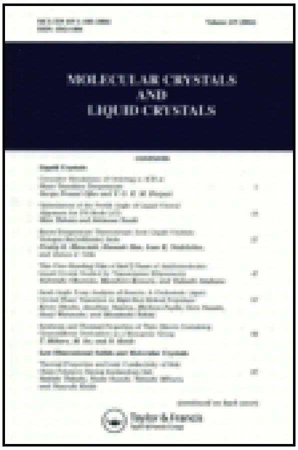

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FLUORINATED POLYIMIDES AND ITS APPLICATION TO OPTICAL WAVEGUIDES

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The performance requirements of polymer waveguides used in optical telecommunication and their future opportunities are discussed. The polymer waveguide is suited for mass production and has an excellent cost performance ratio; therefore, it is to be utilized in the home terminals of FTTH. Fluorinated polyimides will be used for these terminals because they have good optical properties, high heat resistance, and long-term reliability. We have fabricated the fluorinated polyimide planar lightwave circuit integrated with V-groove contributing to high throughput assembly and automated manufacturing of high performance transceiver modules, and confirmed it accurate enough for optical network units.

Keywords: fluorinated polyimide; FTTN; optical network unit; planar lightwave circuit

INTRODUCTION

The popularization of personal computers and the Internet boosted up the demands for telecommunication, which have changed the dominant usage of the optical fiber line from telephone conversation to data communication. In order to take measures to meet this situation, it is necessary to broaden the bandwidth of telecommunication system supported by optical fibers. In fact, the FTTH (Fiber to the home) services have recently started in Japan by several carriers [1]. However, the construction cost of FTTH seems to be still higher than a market requirement from many types of service providers and contents holders.

The high installation cost of FTTH is a most important national issue in every country all over the world in order to prepare for the coming IT (information technology) era [2]. The main reason of the high cost is come from the different nature between the backbone network and the

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access network. The telecommunication infrastructure is constructed hierarchically from the long haul to the access. So the access network needs more than 80% of all optical fibers installed [3], and the huge amounts of the components are necessary for the access terminals. Many attempts are applied to overcome the high cost from many viewpoints of suppliers such as services, systems, equipment, components, and materials.

One example of attempts from the system suppliers is the multiple service capability. It avoids the redundant installation of access networks for every types of contents and provide simple usage and easy understanding for users, which realize a unified communication system capable of dealing with any kinds of services instead of a different means of communication for each service, e.g. phone calls, radio listening, the Internet shopping, CATV including the video on demands, interactive games, real time streaming service of high vision program, home banking or home security services, and so on.

Another example of cost reducing proposal from the system's viewpoint is PON (passive optical network) system. It utilizes passive splitters to branch the optical network line from a central office into 32 homes, which can save the optical fiber installation at the ratio of one 32nd if the splitter is equipped near the homes. The PON architecture has the effect of sharing the expensive equipment at the central office and reducing the FTTH cost per user. More efficient use of bandwidth will be realized by DBA (dynamic bandwidth assignment) technology [4].

The other important technology to reduce the FTTH cost is WDM (wavelength division multiplexing) system. The upstream signal from the home to the central office and the downstream signal are multiplexed by using different wavelengths, 1.3 μm for upstream and 1.55 μm for downstream. This technology enables the single fiber communication between the home and the central office instead of a pair of fibers for every up and down streams, which can reduce the number of fibers by half. On the other hand, it requires the low cost transceiver for the home terminal called ONU (optical network unit).

The activities to realize the low cost transceiver for ONU are the main topics in this paper. The single fiber transceiver module would be realized by assembling a lot of discrete components by existing technologies, if it were not necessary to manufacture the huge amount of modules. In other words, the mass production capability is limited in conventional optical modules as they are manufactured by sophisticated hand-made process, resulting in the expensive modules. Thus it is not suited for the components used in the access network.

The polymer waveguide is suited for mass production and has an excellent cost performance ratio; therefore, it is to be utilized in the hybrid integrated ONUs. Fluorinated polyimide will be the best choice of materials for these units among the many kinds of polymer materials, because they have good optical properties, high heat resistance, and long-term reliability, as well as fabrication capability at an excellent accuracy. The performance requirements for polymer waveguides used in optical telecommunication and important characteristics of polymer materials are described in detail below, featuring an ONU application of fluorinated polyimide. The other applications of polyimide waveguide are touched upon briefly.

POLYMER PLANAR LIGHTWAVE CIRCUIT

PLC (planar lightwave circuit) is analogous to PCB (printed circuit board), in which the optical circuit is made of transparent material in contrast to the electric circuit made of copper. The PLC, which allows a variety of optical waveguide pattern to be fabricated on the silicon wafer or similar substrate material, can transfer optical signal by utilizing the refractive indices difference between the core and the cladding. Since the core region has higher index than the cladding region, a light beam incident on the optical waveguide within a specific angle to the axis propagates through the core by being totally and repeatedly reflected at the interface as shown in, Figure 1. The optical fibers are also kinds of optical waveguide in principle. Though light travels straight in a free space, it can be not only guided to bend or split along the optical waveguide but also diffracted or filtered in a certain wavelength by a proper design of the optical waveguide.

The most dominant commercial application of PLC is AWG (arrayed waveguide grating) for multiplexing and demultiplexing in DWDM (dense WDM) system. The PLC technology platform is applicable to many other types of optical components including optical amplifiers, optical switches, splitters and active components like ONU module. The silica on silicon PLCs are commonly fabricated by FHD (flame hydrolysis deposition) process [5]. Lithium niobate, Silicon on insulator and polymer materials are also common to realize PLCs by proper process for each material, i.e. diffusion, CVD (chemical vapor deposition) and spin coating, respectively.

The typical fabrication process of polymer waveguides is shown in, Figure 2. The under cladding material is spin-coated on the substrate,

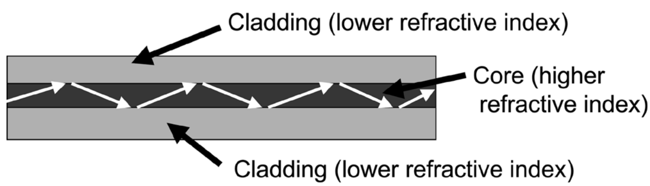


FIGURE 1 Principle of the optical waveguide.

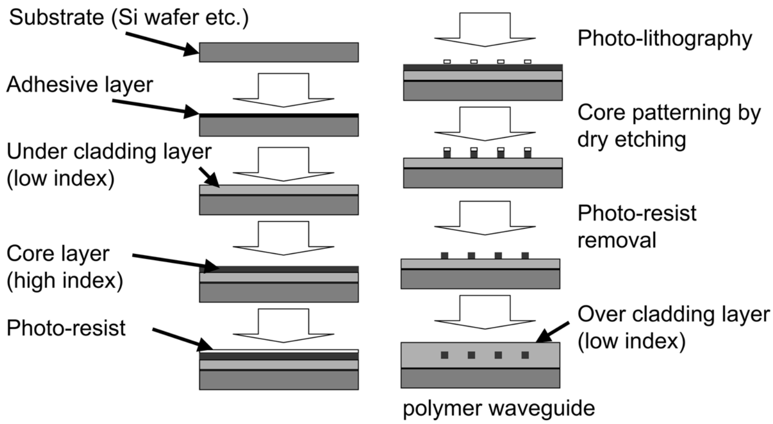
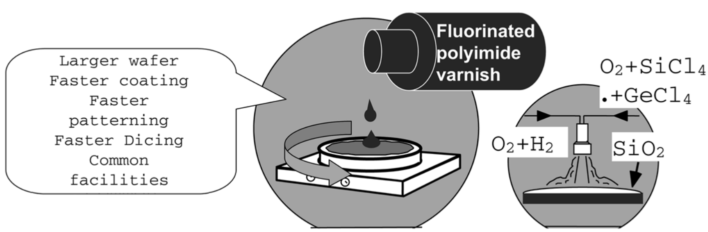


FIGURE 2 Fabrication process of polymer waveguides.

followed by baking, and then the core material is coated and baked in the same manner. The core layer pattern is made by RIE (reactive ion etching) with photolithography technique. Finally, the over cladding material is spin-coated and baked.

Figure 3 illustrates the features of polymer PLC compared with silica PLC. The polymer materials are not only cheaper than special gas materials used in other PLC technologies such as silica on silicon but also it can avoid the facility cost such as exhaust gas treatment for detoxification. The polymer optical waveguide can be deposited on the silicon wafer by simple



Item	Polymer	Silica
Fabrication	Spin coating	FHD
Cost	Affordable	Expensive
Productivity	High	Low
Propagation Loss	Moderate (< 0.4dB/cm)	Low (< 0.1dB/cm)
Proper Application	High Volume / Affordable	Low Volume / Expensive

FIGURE 3 Comparison of polymer PLC with silica PLC.

spin coating technique and successive curing process at low temperature in comparison with the silica waveguides to be processed by FHD or CVD with a custom designed equipments, resulting in the quick and low cost manufacturing. Larger wafer diameter is easily adopted in polymer PLC because of smaller stress induced by thermal expansion mismatch. Though the propagation loss of polymer waveguide is larger than silica one, it is low enough in the case of small PLC application such as ONU module. Because the dominant loss of coupling between LD and optical waveguide is nearly 10 times larger than the total propagation loss of optical waveguide.

FLUORINATED POLYIMIDES FOR PLC

Among the many kinds of polymer materials, fluorinated polyimides have been investigated as a promising material for optical waveguide [6–11]. Recently, thermo set polymers such as fluorinated epoxies are utilized to fabricate a stacked multimode optical waveguide, polymer-silica hybrid materials are used for optical waveguide by molding process with UV eradiation [12–13]. Optimum material and fabrication process should be chosen according to the waveguide structure and application. Since the polymer PLC used for active components such as ONU module should be durable in soldering process, Fluorinated polyimide will be the best choice of materials.

The major advantage of fluorinated polyimides is that it has a very high heat resistance in comparison with other polymer materials as shown in, Figure 4. This feature enables fluorinated polyimide PLC to be robust to AuSn soldering process at more than 300°C since the glass transition

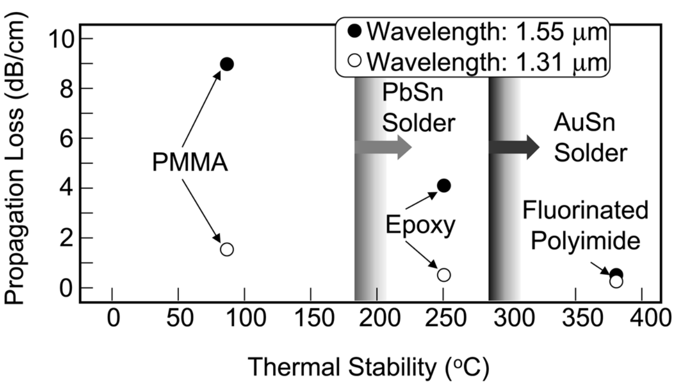


FIGURE 4 Propagation loss at near infrared region and heat resistance of major polymer materials.

temperature of fluorinated polyimides is above 300°C and the degradation temperature is above 500°C.

Another important feature of fluorinated polyimide is accurate control and reproducibility of refractive indices. These features enable precise and wide range design of optical waveguide and stable manufacturing. The features come from chemical nature of synthetic reaction of polyimides. As shown in, Figure 5, polyimides are polymerized from two kinds of monomers called dianhydrides and diamines; the refractive indices of the resulting polyimides are determined at this stage of synthesis, and so they can be designed by selecting their monomer content ratios at the synthesis stage. In the case of thermo set resins such as epoxies, refractive indices are change during curing stage of fabrication process; one should be careful about temperature profile at baking.

Varnishes of polyimide precursors called polyamicacids can be spin-coated on the wafer. Once imidization reaction occurs by baking, the polyimides become insoluble to the organic solvents; therefore, the piled structure required for optical waveguides can be easily fabricated by repeating spin-coating and baking processes. These processes are not available in the case of conventional thermo plastic resins such as acrylics; one should select another type of polymers for each under cladding, core and over cladding layer. One may encounter the difficulty in choosing set of materials that have nearly the same temperature coefficient of physical properties in order to avoid temperature dependence of optical characteristics.

Table 1 shows properties and performance of fluorinated polyimide OPI (optical polyimide from Hitachi Chemical) [14]. Since the birefringence of OPI is constant for any selection of monomer content ratio, a desirable combination of materials can be found for both the core layer and cladding layer of the optical waveguide.

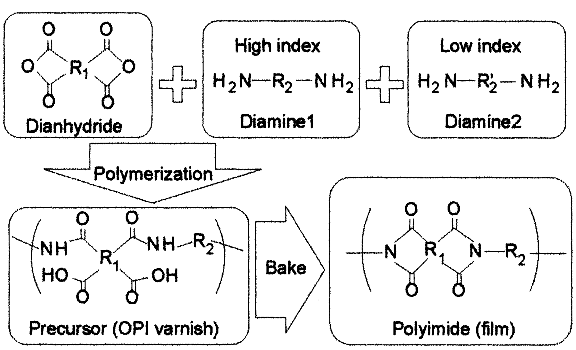


FIGURE 5 Reaction scheme of polyimide.

TABLE 1 Properties and Performance of Fluorinated Polyimide OPI

Characteristics				Unit	N1005	N3205	N3305	N3405
Varnish	Viscosity			dPa.s	50			
	Solid content			wt%	15			
	Thickness*1			μm	3 ~ 8			
Film*2	Index	1.3 μm	TE	–	1.518	1.527	1.531	1.536
			TM	–	1.509	1.518	1.522	1.528
		Δn(TE−TM)		–	0.009	0.009	0.009	0.008
		1.55 μm	TE	–	1.516	1.525	1.529	1.534
			TM	–	1.508	1.517	1.521	1.526
		Δ(TE−TM)		–	0.008	0.008	0.008	0.008
	Loss	1.3 μm	TE	dB/cm	0.5	0.5	0.5	0.5
			TM	dB/cm	0.5	0.4	0.6	0.4
		1.55 μm	TE	dB/cm	0.4	0.4	0.4	0.4
			TM	dB/cm	0.4	0.4	0.4	0.4
	Tg			°C	326	316	313	308
	CTE			ppm/K	43	50	50	54

*1: Spinner revolution: 1500 ~ 5000 rpm.
*2: Baking temperature: 350°C.

The high temperature stability as well as low water absorption of 0.2% (a tenth as small as conventional polyimide or epoxy resins) of fluorinated polyimides lead to robustness at damp heat test. There was no degradation of optical loss after damp heat test for more than 5000 hours under 85°C and 95%RH. We also observed no change of optical loss after temperature cycle test between −40°C and 85°C.

FLUORINATED POLYIMIDE PLC FOR ONU

Figure 6, is a schematic view of the SMT (surface mount technology) type of transceiver module for ONU. A downstream optical signal (1.55 mm) transmitted from the central office through the optical fiber passes through a thin film type WDM filter. It is converted into an electrical signal by the photo diode on the PLC, and then is processed by the terminal equipment. An upstream electrical signal that has been converted into an optical one (1.3 mm) by the laser diode is reflected by the thin film filter, which is then guided to the optical fiber connected to the central office.

The SMT modules with easy connector came out to realize the common soldering process as the conventional electronic ICs [15], though the conventional opto-electronic module should be mounted on PCB and soldered manually because the optical fiber pigtail is not robust for the high

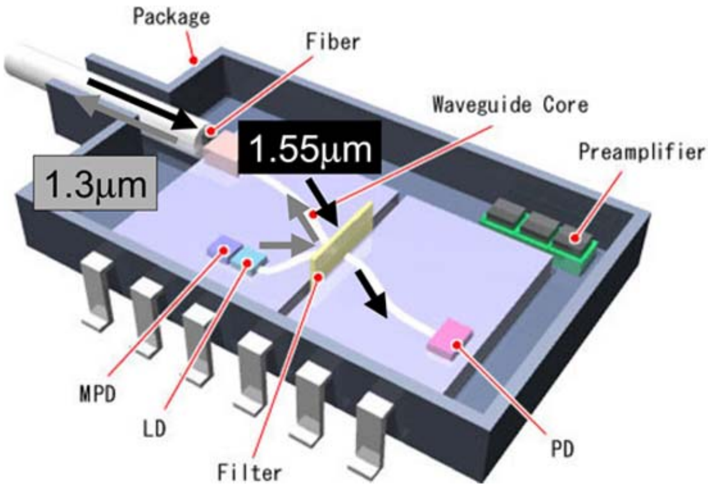


FIGURE 6 Schematic view of transceiver module for ONU. (See COLOR PLATE VI)

temperature process. It will help equipment manufactures to handle all parts including opto-electoronic module in the same manner and realize full automation of assembly process. Since the SMT module is quite compatible with the PLC technology and resin molded packaging [16], there are a lot of activities utilizing PLC to realizing affordable modules for FTTH. The SMT module using the polymer PLC is one of the most promising candidates for optical transceiver used in the FTTH, for it can contribute to the dramatic reduction of size and cost as well as it enables high volume manufacturing in comparison with the conventional free space type module.

Our fluorinated polyimide PLC realized not only affordable cost and high volume but also many benefits for module manufacturers [17]. One of them is the fiber self-alignment capability with the V-groove. The V-groove was etched into silicon wafer using that conventional anisotropic etching technique in the first stage of PLC manufacturing process, that is the most accurate way of fabricating V-groove. In the case of silica PLC, the V-grooves should be etched after the waveguide fabricated. The deep steps of optical waveguide on the wafer make it difficult to realize very accurate V-groove. This is one of the great advantages of polymer PLC manufacturing. The accurate V-groove enables the passive alignment of fiber without monitoring light intensity in a very precise manner; hence high throughput assembly and automated manufacturing of high performance module are available. However the fabrication of the PLC and the V-groove should be very precise. As shown in, Figure 7, the variation of measured misalignment for more than 600 pieces was within 1.5 μm (3σ), resulting in

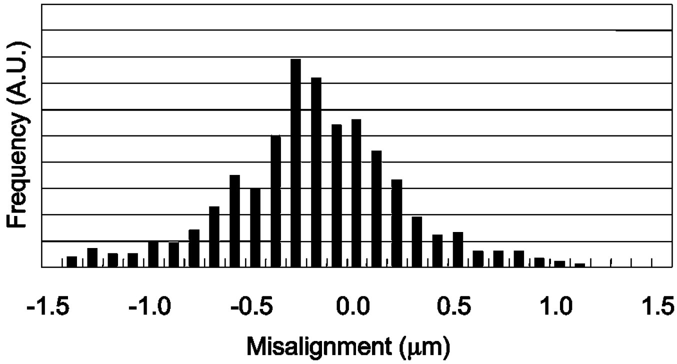


FIGURE 7 Experimental results of the misalignment between the centers of V grooves (guide for mounting optical fibers) and the cores of optical waveguide.

the excess loss of 0.5 dB. Recently, our production engineering efforts improved the standard deviation in the range from 0.2 μm to 0.3 μm; the estimated excess loss for 3σ is from 0.1 dB to 0.2 dB.

The positioning accuracy of the dicing groove for WDM filter was within 2 mm as shown in, Figure 8. The estimated excess loss of mispositioning of filter groove is as small as 0.1 dB. The roughness (r_a) of as-diced facets of polymer waveguide was within the range from 10 nm to 20 nm, which correspond to the mirror surface and so scattering loss at the end face of polymer optical waveguide is negligible. This benefit seems to be caused

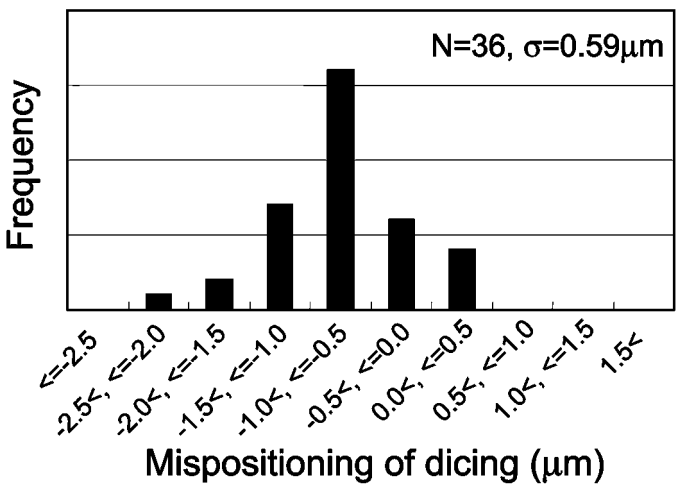


FIGURE 8 Positioning accuracy of the dicing groove for WDM filter.

TABLE 2 Typical Design for Polymer Planar Lightwave Circuits for Optical Network Units Fabricated with Fluorinated Polyimide OPI

Item		Typical design	Comment
	material	SiO_2 on Si	
Substrate	size	125 mmϕ	
	thickness	1 mm	
	material	fluorinate PI	
	core size	6.5 × 6.5 μm	custom design is available
	core height	8 μm	
Waveguide	propagation loss	0.35dB/cm	λ = 1.31 μm
		0.50dn/cm	λ = 1.55 μm
	1.3/1.55 multiplexer	thin film filter	
		<0.2dB	excess loss
Electrode	position tolerance	<0.5 μm	(to waveguide)
Solder	material	Au/Sn	
	position tolerance	< 0.5 μm	(to electrode)
V-groove	Position tolerance	< 1 μm	(to waveguide)

from the elasticity of the material, i.e. fluorinated polyimides. The optical cross talk of PLC alone measured with test pattern [18] was −76 dB. Other typical performance of polymer PLC for ONU module are listed in Table 2.

As another application of the V-groove integrated polymer PLC, we fabricated the 1 × 8 splitter as shown in, Figure 9, which is used in PON system of FTTH. The typical performance of the splitter are listed in Table 3.

CONCLUSION

The performance of polymer planar lightwave circuit made of fluorinated polyimide OPI were good enough for the single fiber transceiver module of

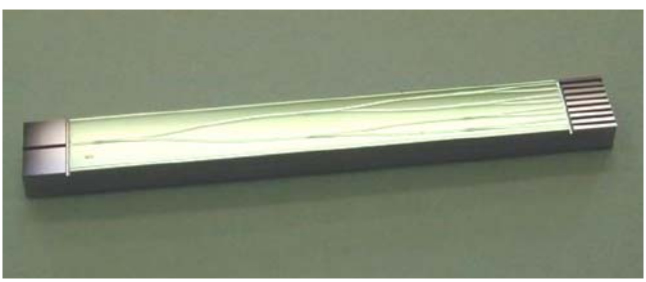


FIGURE 9 1 × 8 splitter fabricated on the Silicon V-groove using fluorinated polyimide. (See COLOR PLATE VII)

TABLE 3 The Typical Performance of 1 × 8 Splitter

Channel No.	Insertion loss (dB)	PDL (dB)
1	12.0	0.2
2	11.4	0.1
3	11.9	0.2
4	11.9	0.3
5	11.3	0.1
6	11.1	0.1
7	11.0	0.1
8	11.1	0.1
Average	11.4	0.1
Uniformity	1.0	–

ONU. The polymer PLC integrated with V-groove turned out to be the best choice to accelerate FTTH deployment by affordable cost and high volume production in cooperation with system activities for PON and packaging efforts such as SMT module. We would like to keep challenging to improve performance from both material and process aspects and spread the application field of polymer PLCs.

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