Being Conscious of Contact Points between Accumulated Experience and External Stimuli

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Overview

Data communications in Japan currently exceeds 2.5 Tbit/s, but it is predicted that demand will rise to 10 Pbit/s by the late 2020s. This forecast is creating concern that the transmission capacity of the existing optical fiber infrastructure could reach its limit. Kazuhide Nakajima is a Senior Distinguished Researcher at NTT Access Network Service Systems Laboratories, where researchers are working to solve this fast-approaching problem. We asked him about the latest research achievements in this field and his mindset as a researcher.

Keywords: optical fiber, multi-core fiber, space division multiplexing

Achieving the world's highest density optical fiber with deployable reliability

—Dr. Nakajima, please tell us about your current research activities.

I am researching the fabrication of multiple cores, that is, optical paths, within optical fiber with the aim of transmitting more information using just a single strand of optical fiber. In an optical fiber, light is confined within a core through the reflection of light generated by a difference in the refractive indices between the core and its outer periphery (cladding). This enables light to propagate within the core with an extremely small amount of attenuation in optical intensity. Here, light travels at an angle with respect to the interface between the core and cladding (including straight-line propagation with an angle of zero degrees). In this regard, there is single-mode fiber that allows the transmission of only one optical signal, and there is multi-mode fiber that allows the transmission of multiple optical signals. In addition, bending an optical fiber will cause a relative change in the angle of optical propagation, which in turn can prevent reflection, which causes light to leak from the core and reduces optical intensity (optical loss). Moreover, the simple fact that silica glass is used in most optical fiber can also give rise to breakage.

Recent years have seen an expansion of FTTH (fiber-to-the-home) services, and we can envision customers, who are not specialized technicians, being able to wire optical fibers themselves inside their homes in the future. In this case, however, the limits of optical fiber "bending" would become particularly

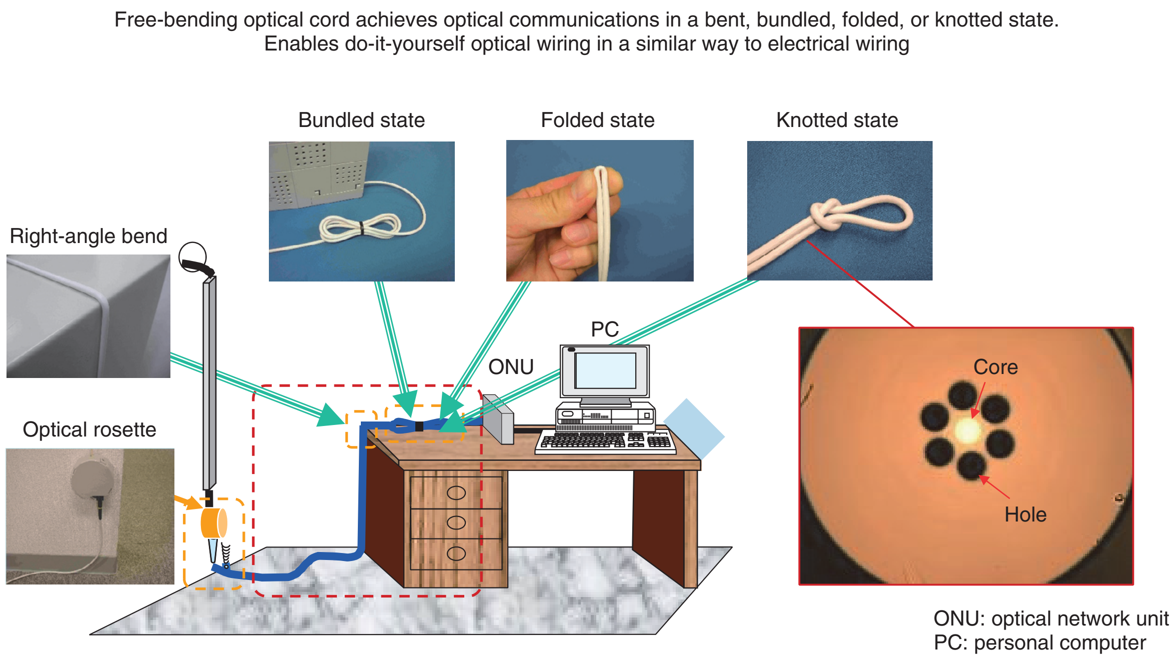

Fig. 1. Free-bending optical cord.

evident. At the same time, it is predicted that the demand for data communications will rise above 10 Pbit/s by the late 2020s, so we can also expect the existing optical fiber infrastructure to eventually reach its limit in transmission capacity.

Against this background, my team has been working on (1) the development and deployment of bendable optical fiber that anyone can use (free-bending optical cord) and (2) the development of optical fiber that can increase transmission capacity without affecting existing facilities such as civil engineering works (optical fiber for space division multiplexing transmission).

We have found that light can be confined within the core even when bending the fiber by placing multiple holes in the cladding of the optical fiber (hole structure) and using the magnitude of the difference between the refractive indices of air and silica glass. Our free-bending optical cord has a structure that enables it to be bent, folded, and knotted (**Fig. 1**). This cord contains both a sheath section surrounding and protecting the optical fiber and a dust-proof connector. This technology has become an international standard in the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T).

One way of increasing transmission capacity in communications is to increase the number of optical fibers, but there is a limit as to how many optical fibers can be accommodated in an optical cable. Additionally, in the event that no space exists for accommodating more optical cables, it would be necessary to reconstruct underground and indoor optical wiring facilities. However, increasing the transmission capacity of optical fiber itself would not have any impact on existing facilities. This can be accomplished, for example, by using multi-mode fiber, which has a larger core than that of single-mode fiber and allows for multiple modes to propagate within a core, or by using multi-core fiber, which arranges multiple single-mode cores within a single optical fiber (space division multiplexing). With either of these configurations, however, it is difficult to achieve more than 50 channels (optical paths). This level of performance is not sufficient to meet the anticipated demand in transmission capacity.

For this reason, research and development (R&D) efforts on arranging multiple multi-mode cores in a single optical fiber (multi-mode multi-core fiber) to overcome existing transmission capacity limitations are progressing around the world. However, if the distance between cores becomes too short when increasing the number of cores, optical interference can arise between cores, and if the cladding surrounding

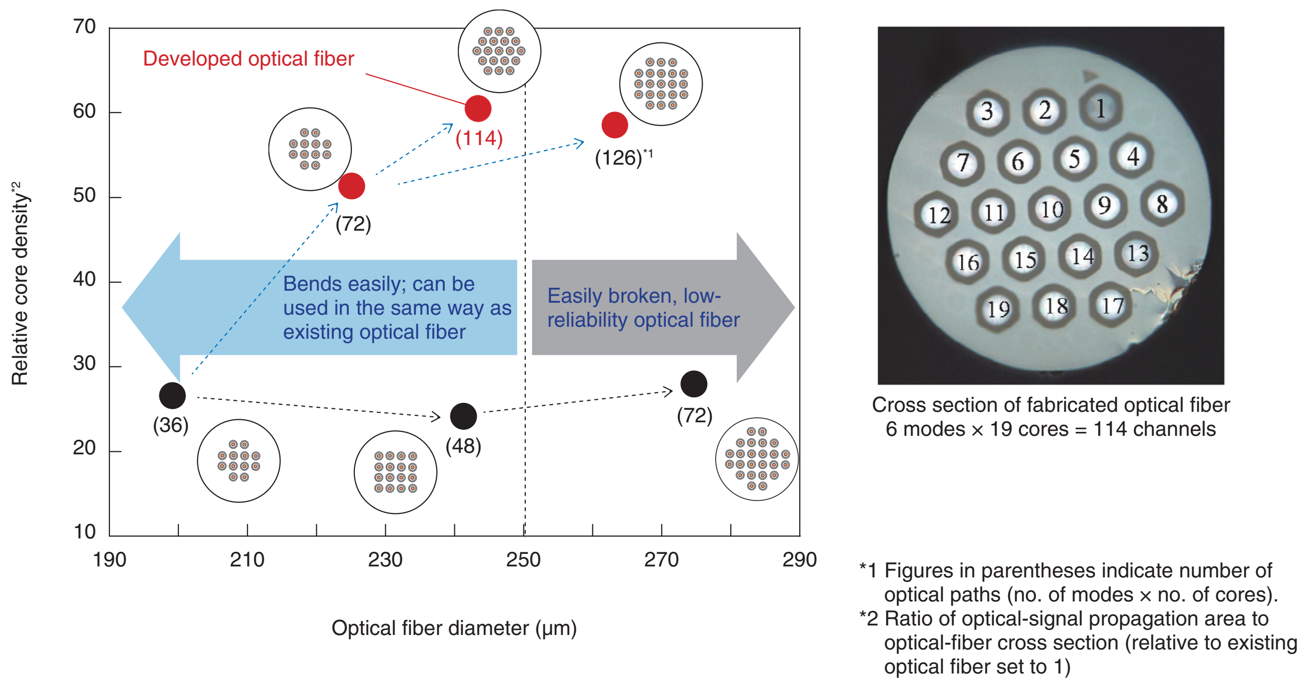

Fig. 2. World's highest density multi-core fiber.

a core is too thin, optical loss can be significant. In addition, optical fiber with a large diameter can easily break, making it unsuitable for deployment. To address these conditions, we teamed up with Fujikura Ltd. and Hokkaido University (Laboratory of Information Communication Photonics) to pursue R&D in this area and succeeded in achieving the world's highest density optical fiber.

We have known that an optical fiber with a diameter less than 250 μm could be used for more than 20 years in the field, so taking future transmission capacity levels into account, we set our objective to develop optical fiber with a transmission capacity of more than 100 channels while having a diameter of less than 250 μm. In the case of multi-mode fiber, the propagation distance differs depending on the optical reflection angle within the core, and as a result, the arrival time of light on the receiving side will likewise differ between modes. This difference makes signal processing on the receiving side complicated, a problem that has to be addressed. We minimized this time difference by adjusting and optimizing the core's refractive index profile. We also succeeded in suppressing optical interference and loss in optical fiber having a diameter of less than 250 μm by adjusting the core arrangement including the inter-core interval. The result was an optical fiber with 19 cores in a honeycomb-shaped arrangement, with each core supporting 6 modes for a multiplexing level of 114 transmission channels (= 6 modes × 19 cores) (**Fig. 2**). This is the world's highest density and is equivalent to more than 60 times that of existing single-mode and single-core optical fiber.

Taking back your remarks is OK—continue to ask yourself what you really want to do

—What kind of research activities were you involved in before obtaining world-leading research results?

I have been involved in the research of optical fiber itself since joining NTT in 1994. To give some background, I had done calculations on the characteristics of dual-core fiber during my university days, and thanks in part to that experience, I developed a desire to spread the use of optical communications throughout the world. With that in mind, I became engaged in this research. At that time, much attention was focused on wavelength division multiplexing (WDM) technology as a means of increasing transmission capacity by multiplexing optical signals of multiple wavelengths. The development of optical fiber applicable to WDM became my exclusive research theme.

Then, from 2000 on, I took up the research of optical fiber having a hole structure. For some time, optical fiber was vulnerable to bending, and it was a request from another department to obtain optical fiber that could overcome this weakness and be used by anyone that got me started in this research. In 2005, we succeeded in developing and deploying for the first time in the world optical fiber with the new structure, which applies the effect of confining light by opening up holes in the cladding. These efforts led to the development of a strong optical fiber with no reduction in transmission performance, even it was accidently crushed by a chair. Since 2010, I have been researching the development of multi-core fiber as my main theme with the aim of increasing the transmission capacity of existing optical fiber.

—What difficulties did you face on your way to achieving such world-first technology?

Optical fiber confines optical signals by using materials with different refractive indices. Commonly used optical fiber creates a difference in the refractive index between the core and the cladding due to the addition of different types of dopants to silica glass. Naturally, the refractive indices of silica glass and air are different, and this property can be used to fabricate holes within the optical fiber and to fabricate a core without having to add any dopants to the silica glass. This is optical fiber with a hole structure. Such optical fiber requires that the holes be uniformly arranged, but doing so requires highly advanced technology. This technology had yet to be developed or reach the deployment stage.

Well, on receiving the request for bendable optical fiber, there were some discussions within my team as to whether to respond to this need as our next research theme or prioritize the development of fiber with a perfect hole structure. But during these discussions, it was discovered that light in optical fiber with a hole structure would not permeate the core boundary and would not leak even if the fiber was bent. We therefore wondered whether bendable optical fiber could be achieved by incorporating holes in fiber having ordinary cores, and we decided that this would be our research theme.

While proceeding with this research, information came to light that announcements on similar technology were being made by other institutions. Although our research had progressed to some extent, we had to bring it to a stage ready for presentation in only two weeks if we were not to be left behind. During this short period, our team made a unified effort not only to accelerate the research but also to prepare a presentation paper, complete procedures for acquiring patent rights, and other tasks. We had to battle time more than our competitors!

—What kind of researcher were you during this roll-out of world-leading technology?

A fascinating thing about research is that you can think freely about anything and about things that don't yet exist in the world and then go out and try to create them. It truly is a world of imagination and creation. That being said, I believe that I have been a very ordinary researcher up to this point. I have been immersed in my own world by probing deeply those things that interest me. For example, optical fiber must be uniform in composition, but when I deliberately tried to make it non-uniform, I was told by my superior to "research something useful," but I paid no attention. However, on hearing about the need for bendable optical fiber, I found that there is no value in just developing optical fiber itself. In other words, I realized that great research results are meaningless unless they can be put to practical use.

One more thing: my work in the standardization of optical fiber for use in telecommunications had a major influence on my research life. Since 2000, I have been participating in an ITU-T meeting that formulates international standards for optical fiber, and it was there that I learned that performance is not the top priority in creating a standard; a more essential requirement is that the standard be versatile and reasonable in use. This is certainly an opposing viewpoint or direction from research that places priority on cutting-edge technology and groundbreaking results (**Photo 1**).

These two experiences helped to make me conscious of the need for practical applications in the real world when researching advanced technology. That is, I came to realize the importance of finding contact points between the real world and the advanced technology of my research.

—Your viewpoint has drastically changed through your research activities. What do you take to heart in going forward?

I advance in a somewhat helter-skelter manner. Even in my present research on large-capacity transmission, I look back at my original objective at every opportunity. The research that we are now working on is of a long-term nature looking ahead 10 to 20

(From left) Kazuhide Nakajima (Question 5 Rapporteur, NTT),
Francesco Montalti (Study Group 15 Vice-Chairman, Tyco, Belgium),
Kazuyuki Shiraki (Question 8 Rapporteur, NTT),
Kunihiro Toge (Question 16 Rapporteur, NTT),
and Noriyuki Araki (Study Group 15 Vice-Chairman, NTT)

Photo 1. At ITU-T Study Group 15 meeting, September 2016.

years, so there will likely be few opportunities to receive concrete feedback. This is precisely why it is important that we closely analyze the results that we have so far obtained with the aim of creating something useful for society. This type of approach can lead to greater self-awareness of the value of our research. Stimuli from other people and from the outside are also important here. Let me give you two examples.

The first one relates to the time of our development of optical fiber that could actually be used inside the ordinary home. This turned out to be a major source of encouragement for me, but there was an incident that revealed that I had not been aware of the significance of that research. I was involved in the training of third-year employees as a lecturer, and one of the trainees asked a question, saying "Mr. Nakajima, why are you researching optical fiber?" I was actually lost for words. Looking back, I had been researching optical fiber since my university days, and although I had been interested in optical communications and optical fiber from the very start, it was not because I had a strong desire to enter this field. Rather, it was a result of chance events in which I seemed to encounter this field whenever I was at a crossroads on my career path. In addition, I considered that my interest in this thing called "optical fiber" and the dreams I had for it were what brought me to the present. After thinking about it for a while, I realized that the results of my ongoing research were now being used in the world and were of benefit to both NTT and society, and I noticed that that had boosted my confidence.

The other example concerns the ITU-T meeting that I have been participating in. This meeting is held every eight months in Geneva, Switzerland. At this meeting, participating countries and organizations make proposals while having heated discussions amid conflicting interests. These discussions are all conducted in English, which I am not totally comfortable with, and our task is to assemble these proposals into an international standard. Although this is a special overseas meeting for me, I would say that my evening meal was about the only thing I looked forward to. I would typically become so focused on the discussions that, without noticing it, I had turned my attention to the discussions themselves instead of searching for common ground to form a conclusion. So, during the weekend in the middle of the two-week session, I would refresh myself with some kind of activity such as mountain climbing. Such external stimuli would help me to clarify things in my head so that I could then bring all those discussions together into an international standard.

Although it's important to set clear goals, no one knows what the future will bring. Research being what it is, you don't know what is right or wrong at first. Our group frequently discusses the direction we should be taking, while taking experimental data and real-world trends into account, and if necessary, we revise our research theme before moving forward. For this reason, I believe it's perfectly acceptable for a researcher to be anxious about his or her research and to retract an earlier statement. I understand there are times when a researcher may steadfastly refuse to back down after making a certain statement, but being bound by something you say may prevent you from advancing at all.

On top of this, I think it's important to listen carefully to what other people have to say. Flexibility is essential to get one's research out into society. Looking for contact points between a variety of matters and one's research results is an important factor in achieving deployable technologies. It's good to stick to one's work, but stubbornly refusing to change may prevent you from spotting those contact points.

Always give thought to what you want to accomplish

—What are your ambitions and outlook for the future?

I am not a theoretician. I have pursued research in a straightforward and persistent manner, continuing to reflect on the experimental data that I have collected until I'm satisfied. Going forward, I would like to improve my skills and abilities by continuing with this approach. My superior, who gave me much guidance from the time I entered the company, left me with these words when he left NTT: "It's too early to express thanks to me. Instead, work to create a path for those coming after you." I will always take these words to heart. Although I don't know when I, too, will leave NTT, at that time, I hope that I will have created such a path for future generations of researchers.

Of course, whether I stay at NTT or go elsewhere, optical fiber will always be part of my life. I want to continue thinking about new ways of using optical fiber. In addition, I want to be a researcher who talks about his dreams, and I want to move forward without abandoning thinking on my own.

A major objective of mine is to develop technology that can be used in future large-capacity transmission systems. The limit of optical fiber now in use is said to be 100 Tbit/s. Once implemented, optical fiber deployed in transmission paths will be used continuously for 20 to 30 years, and when that optical fiber is replaced, the aim is to achieve a transmission capacity about 100 times greater. We think there is the potential to achieve this because we have already achieved a density 60 times the existing level. However, there are still many issues that have to be addressed before actual deployment, so we continue our R&D efforts to achieve better results. Manufacturing technology is the key to deployment, so we plan to hold discussions with manufacturers and make best use of our mutual strengths. It is also important that we get multi-core fiber technology out into the world as soon as possible to plant the seeds of future large-capacity transmission systems.

—As an active researcher, what would you say to young researchers as to what is important to produce results?

Today's young researchers are highly motivated and highly skilled. However, at the risk of being misunderstood, they tend to be quiet and well behaved compared with my generation. In my time, there were even people who did not follow their superiors' directives, but today, such an attitude is not common. Perhaps the low number of entry-level employees has an effect here. It's not that I want to promote a rebellious attitude, but in order to find out why someone is not expressing an opinion, I will often ask: "What do you really want to do? What are you thinking about in your work?" If I ask this question enough times, I may get a brilliant, off-the-cuff reply. If you can form some kind of relationship, that person is apt to tell you exactly what is on his or her mind.

Nowadays, it feels that time is passing by faster than before. For this reason, I think we have less free time. To keep yourself from losing your way under such conditions, please have a dream. At the same time, dig deeply into your research but change your viewpoint if necessary. Please approach your work with this frame of mind.

In addition, don't hesitate to try something even if you feel it's not directly related to your own research. Doing so can broaden your horizons and reveal more of yourself in many ways. It can also help you uncover contact points for making your research results a reality. Last year, I assumed the position of a director in a small academic society. The objective of this society is to act as an intermediary between network operators and vendors. Although my role is as an advisor, I thought when taking this role that it would be an experience that would be hard to come by otherwise, and I felt that it could help me form contact points that could make my research useful to society.

In this way, knowing that young researchers who may be worried or confused are traveling along the same path that I have traveled, I would like to make them reflect on their original objectives, help them set their sights firmly on their final goal, and support them to see other viewpoints. To repeat, I like the work of research and I enjoy thinking about and creating things that do not presently exist in the world. By all means, please come to like and even enjoy the fascinating work of research.

■ Interviewee profile
Kazuhide Nakajima

Senior Research Engineer, Supervisor (Senior Distinguished Researcher) and Group Leader of NTT Access Network Service Systems Laboratories.

He received an M.S. and Ph.D. in electrical engineering from Nihon University, Chiba, in 1994 and 2005. In 1994, he joined NTT Access Network Service Systems Laboratories, where he engaged in research on optical fiber design and related measurement techniques. He is also acting as the rapporteur of Question 5 in ITU-T Study Group 15. Dr. Nakajima is a member of the Institute of Electronics, Information and Communication Engineers, the Institute of Electrical and Electronics Engineers, and the Optical Society of America.