers based on a thin-walled fused silica capillary exhibits superior performance due to inherent integration of the ring resonator structure with the capillary microfluidics.[16–20] The capillary nature allows the gain medium to flow through the core and interact with extremely high-Q WGMs ($\sim 10^9$), which offers an excellent optical feedback for low threshold lasing. Additionally, the lasing emission can be coupled out efficiently by fiber tapers or fiber prisms.[18,20] However, single mode lasing has not been demonstrated in capillary-based lasers to date, which limits their applications in laser spectroscopy and laser metrology. This limitation is shared by all other types of optofluidic ring resonator (OFRR) lasers as well.

In this letter, we use coupled OFRR (COFRR) to generate single mode laser emission. As illustrated in Fig. 1, the COFRR consists of a cylindrical ring resonator fused onto the inner surface of a thin-walled capillary ring resonator. When a solvent with a refractive index (RI) lower than that of the cylinder and the capillary is used, the cylinder and capillary both form a ring resonator and support the WGM that is present at the outer surface of the cylinder and inner surface of the capillary, respectively, to interact with the gain medium flowing through the capillary. Due to the Vernier effect, when the WGMs from each ring resonator are on resonance, they are coupled strongly with each other and provide strong optical feedback for lasing,[21,22] whereas lasing at the nonresonant WGM is suppressed. Due to the high Q-factors (10^6), i.e., sharp spectral linewidth (<1 pm) of the cylinder and capillary, there may exist only one set of resonant WGM within the gain medium spectrum, thus single mode lasing can be achieved. In addition, the COFRR fabrication method is highly compatible with commercial fiber drawing techniques for cost-effective mass production.[20]

To fabricate the COFRR system, a segment of a fiber (125 or 200 μm in diameter) without the polymer coating is first inserted into a fused silica capillary (Polymicro TSP530660, outer diameter=600 μm, wall thickness =40 μm) and then pulled and fused together under CO_2 laser irradiation. The resulting COFRR system consists of a thin-walled capillary (outer diameter=60 μm, wall thickness=5 μm) and a cylinder with 15 μm in diameter (COFRR 1) or 25 μm in diameter (COFRR 2). The contact area resulting from the fusion process is approximately 4–5 μm for both COFRRs.

Figure 1 presents the experimental setup for the COFRR dye lasers. We use 2 mM R6G dye in methanol as the gain medium, and circulate it through the COFRR at a flow rate of 10 $\mu l/min$. A pulsed laser (Opolette, 532 nm, 5 ns pulse width, and 10 Hz repetition rate) is loosely focused on the side of the COFRR such that it illuminates a 2 mm portion of the COFRR. The pump power is varied by an adjustable neutral density filter. The dye emission is collected through free space or by a fiber taper in contact with the COFRR, and is sent to a spectrometer (spectral resolution=0.12 nm).

We first investigate the nature of the coupling between the capillary and cylinder. In the experiment shown in the

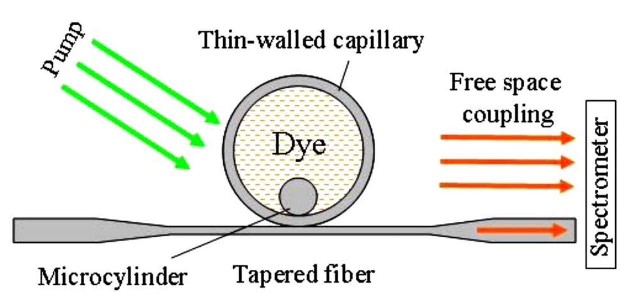

FIG. 1. (Color online) Conceptual illustration of COFRR lasers. The laser emission can be collected in free space or coupled out through a tapered fiber.

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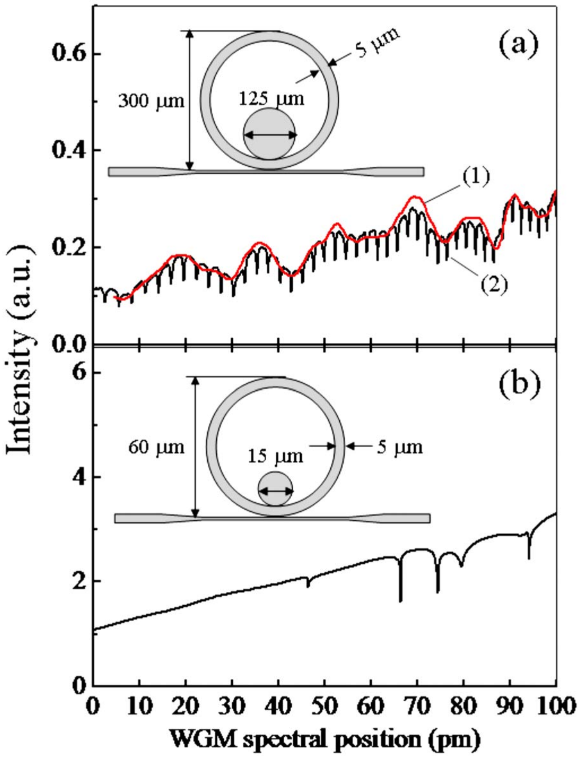

FIG. 2. (Color online) (a) 1550 nm laser transmission spectra measured at the distal end of the fiber taper. Curve (1) The WGM of the capillary in the absence of the fiber ring resonator. Curve (2) The modes when the fiber contacts the inner surface of the capillary. Inset: experimental setup. (b) 1550 nm laser transmission spectrum of COFRR 1 measured at the distal end of the fiber taper. Inset: experimental setup.

inset of Fig. 2(a), we fabricate a thin-walled capillary with an outer diameter of 300 μm and wall thickness of 5 μm by the HF wet etching technique. It is then placed in contact with a fiber taper. Light from a 1550 nm tunable diode laser is transmitted via the taper and scanned across a narrow wavelength range. Curve (1) in Fig. 2(a) shows the WGM of the capillary. The average spectral linewidth is about 3 pm, corresponding to a Q-factor of 5×10^5. The Q-factor is relatively low due to the surface roughness caused by the HF wet etching. When a fiber of 125 μm in diameter is inserted into the capillary and placed in contact with the inner wall of the capillary, much sharper modes from the fiber emerge and are superimposed onto the WGMs of the capillary [see curve (2) in Fig. 2(a)]. As a control, we replace the thin-walled capillary with a thick-walled one (wall thickness=10 μm), only the WGMs from the capillary is observed, and no WGM in the cylindrical ring resonator inside the capillary is excited. The above experiments show clearly that the WGMs in the capillary and cylindrical ring resonator inside are coupled with each other only when the capillary has a thin wall so that the WGM in the capillary has a sufficient evanescent field to excite the WGM in the cylinder ring resonator. Note that in Fig. 2(a), the WGMs from the capillary are sufficiently broad and thus overlap well with those of the cylindrical ring resonator. In the COFRR systems used in our lasing experiments, the WGMs in both capillary and cylinder are expected to be much sharper, making it difficult for the WGMs to be on resonance, which underlies the single mode lasing operation.

The empty Q-factor of the COFRR is characterized with COFRR 1, which is filled with nothing but air. There are much fewer spectral dips in Fig. 2(b) than in Fig. 2(a) because the COFRR has a smaller size. The empty Q-factor of the COFRR is 7×10^6 at 1550 nm. An even higher Q-factor can be deduced for 600 nm where the dye lasing occurs.

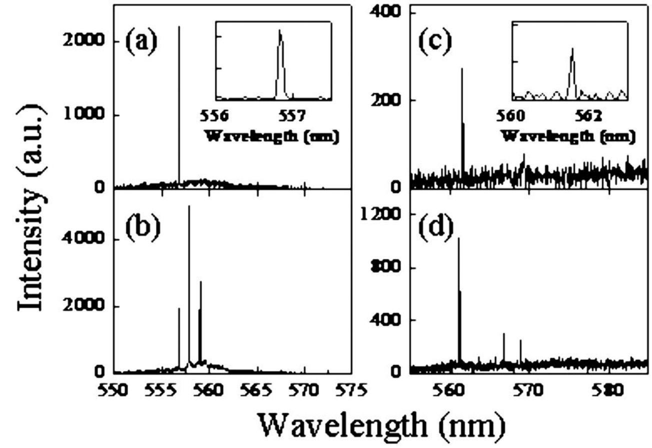

FIG. 3. (a) and (b) show R6G lasing spectra with COFRR 1. The laser emission is collected in free space. (a) Single mode emission spectra at low pump energy density. Inset: the high-resolution spectrum of the single mode. (b) Multimode emission spectra at high pump energy density. (c) and (d) show R6G lasing spectra of COFRR 2. The laser emission is coupled out through a fiber taper. (c) Single mode emission spectra at low pump energy density. Inset: the high-resolution spectrum of the single mode. (b) Multimode emission spectra at high pump energy density.

Figures 3(a) and 3(b) show the lasing spectra of the R6G lasers using COFRR 1. The emission is collected in free space. The single mode emission at 557 nm is measured when the pumped energy density is 9.8 μJ/mm^2 [Fig. 3(a)]. The high-resolution spectrum in the inset shows the linewidth of the single mode emission is limited by the resolution of the spectrometer. When the pump energy density is below 14.5 μJ/mm^2, the COFRR laser can keep stable single mode operation. When the pump energy density is 27.8 μJ/mm^2, multimode lasing emission is measured, as shown in Fig. 3(b). Note that according to the Vernier equation $\Delta\lambda\approx\lambda^2/\pi n_{\text{eff}}(D_1-D_2)$,[22] where n_{eff} is the effective RI of the COFRR, and D_1 and D_2 are the diameters of the thin-walled capillary and microcylinder resonator, respectively. The free spectral range (FSR) of the COFRR 1 is only 1.53 nm, much smaller than the R6G gain spectrum (20–30 nm). However, it should be pointed out that the Vernier equation is only an approximation. It is valid only when the linewidth of WGMs from both resonators are broad so that the optical modes have sufficient overlap after each FSR. In our experi-

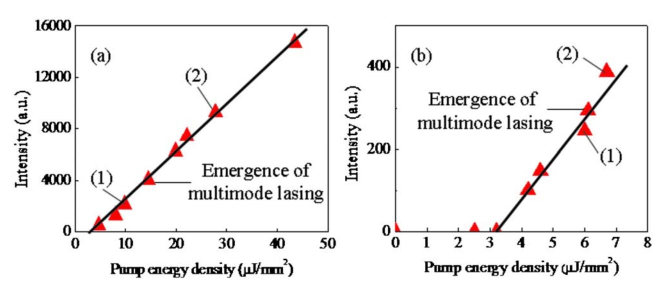

FIG. 4. (Color online) (a) Intensity of the lasing emission vs the pump energy density for COFRR 1. Triangles (1) and (2) correspond to the lasing spectra in Figs. 3(a) and 3(b), respectively. (b) Intensity of the lasing emission vs the pump energy density for COFRR 2. Triangles (1) and (2) correspond to the lasing spectra in Figs. 3(c) and 3(d), respectively.

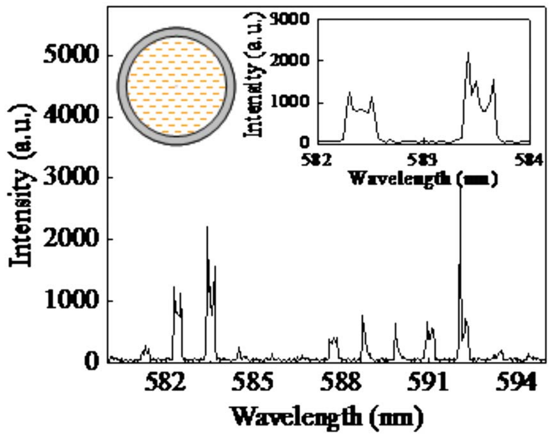

FIG. 5. (Color online) WGM lasing spectra of the capillary-based optofluidic laser. Left inset: cross-sectional view of the capillary laser. Capillary outer diameter=60 μm. Wall thickness=5 μm. Right inset: high-resolution spectrum.

ment, the Vernier equation is no longer applicable for the WGMs that have extremely sharp linewidths.

The ability to directionally couple out the laser emission is highly desirable in many applications.[18,20] Figures 3(c) and 3(d) show the R6G lasing spectra of the COFRR 2 coupled out through an optical tapered fiber in contact with the COFRR. Once again, at low pump energy densities [6.0 μJ/mm^2 for Fig. 3(c)], single mode lasing persists, whereas multimode lasing emerges with the increase in pump energy density [6.7 μJ/mm^2 for Fig. 3(d)]. In our experiments, nearly the same fiber out-coupling spectra are observed regardless the taper-capillary contact position along the capillary circumference.

Figures 4(a) and 4(b) plot the corresponding lasing intensity as a function of the pump energy density of COFRR 1 and COFRR 2, respectively. The lasing threshold is approximately 3.6 μJ/mm^2 for COFRR 1 and 3.0 μJ/mm^2 for COFRR 2, respectively. The thresholds are at par with or better than those for many polydimethylsiloxane-based optofluidic dye lasers.[4,9,10] Note that the lasing threshold of the COFRR laser is much higher than the best reported silica-based OFRR laser.[19] It is caused mainly by the loss to the fused area (4–5 μm in width) between the capillary and the cylinder, which spoils the Q-factor of the COFRR.[20]

To further verify the origin of the wavelength modulation of the COFRR lasers, a capillary of the same dimension in the absence of the cylinder ring resonator is filled with the same concentration of R6G and is pumped below 1 μJ/mm^2. A typical WGM lasing spectrum is shown in Fig. 5. Even at such low pump energy density, the periodic peaks are still measured between 581 and 595 nm. Additionally, the high-resolution spectrum in the inset shows the different radial order WGMs emerging at the same pump intensity due to their similar lasing threshold,[19] which is quite different from the spectrum shown in Fig. 3.

In summary, we demonstrate the single mode dye laser from a COFRR, which is integrated with capillary-based fluidics and can potentially be mass produced in a simple and cost-effective manner. The lasing threshold for the single mode oscillation is approximately 3.0 μJ/mm^2. Future works will be focused on the fabrication method to improve the intrinsic Q-factor of the COFRR lasers. Tuning of the single mode lasing will be also be pursued.

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