# Properties of Siloxane Based Optical Waveguides Deposited on Transparent Paper and Foil

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**Abstract.** *In this paper, we present the properties of flexible planar optical waveguides made of siloxane-based polymer deposited on Xerox transparent paper and PLEXIGLAS foil substrate. Measurement of optical properties such as the waveguiding properties and refractive index is carried out by the prism coupling technique for five wavelengths (473, 632.8, 964, 1311 and 1552 nm) and propagation optical loss were measured by the fiber probe technique at a wavelength of 632.8 nm (He-Ne laser). The measurement proved waveguiding properties for all measured wavelengths and the losses generally did not exceed 0.40 dB·cm$^{-1}$; the best samples had optical losses around 0.24 dB·cm$^{-1}$.*

## Keywords

Optical planar waveguides, siloxane polymer, flexible foil, prism coupling technique

## 1. Introduction

Next-generation internet switches and high-end computers are expected to process aggregate data rates in the order of Tbit/s. In consequence, the interconnections between the processing units will have to handle data rates in the order up to 40 Gbit/s. It is, however, well known from basic physical laws that at such data rates, electrical interconnections will suffer from high transmission losses and severe signal integrity problems [1], [2]. Demand for continuous increase in transmission speed and data capacity drives innovations in the areas of broadband communications not only for long distance communications but nowadays also in transmission for short reach and extra short reach communications. Although silica optical fibers are used for high-speed data transfer over long distance, existing interconnection technologies for shorter distance used mainly metal copper wiring connection. Rising data-rates and their sensitivity to electromagnetic interference will not soon be sufficient due to the metallic wiring disadvantages. Therefore light as a transmission medium for the future interconnections is highly desirable as it has many advantages such as higher bandwidth, immunity from cross-talk and electromagnetic interference, easy fabrication process, low cost and etc. [3], [4].

Conventional optical links for optical interconnections are mainly realized on the base of semiconductors. Due to easy integration process with other optical and electrical elements, it is convenient to deposit the optical waveguides on silicon substrate [5], [6]. But silicon is not generally suitable for making any flexible and bendy optical interconnections. Therefore, new material-technology combinations for such utilization are highly needed to be searched for, esp. what concerns interconnections between rack-to-rack, board-to-board, multi-chip modules, and etc. For these types of data transfer it is necessary to connect optical circuits realized onto FR-4 glass epoxy substrates. For that purpose multimode optical fibers for optical devices interconnections have been already used, however new opportunities in the form of planar optical polymer waveguides are nowadays very tempting solution as well. Such new optical waveguides could be deposited onto transparent paper or foils and may have unique properties such us high transparency, low optical loss, suitable temperature stability and excellent flexibility/bendability.

Also polymer materials for fabrication of flexible planar optical waveguides appeared to be a good choice for their excellent optical properties such as their high transparency from visible to infra-red wavelengths, well-controlled refractive indices, reasonable temporal and temperature stability, low optical losses, easy fabrication process and low costs [7–13]. Substrates play a key role for photonics devices, therefore integration of optical waveguides and opto-electronic components onto transparent paper and flexible foils introduces a new concept of optical interconnection and flexibility into the on-board optical communications [14], [15]. Also over the past few years the demand for flexible substrates and the applications in which these flexible printed circuit boards are being used has been constantly growing [16].

Due to increasing demand for polymers not only for optical interconnection applications but also for other types of photonics structures, unique optical polymers have been recently developed. Unfortunately, only few materials from a large selection of commercially available optical polymers exhibit all of the required characteristics. The list

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| Polymer type | Manufacturer | *α* | *n* |
|---|---|---|---|
| Cyclic olefin copolymer | Topas Advanced Polymers company | 0.5dB/cm @830 nm 0.7dB/cm @1550 nm | 1.53 |
| Cyclotone™ | DOW Chemical | 0.81dB/cm @1300 nm | 1.552 @633nm 1.537 @1310nm 1.535 @1550nm |
| Deuterated polymethylmethacrylate | NTT | 0.02dB/cm @850 nm 0.07dB/cm @1310 nm | 1.4886 @830 nm |
| EpoCore | micro resist technology GmbH | ~0.2dB/cm @850 nm | 1.580 @850nm |
| Exguide™ | FOWG series from Chemoptics Inc. | <0.1dB/cm @850 nm | 1.547 @830nm |
| GuideLink™ | Optical Crosslinks | ~0.1dB/cm @850 nm 0.35dB/cm @1300 nm | 1.505 @850 nm |
| OE-4140 UV | Dow Corning | 0.04dB/cm @850 nm | 1.52 @850 nm |
| Ormocore | micro resist technology GmbH | 0.1 dB/cm @633 nm 0.23dB/cm @1310 nm 0.6dB/cm @1550 nm | 1.553 @635nm |
| Polyguide™ | DuPont | 0.08dB/cm @800 nm 0.35dB/cm @1300 nm | 1.485-1.51 |
| Truemode™ | Exxelis | 0.04dB/cm @ 850 nm | 1.57 @633nm |
| Ultradel 9120D | Amoco chemicals | 0.34dB/cm @850 nm 0.43dB/cm @1300 nm | 1.547 @850nm 1.535 @1550nm |
| *α* - optical losses, *n* - refractive index | | | |

**Tab. 1.** The list of the polymer materials for optical interconnections and photonics applications.

of polymers suitable for photonics applications is summarized in Tab. 1.

In this paper, the siloxane-based system commercially known as LightLink™ (developed by Rohm and Haas, and now commercial available from micro resist technology GmbH) was used for realization of optical waveguides. This polymer has suitable properties (optical losses ~0.05 dB·cm$^{-1}$ at 850 nm, ~0.3 dB·cm$^{-1}$ at 1310 nm, >1 dB·cm$^{-1}$ at 1510 nm [17]) and its easy fabrication process compatible with technology already used for silicon-based devices makes it technologically feasible and cheaper. Here, for our experiments, we used flexible transparent paper Xerox 3R96525 (Xerox Corporation) and PLEXIGLAS® Film OF058 (Evonik Industries AG) as substrates.

## 2. Siloxane Planar Waveguides

LightLink™ is a material from the silsesquioxanes family [18], [19]. These polymers are hybrid organic/inorganic materials that consist mainly of silicon and oxygen and form a highly crosslinked network and might be a significant promise in the optical interconnection market due to their photoimaging, optical, hydrophobic and thermal stability properties. Silsesquioxane is known for its low moisture absorption and good thermal stability; its structure is illustrated in Fig. 1.

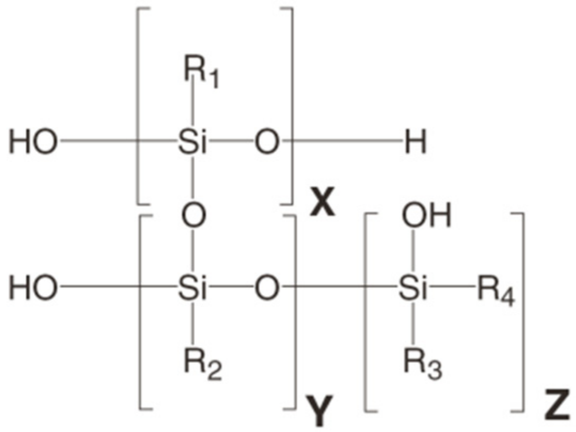

**Fig. 1.** Inorganic/organic polymer backbone of LightLink™ [18].

| Optical properties | |
|---|---|
| | |
| LIGHTLINK™ XH-100145 Clad (Thermal) | 1.480@850 nm* |
| LIGHTLINK™ XP-07423A Clad (Photo-thermal) | 1.480@850 nm* |
| LIGHTLINK™ XP-6701A Core | 1.512@850 nm* 0.05 dB/cm ** 0.30 dB/cm *** |
| Xerox 3R96525 | 1.659@850 nm* |
| PLEXIGLAS® Film OF058 | 1.486@850 nm* |
| * refractive index (-), ** optical losses at 850 nm, *** at 1310 nm | |
| | |
| **Stability** | |
| Sustained performance over 100 thermal cycles between -40°C and +70°C | |

**Tab. 2.** The properties of LightLink™ polymer [17].

The formula lends itself to numerous configurations where R1, R2, R3 and R4 can be a combination of aliphatic and/or aromatic groups [18]. Depending upon the functional groups attached to the polymer backbone, various performance factors can be designed into the material, including dissolution rate, mechanical properties and optical loss. The siloxane nature of the LightLink™ waveguide system minimizes the intrinsic optical loss for 850 nm applications. The main properties of LightLink™ are shown in Tab. 2.

In our case planar optical waveguide is a step-index structure and consists of a high-index dielectric layer created from LIGHTLINK™ XP-6701A Core polymer (65% solids weight in PGMEA) and is surrounded on the bottom side with lower index materials LIGHTLINK™ XH-100145 Clad deposited onto two different types of substrate. We used Xerox transparent paper (see Fig. 2a) or PLEXIGLAS® Film OF058 substrate. Due to low value of refractive index of OF058 substrate it is not necessary to apply cladding layer (see Fig. 2b). Upper side environment is air in both cases (see Fig. 2).

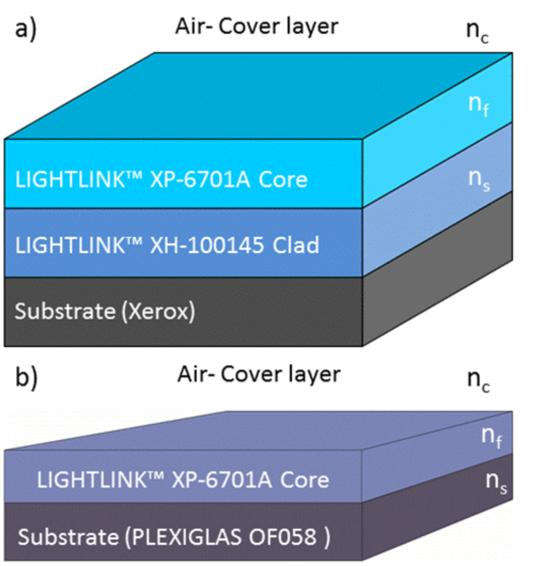


**Fig. 2.** Schema of an LIGHTLINK™ optical planar waveguide on a) Xerox substrate, b) PLEXIGLAS® Film OF058 substrate.

## 3. Experimental Procedures

The experiments were performed on two types of the substrates. The first one was transparent paper Xerox 3R96525 (Xerox Corporation) and the second one was PLEXIGLAS® Film OF058 (Evonik Industries AG) foil. Fabrication process of the planar polymer flexible waveguides for Xerox substrate is illustrated in Fig. 3 step by step.

The first step was a standard cleaning procedure for substrate and followed by deposition LIGHTLINK™ Clad using spin coating (Fig. 3a). The cladding layer was hardened on hot plate at 90°C for 2 min (Fig. 3b). Then LIGHTLINK™ Core was deposited on the clad layer by spin coating (Fig. 3c) and after that soft bake process was applied at 95°C for 2 min on the hotplate (Fig. 3d). Next,

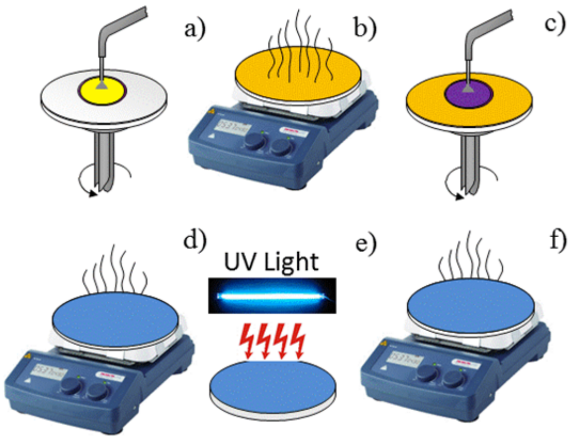


**Fig. 3.** Fabrication process for LIGHTLINK™ planar optical waveguides, a) deposition of LIGHTLINK™ clad layer, b) clad soft bake, c) deposition of LIGHTLINK™ core waveguide layer, d) soft bake process, e) UV curing process, f) post exposure bake.

applying of UV curing process (Fig. 3e) occurred and, finally, post exposure bake was done at 145°C for 60 min on the hotplate (Fig. 3f). Similar processes except the step a) and b) were applied for fabrication of LIGHTLINK™ waveguides onto PLEXIGLAS® Film OF058 substrates.

## 4. Measurements and Results

The thicknesses of the fabricated layers (cladding/ core) were measured by profile-meters Talystep Hommel Tester 1000. The experimentally found thicknesses of the waveguide layers were from 10 to 50 µm depending on deposition condition (mainly depending on the rate of spinning of the spin coater).

Transmission spectra of the used LIGHTLINK™ Core, LIGHTLINK™ Clad, Xerox and PLEXIGLAS® Film OF058 substrate were collected by UV-VIS-NIR Spectrometer (UV-3600 Shimadzu) in the spectral range from 400 to 1600 nm and are given in Fig. 4. Obviously the waveguide layer is transparent within the whole range of the measured wavelengths and therefore LIGHTLINK™ Core polymer has suitable properties for optical waveguides.

Waveguiding properties of the planar waveguides were measured by prism coupling technique using Metricon 2010 prism-coupler system [20] at five wavelengths 473, 632.8, 964, 1311 and 1552 nm. Refractive index of the planar waveguide can be determined by measuring the critical angle of the incidence at the interface between the prism and the material, which is in contact with the coupling prism. The measured sample is brought into contact with the base of the couple prisms by means of a pneumatically-operated coupling head leaving narrow air gap between the waveguide film and the prism. Laser beam strikes the base of the prism and is totally reflected at the prism base onto a photodetector at certain discrete values of the incident angle Θ called mode angles. For more details of these measurement see [14], [21].

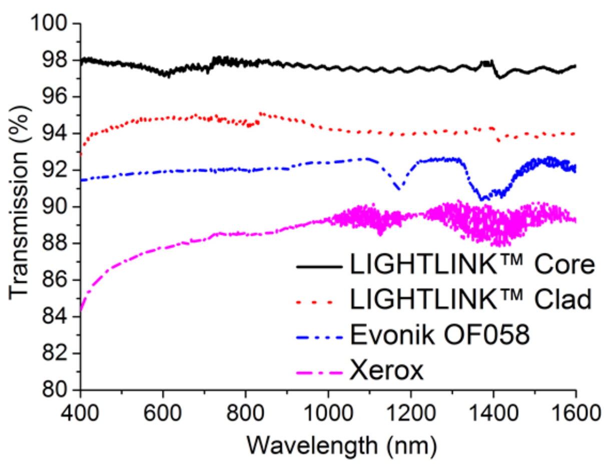


**Fig. 4.** Transmission spectra of the applied LIGHTLINK™ XP-6701A Core, LIGHTLINK™ XH-100145 Clad polymer, Xerox and PLEXIGLAS® Film OF058 substrate.

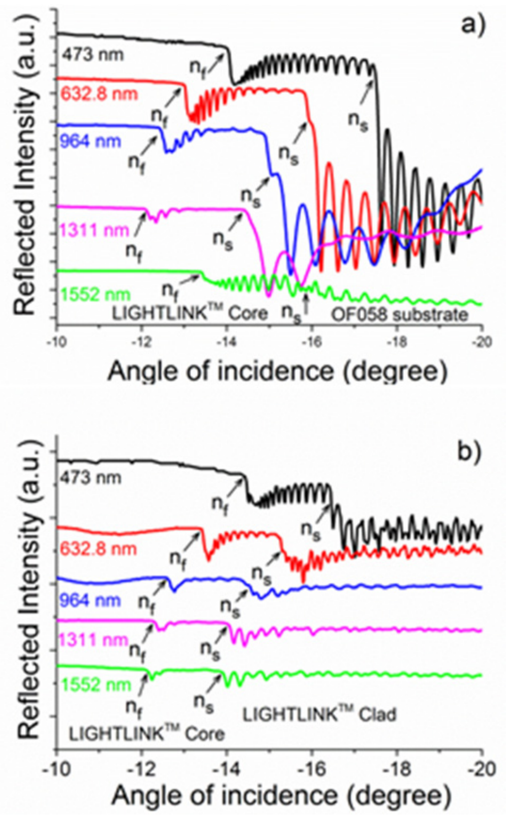


**Fig. 5.** Mode pattern (TE modes) of LIGHTLINK™ XP-6701A planar waveguides deposited onto a) PLEXIGLAS® Film OF058 substrate, b) with LIGHTLINK™ XH-100145 Clad on Xerox 3R96525 paper.

The result in a form of mode spectra for LIGHTLINK™ XP-6701A Core polymer deposited onto PLEXIGLAS® Film OF058 substrate is given in Fig. 5a and LIGHTLINK™ XP-6701A Core planar waveguides with LIGHTLINK™ XH-100145 Cladding deposited onto Xerox paper substrate is shown in Fig. 5b. The arrow with label $n_f$ indicates angel of incidents for refractive index of waveguide layer and label $n_s$ indicates angel of incidents for refractive index of cladding layer respectively.

The first arrows indicate the edge between the cover layer (air) and LIGHTLINK™ Core layer. Abstracting the edge of incidence we get refractive indices of the waveguiding layer $n_f$. The second arrows indicate the edge between LIGHTLINK™ Core layer and LIGHTLINK™ Clad layer and here abstracting the edge of incidence we get refractive indices of LIGHTLINK™ Clad layer $n_s$. Refractive index of the substrate (paper or foil) cannot be determined as the cladding is too thick.

Refractive indices of the LIGHTLINK™ Clad and LIGHTLINK™ Core waveguides determined for the mode patterns are in Fig. 6 compared with the values given by the producer (red line and the black point in the lower part of the figure). The agreement of the data of our waveguiding layer (blue line) with the professional one (red line) is obvious. Refractive indices of our cladding are higher than those given by the producer, and it is so because we used different curing temperatures.

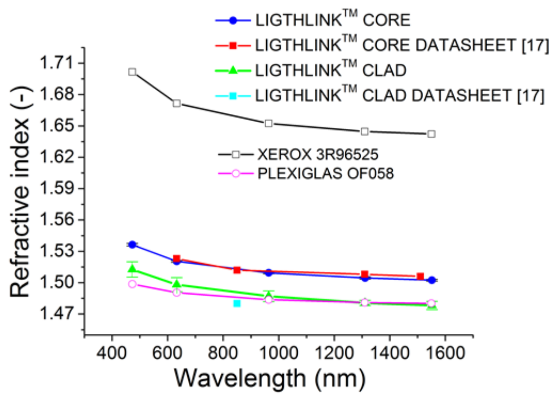


**Fig. 6.** Evaluation of the refractive indices from mode pattern measurement obtained from using Metricon 2010 prism-coupler system (TE modes) and compared with datasheet [17].

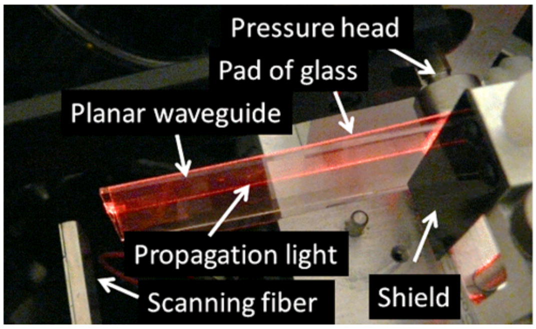


**Fig. 7.** Coupling of the optical signal (632.8 nm) into flexible polymer waveguides for optical loss measurements.

Figure 7 shows an image of planar waveguides supporting optical light at 632.8 nm. This figure shows that our waveguide had good optical properties. The flexible polymer sample must be fixed to a pad of a glass; otherwise the planar waveguides might bend, which would make achieving of quality optical contact difficult and thus making worse the coupling of the laser beam into the waveguide.

Optical losses of the planar waveguides were measured by fiber scanning method [22]. The assumption is that at every point on the propagating streak the light scattered from the surface and picked up by the fiber is proportional to the light which remains within the guide. The best exponential fit to the resulting intensity vs distance curve yields the loss in dB/cm. The results of the optical loss measurements are demonstrated in Fig. 8. Figure 8a shows the results for the sample LIGHTLINK™ Core fabricated on PLEXIGLAS® Film OF058 substrate and Figure 8b shows the results for the sample LIGHTLINK™ Core fabricated on Xerox 3R96525 substrate.

Our optical planar waveguides had optical losses lower than 0.5 $dB \cdot cm^{-1}$ with the best sample having optical losses as low as 0.25 $dB \cdot cm^{-1}$. Just for possible interest: the obtained values of optical losses are comparable with presented data in [23] 0.6 dB/cm (1550 nm), <0.1 (850 nm) and [24] 0.34 dB/cm (1310 nm) or 0.05 dB/cm 850 nm [19], but it must be kept in mind the above mentioned data were given for ridge waveguides.

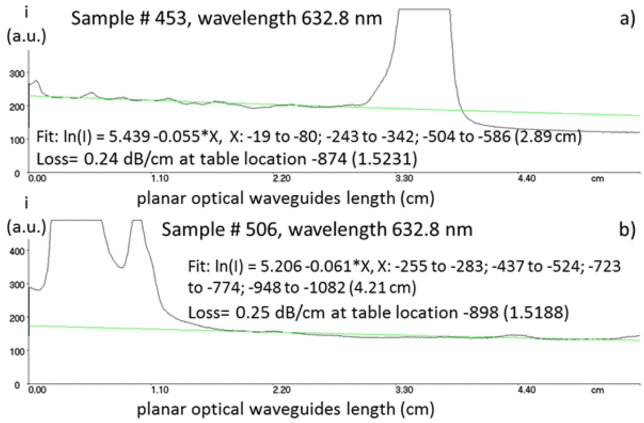


**Fig. 8.** Optical losses of the LIGHTLINK™ XP-6701A planar waveguides deposited onto a) OF058, b) Xerox.

# 5. Conclusion

We report about properties of siloxane (LightLink$^{TM}$) optical planar waveguides deposited onto Xerox 3R96525 transparent paper and PLEXIGLAS® Film OF058 foil. Planar waveguides were deposited by spin coating after that UV curing was applied for hardening of the deposited waveguide layers. Optical waveguiding properties of our planar waveguides samples were characterized by Metricon 2010 prism-coupler system for five wavelengths (473, 632.8, 964, 1311 and 1552 nm) and we proved that our samples had waveguiding properties at all the measured wavelengths. Optical losses were measured by collecting the scattered light using fiber scanning along the waveguide read by the Si photodetector at 632.8 nm. The samples had optical losses lower than 0.5 dB$\cdot$cm$^{-1}$ and our best sample has optical losses around 0.25 dB$\cdot$cm$^{-1}$.

The main advantage of our samples is that they are deposited on flexible substrates what makes them suitable for advanced sophisticated interconnection devices. Next we are going to design and construct multimode flexible ridge waveguides based on the same principle.

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