Broadcasting photonic lab on a chip concept through a low cost manufacturing approach

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A B S T R A C T

A low cost fabrication process for photonic lab on a chip systems is here proposed. For the implementation of the masters suitable for cast molding fabrication, an inexpensive dry film photoresist, patternable using standard laboratory equipment, is benchmarked against standardized SU-8 masters obtained using UV lithography and systems manufacture in clean room facilities. Results show adequate system fabrication and a comparable performance of the photonic structures for absorbance/extinction measurements.

1. Introduction

Due to their vast potential range of applications, the integration of photonic transducers in the vicinity of a lab on a chip (leading to the Photonic lab on a chip – PhLoC – paradigm) [1] is attaining increasing relevance during the past decade. The non-invasive on-chip interrogation of biological and chemical responses by UV–Vis spectrophotometry for their transduction into quantifiable signals has led to a myriad of PhLoC and optofluidic microplatforms [2,3] developed for different purposes, ranging from cell culturing and cell analysis [4–7] to heavy metal ion detection [8,9], enzymatic catalysis for different applications [10,11] or protein concentration measurements [12].

In view of the wide applicability of these systems, the possibility of making PhLoC technology accessible to any laboratory becomes of high interest, and more particularly for applications in nuclear or harsh environments. Therein, the readout can be advantageously remote from the measured zone and be connected to the PhLoC, minimizing any risk related to radiation [13]. An additional advantage is that PhLoC cannot generate spikes due to shortcuts, and therefore they can be considered safer as compared to its electronic counterparts.

Generally, the implementation of micro optical elements comprising the PhLoC is based on well-stablished soft lithography techniques. The most widespread approach relies in SU-8 technology for master mold fabrication and the subsequent cast molding using other materials (e.g. (poly)dimethylsiloxane – PDMS). Processes are usually performed in clean room premises in order to obtain optimal and functional devices. Photonic structures are designed in accordance with the refractive indices of the cast molding fabrication material and air, monolithically integrated with microfluidics and easily obtained in one single replication step [1,14]. However, SU-8 presents noteworthy operation boundaries: initially, and besides the high cost of SU-8 resists and clean room facilities, it requires of a considerable amount of time for spin coating and planarization, pre exposure bakes to remove solvent before UV mask exposition and post exposure bakes prior to structure development. Additionally, development must be performed in a controlled environment due to the highly toxic characteristics of common developers (such as Propylene glycol methyl ether acetate – PGMEA).

Hence, we have developed an alternative to standard SU-8 technology, which is proposed and characterized in this work.

2. Materials and methods

2.1. Microsystems fabrication

With the aim of comparing both fabrication methodologies, a simple PhLoC was designed and manufactured in PDMS (Sylgard 184, Dow Corning, USA) using master molds fabricated with both materials and subsequently characterized. The PhLoC is presented in Fig. 1a. A single microfluidic channel is broadened to obtain 5 different optical paths of 0.25, 0.5, 1, 2.5 and 5 mm. In each optical path, two interrogation regions were implemented (with and without micro-optical elements for beam light collimation) [12], including self-alignment fiber optics channels allowing the hassle-free insertion of

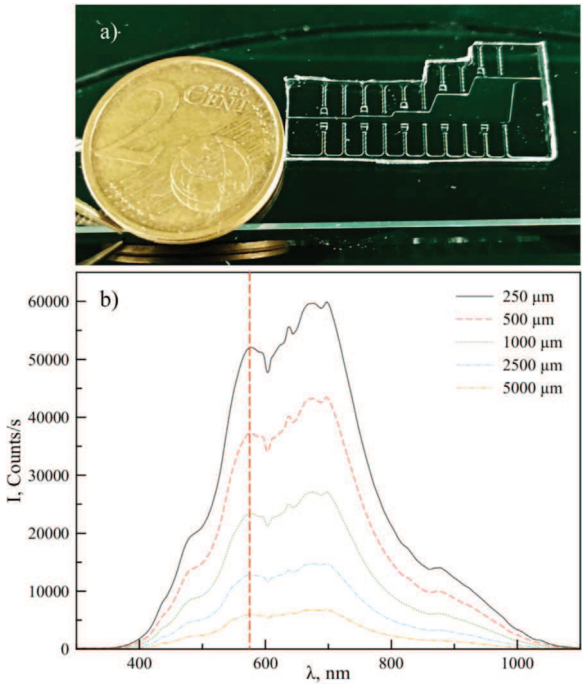

Fig. 1. a) Picture of a PDMS photonic lab on a chip describing 5 different optical paths (0.25, 0.5, 1. 2.5 and 5 mm) for light interrogation; b) typical intensity spectra collected through each PhLoC optical path. Vertical red-dotted line represents the wavelength chosen for PhLoCs benchmarking. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

240 µm diameter pig-tailed fiber optics (200 µm internal core diameter, Thorlabs, Germany) for light coupling/decoupling to the system.

A master mold based on WBR2000 (and MX5000) series (DuPont, USA) dry polymer films [15] was fabricated by lamination of two 120 µm WBR2120 resist layers plus one extra 15 µm MX5015 resist layer on top of a glass cover slide, using an A3 Mega Drive Laminator (Mega electronics, UK) operating at 100 °C. The three dry film layers, comprising a total thickness of 255 µm, were UV-exposed (750 mJ/m2) through a low-cost emulsion film mask defining the PhLoC structure. A post exposure bake of 60 s at 100 °C was followed by a subsequent structure development using an inexpensive K_2CO_3 solution as a developer (5% w/w). Master mold was rinsed with tap water to stop development, and afterwards soaked in toluene for 60 s to enhance its surface properties. Once the toluene was evaporated and the master was dried, PhLoC replicas were fabricated by standard PDMS cast molding and bonded to a glass slide using a low cost Mini Corona treater (Boussey Control, Belgium) [16]. All the manufacturing process was performed in an ordinary laboratory. For comparison, equivalent SU-8 master mold and PhLoC structures were fabricated in a controlled clean room environment using well known protocols previously published [7].

2.2. Microsystems characterization

Light coupling efficiency and lens operation were studied in 10 different PhLoCs manufactured following each fabrication procedure. For this purpose PhLoCs were initially filled with DI water, and a 5W halogen AvaLight-D(H)-S light source and an Avaspec 2048-USB2 spectrometer (Avantes, Netherlands) were used for light coupling and subsequent spectrum analysis. Fig. 1b shows the typical intensity spectra collected through each optical path. An arbitrary wavelength

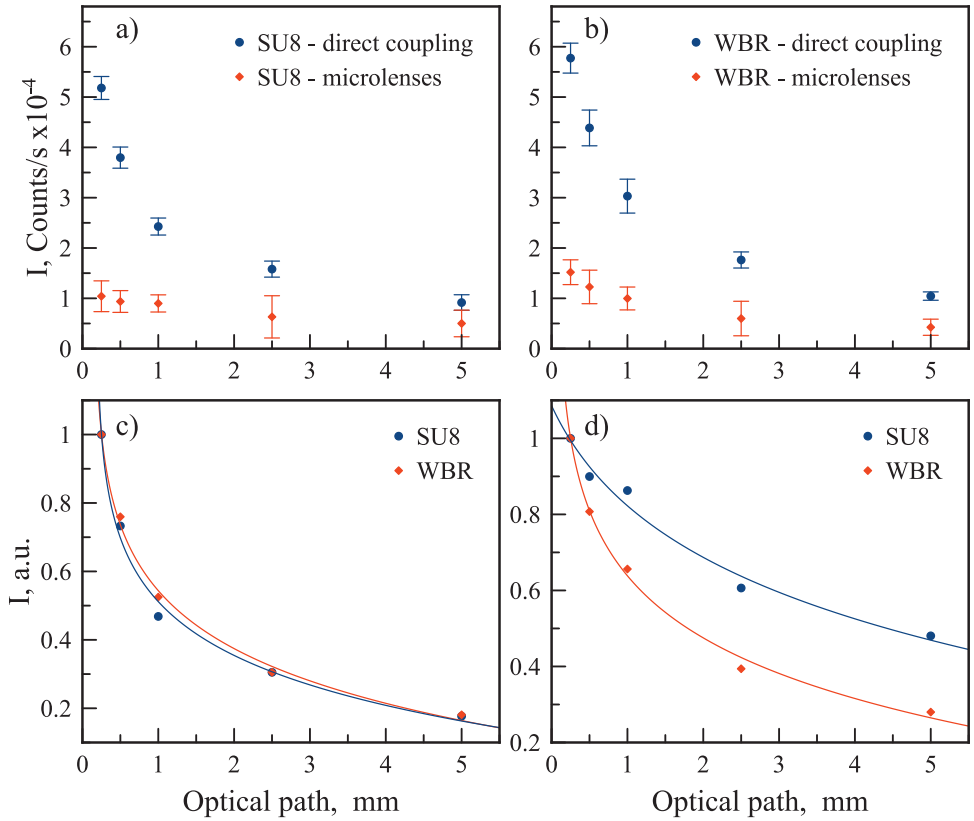

Fig. 2. Light intensity profiles (λ=580 nm) as a function of the optical path for the PhLoCs fabricated using a) SU-8 and b)DuPont (WBR) master molds. Blue circles represent profiles obtained by direct coupling of light and red diamonds represent the profiles collected for light coupling using collimation micro-lenses. c), d): comparison of the normalized intensity profiles for the different PhLoC optical paths respectively for direct light coupling and micro-lenses implementation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

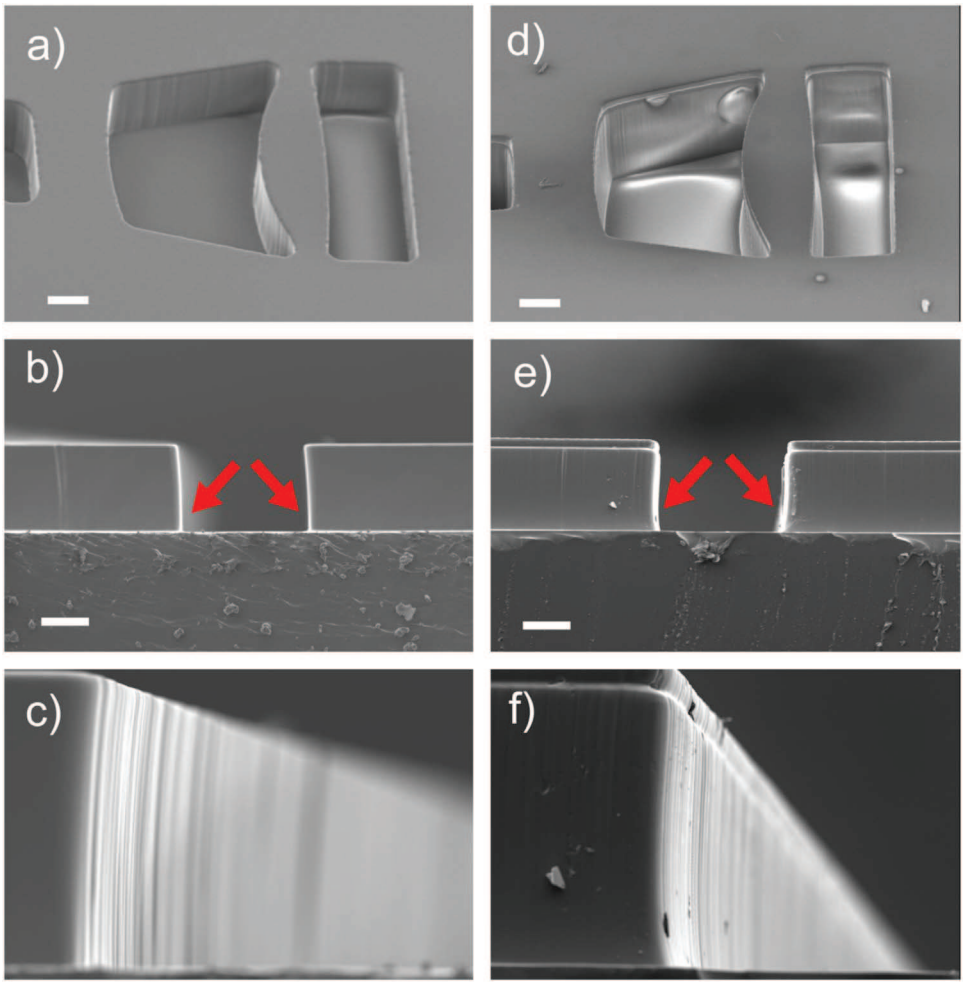

Fig. 3. SEM images collected using LEO 435VP SEM microscope operating at 5.0 kV corresponding to PDMS PhLoC structures manufactured using SU-8 (a,b,c) and dry film technologies (d,e,f). a), d) micro optical elements; b), e) microfluidic channel perpendicular view; c), f) detail of a microfluidic wall, where vertical lines in the PDMS are due to the resolution limit of the low cost emulsion film mask used for master fabrication. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

of λ=580 nm, corresponding to one of the light source's peaks of maximum intensity, was selected to benchmark light coupling efficiency in all the devices manufactured by each fabrication process.

3. Results and discussion

The use of the inexpensive previously mentioned dry film resists (presenting a high resolution and high aspect ratio) for PhLoC master mold fabrication results particularly advantageous when compared to SU-8 fabrication process. First, a direct 10 fold reduction on material costs can be calculated straightforwardly. Second, the fabrication time to obtain a fully operable master mold is radically decreased (few minutes, in contrast to several hours required for an average SU-8 process). Finally, structures development is carried out with the previously mentioned non-toxic K_2CO_3 solution as a developer (5% w/w), thus generating a more environmental-friendly fingerprint during the fabrication process. These advantages become clearly convenient, not only to approach this technology to every laboratory willing to develop specific devices for ad-hoc applications, but especially for rapid and low-cost structures design and prototyping, where iterations for microfluidic and/or photonics are frequently required.

Fig. 2a and b show the light intensity profiles (λ=580 nm) as a function of the optical path for the devices fabricated using SU-8 and DuPont (WBR) master molds respectively. Each point represents an average value with the corresponding standard deviation for the measurements performed through the optical paths of 10 different devices, thus minimizing experimental error coming from fiber optics positioning and possible air micro-bubbles which could interfere with coupled light across the interrogation regions.

As expected, light transmission decreases with the increase of the optical path in both cases, i.e. direct coupling of light and use of micro-optical elements. However there are two observations which are worth to be remarked. First, at the shorter optical paths, the amount of light coupled to the system through the micro optical elements is sensibly lower than the one achieved in the direct coupling configuration. This can be explained by enhanced light-loss due to Fresnel reflections at each interface. Indeed, while in direct coupling, light is only passing through two interfaces (PDMS-solution, solution-PDMS), when micro-optical elements are implemented, 4 extra interfaces are added to the system (PDMS-air, air-lens, lens-air, air-PDMS, PDMS-solution), the latter applying for the light input and output, leading to a total of 10 interfaces. With a simple reflectance calculation in ideal conditions, considering perfectly perpendicular material facets and the refractive indices of PDMS and air (1.41 [17] and 1 respectively) a loss of- 3% of the incoming light can be calculated for each PDMS-air interface. Second, although the amount of light coupled to the system is lower when micro optical elements are implemented, this configuration exhibits less sensitivity to the optical path. Indeed, due to the micro-lenses effect in beam collimation, the decrease in the intensity signal with the optical path is reduced, leading to a more constant signal, as it

can be noticed in Fig. 2a and b. To better compare both types of PhLoC structure, light intensity values were normalized with respect to the maximum measured value. The normalized intensity profiles attained in both types of PhLoCs (e.g. SU8 and WBR) are compared in Fig. 2c and d respectively for direct light coupling and microlenses implementation. It can be observed that light behavior is virtually equal in the case of direct coupling in both types of structures (Fig. 2c). However the performance of micro-optical elements, depicted in Fig. 2d, appears to be sensitive to the fabrication process. Hence, the PhLoC structures manufactured using a SU-8 mold exhibit superior performances than the ones fabricated with dry film technology, especially for the larger optical path where the intensity decrease is 25% lower.

This could have two different, still compatible explanations. In one hand, the amount of light reflected from the PhLoCs in each interface could be higher in the case of structures fabricated using dry film technology due to facet roughness or non-verticality of the facet walls. On the other hand, the micro-lenses light collimation efficiency may be lower in this case. In order to validate the weight and importance of the two hypotheses, Fig. 3 shows SEM images corresponding to the PDMS PhLoC structures manufactured using SU-8 (Fig. 3a–c) and dry film technologies (Fig. 3d–f). It can be noticed that PDMS walls in the SU-8 structures present a slightly straighter and perpendicular interface to light than the low-cost structures, which present a slight curvature at the bottom (red arrows in figures c, f). Concerning the structure fabricated with low-cost technology, no marks of the bonding between the 2 laminated 120 μm layers of WBR resist can be noticed in the PDMS, although there is a clear 15 μm band on top of the structure (Fig. 2e and f), which corresponds to the 15 μm MX5015 layer. Due to the slightly different composition, the bonding and development of both materials seem to be less effective, leading to a more uneven structure. However this fabrication imperfection is not supposed to affect light coupling, as the core diameter of the inserted 245 μm fiber optics (200 μm) remains at least 20 μm over the substrate.

For a qualitative description of light beam collimation, the microfluidic channel of a PhLoC of each type was filled with a saturated fluorescein solution and fluorescence images were taken using a Opolette HE 355LD laser (Opotek, US) as an excitation light source and a PCO.edge sCMOS CCD detector (PCO AG, Germany) coupled to a Wild M3Z microscope (Heerbrugg, Switzerland). Fig. 4a and b show the fluorescence images obtained from the PhLoC structures manufactured with SU-8 and DuPont dry film technology respectively, together with an averaged intensity gray value profile measured at

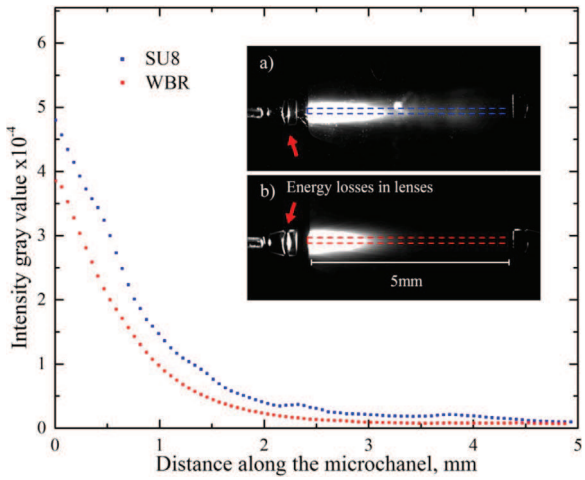

Fig. 4. Fluorescence images of the collimated light beam in an optical path comprising a PhLoC microfluidic channel filled with fluorescein saturated solution, excited with a 365 nm laser. a) PhLoC structure manufactured with SU-8 technology; b) PhLoC structure manufactured with low-cost DuPont dry film technology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

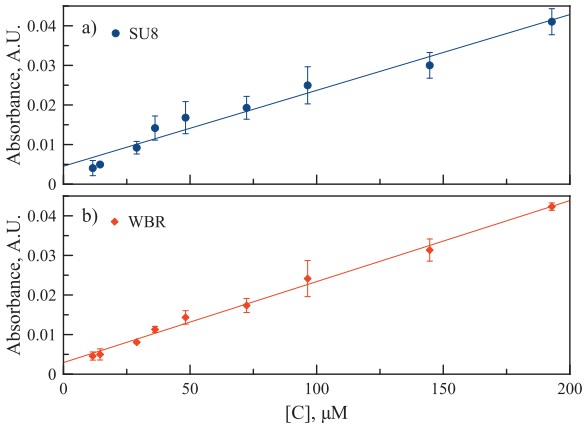

Fig. 5. Plots of absorbance versus concentration of fluorescein in DI water measured in PhLoCs fabricated using a) SU-8 and b) DuPont (WBR) master molds. Lines represent the least squares fitting of the experimental data.

the center of the micro optical elements and in parallel to light beam propagation, as schematically depicted in both figure parts. It can be noticed that the light reflected by the micro-optical elements to the CCD is higher in the structures fabricated with the low-cost technology (red arrows pointing out the light reflection in the micro-lenses), in accordance to the SEM observations. Hitherto, despite of the difference in the initial maximum values (corresponding to the light coupled to the microfluidic channel), the gray value profile described by both structures is equivalent, suggesting that the collimation efficiency of both micro-lenses is analogous.

Finally, to investigate up to which extent the structures quality affect PhLoC sensitivity for analyte species detection, absorbance was plotted as a function of concentration for a model compound (fluorescein, measured at λ=480 nm) This allowed us to calculate the analyte limit of detection [18] in each type of structures (Fig. 5). To this end, the absorbance measurements were performed through the interrogation channel implemented with micro-lenses, positioned in the largest PhLoCs optical path (i.e. where the maximum difference in light coupling efficiency was observed between both types of structure, according to Fig. 2d). Furthermore, in order to determine the minimum detectable concentration above the signal-to-noise level, additional fluorescein solutions were prepared in DI water at the lowest possible concentrations which could be detected using the PhLoCs e.g. down to 11.4 μM. Fig. 5a and b respectively show the plots obtained for the PhLoC structures manufactured using SU-8 and DuPont dry film technology. Lines represent the least-squares fitting of the experimental data. The limit of detection was calculated in accordance to its definition as $LOD=k\cdot s_b/m$ (using a k value of 3, ensuring a confidence level of 99.86%) [18], where the sensitivity, m, was obtained from the slope of the least squares linear fitting for the previously mentioned plots and s_b corresponds to the standard deviation of the blank (DI water in our case). *LOD* results are presented in Table 1, together with the R^2 value of the fitting, showing a good correlation of the experimental data. As it can be observed, due to the low concentrations used and the uncertainty related to experimental error, the *LOD* calculated for the PhLoCs fabricated using standard SU-8 technology was found to be slightly higher (~22 μM), demonstrating that the sensitivity of both types of PhLoCs structures are comparable.

Table 1
LOD and R^2 values obtained for the PhLoCs fabricated using SU-8 and low-cost dry film technology.

PhLoC fabrication technology	*LOD*, μM	R^2
SU-8	22 ± 9	0.97
WBR	8.5 ± 0.3	0.99

4. Conclusions

A low-cost fabrication process for photonic lab on a chip systems, based in an inexpensive dry film photoresist for soft lithography and operated in standard laboratory conditions, was benchmarked against standardized SU-8 master mold and systems manufactured in clean room facilities. This new fabrication protocol, resulting in a 10 fold reduction of the material costs and much faster fabrication, was evidenced to maintain satisfactory performances for analytical purpose. This optimal system fabrication enabling a good performance of the photonic structures is of high interest for fast and low cost structures design and prototyping.

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