Chapter 4
Realization of Photonics Polymer Technologies in the FIRST Program

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Abstract This is a review of progressive efforts to realize novel photonics polymer technologies to contribute to society. The new technologies that we developed at Keio University are represented by the ultra-high-speed graded-index plastic optical fiber (GI POF), highly-scattered optical transmission polymer (HSOT), and zero-birefringence polymer. The phenomena behind each technology were discovered through detailed fundamental studies; for example, how polarized waves or photons relate to various polymer chains, their aggregation, higher-order structures, and huge heterogeneous structures. By using these core technologies, we are developing and proposing a face-to-face communication system that is the world's fastest GI POF with 40 Gbps directly connected to a high-quality large display for homes and offices. It realizes sensational face-to-face communication with clear motion pictures without any time lag. To make these research results practically useful for society, we are actively advancing this research and development in cooperation with more than ten companies under the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) of the Cabinet Office of Japan.

1 Back to Fundamentals

1.1 Advantage of Graded-Index Plastic Optical Fiber (GI POF)

The biggest advantage of the graded-index plastic optical fiber (GI POF) is a much higher bitrate than that of a conventional step-index POF (SI POF). Figure 4.1 shows the refractive-index profiles of both the SI POF and GI POF. In the SI POF the light

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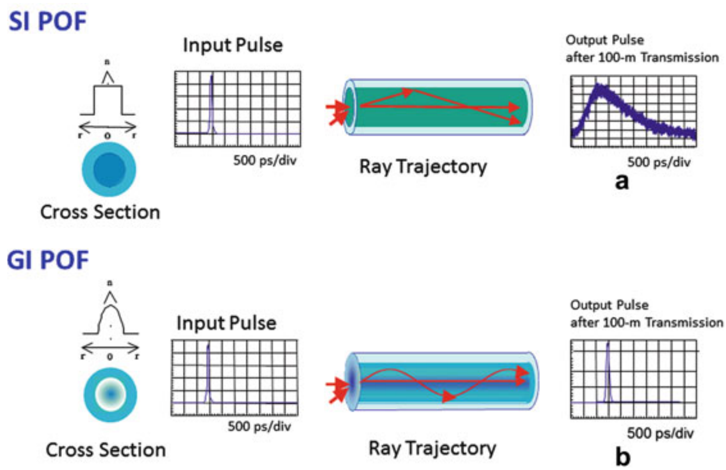

Fig. 4.1 Effect of refractive-index distribution on bandwidth of GI POF (**b**) compared to conventional Step-Index Plastic Optical Fiber (SI POF) (**a**)

going straight has a longer path than the light with many reflections. The output pulse through 100 m of SI POF is then spread enormously as shown in Figure. 4.1a. Conversely, since the GI POF has the refractive-index distribution in the core region, the light basically has a sinusoidal trajectory. The light going straight along the center axis transmits through the region with the higher refractive index, so the velocity of this light is slower. However, because the light with a sinusoidal trajectory has a longer path compared with the light moving in a straight line and very often goes through the periphery region with lower refractive index, it moves faster than the light going along the center axis. These two opposite effects are completely compensated when the refractive index profile is optimized; therefore all lights (modes) through a GI POF arrive at the end of fiber at the same time without time delay, resulting in no broadening of the output pulse as shown in Fig. 4.1b.

1.2 Overcoming Light-Scattering Loss

In the 1980s, I was at a crossroads in my research on whether it was possible to create a GI POF, which could send optical signals at high speeds greater than a gigabit. This was because our trial POF was poorly transparent, the transmission loss exceeded 1,000 dB/km, and light passed through only several meters. To achieve transmission speeds greater than a gigabit, it was necessary to add another material to the fiber and form a concentration distribution in a radial direction to form a refractive-index distribution. However, the important issue at the time was how to remove impurities to make the POF transparent. Conversely, attempting to realize high-speed optical communication by adding a separate material (an impurity?) to form a refractive-index distribution seemed a major challenge and an absurd idea.

No matter how many times we conducted our experiments, light passed only a few meters through the GI POF. The cause was light-scattering loss. The problem of light scattering consumed our time, expense, and energy. We could not assign this as a research theme for an undergraduate or masters student's thesis project because we did not know what results would be obtained, so we continued thinking about this problem. While reading a lot of literature, we came across Einstein's fluctuation theory of light scattering proposed in the early 1900s. This theory is based on micro-Brownian motion in solution, which proposes that light-scattering loss is proportional to isothermal compressibility. When we actually entered the isothermal compressibility value for the POF material polymethylmethacrylate (PMMA), the result was less than 10 dB/km, which was significantly lower than the aforementioned transmission loss of 1,000 dB/km. This meant that transmission in excess of 1 km was possible, which was how we perceived "light" at the time. However, the question then was: What is this 990 dB/km error? To find out what inhomogeneous structure caused this excessive scattering, we thoroughly investigated the light-scattering theory proposed by Debye (who later received the Nobel Prize in Physics) around 1950. We also attempted to work this theory out by ourselves. This theory was extremely useful in analyzing the relationship between the micro heterogeneous structure of polymers and light scattering. What is superior about Debye's light-scattering theory is that by defining the correlation function, the shape and size of the micro heterogeneous structures in polymers can be correlated with light-scattering loss. It became a powerful tool for me in searching for the cause of excessive scattering in polymers.

1.3 Seeing the Essence of the Problem

Using Debye's light-scattering theory, we began to conduct a detailed analysis of the excessive scattering in a 1,000-dB/km plastic optical fiber that allowed light to pass through only 6 m. While carefully reviewing and organizing past data thought to be unsuccessful, we began to see the true nature of light-scattering loss. We began to see how our former method of forming a refractive-index distribution according to differences in reactivity would form an extreme polymer composition distribution in the generated copolymer. It became clear that the more we increased the refractive-index distribution by increasing the difference in reactivity, the larger the inhomogeneous structure formed within the polymer. This large inhomogeneous structure reached more than several hundred Å, and when I applied it to Debye's light-scattering theory, I discovered it to be the cause of a very large scattering loss exceeding several hundred dB/km. This realization was the culmination of many long years of research and made me recognize that the fiber would theoretically not become transparent with processing methods that rely on monomer reactivity.

I decided to reconsider the problem from the beginning. By this time, we were able to visualize the cause of excessive scattering clearly. It did not take much time for me to come up with a new idea for a low-loss fiber. We conducted an experiment based on the completely new idea of forming a graded index using molecular size. April 1st, 1990 is still a memorable day for me. We produced an excellent transparent GI POF preform. It was the moment I emerged from a 10-year-long search for an answer to scattering loss.

People in this industry formerly believed that polymers could not be used in high-performance photonics, due to lower clarity, larger birefringence, larger wavelength dispersion of refractive indices, lower optical uniformity, etc., compared with optical glass. These were considered unavoidable problems peculiar to polymers because they are caused by aggregations of huge molecular chains. In the twenty or so years since then, however, we have seen the birth of photonics polymers with our GI POF.

Research papers written by Einstein and Debye during the early 1900s that delve into the essence of light scattering became my bibles. These papers made us realize that the latest research papers would not necessarily be useful in pursuing leading-edge research. We learned the importance of returning to fundamentals when trying to achieve a larger breakthrough.

2 New Developments in GI POF

Our laboratory was galvanized from this point on. Our course was clearly set, and all student themes were channeled in this direction. Test data on increasingly lower-loss and higher-speed GI POFs were continually produced. We soon obtained a patent, wrote numerous papers, and began joint research with industry. These achievements were widely publicized. News that an optical signal exceeding a gigabit had passed through 100 m of a GI POF for the first time was reported on August 31, 1994 on the front page of the Nihon Keizai Shimbun. The GI POFs developed by our laboratory would go on to break annual records in POF bit rate and transmission distance. The preform method (where a GI preform is created and made into a GI POF through hot stretching) was the main manufacturing method until around 2005 with a focus on interfacial-gel polymerization. However, from around 2005, we began to develop the continuous-extrusion method, and by 2008 had succeeded in 40-gigabit transmission as shown in Fig. 4.2.

This was the world's fastest transmission speed, surpassing the GI-type silica optical fiber. We achieved these results through joint research with Asahi Glass based on the "essential principle of materials" that perfluorinated polymer, used as the POF core material, has small material dispersion compared to silica (material dispersion determines the transmission band). We also developed another type of GI POF through collaboration with Sekisui Chemical to achieve a larger core and easy handling mainly for home networks. Recently, we have studied the microscopic heterogeneous and structural properties of GI POFs to improve further the data transmission properties.

After we proposed the GI POF, there was a sharp rise in research reports on GI POFs coming out of Japan and the West, and the International POF Conference began to be held annually in countries around the world. Many published papers on high-speed optical communication cited our research because of its originality.

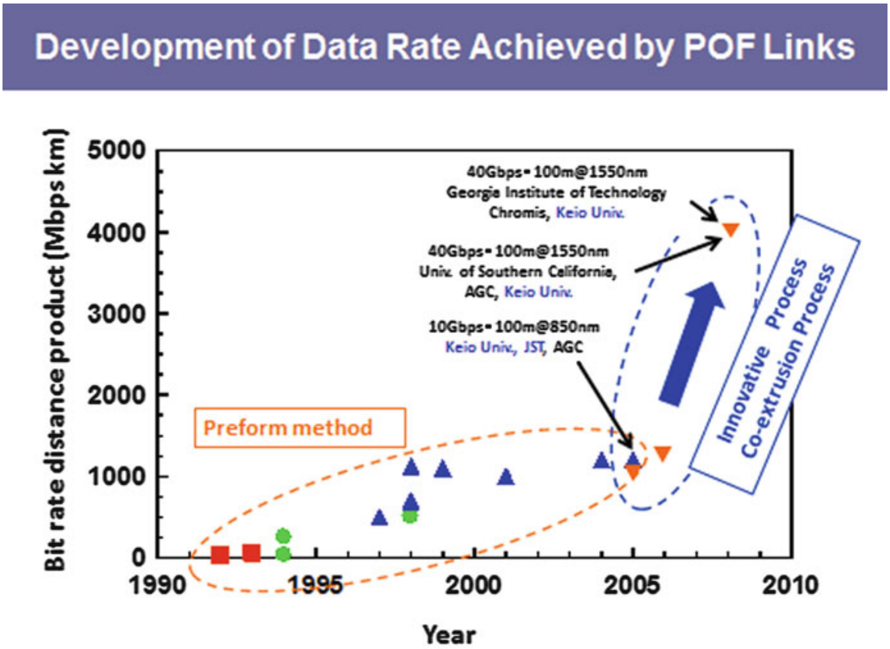

Fig. 4.2 Progress in Fabricating GI POFs

3 Progress from Light-Scattering Loss to Light-Scattering Efficiency

Research on high-resolution and large-screen displays relates back to the research into GI POF scattering loss, which has already been described. Using this knowledge, we studied light-scattering phenomena and focused our research on how to decrease light scattering. We applied what we learned to the question of how to scatter light efficiently in a prescribed direction. As a result, we have proposed the highly scattered optical transmission (HSOT) polymer, which allows double the luminance of conventional transparent LCD backlights. I obtained the basic patent for this technology and succeeded in integrating it into the LCD backlights of various laptop computers such as the Sony VAIO, Sharp, Panasonic, and Toshiba, among others.

The HSOT polymer has greatly contributed to the low power consumption of laptop computers and has been showcased in an episode of “NHK World” that aired in May 2009 as the prime candidate for future ultra-low-power-consumption LED lamps. Before this light-guide plate was released, research on the light-guide plate focused on how to make a transparent light-guide plate with little light scattering. At the time, therefore, such a proposal for a highly efficient light-scattering polymer lacked foundation. However, the HSOT polymer was the only conclusion that could come from the aforementioned series of studies on light scattering.

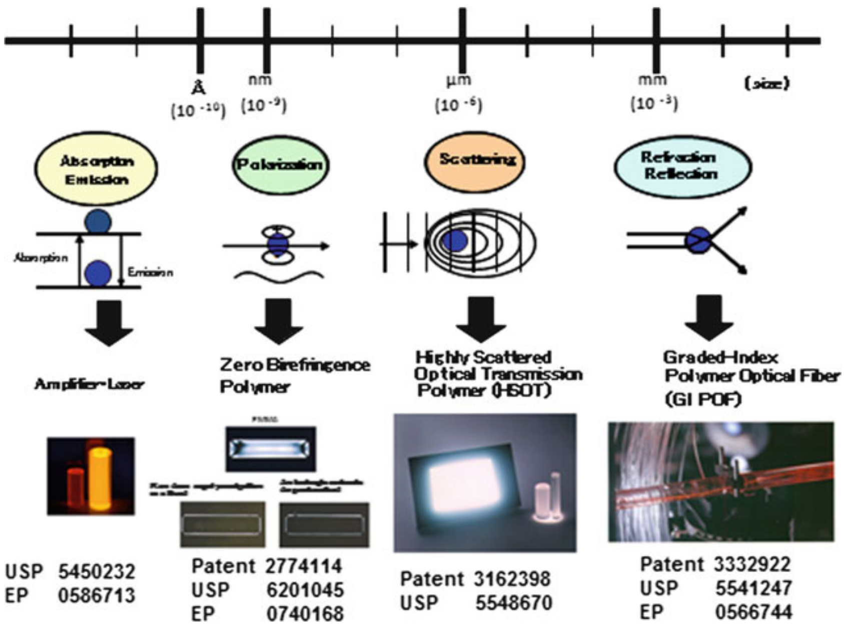

Fig. 4.3 Photonics polymers proposed by Koike Laboratory, for which basic patents have been granted

Another of our inventions, the zero-birefringence polymer, completely removes birefringence, which significantly reduces large-screen LCD performance. It is attracting a great deal of attention as a key technology for large displays.

4 From Basic Research to Developing the Technology for Practical Use

We have obtained basic patents for the GI POF, zero-birefringence polymer, and HSOT polymer. A standard for the GI POF (IEC60793-2-40 Ed.2.0) has also been established by the International Electrotechnical Commission (IEC), the world's foremost authority in the information and communication fields, through the independent proposal of Japan and the joint proposal of Japan, the U.S., and France. A foundation for global deployment has thus been established, with Japan taking a leading role. Also, the zero-birefringence polymer has made extrusion molding possible, which was difficult to do with existing films because of birefringence. It is expected to enhance the image quality of LCD films and significantly reduce costs.

Figure 4.3 shows the relationship between refraction, scattering, and polarization, which are essential light phenomena caused by differences in size of the inhomogeneous structures of polymers, and the technologies that use them-GI POF, HSOT polymer, and zero-birefringence polymer. This diagram shows how refraction and reflection occur if polymer size is measured in mm units, how scattering occurs if polymer size is measured in μm, and how polarization occurs if polymer size is measured in nm. It also shows how to control the behavior of photons and light waves. This research is based upon the essential principles of light, and is the inimitable core technology of our R&D.

Experience from over 30 years in research and development of photonics polymer materials has taught me that the key to innovation is basic research. As previously mentioned, in this age where the trend is to make materials transparent by removing impurities, the concept of the GI POF, which purposefully adds another material (an impurity), is the realization of our many years of exploring the essence of photonics polymers with deep academic insight.

In typical cases of collaborative work between industry and academia, a result tends to lack essential points because a 1- or 2-year rapid industrial result is expected. Therefore a black box often remains unresolved, and no innovation is made. An innovation cannot be achieved within a small timeframe; it takes many years, perhaps a decade, of deep searching.

5 Establishing KPRI for Realizing Face-to-Face Communication System on FIRST Program

The Keio Photonics Research Institute (KPRI) is a new research organization established within Keio University's Faculty and Graduate School of Science and Technology in April 2010 when the application of our research proposal, "Creation of a Face-to-Face Communication Industry through the Application of the World's Fastest Plastic Optical Fiber and Photonics Polymers for High-Definition Large-Screen Displays" was selected by the "Cabinet Office of Japan's Funding Program for World-Leading Innovative R&D on Science and Technology" (FIRST). FIRST is one of the largest government schemes to financially support most advanced research proposals to strengthen the science and technology of Japan. Its system has been specially designed to support selected researchers who are likely to achieve practical results that benefit Japan.

KPRI's target is to create an industry for face-to-face communication that realizes "a sense of really being there" through GI POFs with super-high bitrates, and to develop super-high-resolution large-screen displays. This could not be realized by extending conventional internet technology from Silicon Valley, and is possible only through innovations in photonics technology. For example, this technology enables the elderly in nursing-care centers to talk to their families at home as if they were actually in the same room, and to be surrounded by their warmth whenever they want. Even in an emergency, we can connect one person to another, which provides us with peace of mind and safety. This is a vision of a world that cannot be achieved with our current small-screen and keyboard culture. It will realize a society where people start to treat each other like people again by promoting a culture of real human interaction.

Figure 4.4 shows a conceptual diagram of this research and development. Developing photonics polymer core technology, which is central to this program, can be largely classified into developing ultra-high-speed plastic optical

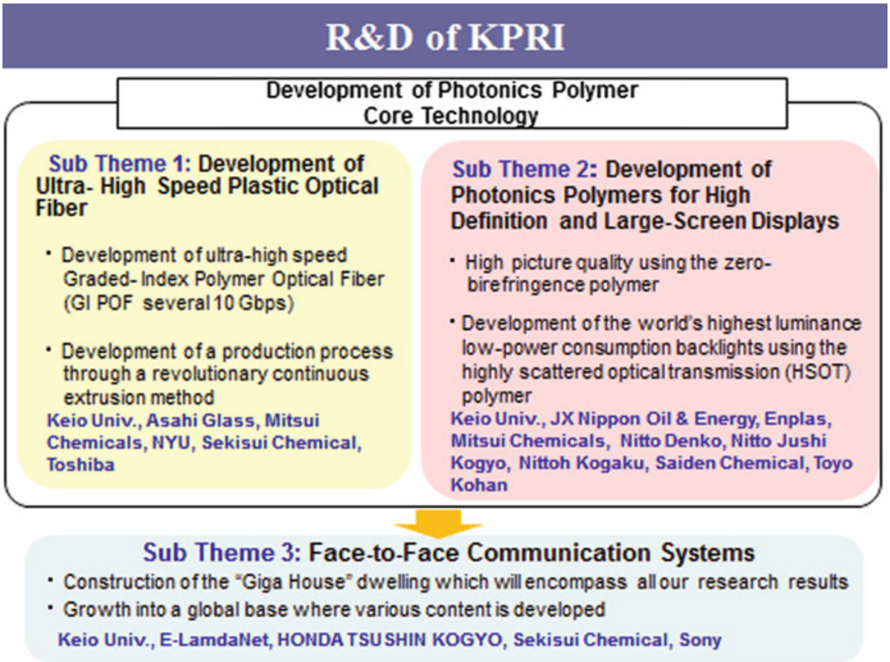

Fig. 4.4 Research and Development of KPRI

fibers and developing photonics polymers for high-resolution and large-screen displays. Research and development in both areas is being vigorously promoted, in addition to developing face-to-face communication. In the latter half of this program, we will construct the "Giga House." By directly linking the Giga House to various bases, visitors can experience first-hand the results of our research and development toward creating a face-to-face communication industry.

We hope that even after this program ends, the Giga House will become a global base where various services will be developed, and will greatly contribute to developing a face-to-face communication industry and society where people become reconnected with one another.

The NHK TV program "Professional: Shigoto No Ryugi" filmed a long documentary about our research activities over a 2-month period and broadcasted it in August 2008. On March 19th, 2010, the activities of KPRI were widely publicized on the front page of the Nihon Keizai Shimbun. Also, Nikkei Business magazine's May 3rd, 2010 edition ran a story on the history of research and development of optical technology and the activities of KPRI titled "Creation of a 10 trillion yen Industry through Optical Technology." The story appeared in a regular series called "Time to Decide and Act," which features the work and achievements of individuals in the business world.

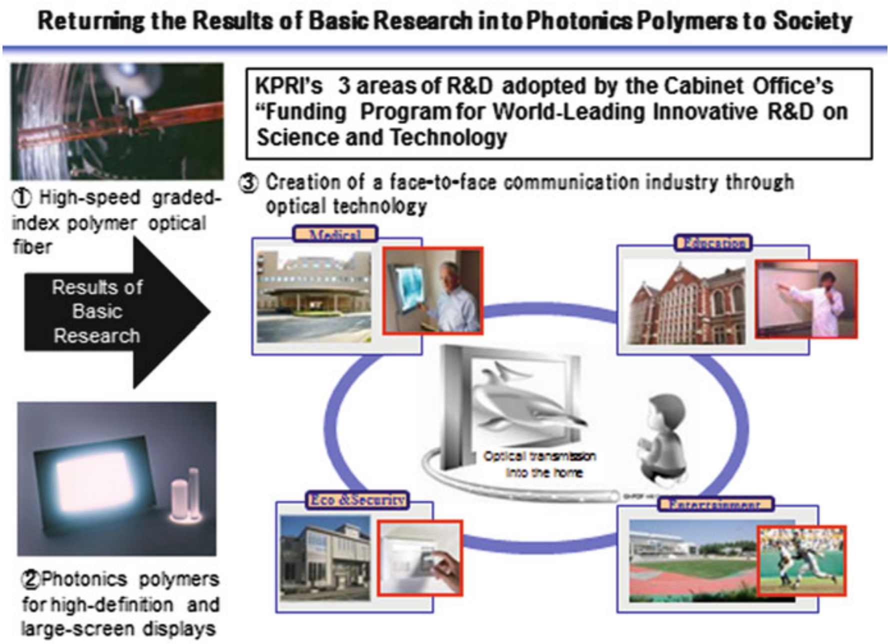

Fig. 4.5 Realizing photonics polymer technologies

6 Returning the Results of KPRI Basic Research to Society

On July 8th, 2010, the Asahi Shimbun ran a story called "Application over Basics: Money Making South Korea." The article pointed out that while the level of basic research at Japanese universities was high; Japan was lagging behind South Korea in the areas of applied research and product commercialization. In recent years, basic research has been the focus of R&D at Japanese universities, and while this has produced results, Japan has not made full use of these results in application and product commercialization.

As the Koike Laboratory has been doing thus far, we at KPRI focus on expediting industry-academia cooperation to return the results of basic research to society through product commercialization and industry creation. Under the FIRST Program we have established a framework for returning the results of KPRI's basic research to society through industry-academia-government cooperation. Currently, we are carrying out research-and-development consignment contracts with 14 companies and a university.

Meanwhile, we are also pursuing separate collaborations with a broad range of business groups such as user businesses, application vendors, and network providers, and are endeavoring to create a face-to-face communication industry through such joint development. Our work was spotlighted on June 30th, 2010 by a Nikkei Sangyo Shimbun article titled "The Changing Face of Leading-Edge Research."

Photonics polymer materials will change our society just as semiconductors created today's information society as shown in Fig. 4.5. To this end, rather than applying new technology to solve existing problems and processes, it is important that we ask new questions to come up with revolutionary technological solutions.

KPRI is resolved to bring about the creation of a face-to-face communication industry by proactively investing itself in industry-academia-government cooperation and by borrowing from the experience and knowledge of industry. The core competence of academia is mainly in basic research, and that of industry is in mass production and business. Because industry and academia play different roles, when working together each player should focus on its core competence, respecting the other's work in the collaboration to benefit society.

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