

Supplementary information for

Optofluidic laser array based on stable high-Q

Fabry-Pérot microcavities

Wenjie Wang,^{a*} Chunhua Zhou,^a Tingting Zhang,^a Jingdong Chen,^a
Shaoding Liu^a and Xudong Fan^{ab*}

^aKey Lab of Advanced Transducers and Intelligent Control System of Ministry of Education,
Taiyuan University of Technology, 79 Yingze Street, Taiyuan 030024, P. R. China

^bDepartment of Biomedical Engineering, University of Michigan,
1101 Beal Avenue, Ann Arbor, Michigan 48109, United States

*wangwenjie@tyut.edu.cn
*xsfan@umich.edu

I. Finesse measurement using the cavity scanning method

As an auxiliary method to characterize the p-c and p-p FP cavities in Type 1 and Type 2 chips, we measured the transmission spectrum at a fixed laser wavelength using the scanning cavity method.^[1] Experimental setup is shown in Fig. S1. The wavelength of a single-mode cw laser was fixed at $\lambda_0=561$ nm. Plano mirror M1 (without any concave structure) was mounted in a one dimensional translation stage (Stage 1) that could move along the z direction and was controlled by a piezo actuator. Mirror M2 with an array of concave microwells on the surface was mounted on a translation stage (Stage 2) that provided four axes of adjustments, including the x and y direction and the two angular orientations. The cavity was first aligned with Stage 2 and then the cavity length was scanned along the z direction by the piezo actuator for a few free-spectral-ranges (FSRs) with the initial cavity length at 50 μm . The transmission spectrum was collected by a photo-detector that was connected to the oscilloscope. The finesse, F , can be obtained by $F=\text{FSR}/\delta\nu$, where $\delta\nu$ is the FWHM (full-width at half-maximum) of the transmission peak using a Lorentzian fit. For a p-c FP cavity, the laser beam passed M1 and a concave microwell on M2. For the corresponding p-p FP cavity, the laser beam passed M1 and a place on M2 that did not have a microwell.

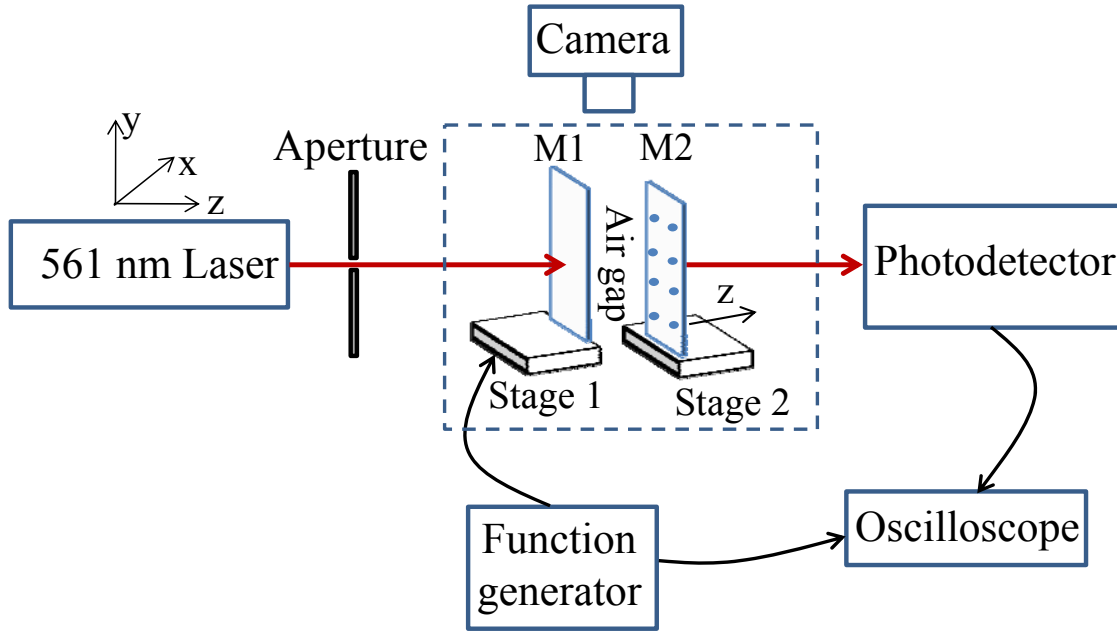


Figure S1 Experimental setup for finesse measurement using the scanning cavity method.

II. Q-factor and finesse estimation using the laser threshold

The lasing behavior of the cavity system for a given dye concentration can be described with a parameter $\gamma(\lambda)$, the minimum fraction of the excited molecules,

$$\gamma(\lambda) = \frac{\sigma_a(\lambda_L)}{\sigma_a(\lambda_L) + \sigma_e(\lambda_L)} \left(1 + \frac{Q_{\text{abs}}}{Q_0}\right) \quad (1)$$

where σ_a and σ_e represent the absorption and emission cross section, respectively; λ_L is the emission wavelength; Q_0 is the empty cavity Q-factor when the cavity is filled with solvent in the absence of dye; Q_{abs} is the Q-factor related to the dye absorption, i.e.

$$Q_{\text{abs}} = \frac{2\pi n}{\lambda_L n_T \sigma_a(\lambda_L)} \quad (2)$$

where n and n_T denotes the refractive index of the solvent and the total concentration of dye molecules, respectively. According to the three-level model at steady state, γ is directly related to the pump threshold P_{th} . After a straightforward derivation, P_{th} is obtained as

$$P_{\text{th}} = \frac{8\pi h c^2 n^2 \Delta t}{\lambda_L^4 \lambda_p E(\lambda_L)} \times \frac{A(1+C)}{1-BC} \quad (3)$$

where h , c , Δt , λ_p , and $E(\lambda_L)$ represent the plank constant, light velocity in vacuum, pulse width, pump wavelength, and fluorescence quantum distribution at emission wavelength, respectively; $A = \sigma_a(\lambda_L)/\sigma_a(\lambda_p)$, $B = \sigma_a(\lambda_L)/\sigma_e(\lambda_L)$, and $C = Q_{\text{abs}}/Q_0$.

The parameters and the Q-factor/finesses for the cavities in Fig. 3 are tabulated in Table S2.

III. Calculation of fluidic dome volume and cavity mode volume

1: Fluidic volume $V_d = \pi a^2 t$, where we use Gaussian fit $f = t \times \exp(-\frac{x^2+y^2}{a^2})$ to approximate the surface profile of a concave microwell.

2: Optical cavity mode volume of TE₀₀ mode

The electric field distribution $E(x, y, z)$ of standing waves in the resonator cavity is

$$E(x, y, z) \propto \exp\left(-\frac{x^2+y^2}{w^2(z)}\right) \cos\left(\frac{2\pi}{\lambda} z\right) \quad (4)$$

where

$$w(z) = w_0 \times \left[1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right]^{1/2} \quad (5)$$

with w_0 the minimum beam waist along z direction.

For the p-c FP microcavity, the radius of plano mirror is $R_1 = \infty$, and the radius of concave mirror is R_2 (we take R_2 as the minimum radius of surface curve of the concave microwell). Then we get $g_1 = 1 - t/R_1 = 1$, $g_2 = 1 - t/R_2$ and the beam waist for the plano and concave mirror is

$$w_1 = \left(\frac{t}{\pi}\right)^{1/2} \left(\frac{g_2}{1-g_2}\right)^{1/4}, \quad w_2 = \left(\frac{t}{\pi}\right)^{1/2} \left(\frac{1}{g_2(1-g_2)}\right)^{1/4} \quad (6)$$

The cavity length t is very short; and the calculated w_1 and w_2 are nearly the same (as shown in Table S3), simply we can get the optical cavity mode volume V_c of the p-c microcavity as

$$V_c = \iiint |E(x, y, z)|^2 dx dy dz \approx \frac{1}{4} \pi w_1^2 t \approx \frac{1}{4} \pi w_2^2 t \quad (7)$$

The parameters, fluidic volume, and cavity mode volumes for the cavities in Fig. 5 are tabulated in Table S3.

Table S1: Summary of optofluidic lasers generated using different types of optical cavities

Cavity type	Pump conditions	Gain medium	Lasing (wavelength, threshold, Q_0 value)	Citations
FP cavity: Cr/Au mirrors, reflectivity 83% and 72%; optical cavity length 21.6 μm	Nd: YAG laser: 532 nm, 5 ns, 10 Hz	R6G, 0.01 M	570 nm, 30 mW/cm ² (~30 $\mu\text{J}/\text{mm}^2$)	Ref. [2]
Four-ring-cavity with total internal reflection	Nd: YAG laser: 532 nm, 0.5 ns, 5 kHz	R6G, 0.01 M	569 nm, 15 $\mu\text{J}/\text{mm}^2$	Ref. [3]
FP cavity: Au coating on plano fiber end; cavity length 600 μm	Nd: YAG laser: 532 nm, 0.5 ns, 5 kHz	R6G, 0.01 M	25 $\mu\text{J}/\text{mm}^2$	Ref. [4]
FP cavity: Au coating on plano fiber end, reflectivity 80%; cavity length 140 μm	Nd: YAG laser: 532 nm, 0.5 ns, 5 kHz	R6G, 1 mM	569 nm, 2 $\mu\text{J}/\text{mm}^2$	Ref. [5]
FP cavity: Au coating on plano fiber end; cavity length 550 μm	Nd: YAG laser: 532 nm, 5 ns	R6G, 5 mM	569 nm	Ref. [6]
FP cavity: Au coating on plano fiber end; cavity length 18 μm	Nd: YAG laser: 532 nm, 0.5 ns	R6G, 1 mM	565 nm, 10 $\mu\text{J}/\text{mm}^2$	Ref. [7]
FP cavity: two concave mirrors (curvatures, 10 mm and 50 mm), DBR coating, reflectivity >99.5%; cavity length 20 μm ;	OPO: 465 nm, 5 ns, 10 Hz	eGFP, ~300 μM	850 \pm 200 pJ (focal lens 30 mm)	Ref. [8]
FP cavity: plano mirrors, DBR coating, reflectivity >99.5%; cavity length 18 μm ;	OPO: 465 nm, 5 ns	GFP, 600 \pm 200 μM (in one bacterial cell)	160 \pm 10 nJ (focal lens 35 mm)	Ref. [9]
FP cavity: Plano mirrors, Ag coating, reflectivities >95% and > 80% (λ >600 nm); cavity length ~125 μm	Nd:YAG laser: 355 nm, 5 ns, 10 Hz	DCM, 2 g/L in DMSO	~646 nm, ~110 nJ (4 \times microscope objective focal lens)	Ref. [10]
High-order (130 th) Bragg grating	Nd: YAG laser: 532 nm, 0.5 ns, 5 kHz	R6G, 20 mM	582.7 nm, 20 $\mu\text{J}/\text{mm}^2$	Ref. [11]
Phase shifted 15 th order distributed feedback structure	Nd: YAG laser: 532 nm, 6 ns	R6G, 1 mM	567.3 nm, ~0.8 mJ/cm ²	Ref. [12]
15 th -order Bragg grating	Nd: YAG laser: 532 nm, 6 ns	R6G, 2 mM	570 nm, 1 μJ	Ref. [13]
Third-order distributed Bragg grating	Nd:YAG laser: 532 nm, 5 ns, 10 Hz	R6G, 0.02M	581.41 nm, 65 $\mu\text{J}/\text{mm}^2$ (in ethanol); 582.72 nm, 40 $\mu\text{J}/\text{mm}^2$ (in glycol); 587.86 nm, 10 $\mu\text{J}/\text{mm}^2$ (in the mixture of ethanol and glycol)	Ref. [14]
Low-order (first, second, and third) distributed feedback resonators	Nd:YAG laser: 532 nm, 4.5 ns	R6G, 1 mg/mL (~2 mM)	569.1 nm, 78 nJ/pulse (~62 $\mu\text{J}/\text{cm}^2$, 20 μm beam radius waist, 5 \times objective focal lens, second order grating)	Ref. [15]
Second order circular distributed feedback grating	Nd:YAG laser: 532 nm, 4.5 ns, 100 Hz	R6G, 1 mg/mL (~2 mM)	571.09 nm, 9.5 $\mu\text{J}/\text{pulse}$ (10 \times objective focal lens)	Ref. [16]
Droplet (levitated in air), diameter ~1 mm	Nd:YAG laser: 532 nm, 5 ns, 10 Hz	R6G, 20 mM	~630 nm, ~500 mW	Ref. [17]
Ring resonator (out-diameter: ten to few hundreds of μm , wall thickness: a few μm)	OPO: 532 nm, 10 ns, 20 Hz	R6G, 2 mM	600 nm, 25 nJ/mm ² (estimated $\eta Q_0 \approx 4 \times 10^6$)	Ref. [18]
Droplets (diameters from 20 to	Nd:YAG laser:	R560 and R640,	~590 and 675 nm,	Ref. [19]

40 μm)	532 nm	5 mM	1 $\mu\text{J}/\text{pulse}$ (beam diameter 30 μm)	
Coupled optofluidic ring resonators	OPO: 532 nm, 5 ns	R6G, 2 mM	570 nm, 6 $\mu\text{J}/\text{mm}^2$	Ref. [20]
A ring shaped channel, inner, outer radius and depth 150, 170, and 40 μm	OPO: 532 nm, 5 ns, 20 Hz	R6G, 1 mM	575 nm, $\sim 15 \mu\text{J}/\text{mm}^2$ (estimated $Q_0 \approx 3.3 \times 10^4$)	Ref. [21]
Optofluidic ring resonators, inner diameter 70-90 μm , wall thickness 1-2 μm	OPO: 433 nm, 5 ns, 20 Hz	Quantum dots(QDs), 2 μM (in bulk solution)	660-665 nm, 0.1 $\mu\text{J}/\text{mm}^2$ (estimated $\eta Q_0 \approx 1 \times 10^7$)	Ref. [22]
Photonic crystal slab, a square lattice of air cylindrical holes	Nd:YAG laser: 532 nm, 5 ns, 10 Hz	R6G, 1 mM	580 nm, 90 nJ/mm^2 (pump laser resonantly enhanced by a factor of 80) (derived $Q_0 = 8.3 \times 10^3$)	Ref. [23]
Biological tissues with scatters as the random resonator infiltrated with laser dye solution	Nd:YAG laser: 532 nm, 100 ps, 100 Hz	R6G	$\leq 2 \mu\text{J}/\text{mm}^2$	Ref. [24]
Cortical bone from bovine femurs immersed in laser dye solution	OPO: 690 nm, 100 fs, 1 kHz	R800 in ethanol or (DMSO), weight ratio: 0.3%	15 mW, size of pump beam: 100 $\mu\text{m} \times 3 \text{ mm}$ (estimated pump density: 50 $\mu\text{J}/\text{mm}^2$)	Ref. [25]
Disordered optofluidic channel with structural disorder as the resonator	Nd:YAG laser: 532 nm, 6 ns, 20 Hz	R6G, 2.5 mM	80 $\mu\text{J}/\text{mm}^2$	Ref. [26]
Disordered optofluidic channel with structural disorder as the resonator	Nd:YAG laser: 532 nm, 7 ns, 10 Hz	R6G, 2.5 mM	561.77 nm, 21 $\mu\text{J}/\text{mm}^2$ (spectrum and intensity of laser can be selected by the pump profile)	Ref. [27]
Plano-concave FP cavity with DBR coating, cavity length = 31 μm	OPO: 532 nm, 5 ns, 20 Hz	R6G, 1 mM	599 nm, 90 nJ/mm^2 (derived $Q_0 = 5.6 \times 10^5$, $F = 4000$)	Current work

Table S2: Parameters used for the calculation of Q_0 -factor/Finesse in Section II

Dye concentration	1 mM			
Pump wavelength λ_p (nm)	532			
Absorption cross section at λ_p (cm^2)	1.9×10^{-16}			
Refractive index of the solvent n	1.366			
Quantum yield q	0.9			
Pulse width Δt (ns)	5			
Chips	Type 1		Type 2	
Microcavity	p-c cavity	p-p cavity	p-c cavity	p-p cavity
Lasing wavelength λ_L (nm)	592	563	599	570
Absorption cross section at λ_L (cm^2)	1.4×10^{-19}	5.6×10^{-18}	5×10^{-20}	1.5×10^{-18}
Emission cross section at λ_L (cm^2)	1.1×10^{-16}	1.7×10^{-16}	1×10^{-16}	1.6×10^{-16}
Fluorescence distribution $E(\lambda_L)$ (1/nm)	6.4×10^{-3}	1.2×10^{-2}	5.6×10^{-3}	1×10^{-2}
Q_{abs} at λ_L	1.7×10^6	4.5×10^4	4.8×10^6	1.6×10^5
A	7.5×10^{-4}	3.0×10^{-2}	2.6×10^{-4}	8.1×10^{-3}
B	1.3×10^{-3}	3.3×10^{-2}	4.8×10^{-4}	1×10^{-2}
$8\pi hc^2 n^2 \Delta t / \lambda_L^4 \lambda_p E(\lambda_L)$ ($\mu\text{J}/\text{mm}^2$)	33	22	36	24
P_{th} ($\mu\text{J}/\text{mm}^2$)	0.33	8.55	0.09	1.1
Q_0	1.3×10^5	3.6×10^3	5.6×10^5	3.5×10^4
Cavity length L (μm)	49	46	31	22
Finesse ($= \lambda Q_0 / 2nL$)	575	16	4000	332

Table S3: Parameters used for the calculation of fluidic volume and cavity mode volume for Type 1 and Type 2 p-c cavities in Fig. 5.

p-c FP microcavity	Type 1	Type 2
Laser wavelength (nm)	590.6	600
Depth t (<i>i.e.</i> , cavity length) (μm)	4	8
a (μm)	24	70
Effective diameter d (μm)	34	100
Fluidic mode V_d (pL)	7	123
g_1	1	1
Radius R_2 (μm)	78	306
g_2	0.9487	0.9739
Beam waist w_1 (μm)	1.7983	3.0550
Beam waist w_2 (μm)	1.8462	3.0957
Optical cavity mode V_c (fL)	11	60

References:

1. D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, and J. Reichel, "A fiber Fabry–Perot cavity with high finesse," *New J. Phys.* **12**, 065038 (2010).
2. B. Helbo, A. Kristensen, and A. Menon, "A micro-cavity fluidic dye laser," *J. Micromech. Microeng.* **13**, 307–311 (2003).
3. J. C. Galas, J. Torres, M. Belotti, Q. Kou, and Y. Chen, "Microfluidic tunable dye laser with integrated mixer and ring resonator," *Appl. Phys. Lett.* **86**, 264101 (2005).
4. J. C. Galas, C. Peroz, Q. Kou, and Y. Chen, "Microfluidic dye laser intracavity absorption," *Appl. Phys. Lett.* **89**, 224101 (2006).
5. Q. Kou, I. Yesilyurt, and Y. Chen, "Collinear dual-color laser emission from a microfluidic dye laser," *Appl. Phys. Lett.* **88**, 091101 (2006).
6. G. Aubry, S. Méance, A.-M. Haghiri-Gosnet, and Q. Kou, "Flow rate based control of wavelength emission in a multicolor microfluidic dye laser," *Microelectron. Eng.* **87**, 765-768 (2010).
7. G. Aubry, Q. Kou, J. Soto-Velasco, C. Wang, S. Meance, J. J. He, and A. M. Haghiri-Gosnet, "A multicolor microfluidic droplet dye laser with single mode emission," *Appl. Phys. Lett.* **98**, 111111 (2011).
8. M. C. Gather, and S. H. Yun, "Single-cell biological lasers," *Nature Photon.* **5**, 406-410 (2011).
9. M. C. Gather, and S. H. Yun, "Lasing from *Escherichia coli* bacteria genetically programmed to express green fluorescent protein," *Opt. Lett.* **36**, 3299-3301 (2011).
10. A. J. C. Kuehne, M. C. Gather, I. A. Eydelnant, S.-H. Yun, D. A. Weitzad, and A. R. Wheeler, "A switchable digital microfluidic droplet dye-laser," *Lab Chip* **11**, 3716-3719 (2011).
11. S. Balslev, and A. Kristensen, "Microfluidic single-mode laser using high-order bragg grating and antiguiding segments," *Opt. Express* (2005).
12. Z. Li, Z. Zhang, T. Emery, A. Scherer, and D. Psaltis, "Single mode optofluidic distributed feedback dye laser," *Opt. Express* **14**, 696-701 (2006).
13. Z. Li, Z. Zhang, A. Scherer, and D. Psaltis, "Mechanically tunable optofluidic distributed feedback dye laser," *Opt. Express* **14**, 10494-10499 (2006).
14. M. Gersborg-Hansen, and A. Kristensen, "Optofluidic third order distributed feedback dye laser," *Appl. Phys. Lett.* **89**, 103518 (2006).
15. W. Song, A. E. Vasdekis, Z. Li, and D. Psaltis, "Low-order distributed feedback optofluidic dye laser with reduced threshold," *Appl. Phys. Lett.* **94**, 051117 (2009).
16. W. Song, A. E. Vasdekis, Z. Li, and D. Psaltis, "Optofluidic evanescent dye laser based on a distributed feedback circular grating," *Appl. Phys. Lett.* **94**, 161110 (2009).
17. H. Azzouz, L. Alkhafadiji, S. Balslev, J. Johansson, N. A. Mortensen, S. Nilsson, and A. Kristensen, "Levitated droplet dye laser," *Opt. Express* **14**, 4374-4379 (2006).
18. S. Lacey, I. M. White, Y. Sun, S. I. Shopova, J. M. Cupps, P. Zhang, and X. Fan, "Versatile opto-fluidic ring resonator lasers with ultra-low threshold," *Opt. Express* **15**, 15523-15530 (2007).
19. S. K. Tang, Z. Li, A. R. Abate, J. J. Agresti, D. A. Weitz, D. Psaltis, and G. M. Whitesides, "A multi-color fast-switching microfluidic droplet dye laser," *Lab Chip* **9**, 2767-2771 (2009).

20. W. Lee, H. Li, J. D. Suter, K. Reddy, Y. Sun, and X. Fan, "Tunable single mode lasing from an on-chip optofluidic ring resonator laser," *Appl. Phys. Lett.* **98**, 061103 (2011).
21. H. Chandralalim, Q. Chen, A. A. Said, M. Dugan, and X. Fan, "Monolithic optofluidic ring resonator lasers created by femtosecond laser nanofabrication," *Lab Chip* **15**, 2335-2340 (2015).
22. A. Kiraz, Q. Chen, and X. Fan, "Optofluidic Lasers with Aqueous Quantum Dots," *ACS Photonics* **2**, 707-713 (2015).
23. B. Zhen, S.-L. Chua, J. Lee, A. W. Rodriguez, X. Liang, S. G. Johnson, J. D. Joannopoulos, M. Soljačić, and O. Shapira, "Enabling enhanced emission and low-threshold lasing of organic molecules using special Fano resonances of macroscopic photonic crystals," *Proc. Natl. Acad. Sci. USA* **110**, 13711-13716 (2013).
24. R. C. Polson, and Z. V. Vardeny, "Random lasing in human tissues," *Appl. Phys. Lett.* **85**, 1289-1291 (2004).
25. Q. Song, S. Xiao, Z. Xu, J. Liu, X. Sun, V. Drachev, V. M. Shalaev, O. Akkus, and Y. L. Kim, "Random lasing in bone tissue," *Opt. Lett.* **35**, 1425-1227 (2010).
26. B. N. Shivakiran Bhaktha, N. Bachelard, X. Noblin, and P. Sebbah, "Optofluidic random laser," *Appl. Phys. Lett.* **101**, 151101 (2012).
27. N. Bachelard, S. Gigan, X. Noblin, and P. Sebbah, "Adaptive pumping for spectral control of random lasers," *Nature Phys.* **10**, 426-431 (2014).