Dense Space Division Multiplexing (DSDM) Long Distance Optical Fiber Transmission Technology

Takayuki Mizuno, Kohki Shibahara, Doohwan Lee, Takayuki Kobayashi, and Yutaka Miyamoto

Abstract

Multi-core and multi-mode space division multiplexing (SDM) technology is being studied as an optical transmission technology targeted for the next generation high-capacity optical communication network. In this article, we describe the latest trends in optical transmission using SDM technology. We introduce the world's most advanced ultra-high-capacity long distance optical transmission realized by dense space division multiplexing (DSDM) with a spatial multiplicity above 30, which was achieved in joint global academic and industrial research collaborations.

Keywords: dense space division multiplexing (DSDM), multi-core multi-mode, long distance high-capacity optical fiber transmission

1. Introduction

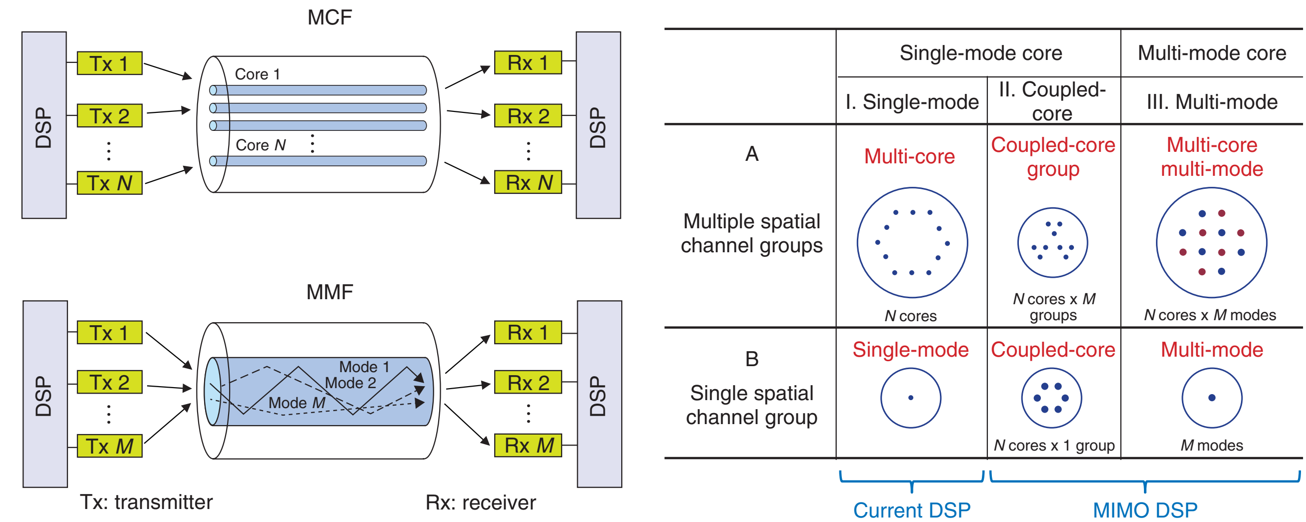
With the rapid spread of new information and communication services such as cloud computing, wireless communication, and high-definition video communication services, the data traffic flowing through the optical network is expected to continue to increase. Along with this traffic growth, a further increase in transmission capacity over optical fiber is required. The NTT laboratories have been developing optical transmission technologies over the past 30 years involving time division multiplexing, wavelength division multiplexing, and digital coherent technology, and have succeeded in realizing a 100-Tbit/s-class high transmission capacity per optical fiber in research, and a 10-Tbit/s-class transmission capacity in commercial large-capacity backbone optical transmission systems.

To further increase the transmission capacity, it is necessary to increase the power input to an optical fiber. However, increasing the power too much will give rise to nonlinear optical effects and a fiber fuse phenomenon. Thus, there is an upper limit to the allowable optical power transmitted through a fiber. The capacity limit due to these physical limits is known to be around 100 Tbit/s, and we may reach this upper limit within the next decade in commercial communication systems.

At NTT Network Innovation Laboratories, we have been promoting research on spatial multiplexing technology since 2009 in cooperation with related research groups within NTT, and in collaboration with other companies and universities, in order to realize the next generation ultra-high-capacity optical transmission technology.

Space division multiplexing (SDM)[*1] is attracting attention as a state-of-the-art optical transmission technology that can increase the transmission capacity by several orders of magnitude relative to a conventional single-mode fiber (SMF) by spatially multiplexing optical signals in a transmission line. Advanced research is being conducted in various

*1 SDM: An optical transmission technology that multiplexes and transmits optical signals using a spatial dimension. Global research and development is progressing towards next generation high-capacity optical transmission technology.



(a) Schematic of SDM optical transmission system using multi-core fiber (MCF) and multi-mode fiber (MMF) as a transmission medium

(b) SDM optical transmission methods

DSP: digital signal processing
MIMO: multiple-input multiple-output

Fig. 1. SDM optical transmission technology.

research institutions around the world. A schematic of an SDM optical transmission system using a multi-core fiber (MCF) and a multi-mode fiber (MMF) as a transmission medium is shown as a representative example in **Fig. 1(a)**. With SDM, we can increase the transmission capacity by *N* or *M* times that of SMFs currently being used in backbone optical networks, where *N* and *M* are the number of cores and modes, respectively. Various SDM optical transmission methods have been reported so far and are depicted in a matrix in **Fig. 1(b)**.

The transmission capacity per optical fiber is plotted as a function of transmission distance in **Fig. 2**. These examples have been demonstrated in recent transmission experiments using SDM technology. In 2012, a transmission experiment reported a 305-Tbit/s capacity over a 10.1-km 19-core MCF, proving for the first time that the capacity could exceed the capacity limit of an SMF by using SDM technology. In the same year, NTT Network Innovation Laboratories collaborated with optical device research groups in NTT, an optical fiber manufacturing company, and universities in Japan and Europe to demonstrate the world-first 1-Pbit/s transmission [1] using a one-ring structured 12-core MCF, which is an order of magnitude larger than the capacity limit of an SMF. The following year, in 2013, we demonstrated the first capacity distance product exceeding 1 Ebit/s x km by applying a bi-directional transmission scheme in a two-ring structured 12-core MCF to reduce inter-core crosstalk [2].

Although SDM optical transmission technologies have proven that they can exceed the capacity limit of a conventional SMF, it is necessary to further increase spatial multiplicity, that is, the number of cores or modes multiplexed in an optical fiber, to further increase capacity. Therefore, developing new technologies for massive spatial multiplexing is the next challenge.

2. Towards dense space division multiplexing (DSDM)

We have been working to further increase the capacity of optical fiber transmission systems using SDM technology by developing new fundamental technologies with the goal of realizing dense space division multiplexing (DSDM)*2 with a spatial multiplicity of 30 or more. To establish DSDM long distance optical transmission using an MCF, we must

*2 DSDM: High density SDM technology with spatial multiplicity above 30, which we proposed and demonstrated in 2014 for the first time.

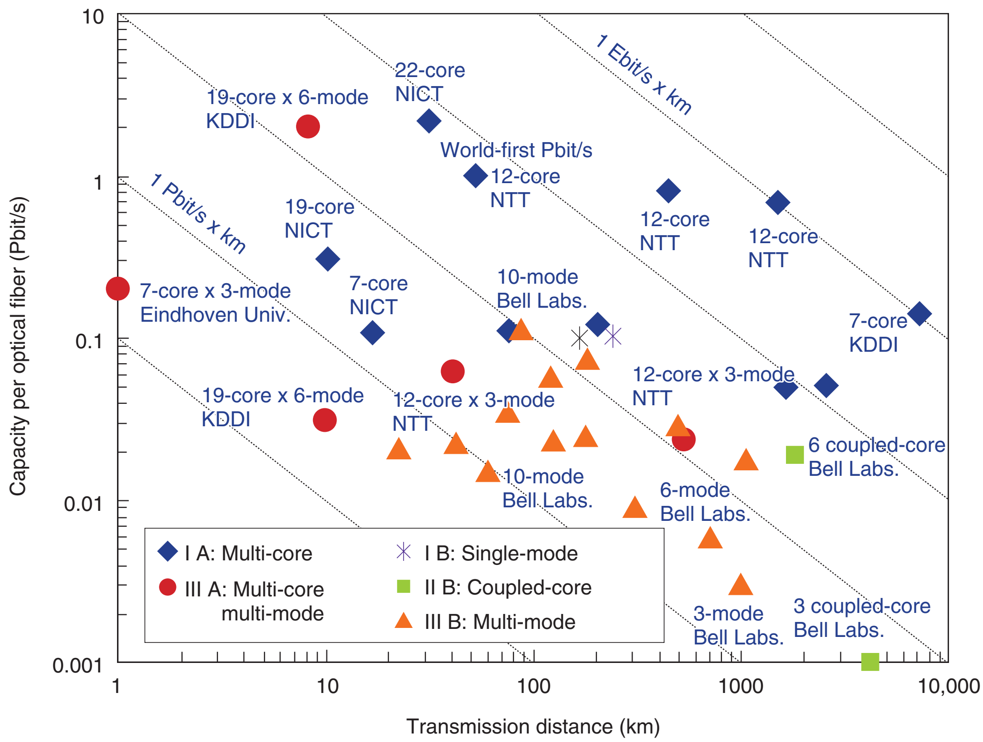


Fig. 2. Transmission capacity per optical fiber as a function of transmission distance.

arrange 30 or more cores in an optical fiber with a cladding diameter within 250 μm, taking fiber strength and reliability into consideration. At the same time, each core should have an effective area of 80 μm^2 or more, which is equivalent to that of a conventional SMF. Since the core arrangement in the optical fiber becomes dense, crosstalk between cores increases, which leads to the degradation of transmission quality.

As an example, the inter-core crosstalk after 1000-km transmission is shown in **Fig. 3** as a function of spatial multiplicity. The vertical axis indicates the worst inter-core crosstalk in an MCF after 1000-km transmission for terrestrial optical communication systems. The higher a position is on the graph, the lower the crosstalk value is, which means that the effect of crosstalk from signals in other cores is small on long distance transmission characteristics.

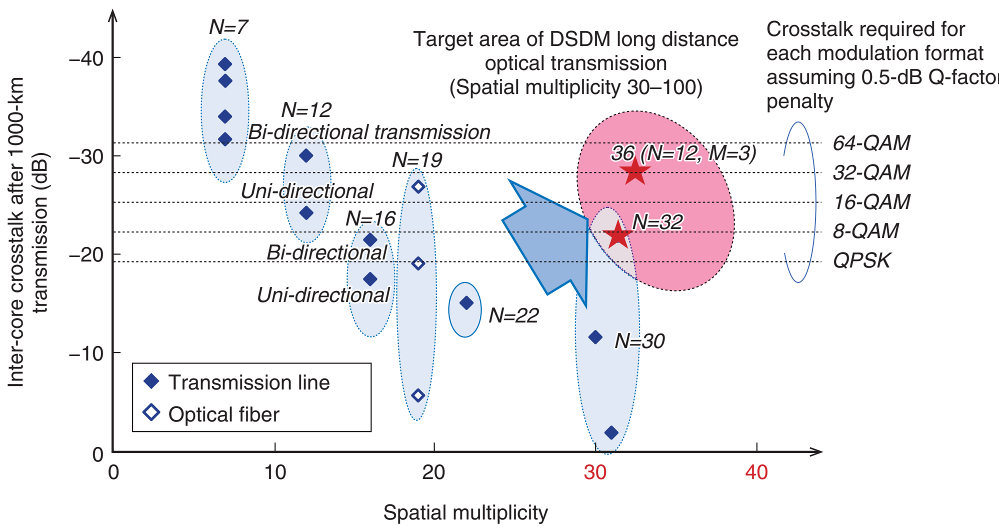
The dotted lines in the graph are the inter-core crosstalk values required for each modulation format, assuming a Q-factor penalty of 0.5 dB. The higher the multilevel degree, the larger the transmission capacity can be with the same resource, but the crosstalk requirement becomes stricter. For example, it is necessary to suppress the inter-core crosstalk to less than –25 dB to apply a polarization division multiplexed 16-quadrature amplitude modulation (16-QAM)*3 format. As shown in Fig. 3, as we increase the number of cores by 7, 12, and 19, the core arrangement becomes dense, so the inter-core crosstalk increases. Therefore, we have set the spatial multiplicity of 30 to 100 and the inter-core crosstalk of < –25 dB as the target area for achieving DSDM long distance optical transmission.

3. World's first DSDM optical transmission

As a first approach, we examined the combination of multi-core and multi-mode optical transmission. In mode-division multiplexed optical transmission, the application of multiple-input multiple-output (MIMO)*4 signal processing, a technique used in

*3 16-QAM: A modulation format that associates 16 values of digital signals with 16 types of intensity and phase combinations of the optical signals in a carrier wave, and transmits 4 bits per modulation.

*4 MIMO: A digital signal processing method used in practical wireless communication systems. Application to SDM transmission systems is being considered for the purpose of separating spatially coupled optical signals.



QAM: quadrature amplitude modulation
QPSK: quadrature phase-shift keying

Fig. 3. Inter-core crosstalk after 1000-km transmission as a function of spatial multiplicity.

commercial wireless communication systems, is being considered in order to separate optical signals between different modes that are coupled during propagation. The amount of computation required for MIMO signal processing is proportional to the magnitude of the differential mode delay (DMD)*5. Since there is a limit to the load that can be tolerated by digital signal processing (DSP), it is necessary to suppress DMD. In addition, mode dependent loss (MDL)*6 has a tremendous effect on the transmission characteristics in mode-division multiplexed transmission.

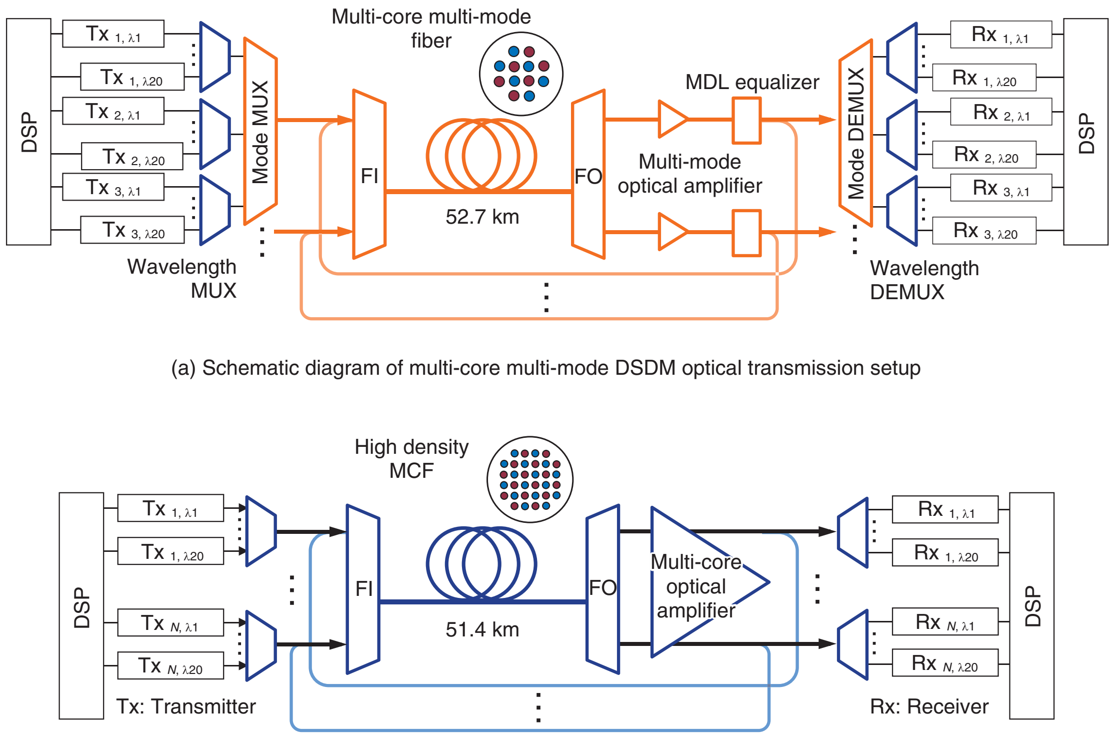
While conducting research on multi-mode transmission, we found that it was difficult to fully compensate for the degradation caused by MDL with DSP, and MDL was one of the largest factors limiting the transmissible distance. As described above, advanced technology is essential even in mode-division multiplexing itself, and it was extremely difficult to realize multi-core and multi-mode optical transmission at the same time. Thus, there had been no reports on multi-core multi-mode transmission from any research institute at that time.

With a view to solving these issues, we proposed a novel parallel MIMO time domain equalization method to reduce the load of DSP. Also, in cooperation with an optical fiber manufacturer and universities, we developed a low-loss and low-crosstalk multi-core multi-mode optical fiber. Furthermore, in cooperation with research groups in NTT studying optical devices, we developed a multi-core multi-mode fan-in/fan-out (FI/FO) device for spatial multi/demultiplexing, a low-loss mode multi/demultiplexer based on a silica planar lightwave circuit (PLC), and an integrated optical receiver for SDM systems fabricated using commercially available silica PLC technology. We combined these fundamental technologies and in 2014 successfully achieved multi-core multi-mode DSDM optical transmission for the first time in the world, with a spatial multiplicity of 36 (12-core multiplexing × 3-mode multiplexing) [3]. The combination of the multi-core and multi-mode transmission greatly enhanced the spatial multiplicity because of the multiplication effect of the core and mode multiplexing.

In 2015, we proposed a novel parallel MIMO frequency domain equalization method to further reduce the complexity of DSP and moreover realized a graded-index type multi-core multi-mode optical fiber with an order of magnitude lower DMD. In addition, we realized a free-space optics type MDL

*5 DMD: Difference in group delay time between modes. It is known that the DMD can be reduced by using the graded-index type refractive index distribution. Reducing DMD will reduce the load of digital signal processing in multi-mode transmission.

*6 MDL: Loss difference between multiple modes. It is one of the largest factors limiting the transmission distance in mode-division multiplexed optical transmission.



(b) Schematic diagram of multi-core DSDM optical transmission setup

DEMUX: demultiplexer
MUX: multiplexer

Fig. 4. DSDM optical transmission technology.

equalizer and a multi-mode optical amplifier with low mode dependency in gain, both of which greatly reduce the MDL in the optical transmission line. These DMD and MDL suppression technologies made it possible to achieve long distance multi-mode transmission, and this enabled us to successfully demonstrate the world-first long distance multi-core multi-mode DSDM optical transmission over 527 km [4]. A schematic diagram of the multi-core multi-mode DSDM optical transmission setup we used in the experiment is shown in **Fig. 4(a)**.

4. World's first multi-core DSDM long distance optical transmission

As another approach, we have also been conducting studies of high density MCF in a Japanese-European collaboration [5]. In our first study, we fabricated high density 30-core and 31-core MCFs about 10 km long and confirmed good transmission characteristics. However, the crosstalk between cores was large, and thus, these MCFs were not suitable for long distance optical transmission. We improved the MCF design and fabricated a 32-core high density MCF 51.4 km in length. With this MCF, we succeeded in suppressing the core-to-core crosstalk to less than –21.6 dB even after 1000-km transmission, and we reached the target area of DSDM transmission shown in Fig. 3 for the first time with a single-mode MCF.

In 2016, we demonstrated the first multi-core DSDM long distance optical transmission exceeding 1600 km [6] using this low-crosstalk high density MCF. A schematic diagram of the multi-core DSDM optical transmission setup we used in the demonstration experiment is shown in **Fig. 4(b)**. The long distance DSDM transmission with a spatial multiplicity higher than 30 and a transmission distance over 1000 km was a world-first achievement and has been the only successful such demonstration up until now.

To use this multi-core DSDM optical transmission in a real system, a high density multi-core optical amplifier is essential. In cooperation with the

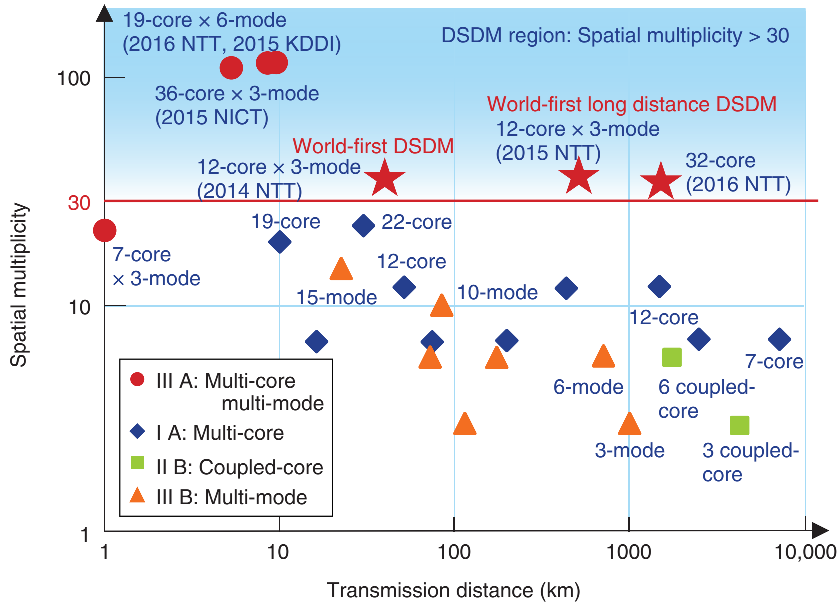


Fig. 5. Spatial multiplicity versus transmission distance.

members of the EU-Japan project, we also conducted studies on MCF amplifiers and developed a 32-core cladding-pumped multi-core erbium/ytterbium-doped fiber amplifier (MC-EYDFA) for the first time. Using the 32-core MCFs and the 32-core MC-EYDFA, we have constructed a 111.6-km 32-core inline amplified DSDM transmission setup and experimentally verified good transmission characteristics over all 32 cores [7].

The spatial multiplicity versus transmission distance in SDM optical transmission reported so far is shown in **Fig. 5**. At the beginning of our study on DSDM, the highest spatial multiplicity reported in multi-core optical transmission was 19. For 1000-km-class long distance optical transmission, the spatial multiplicity was even more limited, with 12 being the maximum. Under these circumstances, we succeeded in 2014 in carrying out the first DSDM optical transmission with a spatial multiplicity above 30. Moreover, we extended the transmission distance from 40 km to over 500 km, and then to over 1600 km with DSDM. More recently, other research institutes have subsequently studied DSDM, and DSDM with spatial multiplicity above 100 has been reported.

5. Future directions

In this article, we introduced the latest trends in SDM optical transmission technology and the DSDM optical transmission system with efforts to further increase the transmission capacity for the next generation high-capacity optical communication technology. We will continue to promote the research and development of SDM optical transmission technology as part of efforts to achieve an ultra-high-capacity long distance optical transmission system as the foundation for the future optical network.

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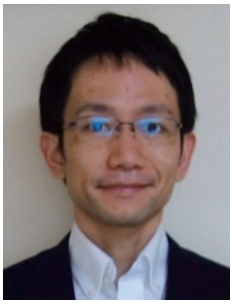

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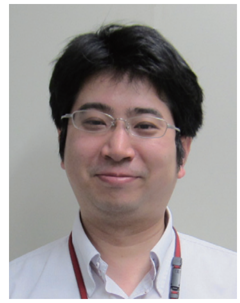

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