World's Highest Density Optical Fiber for Space Division Multiplexing with Deployable Reliability

Taiji Sakamoto, Takashi Matsui, Shinichi Aozasa, Kyozo Tsujikawa, and Kazuhide Nakajima

Abstract

Space division multiplexing (SDM) technology has been intensively investigated in order to substantially increase the network capacity of optical fiber telecommunication. Multi-core or multi-mode fiber is a promising candidate for next-generation optical fiber. In this article, we describe our optical fiber for SDM transmission that can realize 100 times larger capacity than that of standard single-mode fiber while maintaining deployable mechanical reliability.

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

1. Introduction

Existing telecommunication networks mainly utilize single-mode fiber (SMF), whose low loss and broadband characteristics have resulted in increased network transmission capacity. The progress in the capacity per optical fiber of the core network in Japan is shown in **Fig. 1**. The transmission capacity has steadily increased year by year, and the rate of increase grew by 1000 times in a 20-year period (from 1.6 Gbit/s in 1987 to 1.6 Tbit/s in 2007). This rapid increase in capacity is due to the development of transmission technologies such as time division multiplexing and wavelength division multiplexing, as well as the development of optical amplifiers such as erbium-doped fiber amplifiers.

A transmission system using digital coherent technology was recently introduced, and 8-Tbit/s capacity has been achieved by using a multi-level modulation format with high spectral efficiency. However, it is expected that the capacity limit of the standard SMF is around 100 Tbit/s [1]. Therefore, it is necessary to develop a new transmission medium to achieve 1000 times larger capacity in the next 20 years. Space division multiplexing (SDM) technology using multi-core or multi-mode fiber has been intensively investigated as a promising candidate for a next-generation transmission system. In the following section, we report our latest research results on the development of optical fiber for an SDM system taking the spatial density and mechanical reliability into account.

2. Optical fiber for SDM system

Multi-core and multi-mode fibers are depicted in **Figs. 2(a)** and **(b)**. Multi-core fiber has multiple cores within a cladding, and multiple signals can be transmitted in parallel by using multiple cores. Multi-mode fiber typically has a larger core than that of SMF, and multiple modes can propagate within a core. Each mode is orthogonal to each other and is treated as an independent transmission path. Thus, mode division multiplexing (MDM) is realized, where multiple signals can be transmitted through multiple modes.

Multi-mode multi-core fiber has been studied recently in order to achieve ultra-high capacity transmission. This fiber combines multi-core and multi-mode technologies. The structure of the multi-mode multi-core fiber is shown in **Fig. 2(c)**. There are multiple

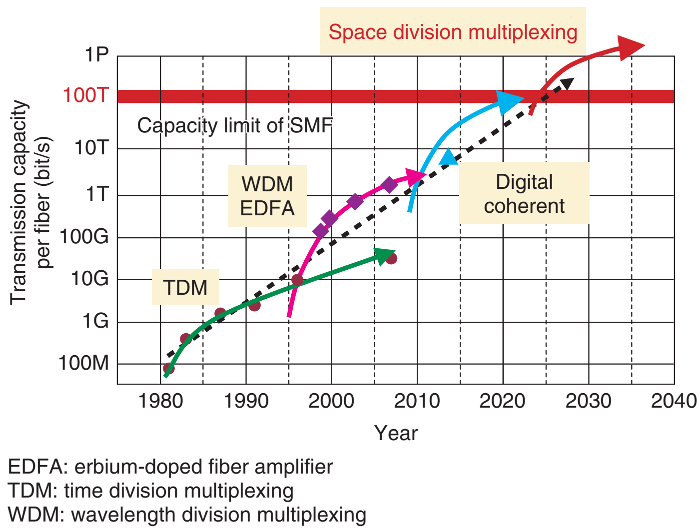

Fig. 1. Progress in transmission capacity per optical fiber.

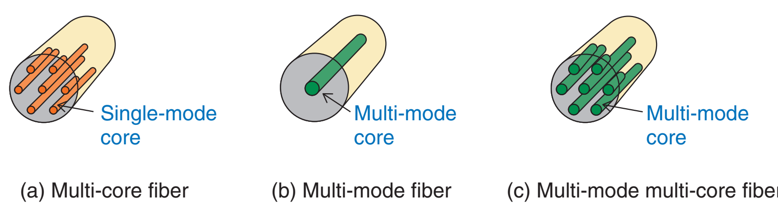

Fig. 2. Schematic diagram of multi-core and multi-mode fibers.

cores, and multiple modes can propagate within each core. This enables us to employ MDM transmission using each core. As a result, $m \times n$ transmission channels are obtained with n-mode m-core fiber.

The transmission channels per fiber as a function of fiber diameter of recently reported multi-core fiber are shown in **Fig. 3**. The results for multi-core fiber with single-mode cores and multi-mode cores are respectively plotted as open and solid circles. It can be seen that the multi-mode multi-core fiber makes it possible to achieve substantially more transmission channels compared to single-mode multi-core fiber. In fact, more than 100 transmission channels can be obtained with multi-mode multi-core fiber. However, more transmission channels results in a larger fiber diameter. Next, we describe some important parameters when designing the SDM fiber.

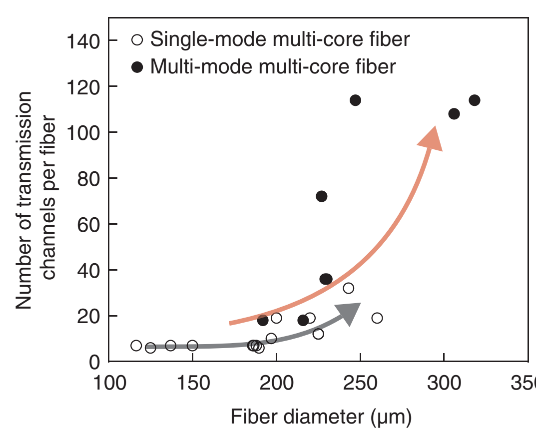

Fig. 3. Relationship between transmission channels per fiber and fiber diameter.

2.1 Mechanical reliability

Failure probability, which means the probability that a fiber will be broken, increases as the fiber diameter increases when fiber is bent owing to the inherent nature of the glass. A failure in a transmission line causes a disconnection of the network service and

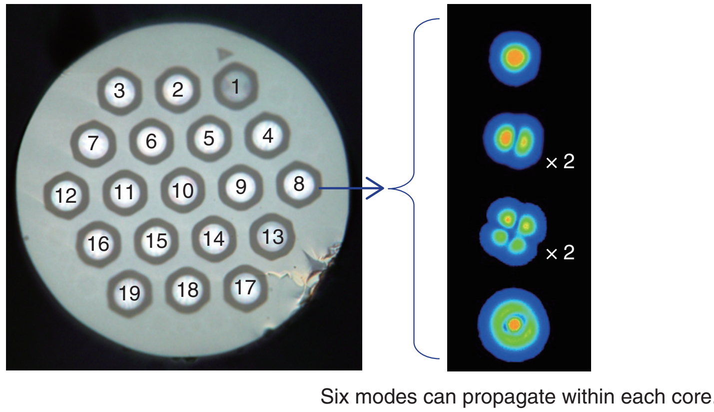

Fig. 4. Cross section of fabricated 6-mode 19-core fiber.

should be avoided so as not to degrade the network reliability. Thus, the fiber diameter cannot be increased in an unlimited fashion in order to deploy a larger number of cores, and a fiber diameter design that maintains flexibility and reliability is required.

2.2 Spatial density

It is important for the telecom operator to design a multi-core fiber with the cores packed as closely as possible because we need to efficiently utilize the limited space of the telecom infrastructure such as the cable duct space underground. The spatial density, namely the number of cores per unit area, is one of the parameters used to evaluate the density.

2.3 Transmission characteristics

The transmission channels in the SDM fiber need to have better performance than those of the SMF. This means that the SDM fiber should have low transmission loss characteristics comparable to the SMF, and the inter-core crosstalk should be suppressed by properly designing the distance between neighboring cores. The differential mode delay (DMD) is also an important parameter for multi-mode multi-core fiber. DMD is the group delay difference between the propagation modes. The propagation modes typically have different group velocities. Reducing the DMD in an MDM system is strongly required because it becomes more difficult to recover the transmitted signals at the receivers when the DMD is large.

3. Fabricated fiber with world's highest spatial density

A cross section of the fabricated fiber is shown in **Fig. 4**. It has a hexagonally arranged 19-core structure with 6-mode cores, and there are 114 transmission channels per fiber in total. This fiber has the following advantageous features.

3.1 Deployable mechanical reliability

Our fiber was designed to have a suitable fiber diameter for maintaining deployable mechanical reliability. The relationship between the fiber failure probability and fiber diameter is shown in **Fig. 5**. It is clear that an increase in the fiber diameter causes an increase in failure probability, which reduces the reliability of the fiber. Fiber reliability depends on the bending radius and proof testing as well as the fiber diameter. Proof testing is a process to improve the reliability of the fiber by applying longitudinal stress to the fiber during the fabrication process. A 1–2% proof level is commonly used in the current manufacturing process, and a bending radius of less than 15 mm is assumed for recent high density optical fiber cable design, so we have targeted a fiber diameter of less than 250 µm to obtain the same mechanical reliability as that of SMF. The fabricated fiber has a fiber diameter of 246 µm. Thus, deployable mechanical reliability for a telecommunication network is obtained.

3.2 Highest spatial density

Our fiber has the world's highest spatial density among reported SDM fibers. To achieve this, we investigated the optimum core structure to incorporate the transmission channels efficiently within a fiber diameter of less than 250 µm. The relationship between the spatial density and the fiber diameter of various multi-mode multi-core structures is shown in

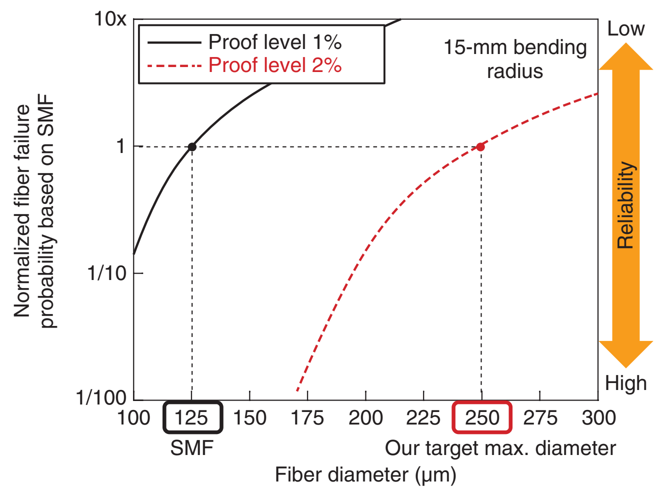

Fig. 5. Relationship between fiber failure probability and fiber diameter.

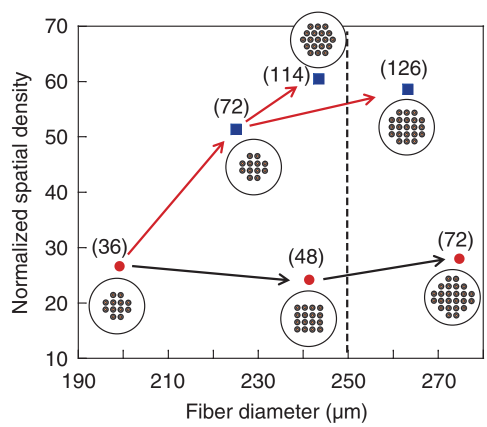

Fig. 6. Relationship between spatial density and fiber diameter of various multi-mode multi-core structures.

Fig. 6. The number of spatial channels is noted in parentheses. Here, the spatial density is the number of transmission channels divided by unit area of the cross section, and it is normalized by that of SMF. We assumed 12–21 core structures with 3-mode cores (red symbols) or 6-mode cores (blue symbols). We found that 6-mode multi-core fiber can achieve larger spatial density than that of 3-mode multi-core fiber, and the 6-mode 19-core structure can be obtained within a fiber diameter of less than 250 μm. We fabricated the 6-mode 19-core fiber as shown in Fig. 4 and achieved the world's highest spatial density of more than 60.

3.3 Optical properties suitable for long-haul transmission

Our fiber has suitable optical properties for long-haul transmission owing to the well-controlled fabrication process. The refractive index profile of the core is shown in **Fig. 7(a)**. It has a graded index core with a low index trench. The graded index core profile enables us to reduce the DMD, and the low index trench can reduce the inter-core crosstalk. The transmission loss as a function of the DMD value of reported multi-mode multi-core fibers is plotted in **Fig. 7(b)**. As shown in the graph, our fiber had the lowest loss (less than 0.24 dB/km) and DMD (less than 0.33 ns/km) among various fibers. In addition, the inter-core crosstalk was suppressed below

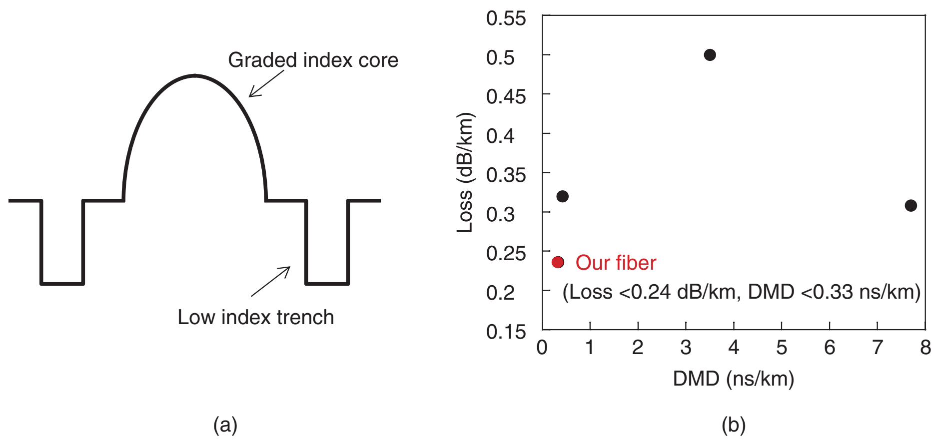

Fig. 7. (a) Schematic diagram of trench assisted graded-index core profile, (b) transmission loss vs. DMD of recently reported few-mode multi-core fibers.

–30 dB/100 km, which corresponded to having the potential to transmit quadrature phase shift keying (QPSK) signals over 1000 km with negligible power penalty induced by the crosstalk. We experimentally confirmed that QPSK signals through 114 transmission channels were successfully transmitted over an 8.85-km-long fiber [2]. This indicates that our fiber has suitable transmission characteristics for long-haul SDM networks.

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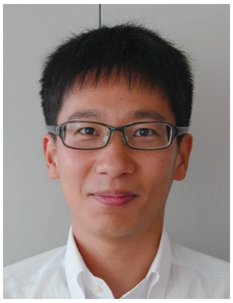

Taiji Sakamoto

Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. in electrical engineering from Osaka Prefecture University in 2004, 2006, and 2012. In 2006, he joined NTT Access Network Service Systems Laboratories, where he has been conducting research on optical fiber nonlinear effects, low nonlinear optical fiber, few-mode fiber, and multi-core fiber for optical multiple-input multiple-output transmission systems. Dr. Sakamoto is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Takashi Matsui

Senior Research Engineer, Access Media Project, NTT Access Network Service Systems Laboratories.

He received a B.E., M.E., and Ph.D. in electronic engineering from Hokkaido University in 2001, 2003, and 2008. He also attained the status of Professional Engineer (P.E.Jp) in electrical and electronic engineering in 2009. In 2003, he joined NTT Access Network Service Systems Laboratories, where he researches optical fiber design techniques. Dr. Matsui is a member of IEICE.

Shinichi Aozasa

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.S. and M.S. in chemistry from Hokkaido University in 1996 and 1998 and a Ph.D. in engineering from the University of Tokyo in 2008. In 1998, he joined NTT Opto-Electronics Laboratories, where he researched and developed optical fiber amplifiers and planar lightwave circuits used in high-capacity optical transmission. In 2014, he joined NTT Access Network Service Systems Laboratories, where he has been researching optical fiber and its fabrication process. Dr. Aozasa is a member of IEICE and the Institute of Electrical and Electronics Engineers (IEEE).

Kyozo Tsujikawa

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received a B.S. and M.S. in chemistry, and a Ph.D. in engineering from Tokyo Institute of Technology in 1990, 1992, and 2006. Since joining NTT, he has undertaken research on glass materials for low-loss optical fibers, measurement of optical fibers, and measurement of optical properties of fiber cables. Dr. Tsujikawa is a member of IEICE.

Kazuhide Nakajima

Senior Research Engineer, Supervisor (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 Rapporteur Q5/SG15 of ITU-T. Dr. Nakajima is a member of IEICE, IEEE, and the Optical Society of America.