TECHNICAL PAPER

Inorganic–organic hybrid polymer multimode optical channel waveguides

Vaclav Prajzler[1] · Vaclav Chlupaty[1] · David Mares[1] · Agaje Bedemo Beyene[2] · Wei-Nien Su[2]

Abstract

The paper reports on the fabrication and characterisation of the hybrid polymer multimode optical channel waveguides that have been used for core layers, namely OrmoClear®FX and OrmoCore. UV photopolymer was utilised for the cladding layers. The optical losses of the channel waveguides were measured by the cut-back method, and the lowest value for channel waveguides with the OrmoClear®FX core, specifically 0.22 dB/cm, was observed at 650 nm. The optical losses at 850 nm were 0.30 dB/cm and at 1310 nm, they were 0.47 dB/cm. OrmoCore channel waveguides had the lowest optical losses of 0.26 dB/cm at 850 nm, 0.32 dB/cm at 650 nm and 0.48 dB/cm at 1310 nm. The study has demonstrated that both hybrid polymers have suitable properties for the fabrication of optical waveguides for micro-opto-electro-mechanical systems and integrated optics applications for operating at 650 nm, 850 nm and 1300 nm.

1 Introduction

Micro-Opto-Electro-Mechanical Systems (MOEMSs) offer many application possibilities that include optical communications (optical splitters and combiners, switches, multiplex systems, etc.), digital image processing, adaptive optics, optical sensor applications, and medical applications (Motamedi 2005). MOEMS structures are fabricated using micro-optics and standard micromachining technologies from semiconductor materials such as silicon, silicon dioxide, silicon nitride, gallium arsenide, and group-III nitrides semiconductor. In the last decades, MOEMS devices and structures fabricated from polymers have been intensively studied (Eldada and Shacklette 2000; Guan et al. 2013a; Prajzler and Chlupaty 2020). The reason for this is that polymers are very promising not only for MOEMSs but also for optics applications because of their easy fabrication processes, which make it possible to utilise already existing compatible technologies and suitable

properties of the polymers, such as low absorption, tunability of refractive indices and refractive index contrasts, environmental stability including absorption stability, mechanical characteristics as well as humidity and temperature resistance (Wong et al. 2006).

The increased applications for ground-breaking Microelectromechanical systems (MEMSs) (Judy 2001) and Micro-Electro-Mechanical-Systems for Radio-Frequency applications (RF-MEMS) have stimulated great interest in the industry and also in basic research (Iannacci et al. 2011). It is attributable to a wide range of application possibilities, including low-loss/high-isolation ohmic/capacitive switches, high Q-factor (variable) inductors, and wideband vibration energy harvesting devices (Iannacci et al. 2016).

As far as the planar optical waveguides are concerned, they are an essential building element not only for optical communications but also for MOEMS applications. For that reason, various new optical polymers have already been studied. They include e.g. acrylate, polyimides, fluorinated polymers, polyimide siloxane, epoxy polymers, benzocyclobutene, and elastomers (Ma et al. 2002; Yeniay et al. 2004; Nordstrom et al. 2007; Yahya et al. 2012; Elmogi et al. 2016; Prajzler et al. 2018; Ibrahim et al. 2020). These polymers have been found to exhibit suitable optical and mechanical properties such as low absorption at the key optics operating wavelengths from the visible to the infrared spectrum, tunability and well-

✉ Vaclav Prajzler
Vaclav.Prajzler@fel.cvut.cz

1 Department of Microelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, 166 27, Prague, Czech Republic

2 Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology, Taipei 106, Taipei, Taiwan

controlled values of the refractive indices, thermal and chemical resistance, environmental stability, and low cost.

For practical application of the optical waveguides, the refractive indices and optical losses are the parameters that should be closely observed. The refractive index of the waveguide core must be higher than that of the waveguide cladding. What is also important is the contrast between both indices, the higher it is the smaller could be geometrical dimensions of such a single-mode optical waveguide. What concerns the refractive index values and their contrasts, there could be found quite a scale of several types of suitable polymers having low refractive index values, for instance PDMS 1.41, acrylate based polymers with refractive indices around 1.49, or epoxide ones having refractive indices about 1.53, or hybrid polymers with the refractive index around 1.55. The low optical losses at the operating wavelengths are a necessary condition for practical applications, where the common wavelengths used in optics communications are 850 nm, 980 nm, 1300 nm and 1550 nm. For sensor applications, the waveguides have low optical losses in the visible spectrum (530 nm, 650 nm, etc.).

Nevertheless, new types of polymers with even better and more versatile properties are being sought and developed. For example polymer PCW250-50 core and TC-447–20 cladding from Panasonic (Shi et al. 2023), acrylic resin XS-CA02k2.2 and X-CL01k2 Kyoritsu Chemical (Hatai et al. 2022). ZPU resin was developed by ChemOptics Inc. (Daejeon, Republic of Korea), and new epoxy polymers E3135 and E3129 were developed by NTT Advanced Technology (Japan) (Prajzler and Chlupaty 2020). Micro resist technology GmbH (Germany) in cooperation with Fraunhofer ISC developed different types of epoxy resin (Elmogi et al. 2016). Several types of clear, colourless, liquid photopolymers intended for optical application were developed as well and they are now commercially available from Norland Optical Adhesive (USA).

Another new type of polymer for optics and photonics applications could be UV-curable inorganic–organic hybrid polymers. These polymers consist of organic and inorganic units, so that they could exhibit a combination of superior properties of both types in one material (Gruetzner et al. 2014; Prajzler et al. 2019a). The main advantages of this type of polymer are high transparency from the visible to the infrared spectrum, the excellent thermal stability of cured patterns up to 300 °C in the short term and 270 °C in the long term, the high mechanical and chemical stability of cured patterns, and high resolution down to the 100 nm feature size. Other important advantages also comprise their compatibility with UV-imprint and moulding-technology processes, including their low processing temperatures (below 180 °C) and compatibility with the

polydimethylsiloxane (PDMS) elastomer (Robertsson et al. 2001).

Such polymer materials have excellent properties and a wide range of applications, including fabrication optics devices and structures such as moulded prisms and gratings, optical prisms, microlenses, optical couplers and connectors, and also including microfluidic systems applications. Consequently, several types of inorganic–organic hybrid polymers are commercially available now. One of the developers is the Fraunhofer Institute of Silicate Research, which has developed the hybrid polymer ORMOCERs (ORganically Modified CERamics) (Fraunhofer Institute for Silicate Research ISC web https://www.isc.fraunhofer.de/en/fields-of-activity/materials/ormocer.html), offering UV-curable hybrid polymers for microoptical components including OrmoComp, InkOrmo, OrmoCore, OrmoClad and OrmoStamp. Recently, new hybrid polymers for the photonics applications OrmoClear and OrmoClear®FX have been developed as well (UV-Curable Hybrid Polymers for Micro Optical Component; https://www.microresist.de/en/?jet_download=9684).

Recently, many technological procedures and processes for the production of the structures for MOEMS and integrated optics applications have been presented, including, among others, the mask photolithographic technology or laser direct writing technology and subsequently the wet etching process (Elmogi et al. 2016; Prajzler et al. 2019b), photo-resist patterning combined with reactive ion etching (Kagami et al. 2001), electron beam writing (Wong et al. 2001), hot embossing process (Choi 2004), flexographic and inkjet printing (Wolfer et al. 2014), and Roll-to-Roll (R2R) (Shneidman et al. 2018) and Roll-to-Plate (R2P) nanoimprint lithography processes (Prajzler et al. 2021). Nevertheless, there is still a demand to find and develop new perspective approaches. One of them is presented in this paper.

This paper deals with the fabrication process of multimode optical channel waveguides with dimensions of 50×50 μm^2 (width $\times$ height) with the hybrid polymer core and UV acrylate polymer cladding layer made by the doctor blade method. The dimensions of the waveguide cores have been chosen to be suitable for MOEMS applications and also for the multimode fibre optics communications standards OM2 using wavelengths of 850 nm and 1300 nm.

2 Optical polymer channel waveguides

A schematic picture of the multimode optical channel waveguides of 50×50 μm^2 (width $\times$ height) with a pitch of 250 μm is shown in Fig. 1. The optical channels consist of the substrate (n_s—refractive index of the substrate), the
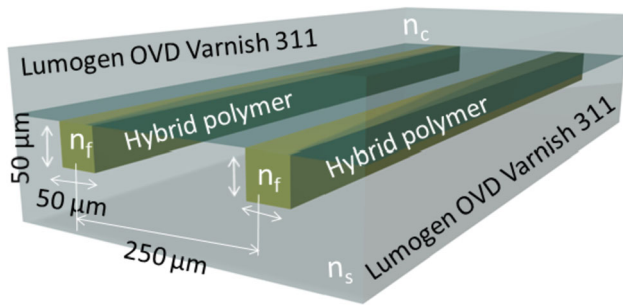
Fig. 1 A scheme of the multimode optical channel waveguides with UV-curable inorganic–organic hybrid polymer core layer and UV acrylate polymer cladding layer (n_f—refractive index of the core, n_s—refractive index of the substrate, n_c—refractive index of the cover layer)

core of the waveguide (n_f—refractive index of the core) and the upper cladding (n_c—refractive index of the cover layer).

For the cladding layer, the UV photopolymer Lumogen OVD Varnish 311 (BASF) was used, whereas the core layer consists of two types of UV-curable inorganic–organic hybrid polymers, namely OrmoCore and OrmoClear®FX (both—micro resist technology GmbH, Berlin, Germany). The tabular values of the refractive indices provided by the supplier for OrmoCore and OrmoClear®FX as well as the published data for Lumogen OVD Varnish 311 are given in Table 1.

3 The fabrication procedure and measurement methods

3.1 The fabrication procedure

The fabrication process for the multimode optical channel waveguides is shown step by step in Fig. 2. For the cladding layer, we used the UV photopolymer Lumogen OVD Varnish 311 supported by BASF (density of 1.1 g/mL

(22 °C), viscosity of 75–120 mPa·s measured by Brookfield (12 rpm), the refractive index measured by ellipsometry using He–Ne laser $n = 1.507@623.8$ nm) (Technical Data Sheet 2019) and UV-curable inorganic–organic hybrid polymer OrmoCore (density of 1.18 g/cm^3, viscosity (25 °C—solvent free) of 3.1–3.9 Pa·s) (Processing Guidelines OrmoCore) and OrmoClear®FX (viscosity (25 °C—solvent-free) of 1.5 ± 0.3 Pa·s) (Processing Guidelines OrmoClear®FX) from the micro resist technology GmbH, Berlin, Germany.

The fabrication process was as follows: polydimethylsiloxane (PDMS) elastomeric stamps were made using a nickel negative mould. The mould, which was 8 cm long and had twelve channels with dimensions of 50×50 μm^2 with a 250 μm pitch between the channels (Fig. 2a), was made by an electroforming process.

The negative nickel mould was made in three steps, a simplified description of which is given below:

1. A thin silver layer with a thickness of 150 nm was deposited on a glass plate. Subsequently, it was coated with a 2 μm thick layer of the positive photoresist Microposit S 1800 using a spin coater. The layer was then soft-baked on a hot plate at 102 °C for 4 min. For optical waveguide mastering, the photosensitive layer was exposed using the laser-beam lithography HoloWriter in the vector mode, after which the photoresist layer was developed using the diluted developer Microposit 303A. In the exposed places, the resist was removed completely to the remaining silver film, which was then etched out by chrome-sulfuric acid. After that, the rest of the resist is then removed by immersion into a sodium hydroxide solution. In this way, a photolithographic mask was prepared on a glass plate.

2. The intended channels were then made in this way: a 50 μm thick layer of the photonegative photoresist SU-8 was deposited directly on the silver mask using a spin coater, and the coated layer was baked on a hot plate at 95 °C for 40 min. Subsequently, the mask with the

Table 1 The values of the refractive indices for the hybrid polymers OrmoCore, OrmoClear®FX and Lumogen OVD Varnish 311

Name of the hybrid polymer	State of the material	Refractive index (−)	References
OrmoCore	Liquid material (uncured)	1.538 @ 589 nm	Processing Guidelines - OrmoCore
	Solid polymer (cured)	1.552–1.553 @ 635 nm	
		1.545–1.546 @ 810 nm	
OrmoClear®FX	Liquid material (uncured)	1.535 ± 0.002 @ 589 nm	Processing Guidelines - OrmoClear®FX
	Solid polymer (cured)	1.555 ± 0.003 @ 589 nm	
Lumogen OVD Varnish 311	Solid polymer (cured)	1.5132 ± 0.0005 @ 654.2 nm	Prajzler et al. (2021)
		1.5069 ± 0.0005 @ 846.4 nm	

Fig. 2 The fabrication procedure for the OrmoCore and OrmoClear®FX hybrid polymer optical channel waveguides: **a** the fabrication of the negative nickel matrix, **b** the fabrication of the PDMS stamp, **c** the fabrication of the Lumogen OVD Varnish 311 substrate, **d** the PDMS stamp imprinted into the Varnish 311 UV photopolymer substrate, **e** the deposition of the OrmoCore or OrmoClear®FX core layer using the doctor blade technique, **f** the fabrication of the Varnish 311 UV cover cladding layer by the doctor blade technique, **g** the separation of the waveguiding structure from the glass substrate, **h** channel waveguide edge polishing
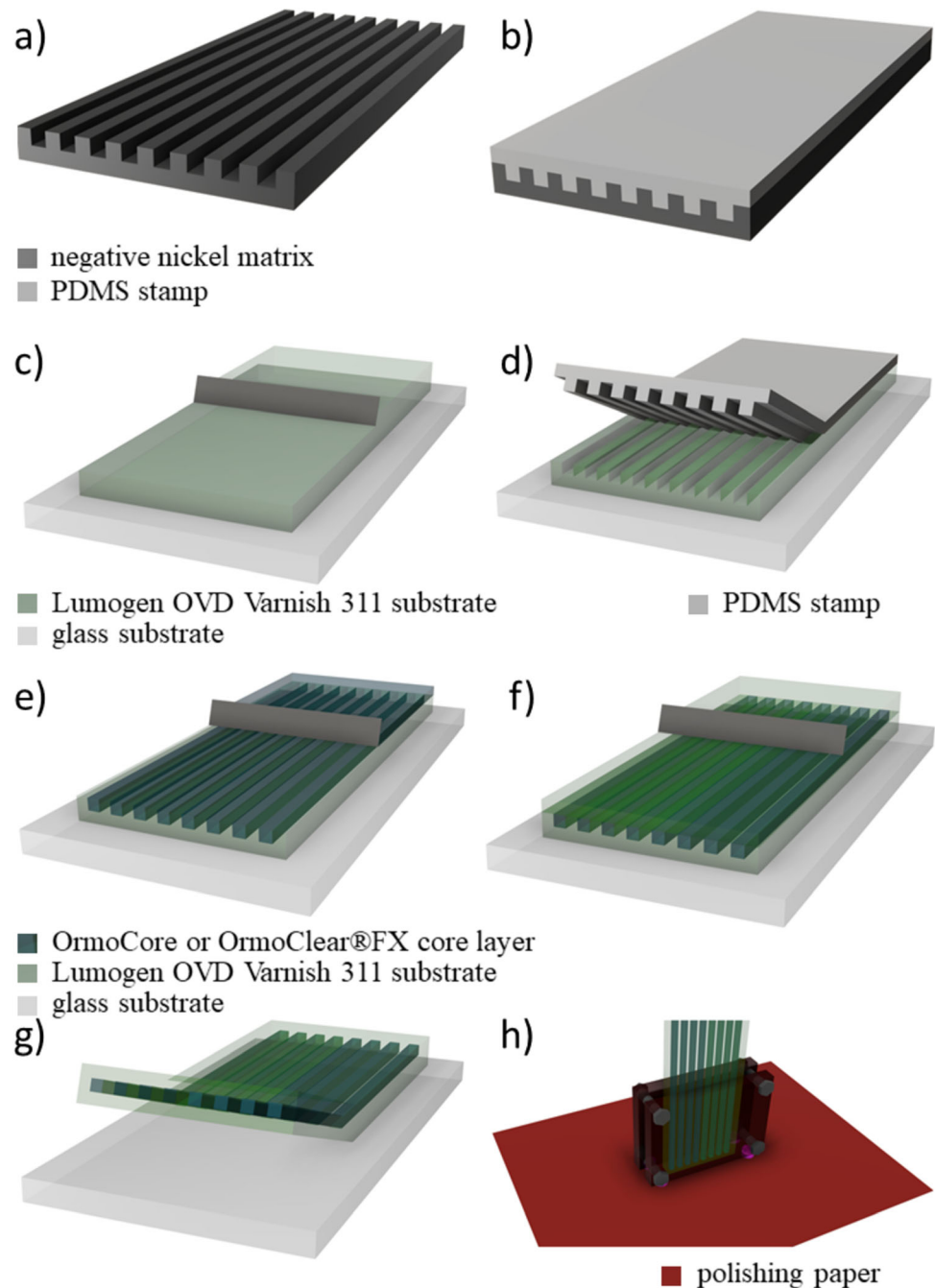
photoresist was exposed to UV light from the glass side followed by soft-baking at 95 °C for 30 min to network the exposed places. The non-exposed places were then removed using the Dev 500 developer. This produced the 3D master of the channels, which was further copied.

3. The process continued with making the final nickel mould by means of the nickel electroforming process. The plate with channels was silvered to obtain a thin conductive layer. The silvered plate was contacted with a special frame and inserted into the nickel-sulphate electroforming bath. When the current source was switched on, nickel ions were reduced on the surface of the plate with channels. After some time (depending on the current density), an approximately 200 μm thick nickel layer was deposited on the plate. The frame with the plate was removed from the bath and the nickel copy was separated from the master. Copies of the nickel copy were produced in a similar way. The third copy was again a negative copy of the SU-8 master and it was used as a mould for PDMS casting.

The PDMS stamps were made from the two-part SYL-GARD 184 silicone elastomer (Dow Corning). The A and B agents were mixed in the ratio of 10:1, after which the mixture was evacuated in a desiccator for 60 min. Subsequently, the elastomer was poured into a nickel mould (Fig. 2b) and the hardening process was carried out in an oven at 125 °C for 20 min. After cooling, the PDMS stamp was carefully separated from the nickel mould and treated with the SP-3 separator (ELCHEMCo). The liquid separator was dropped onto the nickel mould and spread using a spatula.

The Lumogen OVD Varnish 311 polymer with a thickness of 500 μm was deposited onto the glass substrate using the doctor blade technique (Fig. 2c). This technology has already been described in detail for example in Dangel et al. (2013); Prajzler et al. 2019c), and it is based on spreading the polymer with a defined thickness using a blade (spatula). Afterward, the PDMS stamp was imprinted into the Varnish 311 UV photopolymer (Fig. 2d) and the polymer was hardened by UV curing. Next, the cured Varnish polymer was separated from the PDMS stamp. The Varnish polymer was then used as the lower cladding layer and, after separation from the PDMS stamp, it was filled with the core layer using the doctor blade technique (Fig. 2e) followed by the hardening of the core layer, done again by using the UV-curing process.

For the core layers, two types of hybrid polymer were used, namely OrmoClear®FX and OrmoCore. Furthermore, a Varnish 311 UV photopolymer cover layer was deposited by the doctor blade technique (Fig. 2f), and the subsequent hardening was done again by the UV-curing process. Finally, the waveguide structure was separated from the glass substrate (Fig. 2g), and the edges of the waveguides were cut and polished (Fig. 2h). The polishing process consisted of three stages, using polished (lapping) sheets with a grain size of 3 μm, 1 μm, 0.2 μm and we used a polished process commonly used for the 1 mm PMMA (acrylic) Plastic Optical Fibre (POF).

We started with the preparation of bulk free-standing samples to confirm suitable optical properties for the next fabrication of optical channel waveguides. The refractive index of the waveguide core must be higher than that of the waveguide cladding. What is also important is the contrast between both indices, the higher it is the smaller could be geometrical dimensions of such a single-mode optical waveguide. The most important are low optical losses at the operating wavelengths (530 nm, 650 nm, 850 nm, 980 nm, 1300 nm and 1550 nm, etc.).

Photographs of such OrmoCore, OrmoClear®FX and Lumogen OVD Varnish 311 UV thick free-standing polymer samples are shown in Fig. 3, where Fig. 3a depicts the OrmoCore sample, Fig. 3b OrmoClear®FX and Fig. 3c Lumogen OVD Varnish 311 UV. The samples were made by casting between two PMMA sheets treated with an SP3 separator and the spacers placed around the edges of the lacquered plate. A suitable amount of liquid polymer was poured into the center of the plate using a dropper and the cover PMMA sheet plexiglass plate was then carefully put over it. Next, UV-light curing was applied and finally, the PMMA cover was removed and the polymer layer was peeled away from the PMMA substrate. The samples shown in Fig. 3 were used to measure the thicknesses, the transmission spectra and also refractive indices.

4 Measurement

The bulk sample thicknesses were measured using the dial thickness gauge LIMIT12.5/0.001 and the transmission spectra were measured by the UV–VIS-NIR spectrometer (UV-3600 Shimadzu, Shimadzu Deutschland GmbH, Duisburg, Germany) at the spectral range of 250–2200 nm.

The absorption coefficients α are described by the following equation (Prajzler et al. 2020):

$$\alpha(\lambda) = -\ln\left(\frac{T(\lambda)}{100}\right) \cdot \frac{1}{t}, \tag{1}$$

where T is the transmission spectrum, t is the sample thickness and λ is the wavelength. This equation was used to determine the absorption spectra from the measured transmission spectra.

The refractive indices of the samples were measured by the prism-coupling technique using the Metricon 2010/M system. Transverse-electric (TE) polarisation was measured at six wavelengths, namely 532.0 nm, 654.2 nm, 846.4 nm, 1308.2 nm, 1549.1 nm and 1652.1 nm, and using the prism #200-P-4a with the refractive index n = 2.1558 (λ = 632.8 nm) for the coupling. The applied prism enabled the measurement in the effective refractive index range of 1.2–2.02 at the wavelength of λ = 632.8 nm. The principle of that method is shown in Fig. 4 and has been already published in Prajzler et al. (2020); the accuracy of the determination of refractive indices has been proved to be $\pm$ 0.0005.

The refractive index of the measured sample is determined from the critical angle of incidence θ_c and from the refractive index value of the coupling prism n_p. The measured sample with the refractive index n is in contact with the coupling prism of the refractive index n_p. Since the sample and coupling prism rotate with respect to the stationary laser beam, the light striking the base of the prism is totally reflected to the system photodetector until the angle of incidence becomes less than the critical angle, θ_c, for which the following equation is valid (Prajzler et al. 2020):
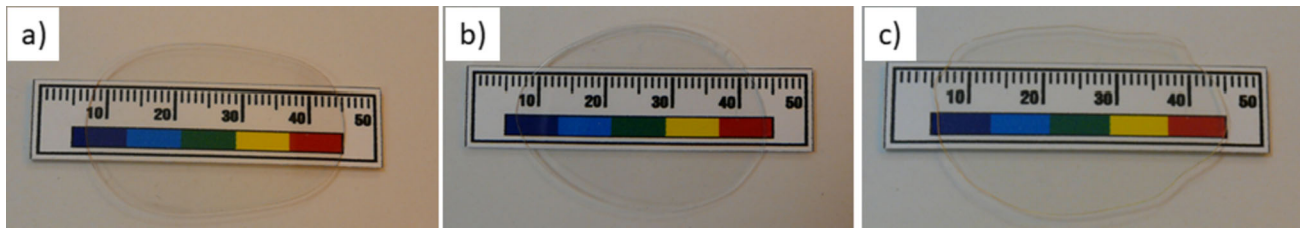
Fig. 3 The photographs of the free-standing polymers used for the fabrication of optical channel waveguides: **a** OrmoCore, **b** OrmoClear®FX and **c** Lumogen OVD Varnish 311

Fig. 4 The principle of the measurement of the bulk material (Prajzler et al. 2020): **a** a schematic view of the Metricon Model 2010/M Prism Coupler, **b** the determination of the critical angle of incidence used for refractive index calculation
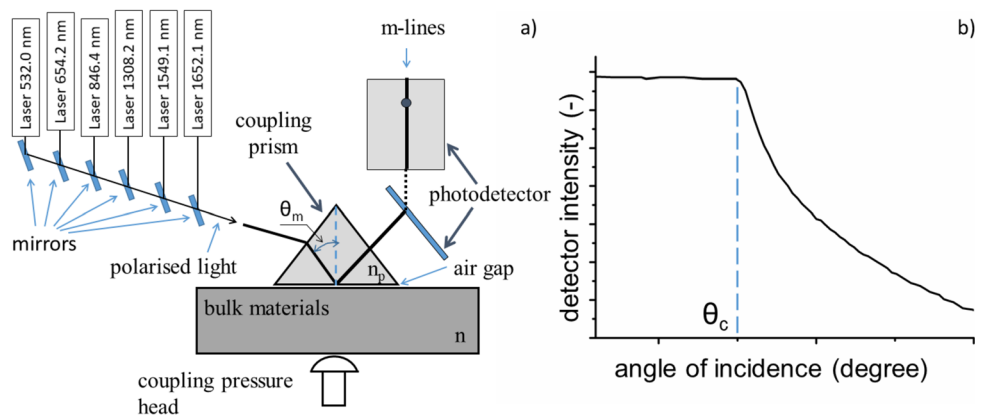
$$\theta c = arcsin\left(\frac{n}{n_p}\right). \qquad (2)$$

As mentioned above, the refractive indices were measured at only six wavelengths, after which the values of the refractive indices for the other wavelengths were estimated by the Sellmeier approximation with an infrared correction (Prajzler et al. 2020):

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C} - D\lambda^2, \qquad (3)$$

where n is the refractive index, λ is the wavelength, and A, B, C and D are experimentally determined Sellmeier coefficients. The reason for using this approximation was that our research had already proved that this method was the most suitable for our setup (Prajzler et al. 2020).

The geometrical dimensions and quality of the fabricated multimode optical channel waveguides were examined using an ARTCAM optical digital camera equipped with optical head ZOOM Optics (Olympus Czech Group Ltd., Prague, Czech Republic) by the QuickPHOTO software (Version 3.0, PROMICRA, Prague, Czech Republic).

The optical losses of the channel waveguides were measured using the cut-back method at four wavelengths: 650 nm (laser Safibra OFLS-5-FP-650), 850 nm (laser Safibra OFLS-6-LD-850), 1310 nm (laser Safibra OFLS-6CH, SLED-1310) and 1550 nm (laser Safibra OFLS-5-DFB-1550). The optical power was measured by a Thorlabs PM200 optical power meter, with the compact silicon

photodiode power sensor Thorlabs S151C being used for the measurement at the wavelengths of 650 nm and 850 nm and the Indium gallium arsenide photodiode power sensor Thorlabs S155C being used to measure the wavelengths at 1310 nm and 1550 nm. The measurement was done on the optical bench utilising precision 3-axis stages with a multi-mode optical fibre with a 50 µm diameter core, used for input light coupling and an optical fibre with a core diameter of 62.5 µm, used for the coupling from channel waveguides into the photodiode power sensor (the method has been already described in more detail in Prajzler et al. (2018)).

5 Results and discussion

The transmission spectra obtained are shown in Fig. 5a and the absorption spectra calculated from the transmission spectra are shown in Fig. 5b. The required thicknesses of the samples (0.323 mm for OrmoCore, 0.313 mm for OrmoClear®FX and 0.270 mm for the Lumogen OVD Varnish 311) were acquired using the dial thickness gauge measurement of the samples illustrated in Fig. 3. In the transmission spectra in Fig. 5a, there is seen a lower transmission of the hybrid polymers OrmoCore and OrmoClear®FX at 379 nm, 1185 nm, 1684 nm, 2152 nm and 2179 nm. The UV photopolymer Lumogen OVD Varnish 311 had lower transmission at 1183 nm, 1430 nm,
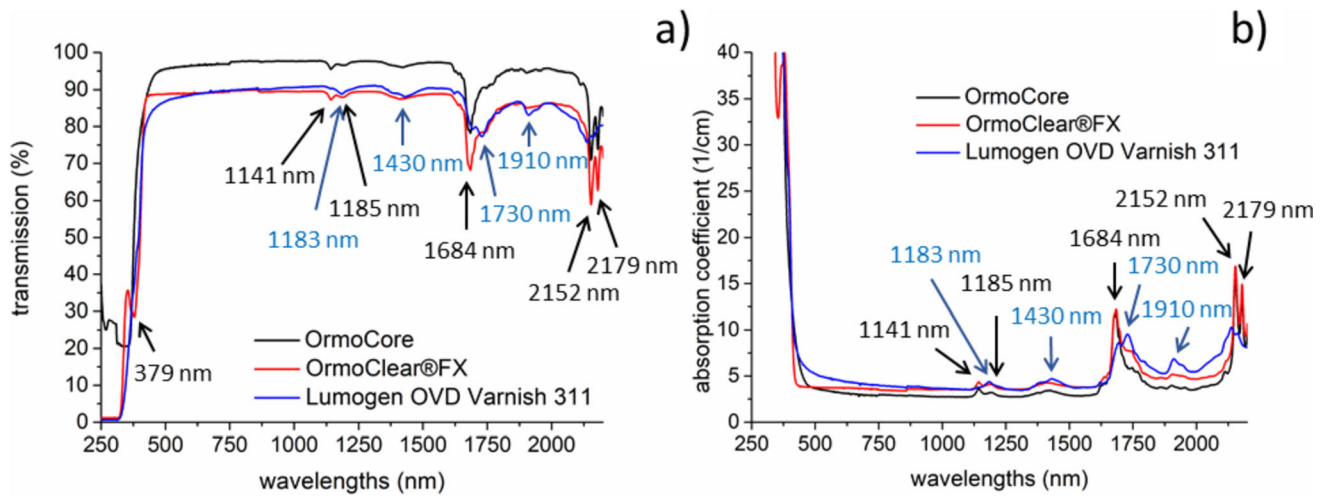
Fig. 5 a The transmission spectra of the materials used inorganic–organic hybrid core polymers (OrmoClear®FX and OrmoCore) and the UV photopolymer (Lumogen OVD Varnish 311), **b** the absorption coefficient (α) properties of the inorganic–organic hybrid core polymers (OrmoClear.®FX and OrmoCore) and the cladding polymer (the UV photopolymer Lumogen OVD Varnish 311)

1730 nm and 1910 nm, all of which are clearly made evident in the absorption spectra in Fig. 5b.

The absorption spectra of the inorganic–organic hybrid polymers reveal that both polymers OrmoCore and OrmoClear®FX have low absorption not only in the visible spectrum but also in the near-infrared spectrum including the wavelengths of 850 nm and 1300 nm. The low absorption at these wavelengths is especially important for the fabrication of optical waveguides because such wavelengths are used in optical multimode optics communication systems. Therefore, the absorption spectra shown in Fig. 5b have proved that the hybrid polymers examined have suitable properties for the core layer of the optical waveguides.

The refractive indices of the samples were measured by the prism-coupling technique using the Metricon 2010/M system and the results are shown in Fig. 6. Based on them, the inorganic–organic hybrid polymer OrmoClear®FX had higher values of the refractive indices than the OrmoCore polymer (the refractive-index differences Δ were $\Delta532.0$ nm $= -0.0002$, $\Delta654.2$ nm $= 0.0009$, $\Delta846.4$ nm $= 0.0012$, $\Delta1308.2$ nm $= 0.0018$, $\Delta1549.1$ nm $= 0.0023$ and $\Delta1652.1$ nm $= 0.0016$). The measurement has also proved that the UV photopolymer Lumogen OVD Varnish 311 layer had lower values of the refractive indices than both hybrid polymers, which makes this polymer a good candidate for the optical waveguide cladding layer. The obtained values of the refractive index are in good agreement with previously published data (Prajzler et al. 2021), although our values were slightly higher than the data from datasheets. This may be caused by different layer preparation procedures.

As mentioned above, we used the Sellmeier approximation with an infrared correction for the determination of
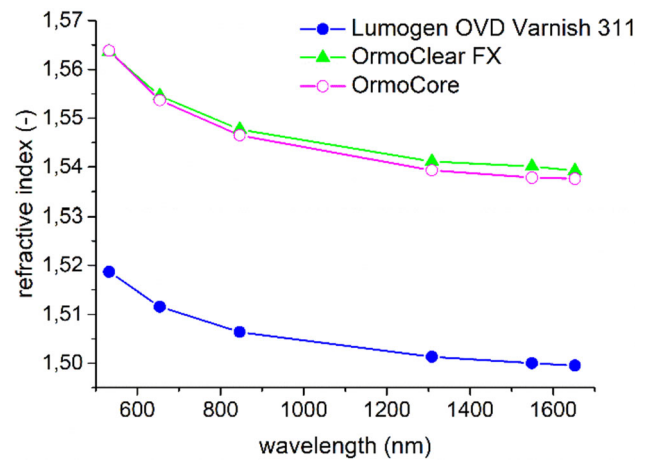

Fig. 6 The values of the refractive indices measured by the prism-coupling technique for the applied materials—inorganic–organic hybrid core polymers (OrmoClear.®FX and OrmoCore) and the UV photopolymer (Lumogen OVD Varnish 311)

the refractive indices for a wider wavelength spectrum. The experimentally determined Sellmeier coefficients A, B, C and D are summarised in Table 2.

The simplest optical waveguide structure is a planar waveguide composed of a core layer deposited on the substrate and cover layer. The light is guided inside the core planar layer by the total internal reflection enabled by the higher value of the refractive index than the value of the refractive index of the substrate and the cover layer. For practical MOEMS applications and integrated optics applications, it is very important to determine whether the pertinent waveguide is a multi- or single-mode operation. Therefore, it is inevitable to determine the critical thickness h_f. of the waveguide.

Table 2 The determined Sellmeier coefficients (A, B, C and D) with an infrared correction for OrmoClear®FX, OrmoCore and the UV photopolymer Lumogen OVD Varnish 311

Polymer	Sellmeier coefficients with an infrared correction			
	A	B	C (μm^2)	D (μm^{-2})
OrmoCore	−0.030921	2.3883	0.010077	0.00093967
OrmoClear®FX	−5.4867	7.8505	0.0028979	0.00095567
Lumogen OVD Varnish 311	1.7546	0.4948	0.029554	0.0023268

In the waveguiding layers, a standing wave is formed based on the principle of transverse resonance, from which it is possible to derive the dispersion and, after this equation is solved, we can determine the thickness h_f for single-mode operation optical planar waveguides for TE (Eq. (4)) and TM modes (Eq. (5)) (Prajzler et al. 2019a):

$$h_f(TE) = \lambda_O \cdot \frac{k + \frac{1}{\pi} \cdot arctan(\sqrt{\frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}})}{2 \cdot \sqrt{n_f^2 - n_s^2}}, \qquad (4)$$

$$h_f(TM) = \lambda_O \cdot \frac{k + \frac{1}{\pi} \cdot arctan(\frac{n_f^2}{n_s^2} \sqrt{\frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}})}{2 \cdot \sqrt{n_f^2 - n_s^2}}, \qquad (5)$$

where λ_O is the vacuum wavelength, h_f is the thickness of the planar waveguide, n_f is the refractive index of the core layer (in our case the hybrid polymer OrmoClear®FX or OrmoCore), n_s is the refractive index of the substrate (in our case Lumogen OVD Varnish 311), n_c is the refractive index of the cover layer (in our case Lumogen OVD Varnish 311), and k is an integer number $k = 0, 1, 2$ ….

We have calculated the critical thickness for the TE and TM modes at the wavelengths of 650 nm and 1310 nm. These two wavelengths are important as they are used in the visible spectrum as the red light in sensors (650 nm) and in optical communication systems for the single-mode waveguides (1310 nm).

For the calculation, we have used the refractive indices of the polymer Lumogen OVD Varnish 311, OrmoCore and OrmoClear®FX measured by the prism-coupling technique presented in Fig. 6. The refractive-index values used for the calculation are shown in Table 3.

The results of the mode calculations performed for OrmoCore and OrmoClear®FX waveguides for the wavelengths of 650 nm and 1310 nm are shown in Fig. 7. and present the spreading of the light in the OrmoClear®FX polymer. Figure 7a and b show the results for

the wavelengths 650 nm and 1310 nm, resp. and Fig. 7c and d then concern the spreading of the light in the waveguide having the core made of OrmoCore polymer. The values of the refractive indices for the OrmoCore and OrmoClear®FX hybrid polymers are very similar and also both types of waveguides use the same cladding layers (Lumogen OVD Varnish 311). Therefore, the critical thickness for both types of waveguides is not significantly different.

Based on the calculations at the wavelength of 650 nm, the minimum thickness for supporting TE_1 modes was 0.895 μm for the OrmoClear®FX polymer and 0.906 μm for the OrmoCore polymer. At the wavelength of 1310 nm, the minimum thickness for supporting TE_1 modes was 1.902 μm for the OrmoClear®FX polymer and 1.927 μm for OrmoCore. From the calculation performed, it may be concluded that for the implementation of the waveguides from OrmoCore and OrmoClear®FX (as the core) and for Lumogen OVD Varnish 311 (as the cladding), which would support only the TE_0 and TM_0 modes, the actual channel waveguides for OrmoClear®FX (core) must be smaller than 0.895 nm for the wavelength of 650 nm and smaller than 1.902 μm for 1310 nm.

Photographs of the fabricated optical channel waveguides before cutting for the measurement of waveguiding properties are shown in Fig. 8, where Fig. 8a shows the sample with the OrmoClear®FX core layer and Fig. 8b shows the sample with the OrmoCore core layer. Figure 8c then demonstrates the flexibility of the waveguides, which allows for the bending of the samples.

The obtained microscopic pictures of the OrmoClear®FX multimode optical channel waveguides are shown in Fig. 9a, b, where Fig. 9a shows a cross-sectional view of the channel waveguides and Fig. 9b shows a detail of one channel waveguide. The OrmoCore multimode optical channel waveguides are depicted in Fig. 9c, d, which show that the channels have the dimensions of approximately 50×50 μm² (height × width) with the

Table 3 The values of the refractive indices used for the calculation of the critical thicknesses of the OrmoCore and OrmoClar®FX optical planar waveguides

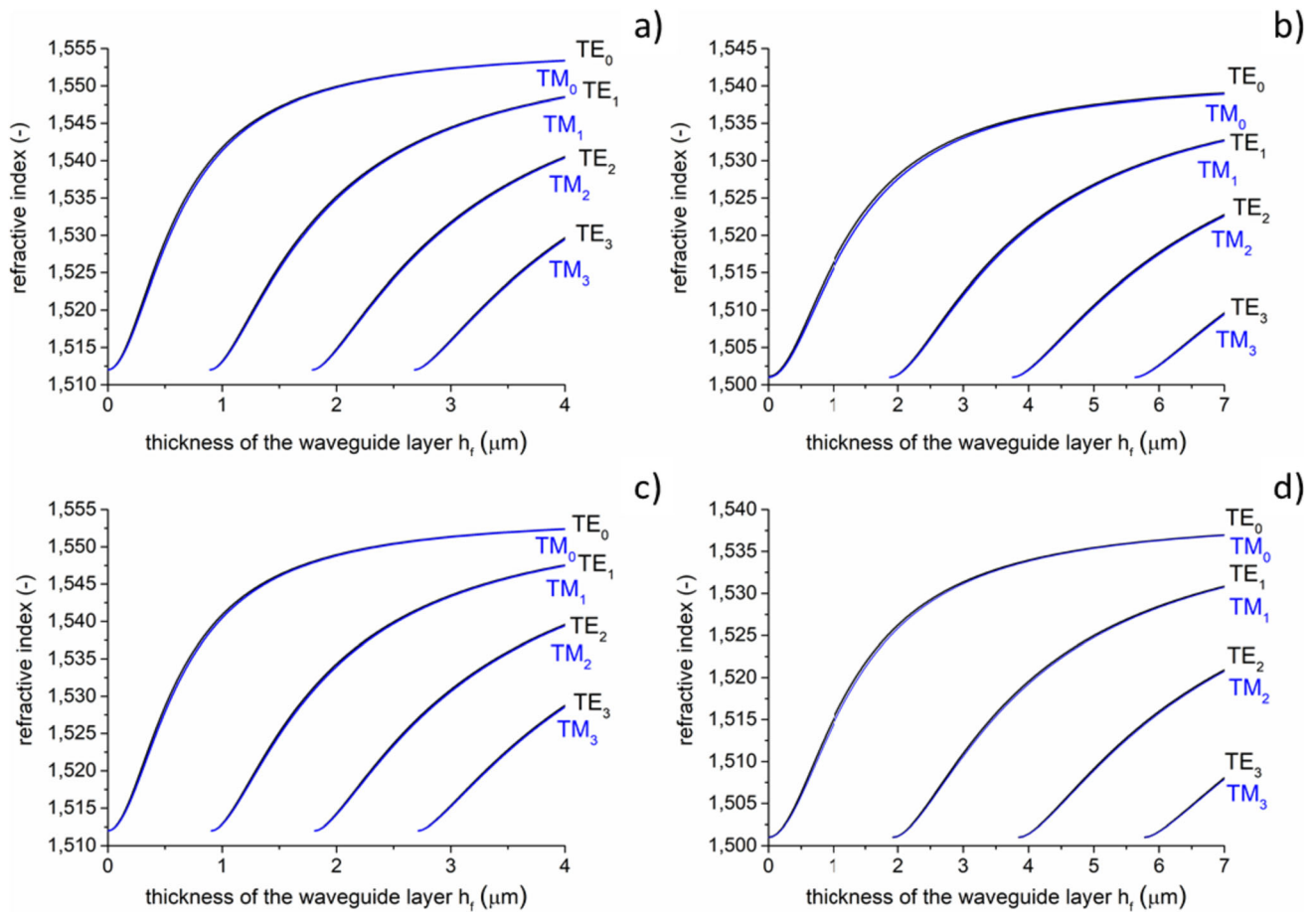| Wavelength (nm)	Refractive index (−)		
	Lumogen OVD Varnish 311	OrmoCore	OrmoClear®FX
650	1.512	1.554	1.555
1310	1.501	1.539	1.540

Fig. 7 The calculation of the modes (TE and TM) of the hybrid polymers: **a** OrmoClear®FX at 650 nm, **b** OrmoClear®FX at 1310 nm, **c** OrmoCore at 650 nm, and **d** OrmoCore at 1310 nm

Fig. 8 A photographic top view of the channel waveguides before the samples were shortened for optical loss measurements: **a** the optical waveguides with the OrmoClear®FX core layer, **b** the optical waveguides with the OrmoCore core layer, **c** the demonstration of the flexibility of the optical channel waveguides
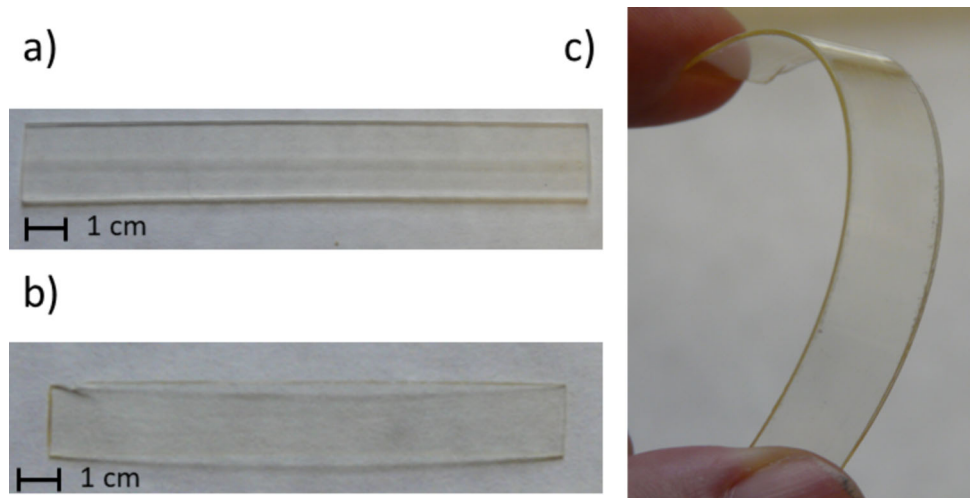
channel pitch of 250 μm with the required accuracy dimensions of ± 5 μm.

The optical losses of the waveguides measured by the cut-back method showed the losses of the OrmoClear®FX channel waveguides below 0.74 dB/cm at the wavelengths of 650 nm, 850 nm and 1310 nm and below 1.26 dB/cm at 1550 nm. The average values were 0.32 dB/cm (650 nm), 0.37 dB/cm (850 nm), 0.58 dB/cm (1310 nm) and 1.13 dB/cm (1550 nm). The lowest values of the optical

Fig. 9 A microscopic picture of the OrmoClear®FX multimode optical channel waveguides: **a** a cross-sectional view of the optical channel waveguide structure, **b** a detailed view of a cross-section of a single optical channel waveguide. A microscopic picture of the OrmoCore multimode optical channel waveguides, **c** a cross-sectional view of the optical channel waveguides, **d** a detailed view of a cross-section of a single optical channel waveguide
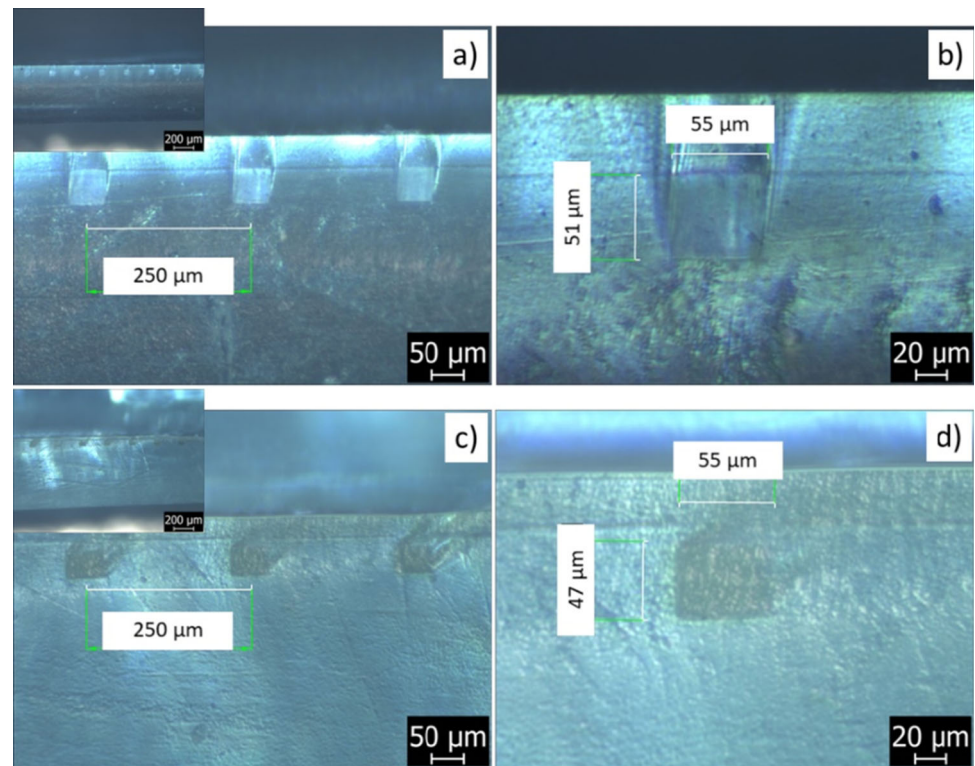
losses were 0.22 dB/cm at 650 nm, 0.30 dB/cm at 850 nm and 0.47 dB/cm at 1310 nm.

The optical losses of the OrmoCore channel waveguides were lower than 0.71 dB/cm at the wavelengths of 650, 850, 1310 nm and 1.31 dB/cm at 1550 nm. The average values were 0.40 dB/cm (650 nm), 0.36 dB/cm (850 nm), 0.59 dB/cm (1310 nm) and 1.15 dB/cm (1550 nm). In this case, the lowest values of the optical losses were 0.32 dB/cm at 650 nm, 0.26 dB/cm at 850 nm and 0.48 dB/cm at 1310 nm. The results are summarised in Table 4.

The values obtained have proved that the optical losses of the OrmoClear®FX and OrmoCore polymers are not significantly different. Both materials seem to be

suitable for the fabrication of the optical channel waveguides transmitting the red light (650 nm), also at the wavelengths used for the standard OM2 multimode optical waveguides operating at 850 nm and 1300 nm. Since the optical losses for both polymers at the wavelength of 1550 nm are higher than 1 dB/cm, it seems that these polymers are not suitable for such a wavelength.

We have also compared our results with the waveguides demonstrated in our former works in which we presented the properties of the optical polymer planar waveguides with three types of hybrid polymers, namely OrmoClear, OrmoClear®HI01 XP and OrmoClear®FX, deposited on a glass substrate (Prajzler et al. 2019a). We have measured

Table 4 The optical losses of the OrmoClear®FX and OrmoCore multimode optical channel waveguides

Wavelengths (nm)	OrmoClear®FX				OrmoCore			
	Optical losses (dB/cm)				Optical losses (dB/cm)			
	650	850	1310	1550	650	850	1310	1550
Channel 1	0.22	0.30	0.47	1.09	0.34	0.45	0.62	1.16
Channel 2	0.34	0.38	0.57	1.16	0.47	0.27	0.48	1.00
Channel 3	0.28	0.30	0.48	1.07	0.46	0.38	0.62	1.13
Channel 4	0.34	0.33	0.61	1.03	0.32	0.34	0.56	1.13
Channel 5	0.34	0.45	0.74	1.26	0.34	0.26	0.50	1.13
Channel 6	0.33	0.37	0.57	1.16	0.47	0.52	0.71	1.30
Channel 7	0.38	0.44	0.62	1.10	0.36	0.28	0.54	1.05
Channel 8	0.36	0.38	0.57	1.16	0.46	0.41	0.65	1.31
Average value	0.32	0.37	0.58	1.13	0.40	0.36	0.59	1.15

optical losses by the fibre scanning method. The results have shown optical losses lower than 0.76 dB/cm for all the measured wavelengths (632.8, 964, 1311 and 1552 nm). The lowest value (0.41 dB/cm at 632.8 nm) of the optical losses has been found with the planar waveguide made of OrmoClear®FX. The lowest optical loss value measured at the telecommunication wavelength of 1310 nm has been found in the case of the OrmoClear polymer (0.44 dB/cm) (Prajzler et al. 2019a).

We have also already made multimode optical channel waveguides by the Roll-to-Plate method using the Ormo-Clear®FX hybrid polymer core layer and UV photopolymer Lumogen OVD Varnish 311 (Prajzler et al. 2021). In that case, the average values of optical losses were 0.43 dB/cm at 850 nm, 0.56 dB/cm at 1310 nm and 0.54 dB/cm at 650 nm, respectively. In this paper, we have thus demonstrated that it is in principle possible to fabricate low-loss multimode optical channel waveguides without the need to use the R2P technology.

The properties of the ORMOCER polymer and its possible applications have also been presented by the ORMOCER producer of the micro resist technology (Gruetzner et al. 2014; Schleunitz et al. 2015). Other results on the ORMOCER-based 7.1 cm long channel waveguides with a cross-section of 6×6 μm^2 have been presented by Buestrich et al. (Buestrich et al. 2001), who reported on the optical losses of 0.3 dB/cm at 1320 nm and 0.6 dB/cm at 1550 nm (strip waveguide), which means excellent values for most board-size applications in telecommunications. The properties of the ORMOCER-based optical waveguides with cross-sections of 5×5 μm^2 have also been reported by Houbertz (Houbertz et al. 2003), who determined the optical losses at telecom wavelengths as 0.2 dB/cm at 1310 nm and as 0.5–0.6 dB/cm at 1550 nm.

SUNCONNECT (Nissan Chemical Ind.) organic–inorganic hybrid optical waveguides have been reported by Ishigure et al. (2015). The presented waveguides were 5 cm long with a circular shape and a diameter core of approximately 50 μm. The propagation losses were measured using the cut-back method – they were 0.25 dB/cm at 1310 and 0.56 dB/cm at 1550 nm. The authors also published the properties of the single-mode waveguides with a core diameter of 8 to 10 μm (which is enough to satisfy the single-mode condition at 1550 nm) and optical losses of 0.5 dB/cm at 1550 nm (Ishigure et al. 2015).

The above-mentioned papers have stated that the use of hybrid polymers makes it possible to fabricate optical channel waveguides with low optical losses at 1310 nm and 1550 nm (Buestrich et al. 2001; Houbertz et al. 2003; Ishigure et al. 2015). Here we have shown that the OrmoClear®FX and OrmoCore hybrid waveguides are also suitable for low-loss multimode waveguides with the core dimensions of 50×50 μm, which are compatible with the OM2 standard. A MOEMS structure fabricated from the epoxy-based polymers EpoCore/EpoClad and Su8 has already been reported earlier (Guan et al. 2013b). We have proved that the optical channel waveguides fabricated from hybrid polymers have low optical losses not only in the infrared spectrum including 1310 nm but also in the visible spectrum, which is a new and useful finding for MOEMS and integrated optics applications.

6 Conclusion

The paper presents the properties of the free-standing multimode optical polymer channel waveguides with two types of cores made of the layers of the inorganic–organic hybrid polymers OrmoClear®FX and OrmoCore. The absorption spectra of both polymers showed low absorption not only in the visible spectrum but also in the near-infrared spectrum including the wavelengths 850 nm and 1300 nm.

The refractive indices were measured by the prism-coupling method and the Sellmeier approximation with an infrared correction was then used for the determination of the refractive indices at other wavelengths in the spectral range of 530–1700 nm. The results showed that the inorganic–organic hybrid polymer OrmoClear®FX had higher values of the refractive indices than the polymer OrmoCore.

The optical channel waveguides prepared had dimensions of 50×50 μm^2 (width x height) and a pitch of 250 μm. The optical losses of the channels were measured by the cut-back method at four wavelengths (650 nm, 850 nm, 1310 nm and 1550 nm); for the OrmoClear®FX channel waveguides, they were lower than 0.74 dB/cm for the wavelengths of 650 nm, 850 nm and 1310 nm and 1.26 dB/cm at 1550 nm. The optical losses of the Ormo-Core channel waveguides were lower than 0.71 dB/cm for the wavelengths of 650 nm, 850 nm and 1310 nm and 1.31 dB/cm at 1550 nm.

As the optical losses of the channel waveguides made of either the OrmoClear®FX or OrmoCore polymer were similar, it may be concluded that both are suitable for the optical waveguides operating at 650 nm, 850 nm and 1300 nm. The advantage of OrmoClear®FX may be its compatibility with the PDMS moulds, making it possible to use the replication fabrication methods and also achieve a higher degree of integration when using the PDMS substrate.

Our technology process using a hybrid polymer as the core for optical multimode waveguides may find its application for MOEMS systems. It could also be used in integrated optics such as high-speed short reach

interconnection applications in new high-speed on-board optical interconnects used in data centres and in super high-speed computers. The important aspect demonstrated in this paper is that the presented technology does not need any specialised R2P technology. We believe that after optimisation, this technology procedure could be universally used not only for hybrid polymers but also for other types of polymer materials. We are convinced that hybrid polymers have suitable properties for the fabrication of high-quality low-loss single-mode waveguides operating from the visible to the infrared spectrum including the wavelength of 1310 nm, which substantially expands the field of their application.

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