Optofluidic ring resonator based dye laser

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The authors demonstrate a microfluidic dye laser using a liquid core optical ring resonator (LCORR). The LCORR is made of a fused silica capillary with a wall thickness of a few microns. The circular cross section of the capillary forms a ring resonator that supports whispering gallery modes (WGMs) and provides an optical feedback for lasers. Due to the high Q factor of the WGM (10^7), a low lasing threshold is achieved (1 $\mu J/mm^2$). In addition, they show that the laser can be coupled out via a tapered fiber in touch with the LCORR, thus providing a mechanism for easy laser delivery. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2743884]

Optofluidics integrates photonics and microfluidics and is being explored for developing functional lab-on-a-chip systems.[1] Recently there is growing interest in microfluidic dye lasers that incorporate optical feedbacks with microfabricated fluidic channels.[2–7] These systems provide simpler liquid handling and optical settings at the microsized level, as compared to bulky conventional dye lasers. Optical feedback in these microfluidic dye lasers is provided by Fabry-Pérot-type cavities[2–4,7] or embedded distributed feedback gratings.[5,6]

Optical ring resonators in the form of microdroplets[8] and glass capillaries with a wall thickness of tens to hundreds of microns[9–12] have also been employed for a microfluidic laser. In a ring resonator, the whispering gallery modes (WGMs) form due to the light total internal reflection along the curved interface between the high and low refractive index (RI) media.[13] WGMs can have extremely high Q factors ($>10^6$) resulting in a significant reduction in lasing threshold. However, these ring resonator configurations impose a number of limitations that have hindered their applications as practical miniaturized optical devices. Microdroplets are difficult to manipulate and the related devices are hard to miniaturize.[8] In cylindrical ring resonators, dye solution is required to have a RI higher than that of the capillary wall ($n=1.45$), thus essentially becoming a ring resonator by itself.[9] High RI organic solvents are often toxic and may be chemically incompatible with plastic tubings and connectors that are a part of fluidics. Alternatively, a solid optical fiber is inserted into a larger diameter capillary,[10] or a polymer layer is coated on the capillary inner surface to act as a ring resonator.[11] In these three configurations, the laser light is predominantly confined within the inner part of the capillary and is accessible only through scattering. Additionally, polymer coatings are mechanically fragile and tend to degrade after a few hours of operation.[11] Recently, dye lasing was also observed with an ethanol ($n=1.36$) filled capillary.[12] However, the laser operation has to rely on very high order WGMs with much lower Q factors (10^3–10^4), drastically increasing the lasing threshold.

In this letter, we demonstrate another type of a micro optofluidic dye laser based on liquid core optical ring resonators (LCORRs).[14,15] As illustrated in Fig. 1, the LCORR is made of a glass capillary with an outer diameter (OD) of a few hundreds of microns and wall thickness of a few microns. When the core is filled with the low RI solvent, the cross section of the capillary forms a ring resonator. The wall of the LCORR is sufficiently thin so that the WGMs of high Q factors (10^7) can be exposed in the core to support the low-threshold laser oscillation. Additionally, the WGM has the evanescent field on the LCORR outer surface, enabling outcoupling of the laser through tapered fibers or waveguides in touch with it for easy light guidance. The LCORR serves as a ring resonator and as a microfluidic channel and requires no additional optical feedback components and alignment, which makes the LCORR laser insensitive to small vibrations. Furthermore, it is mechanically robust and chemically inert and can accommodate various solvents and dyes. Finally, as shown in Fig. 1(a), the LCORR is scalable to create an array of ring resonators along the capillary, thus providing multiple independent light sources.

Figure 1 presents the experimental setup for the LCORR dye laser. The fused silica LCORR (OD=75 μm and $n=1.45$) is fabricated using an in-house CO_2 laser pulling station, followed by HF etching of the interior surface, as detailed previously.[14] 1 mM R6G dye in ethanol is circulated through the LCORR with a peristaltic pump at a flow rate of 10 μL/min. A pulsed laser (Opolette, 532 nm, 10 ns pulse width, and 20 Hz repetition rate) is loosely focused onto the side of the LCORR through a cylindrical lens so that approximately a 3 mm portion of the LCORR is homogeneously pumped. The emission spectra are acquired by an Ocean Optics USB4000 spectrometer with a spectral resolution of 3.7 nm.

For characterization of the empty cavity Q factor, the LCORR is initially filled with ethanol in the absence of dye. We use a tunable diode laser at 690 nm and a wavelength close to the dye emission (~600 nm). The laser is transmitted via a fiber taper and is scanned in wavelength. When the laser wavelength coincides with the resonant wavelength of a WGM, the light is coupled into the LCORR, leaving a spectral dip at the fiber output. Figure 2(a) shows the spectral linewidth of 0.068 pm, corresponding to a Q factor of

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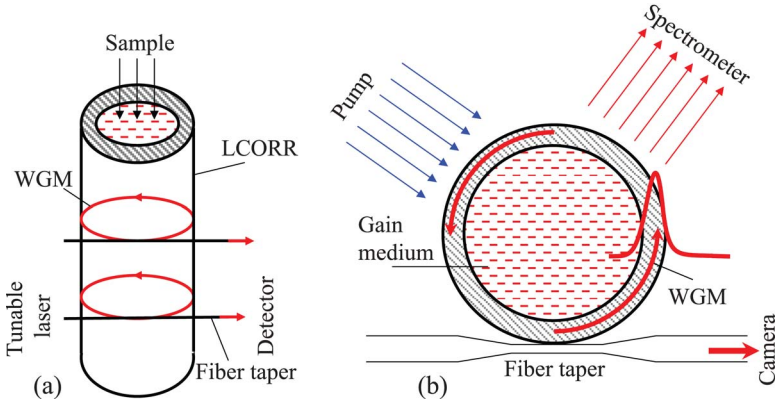

FIG. 1. (Color online) Schematic of an optofluidic laser based on the LCORR. (a) LCORR characterization (side view). (b) Optofluidic laser setup (cross-section view)—fiber taper is used to evanescently couple out the laser emission.

1.0×10^7, indicative of the high quality of the LCORR as a laser cavity. The observed Q factor has the contribution from the scattering loss at the LCORR inner surface, ethanol absorption, and fiber coupling loss, i.e., $Q^{-1}=Q_{\text{scatter}}^{-1}+Q_{\text{absorption}}^{-1}+Q_{\text{fiber}}^{-1}$. $Q_{\text{absorption}}$ is estimated to be much larger than 10^8 using the relation $Q_{\text{absorption}}=2\pi n/\eta\alpha\lambda$, where $\alpha=0.0015\ \text{cm}^{-1}$ is the ethanol absorption coefficient,[16] n and λ are the LCORR refractive index and the dye laser wavelength, respectively, and η is the evanescent fraction of the WGM light in the core. Q_{fiber} is approximately 50 times larger than $Q_{\text{scattering}}$ based on the undercoupling condition and the WGM depth ($\sim$7%) observed in Fig. 2(a).[17] Therefore, at 690 nm, the Q factor is mainly determined by the surface roughness resulting from the HF etching. For a comparison, at 1550 nm, a Q factor of 6×10^6 and in excess of 10^7 are obtained when the LCORR is filled with ethanol and air, respectively, indicating that the ethanol absorption plays a more significant role in determining the LCORR Q factor in the near infrared regime.

The LCORR wall thickness is important, as it determines the fraction of the light in the core that interacts evanescently with the gain medium. To precisely characterize the LCORR thickness noninvasively, we use the method developed previously,[14] in which various concentrations of water-ethanol mixtures are passed through the LCORR and the WGM spectral shift in response to RI changes in the core is monitored. We choose to use 1550 nm, as it is more sensitive than 690 nm.[15] By matching the experimental sensitivity results [Fig. 2(b)] with those obtained from our simulation based on Mie theory, we find that 3.5 nm/RIU (RIU denotes refractive index unit) corresponds to the second order radial mode and a wall thickness of approximately 3.8 μm. This wall thickness is close to what has been reported in Ref. 14, which was verified by scanning electron microscopy imaging.[14] As compared to the thick-walled capillaries,[12] the thin-walled LCORRs permit relatively large fraction of the evanescent field in the core for those lower order WGMs of much higher Q factors, as discussed later.

Figure 3(a) shows the LCORR emission spectrum at various levels of pump power. Below the lasing threshold, only a broadband R6G emission is observed. With the increased power, the laser starts to emerge at the longer wavelength side of the dye spectrum ($\sim$573 nm). Although the actual spectral linewidth and the free spectral range ($\sim$1 nm) are not fully resolved due to the low spectral resolution of the spectrometer, modulations in the lasing spectra can easily be identified. At a higher pump power ($>8\ \mu\text{J/mm}^2$), a new lasing peak related to a higher order WGM appears at 587 nm, as discussed in Ref. 10. Figure 3(b) plots the peak intensity of the emission at 573 and 587 nm versus the pump power density. The lasing threshold for 573 nm is estimated to be 1 $\mu\text{J/mm}^2$ per pulse, corresponding to a peak power density of 10 kW/cm^2. The laser emission persists when the excitation spot moves along the LCORR longitudinal axis or the resonator is tilted with respect to the pump laser. The LCORR can be rinsed and reused many times; dye solutions are easily changed to allow us for tuning in a broad wavelength range, as exemplified in the inset of Fig. 3(a).

The LCORR utilizes the gain in the evanescent field, which was studied in detail by Moon *et al.*[10] The lasing is achieved at the wavelength with the largest gain, which depends on the modified Q factor, ηQ. To identify the WGM responsible for the lasing, we analyze the radial distribution of fifth, sixth, and seventh order WGMs (Fig. 4) with modified Q factors of 6×10^3, 4×10^4, and 1.5×10^5, respectively. The observed lasing is at 570–580, indicating that the lasing

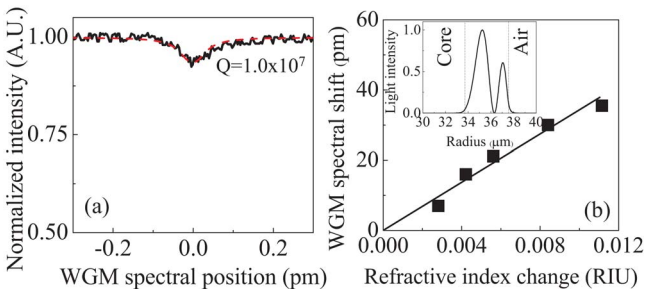

FIG. 2. (Color online) (a) Q factor measured at 690 nm. Lorentzian fit (dashed line) shows a linewidth of 0.068 pm. (b) Response of the WGM around 1550 nm to the RI change in the core. A sensitivity of 3.5 nm/RIU corresponds to a wall thickness of 3.8 μm. Inset: radial distribution of the second order WGM ($\sim$1550 nm).

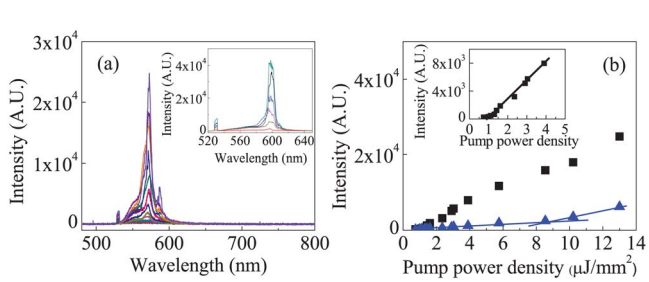

FIG. 3. (Color online) (a) emission spectra of the LCORR R6G laser. Inset: emission spectra of the rhodamine B dye laser. (b) Peak intensity at 573 nm (square) and 587 nm (triangle) vs pump power density for the R6G laser. Inset: the laser threshold for 573 nm peak is 1 $\mu\text{J/mm}^2$.

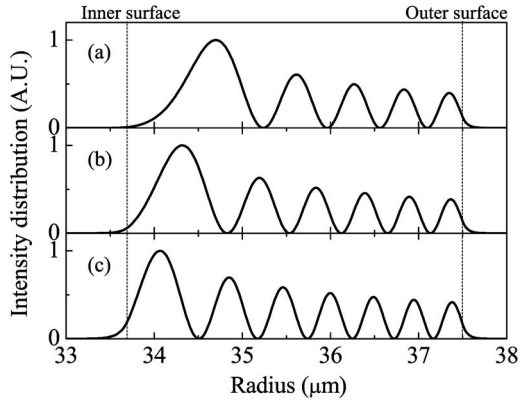

FIG. 4. Radial distribution for the (a) fifth, (b) sixth, and (c) seventh order TM WGMs near 570 nm with 0.06%, 0.4%, and 1.5% of the light in the core. RI: 1.36 (core), 1.45 (wall), and 1.0 (air).

mode is the sixth order WGM, according to the results in Ref. 10. The lower order WGMs are still confined within the wall and are inaccessible for lasing. Higher order WGMs (e.g., seventh order) have a larger portion of light in the core and their radiation and absorption limited Q factors are still higher than 10^8. However, lasing at a longer wavelength (587 nm) appears at a higher threshold (Fig. 3), suggesting that those modes may suffer degradation in Q factors due to the inner surface roughness. Note that although the LCORR lasing threshold is lower than in many microfluidic dye lasers[2,3,5,7], it is still two orders of magnitude higher than that in a core-resonance based capillary dye laser,[9] in which the modified Q factor is 2×10^6. The LCORR modified Q factor is also lower than that reported in Ref. 10 due to the lower η. Further reduction in the LCORR lasing threshold requires an increase in the fraction of the WGM in the core while avoiding Q factor degradation by the surface roughness.

The WGM laser can be outcoupled into the taper via evanescent coupling.[18] To achieve this, a tapered fiber is brought in touch with the LCORR [Fig. 5(a)]. The inset in Fig. 5(b) shows a picture of the laser output at the distal end of the fiber, which consists predominantly of the laser emission, as seen on the picture and as further verified by inserting a color filter. This corroborates that the laser is indeed supported by the WGM. In contrast, the green pump light,

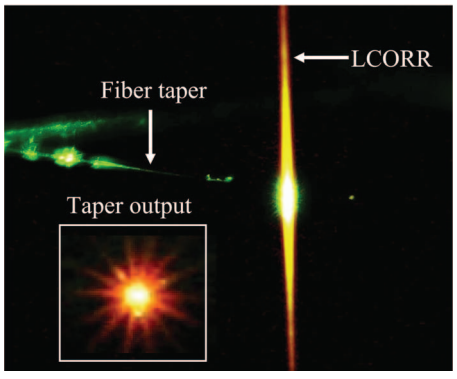

FIG. 5. (Color) Picture of experimental setup for directional laser outcoupling. Inset: dye laser output at the distal end of a tapered fiber.

although much stronger, does not circulate along the ring resonator and therefore is not coupled out. Therefore, the optical taper also acts as a filter to remove the undesirable excitation light.

The LCORR is scalable in the number of its laser channels. Previous work has shown that the crosstalk between two ring resonators along the LCORR becomes negligible if they are separated by 1 mm.[15] Therefore, multiple light sources will be obtained when multiple outcouplers are placed in contact with the LCORR. Additionally, the LCORR laser can potentially be scaled up in terms of the total output power by using large diameter fiber prisms[19,20] or a wide waveguides[21,22] to collect more light along the LCORR longitudinal axis.

In summary, we have demonstrated an optofluidic dye laser using the LCORR. Due to the thin wall, the high Q-factor WGMs (10^7) have sufficient exposure in the core, leading to a low laser threshold of only 1 $\mu J/mm^2$. The laser wavelength can be changed by simply adding a new dye solution to the LCORR. We have also shown the feasibility of directional laser coupling using a tapered fiber, which provides a mechanism for light delivery and filtering of the excitation light.

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