Research article

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Optofluidic laser based on a hollow-core negative-curvature fiber

<https://doi.org/10.1515/nanoph-2018-0014>

Received January 30, 2018; revised April 22, 2018; accepted April 23, 2018

Abstract: An optofluidic laser based on a hollow-core negative-curvature fiber (HC-NCF) is proposed and demonstrated. The submicron-thick circular capillary tubes embedded in the cladding of the HC-NCF act as antiresonant elements and are used as both a resonator and dye microfluidic channels. A stable optofluidic dye laser with a low threshold of 15.14 nJ/mm^2 is achieved. The laser is compact and robust and exhibits directional output.

Keywords: optofluidic dye laser; hollow-core photonic crystal fiber; microring resonator; low threshold.

1 Introduction

Optofluidic lasers integrate a microcavity, microfluidic channel, and fluorescent material in solution. They are a rapidly developing technology because of their low energy consumption, compact structure, and unique optical performance [1]. They have a broad range of applications, including in miniature coherent light sources [2, 3] and biochemical analysis. When applying an optofluidic

laser in biology, the gain medium usually combines with a biological material, such as a fluorescent protein [4], DNA [5], live cells [6], and interstitial tissue [7]. Therefore, optofluidic lasers are known as optofluidic biolasers in biomedical testing. Compared with traditional fluorescence-based detection, optofluidic laser methods can provide much higher sensitivity. In an optofluidic laser, the quality of the microcavity is of paramount importance. Various microcavities have been developed including microknots [3], solid microspheres [8], cylindrical microcavities [6, 9], and microdisks [4]. Subwavelength microfiber-based resonators consisting of coiled [10], looped [11], or knotted [12] structures have been reported and show great potential in miniature photonic devices. Light can be confined in the submicron-diameter waveguide with low transmission loss. Microfiber resonators combined with a fluorescent material in solution produce stable lasers with low thresholds. However, such lasers have drawbacks including their fragility and need for an additional microfluidic cavity.

Hollow-core microstructured optical fibers (HC-MOFs) consist of tiny air holes along the length of the fiber. HC-MOFs have been shown to be excellent platforms for fiber-based optofluidic devices [13–15]. HC-MOFs can be classified into two categories according to their light guiding mechanism, which are hollow-core photonic bandgap fibers and hollow-core antiresonance fibers (HC-ARFs). HC-ARFs limit light in the hollow core by the antiresonant reflecting optical waveguide (ARROW) principle [16]. This differs from hollow-core photonic bandgap fibers that guide light via the photonic bandgap effect formed by a two-dimensional periodic cladding structure. The advantages of HC-ARFs include their broad light transmission bandwidth, simple structure, and easy fabrication. These factors make HC-ARFs attractive in applications involving high-efficiency interactions between light and matter [17], high-power pulse delivery [18], and chemical sensing [19].

A hollow-core negative-curvature fiber (HC-NCF) with excellent light-guiding performance was recently reported [20–22]. This HC-NCF is a type of HC-ARFs and contains

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one layer of six-to-eight untouched circular thin silica tubes that act as antiresonant elements. To realize the low loss of guided light in the near-infrared waveband, the wall thickness of the silica tubes in the HC-NCF should be 300–500 nm. The circular capillary tubes embedded in the cladding of the HC-NCF have subwavelength-thick walls and potentially allow for an optofluidic laser. These tubes can serve as resonators with a high Q factor and can also serve as microfluidic channels. Integrating the resonators and microfluidic channels allows for a compact and robust structure. The microchannels allow for the high-efficiency interaction between light and gain medium or between different fluorescence materials. Herein, we report an optofluidic microring laser based on a homemade HC-NCF. One circular side-capillary tube embedded in the cladding of the HC-NCF is used as a ring microcavity and microfluidic channel. A stable optofluidic dye laser with a low threshold of 15.14 nJ/mm^2 is obtained, when the HC-NCF is side-pumped by a 532 nm wavelength pulse laser.

2 Experimental setup

Figure 1A shows a scanning electron microscopy image of the cross section of the HC-NCF. The circular capillary tubes and tube wall indicated by the white dashed rectangles are shown magnified in Figure 1B and C, respectively. The six nodeless microscale tubes, acting as antiresonance elements, have a diameter of $\sim 21 \mu\text{m}$ and a wall thickness of $\sim 390 \text{ nm}$. Any of the side capillaries can be used as a microring resonator and microfluidic channel. In our experiment, the gain medium is selectively injected into one side capillary, and the others are filled with air. To fill a specific side capillary of the HC-NCF with the gain medium, an improved direct manual gluing technique [23] is used. First, a silica glass tip with an outer diameter of $\sim 6 \mu\text{m}$ is fixed on a three-axis flexible stage. With the assistance of the glass tip, a polystyrene microsphere with a diameter of $\sim 25 \mu\text{m}$ is then picked up from a glass slide and placed on the end face of the specific side capillary

under observation using a microscope (Olympus Corporation, Tokyo, Japan). The microsphere is then heated and melted using an electric soldering iron to provide a short blockage in the selected side capillary. The end face is then submerged in molten paraffin for several seconds. The melting point of paraffin is lower than that of polystyrene. Thus, paraffin oil invades the other capillaries to depths of 2–3 cm, while no paraffin oil invades the specific side capillary. After the paraffin oil solidifies, the end face is cut off to expose only the specific side capillary. This side capillary can now be filled via the capillary effect or by using a peristaltic pump.

In the simulation, to verify the possibility of building an optofluidic laser with the HC-NCF considering the process tolerances, the finite element analysis software package COMSOL (Comsol Inc., Stockholm, Sweden) is used to analyze the energy distribution in the wall of the liquid-filled side capillary. The geometric parameters are set to approximate the actual fiber used in experiments. The refractive index of the liquid gain medium is set to 1.358. Figure 2A shows the schematic diagrams of the HC-NCF with different deviations of the side capillary on the left and corresponding typical energy distributions on the right. Because the ideal side capillary is tangent to the cladding, the deviation refers to the transverse offset from the ideal tangent position. It proves that the circular silica wall can support whispering gallery modes in the fluorescence emission band even with the imperfect fiber structures. Figure 2B shows the normalized energy distribution of the typical modes in the silica wall, where r/r_0 is the normalized radius. The vertical lines indicate the inner and outer boundaries of the subwavelength-thick silica wall. Figure 2B shows that an evanescent field extends into the gain medium. This is evidence that the submicron-thick silica wall can act as a laser resonator based on the mechanism of evanescent-wave-coupled gain [24]. The fluorescence generated in the tube continuously couples into the submicron silica wall, where it is trapped by optical confinement. The imprisoned fluorescence returns in-phase round and round. Laser emission arises when the gain is larger than the loss.

Figure 1: Scanning electron microscopy images of the (A) cross section of the HC-NCF, (B) circular side-capillary tube, and (C) tube wall. Images in (B) and (C) are enlargements of the regions indicated in (A) and (B), respectively.

Figure 2: The conditions of typical energy distribution in the silica wall of the side-capillary. (A) Schematic diagrams of the HC-NCF with different deviations of the side capillary on the left and corresponding typical energy distributions on the right. (B) Normalized energy distribution of modes in the silica wall, as a function of the normalized radius r/r_0 .

Figure 3A shows a schematic diagram of the laser. A focused pumping laser pumps the gain-medium-filled HC-NCF using a convex lens (CL), by the method of side pumping. The other optical components, such as fiber rotator, long-pass filter, tunable attenuator, three-axis flexible stage, are all provided by Thorlabs Inc., Shanghai, China. The pumping laser is a 532 nm wavelength Q switched pulsed laser (Changchun New Industries Optoelectronics Technology Co., Ltd., Changchun, China), with a pulse duration of ~ 5.6 ns. The CL has a focal length of 50 mm. In the experiment, the pump focal area is measured using a charge-coupled device camera (Beijing PDV Instrument Co., Ltd., Beijing, China) and coordinate (i.e. grid) paper containing 1 mm $\times$ 1 mm squares. The coordinate

Figure 3: Schematic diagrams of the experiment layout, HC-NCF and microring resonator. (A) Schematic diagram of the experimental layout. (B) Enlarged schematic diagram of a part of the HC-NCF. (C) Schematic diagram of the microring resonator contacting with the fiber cladding.

paper is used as an optical screen to project the pumping laser. The charge-coupled device camera connected to a computer is used to observe the light spot on the coordinate paper. Stray light can be eliminated by image processing. A pump focal area of 0.5 mm^2 is estimated by comparing the number of pixels for the diameter of the light spot and the side length of the squares. To adjust and rotate the HC-NCF, the HC-NCF is clamped on a fiber rotator fixed on a three-axis flexible stage. A tunable attenuator is placed before the CL to control the intensity of the pumping laser. An optical spectrometer analyzer (OSA, Ocean Optics HR4000; Ocean Optics Inc., Shanghai, China) with a resolution of 1 nm is used to record the emission spectrum of the laser. The fiber detecting probe (numerical aperture: 0.22) of the OSA, clamped by another three-axis flexible stage, is placed on the lateral of the HC-NCF. To eliminate the influence of scattered pumping light on the laser output, a long-pass filter is installed between the HC-NCF and detecting probe. The side-pumping method is used to reduce the coupling loss, rather than the axial-pumping method. Figure 3B and C show schematic diagrams of a part of the HC-NCF and the microring resonator contacting with the fiber cladding, respectively.

3 Results and discussion

To evaluate the performance of the microring laser based on the HC-NCF, the threshold characteristic is first measured. The gain medium, 4 mmol/l rhodamine B (RHB) [Merck Life Science (Shanghai) Co., Ltd., Shanghai, China] solution, is injected into one of the side capillary in the HC-NCF. As the pumping power increases, visual observation through a 532 nm wavelength protective eyewear shows that the emission changes from pale orange to a brighter red orange. Figure 4 shows a typical emission spectrum of the laser. The wavelength spacing between the two peaks is 3.86 nm . Equation (1) is used to calculate the free spectral range $\Delta\lambda$:

$$\Delta\lambda = \frac{\lambda_0^2}{2\pi R n_{\text{eff}}} \quad (1)$$

where λ_0 is the resonant wavelength (596.6 nm), n_{eff} is the average effective refractive index of the modes we got in the simulation (~ 1.389), and R is the radius of the side capillary ($10.5 \text{ }\mu\text{m}$). The calculated $\Delta\lambda$ of $\sim 3.89 \text{ nm}$ is in good agreement with the wavelength spacing between the two peaks in Figure 4. The small deviation between the theoretical and calculated values is caused by measurement error and deformation of the circular ring.

Figure 4: Typical emission spectrum of the laser.

Figure 5A shows the typical spectra of the laser emission under different pumping power. These spectra are collected at a different angle to the spectrum in Figure 4. The green dashed lines are visual guides. The resonance wavelengths are stable, and no gain narrowing is observed. The defect in peak ii is caused by the low resolution of the optical spectrometer analyzer. The wavelength spacing between peaks ii and iii (3.98 nm) is in good agreement with the calculated free spectral range. The wavelength spacing between peaks i and ii deviates from the calculated spectral range. The spectra in Figure 5A are collected at a different angle to that in Figure 4, so the deviation in wavelength spacing may result from the counter-propagating resonance, as shown in Figure 3C. Peaks ii and iii are derived from the same resonance, and peak i is derived from another resonance. Peaks derived from the resonance in the same direction as peak i may disappear, because of the relatively high mode loss or mode competition. The relationship between the integrated intensity of the HC-NCF based laser and the pumping power is shown in Figure 5B. The spectra recorded under selected pumping powers (power I: $15.89 \text{ }\mu\text{W}$, power II: $66.74 \text{ }\mu\text{W}$, and power III: $102.56 \text{ }\mu\text{W}$) are also shown. An obvious dual slope efficiency profile is observed in Figure 5B. Laser emission arises at the low pumping power of $15.89 \text{ }\mu\text{W}$. When the repetition rate of the pumping laser is $\sim 2.1 \text{ kHz}$ and the laser focal area is $\sim 0.5 \text{ mm}^2$, the threshold energy is lower than 7.57 nJ/pulse or 15.14 nJ/mm^2 . Compared with Figure 5A and B, Figure 6A and B show the analogous result when the concentration of the RHB solution is 1 mmol/l . The threshold is $\sim 15.38 \text{ nJ/mm}^2$, and again spectra under different selected pumping powers (power I': $16.15 \text{ }\mu\text{W}$, power II': $18.87 \text{ }\mu\text{W}$, and power III': $33.32 \text{ }\mu\text{W}$) are also enumerated. The two emission peaks are derived from

Figure 5: Slope efficiency curve of the laser and typical emission spectra under various pumping powers when 4 mmol/l RHB solution is used. (A) Typical laser emission spectra recorded under different pumping powers when the RHB concentration is 4 mmol/l. (B) Relationship between the integrated laser emission intensity and pumping power, and spectra recorded under various pumping powers.

counter-propagation resonances, and the peak at short wavelength emerges when the pumping power is above level II'. The fluctuation resembling a fluorescence tail in Figure 6B is the tail of the pumping laser, as no filter was used. The differences in the integrated intensity and slope

efficiency in Figures 5B and 6B are caused by the different side capillaries that were used as resonators. Figure 3C shows the skewing of the microring, with the intersection angles between the microring and cladding (α , β) differing, so the tangency is imperfect. The microring can be

Figure 6: Slope efficiency curve of the laser and typical emission spectra under various pumping powers when 1 mmol/l RHB solution is used. (A) Typical laser emission spectra recorded under different pumping powers when the RHB concentration is 1 mmol/l. (B) Relationship between the integrated laser emission intensity and pumping power, and spectra recorded under various pumping powers.

considered as two resonators with different Q factors that support counter-propagating resonances, which is shown as the red and blue arrows in Figure 3C. This is the reason why the laser exhibits dual slope efficiency. In consideration of the effect of the concentration, the result is much lower than many previous works in microfluidic lasers

[1, 3, 24–27]. The low threshold mainly results from the high Q factor that is characteristic of the circular side capillary in the HC-NCF. The resonator in the current study is similar to the capillary used in the works of Lacey et al. [26] and Knight et al. [27], except that the current resonator is smaller and thinner. The thinner silica wall of the

capillary used in Lacey et al. [26] results in a higher Q factor. A thinner wall also leads to more of the evanescent field energy being distributed in the gain medium, which enhances the effect of the evanescent wave-couple gain. Thus, a low lasing threshold can be realized. Apart from the submicron wall, the capillaries integrated in the HC-NCF are highly circular and have a lower surface roughness, which also lead to the high Q factor of the current resonators. Thus, the disadvantage of a large radiation loss is offset. The side capillary is integrated into the cladding, so it is not possible to separate it out and measure the Q factor experimentally [28]. By referring to the works of Lacey et al. [26] and Shopova et al. [28], the Q factor of the current resonator is estimated to be 10^7 – 10^9 .

In the process of experiment, the laser emission intensity varies greatly when the fiber is rotated, and it is particularly high in a certain range of angles. Consequently, the output of the HC-NCF-based laser is considered to be directional. This result differs from the typical optofluidic ring resonator laser without particular coupling elements, which is described in previous works [24, 29]. The relationship between the laser emission intensity and output direction was measured to validate this. The side capillary has a circular symmetric structure, so the output in different directions can be measured simply by rotating the fiber. The position of the fiber and the detecting probe is also adjusted via the three-axis flexible stage, to ensure a highest effective pumping intensity and maximum collection efficiency. The pumping power is constant during the measurement, to ensure the laser emission intensity does not exceed the measurement range of the OSA under the pumping power. Spectra are recorded every 20° , and the corresponding curves are plotted in Figure 7A. The rotation angles are read from the scale on the fiber rotator, as shown in Figure 3A. The 0° position is a relative value representing the initial position. In addition, on the premise of achieving a certain output intensity, the relation between the pumping power and angle of the HC-NCF is also measured, as shown in Figure 7B. Figure 7C shows the filtered output emission irradiating on a columnar screen surrounding the HC-NCF. The bright spot in the white circle is the dye-filled HC-NCF. The emission in the two green ellipses is much stronger than in other parts. This is consistent with the results of the curves in Figures 7A and 8B. Figure 7A shows that the ratio of the maximum to minimum values of the laser intensity is larger than 170. Therefore, the HC-NCF-based microfluidic laser is a directional emission laser. To eliminate the influence of the gain medium concentration and sampling points, the measurement is repeated using 5, 4, and 3 mmol/l RHB solutions,

Figure 7: Relations between output intensity, pumping power and different output directions, and output pattern. Relationship (A) between the laser emission intensity and output direction, and (B) between the pumping power and output direction. (C) Filtered output emission irradiating on a columnar screen surrounding the HC-NCF.

and the sampling frequency is increased to 15° . These results are shown in Figure 8A, B and C, respectively, all of which are similar to that shown in Figure 7A. To

Figure 8: Relationship between the laser emission intensity and output direction at a sampling frequency of 15°, for gain medium concentrations of (A) 5, (B) 4 and (C) 3 mmol/l.

avoid the influence of residual gain medium of different concentrations, each experiment is carried out on a different segment of the HC-NCF. Because of this, the effect of variations in microstructure of different segments of fiber and capillary cannot be eliminated. The specific effect of concentration cannot be precisely determined.

Figure 9: Sketches of possible orientations of the HC-NCF at (A) 0°, (B) 75° and (C) 210° corresponding to Figure 8B.

However, the results in Figure 8A, B and C are similar, and the threshold pumping powers are of the same order of magnitude. This indicates that the gain medium concentration does not affect the characteristics of directional output and the low lasing threshold.

As shown in Figure 3C, the part of the cladding contacting with the microring can act as a coupling element and cause directionality in the laser output. The angle intervals between the two peaks in Figures 7A, 8A, B and C are about 130–150°. This fluctuation may be caused by the small parameter change in the fiber structure, as different sections and tubes of the HC-NCF were used in these experiments. Based on the analysis above, the possible orientation of the HC-NCF can be obtained. Corresponding to Figure 8B, the sketches of the HC-NCF at 0° (initial position), 75° (peak 1), and 210° (peak 2) are shown in Figure 9A, B and C, respectively. The output directionality gives the HC-NCF-based laser potential application in the

simultaneous detection of multiple biological materials, by injecting them into different tubes.

4 Conclusions

In summary, an optofluidic microring laser with low threshold based on a nodeless HC-NCF has been demonstrated. The laser has the advantages of compactness and relative ruggedness, as the microscale tubes with silica wall of subwavelength thickness can serve as the synthesis of resonators and microfluidic channels. The emission of the laser exhibits directionality, which is verified by multiple sets of experimental data and emission patterns projected onto a columnar screen. The structure of the HC-NCF and the low threshold, directional output, and energy concentration of the HC-NCF-based laser give it potential in biomedical analysis.

Funding: This study was jointly supported by the National Natural Science Foundation of China (NSFC; grant nos. 11674177, 61775107, 61675011, 61527822, 61535009) and the Tianjin Natural Science Foundation, P. R. China (grant no. 16JCZDJC31000). We thank Liwen Bianji, Edanz Group China (www.liwenbianji.cn/ac), for editing the English text of a draft of this manuscript.

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