Tunable optofluidic microring laser based on a tapered hollow core microstructured optical fiber

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Abstract: A tunable optofluidic microring dye laser within a tapered hollow core microstructured optical fiber was demonstrated. The fiber core was filled with a microfluidic gain medium plug and axially pumped by a nanosecond pulse laser at 532 nm. Strong radial emission and low-threshold lasing (16 nJ/pulse) were achieved. Lasing was achieved around the surface of the microfluidic plug. Laser emission was tuned by changing the liquid surface location along the tapered fiber. The possibility of developing a tunable laser within the tapered simplified hollow core microstructured optical fiber presents opportunities for developing liquid surface position sensors and biomedical analysis.

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1. Introduction

Optofluidic-based microcavity dye laser is an emerging technology that integrates microfluidics, optical microcavities and a laser gain medium [1–5] and can be used for light manipulation [6, 7] and biochemical detection [1, 8–12]. The liquid gain medium fills a microfluidic channel, which also forms an optical microcavity that provides optical feedback for lasing. Microcavities that contain fluid are high quality and have a low energy consumption. Among the current optofluidic microcavity lasers, microcavities based on capillaries are of particular interest as they have a small environmental footprint, reduced sample requirements and facilitated microflow control. However, they are relatively large in size and have a high transmission loss. The larger size of the resonator allows for more transmission modes, causing serious mode competition, reducing the laser efficiency and causing the lasing wavelength to become unstable [13, 14]. High transmission losses of the resonators limit their applications in guiding light in a flexible and independent way [15, 16]. Recently, sub-wavelength microfiber-based microresonators consisting of loop [17], coil [18], or knot [19] structures have been fabricated, which have potential applications in miniature photonic devices. Light can be confined in the submicron diameter waveguide with low transmission loss and very large evanescent field [20]. Microfiber resonators produce low-threshold, stable lasers but also present some drawbacks because of their fragility and the need for an additional microfluidic cavity.

More recently, Stolyarov et al have reported a cylindrical Bragg fiber cavity that supports purely radial modes. The laser was produced in Fabry–Perot resonators formed by the fiber’s symmetric inside walls [7]. We have also demonstrated a highly stable laser within a single simplified hollow core microstructured optical fiber (SHMOF) in a recent report [21]. Strong resonance was generated using a firm microring resonator formed by the microring around the SHMOF center hole, which is different from the hollow core Bragg reflection fiber cavity reported by [7]. The advantages of the hollow core microstructured optical fiber (HC-MOF)-based lasers are their small internal connection losses, compactness, and enhanced versatility. However, in conjunction with the limited tuning range because of the monolithic design of general optofluidic ring resonators, tuning of microresonators to an arbitrary frequency is essential for laser applications [22]. Though tunable lasing has been achieved in the literature [17, 21] by replacing different sized HC-MOFs, the complex manipulations and extra expenses are disadvantages.
In this paper, we demonstrate a tunable microring dye laser within a tapered SHMOF. The fiber core was filled with the microfluidic gain medium (Rhodamine B (RhB) and Rhodamine 6G (R6G)) plug and was axially pumped by a nanosecond pulse laser at 532 nm. Light was limited in the silica microring and can show strong resonance. Lasing was achieved around the interface of the microfluidic plug and the air inside the microring. Both strong radial emissions (around 585 nm) and low-threshold lasing (16 nJ/pulse) were achieved. Also, the size of the silica microring around the gain medium was continuously reduced along the characteristic fiber lengths of several micrometers, which allowed variations of the resonant cavity lengths. Tunable laser emission was achieved by changing the liquid surface location of the gain medium along the tapered fiber.

2. Theoretical analysis

![Fig. 1. (a) Optical micrograph of the cross section of the SHMOF. (b) An image of the longitudinal profile of the fiber with an outer cladding diameter of 170 μm. (c) An image of the longitudinal profile of the tapered fiber with an outer cladding diameter of 113 μm. (d)-(h) are the calculated field distributions of several typical modes (at 532 nm) supported by SHMOF. (i)-(o) are some calculated higher-order modes (at 585 nm) guided in the dye-filled LC-SMOFs.](image)

The SHMOF used in our experiments was manufactured by the Yangtze Optical Fiber and Cable Corporation Ltd., China, and was composed of a large hexagonal core with six surrounding crown-like air holes, as shown in Fig. 1(a). The inner six thin silica membranes had a width of ~15 μm, a thickness of ~0.37 μm and a silica outer cladding with a diameter of 170 μm. The inner thin silica layer was connected to form the center microring and connected the thick silica cladding outside by six silica holders to form a firm structure. The fiber structure can be regarded as a Kagomé-lattice MOF with a single layer of surrounding air holes [23]. This SHMOF provides a cylindrical microcavity of two-dimensional space, which can confine the light into the hollow core. Using the cut-off method, the fiber transmission loss was measured to be about 15 dB/m at 532 nm. When the fiber was selectively filled with liquid dye solution, it will form a liquid core SMOF (LC-SMOF) with the low loss transmission properties of index-guiding MOFs.

First, we investigated the transmission characteristics of the LC-SMOF. In the simulation processes, we set the geometric size of the SHMOF to be the same as the actual fiber, as shown in Fig. 1(a). However, the structure was simplified to be fully symmetric and used a uniform structural model. In the schematic diagram of the dye-filled LC-SMOF, the refractive index (RI) of the outer cladding and the microring around the inner hole, n1, was set to 1.46, while the RI of the center hole filled with the gain medium (n2) and the hollow cladding holes (air) (n3) were set to 1.35 and 1, respectively, as shown in the inset of Fig. 1(a). The mode profiles of
some representative modes (at 532 nm) supported by the SHMOF were theoretically investigated using the software COMSOL, which is based on the finite element method. The core mode profiles of LP_{01}, LP_{11}, LP_{21a}, LP_{21b}, and LP_{31} are shown in Figs. 1(d)–1(h) from left to right, respectively.

As the pump light was coupled into the hollow core fiber mode LP_{01}, it had a large overlapping area with the gain medium in the core of the SHMOF. This strong light-matter interaction led to the generation of intense radiation at the surface of the gain medium. A great number of dye molecules near the interface were motivated when coupled from the mode of the hollow core SMOF to the mode of the LC-SMOF. A large part of the stimulated fluorescence was scattering and leakage because the inwardly curved surfaces of the liquid dye plug acted as concave lenses. A large amount of the emission light was coupled into the higher-order mode of the LC-SMOF [24]. Because of the high RI difference between the fiber liquid core and cladding, there are more higher-order core modes (at 585 nm) in the LC-SMOF [25], shown in Figs. 1(j)–1(o). We can see that the electric fields in these higher-order modes are mostly distributed at the edge of the center hole. This allows the emission light to be more easily coupled into the silica microring around the liquid core. Figure 1(i) shows a calculated higher-order mode (at 585 nm) guided in the silica microring of the LC-SMOF. This indicates that most of the power density forms a near-ring distribution within the thin silica wall, and expresses a strong resonance [26]. Because the silica wall is of nanoscale thickness, there is a large evanescent field. The light limited to the silica microring interacts with the gain medium near the cavity and allows for stimulated emission. As the pump energy is above the stimulated radiation threshold, there is the generation of laser emissions [21].

3. Experimental results

![Fig. 2](image)

**Fig. 2.** (a) The configuration of the tapered fiber-based microring dye laser system. Inset: the enlarged liquid column in the fiber core. (b) The filtered output of the lasing ring on a conical screen on the lateral side of the SHMOF, with the gain medium of R6G (left) and RhB (right).

The manufacture of the tapered SHMOF was depended on fusing tapered technology which used oxyhydrogen flame. To keep the original microstructure of the inner hole of the SHMOF, we used the ‘fast and cold’ tapering method [27]. In the tapering processes, we set the hydrogen flow rate to be 100 ml/min (we used the oxygen in air), and the flame edge to tangent to the fiber. So the silica in the fiber was in the critical melting state with low heating temperatures, which was soft but not molten. Meanwhile, the tapering speed was set as low as 100 μm/s, producing a small stress and making the soft fiber stretch steady. Both ends of the fiber were connected with atmosphere, so the inside air pressure would keep balance with the outside air pressure. Moreover, the advance delay and retreat delay of the flame in the beginning and end of the tapering processes were both set as 2 s, allowing the thermal relaxation time of the fiber...
to be long enough. In this way, air-hole collapsing was avoided. We finally obtained a 17-mm-long hyperbolic profile of the tapered region, while the diameter of the outer cladding of the fiber ranged from 113 μm to 170 μm as shown in Figs. 1(c) and 1(b), respectively. Because of the small angle of the fiber taper (0.005 rad), the transmission loss from the taper was neglected. In the tapering region of the fiber, the thickness of the microring would change. However, the change was very small. As the diameter of the outer cladding of the fiber ranged from 170 μm to 113 μm, the variation of the thickness was 0.07 μm. Occupations of light energy in the core were calculated to range from 55% to 60%. So the effective refractive index change induced by wall thickness change was negligible compared with the cavity length change. Different minimum sizes and thicknesses of the microrings were obtained using the appropriate flame temperature and tapering speed. This method results in uniform variation of the diameter of the inner microring without destroying the structure of the microring.

The tapered SHMOF-based laser system [as shown in Fig. 2(a)] is formed using a 532-nm passively Q-switched pulsed laser as the optical pumping source with a pulse duration of 1.60 ns and a repetition rate of 2 kHz. The maximum energy of the laser is 26.6 μJ. A 40 × objective lens with an effective working distance of 0.48 mm and a numerical aperture of 0.69 was used to couple the light into the fiber. The LC-SMOF was achieved by blocking the cladding holes around the center hole of the SHMOF [28]. We used laser dye (both RhB and R6G) dissolved in a mixed ethanol and water (1:1) solution (n = 1.35) at a concentration of 1 mM as the active medium. After the fiber core was filled by the sample liquid using capillary action, a syringe was connected to the filling end of the fiber. The syringe’s plunger was pulled backward or pushed forward to control the air pressure inside the fiber hole. We can therefore control the length and position of the liquid column inside the fiber core. We set the center of the tapered region in the SHMOF to the zero position, and defined the distance of the surface of the gain medium relative to the center of the tapered region as the relative position [as shown in Fig. 2(a)]. The transmitted lasing signal in the radial direction of the fiber was sent to an optical spectrum analyzer (OSA) (Ocean Optics HR4000) placed on the lateral position of the fiber.

At high pumping energy above threshold, a unique radiation field pattern emerged in the radial direction of the fiber. Figure 2(b) shows the lasing ring from the filtered output on a conical screen surrounding the SHMOF, which is the evidence of a radial emission profile from the SHMOF laser. Considering the effect of the shooting angle of the camera and the shadow of the fiber holder, we obtain a full laser circle around the fiber. The circles on the left and right respectively indicate the R6G and RhB gain media. The difference in color of the circles is because of the variation of the lasing wavelength of R6G (around 565 nm) and RhB (around 585 nm). The lasing was found to be concentrated at the interface of the liquid dye and the air inside the microring. To explain this, we must consider the influence of the inwardly curved interface of the liquid column [shown in the inset of Fig. 2(a)]. We can see that by using axially pumping method, the pump light interacts with the gain medium in the fiber core directly. And the direction of pump light along the fiber length is perpendicular to the lasing along the fiber radial. Therefore, both strong light-matter interactions and auto-segregation of the pump light and lasing were realized within the SHMOF [28].

The variation of the normalized output lasing energy with the pump energy of the tapered SHMOF-based laser system is shown in Fig. 3(a), indicating a threshold of 35 nJ. This result, obtained using a 1-mM RhB-doped plug, is lower than that reported in [7]. The slope of the curve of the variation of the output energy with pump energy above the threshold is 50 times larger than below the threshold. The inset in Fig. 3(a) shows the lasing spectrum below threshold (black line) and above threshold (red line). For pump energies above threshold, laser oscillation was observed at a wavelength of about 583 nm. The measured full width at half-maximum of the lasing mode was approximately 1 nm (0.3 GHz), which may be limited by the spectral resolution of the optical spectrum analyzer (1 nm).
When recycling total internal reflection occurs within a ring cavity, standing waves can be defined by

$$N\lambda_N = n_{\text{eff}} L_c,$$

where $N$ is an integer, $n_{\text{eff}}$ is the effective RI of the fiber ring, and $\lambda_N$ is the lasing wavelength corresponding to the $N$th longitudinal mode. Then the circumference can be easily deduced from Eq. (1) as follows:

$$L_c = \frac{\lambda_N^2}{(n_{\text{eff}} \cdot \Delta \lambda_N)}.$$  

where $\Delta \lambda_N$ is the free spectral range (FSR) of the corresponding longitudinal modes in the microring resonator. We can see that the longitudinal mode interval and the lasing wavelength of the SHMOF-based laser depend on the size and the effective RI of the silica microring. The circumference of the silica rings around the hollow core in the fiber was about 90 $\mu$m. By substituting the measured peak wavelength, $\lambda_N = 586.15$ nm, longitudinal mode interval, $\Delta \lambda_N = 2.8$ nm from Fig. 3(b), and the calculated effective RI, $n_{\text{eff}} = 1.360$, for the fiber into Eq. (2), the cavity length is about $L_c = 90.2$ $\mu$m, which is in good agreement with the measured ring circumference of the microring.

After the SHMOF was tapered, the size of the microring changed proportionally. We now demonstrate adjustability of the cavity length ($L_c$) of the microring resonator using the setup shown in Fig. 2(a). The measurement was performed by carefully controlling the gain medium plug in the tapered region to change the location of the lasing with different cavity lengths ($L_c$). According to Eq. (1), the resonance wavelength of the $N$th longitudinal mode is related to the cavity length ($L_c$). In Fig. 4(a), the resonance wavelengths of the $N = 138$th (black spots) and $N = 139$th (red stars) lasing longitudinal modes were measured for varying cavity length ($L_c$) along the tapered region of the SHMOF, respectively. We used the R6G-doped plug in the ringdown measurement. The experimentally measured longitudinal FSRs of $\Delta \lambda_N$ changed with cavity lengths ($L_c$) in different positions. The measured normalized lasing spectrum with different cavity lengths ($L_c$) corresponding to the $N = 138$th and $N = 139$th longitudinal modes are shown in Figs. 4(b) and 4(c), respectively. The distances of the lasing location relative to the center of the tapered region were from 0 to 5 mm. The tuned lasing wavelengths were from 564.84 nm to 573.32 nm. So, a SHMOF dye laser can be tuned by varying the surface location of the microfluidic gain medium in the tapered region of the fiber.
The measured resonance wavelength of the $N = 138$th and $N = 139$th lasing longitudinal modes as a function of various locations of the surface of the gain medium relative to the center of the tapered region. (b) and (c) are the measured normalized lasing spectra corresponding to $N = 138$th and $N = 139$th longitudinal modes, respectively.

Fig. 5. The measured variation of the calculated cavity lengths (red squares), measured cavity lengths (red line and dots) and the laser threshold (blue line and dots) along the length of the tapered fiber are plotted. The calculated cavity lengths ranged from 57.9 $\mu$m to 89.0 $\mu$m, the measured cavity lengths ranged from 59.9 $\mu$m to 90.9 $\mu$m and the thresholds ranged from 16 nJ to 44 nJ.

The variational diameters of the tapered fiber along its length were directly measured under the microscope, which are in proportion to the size of the inside microring. We also measured the variation of the laser threshold and longitudinal mode interval along the length of the tapered fiber from the lasing spectrum. From Eq. (1) we can obtain the lengths of the resonant cavities along the length of the fiber, which is also the circumference of the microring, as shown in Fig. 5. The curves in Fig. 5 indicate that the threshold (blue line and dots) varied from 16 nJ to 44 nJ. Meanwhile, the cavity lengths (red line and dots) was calculated to be from 57.9 $\mu$m to 89.0 $\mu$m and measured to be 59.9 $\mu$m to 90.9 $\mu$m, respectively. We can see that the calculated cavity lengths were in good agreement with the measured cavity lengths from Fig. 5. For a uniform shaped cylindrical with smooth surface, the quality factor of the ring cavity surround the cylindrical is high, leading to a low threshold. On the contrary, when the shape of the cylindrical is change sharply, the ring cavity quality is low for the induced rough surface, leading to a high threshold. So in the tapered microcavity, the highest threshold lied in the acutest variation position of the cavity length while in the smoothly variation position such as the center part or the end part of the tapered region, we got relatively low emission thresholds. The highest threshold was in the position corresponding to a cavity length of 71.6 $\mu$m and the lowest threshold corresponded to a cavity length of 82.5 $\mu$m. The threshold in Fig. 3(a) at a distance of 5 mm relative to the center of the tapered region was determined. The spectrum in Fig. 3(b) was also measured at a distance of 8.5 mm. The calculated resonant cavity length matched the actual cavity length of the tapered microring. We can see that the location of the
liquid surface can be obtained by monitoring the lasing spectrum of the liquid dye in the SHMOF. This provides a flexible method for liquid surface position sensing.

4. Summary

We have realized a tunable microring dye laser within a tapered SHMOF. The fiber core was filled with a microfluidic gain medium (RhB and R6G) plug and axially pumped by a nanosecond pulse laser. Both strong radial emission and low-threshold lasing (16 nJ/pulse) were achieved. Lasing was achieved around the surface of the microfluidic plug. By axially pumping, both strong light-matter interactions, and an auto-segregation of the pump light and lasing were realized within the SHMOF [28]. Also, the size of the silica microring around the gain medium was continuously reduced along the characteristic fiber lengths by several micrometers, which provided a variation of the resonant cavity length. A reduced cavity length has the advantage of a small mode volume and has a large frequency spacing between consecutive modes. Tunable laser emission was realized by changing the stimulated location along the tapered fiber. We calculated sizes of the tapered silica microring along the fiber length from the measurement of the laser spectrum to obtain a sensitive liquid surface position sensor.

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