Spatial-mode Optical Measurement Technology to Support Diverse Global Services in the Future

Atsushi Nakamura
Distinguished Researcher, NTT Access Network Service Systems Laboratories

Abstract

Communication traffic continues to increase each year and to continue to support this demand in the future, it will be necessary to shift from conventional single-mode fiber to next-generation optical fiber lines, utilizing multi-core and multi-mode fiber. However, to implement high-quality next-generation optical fiber lines requires consideration of different physical phenomena than those considered in the past. We spoke with Distinguished Researcher Atsushi Nakamura about his spatial-mode optical measurement technology, which can visualize and grasp such phenomena.

Keywords: optical measurement technology, spatial modes, optical-fiber transmission line

Spatial-mode optical measurement technology is essential for high-quality, next-generation optical-fiber transmission lines

—Can you tell us what "next-generation optical-fiber transmission lines" are?

Communication traffic has continued to increase in recent years, and society's demand for more capacity on optical fiber networks is increasing. Transmission methods on conventional optical fiber networks have used single-mode fiber, meaning a single optical fiber carried only one optical signal. However, we are approaching the limits of per-fiber transmission capacity for single-mode fiber, which will make it difficult to increase transmission capacity in the future. As such, new transmission methods that overlap multiple signals spatially will be needed in order to continue to meet the increasing demand for communication capacity in the future.

The simplest method for spatially overlap signals is to build multiple conventional single-mode fiber transmission systems in parallel. However, with this method, increasing the transmission capacity by a factor of N would also increase the cost by a factor of N, which would not be practical or economically feasible. Thus, to continue increasing transmission capacity, methods incorporating multiple cores within a single optical fiber, and methods that create multiple optical signal paths (spatial modes) within a single core (space-division multiplexing) are being studied (**Fig. 1**).

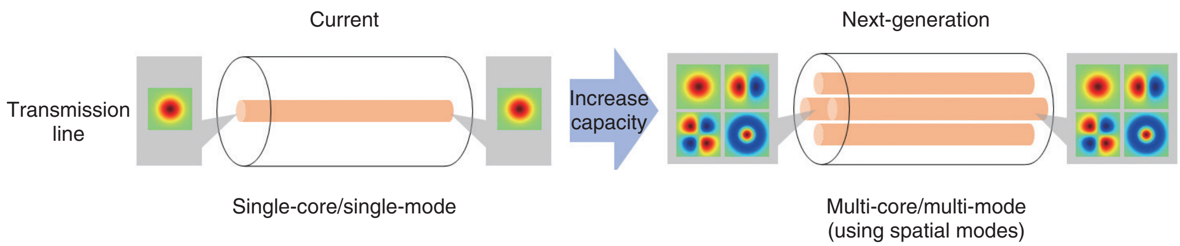

Fig. 1. Next-generation optical fiber technology using spatial modes.

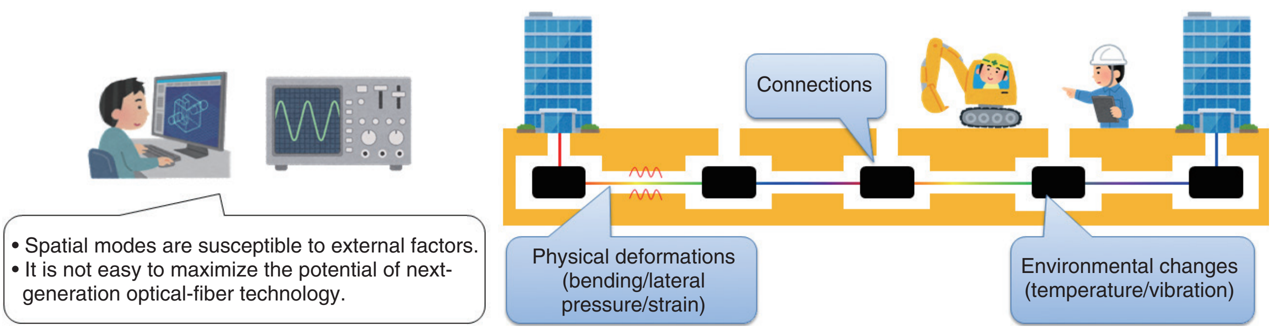

Fig. 2. External factors when constructing optical-fiber transmission lines in real environments.

—Can you tell us about any difficulties encountered in implementing next-generation optical-fiber transmission lines?

Next-generation optical fiber is a promising technology for dramatically increasing the transmission capacity of a single optical fiber, but it is not easy to implement transmission lines that can maximize this potential. With conventional single-mode fiber, communication uses only a single spatial mode, so when creating a transmission line with single-mode fiber, quality could be ensured mainly by evaluating losses in the optical signal. However, multiple spatial modes are used for communication in next-generation optical fiber, so in addition to optical signal losses, it is necessary to consider complex optical characteristics such as interference and loss differences between the spatial modes. These characteristics are susceptible to external factors, so even the smallest changes can alter their behavior. To maximize the potential of next-generation optical-fiber technology, it is important to evaluate how these complex optical characteristics change due to external factors, and to create optical-fiber transmission lines that minimize the effects of such changes. For these reasons, it is extremely important to have optical measurement technology that can visualize the quality of transmission lines.

Additionally, creating optical-fiber transmission lines in real environments introduces various external factors, including physical deformation due to bending, lateral pressure, and strain; optical fiber connections; and environmental factors such as temperature and vibration (**Fig. 2**). For example, when the two communication buildings on the left and right in Fig. 2 are connected, an optical-fiber transmission line is created by installing several kilometers of optical cable through conduits, with successive connections between them. If there are any quality issues with connections or other factors when building this transmission line, it will need to be rebuilt to ensure communication quality. If any issues are detected after the entire transmission line has been built, manual work to re-connect, or to remove and reinstall optical cables will be required. To avoid the additional effort of redoing this work requires testing the quality every time a connection is made.

The difficulty here is the need to evaluate characteristics at any point along the transmission line from one end of an optical fiber cable, while the transmission line is being built. This is because optical cables and connection points are on outdoor and underground segments when building a transmission line and it is not operationally practical to transport measurement equipment to each location. As such, we require measurement equipment that can be placed within the communication facility buildings and can evaluate the quality of the line being built at any distance from the building. Establishing this sort of optical measurement technology will enable us to build and operate next-generation optical-fiber transmission lines with a thorough understanding of spatial-mode characteristics and will contribute to taking the lead globally in implementing next-generation ultra-high-capacity optical communication services.

—Specifically what sort of research are you conducting to implement these next-generation optical-fiber transmission lines?

A specific area of research has involved devising and verifying testing methods to be used when building optical-fiber transmission lines with multi-core fiber, which has multiple cores within a single optical fiber. If the spacing between cores becomes too narrow, optical signals can leak between the cores (causing "crosstalk") and can degrade communication quality when creating multi-core fiber transmission lines. The effects of such crosstalk on communication quality can vary greatly depending on the quality of work when performing construction in real environments, so it is necessary to evaluate such effects at every stage of transmission line construction. If such tests are not done and poor quality is identified only after construction is completed, the line may have to be rebuilt, as mentioned earlier, incurring great additional time and expense. However, directly measuring crosstalk requires very expensive equipment, which is a major obstacle for businesses. Existing single-mode fiber will continue to be used even after multi-core fiber is introduced, so new equipment will also need to be compatible with single-mode fiber. For these reasons, we also devised and verified a method to evaluate changes in crosstalk characteristics based on loss values that can be measured using an ordinary optical-pulse tester, which is also used for testing single-mode fiber. This enables us to use existing equipment to ensure construction quality when building next-generation optical-fiber transmission lines using multi-core fiber in real environments.

Explaining spatial-mode characteristics, establishing methods to evaluate transmission-line quality, and creating new added value

—Could you tell us about your research objectives and vision for the future?

Next-generation optical-fiber transmission line technology is an important technology for achieving "125x transmission capacity," which is one of the performance objectives for the All-Photonics Networks (APN), as part of the Innovative Optical and Wireless Network (IOWN) plan. The optical measurement technology that I am currently researching to visualize spatial-mode characteristics and behavior will contribute to building and operating next-generation optical-fiber transmission lines with high capacity and stable communication quality. In future research, we hope to realize a world in which next-generation optical-fiber transmission lines are used continuously as indispensable social infrastructure to support all kinds of services around the world.

In a future initiative, I would like to be able to fully control spatial modes so that they can be used for optical measurements. I do not have concrete ideas for this technology yet, but I think we should be able to create new optical measurement technologies using the characteristic of spatial modes that they are sensitive to minute changes. For example, no changes can be observed before an earthquake using existing optical measurement technologies, but it may be possible to use spatial modes to take measurements and visualize phenomena that could not be observed earlier. Using spatial-mode characteristics could contribute to early detection of disasters in this way, or to solving other societal issues (**Fig. 3**).

—What are some important aspects of research for you?

I conduct research with the idea that technology does not produce any value until it is used by someone. Research is the first step, and I am careful to consider where what I am researching will ultimately be used, what it will be useful for, what approach will achieve it, and what impact all of these will have on my final objectives. Research also involves competition with other institutions, so a sense of momentum and urgency is important. Of course, we want to take the time needed to produce good technology, but there is always the chance of being second to the market, which reduces the value of the technology. To

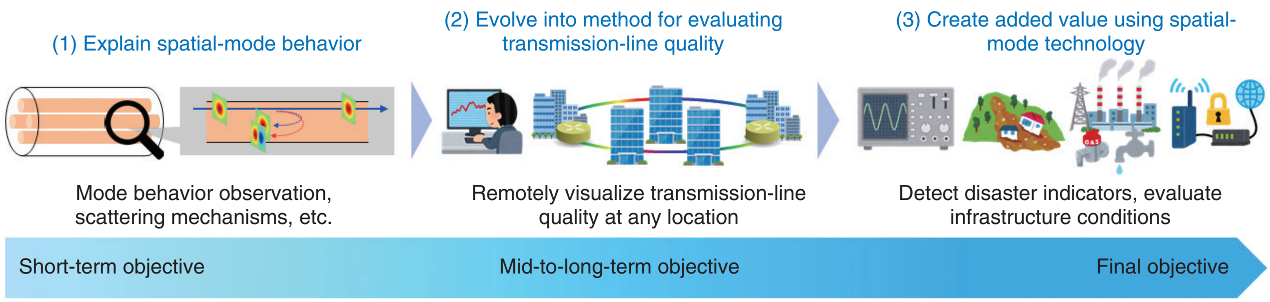

Fig. 3. Initiatives and objectives in spatial-mode optical measurement technology.

avoid such an outcome, I set objectives and priorities to be the first to achieve them. I also approach research with the intention of always producing a result in the form of a patent or published paper on the subject being studied. Including other group companies, NTT is a large corporation, so what we research can be made into something that is actually put to use within the group. This makes it possible to accumulate results that have been implemented, which gives me a sense of the value of my efforts and experience.

The ability to produce good results is not something we are born with, but is determined by our knowledge and experience. Especially now, technology and conditions in society are changing quickly, and what is needed changes accordingly. Under such conditions, insufficient preparation and effort can result in missed opportunities, so I try to maintain steady effort in my studies. Even for business or events that initially seem unrelated to my research, I always try to find something that I can get from them, because changing my perspective can provide a chance to gain a new way of thinking or new experience.

—Dr. Nakamura, please leave us with a message for other researchers, students, and business partners.

NTT Access Network Service Systems Laboratories, where I work, has wide ranging initiatives from basic research to applications, mainly in communications infrastructure technology. There are many excellent researchers, each with different knowledge and experience, so I have strong connections in many fields, and by conducting research as a team in such an environment, I can achieve things I could not do as an individual. I feel this is a real strength of NTT. As I continue my research, I always feel that it would be difficult for me to produce major results by myself, and my social connections are extremely important for the smooth progress of my research. As an example, for research it is important to collaborate with people in many fields, but if I have no relationship with someone and suddenly try to ask them to do something new, they basically would not listen to me. For starting new research, it is very important to build a broad network. When someone has a network in another laboratory within or outside of NTT, it can also help to make connections through them. Having people with many connections around me in this way also helps me to steadily advance my research.

When research advances to a completed product or technology, no matter how good it is, the result will be meaningless if we cannot describe it to users in a way that makes them want to use it. Someone with experience in business will have better skills in this area than a researcher like me. I am also very thankful that I can collaborate with people around me who are skilled at tasks that I cannot do myself.

I suppose there may be young researchers reading this who would like to stay inside their own world doing their research. When I was a student, I don't think I was very courteous with people that seemed unrelated to my research either. However, after entering the work-force, we sometimes meet people that do not seem to have anything to do with our research, or even have to work with them on research, and this can lead to new and different opportunities. I hope that you will always value the connections you have with the people you meet, to find as many opportunities as possible and not miss any.

■ Interviewee profile

Atsushi Nakamura completed a master's degree at Osaka Prefecture University in 2012 and joined NTT the same year. He completed a Ph.D. at Osaka Prefecture University in 2018. He has been a distinguished researcher at NTT Access Network Service Systems Laboratories since 2022, conducting research on optical measurement technology and contributing to realizing next-generation optical-fiber transmission lines. He has received awards including a 2018 IEICE Young Researcher's Award.