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Polymer microlasers with a suspended cavity design

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Suspended, three dimensional microlasers are fabricated using proton beam writing of two different energies in a single layer of Rhodamine B doped SU-8 polymer. The optical excitation under ambient atmosphere shows the microlaser emission near 600 nm. A lasing threshold as low as $0.5 \mu\text{J}/\text{mm}^2$ is achieved by raising the microlaser from the substrate, which is an improvement by factor of 2 when compared to planar microlasers. Also the directionality is observed in whispering gallery mode lasers with spiral cavity with extended waveguide design. These suspended microlasers are not only useful in reducing the lasing threshold but also have significance in 3D photonic integrated circuits. © 2014 Optical Society of America

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High quality factor optical microcavities based on whispering gallery mode (WGM) resonators have been extensively studied in recent years due to their numerous applications in integrated optics [1], sensing [2] and cavity quantum electrodynamics [3]. The high quality factors of these resonators is due to strong total internal reflection from the smooth boundary of the cavity which results in high confinement of electromagnetic fields [4]. The most common designs for these microresonators are the microdisk, microring and the microsphere [5–7]. Using these designs, quality factors as high as 3×10^6 have been obtained in semiconductors [5], and 8×10^9 in silica and quartz [8]. In terms of fabrication, 2-dimensional designs are far easier to implement and integrate with other optical components, however the in-plane confinement is usually weak due to the substrate on which the microresonators are fabricated.

One of the most promising applications of these microresonators is their use as microlasers [8]. Microlasers have applications in hybrid optoelectronic circuits [9], optical sensing [10] and optical storage [11]. Although regular circular WGM microcavities like the microdisk or microsphere are able to obtain low threshold lasing, the disadvantage of these highly symmetric designs is their lack of directionality. Nöckel et al first proposed and demonstrated directionality in such microlasers by introducing a deformation to the regular circular geometry [12]. Later several groups showed directional behaviour in microcavity lasers by utilizing different cavity designs like elliptical cavities, stadium shaped cavities and spiral cavities [13–15]. These designs were implemented at the expense of a reduced quality factor when compared to a regular microdisk cavity.

In this paper we develop a method for fabricating suspended microlasers in dye doped polymers which offer increased three-dimensional optical confinement and directionality in emission which improves their applicability

for integration with other passive or active optical components. We fabricate several 2D and 3D designs that allow for direct comparison of their emission properties, directionality and lasing thresholds.

Fig. 1. SRIM Monte Carlo simulation showing the proton depth in SU-8 photoresist for two energies used in the experiment (a), schematic showing the fabrication procedure to obtain the suspended microcavities using proton beam writing (b).

Suspended microcavities were fabricated in gain medium, Rhodamine B doped SU-8 polymer. This type of gain medium is attractive because of the flexibility in deciding the operating wavelength of the final laser device which entirely depends on the laser dye employed. The preparation and the optimization of the dye concentration is reported in ref [16]. Proton beam writing (PBW) is implemented to fabricate the suspended microlasers. PBW is a high resolution direct write lithographic technique that utilizes high energy protons (typically 100 keV to 3 MeV). The unique characteristics of the technique are the ability to fabricate smooth, high aspect ratio and multi-level structures in single layers of photo resist by careful selection of the beam energy [17]. In addition, when PBW is used to fabricate structures in photoresists like SU-8, no post exposure bake step is required. This is advantageous when using dye doped polymers that tend to degrade when subjected to el-

evated temperatures. Details of the technique are described elsewhere [18]. In recent years, PBW has been applied to many applications in optics and photonics including waveguides [19], microlens arrays [20], metamaterials [21], and photonic crystals [22].

The penetration depth of MeV ions in polymer or any other material is primarily depends on the ion species and their energy. In the present work the suspended microlasers are fabricated by utilizing the two different proton energies. A Stopping and Range of Ions in Matter (SRIM) [23], Monte Carlo simulation software package, is used to determine the proper proton energy for the laser cavity fabrication and is shown in Figure 1(a). From the Figure it is evident that the ionization profile of 200 keV protons shows that it can penetrate upto $2\ \mu\text{m}$ in SU-8 which defines the thickness of laser cavity. The profile of 2 MeV protons shows that it deposit most of its energy in the substrate, which is a silicon wafer with a $4\ \mu\text{m}$ thermal oxide layer on top. First lower energy focused proton beam (200 keV) is used to fabricate the laser cavity near the surface of the $20\ \mu\text{m}$ gain material layer which is spin coated on the substrate. A second high energy focused proton beam (2 MeV) is used to fabricate a pedestal that connects the laser cavity to the substrate. In both cases the proton beam is focused down to $100\ \text{nm}$ in lateral and $150\ \text{nm}$ in vertical directions. The fabrication procedure is schematically represented in Figure 1(b). After the PBW, subsequent chemical development reveals the suspended cavities which can be seen in figure 2. It is important to note there is no post exposure bake required in case of PBW. The SEM and optical micrographs of the fabricated microdisk cavity with $20\ \mu\text{m}$ diameter is shown in Figure 2(a) and the spiral cavity of $20\ \mu\text{m}$ diameter with an integrated waveguide of $2.5\ \mu\text{m}$ width is shown in Figure 2(b). A $5\ \mu\text{m}$ diameter pedestal can also be seen in both cavities. In this work, two energy approach is used to fabricate three dimensional suspended microlasers where as single energy fabrication is used for the planar cavities. A proton fluence of $80\ \text{nC}/\text{mm}^2$ is used for all the cavities.

Fig. 2. cross-sectional SEM micrographs of the fabricated suspended microcavities, microdisk laser (a), micro spiral disk with waveguide (b), inset shows the optical micrographs of the same images.

The fabricated microlasers are characterized using free space optical excitation with a frequency doubled Nd:YAG pulsed laser operating at $532\ \text{nm}$ wavelength

with $7\ \text{nsec}$ pulse duration and $10\ \text{Hz}$ repetition rate. The free space optical excitation set-up is shown in Figure 3 (a). The pump laser is directed onto the sample using a 45° mirror and the laser beam is passed through a $600\ \mu\text{m}$ aperture in order to generate a well defined and reproducible excitation volume on the sample plane. A $10\times$ objective lens together with a fiber coupled spectrometer (Ocean Optics HR4000CG-UV-NIR) is used to collect the emission from the microlaser.

Fig. 3. (a) Schematic of the free space optical excitation set-up for pumping the fabricated laser cavities. (b) Emission spectrum obtained from different cavities above the threshold pump fluence. The threshold curve for the micro disk (c) and the micro spiral with waveguide (d). Cross-sectional optical images of the fabricated microdisk (e) and spiral cavity with waveguide (f) under pumping laser, which clearly shows the directional behavior of spiral cavity with waveguide.

To determine the lasing threshold, the microlaser emission was monitored as a function of pump laser intensity. Figure 3(b-d) shows the laser characteristics of all the fabricated cavities. The threshold curves for the microdisk cavities and spiral cavities are shown in Figure 3(c) and Figure 3(d). The laser emission spectra is shown in Figure 3(b). The directionality of the laser cavities was observed qualitatively by obtaining the cross sectional optical images under the pump laser excitation. Figure 3(e) and 3(f) shows the optical micrographs of the laser cavities obtained by replacing the fiber coupled spectrometer with a high sensitivity visible CCD camera (Q Imaging Retiga Exi) in the optical set-up. As expected

the microdisk laser emits light in all directions. In case of spiral cavity with waveguide the emission is directional and the emitted light is confined to the $2.5 \mu\text{m}$ width waveguide region which is clearly visible in Figure 3 (f).

Table 1. Summary of laser characteristics

Cavity Design	Emission Band (nm)	Threshold Fluence ($\mu\text{J}/\text{mm}^2$)	
		2D	3D
Disk	630-650	1	0.5
Spiral WG	590-610	5	2.4

The lowest threshold fluence is obtained for 3D microdisk which is $0.5 \mu\text{J}/\text{mm}^2$. The primary factors that influence the threshold fluence required for lasing in microcavities are the quality factor of cavity and the efficiency of the gain media. Although the direct measurement of the quality factor was not performed in the present study, it is expected to be higher than the planar cavity [24] and is also evident from the laser performance when compared to planar microlaser. The results from the suspended microlasers are compared with its planar counterparts and the results are summarized in Table 1. The suspended microlaser cavities showed lower pump threshold compared to the planar microlaser cavities of the same dimensions. By making the microcavities suspended, the surrounding medium becomes air and the index contrast is increased when compared with the planar cavities which are on the thermally grown silicon dioxide on silicon. The increase in index contrast further improves the optical confinement in the microcavity and raising these microlasers reduce the substrate losses which results in increasing the quality factor. From the results shown in Table 1, the laser threshold is improved by a factor of 2 by suspending the cavities in air. The measured threshold fluence required for spiral cavity with waveguide is $2.4 \mu\text{J}/\text{mm}^2$ which is higher than the fluence measured for the microdisk design. This causes from the asymmetry introduced in the spiral cavity which reduces the quality factor. And in the case of laser emission, the emission bands are different for different cavity designs which is attributed by the fact that the dimension dependence on WGM resonance. The circumference of the two cavity designs is different which is the reason for different emission bands.

In conclusion we showed the fabrication of suspended microlaser cavities in Rhodamine B doped SU-8 polymer using proton beam writing. PBW showed its uniqueness in fabricating three dimensional microlasers in a single polymer layer with controlled cavity thickness compared to other techniques [25, 26]. The free space optical excitation of the suspended microlasers revealed that these microlasers have improved laser performance compared to its planar counterparts of same dimensions. The directional behavior of the spiral cavity with waveguide was also observed using the simple cross section optical imaging.

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