



Flexible multimode polydimethyl-diphenylsiloxane optical planar waveguides

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Abstract

The paper reports on the fabrication and characterization of flexible optical multimode silicon-based organic elastomer planar and rectangular waveguides, where polydimethyl-diphenylsiloxane (PDMDPS) was used for the waveguide core and polydimethylsiloxane was used for the cladding and cover protection layers. We measured waveguiding properties of PDMDPS planar waveguides deposited on glass substrate using the prism coupling technique and the optical scattering losses of the waveguides by the fiber probe technique at the wavelengths region from visible to infrared. The design of the rectangular waveguides was planned for the geometric dimensions of the core $50 \times 50 \mu\text{m}^2$ and the proposed shapes were realized by the doctor blade technique into a nickel mold. Insertion optical loss measurement of rectangular waveguides was done by the cut-back method and the best samples had optical losses lower than 0.35 dB cm^{-1} at 532, 650, 850 and 1310 nm. The main virtue of the waveguides is their flexibility, suitable in particular for optical connections in a wide range of the wavelengths.

1 Introduction

In recent years, we have witnessed growing demand for increasing transmission capacity in the frame of data communications. For such communication over a short distance, metal wiring-based connections have dominated [1]. However, this type of connection no longer fulfills the expectations for increased transmission capacity of data communications, mainly because of disadvantages such as electromagnetic interference and crosstalks, power and heat dissipation issues at high operating frequencies, and high consumption of power at high data rates [2].

Optical interconnection technology seems to be a promising solution for data transmission at high rates and onto parallel optical data links through a large number of channels [3]. Here, integrated optical interconnections and optoelectronics on flexible substrates open new possibilities not only for data communications but also for optical sensing, among other things [4].

Flexible optical waveguides are currently made by standard microelectronic techniques from polymer materials. The main advantages of this approach are that they are compatible with existing semiconductor technologies, have minimal impact on the environment, good optical and mechanical properties, and, last but not least, a low cost. Polymers have long been recognized as leading candidates for fabrication of low-cost integrated optical components [5] and flexible foil substrate using low-cost assembly and packaging methods. There are a number of different polymers that were specifically targeted for photonics applications, photonics structures and devices, for example, Cyclotone™ (manufactured by DOW Chemical), Polyguide™ (DuPont), Truemode™ (Exxelis), Ultradel 9120D (Amoco chemicals), and OE-4140 UV (Dow Corning) [6–8]. Some polymers intended for these purposes have been developed in the last few years and nowadays they are even commercially available, such as Exguide™ (FOWG series from Chemoptics Inc.) [9], EpoCore [10], SU-8 polymer [11], ORMOCER Ormocore [12] and LIGHTLINK™ (micro resist technology GmbH) [13, 14]. As well as the above mentioned polymers, other materials are also attracting interest; one of these is the elastomer Polydimethylsiloxane (PDMS), which is in the Lab on chip technology commonly used to fabricate microscale fluidic systems.

PDMS has also been used to fabricate optical waveguides, for example:

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1. Single-mode waveguide prepared by using two approaches that differ for low-refractive and high-refractive contrast waveguides [15].
2. Multimode waveguides presented in [16] with different mixing ratios of the curing agent.
3. Multimode waveguides [17] where the hardening was done by variation of hardening temperatures.

The PDMS elastomer is available as silicon elastomer kit, where the kit contains two chemicals: base agent (part A) and curing agent (part B). Generally, in the PDMS waveguides the refractive index contrast between waveguiding layers and cladding layers are realized by variation of the agent A and B ratios (higher A:B ratio usually means lowering of the refractive index) or varying the hardening temperatures (higher hardening temperature means increasing of the refractive index) while the A:B ratio is kept constant. However, this option causes only a small increment of the refractive index [15–18].

One of the interesting advantages of the PDMS is its low refractive index value 1.41 ($\lambda = 589$ nm). This factor enables the use of many potentially suitable optical materials with higher refractive index as waveguides cores, which may assure higher refractive index contrasts. On the other hand, the disadvantage of the PDMS polymers is their poor wettability (i.e. compatibility) with regard to other polymers, with few exceptions such as Polydimethyl-diphenylsiloxane (PDMDPS), which possess high chemical and thermal stability, is non-toxic, inert and optically clear in a wide spectral range of material, and its refractive index is 1.43 at $\lambda = 589$ nm [18, 19], which means higher than that of PDMS [18, 20].

In this paper we are going to present our new approach to realize multimode flexible polymer rectangular waveguides for optical interconnection applications made of PDMDPS as a core and PDMS elastomers as a cladding layer. We started by fabricating multimode optical planar PDMDPS waveguides deposited on glass substrate that

already had a PDMS cladding layer, and we continued by making freestanding flexible PDMDPS rectangular optical waveguides with a PDMS cladding layer.

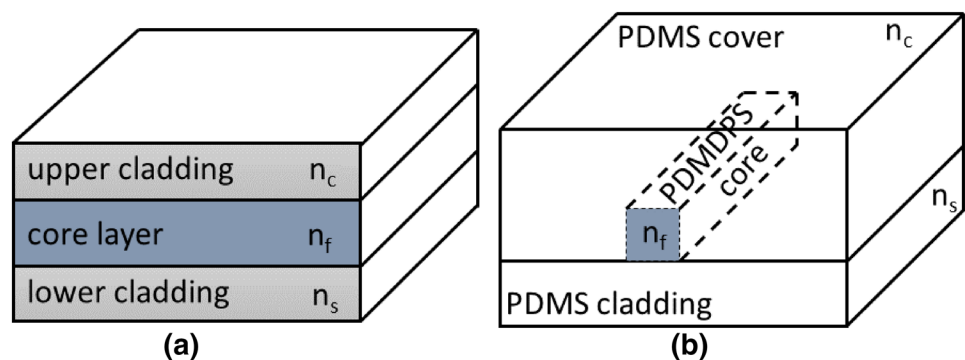
2 Design of optical planar and rectangular waveguides

Planar waveguides consist of a high-index dielectric layer surrounded on either side by materials with a lower refractive index. This setting is based on the premise that effective waveguiding will work only when total internal reflection occurs at the core–substrate interface so that the light propagates inside the core. In our case the structure of a planar optical waveguide would consist of PDMDPS waveguide layer (n_f) on glass substrate with PDMS cladding layer (n_s) and air as the upper cladding layers (n_c) (Fig. 1a). The rectangular waveguide has PDMDPS elastomer as the core waveguide layer (n_f), and the substrate (n_s), and the cover layer (n_c) is made of PDMS elastomer. This combination of materials would make the whole structure sufficiently flexible (Fig. 1b).

Suitability of the elastomers PDMDPS and PDMS for the cores and claddings of the planar waveguides was checked by measuring of their absorption spectra by UV–Vis–NIR Spectrometer Shimadzu (UV-3600) (Fig. 2).

The figure shows that both elastomers are transparent in visible and near-infrared range up to 1100 nm (including 850 nm, which is known as the first telecommunication optical window), and also in infrared spectra from 1200 to 1360 nm (including the optical window around the 1300 nm, i.e. the second telecommunication optical window). The spectrum also shows that even though there are some absorption peaks from 1430 to 1650 nm they are not so high as to prevent use of both elastomers in the region around 1550 nm, i.e., in the third telecommunication optical window.

Fig. 1 Cross-sectional view of PDMDPS/PDMS optical waveguide **a** optical planar waveguide and **b** rectangular waveguide



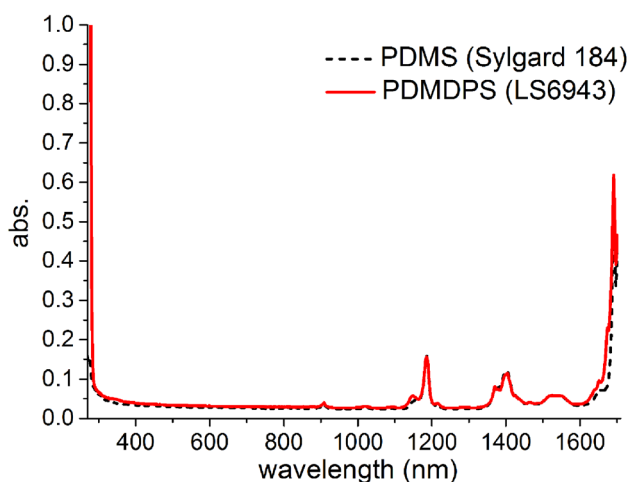


Fig. 2 Absorption spectra of PDMDPS (LS6943) and PDMS (Sylgard 184) elastomer (A:B 10:1, 100 °C 60 min)

3 Fabrication

For our research we chose as the core waveguide material PDMDPS—LS6943 (NuSil Technology) [19] and as the cladding layer PDMS elastomer—Sylgard 184 (ELCHEMCo/Dow corning) [20]. The PDMDPS and PDMS elastomers were made by mixing the A (base agent) and B (curing agent) agents in the ratio 10:1. After the thorough mixing of the components, the solutions were evacuated 30–60 min in a desiccator to get rid of all the bubbles.

PDMDPS planar waveguides were deposited onto glass substrates using the doctor blade method. Glass substrates were cleaned by acetone, isopropyl alcohol and demineralized water using spin coater.

Then the PDMS layer was deposited onto the clean substrate, and then covered with the waveguiding PDMDPS layer. No upper cladding layer was applied to allow the optical coupling needed for dark-mode spectroscopy

measurement. The thickness of the PDMS layers were $20 \pm 5 \mu\text{m}$ and those of the PDMDPS, $50 \pm 5 \mu\text{m}$.

PDMDPS rectangular optical waveguides were fabricated using a nickel negative mold made by the galvanoplastic process of a photoresist master produced by photolithographic method. The mold had 250 μm pitched 12 channels that were 8 cm long and their dimensions were $50 \times 50 \mu\text{m}^2$. The process of making the rectangular waveguides is shown in Fig. 3 and it was as follows:

1. The nickel mold is washed subsequently with acetone, isopropyl alcohol and demineralized water, and dried by compressed nitrogen. On the surface of the mold a thin film of the separator SP3 (ELCHEMCo) is formed by spin-coating at 3000 rpm.
2. Negative mold channels are filled with liquid PDMDPS silicone (LS6943) and remaining liquid is removed from the upper surface of the mold with a blade. The elimination of the microbubbles and homogenization of the mixture is done by evacuation in the desiccator for 15 min. The next step is hardening of the mixture done by 60 min heating on a 100 °C hot plate (see Fig. 3a).
3. The PDMS (Sylgard 184) cladding layer is then deposited by the doctor blade technique. The flat mold with filled channels is covered with a 1 mm thick layer of PDMS liquid. The remaining microbubbles formed during the deposition process are again removed by 30 min evacuation in the desiccator. The cladding is then hardened for 60 min at 100 °C (see Fig. 3b).
4. The channels are firmly adhered to the cladding layer but not to the nickel mold due to the applied separator. Hence the cold elastomers, in the form of thin foil with rectangular looming channels, are then carefully removed from the nickel mold (see Fig. 3c).
5. Finally, the upper PDMS (Sylgard 184) layer 1 mm thick is deposited by the doctor blade technique. The sample is then evacuated in the desiccator for 30 min in a horizontal position and left to harden for 60 min at 100 °C (see Fig. 3d).

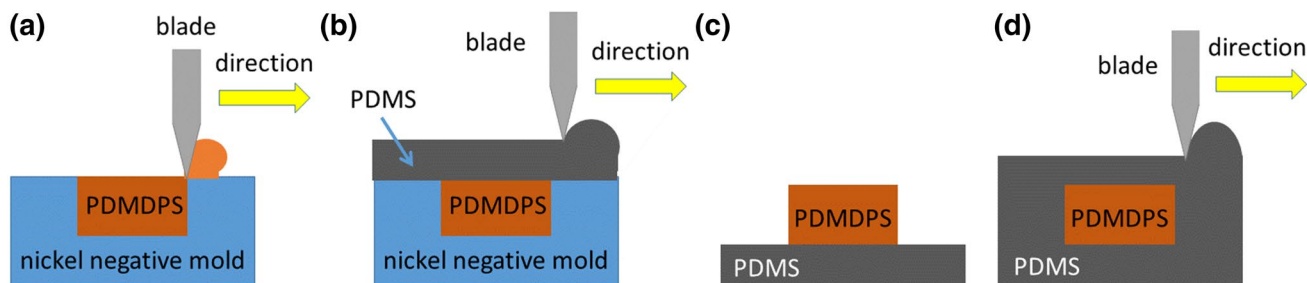


Fig. 3 Fabrication process of PDMDPS optical rectangular waveguides by doctor blade technique **a** deposition of PDMDPS core waveguide layer, **b** deposition of PDMS lower cladding layer, **c** separa-

rating of the foil-shaped elastomer from the nickel mold, **d** deposition of PDMS upper cladding layer

4 Measurements and results

The thicknesses of the fabricated polymer layers were measured by the profile-meters Talystep Hommel Tester 1000 and dial digital indicator KINEX. The found thicknesses of the cladding layer were around 20 μm and those of the core waveguide layers were 50 μm.

Waveguiding properties of the planar waveguides (glass/PDMS/PDMDPS) were examined by dark mode spectroscopy using Metricon 2010 prism-coupler system [21] at five wavelengths (473, 632.8, 964, 1311 and 1552 nm). The refractive index of the planar waveguide can be determined by measuring the critical angle of the incidence θ_c at the interface between the prism and the material in contact with the coupling prism. The refractive indices were calculated from following equation (Eq. 1):

$$\theta_c = \arcsin \frac{n}{n_p} \tag{1}$$

where n_p is refractive index of the used coupling prism and n is then the value of the refractive index of the core n_f or the cladding layer n_s respectively. The result in the form of mode spectra is given in Fig. 4 and shows that all the layers had waveguiding properties. Critical angles of incidence determine refractive indices of the PDMDPS layer, which is the

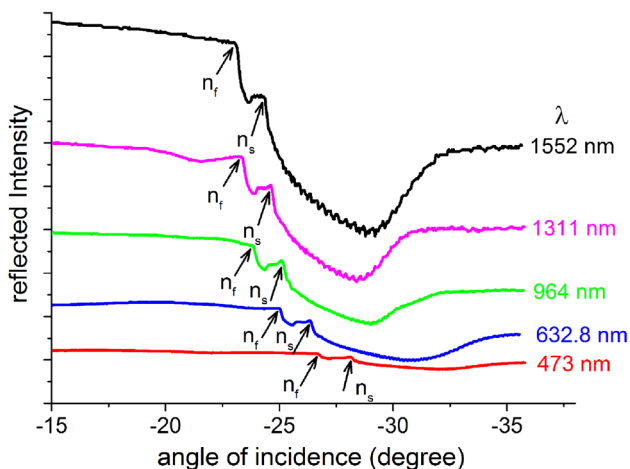


Fig. 4 Mode pattern of PDMDPS optical planar waveguide fabricated onto glass substrate with PDMS cladding layer

Table 1 Waveguiding properties of the planar PDMDPS waveguides: angle of incidence of the TE modes

Wavelengths	(nm)	473	632.8	964	1311	1552
Angle of incidence for PDMDPS	(degree)	-23.7	-25.005	-23.85	-23.37	-23.1
Refractive index of PDMDPS (n_f)	(-)	1.4378	1.4289	1.4216	1.4184	1.4176
Angle of incidence for PDMS	(degree)	-28.2	-26.385	-25.17	-24.645	-24.375
Refractive index of PDMS (n_s)	(-)	1.4198	1.4122	1.4056	1.4030	1.4022

waveguiding layer (n_f), and that of the PDMS layer, which forms the cladding (n_s). Because the layers above the glass were too thick, the substrate glass could not be seen in the spectra and therefore its refractive index could not be determined. For more details of such measurement see [19, 22]. Based on the data from Fig. 4 we calculated the refractive index values given in Table 1; the data were then used for formulation of the fitting equations for refractive indices of PDMDPS layer (Eq. 2) and PDMS layer (Eq. 3), see below.

$$n = 1.4151 + (6.1703 \times 10^3) \times \lambda^{-2} + (-2.4347 \times 10^8) \times \lambda^{-4} \tag{2}$$

$$n = 1.3999 + (5.5152 \times 10^3) \times \lambda^{-2} + (-2.3889 \times 10^8) \times \lambda^{-4} \tag{3}$$

The measured values of the refractive indices of the applied elastomers were compared with the values given by the supplier [19, 20], and it was found that our measured values of refractive index of PDMDPS (LS6943) were slightly higher. We believe that it is because the supplier does not give any precise deposition conditions, which might be different from those used in our case.

Optical scattering losses of our planar waveguides were measured by fiber probe technique. The principle of the measurement involves a measurement of transmitted and scattering light intensity as a function of propagation distance along the waveguide [23, 24]. The light is coupled into the planar waveguides through the optical coupling prism and the outgoing scattered light intensity was detected by the optical fiber connected to InGaAs detector. The measurement was done for three planar waveguide samples and the results of the optical scattering loss measurements of the planar waveguides are given for various wavelengths in Fig. 5 and summarized in Table 2.

Regarding the rectangular waveguides: their dimensions were checked by optical digital camera ARTCAMI equipped with optical head ZOOM Optics (Olympus Czech Group Ltd.), which was controlled by QUICKFOTO software. The images of the rectangular waveguides are shown in Fig. 6 where Fig. 6a, b show the top view images and Fig. 6c, d show the edge views. The photos and the measurement showed that geometrical dimensions of the channels were those expected $50 \times 50 \mu\text{m} \pm 5 \mu\text{m}$.

Insertion optical loss measurements for rectangular optical waveguides were taken using the cutback method.

Fig. 5 Optical scattering losses measured of the PDMDPS (LS6943)/PDMS (Sylgard 184) planar waveguides deposited on glass substrate for five wavelengths (sample #1–813C) **a** 473 nm, **b** 632.8 nm, **c** 964 nm, **d** 1311 nm, **e** 1552 nm

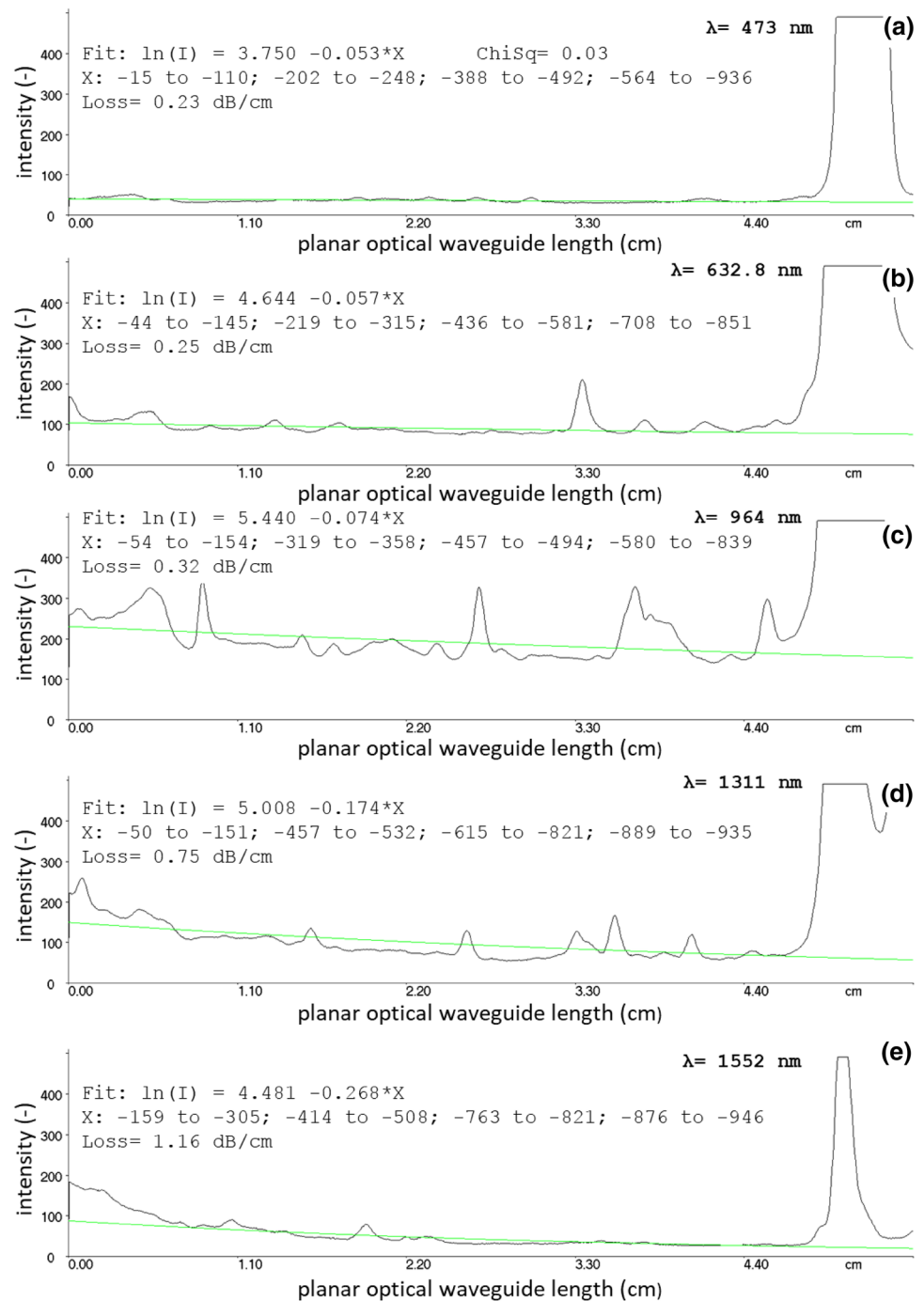
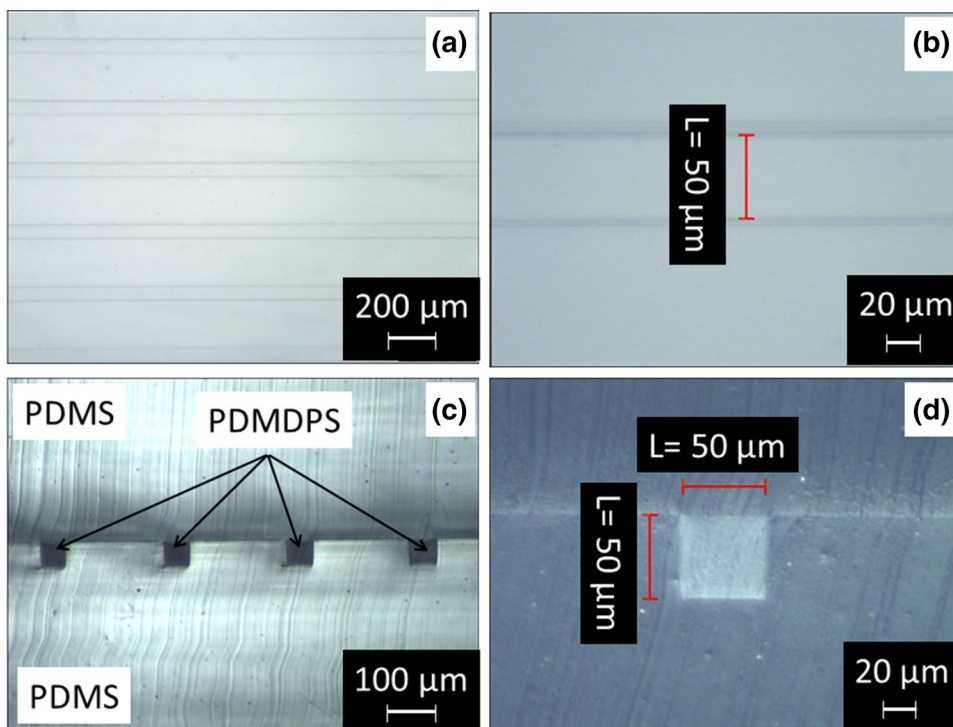


Table 2 Optical scattering losses of the PDMDPS (LS6943)/PDMS (Sylgard 184) planar waveguides deposited on glass substrate and insertion optical losses of the optical PDMDPS rectangular waveguides

Wave-lengths (nm)	Scattering optical loss planar waveguide (dB cm^{-1})		Wave-lengths (nm)	Insertion optical loss rectangular waveguide (dB cm^{-1})		
	Sample #1	Average value		Highest value	Lowest value	Average value
473	0.18	0.26	532	0.96	0.11	0.46
632.8	0.25	0.31	650	0.77	0.15	0.43
964	0.32	0.54	850	0.46	0.33	0.30
1311	0.75	0.99	1310	0.51	0.32	0.41
1552	1.16	1.16	1550	2.22	1.23	1.60

Fig. 6 Images of PDMDPS rectangular waveguides, **a, b** top views and **c, d** edge views



The principle of the method is shown in Fig. 7a. Figure 7b then shows a photo of the experimental set-up of the measurement. The measurement started with determination of the optical power (P_1) emitted from the source and passing through the whole length l_1 of the rectangular waveguide and then proceeding through to the detector via output fiber waveguides. P_2 is the output optical power obtained after breaking the waveguide, where l_2 is the length of the broken part of the optical waveguide. Optical losses A were calculated from Eq. (5), where α is defined by Eq. (4).

$$\alpha = 10 \times \log \frac{P_1(W)}{P_2(W)} [\text{dB}] \tag{4}$$

$$A = \frac{\alpha}{l_1 - l_2(\text{cm})} [\text{dB cm}^{-1}] \tag{5}$$

The measurements were done at green light (532 nm, Nd:YVO₄ laser), red light (650 nm, laser Safibra OFLS-5-FP-650), at 850 nm (laser Safibra OFLS-6 LD-850), at 1310 nm (laser Safibra OFLS-6CH, SLED-1310 nm) and at 1550 nm (laser Safibra OFLS-5-DFB-1550). The output lights were measured by optical powermeter Thorlabs PM200 with Si detector S151C (measurements for wavelength 532, 650 and 850 nm) and InGaAs detector S155C (measurements at 1310 and 1550 nm). The accuracy of the measurement set-up is estimated to be $\pm 5\%$.

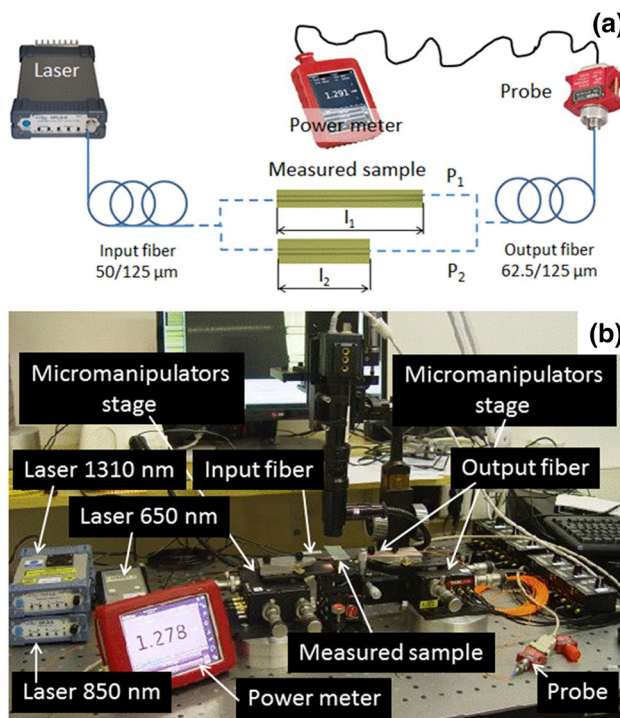


Fig. 7 Principle of insertion optical loss measurement **a** schematic view of the set-up, **b** photo of the set-up

Measurements were done for l_2 rectangular channels, and the highest and the lowest, as well as the average, values are given in Table 2.

Our fabricated optical rectangular waveguides had insertion optical losses lower than 0.5 dB cm^{-1} (average values for 532, 650, 850 and 1310 nm) and 1.6 dB cm^{-1} (average value for 1550 nm) and the best sample had optical insertion losses 0.15 dB cm^{-1} at 650 nm, 0.33 dB cm^{-1} at 850 nm and 0.32 dB cm^{-1} at 1310 nm.

5 Conclusion

We report on the properties of PDMDPS optical elastomer planar waveguides deposited onto glass substrate, which have PDMS cladding layer, and on flexible optical PDMDPS rectangular waveguides. Rectangular waveguides were deposited by the doctor blade process.

Optical waveguiding properties of planar waveguides samples were characterized by dark mode spectroscopy at five wavelengths (473, 633, 964, 1311 and 1552 nm) and their optical losses were measured by collecting the scattered light using fiber scanning along the waveguide and reading them using the InGaAs photodetector. The best planar waveguide samples had optical losses $< 0.32 \text{ dB cm}^{-1}$ at 473, 632.8 and 964 nm, and 0.75 dB cm^{-1} at 1311 nm. The scattering losses at 1552 nm were $< 1.16 \text{ dB cm}^{-1}$. Insertion losses of the rectangular waveguides were measured by cut-back method and the samples had optical losses lower than 0.6 dB cm^{-1} . The best samples had optical losses 0.11 dB cm^{-1} at 532 nm, 0.15 dB cm^{-1} at 650 nm, 0.33 dB cm^{-1} at 850 nm and 0.32 dB cm^{-1} at 1310 nm.

The presented waveguides will allow for realization of a flexible optical waveguiding structure suitable for various applications. Because of their low optical losses, they would be useful for operations not only in the visible spectral region, but also in infrared at 850 and 1310 nm, which are the regions of major interest in optical interconnections.

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