Optofluidic Circular Grating Distributed Feedback Dye Laser

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Abstract: We demonstrate a surface emitting optofluidic dye laser using a second order circular grating distributed feedback resonator. The optofluidic dye laser offers a low-cost and integrated coherent light source for lab-on-a-chip spectroscopy systems.

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Optofluidics has emerged as a new field for its various novel implementations in biotechnology [1]. In particular, on-chip liquid dye lasers allow the integration of coherent light sources with other microfluidic and optical functionalities, and provide possibilities for building more complete “lab-on-a-chip” systems. In this paper, a surface emitting optofluidic dye laser has been developed using a hybrid material microfluidic system. For the laser cavity, we choose the circular grating distributed feedback (DFB) structure to obtain low-threshold, high-efficiency operation, and vertical emission out of the device plane [2].

The schematic diagram of the optofluidic circular grating dye laser is shown in Fig. 1. The laser chip is a hybrid microfluidic device made of poly(dimethylsiloxane) (PDMS) and perfluoropolyether (PFPE). A microfluidic channel with the circular grating structures embedded is filled with dye solutions. The gain medium is a dye solution of Rhodamine 6G in a benzyl alcohol and methanol mixture. The PDMS forms the microfluidic channel and serves as the upper cladding of the cavity. The lower cladding material is PFPE, which also forms the circular grating that provides the feedback necessary for the laser action.

The circular grating structure provides a natural 2-D extension of the basic DFB structure. The corrugations in the grating structure provide both distributed feedback and output coupling of the guided optical mode. Second order gratings are used to obtain surface emission, because the first order Bragg reflection from a second order grating can phase match radially propagating waves to vertically propagating plane waves, as illustrated in Fig. 1.

To successfully fabricate microfluidic channels with the sub-200 nm laser cavity structures embedded, we require the soft lithography material to have both high replication resolution and superior bonding property. PFPE is a photocurable polymer with high replication resolution [3]. Here, we chose a composite bilayer patterning method due to the limitation of pattern replication of PDMS [4]. Therefore, our optofluidic dye laser is composed of two layers, a stiff layer (PFPE) supported by a flexible layer (PDMS). This composite bilayer patterning method combines the attractive features of both the materials.

Fig. 1. Schematic diagram of optofluidic circular grating dye laser

Fig. 2. Optofluidic circular grating DFB dye laser spectrum

The optofluidic dye laser device was fabricated by multilayer soft lithography techniques [5]. The chip consisted of two layers, the grating layer and the flow layer. The replication hard mold was fabricated on SiO₂

substrate, and the grating pattern was defined by e-beam lithography with proximity correction. In order to obtain a deep, steep-sided grating profile, we chose a deep reactive ion etching (DRIE) process to transfer the pattern to the SiO₂. The chip fabrication started by spinning PFPE on the grating area of the mold, followed by UV exposure to cure the material. Then the PDMS prepolymer was poured onto the PFPE layer and thermally cured. This process formed a support layer for the composite PFPE/PDMS structure. The PFPE/PDMS layer was peeled from the grating mold and aligned to another PDMS layer with flow channels inside. Finally, the device was baked overnight to ensure bonding between the two layers. The bonding between PFPE and PDMS is not very strong, but the adhesion is sufficient for the laser chip operation.

The optofluidic dye laser chip was optically pumped with 6 ns Q-switched Nd:YAG 532 nm laser pulses. A fluidic control tubing with a pressure source was used to circulate the dye solution in the flow channel. The optofluidic version of the circular grating dye laser allows us to constantly change the dye to increase the device lifetime. A typical single-frequency lasing spectrum is shown in Fig. 2. For the circular grating resonator with the period of 410 nm, the lasing wavelength is 581.13 nm. Lasing occurs near the Bragg resonance, determined by the Bragg condition $m\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda$, where $m = 2$ is the order of diffraction, n_{eff} is the effective refractive index of the propagation mode, and Λ is the grating period. The inset of Fig. 2 shows the variation of the output laser power as a function of absorbed pump energy, and the threshold pump fluence is estimated to be 0.96 $\mu\text{J}/\text{mm}^2$. The laser has a low pump threshold and a geometry well matched to laser diode pump sources, therefore this laser configuration represents a very promising structure for the construction of compact laser diode pumped portable dye lasers. The microfluidic compatibility of the laser chip also suggests that we can achieve wavelength tuning by changing dye solutions with different refractive indices.

In summary, we demonstrate an optofluidic dye laser with second-order circular grating distributed feedback structure. We achieved surface emitting single frequency lasing and low threshold operation. The improved soft lithography technique with a hybrid PFPE/PDMS material system enables the fabrication of low cost, disposable, high quality and mass producible laser arrays compatible with microfluidic systems. The construction of compact and inexpensive coherent light sources fully integrated with microfluidics provides an efficient approach to realize complete "lab-on-a-chip" systems.

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