Planar fabrication of liquid core optical waveguides and microfluidic devices

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Abstract

We have developed a method for fabricating non-solid-core waveguides and microfluidic systems on a silicon substrate. The motivations for integrating these structures for biophotonics are discussed. We report on our fabrication process for these devices and discuss the various core geometries attainable with this process. Optical characterization of the waveguides is also reported.

Keywords: waveguides, biophotonics, microfluidics

1. ARROW waveguides and microfluidic systems

The waveguides discussed here are based on the anti-resonant reflecting optical waveguide (ARROW) structure, which uses alternating dielectric layers to create a Fabry-Perot cavity for low-loss light propagation in a non-solid core [1-3]. The thicknesses of the dielectric layers can be varied to guide only specific wavelengths of light.

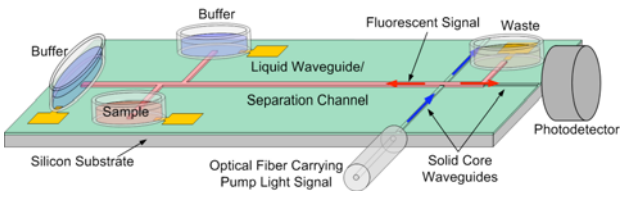


Fig. 1. Proposed structure used to demonstrate planar optical detection system based on liquid waveguides. See text for details.

Light propagation in a gas or liquid core is especially attractive for creating chemical and biological sensor platforms. In particular, small microfluidic channels on a chip that can route both liquids and optical signals allows for unprecedented design flexibility. Figure 1 shows an example platform that could be used in the area of proteomics for protein separations that illustrates how on-chip ARROW waveguides and microfluidic channels are well suited for biophotonic applications requiring high sensitivity. In this example, a sample containing a mixture of fluorescently tagged proteins is introduced in an on-chip reservoir. Voltages applied to pads electrically connected to this and other reservoirs drive fluid through the system by electrophoresis. In this way, proteins in the sample are separated as they pass down the length of the waveguide. Near the waste reservoir, the waveguide is intersected by a solid-core waveguide, which carries pump light from a laser. When the sample reaches this point and is illuminated by the pump laser, fluorophores attached to proteins fluoresce, and this signal is guided through the liquid for detection. The end of the ARROW waveguide is abutted by a solid-core waveguide to permit light guiding to an off-chip detector, while maintaining the integrity of the microfluidic system.

Any sample that can be placed in solution and made to fluoresce when illuminated by a pumping laser can be detected with high sensitivity with this technology. Of particular interest are biomolecules, which can be tagged with fluorophors according to the specific attributes of the molecule. For example, the quantity of DNA in a sample that contains a specific nucleotide sequence can be easily determined, using minimal off-chip tools.

The union of microfluidics and waveguiding can create an extremely sensitive sensor platform that also has the benefits of small size and low cost because it can utilize existing microfabrication techniques. Thousands of waveguides and optical probe points on

a small microchip are conceivable – producing huge amounts of data for chemical and biological analysis.

2. Fabrication technique

Both the ARROW waveguides and the microfluidic systems presented in this paper are fabricated using a sacrificial etch process as illustrated in Figure 2. This results in a smooth, hollow core that is required for low loss in the waveguides and unperturbed fluid flows.

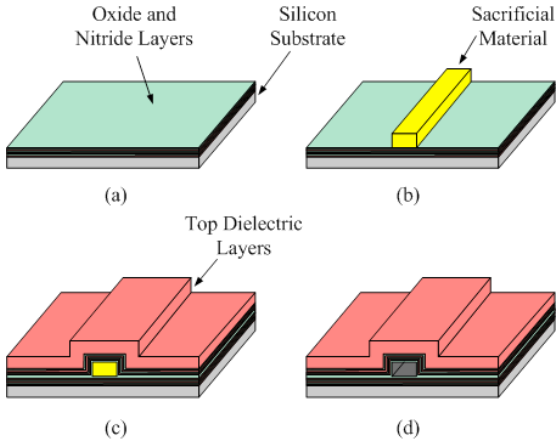


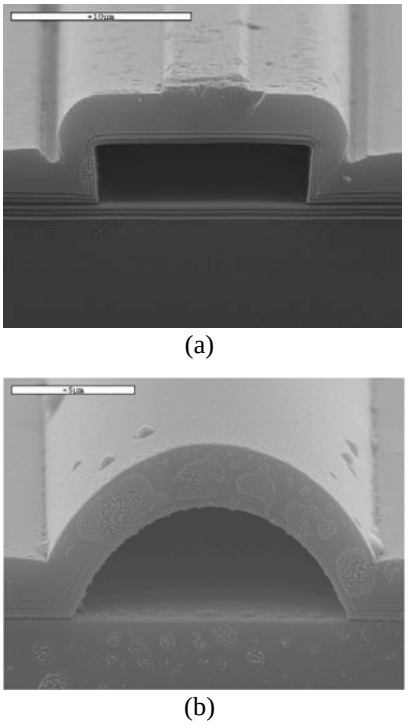
Fig. 2. Fabrication steps for a hollow waveguide. (a) Bottom layers are deposited. (b) Sacrificial core defined using standard photolithography. (c) Top layers are deposited. (d) Sacrificial core is removed with an acid etch

To create the Fabry-Perot cavity necessary for waveguiding in a low-index core, our ARROW waveguides use multiple alternating layers of SiN_x and SiO_2, with the silicon nitride always adjacent to the core. We currently deposit three pairs of layers below and above the core. More or less layers can be used, with a trade-off between ease of fabrication and performance. Our current design is optimized to transmit fluorescence of wavelength 785 nm. We use silicon nitride layers 126 nm thick with a refractive index of 2.01, and silicon dioxide layers 326 nm thick with an index of 1.46. All parameters are controlled to within 1%.

Once the lower dielectric layers are deposited, the sacrificial core is prepared using standard photolithography methods. To create a rectangular core, we use SU-8 photosensitive epoxy. The core is defined in various widths from 9 µm to 15 µm, and is 3.5 µm high. Once the sacrificial cores are defined, the upper dielectric layers are deposited. Due to the PECVD deposition process, the thickness of lateral ARROW layers is approximately 1.26 times thinner than that of the horizontal top layers. Optical loss is dominated by the side layers, so the top layers are deposited 1.26 times thicker than their bottom-layer counterparts to maintain correct thicknesses for optical confinement on the lateral walls of the waveguide. The topmost layer of 2 µm SiO_2 is finally deposited for mechanical strength.

Once dielectric deposition is complete, the sample is patterned and a reactive ion etch is performed to define the solid-core waveguides that abut and intersect the ARROW waveguide. The sample is then placed in a Nanostrip™ (commercial buffered piranha) acid etch for core removal. It has been found that 2 mm of SU8 core can be removed in the first 24 hours, with the etch rate decreasing over time with a square-root dependence [4].

3. Waveguide geometries and intersections



(a)

(b)

Fig. 3. SEM images of (a) rectangular and (b) hemispherical ARROW waveguides

The sacrificial core method of fabricating ARROW waveguides and microfluidic systems lends itself to creating various core geometries simply by changing the sacrificial core material. We have created rectangular waveguides using SU-8 and hemispherical waveguides using positive photoresist (AZ 3330) which has been reflowed at 250°C for 15 minutes (Figure 3). No hemispherical ARROW waveguides have been optically tested to date, though they show great promise for loss, strength, and ease of

fabrication. By defining the photoresist core on top of a thin aluminum layer, core removal times can be cut by a factor of 10 or more for waveguides over 4 mm in length due to the rapidity of the aluminum etch.

Using the same fabrication technique described above, we have also successfully created T-junctions between hollow-core structures very similar to ARROW waveguides (Figure 4). This property will allow us to create complex branching networks of microfluidic channels integrated with ARROW waveguides.

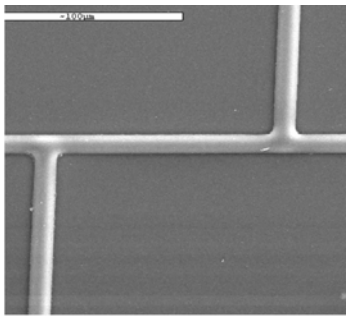
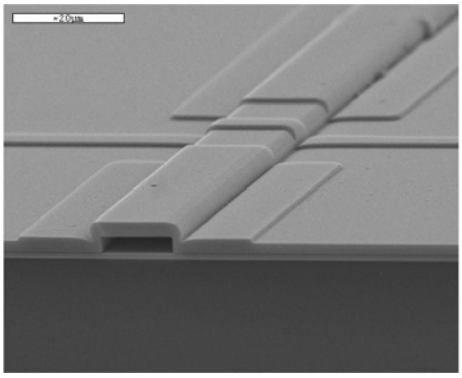
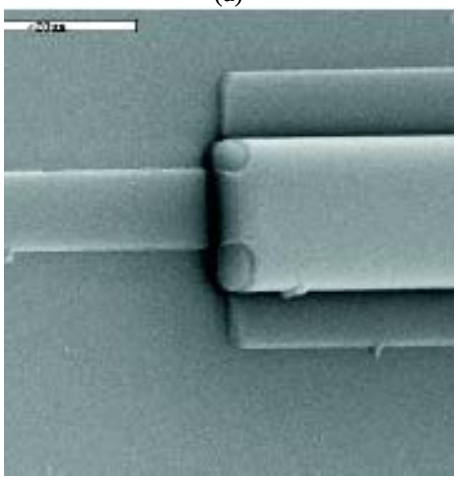


Fig. 4. SEM image of intersections in a hollow-core, on-chip microfluidic system



(a)



(b)

Fig. 5. SEM images of solid-core waveguides (a) intersecting and (b) abutting ARROW waveguides

Intersections between hollow-core ARROW waveguides and solid-core waveguides can be fabricated with a single reactive ion etch step. After deposition of the final (2 μm-thick) dielectric layer, a photoresist mask is patterned and the etch subsequently defines the solid-core waveguides. These solid-core waveguides intersect the hollow-core ARROW waveguides and can provide pumping light for fluorescence measurements. Solid-core waveguides that abut the ends of the ARROW waveguides can be used to route optical modes guided by the ARROWs to off-chip detectors, while completely covering the open end to maintain the integrity of the microfluidic system.

4. Waveguide results

To date, the lowest loss measured in a liquid-core ARROW waveguide is 0.33cm^{-1} for 2nd generation samples with the modified top-layer thicknesses as discussed in section 2 [6]. This compares to a minimum of 1.7cm^{-1} for 1st generation samples, showing a marked improvement. Measurements were made on structures filled with ethylene glycol, chosen because its slow evaporation rate allowed time to align an optical source and detector with the waveguide. Loss calculations were made by measuring transmission through waveguides of varying lengths using a 785 nm laser.

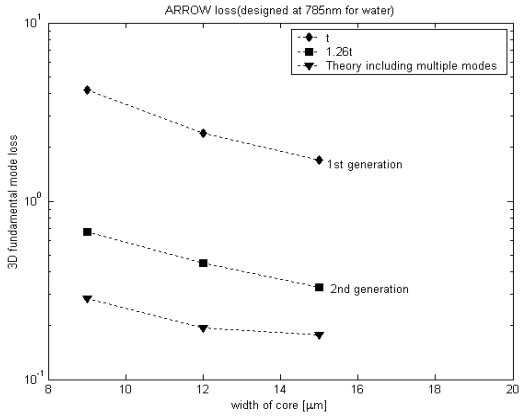


Fig. 6. ARROW waveguide loss measurements

After verifying that the ARROW waveguide allows for low loss light confinement and propagation through a liquid core, Alexa 647 dye molecules of varying concentration were added to the core liquid to explore the possibility of fluorescence detection from these structures. Fluorescence studies are more demanding due to the expected signal reduction based on the quantum efficiency of the dye, photobleaching [5], and signal coupling efficiency into the ARROW mode. The setup for these experiments is depicted in

Fig. 7. The setup is fully planar and excites the molecules at the peak of the guided mode rather than using the tails of exponentially decaying evanescent fields.

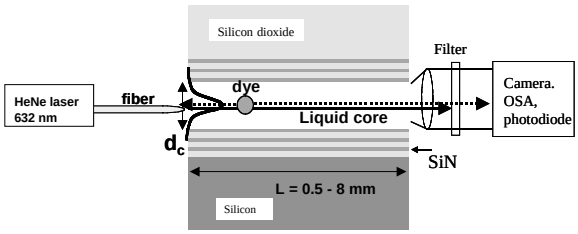


Fig. 7. Illustration of measurement setup used to evaluate fluorescence excitation and guiding in an ARROW.

Fluorescence from Alexa 647 dye molecules was successfully observed. The spectrum of this signal is shown in Fig. 8, clearly demonstrating that its origin is molecular fluorescence. Using a conventional Si photodiode, we were able to detect signals of dye concentrations as low as 10^{-8} mol/l, corresponding to less than 100,000 molecules in the waveguide. With a more sensitive APD or photomultiplier detector, single molecule sensitivity can be reached.

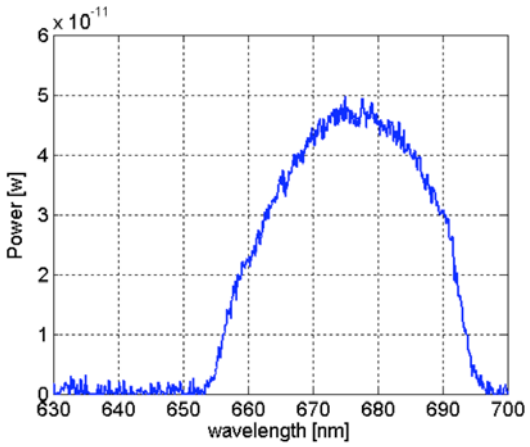


Fig. 8. Output spectrum showing guiding of fluorescent light from Alexa 647 dye molecules.

5. References

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