

Early Days of VAD Process

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Invited Paper

Abstract—This article describes early days of a preform fabrication process for optical fibers named Vapor-phase Axial Deposition (VAD) method. This includes not only technical aspects but also the processes of the invention and research environment. It was about 10 years from 1970 to 1980 just before the optical fiber communication systems were introduced into a practical application.

Index Terms—Optical fiber, silica glass, VAD.

I. INTRODUCTION

BETWEEN 1965 and 1970, I was conducting research for a Ph.D. thesis on gas lasers and holography at the Department of Electronics, the University of Tokyo. Although involved in the precision glass working for my experiments, such as making He-Ne laser tubes, I had absolutely no specialist understanding of glass itself. My interest in glass and optic fiber was initially quite coincidental, rather than something I had worked toward from the outset. Similarly, it was a series of coincidences that made me increasingly interested in glass.

One day in the autumn of 1969, as my doctoral thesis neared completion, my supervisor arranged for us to view a piece of optical fiber. An executive of NEC brought in a one-meter length of a graded-index fiber, developed jointly by Nihon Sheet Glass and NEC. He asked us to think of applications for the new fiber.

But I was much more interested in how the fiber was made than in how it could be used. I spoke with my professor about how I imagined it had been made, and about fiber manufacturing processes and potential applications. My professor related to me an experiment he had performed during his student days that he thought might be of interest. He had successfully built a photocell back in the days when vacuum deposition technology was poor.

An evacuated flask containing an electrode is immersed in molten NaNO_3 . A voltage is applied between the electrode inside the flask and a second electrode immersed in the molten salt. The electric field causes sodium ions in the molten salt to migrate into the flask. Once inside, the sodium ions evaporate in the vacuum conditions, creating a sodium thin film on the inner surface of the flask near the electrode. Fig. 1 illustrates the principles of the experiment as depicted in the original paper [1] published as far back as 1925.

I was amazed to know that single-charge ions could move freely through glass, and this was what first sparked my interest

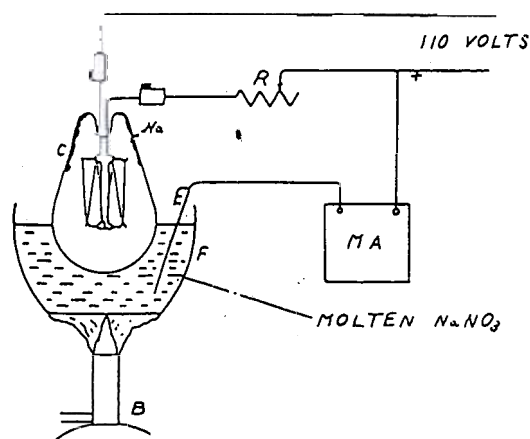


Fig. 1. Original figure of the experiment for making a photo detector tube by electrolysis through glass.

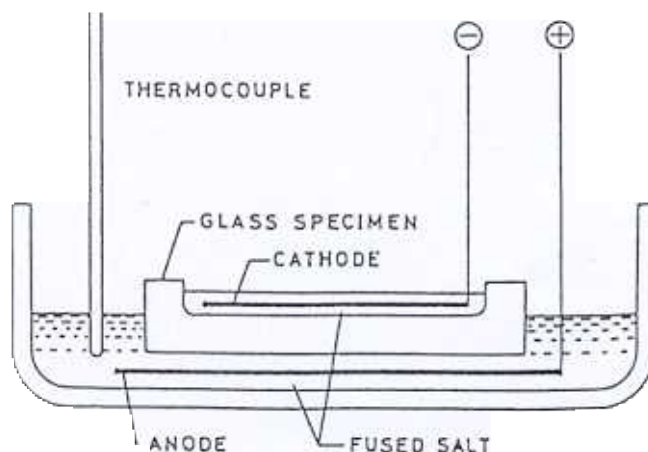


Fig. 2. Schematic diagram for making a planar lightwave circuit by electro-migration of ions.

in glass. Hearing about the old experiment I believed firmly that my assumptions about the fabrication process of the graded-index fiber were indeed correct.

II. PLANAR LIGHT-WAVE CIRCUITS FORMED BY ELECTRO-MIGRATION OF IONS

The first research I tackled after joining the NTT laboratory in 1970 was the development of planar light-wave circuits. I thought when we got optical fibers for communication systems, then we would soon need optical printed circuit boards or planar light-wave circuits.

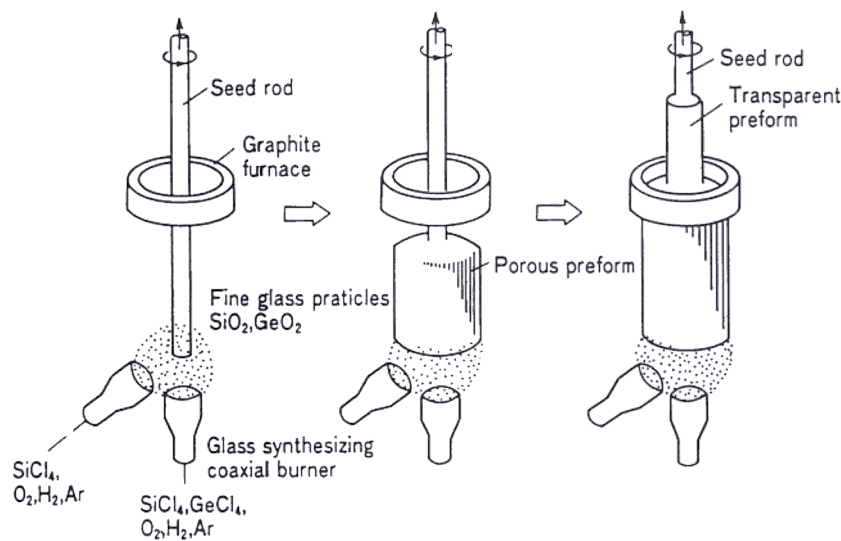


Fig. 3. Schematic diagram of the new fabrication process for optical fiber preform

The aim is to create planar lightwave circuits with minimal scattering loss. I thought the old experiments by Burt were applicable for making high index part or core of planar optical waveguide. A voltage is applied to the glass, and thallium (Tl) ions (or similar) are diffused over the surface of the glass to increase the refractive index, followed by Na or K ions to decrease the refractive index of the glass surface. Through this second diffusion, the high refractive index layer moves into the glass.

Fig. 2 shows the experimental set-up [2]. The experiment is actually very easy to perform. By using a mask of relatively impermeable to the ions for the first diffusion layer, we found it was possible to form a planar lightwave circuit with low loss in any shape or form. Although the use of diffusion unfortunately prevented us from creating a small, single-mode waveguide, we succeeded in fabricating multi-mode circuits and planar-light-wave-circuit lasers [3].

III. THE FIRST STEP IN THE OPTICAL FIBER RESEARCH PROJECT

During the course of these experiments, I noticed that the graded-index fiber caused unacceptable levels of optical transmission loss. This prompted me to start looking for ways to reduce the transmission loss of fibers. While studying optical glass and investigating the manufacture of high-purity glass, I heard news [4] of a new optical fibers for communications developed by Corning.

This was in the autumn of 1970. I was initially devastated and on the verge of abandoning my research altogether, but then resolved to check the findings for myself. Corning had not revealed the materials used or how the fiber was made, so I had to rely on my own intuition and the clues provided by some of the references listed in Corning's research paper.

My guess was that the optical fiber was made of synthetic quartz glass containing TiO_2 produced in much the same way as low-expansion glass. I made some TiO_2 doped silica glass and found that it had a faint purple tinge. Thinking that colored glass would generate significant losses, I consulted the *Glass Handbook* and found that the purple tinge in glass containing

TiO_2 is caused by a lack of oxygen and can be eliminated via heat treatment in a high-temperature oxygen-rich environment.

This discovery firmed my resolve. I made a optical fiber preform with the TiO_2 doped silica glass clad with pure silica glass tube, then drew out optical fiber from the preform. The fiber was wound up on a silica glass drum and subjected to high-temperature heat treatment for a full day and night. The result was optical fiber with a loss figure of 20 dB/km, the same as Corning's fiber.

The optical fiber was far from perfect, however. Heat treatment had made it very brittle, and it snapped very easily. Thus, the material and the method were right, but the end result was still quite unsuitable for communication applications. Clearly, there was much more research and development to be done.

IV. GeO_2 DOPED SILICA GLASS

In the search for an additive that would enable me to control the refractive index of glass, I experimented with oxides of every element in the periodic table. It soon became apparent that most of the oxides were unsuitable because they produced coloration and tended to absorb visible and infrared light. No more than five or six of the oxides could potentially be used without increasing the fiber loss.

Of these, only GeO_2 was capable of properly controlling the refractive index of glass. Today, GeO_2 is used extensively as a core glass dopant in optical fiber, but at that time, it was relatively unknown. I made up some glass with GeO_2 in the same way as for TiO_2 glass, but the GeO_2 all but disappeared. Because of its high vapor pressure, GeO_2 evaporates in the oxy-hydrogen flame used to synthesize glass. (TiO_2 , on the other hand, has a low vapor pressure and can be added to glass even at the SiO_2 melting point temperature.) Adding GeO_2 to glass was proving a more difficult task than initially thought.

V. ANOTHER ATTEMPT

The next attempt was made in the summer of 1975. Two new groups had been set up at the NTT laboratory—one to make op-

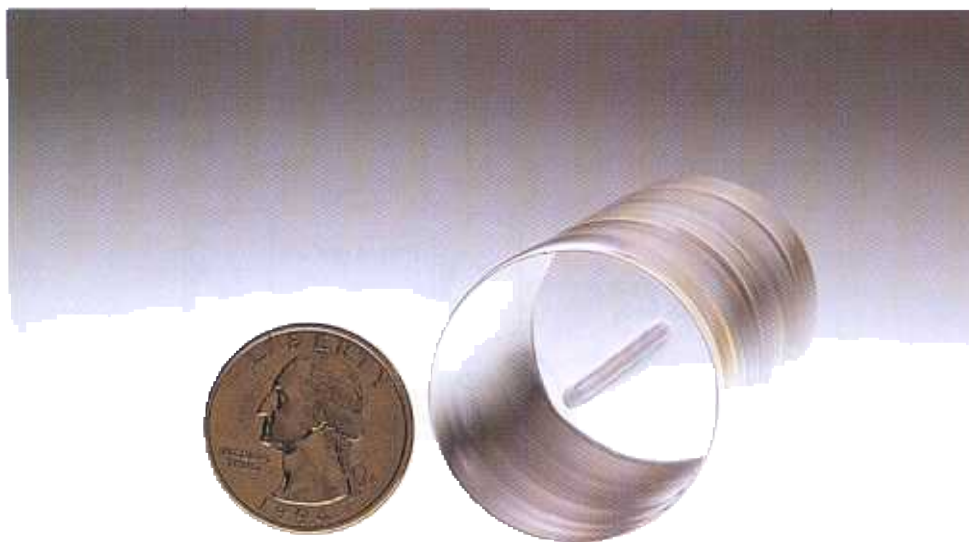


Fig. 4. Fiber preform model for getting research budget.

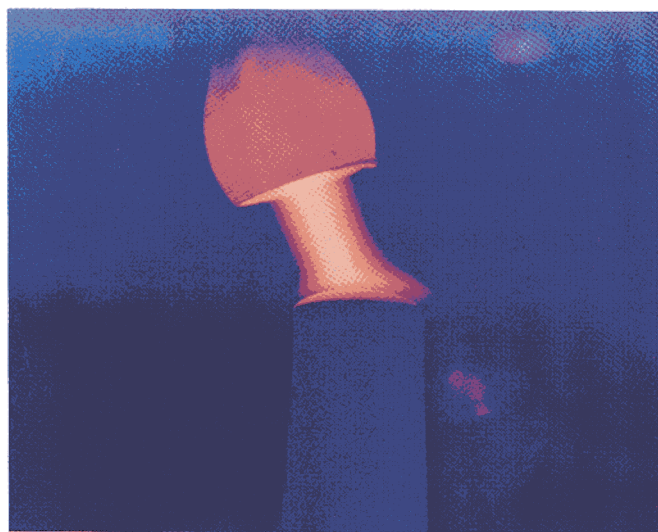


Fig. 5. Picture of porous preform grown downwards.

tical fiber via the MCVD [5] method published the previous year by Bell Laboratories, and the other to develop new methods for manufacturing optical fiber. I was in charge of the latter group. MCVD is a simple but very effective technique for adding GeO_2 to glass at high vapor pressure, yielding optical fiber with excellent properties. It is, however, a rather time-consuming process, and it is not suitable for making large optical fiber preforms.

We set about the task of developing a more efficient process for manufacturing large-diameter optical fiber preforms. We had a number of different ideas, but after considerable discussion, often including colleagues from the other group, we eventually narrowed it down to a single contender. There were three of us on the team—myself, Shoichi Sudo, and Fumiaki Hanawa, who boasted considerable experience in testing and experimentation.



Fig. 6. Equipment for the new fabrication process for optical fiber preforms.

The team had two primary ideas. The first was to prevent vaporization of GeO_2 by separating the manufacturing process



Fig. 7. Porous preform of early stage fabricated without precise control system.

into two stages—making the porous glass preform, then consolidated into transparent preform. In the first stage, fine glass particles containing GeO_2 are synthesized at low temperature, then deposited into a porous core glass; the outer surface is then deposited in a layer of pure silica glass particles to create the porous optical fiber preform. In the second stage, the porous preform is consolidated into a transparent preform by zone-heating. This two-stage process for synthesizing quartz glass was nothing new at the time, having been invented in around 1930.

The idea was that dividing the manufacturing process into two stages would enable GeO_2 to be added to the glass more efficiently, while cladding the core with silica glass would significantly reduce GeO_2 vaporization during the high-temperature consolidation process.

The second main idea was to increase the length of the optical fiber material in the axial direction. In the MCVD and OVD [6] methods, the length of the optical fiber preform is governed by that of the starting material. We took an axial growth process in the porous preform fabrication in order to produce optical fiber preforms as long as possible by eliminating the restrictions of the starting material. Fig. 3 shows the basic concepts of this new fabrication process.

At this time, research funding was becoming an enormous problem, mainly because my director refused to listen to me. So I devised a plan: I would make a model of extra-large optical fiber preform. The model preform, made by cladding a thick quartz sheath around MCVD optical fiber preform, had an outer diameter of 35 mm and was approximately 160 mm long. Since the MCVD optical fiber material being produced at that time had an outer diameter of no more than around 10 mm, the model would have left a distinct impression.

Using the model, I pitched an appeal directly to the budgeting manager of NTT R&D, saying that I needed the funding to develop a manufacturing process capable of producing optical fiber material of the size of the model. Happily, my efforts were enough to convince a number of people, and I duly received around \$1 million in funding. I still have the model (see Fig. 4), which remains one of my most treasured possessions.

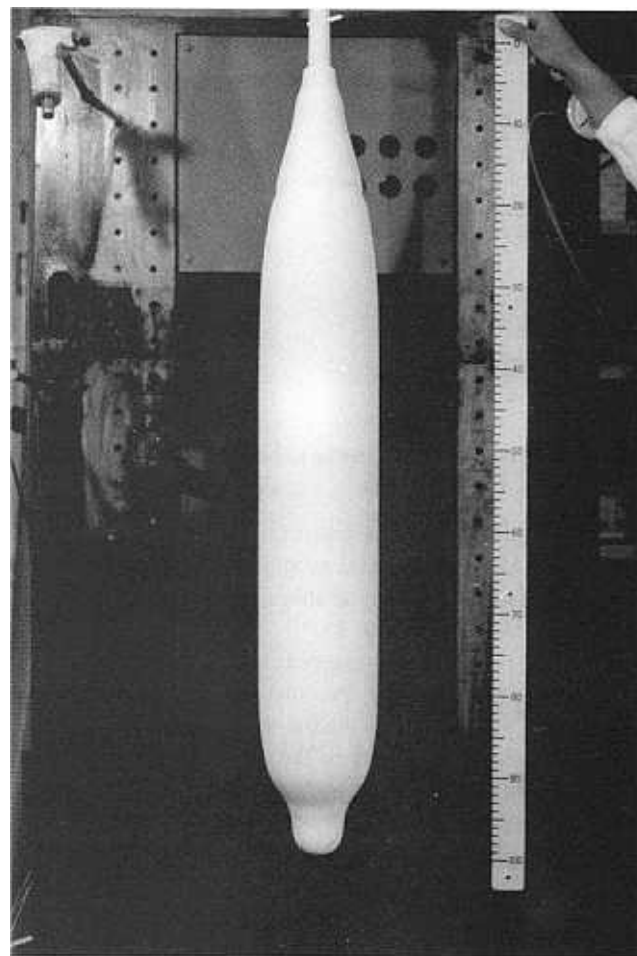


Fig. 8. Porous preform fabricated with precise control system.

VI. THE FIRST HURDLE

In order to produce long fiber preform, we needed to grow the glass in the axial direction. The first step was to produce a column of porous glass by forming a deposit of glass particles on the tip of the starting material. We began with the oxyhydrogen burner aimed downwards to form the deposit of glass particles

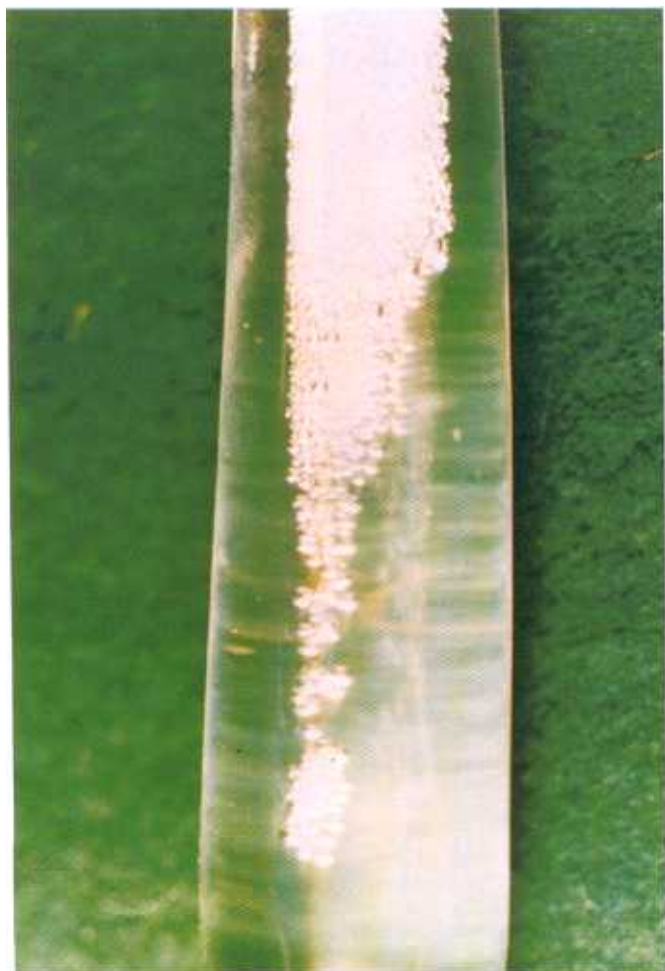


Fig. 9. Consolidated preform remaining air bubbles.

on the starting material. This approach is similar to the Verneuil method used to make artificial sapphire: excess glass particles simply fly off upwards, and the shape of the porous material is very easy to control (see Fig. 5).

Pulling the porous glass downwards, however, proved to be a difficult way to make long fiber material. For example, as the porous preform grew longer, the tip would waver and the shape would become harder to control. We decided instead to reverse the orientation, and resolved to build again all the necessary equipment ourselves. In the spring of 1976, we designed and built equipment such as: a gas controller for regulating the supply of silicon tetrachloride, germanium tetrachloride, oxygen, hydrogen, nitrogen, and argon; a pulling machine for the fiber preform to lengths of over 1 meter; glass synthesis chambers and torches; and an ultra-pure carbon resistance furnace for the consolidation process. Fig. 6 shows the equipment.

While the equipment itself was excellent, the experiment ran into more difficulties. Glass particles were getting stuck in the torches; the porous fiber preform shape was not consistent (see Fig. 7); and most of the glass particles were sucked out before forming the required deposit. We made and tested over 200 torches and modified the chamber more than 50 times. We also made a number of modifications to the exhaust gas processor.



Fig. 10. Consolidated porous preform into transparent preform.

We developed a number of instruments for accurately controlling the outer diameter of the porous preform such as: the instruments to maintain a constant distance between the tip of the fiber material and the torch by regulating the pulling speed on the fiber; the gas flow controller to keep the deposition rate constant by regulating the exhaust gas from the glass synthesis chamber. Thanks to the experimental skills of Mr. Hanawa, before long we had managed to produce porous glass with uniform

where the GeO_2 was doped in the glass (see Fig. 9). We had expected that if the high temperature zone was kept short, then the air bubbles in the center would simply float up and escape, but the reality was not that simple.

We tried various different shapes for the heater and the thermal insulation but met with no success whatsoever. In the summer of 1976, I was summoned by my director and ordered to abandon the project. We decided to ignore his order and press on, but little progress was made. By early autumn, we thought of trying an experiment which we had previously been putting off for budgetary reasons, but which we believed had a reasonable chance of success. The idea was that if the research was to be abandoned, we should at least try as many different ideas as possible before finishing.

The experiment was the introduction of He gas, which has high thermal conductivity, into the electric furnace. The He gas proved spectacularly successful from the outset, yielding transparent glass material with no foaming. The incredible sense of elation I felt at that moment was something that a researcher only experiences once or twice in a lifetime. By that stage, we had made over 200 samples of glass material. Fig. 10 shows one of the specimens made with the newly perfected outer diameter controller and consolidation process. The cross section is perfectly round, and the porous preform was consolidated into completely transparent.

At that time, I was starting work on the experiments from around 4 a.m. in the morning. After analyzing test data, discussing modifications, and sending orders to the glassmaking workshop, I would not get home until after midnight. I was also suffering from severe asthma attacks; I had to take bronchodilators throughout the day just to breathe, and my days off were entirely consumed with asthma treatment. To have been freed from this terrible existence by the success of the final experiment was absolutely wonderful. The new fabrication process was named Vapor-phase Verneuil method at early stage and renamed Vapor-phase Axial Deposition (VAD) method [7], [8].

VIII. BASIC PROPERTIES OF VAD OPTICAL FIBER

Once we had developed a successful consolidation process, making the low-loss optical fiber was not at all difficult. Since GeO_2 on the surface of core material made with even the single torch shown in Fig. 11 would still evaporate, it was relatively easy to make the low-loss optical fiber by cladding it in a quartz sheath. We were able to make fiber material with a thicker cladding layer by providing two additional torches specifically for the cladding as shown in Fig. 12.

Although the level of transmission loss was equivalent to that of MCVD optical fiber, our fiber still needed further improvement. For instance, research on the MCVD method had shown that moisture in the fiber exacerbates loss at longer wavelengths. VAD optical fiber had a high moisture content because the glass particles were produced through a reaction between water vapor produced by the oxyhydrogen flame and silicon tetrachloride. Although many people believed the problem to be insurmountable, I was confident that the moisture could easily be removed via chemical processing of the porous material.

Another problem was that the frequency characteristics of the VAD fiber were inferior to those of MCVD fiber, at a time when graded index fiber was in widespread use. I argued that by using more torches to create the core layer deposit, we could make optical fiber with a perfect refractive index distribution (as shown in Fig. 13), but I was unable to convince the people that mattered.

I was actually not that interested in working on the refractive index distribution, as I was predicting a gradual shift away from graded index fiber in favor of single mode fiber. As it turned out, single mode fiber became popular within just a few years.

The basic properties of VAD optical fiber were presented at IOOC in 1977, the first international conference on optical fiber to be held in Japan. The VAD method is currently used to produce large fibers measuring 150 mm in diameter and 2000 mm in length (see example in Fig. 14).

In February 1978, while working on solutions to the refractive index distribution and moisture problems, I was again ordered by my director to remove myself from the optical fiber research group. I put up considerable resistance, but this time my efforts were to no avail. Happily, the moisture elimination problem was successfully resolved soon after my leave by the junior researchers.

IX. LOSS LIMIT OF OPTICAL FIBERS

Another important area of my interest was loss reduction. At around that time, it was reported that the MCVD method had been used to produce optical fiber with losses as low as 0.47 dB/km [9]. In the absence of data on signal loss in glass over a wide range of wavelengths, however, it was difficult to interpret this figure in terms of loss limits.

We decided to set up another group to measure the physical properties of glass, including losses in the infrared region. The group measured absorption of molecular vibration in Si-O bonds for various thickness of silica glasses. Based on these results, we estimated the loss limit of optical fibers made of silica glass. Together with loss characteristics in the visible, near-infrared and far-infrared wavelength regions, we estimated that the loss in silica glass fiber was unlikely to ever fall below 0.1 dB/km [10], [11]. Our prediction remains true to this day despite the range of different materials trial over the years. There seems little prospect of an optical fiber with losses of less than 0.1 dB/km emerging in the near future.

X. PLANAR LIGHT-WAVE CIRCUIT DEVELOPMENT

After leaving the optical fiber group, I joined a basic research group of NTT Labs. The director abruptly told me to begin some new research. After a few months not knowing quite what to do, we finally hit on the idea of reviving earlier research into planar light-wave circuits. We knew that the nearby LSI Processing Technology Research Group had developed an excellent new technique for creating deep grooves, which was capable of producing near-vertical cross sections in etching on thick film such as SiO_2 .

We decided that we could utilize the new technology for precision processing of cores that were smaller than planar light-wave circuits made by electro-migration. The idea was

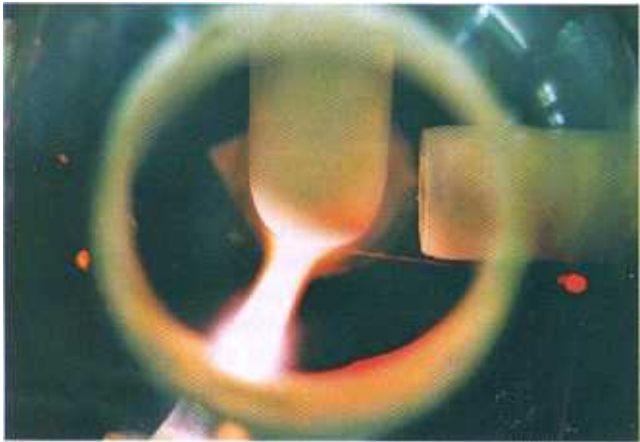


Fig. 11 Deposition process of fine glass particles with single torch.



Fig. 12 Deposition process of fine glass particles with 3 torches.

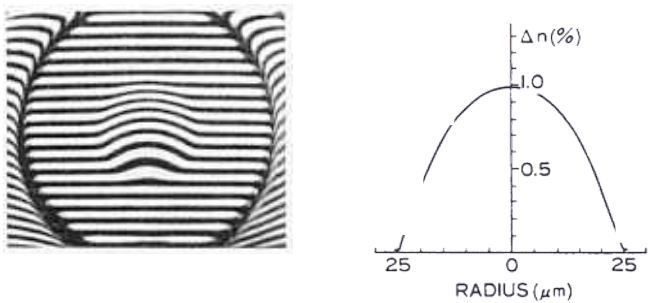


Fig. 13 Refractive index profile of a fiber fabricated by VAD method.

outer diameter. Fig. 8 shows the fully controlled porous fiber preform.

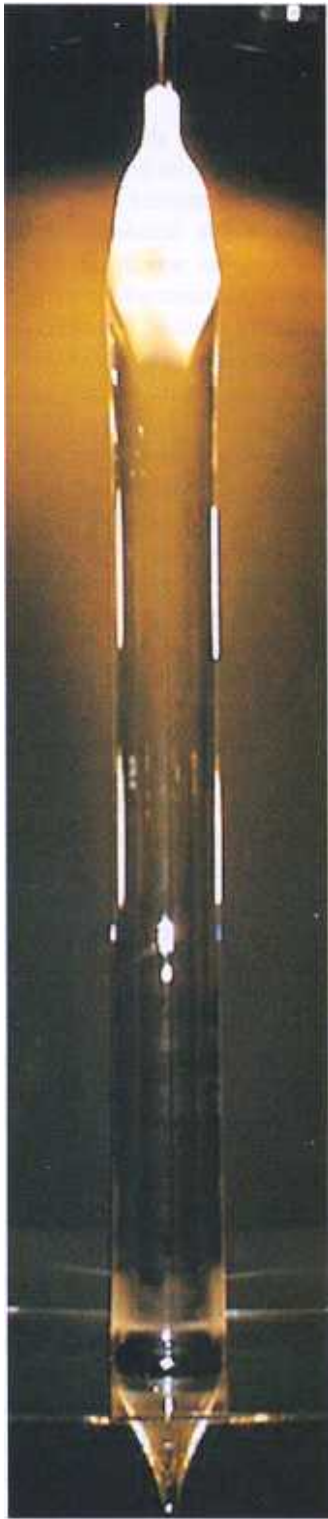


Fig. 14 Optical fiber preform fabricated by VAD method. It is about 150 mm in diameter and 2000 mm in length.

VII. THE SECOND BARRIER

The consolidation process to make transparent porous preforms proved even more difficult. When heated in the electric furnace, air bubbles remained in the core part of the preform

to form a porous glass layer containing GeO_2 on a silica glass substrate followed by a deposit of SiO_2 particles and consolidate it transparent as per the VAD method. Then process it using the new etching technology, and finally bury the core section beneath a further deposit of SiO_2 particles, thereby producing a single mode planer light-wave circuit with low scattering loss [12].

The experiment was essentially a success, notwithstanding a number of problems such as a tendency for deformation in the base foundation. The project was subsequently transferred across to the Optical Fiber Research Group where, after extensive modifications, it eventually evolved into what we now know today as PLC technology.

XI. CONCLUSION

The VAD and planer light-wave circuit research was performed in conjunction with many colleagues; I myself was no more than the person in charge at the initial stages of development. The technology we developed has since been refined and perfected by many other researchers and engineers, and is now used in a wide range of applications. At the time, I had no idea that the technology we were developing would eventually play such an important role in the world of communications. As a researcher, I am naturally honored to have been able to make a useful contribution to society.

This paper is based on an address given as part of the 25th anniversary celebrations held at the Optical Fiber Communication Conference (OFC 2000) in March 2000. I have tried to describe the background to the optical fiber and planer light wave circuit research conducted at the NTT laboratories where I worked, particularly regarding the early stages of development. I should point out that this paper represents my own personal interpretation of events based on recollections of my time as a young researcher, and as such does not claim to be a totally objective portrayal.

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Tatsuo Izawa (S'65–M'67–SM'67–F'99) is a pioneer in the field of low-loss optical fibers and silica-glass waveguides. In 1977, he invented and developed the VAD method as a leader of the project. Recently, the optical fiber installed that was fabricated by the VAD method reached 25% of the total amount of fiber installed throughout the world. Furthermore, he developed the basic technology for glass waveguide fabrication. On the basis of this study, NTT developed the silica waveguide on silicon, which is now known as the planar lightwave circuit (PLC).

Dr. Izawa has been honored with several awards acknowledging his great contribution to his work.