Fabrication and characterization of microcavity lasers in rhodamine B doped SU8 using high energy proton beam

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The authors present their results on the characterization of individual dye-doped microcavity polymer lasers fabricated using a high energy proton beam. The lasers were fabricated in rhodamine B doped SU8 resist with a single exposure step followed by chemical processing. The resulting trapezoidal shaped cavities had dimensions of $\sim 250 \times 250\ \mu m^2$. Physical characterization of these structures was performed using a scanning electron microscope while the optical characterization was carried out by recording the emission subsequent to pumping the lasers with 532 nm, 6 nanosecond pulses. The authors observed intense, narrow emission near 624 nm with the best emission linewidth full width at half maximum of ~ 9 nm and a threshold $\sim 150\ \mu J/mm^2$.
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Polymer based materials and devices find impending applications in telecommunications, displays, biomedicine, and laboratory-on-a-chip (LOC) systems.[1–5] Miniature dye lasers, in particular, solid state, that are robust and maintenance-free find relevance in communication networks, sensors, and microfluidic device applications.[6–10] Polymer based lasers and devices are an attractive alternative to more commonly used solid state lasers for their versatility, low cost, and tunability. Solid state dye laser with continuous wave pumping[11] has been demonstrated recently which enhances the significance of such devices' utility in the near future. Much of the earlier work on solid polymer and other solid state matrices containing laser dyes relied on external and macroscopic laser cavities.[6–8] Different configurations for the dye lasers such as distributed feedback, thin film/waveguide, photonic crystal, and microdroplet types have been investigated recently.[12–14] However, recently, a group at Technical University of Denmark working on laboratory-on-a-chip systems and nanoimprint lithography has developed solid state microlaser cavities with triangular and trapezoidal shapes with dimensions of the cavities in the range of a few hundred microns.[15–25] They utilized diverse techniques such as deep reactive ion etching and thermal imprint lithography for fabricating lasers in polymethylmethacrylate (PMMA) and SU8 doped with rhodamine B (RhB) and rhodamine 6G perchlorate. They obtained the best results for the trapezoidal shaped cavities. Here, we present results of fabrication and characterization of direct written microlaser structures in SU8, doped with rhodamine B dye, employing a high energy (2 MeV) proton beam. Proton beam writing (PBW) is a new direct write technique capable of creating three-dimensional, high aspect ratio micro- and nanostructures with straight and smooth sidewalls in resists, polymers, glasses, and other materials.[26–28] PBW is particularly attractive in fabricating arbitrary shape waveguide patterns (e.g., Y branch, Mach-Zehnder interferometer) along with micro-/nanofluidic channels in different materials such as polymers, silicon, and Foturan glass. Some of the earlier demonstrations of passive devices include SU8 channel waveguides[29] with extremely high quality sidewalls[30] and Y branches,[31] PMMA buried channel waveguides,[32] micro- and nanochannels[33] using direct write as well as imprinting,[34] waveguides and channels in Foturan glass,[35] microlens array,[36] and microstructures in silicon.[37]

The design of the laser cavity for the structures in the present study was employed from Refs. 16–19. 1% (by weight) rhodamine B was dissolved in commercially available SU8-2005 (in cyclopentanone) and was left in an ultrasonic bath for a few hours. The clear solution thus obtained was spin coated onto a 2 in. diameter silicon substrate coated with gold and chromium. The substrate was prebaked on a hot plate to a temperature of 200 °C for about 10 min to remove the excess moisture and postbaked for 3 min at 90 °C. The preparation of solutions and spin coating were carried out in a class 1000 clean room. A 2.0 MeV proton beam with focused spot size of $<1\ \mu m$ and a fluence (ion dose) of $\sim 50\ nC/mm^2$ was used to fabricate the trapezoidal shaped cavities with dimensions of $\sim 250 \times 250\ \mu m^2$. After exposure the samples were developed in a suitable chemical solvent. SU8 acts as a negative resist to the proton beam and therefore the irradiated part was retained while the rest was washed out.

Figure 1(a) shows the design of the trapezoidal shaped microlasers adapted from Ref. 16. The angle of laser emission is expected to be ~78° on both sides of the normal

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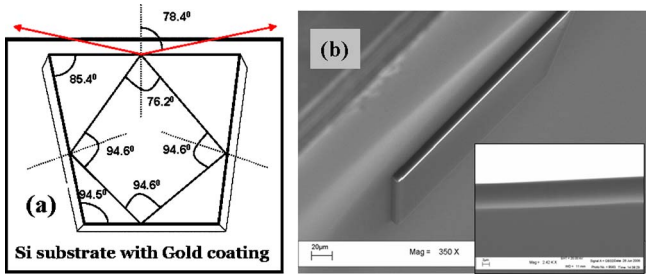

FIG. 1. (Color online) Design of the laser structure fabricated (adapted from Ref. 16). The laser emission angle expected for this structure is ~78°. (b) Scanning electron microscope image of rhodamine B doped SU8 microlaser with view of sidewalls. Inset shows roughness of one sidewall with higher resolution (2 μm scale).

drawn with respect to the top surface.[15,16] Figure 1(b) shows a high resolution scanning electron microscopy image of one microlaser. Typical height of the microlasers estimated from the data was ~7.6 μm. The inset of Fig. 1(b) depicts the sidewall roughness with a field of view of 2 μm. The sidewall roughness is an important parameter which will affect the reflectivity and thereby the propagation of laser pulses within the cavity. Our recent studies on the measurements for sidewall roughness of passive SU8 waveguides indicated a rms roughness of <10 nm.[30] Though we could not precisely measure the roughness of our dye-doped SU8 microlasers we expect a similar order of magnitude as observed in passive devices. Inspection of the structures with a laser confocal microscope confirmed the uniformity of doped RhB dye in SU8. Optical characterization was carried out using a nanosecond neodymium-doped yttrium aluminum garnet laser (6 ns at 532 nm) delivering pulses with a maximum energy of ~300 mJ. The emission from the structures was collected using a multimode fiber connected to a spectrometer (Ocean Optics Inc., model SD2000 with spectral range of 200–850 nm and resolution of 1.5 nm) interfaced to a personal computer. The energy of the input laser was varied using neutral density filters. Since the fabricated structures were far from the edge of the substrate, the emission was collected at a distance of ~3–4 mm from the structures.

We tried two different configurations for characterizing the microlasers. Initially the input beam was loosely focused (with estimated spot size of ~300 μm) onto the individual lasers for stronger emission. All the studies were carried out with the pump beam incident ~85° to the plane of microlasers. For such a configuration Figs. 2(a)–2(f) portray typical emission intensities in the focused geometry for different laser energy densities ranging from 15 to 200 μJ/mm^2. These values were approximated with an error of ±20% arising from the errors in the estimation of the spot size at focus. It is evident that linewidth decreases drastically with increasing pump energy densities. Figure 3 shows the Gaussian fits for the emissions obtained at energy densities of ~15 μJ/mm^2 (solid triangles) and ~200 μJ/mm^2 (hollow circles), respectively. The weak emission at very low energy density was broad with a full width at half maximum (FWHM) of ~52 nm while the FWHM obtained for the highest energy density was narrow with a FWHM of ~12 nm. The least FWHM obtained was ~9 nm for pumping close to 300 μJ/mm^2. This is in good agreement with the FWHM of the laser emission (~8 nm) observed from a RhB liquid dye laser pumped by 532 nm pulses.[38] The intensity of the emission increased for higher pump energy densities with signature of a clear threshold as depicted in the inset of Fig. 3. The emission obtained was highly directional in the sense that in random directions the emission was very weak and broad compared to the emission near 60°. The estimated emission angle for our structures was 60°±5° and is different from the predicted value of 78°. The laser emission peaked at 624 nm (Fig. 2) in conjunction with the fluorescence emission near 620 nm. The peak wavelength of the emission depends critically on pumping angle and the focusing conditions. We observed a blueshift in the peak wavelength with increasing pump energies for different angles of pumping. Variations from the ideal emission angle and the blueshift of peak wavelength could arise from (1) discrepancy in the actual device angles due to the lithographic process, (2) differ-

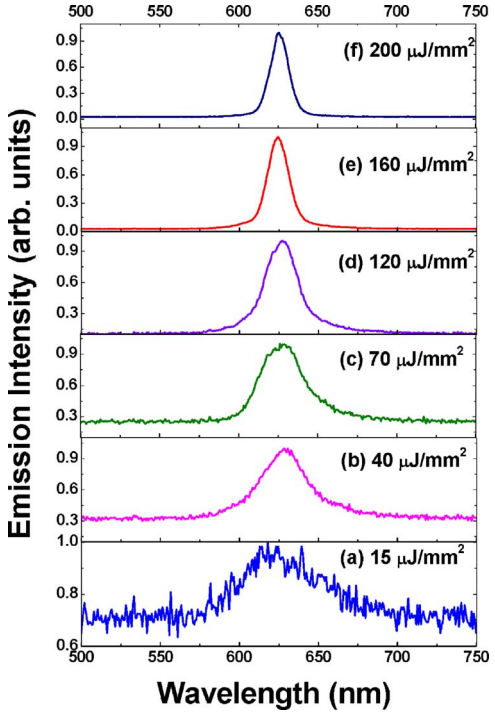

FIG. 2. (Color online) [(a)–(f)] Emission intensities plotted as a function of wavelength for different pump energy densities in the focused geometry.

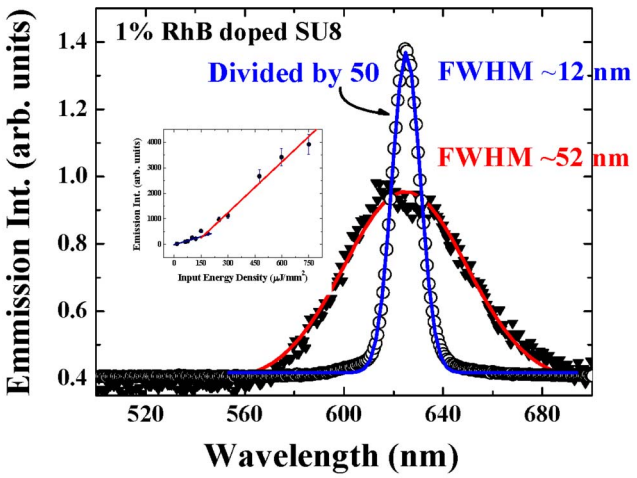

FIG. 3. (Color online) FWHM of emissions at low energy density of 15 μJ/mm^2 (solid triangles) and high energy density of 200 μJ/mm^2 (open circles). Solid lines are best fits to a Gaussian. Inset shows the threshold behavior of the emission intensity plotted as a function of input energy density. The change in color of the solid line indicates change in slope.

ent modes/path lengths supported by the thicker cavity of our structures, and (3) possible degradation of dye in the polymer postfocusing. An interesting aspect of the proton beam irradiated doped SU8 film is the redshifting of the emission spectrum compared to unirradiated, doped SU8 film. There are no previous studies to corroborate or contradict our observation but we expect the redshift due to some structural modifications of the SU8 induced by the proton beam.

In the second configuration the lasers were pumped directly by the nanosecond pulses without any focusing optics. We could obviously observe the linewidth reduction and threshold behavior. The threshold calculated using this procedure was $\sim 150\ \mu J/mm^2$. However, the estimated threshold was higher ($\sim 400\ \mu J/mm^2$) with the focusing lens. This disagreement could be due to the errors compounded in the estimation of the exact spot size at input and at the focus along with calibration of the neutral density filters. The increased threshold when compared to similar laser structures in SU8 ($\sim 25\ \mu J/mm^2$ for structures of similar dimensions) reported in literature[17,18] is attributed mainly to the thickness of our films ($\sim 7.6\ \mu m$) leading to higher losses in the cavity. With different laser cavity dimensions and doping concentrations we expect to control and lower this threshold further.

We have also tried pumping these lasers with 150 femtosecond pulses at 532 nm. However, due to lack of sufficient energy from the optical parametric amplifier at this wavelength we could only observe the broad emission and not the linewidth reduction. The advantages of direct writing laser structures using PBW is evident from the fact that we could demonstrate active and passive waveguides in SU8 and PMMA along with micro- and nanochannels using both techniques of direct writing as well as imprinting. Moreover, the capability of PBW to produce very high quality stamps[33,34] makes it possible to fabricate the laser sources, waveguides, and channels on a single substrate, key components for a LOC device, during a single exposure step. Combined with the capacity of PBW to micromachine silicon too, the possibilities exist for manufacturing hybrid devices useful in LOC and microfluidic applications. However, there are several issues to be thoroughly explored among which the most significant are as follows: (1) Understanding the mechanism of tuning the emission wavelength by varying the thickness of the microlasers, concentration of the dye, cavity dimensions, pumping angle, etc., (2) dye doping in PMMA and other compatible polymers, and (3) exploring the possibilities of imprinting the laser structures along with waveguides and microchannels for wafer scale fabrication.

In conclusion we have fabricated and characterized (at 532 nm) microlasers in SU8 doped with rhodamine B. Laser cavities with dimensions of $\sim 250 \times 250\ \mu m^2$ were fabricated with a single step exposure to high energy proton beam and followed by chemical processing. Individual microlasers were physically and optically characterized with the laser emission near 624 nm and an estimated threshold of $150\ \mu J/mm^2$.

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