Reports Res. Lab. Asahi Glass Co., Ltd., 56 (2006)

UDC：678.743.4：621.397.74

7. High-performance and Low-cost Optical Waveguide Module Made of Perfluoropolymer

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In the access network market, there is a high demand of low-cost optical modules without sacrificing high performances. We have been developing optical devices meeting this demand, and finally we have obtained low propagation loss of 0.03dB/cm even at 1650nm and low polarization dependent loss (PDL) by using the polymer optical waveguide with the dopant-free core made of perfluorinated amorphous polymer. They are the top data of the polymer optical waveguides up to date. The high durability to humidity, which was required in practical use, was also shown. As an application, a 1×32 optical splitter module was successfully demonstrated. Insertion loss and PDL at 1310, 1550 and 1650nm were practically low.

1. Introduction

Recently, optical communication network extends to homes and premises. Cost reduction of the optical modules such as optical splitter is required for the access network such as FTTH (Fiber to the homes) or FTTP (Fiber to the premises). Instead of the silica optical waveguide, a polymer optical waveguide has been a candidate to reduce the cost due to its ease in processing.

However, the optical transparency of ordinary optical polymers is not suitable in the near-infrared region, including 1260-1650 nm for the communication window. This is due to the absorption loss caused by the resonance to the oscillation energies of hydrocarbon bond (C-H) and hydroxyl bond (O-H). Those bonds exist ubiquitously in the polymers because they are the major groups constructing the molecules, and H_2O, which contains O-H bond, is absorbed due to hygroscopicity of the molecules. In order to decrease these absorption losses, the substitution of fluorine or deuterium for hydrogen has been reported[(1)-(3)]. These substitutions shift the absorption peak to the longer wavelength, hence the overtones in the communication window become higher orders, then the absorption losses decrease. Furthermore, the substitution of fluorine for hydrogen, namely fluorination, is also effective to decrease the hygroscopicity.

The optical waveguide using perfluoropolymer, which is fully fluorinated, has been reported by Yeniay et al.[(3)]. According to their paper, the low propagation losses of <0.05 dB/cm at 1310 nm and <0.07 dB/cm at 1550 nm were obtained using the perfluoropolymer optical waveguide on polymer substrate.

We have been developing the perfluoropolymer Poly(perfluorinated butenyl vinyl ether) (PBVE) (known as Cytop™) since 1988 for optics and electronics use[(4)]. Because its theoretical limit of optical loss is estimated less than 10 dB/km in the near-infrared region[(5)], PBVE has been applied to the polymer optical fiber (Lucina®) for the practical use in the local area network and so on.

We have reported the PBVE optical waveguide with the propagation loss of 0.1 dB/cm[(6)]. We used some non-perfluorinated dopant to tune the refractive index of the core for the optical waveguide. Unfortunately, some small absorption peaks of this dopant appeared in the communication window, therefore the loss reduction was limited. In this paper, we will report on the fabrication of the novel

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optical waveguides using dopant-free perfluoropolymer as a core material, and on very low propagation loss in all over the communication window even at the wavelength of 1650 nm[7]. And we will also report on the application of the PBVE optical waveguides to a 1×32 optical splitter module as an example of passive optical waveguide devices[8].

2. Material and Fabrication of Optical Waveguides

Figure 1 shows the comparison between the chemical formula and 3D structure of PBVE and Polytetrafluoroethylene (PTFE) among the major perfluoropolymers. The structure of PTFE is straight while PBVE is twisted due to the large aliphatic ring. As the twist prevents crystallization, PBVE has amorphousness which brings solubility to specific solvents and high transparency due to lack of scattering centers.

In this paper, we used PBVE with slightly chemical modification within the framework of perfluoropolymers, as both the clad and the core materials, in order to tune the refractive index without dopant. This dopant-free structure would be the ideal one to bring out the maximum potential properties of perfluoropolymers. We can tune the relative refractive index difference between core and clad (Δ), up to 1%.

The fabrication of the dopant-free PBVE optical waveguide was carried out using the traditional photolithographic technique as follows. After the clad and the core were layered on the substrate by spin-coating and drying-up, the core was patterned with photoresist using a contact mask aligner. The core ridge was formed by reactive ion etching, where the photoresist itself was used as the etching mask. And then, the remaining photoresist on the core ridge was stripped by a wet process. Finally, the overclad was formed by spin-coating and drying-up again. **Figure 2** shows the cross-sectional view of the dopant-free PBVE optical waveguide. The size of the core is 6.5 μm×6.5 μm square. The Δ was tuned to 0.5% in consideration of the coupling loss.

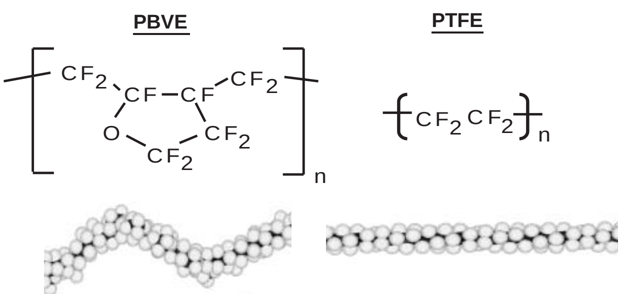

Fig. 1 Chemical formula and 3D structure of PBVE and PTFE.

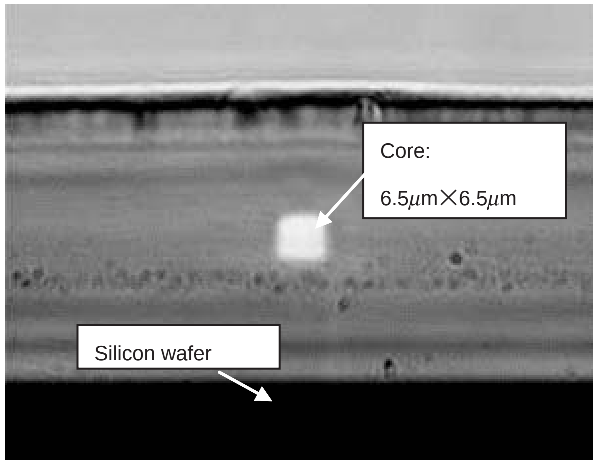

Fig. 2 Micrograph of the cross-sectional view of the dopant-free PBVE optical waveguide.

3. Measurements and Discussions

The propagation loss of the optical waveguide was evaluated using the cutback method. The straight optical waveguide of 10-cm long was prepared, and then the insertion loss (IL) was measured every time that the length of the optical waveguide was shortened in 2-cm step. Both edges of the waveguide were cut by dicing saw and not polished. In order to measure IL at each length, we butt-coupled the light from 1550 or 1650 nm lasers into an optical waveguide with a single mode fiber and collected the output light into also a single mode fiber connected to a detector. Both fibers were aligned to the best coupling position by the 6-axes-auto-alignment system controlled by computer. The results are shown in **Fig. 3**.

The propagation losses at 1550 and 1650 nm, which were obtained from the slope of the approximated line in **Fig. 3**, were 0.03-0.04 dB/cm.

This low loss even at 1650 nm is reasonable due to the optical properties of PBVE, and it is the lowest propagation loss of polymer optical waveguide to the best of our knowledge.

The polarization dependent loss (PDL), which shows the robustness to the fluctuation of the polarization, was measured with similar setup connecting the polarization scrambler between lasers and straight optical waveguides. The measured PDL was 0.01-0.02 dB/cm, which is as small as the detection limit of our setup, at both wavelengths of 1550 and 1650 nm.

One reason for this low PDL is the isotropic optical features brought by amorphousness of PBVE.

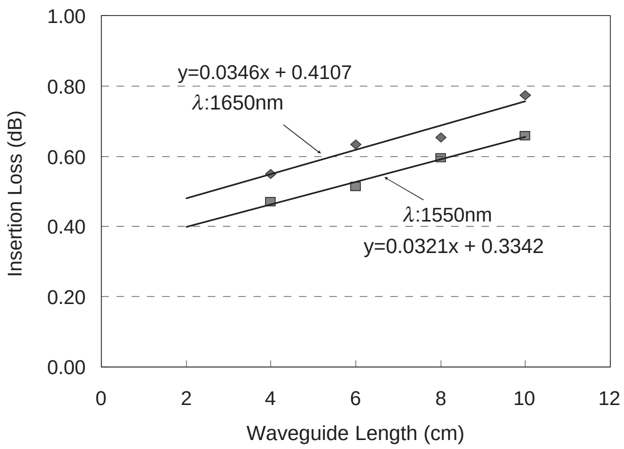

Fig. 3 Cutback measurement of dopant-free PBVE optical waveguide at 1550 and 1650 nm.

And we believe that the relatively small optical photoelastic constant ($6.5\times10^{-12}Pa^{-1}$) of PBVE is also advantageous in lowering the PDL.

Figure 4 shows the comparison of the insertion loss spectrum between dopant-containing and dopant-free PBVE optical waveguides over 1200-1700 nm. The length of the waveguide is 10 cm.

The insertion loss spectrum of the dopant-containing PBVE optical waveguide has large peaks near the 1400 nm. These peaks are assigned to the absorption by the dopant molecules. On the other hand, the insertion loss of dopant-free PBVE is less than 1 dB all over 1260-1650 nm. This flat spectrum feature shows that the propagation loss of dopant-free PBVE optical waveguide is insensitive to the wavelength in this range. Insensitivity to wavelength is important and advantageous in designing optical devices. It is a remarkable feature compared to other polymer optical waveguides, and nearly match that of silica optical waveguides.

In addition to the propagation loss and the PDL, the reliability is also one of the main issues of the polymer optical waveguides. We tried the reliability test at 85℃ and in 85% relative humidity, using the dopant-free PBVE 4.5-cm long straight optical waveguide chip. The chip was not covered with a glass lid.

The insertion loss change at 1550 nm was less than 0.2 dB, after the treatment for 2000-hour. We speculate this durability is due to the chemically stable and non-hygroscopic properties of PBVE, one of the perfluoropolymers.

4. Application to Optical Splitter Modules

After the clarification of the basic characteristics of the straight optical waveguides described above, we tried to apply PBVE optical waveguides to an optical splitter module which is one of practical optical devices used in the access network. The type of the splitter module depends on each network system. Our choice is a 1×32 optical splitter which is widely used in North America.

After the wafer process described in the section 2, we cut the wafer with a dicing saw, then covered the diced chip with a glass lid, and finally polished the both waveguide edges of the chip[(8)]. **Figure 5** shows the schematic layout of our 1×32 optical splitter chip.

The size of the chip is 27×5.8 mm^2. Optical fiber (SMF-28) blocks were aligned and bonded to the chip, and then we packaged it in the case whose size is approximately $55\times7\times3$ mm^3. **Figure 6** shows a photograph of a 1×32 optical splitter module before packaged in a case.

After the fabrication of the modules, IL of the module was measured by using three light sources at the wavelengths of 1310, 1550 and 1650 nm, respectively. The results are summarized in **Table 1**.

The IL is less than 17.9 dB and the uniformity (Max-Min) of the insertion loss at each port is less

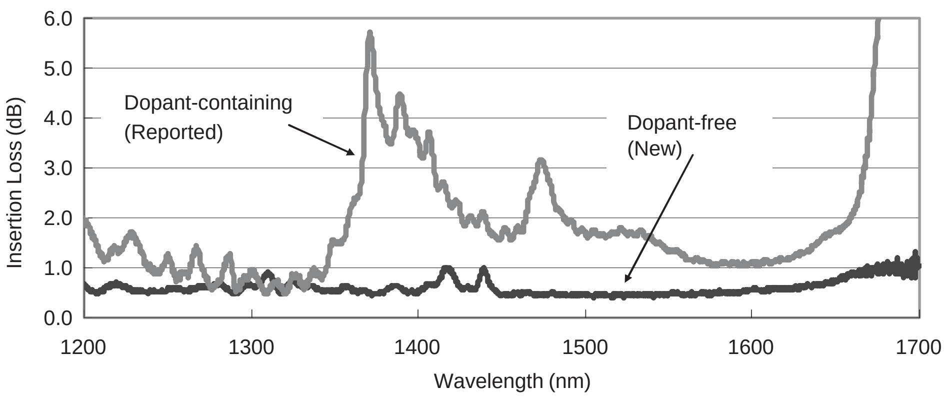

Fig. 4 Insertion loss spectra of 10-cm long straight PBVE optical waveguides.

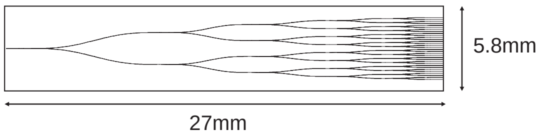

Fig. 5 Schematic layout of the 1×32 optical splitter chip.

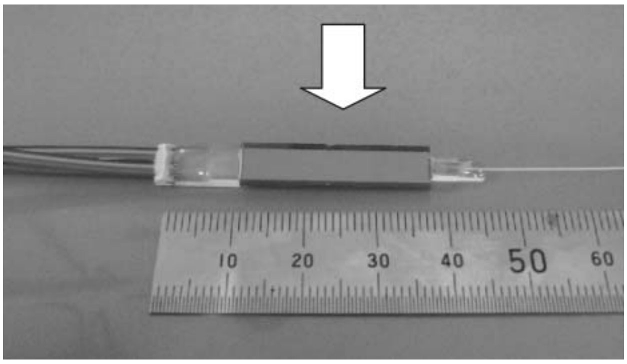

Fig. 6 1×32 optical splitter module (before packaged in a case).

Table 1 Summary of Insertion Losses of the 1×32 Optical Splitter Module.

Wavelength	Max	Min	Max-Min	Ave
1310nm	17.83	16.32	1.51	16.69
1550nm	17.18	15.92	1.27	16.45
1650nm	17.24	16.19	1.05	16.64

(dB)

than 1.6 dB throughout the four wavelengths. The theoretical loss of the 1×32 splitter is 15.05 dB, therefore the excess loss of this module is less than 2.9 dB, which is larger than the value expected by the propagation loss of 0.03 dB/cm. We believe this excess loss is mainly due to the fabrication errors and the waveguide design which is not optimized.

The PDL was also measured by using polarization scrambler at the same wavelengths. The results are summarized in **Table 2**.

The PDL is less than 0.3 dB at the three wavelengths. We also believe that this low value of PDL is due to the optical feature of the material PBVE.

These ILs and PDLs nearly compete with the features of inline products made of silica (for example, IL: 17.2dB, Uniformity: 1.5dB, PDL: 0.3dB).

5. Conclusions

We fabricated single mode optical waveguides with perfluoropolymers. The used materials are Poly (perfluorinated butenyl vinyl ether) (PBVE) and the chemically-related ones. Propagation loss of PBVE optical waveguide was 0.03 dB/cm even at 1650 nm. We believe that this is the lowest

Table 2 Summary of Polarization Dependent Losses of the 1×32 Optical Splitter Module.

Wavelength	Max	Min	Max-Min	Ave
1310nm	0.23	0.05	0.19	0.13
1550nm	0.20	0.04	0.16	0.12
1650nm	0.28	0.03	0.26	0.11

(dB)

value among the reported values for the polymer optical waveguide at this wavelength ever reported. The spectrum analysis and PDL measurement showed that PBVE optical waveguide was almost insensitive to both wavelength and polarization. Furthermore, this optical waveguide endured the 85℃/85%RH test at least for 2000 hours. The presented results show that the dopant-free PBVE optical waveguide can be a good substitute for the silica optical waveguide, in both optical properties and reliability.

Then, we successfully fabricated and demonstrated a 1×32 optical splitter module using PBVE. The insertion loss of the module is less than 17.9dB, and polarization dependent loss is less than 0.3dB, at the wavelengths of 1310, 1550 and 1650nm. This is the first report, to our knowledge, on the polymer optical splitter module usable at 1650 nm. These optical characteristics are promising for the simultaneous pursuit of low cost and high performance of passive optical devices, using PBVE instead of silica which is widely used. Optical characteristics of the module can be improved by optimizing the waveguide design and refining the fabrication process.

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