Fluoropolymer-based integrated biophotonics

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***Abstract* —We describe how an amorphous fluoropolymer, which is well index-matched to aqueous solutions, can be used as a waveguide cladding material, enabling a range of applications in highly integrated biophotonics. Specifically, we report on fluoropolymer waveguide chips integrated with conventional microfluidic circuits, representing a novel lab-on-a-chip platform for evanescent-wave excitation or sensing, with integrated passive and/or thermo-electrically controlled optical circuits for light manipulation. We have also investigated fluorescent conjugated waveguide core polymers as potential on-chip light sources.**

Keywords - Biosensor; Lab-on-a-chip; Polymer waveguides; Integrated biophotonics.

I. INTRODUCTION

Over the last decade there has been rapidly increasing interest in different bio-sensing principles and in new types of biosensors. Among these are optical biosensors which are increasingly being employed for sensing and monitoring applications. Optical sensors are favorable due to their high sensitivity and functional diversity, but also because integrated waveguide circuits can easily be combined with electrical, microfluidic and/or micromechanical components in complex lab-on-a-chip devices for (bio)chemical analysis [1]. Polymers are highly suitable as a material platform, offering a wide range of optical, physical and chemical properties, bio-compatibility, low cost and a large variety of possible processing and patterning techniques.

We have developed an all-polymer waveguide platform that can be used for various types of applications, but is especially suited for excitation and sensing of biological samples and aqueous solutions [2-4]. A special fluorinated polymer, CYTOP (Asahi Glass Co.), with refractive index n=1.34, is used as bottom and (partially) as upper cladding material. An optical polymer of choice can be used as core material. In our studies, we used mainly polymethyl methacrylate (PMMA) or Ormoclear (micro resist technology GmbH), with refractive indices n=1.49 and n=1.54, respectively. Water, buffer solution or a biological solution (refractive index typically in the range 1.33-1.35), containing the specimen to be optically probed or excited, forms a part of the upper cladding layer of the waveguide structure.

CYTOP exhibits high transparency from 200 nm to beyond 2000 nm wavelength and offers strong chemical resistance, non-toxicity and resistance to biodegradation [5]. In spite of its excellent optical characteristics, the use of CYTOP in waveguide fabrication for biophotonics is still not widespread, presumably due to fabrication issues. The untreated CYTOP surface is hydrophobic and securing adhesion in multi-layer photonic structures, such as slab waveguides, has been generally considered to be difficult or even impossible. However, as described below, these difficulties can be overcome, making CYTOP an attractive option as cladding material for a waveguide platform for biophotonics and other dielectric multilayer applications where a low-index optically transparent and chemically stable polymer is needed.

Here, we present the first report of a CYTOP-PMMA-CYTOP waveguide structure fully integrated with a microfluidic circuit, representing a unique lab-on-a-chip platform for biophotonics. Furthermore, we have investigated the use of novel fluorescent polymers as on-chip light sources.

II. FABRICATION

Fig. 1 illustrates a possible fabrication process for a biophotonic chip involving thermo-electric control and integration with microfluidic circuits. Roughly speaking, the process involves the following steps: A suitable substrate is treated with a silane coupling agent to increase adhesion (a). CYTOP is spin-coated and baked at 180°C in an oven. A thin layer of aluminum is deposited on the surface and subsequently removed by wet-etching (b). This treatment is a key factor in making the CYTOP surface hydrophilic and improves adhesion between the CYTOP layer and a subsequently spin-coated polymer layer forming the waveguide core (c). The waveguide core layer can be patterned, e.g., by UV or e-beam exposure (d,e). A photoresist etch stop layer (f) is used to define a sensing region (g). Finally, waveguide channels are encapsulated by spin-coating a CYTOP top cladding layer (h). A layer of photoresist for defining the contact layer is spin-coated on top of a pre-treated CYTOP surface (i), followed by patterning, metallization and liftoff (j). Photoresist is again used to define the sample well (k). Reactive ion etching (RIE) is carried out to selectively etch away the top cladding (l). After RIE, the remaining photoresist is removed using a photoresist remover (m). The surface of the optical chip can now be treated with aminopropyltriethoxysilane (APTES) and bonded to polydimethyl-siloxane (PDMS) for microfluidic applications, following an oxygen plasma treatment (n). Finally, a sample of interest is introduced onto the sensing area in an aqueous solution.

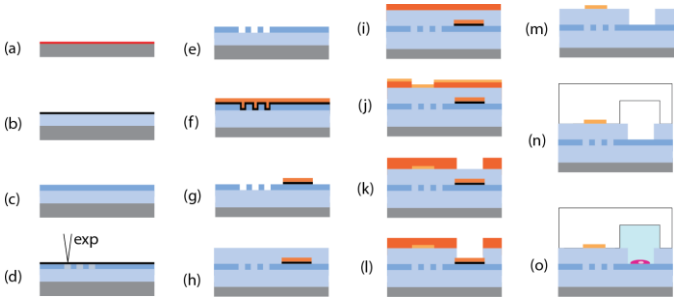

Figure 1. Process flow for fabricating a biophotonic chip with CYTOP waveguide cladding (structures are not to scale). Details are given in the text.

III. PERFORMANCE

Light can be coupled into the high index contrast ($\Delta n \approx 0.25$) waveguides using end-fire coupling from a conventional single-mode optical fiber, or from a tapered lensed fiber to reduce coupling loss. The light can be switched, filtered, modulated, or otherwise manipulated using integrated devices before it is directed to the sensing region(s) were the evanescent part of the guided mode interacts with the sample volume within the penetration depth of the field. The CYTOP bottom cladding plays a crucial role in extending the range of achievable penetration depths of the evanescent part of the mode into the sample, well beyond what is possible with more conventional slab-waveguide systems, such as a high-index oxide on glass, and results in a larger fraction of the excitation power being carried in the evanescent tail on the sample side. For refractive index sensing, this gives improved sensitivity of the guided mode to the cover index [6].

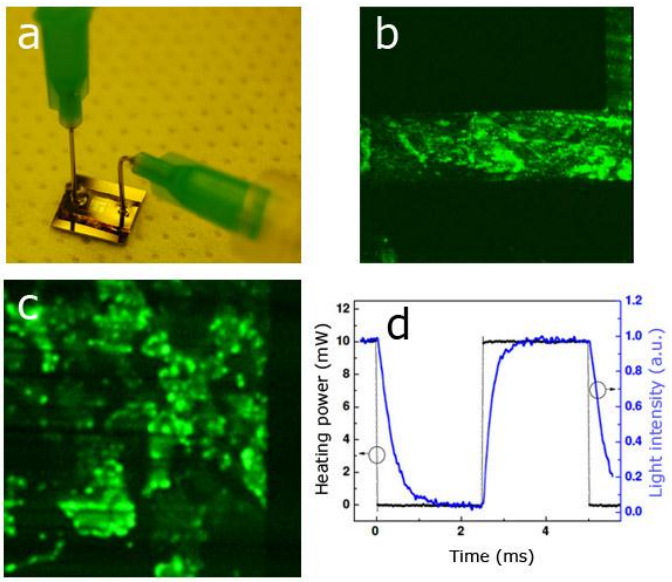

Figure 2. (a) CYTOP-PMMA-CYTOP waveguide chip bonded to a microfluidic circuit. A square-shaped sensing area is visible in the center of the chip. (b) Image of fluorescent beads in water solution passing through a 100-µm wide microfluidic channel above the sensing area. (c) Live dSH2-GFP-expressing cells at the edge of the sensing area. The GFP attaches to focal adhesions in the cells. (d) Example of thermo-optic control; intensity modulation (blue curve) using a Mach-Zehnder interferometer device with a 500 µm x 50 µm footprint, 10 mW driving power and sub-ms response time.

Fig. 2(a) shows a separately patterned PDMS microfluidic circuit with 40-µm deep channels bonded to the waveguide chip. We followed the approach of Ref. [7], using APTES-coating and oxygen plasma treatment to secure a strong polymer-PDMS bond. In Fig. 2(b), fluorescence from polymer beads (Invitrogen FluoSpheres®) in water suspension passing through the microfluidic channel is depicted. Similarly, the near-surface region of live cells expressing a green fluorescent protein (GFP) can be imaged using the evanescent-wave excitation, as shown for transfected pig kidney epithelial (LLC PK1) cells in Fig. 3(c). For applications such as time-lapse imaging of live cells, the excitation can be modulated using on-chip thermo-optic control with a high extinction ratio and sub-ms response time, as illustrated in Fig. 2(d).

End-fire coupling of light from an optical fiber into the waveguides can be highly efficient and wavelength-insensitive. Fiber alignment to high index contrast waveguides, however, imposes a strict tolerance on fiber positioning (10's of nm). This could be partly alleviated using on-chip adiabatic mode conversion, but another interesting option is the incorporation of a light source directly into the waveguide layer. To this end, we have investigated the use of highly efficient fluorescent polymers as waveguide core material, with the potential of realizing optically pumped integrated single-mode laser sources. In particular, we have incorporated an orange-emitting conjugated polymer ADS104RE (American Dye Source) into the CYTOP cladding and tested its performance with respect to external excitation. Fluorescence generated within the waveguide layer was used to monitor scattering from gold nanoparticles in suspension.

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