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FAST TRACK COMMUNICATION

Characterization of channel waveguides and tunable microlasers in SU8 doped with rhodamine B fabricated using proton beam writing

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Abstract
We present our results on the fabrication and characterization of buried channel waveguides and tunable microlasers in SU8 doped with rhodamine B achieved using direct writing with a 2.0 MeV proton beam. The channel waveguides, fabricated in single exposure, had an optical propagation loss of <0.5 dB cm^{-1} at 532 nm measured using the scattering technique while the microlasers with dimensions of $250 \times 250\ \mu$m^2 had a threshold of $\sim 150\ \mu$J mm^{-2} when pumped with 532 nm nanosecond pulses. The emitted wavelength from the microlasers was tunable to an extent of $\sim$15 nm with increasing pump intensity and different pumping angles. The advantages of such micro-photonic components for the realization of a lab-on-a-chip device are discussed briefly.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Polymer based fluidic and optical devices are attractive for diverse applications such as lab-on-a-chip (LOC), telecommunications, displays and biomedicine [1–11]. Polymers are an appealing alternative for silicon and glasses for their versatility, low cost and tunability. Some of the common polymers/resists used in various lithographic techniques for fabrication of devices are polymethyl methacrylate (PMMA), cyclic olefin copolymer and SU8. The important requisite for the realization of LOC devices is the integration of passive and active structures on a single substrate enabling different functionalities and that for optofluidic devices is the realization of fluidic channels and optical structures on a single substrate. Techniques, especially those which employ direct writing, with the ability of mass replication and simultaneous production of high quality three dimensional structures are quite a few [12]. Proton beam writing (PBW) is a new direct-write technique developed at the Centre for Ion Beam Applications, National University of Singapore, for creating three-dimensional, high aspect ratio micro- and nano-structures with straight and smooth sidewalls in resists, polymers, glasses and other materials [12–28]. Direct writing with high-energy proton beams is effective in fabricating arbitrarily shaped three dimensional structures (e.g. Y-branch, Mach–Zehnder type, ring resonator structures) along with micro-/nano-fluidic channels in a variety of materials such as polymers, silicon and bio-compatible Foturan glass. Some of the earlier successful demonstrations of passive devices using this technique include SU8 channel waveguides [16, 17] with extremely high quality side walls [18] and Y-branches [19], PMMA buried channel waveguides [20], erbium doped phosphate glass waveguide

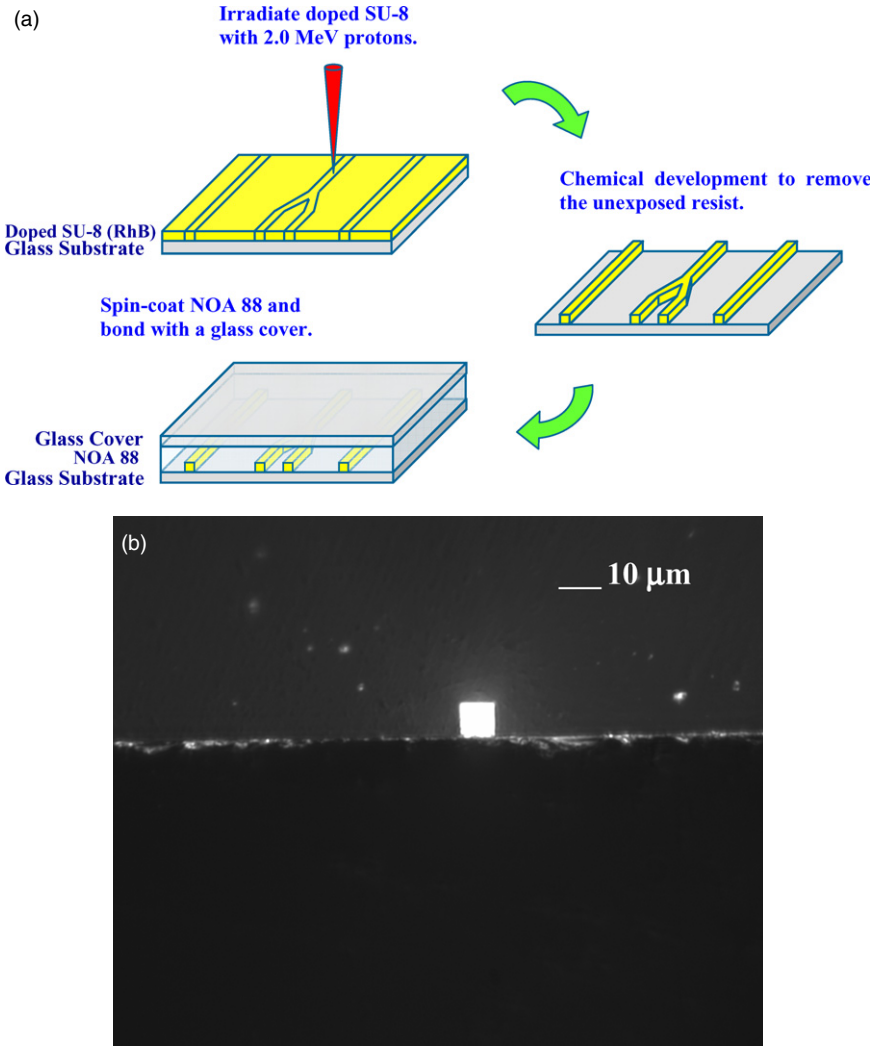

Figure 1. (*a*) Procedure for fabricating waveguides in SU-8 doped with rhodamine B. (*b*) Optical picture of end facet of the channel waveguide obtained in SU8 waveguide (doped with RhB) with white light.

amplifiers [21], micro- and nanochannels [22, 23] using direct write as well as imprinting [23], waveguides and microchannels in Foturan glass [24, 25] microlens array for tweezing applications [26] and microstructures in silicon [27]. The recent achievement of writing 22 nm structures in hydrogen silsesquioxane resist [14] highlights the potential of this technique in manufacturing high aspect ratio structures. The advantages of PBW compared with other techniques like optical or x-ray lithographies is the non-involvement of external mask and in tandem with nanoimprint lithography enables rapid prototyping of smooth, high aspect ratio three dimensional structures. The manifestation of such devices in photonic, microfluidic and LOC applications has been well established in the last couple of years [9, 10]. Recently, we had successfully fabricated microlasers in SU8 doped with rhodamine B dye and demonstrated lasing action with low threshold near the 600 nm spectral region [28]. Earlier, we had also demonstrated very low-loss passive waveguides in SU8 and this combination can result in microfluidic dye lasers essential for a variety of applications in sensing and biomedicine. Here we present our results on the fabrication of millimetre-long active waveguides in SU8 and the tunability of laser emission from the microlasers in rhodamine B doped SU8.

2. Experiment

PBW was carried out using the high-brightness 2.0 MeV Singletron facility at the Centre for Ion Beam Applications, National University of Singapore. SU8-2005 was purchased from MicroChem and used as is. Rhodamine B was dissolved in SU8-2005 (in cyclopentanone) and left in an ultrasonic bath for a few hours to obtain a clear solution. For waveguide fabrication, SU8 doped with RhB (1% by weight) was spin coated onto a glass (GE124, refractive index of ∼1.457) substrate. Upon proton beam irradiation and followed by chemical processing the cross linked SU8 was retained while the rest of the resist was washed out. We later spin coated NOA88 (a UV adhesive) over these structures to achieve buried waveguides with SU8 + RhB acting as the core. A glass plate was placed over the structure for protection and easier handling purposes. The end facets were optically polished for coupling light into the waveguides. The different steps involved in the procedure are depicted in figure 1(*a*). In

the case of microlaser fabrication, the SU8 + RhB solution was spin coated onto a silicon substrate pre-coated with gold and chromium. The substrate was pre-baked on a hotplate to a temperature of 200 °C for ∼10 min to remove the excess solvent present in the samples and post-baked for ∼3 min at 90 °C. The preparation of solutions and spin coating were carried out in a class 1000 clean room in order to reduce the chances of depositing unnecessary particles on the samples. A 2.0 MeV proton beam with a focal spot size of $<1\,\mu$m and an ion fluence of ∼50 nC mm^{-2} was used to fabricate the few-millimetre-long waveguides and laser cavities with dimensions of 250 × 250 μm^2. Post exposure, the sample was developed in a suitable chemical solvent.

3. Results and discussion

Figure 1(*b*) shows the optical image of a typical channel waveguide fabricated in SU8 + RhB (1% by weight) which was obtained with white light illumination and a CCD camera (QImaging). Typical dimensions (width and height) of the waveguides were in the range of 8–10 μm. Several millimetre-long waveguides were easily fabricated without the obscurity of damage. Figure 2(*a*) shows the propagation loss profile of a typical waveguide obtained using the standard scattering technique [29], where the scattered light out of the waveguide is captured normal to the propagation direction. Assuming the sample is homogeneous the propagation loss is then estimated through a simple exponential decay fit to the data. We could not observe the output of the coupled He–Ne laser (633 nm) light probably due to self-absorption effects, which was later confirmed from the thin film emission spectrum of SU8 + RhB irradiated with a proton beam. A 532 nm continuous wave laser was used as a source for observing the strong fluorescence from the waveguide which was utilized for the estimation of the propagation loss. The value obtained with a plot of fluorescence emission (collected after 532 nm coupling) versus the length of the waveguide was measured to be ∼3.2 dB cm^{-1} (∼0.72 cm^{-1}) through a best fit which is illustrated in figure 2(*b*). The data were collected twice and the loss value was averaged from the two independent measurements. The higher loss value is predominantly due to the absorption of 532 nm radiation along the waveguide. Through the absorption data of the RhB + SU8 film we arrived at the absorption coefficient of ∼0.6 cm^{-1} for the 1 cm long waveguide with which we estimate much lower propagation losses of <0.5 dB cm^{-1}. Confocal images of the waveguide shown in figures 3(*a*) and (*b*) indicated a clear dispersion of the dye in SU8 and no aggregation effects responsible for scattering of the propagating light. Two dimensional sliced imaging revealed the side walls to be devoid of corrugations through the length of the waveguide. Atomic force microscopy measurements [18] on the roughness of the side walls in passive SU8 waveguides studied previously indicated a root mean square value of <10 nm implying that the scattering losses from the sidewalls is minimal. Depending on the concentration, RhB is known to aggregate, which can lead to scattering of the propagating light enhancing the propagation losses. A systematic study on the concentration dependence

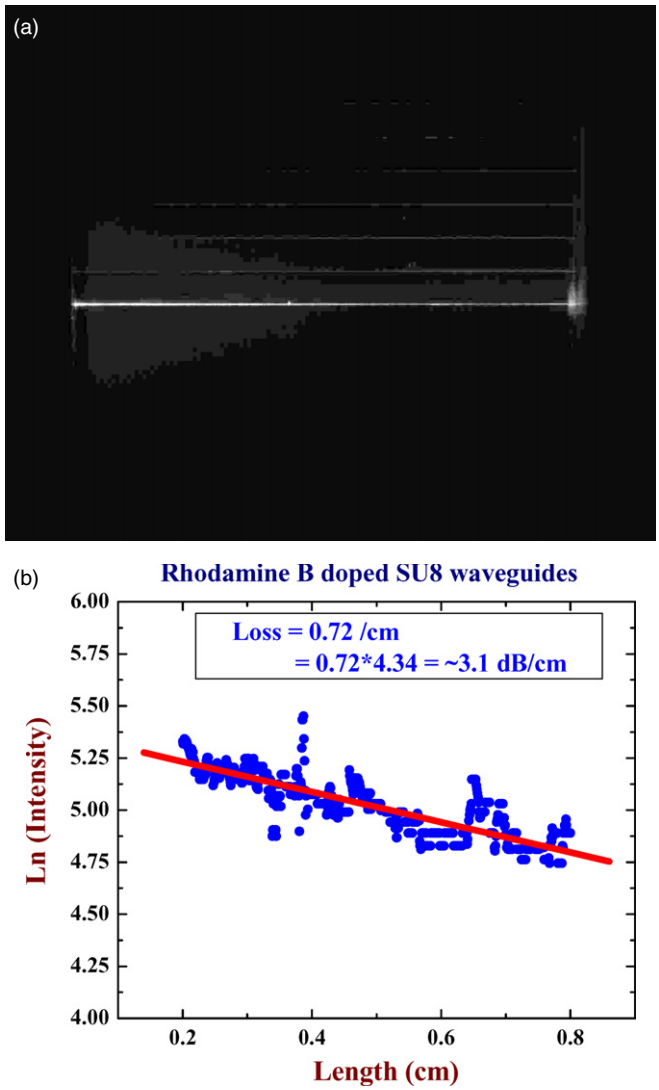

Figure 2. (*a*) Optical picture of the light propagating within the waveguide captured using a CCD camera and microscope combination. Several other waveguides with different lengths are also visible. (*b*) Plot of intensity of the light along the waveguide. The estimated propagation loss was ∼3.1 dB cm^{-1} which includes the absorption component from rhodamine B.

of propagation loss is essential and we expect to optimize the propagation losses in these active waveguides with improved fabrication procedures.

Following the interesting work done by a group at the Technical University of Denmark [30–52] on the fabrication of microlasers, fluidic channels in PMMA and SU8 resulting in optofluidic structures, we had fabricated microlasers with a trapezoidal cavity. Figure 4(*a*) shows the scanning electron microscope pictures of the microlaser samples. Six lasers were fabricated during a single exposure. Typical dimensions of the lasers were ∼250 × 250 μm^2. The inset of the figure shows a clear view of a single microlaser. The side walls were found to be smooth with different orientations of the sample in SEM measurements. Optical characterization was carried out with a nanosecond Nd : YAG laser operating at 532 nm. The complete details of the experimental set up and the initial results obtained were reported elsewhere [28].

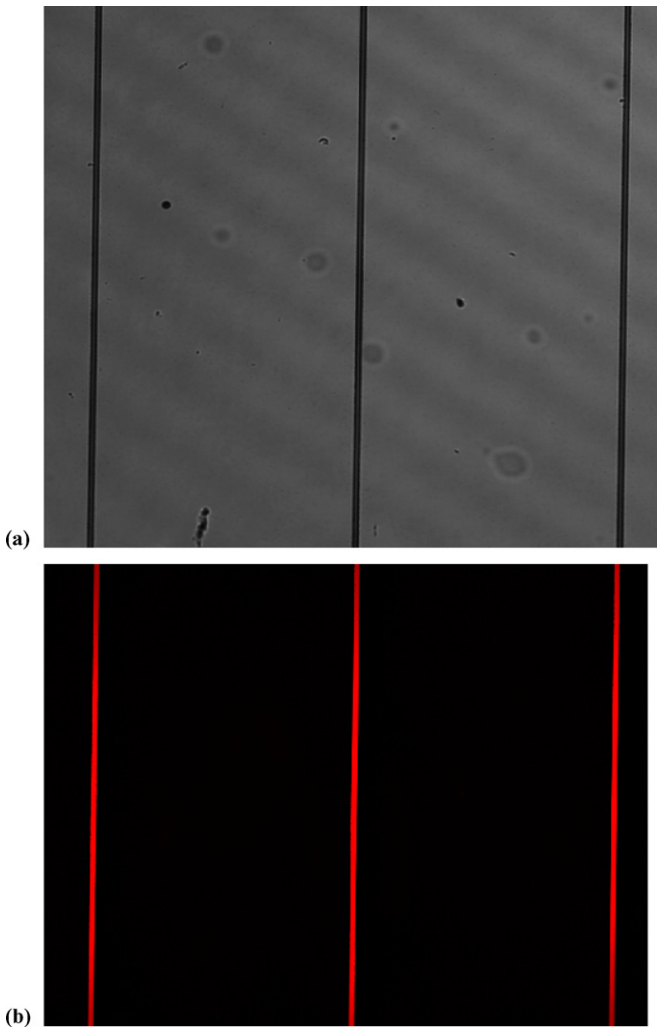

Figure 3. Laser confocal images of the few millimetre-long waveguides fabricated in SU8 + RhB. Pictures indicate the uniformity of the dye doping in SU8 and stability of the long structures.

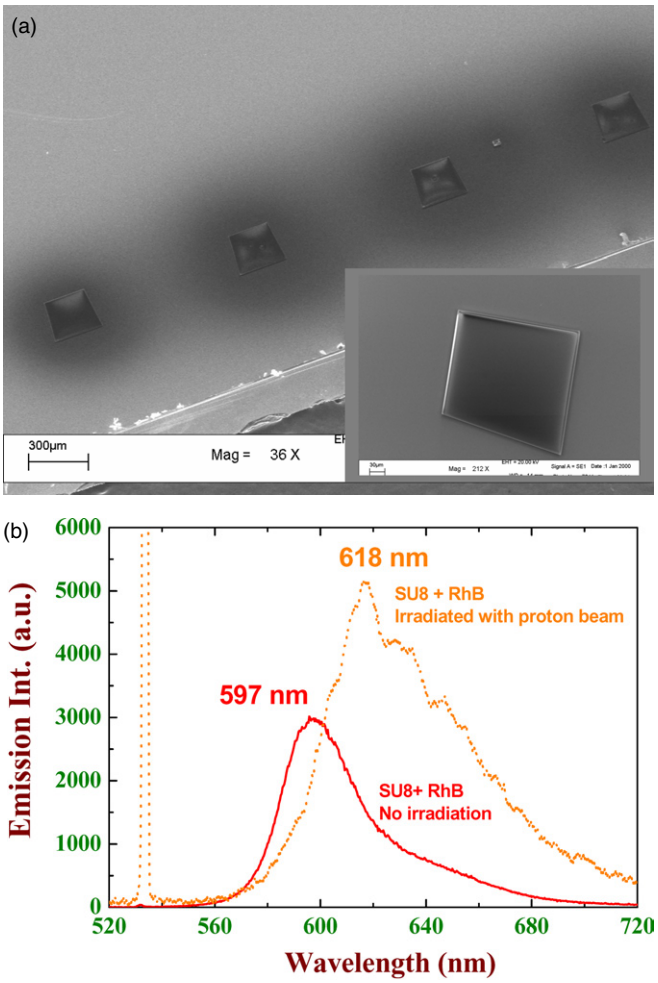

Figure 4. (*a*) Scanning electron microscope pictures of the rhodamine B doped SU8 microlasers, the scale bar is 300 μm. Inset shows the picture of a single microlaser. (*b*) Emission spectrum of SU8 doped with rhodamine B (solid line) before irradiation and after irradiation (dotted line).

Briefly, the laser emission was observed near 624 nm and the measured threshold of the devices was estimated to be $\sim$150 μJ mm^{-2}. By reducing the thickness of the films (lasers) we expect to further reduce the threshold. Figure 4(*b*) shows the emission spectra of SU8 doped with RhB and irradiated with the proton beam. An interesting aspect of the proton beam irradiated doped SU8 film observed was red-shifting (illustrated in figure 4(*b*)) of the emission spectrum compared with pristine doped SU8 film. There are no previous studies, to the best of our knowledge, to corroborate or contradict our observation but we expect the red-shift could be due to some structural modifications of the SU8 by the proton beam. The effects of ion beam dose and the concentration of RhB on the emission wavelength is being investigated.

Figure 5 demonstrates the tunability of the emission obtained from two identical lasers (L1 and L2) as a function of pump laser beam intensity and the angle of incidence. Our earlier study [28] on a pristine single microlaser indicated peak emission near 620 nm. However, pumping of the laser with a few thousand pulses continuously, the observed emission shifted from about 620 to 605 nm with a tunability of $\sim$15 nm achieved in tandem with increasing energy densities from 200 to 400 μJ mm^{-2} ((c) to (a) for L1 and (f) to (d) for L2) and a change in the angle of pumping by about 15° from 90° to 75°. The observed shift in the emission wavelength was due to both the changing energy densities as well as the pumping angle. A further change in angle beyond 75° resulted in plain, broad emission. Several reasons could be attributed to this tunability as a function of the incident pump angle and increasing intensity/energy density. The length of the cavity accessed by laser pulses will modify with the angle of incidence possibly resulting in a different wavelength observed. Interestingly, a recent report [53] presented the thermally induced wavelength tunability of microcavity solid-state dye lasers. The physical phenomena responsible for the shift in wavelength, of a dye doped system similar to ours, were identified as (a) thermal expansion of the microcavity material and (b) thermo-induced change of the refractive index. They achieved a tunability of a few nanometres with the above phenomenon in Rhodamine 6G doped PMMA dye laser. The tunability observed in our case could be from the amalgamation of the above factors since tunability of the emission was observed after loose focusing of

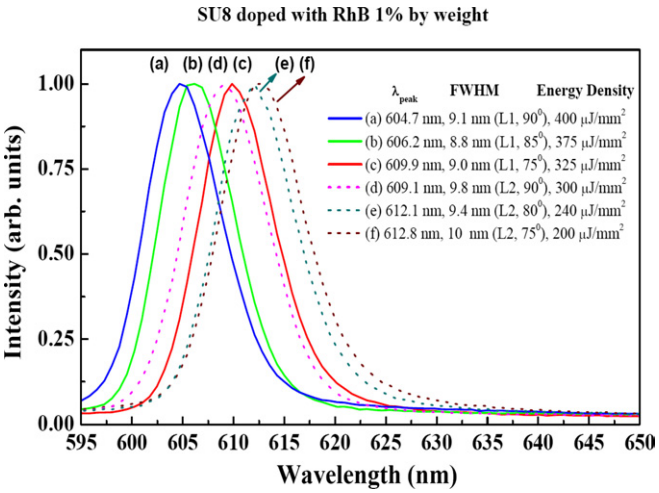

Figure 5. Emission spectra of two identical microlasers L1 and L2 obtained with different pumping angles and pump intensities. (a), (b) and (c) correspond to the laser L1. (d), (e) and (f) correspond to the laser L2.

the 532 nm nanosecond laser pulses. This could have resulted in heating of the dye + SU8 system and therefore ensuing thermal expansion and/or a change in the refractive index as a consequence of the absorption of light. Further detailed studies are in progress to identify the contribution from each of these aspects and will be reported at a later stage.

We anticipate that pumping these structures using low repetition rate (kHz) femtosecond pulses will result in compact, tunable femtosecond dye laser. Doping SU8 and PMMA with a variety of dyes and utilizing different configurations [54–59], we can accomplish miniature solid-state dye lasers and fluidic channels on a single substrate using this technique with enormous potential in bio-sensing and LOC applications. The advantages of direct writing laser structures using PBW is evident from the fact that using PBW we could demonstrate active and passive waveguides in SU8 and PMMA along with micro- and nanochannels using both techniques of direct writing plus imprinting. Moreover, the capability of PBW to produce very high quality stamps [23] makes it possible to fabricate the laser sources, waveguides and channels on a single substrate, key components for any LOC device, and during a single exposure step. Combined with the capacity of PBW to micro-machine silicon facilitating tunable fluorescence in the visible spectral region, the possibilities are enormous for making hybrid devices useful in LOC and microfluidic applications.

4. Conclusions

In conclusion, we have successfully fabricated and characterized rhodamine B doped SU8 channel waveguides and microlasers. Laser cavities with dimensions of $\sim 250\,\mu$m were fabricated and the laser emission was observed in the 600–630 nm spectral range. The fabricated channel waveguides had an optical propagation loss of $<0.5\,\mathrm{dB\,cm^{-1}}$ at 633 nm measured using the scattering technique while the microlasers had a threshold of $\sim 150\,\mu\mathrm{J\,mm^{-2}}$ when pumped with 532 nm, nanosecond pulses. The emitted wavelength from the microlasers was tunable to the extent of ∼15 nm with increasing pump intensity and different pumping angles.

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