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Flow rate based control of wavelength emission in a multicolor microfluidic dye laser

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ABSTRACT

An original method is investigated to monitor the emission of a microfluidic dye laser. It relies on the flow rate of a dye mixture solution. The two dyes are at the origin of laser effects at two distinct wavelengths. In function of the dye mixture flow rate, one wavelength or the other can be selected. The purpose is to achieve a wavelength on-demand system which would be of great interest for spectroscopic analysis of biochemical samples.

1. Introduction

Optical diagnostics are of great interest for biochemical analysis: absorption, fluorescence, Raman spectroscopy, surface plasmon resonance, interferometry. These techniques are successfully applied to microsystems, however even if the samples are manipulated on the microscale, there is an increasing demand for miniaturizing elements such as optical sources and detectors. So an effort has been made to develop microfluidic lasers [1]. Microfluidic lasers fit well for such applications mainly due to their easy integration with other components and their tunability. Linear cavities, ring cavities, distributed feed back structures have been investigated for single mode lasers, multicolor lasers, tunable lasers and their integration into micrototal analysis systems [2–4].

The selection of the emission wavelength is a crucial issue for laser based applications such as bandwidth selection for absorption or excitation of fluorophores, or probing resonances. This way, the optical source may be adapted to analyze different samples. Considering only one dye and one cavity, wavelength tunability can be achieved using different concentrations [5]. However the range is limited to 10 nm and reaching larger tuning range requires using several dyes, multiple laser cavities [6] or an external activator [7]. Such systems imply a higher degree of complexity in their fabrication process or in their manipulation.

In our group, we have demonstrated a microlaser that delivers a simultaneous collinear dual-color emission [8]. This is based on a mixture of two dyes that generates laser effects at two discreet wavelengths. Presently, we further investigate the dye flow rate dependence of the lasing emission. We show that the output wavelength can switch from one value to the other depending on the dye mixture flow rate. It provides for an alternative way to control the laser emission and results in a wavelength selective laser system.

2. Microfabrication and experimental set up

Poly(dimethylsiloxane) (PDMS) and a glass substrate created the microfluidic channels, optical fibers were used to define the optical cavity. The optical fibers were cleaved, both metalized on the ends with 2 nm Titane then covered with 30 nm Gold for the fiber acting as the output mirror and 100 nm Gold for the fiber acting as a back mirror. The channels' design was patterned in a 125 μm thick photoresist layer (Microchem SU8 2100). Another pair of optical fibers, non-metalized sacrificial fibers, was placed between spacers. Fig. 1a shows the microphotograph of the moulder. The moulder was then treated with trichloromethylsilane (TMCS) anti-adhesive agent for 3 min. PDMS was poured on top of it and left curing at 60 °C for 3 h. The polymerised PDMS layer was taken off, the sacrificial fibers were removed and the metalized definitive fibers placed instead. The PDMS layer and the glass substrate received an oxygen plasma treatment for 30 s, they were bonded together and placed in the oven at 60 °C for 2 h.

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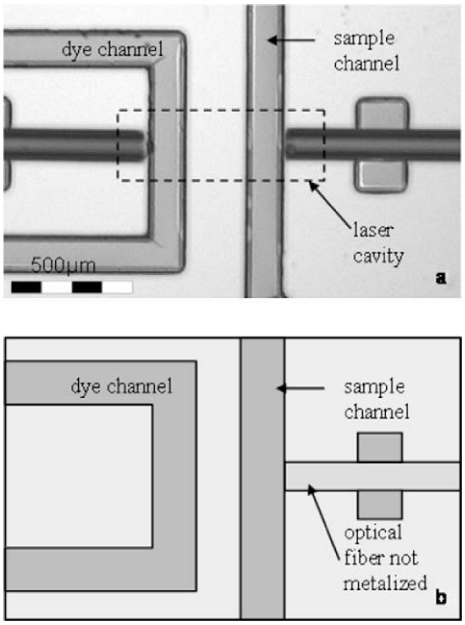

Fig. 1. (a) Microphotograph of the mould for the microlaser: 2 channels (130 µm wide) cross the laser cavity (550 µm long). (b) Schematics of the device fabricated for the fluorescence measurements.

Fig. 1b represents another device fabricated to study the fluorescence spectrum avoiding any optical resonance. Using the same SU8 mould as previously, only one non-metalized fiber was placed in the spacers. Then the mould was treated with TMCS, covered with PDMS. After curing, the PDMS layer was removed, the trapped fiber is left in the PDMS and the bonding step is performed according to the same parameters as enounced above.

Single-dye solutions are prepared for Rhodamine 6G (Rh-6G), Sulforhodamine 640 (Su640), dissolved in ethanol at 5.10^{-3} mol/L. The final solutions are obtained by selecting two original solutions and mixing them. All the ratios indicated are ratios in volume. The gain medium is injected in the channel via a syringe pump. The length of laser cavity is 550 µm (see Fig. 1a). Two channels are visible but only one is used in the present experiments: the one called "dye channel". The other channel is designed for future biochemical analysis experiments.

A doubled frequency Nd:YAG pulsed laser at 532 nm is used to pump the gain medium. The average power is 10 mW and the pulse time duration 5 ns. The beam goes through a ×2.5 objective and is focused on the dye channel between the two golden fibers. The output fiber collects the signal and sends it outside the chip. There, another multimode fiber is used to drive the light to a spectrometer (Ocean Optics USB2000+).

3. Results and discussion

Fig. 2a gives the spectra of the lasing effects when individual dye solutions are successively introduced in the "dye channel". Rh6G in ethanol at a concentration of 0.005 mol L^{-1} generates a lasing effect at 568 nm while Su640 in ethanol at the same concentration has a peak at 612 nm. Their bandwidths are 3 and 4 nm respectively, due to the spectrometer resolution and multimode regime in reason of cavity length. Indeed the cavity length is 550 µm while a monomode regime requires a cavity length less than 30 µm. These lasing effects are steady when the dye flow rate varies from 0.5 to 10 µL/min. Looking at the fluorescence spectra (Fig. 2b), the curves are distant enough to lead a mixture of these two dyes to multicolor lasing.

The spectra for a dye mixture are given in Fig. 3. The mixture is prepared upon the two previous solutions of Rh6G and Su640 in ratio 2:1 in volume respectively and injected in the device. The spectra are taken at different dye flow rates. At flow rates lower than 2 µL/min, Rh6G's lasing effect is predominant over the Su640's one. Then a balance is reached at 3 µL/min, two lasing peaks are observed. Note that their intensities are diminished. When the dye flow rate goes over 5 µL/min, Su640's lasing effect strengthens and gains the upper hand.

Figs. 4 show the results of fluorescence experiments performed with the device presented in Fig. 1b. This device enables to collect the fluorescence spectrum outside any optical cavity in the same experimental conditions as the microlaser device. Fig. 4a shows the evolution of fluorescence in function of dye flow rate in case of a 2:1 Rh6G–Su640 ratio. An inversion of the major contribution from each dye to the fluorescence clearly appears. At lower flow rate, the fluorescence of Rh6G is predominant, while at higher flow rate the fluorescence of Su640 becomes more important. This means that for a given wavelength the gain of the liquid amplifier medium can be modulated using its flow rate. This is in good agreement with the observations made on the lasing effects. At lower flow rate, the fluorescence of Rh6G is more important than the one of Su640, which leads in the lasing competition to the domination of Rh6G's lasing effect and the reverse at higher flow rate. The potential deformation of PDMS and the cavity due to the difference of pressure inside the channel with the increasing flow rate is not crucial. Injecting another liquid at different pres-

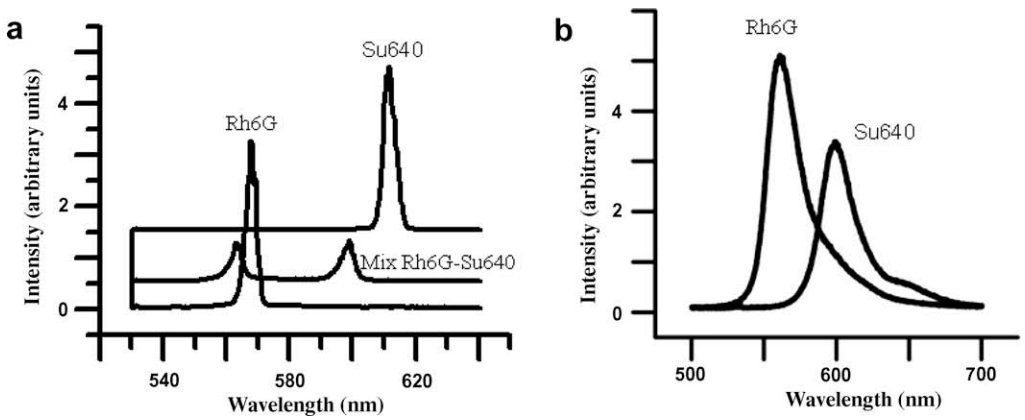

Fig. 2. (a) Spectra for ethanol solutions of (1) rhodamine 6G, (2) sulforhodamine 640, (3) a mixture of the two previous rhodamine and sulforhodamine solutions (2–1 in volume). (b) Shows the fluorescence spectra of the two dyes.