Microfluidic channels as waveguides.

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We investigated the resistance of microchannels made of Poly(dimethylsiloxane) (PDMS) to organic solvents. The purpose of this study was to search for microfluidic systems that exhibited wave guiding properties. To decrease the index of refraction of the internal media we coated the walls of the PDMS channels with Teflon. We tested if the teflonized channels can contain organic solvents that have high affinity for absorbing PDMS. Our test with toluene and diisopropylamine indicated that these organic solvents permeate through the Teflon coating soak in the PDMS and damages the integrity of the channel. We conclude that PDMS microfluidic channels can be used only with solvents that do not swell PDMS (e.g., DMSO, DMF and water) even if the channel walls are cover with thin coating of Teflon.

1. Background

1.1. Waveguiding. The refractive index (n) of a material is defined by the ratio between the velocities of light in vacuum and the velocities of light traveling in a material. The refractive index of a solid material, a gas, or liquid will always be greater than 1. Furthermore, different wavelengths of light travel at different speeds through the same material. Resulting in wavelength dispersion. Thus, different frequencies of light will have different indices of refraction in a given material. A light wave incident on an interface between two materials will refract and reflect at angles determined by the refractive indexes of the media on the two sides of the interface. Such behavior is described by Snell's law:

$$n_i(\omega) \sin \theta_i = n_t(\omega) \sin \theta_t$$

The angels θ_i and θ_t are shown schematically on Fig. 1, and ω is the frequency of the light wave.

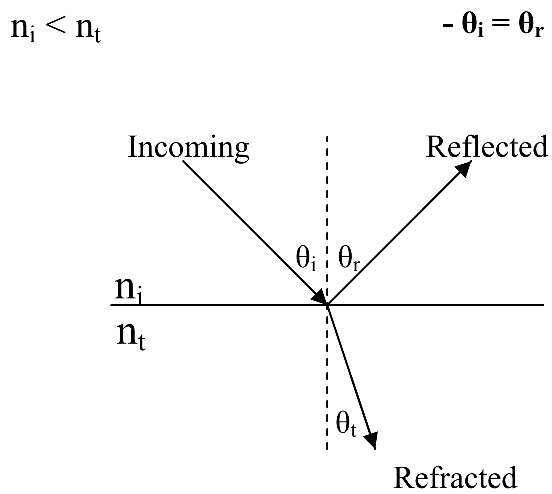

Fig.1. Illustration of Snell's law. Reflection and transmission of incoming light.

In order to see The behavior depicted on Fig. 1, n_i, should be lower than n_t, i.e. if the incidence medium has a lower index of refraction than the transmission medium, sin θ_t from the Snell's law is always less than 1: $\sin \theta_t = (n_i / n_t) \sin \theta_i$, thus, θ_t is always real. If the medium of incidence, however, has a higher refractive index than the transmission medium, there will be an angle of incidence for which transmission is not possible for any polarization because sin θ_t will be greater than 1, (Fig. 2). The angle of incidence at which the transmitted angle reaches 90^0 is called the angle of total internal reflection, or the critical angle.

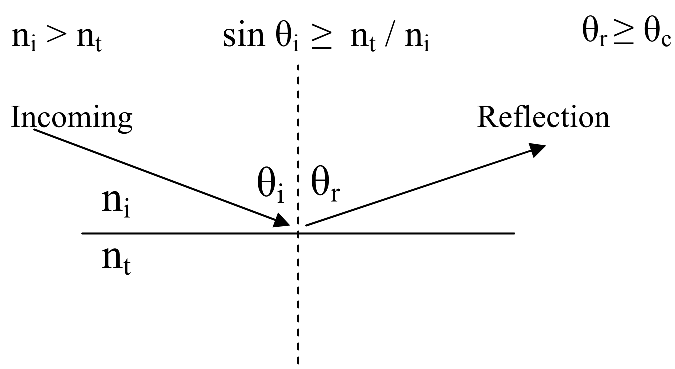

Fig. 2. Total internal reflection of the incoming light when θ_t is 90^0.

If a light beam is introduced to a material with refractive index n_i sandwiched between another material with a refractive index $n_0 < n_i$ and the angle of incidence towards the two interfaces is larger than θ_c, the light wave will be contained in the media in the middle due to complete internal reflection (Fig. 3). This phenomena is called waveguiding and waveguides are of great importance for photonics information technology.

1.2. Microchannels as wave guides.

Microfluidics systems. Microfluidics is the manipulation of liquids and gases in channels having cross-sectional dimensions on the order of 10 – 100 μm.
In a microchannel, the fluid that can be introduce inside, should have a higher refractive index than the material the microchannel, in order to observe total internal reflection. In our experiment the material of the microfluidic channel (refractive index n_0 on Fig. 3) is a polymer, Poly(dimethylsiloxane) (PDMS).

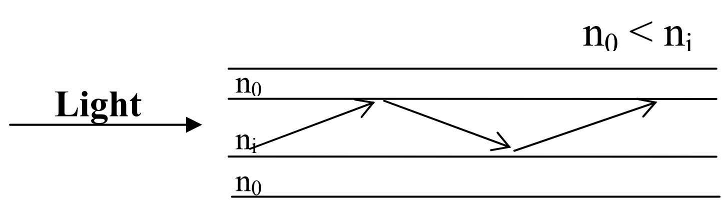

Fig. 3. Total internal reflection of light in a microchannel.

Therefore, for waveguiding n_i is limited to fluid with higher refractive index than PDMS. Table 1b shows a list of refractive indexes of liquids that can be introduced to PDMS microchannels.

Channel material	n
PDMS	1.45
Teflon	1.30

a

Fluid	n
Air	1.00
Water	1.33
DMF	1.43
DMSO	1.48

b

Table 1. (a) Channel materials and their refractive indexes. **(b)** Different fluids and their refractive indexes.

Apparently the only fluid, from these examples, that we will result in wave guiding is with Dimethylsulfoxide (DMSO) since it has higher refractive index (1.48) than the refractive index of PDMS (1.45). With water, dimethylformamide (DMF) and air, however, the light will be reflected and refracted, leading to loss light and not waveguiding.

One of our goals is to prepare microchannels with walls that have lower refractive index than the refractive indexes of most liquids used in PDMS microfluidic.

2. Results and Discussion

Teflon is a good choice for covering of microfluidic channels for waveguiding, because its refractive index is 1.30 (Table 1a) (Fig. 4)

One to three coatings of Teflon were introduce to 100 μm and 200 μm microfluidic channels.

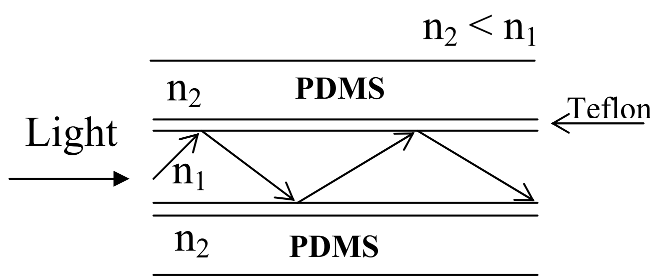

Fig. 4. Covering of microfluidic channels with Teflon.

We conducted tests to determine whether or not different organic solvents that swell PDMS will be contained in microchannels whose walls are coated with Teflon. First we tested the resistance of the channels against toluene. To see the differences, we took a picture, using a microscope, of the channel before and after the solvent was passed trough it. Fig. 5 shows the opticalmicrographs.

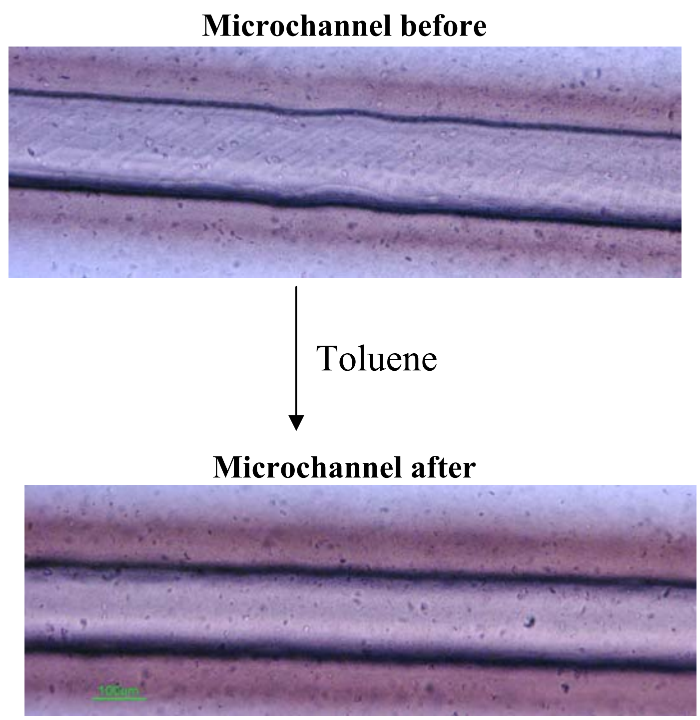

Fig. 5. Opticalmicrograph of the channel before and after passed trough it toluene. Channel width is 200 μm.

Even though the channel walls are coated with Teflon, the toluene penetrates into the PDMS. As indicated by the darker lines of the passing of the solvent (Fig. 5).

A possible alternative to resolve these problem introduce several layers of Teflon on the walls of the microchannel. We also tested the resistance of the channel against another solvent, diisopropylamine, that has a higher affinity for PDMS. The opticalmicrographs of the microchannel before and after the passing of the solvent, are shown in Fig. 6.

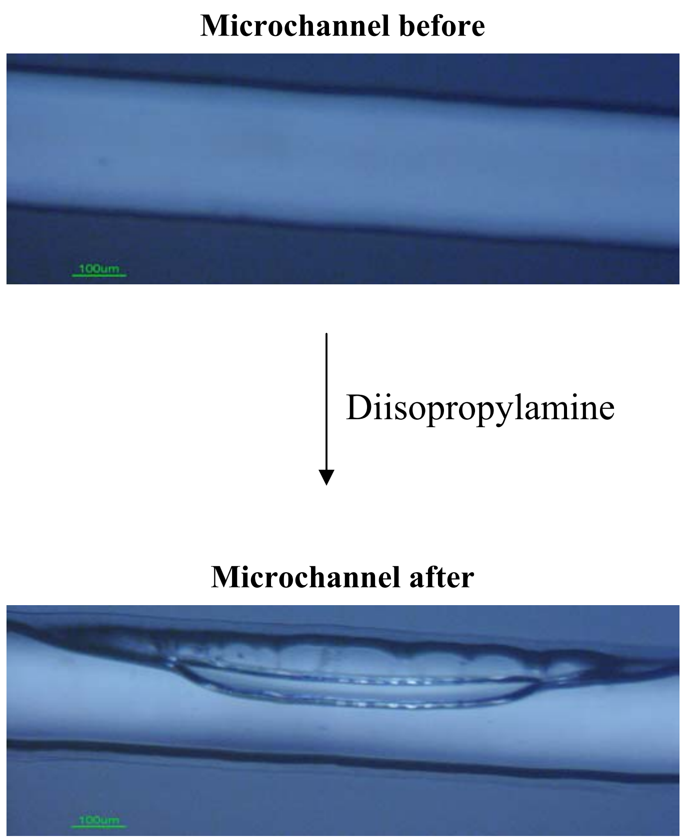

Fig. 6. Opticalmicrograph of the channel before and after passing trough it diisopropylamine.

Discussion

Diisopropylamine test show less desirable results than the toluene tests. It is clear that after the solvent was passed, the Teflon coating falls off the walls of the channel. (Fig. 6)

Conclusion

We prepare PDMS microchannels of 100 and 200 μm size and coated their walls with Teflon. Tests with toluene and diisopropylamine show that these solvents permeates through the Teflon coating. Tests with DMF and DMSO that do not swell PDMS are under way.

3. Experimental

3.1. Methods for fabrication of PDMS microchannels.

A general procedure for replica molding and rapid prototyping is outline on Fig. 7. Soft lithography starts with the production of a PDMS replica of a master. The PDMS used in these experiment is supplied in two components, a base and a curing agent. To produce a replica, we mix the two parts together (10:1, base: curing agent) pour the liquid prepolymer over the master, that has been silanized with Perfluoro (methyldecalin) before hand, and cure it. The liquid prepolymer conforms to the shape of the master with high fidelity. The low surface free energy and elasticity of PDMS allow it to release it from the masters without damaging the master or the replica. To form an irreversible seal, we expose the replica, and a flat slab of PDMS, to an air plasma for 50 sec. This treatment generates silanol groups (Si-OH) on the surface of the PDMS by the oxidation of methyl groups. The two surfaces must be brought into contact quickly (< 1 min.) after oxidation, because the surface of oxidized PDMS reconstructs in air.

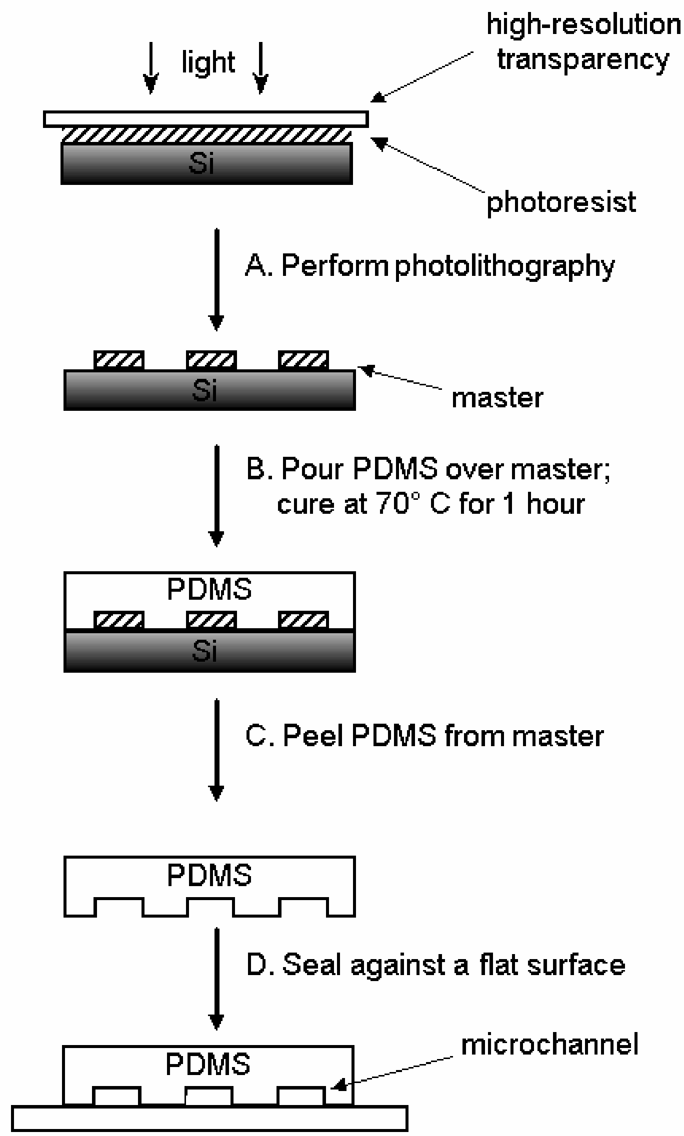

Fig. 7. A system of channels is designed in a CAD program. A commercial printer uses the CAD file to produce a high - resolution transparency. This transparency is used as a photomask in contact photolithography to produce a master. A master consist of a positive relief of photoresist on a silicon wafer and serve as a mold for PDMS. Liquid PDMS pre – polymer is poured over the master and cured for 1 h at 60 – 70^0C. The PDMS replica is peeled from the master, and the replica is sealed to a flat surface, made also with PDMS, to enclosed the channels. (Ref. (1) J.Cooper Mcdonald and Gorge Whitesides, 2002)

Design of the master. Fig. 8 shows the two types of masters used in this study. Masters with radii of 20, 30, 40 and turn angles of 45^0 and 90^0 were prepare.

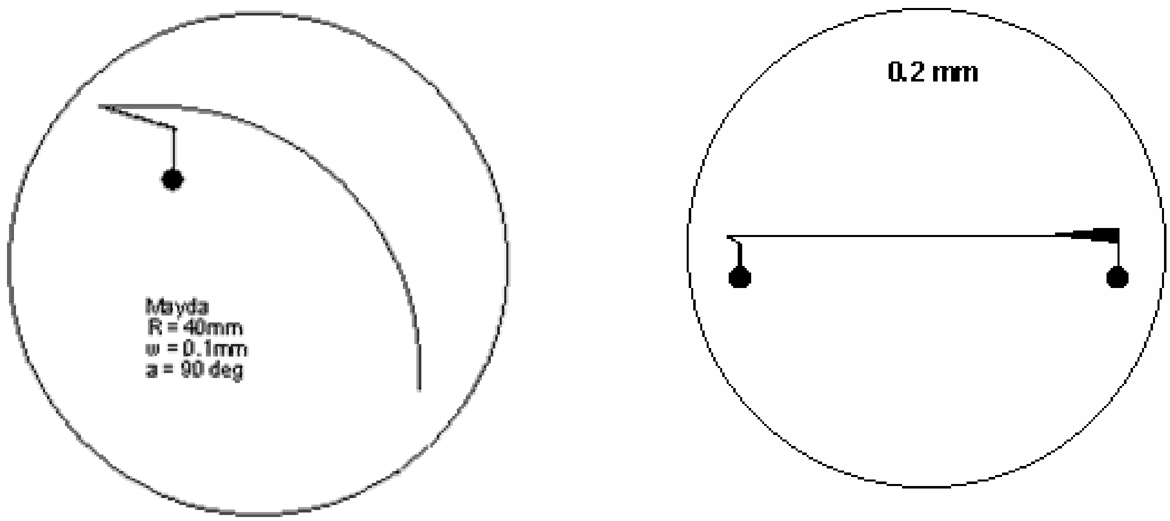

Fig. 8. Examples of a silicon wafers that serves as a mold for PDMS.

3.2 Teflonization

In order to have microchannels with Teflon coated walls, first we punched round holes at the ends of the channels (were the circle is, Fig. 7) before the PDMS was exposed to the plasma. We put two tubes (internal diameter = 0.0310", external diameter = 0.0630") on these holes and seal them with a light curable glue after the channels were assembled. With a syringe we pass Teflon prepolymer trough the channel. To let the Teflon dry, we put the microchannel in an oven at 120^0C for ~ 1hr.

3.3 Test for resistance against solvents.

Picture was taken of channels with and without Teflon. The channel were filled with solvent (Toluene and diisopropylamine) and the pictures were taken 1 – 2 minutes after the solvent pass trough the channel.

References

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(3) Simmons J.H.; Potter K. in "*Optical Materials*," Academic Press, 2000.