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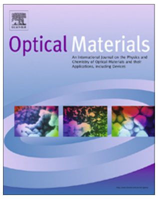

Polymer microlasers with a suspended cavity design

Sudheer Kumar Vanga [a], Venkatram Nalla [b], Andrew A. Bettiol [a],*

[a] *Centre for Ion Beam Applications, Department of Physics, National University of Singapore, 2 Science drive 3, 117551, Singapore*
[b] *Centre for Disruptive Photonic Technologies, Nanyang Technological University, 637371, Singapore*

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ABSTRACT

We report on the fabrication of microlasers with suspended cavity design in a thin layer of Rhodamine B doped SU-8 polymer using proton beam writing. Optical characterization of the fabricated three-dimensional microlasers under ambient atmosphere results in low lasing threshold of 0.5 μJ/mm^2, which is an improvement by factor of 2 when compared to planar microlasers. The directional behavior is also observed in whispering gallery mode microlasers with spiral cavity design. These microlasers with suspended cavity design are not only useful in reducing the lasing threshold but also have significance in 3D photonic integrated circuits.

1. Introduction

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]. One of the most promising applications of these microresonators is their use as microlasers [5]. Microlasers have applications in hybrid optoelectronic circuits [6], optical sensing [7] and optical storage [8]. 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 [9]. Later several groups showed directional behavior in microcavity lasers by utilizing different cavity designs like elliptical cavities, stadium shaped cavities and spiral cavities [10–12]. These designs were implemented at the expense of a reduced quality factor when compared to a regular microdisk cavity.

In terms of fabrication of these microcavities, 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 microcavities are fabricated. To enhance the optical confinement in these cavities, we report on the fabrication of three-dimensional microlasers with suspended cavity design in a thin layer of dye doped polymer using proton beam writing (PBW) with two energies. 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, nano/micro structures with high-aspect ratio geometry in different materials like polymers, semiconductors and insulators [13–15]. 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 elevated temperatures. Details of the technique are described elsewhere [16]. In recent years, PBW has been applied to many applications in optics and photonics including waveguides [17], microlens arrays [18], metamaterials [19], and photonic crystals [20].

In this paper we develop a method for fabricating microlasers with suspended cavity design 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.

2. Experimental details

Microcavities with suspended cavity design 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

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* Corresponding author.
E-mail address: a.bettiol@nus.edu.sg (A.A. Bettiol).

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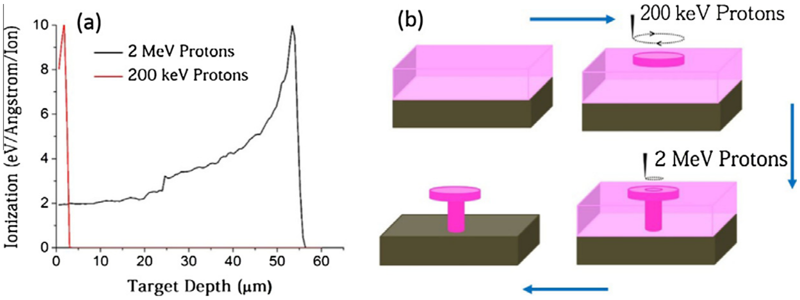

Fig. 1. (a) SRIM Monte Carlo simulation showing the proton depth in SU-8 photoresist for two energies used in the experiment, and (b) schematic showing the fabrication procedure to obtain the suspended microcavities using proton beam writing.

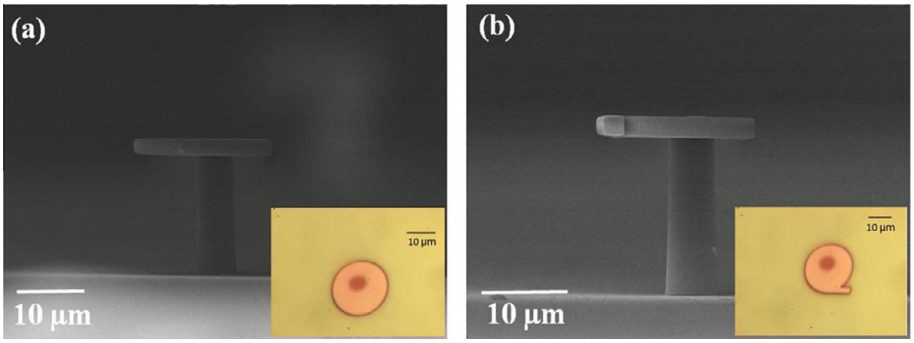

Fig. 2. Cross-sectional SEM micrographs of the fabricated suspended microcavities, (a) microdisk laser, and (b) micro spiral disk with waveguide, inset shows the top view optical micrographs of the same cavities.

operating wavelength of the final laser device which depends on the laser dye employed. The preparation and the optimization of the dye concentration was reported in Ref. [21]. 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 microlasers with suspended cavity design were fabricated by utilizing the two different proton energies. A Stopping and Range of Ions in Matter (SRIM), Monte Carlo simulation software package [22], was used to determine the energy of proton beam for the laser cavity fabrication and is shown in Fig. 1(a). From the figure it is evident that the ionization profile of 200 keV protons shows that it can penetrate up to 2 µm 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 µm thermal oxide layer on top. First lower energy focused proton beam (200 keV) was used to fabricate the laser cavity near the surface of the 20 µm thick gain material layer which was spin coated on the substrate. A second high energy focused proton beam (2 MeV) was used to fabricate a pedestal that connects the laser cavity to the substrate. In both cases a proton fluence of 80 nC/mm^2 was used and the proton beam was focused down to 100 nm in lateral and 150 nm in vertical directions. The fabrication procedure is schematically represented in Fig. 1(b). After the PBW, subsequent chemical development reveals the suspended cavities which can be seen in Fig. 2. It is important to note that there is no post exposure bake required in the case of PBW. 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.

The fabricated microlasers were characterized using free space optical excitation with a frequency doubled Nd:YAG pulsed laser operating at 532 nm wavelength with 7 nsec pulse duration and 10 Hz repetition rate. The free space optical excitation set-up is shown in Fig. 3(a). The pump laser was directed onto the sample using a 45° mirror and the laser beam was passed through a 600 µm aperture in order to generate a well defined and reproducible excitation volume on the sample plane. A 10× objective lens together with a fiber coupled spectrometer (Ocean Optics HR4000CG-UV-NIR) was used to collect the emission from the microlaser.

3. Results and discussion

The SEM and optical micrographs of the fabricated microdisk cavity with 20 µm diameter is shown in Fig. 2(a) and the spiral cavity of 20 µm diameter with an integrated waveguide of 2.5 µm width is shown in Fig. 2(b). The thickness of the laser cavity is 2 µm which is determined by the proton beam energy. Thickness of the laser can be controlled precisely by proper selection of the proton beam energy. A 5 µm diameter pedestal can also be seen in both cavities. Since the mode field is confined along the circumference of the cavity, the pedestal has no influence on the laser properties.

To determine the lasing threshold, the microlaser emission was monitored as a function of pump laser fluence. Fig. 3(b–d) shows the laser characteristics of the fabricated three dimensional and planar cavities. The threshold curves for the microdisk cavities and spiral cavities are shown in Fig. 3(c) and (d). The lowest threshold fluence is obtained for 3D microdisk which is 0.5 µJ/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 due to the poor spectral resolution, it is expected to be higher than that of planar cavity [23] and is also evident from the laser