Latest Trends and Future Outlook of SDM Optical Transmission Technology

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1. SDM Optical Transmission Technology

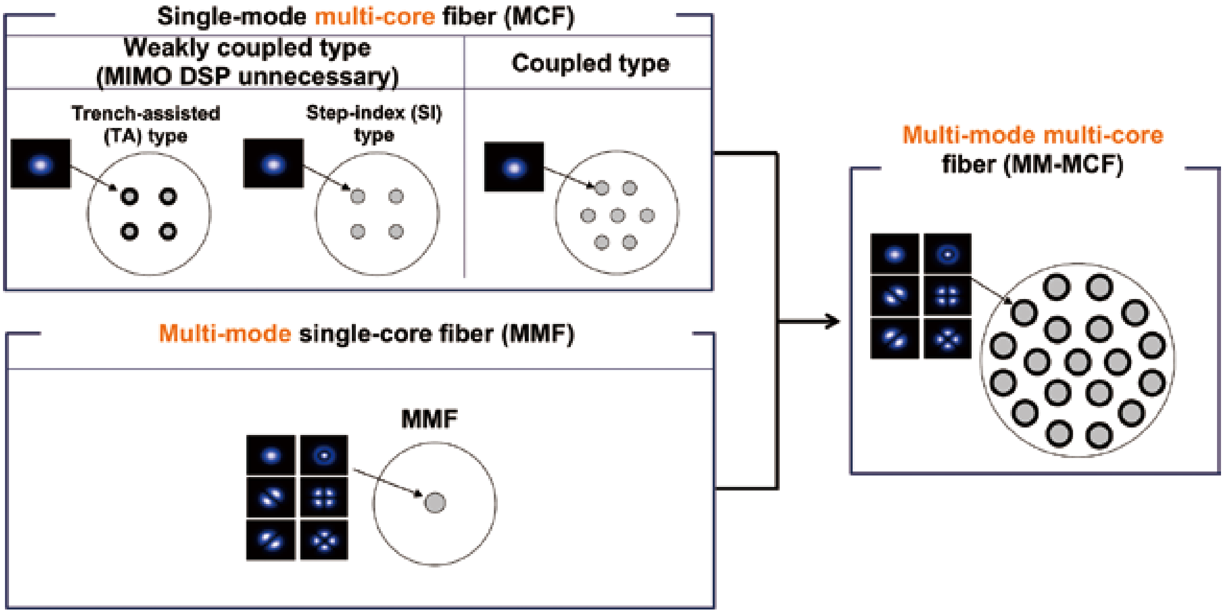
Space-division-multiplexing (SDM) optical transmission systems are being studied to achieve dramatically higher capacities in optical transmission systems. As shown in Figure 1, there are two main categories of optical fiber for SDM: multi-core fiber (MCF) having multiple cores and multi-mode fiber (MMF) having multiple propagation modes.

Additionally, MCF is divided into weakly coupled MCF and coupled MCF according to the degree of inter-core crosstalk. Weakly coupled MCF suppresses crosstalk by designing the refractive index across the fiber cross-section. This type of MCF can be used with conventional optical transmitters and receivers. Furthermore, in terms of the design of weakly coupled MCF, there is the step index (SI) type that holds costs down by using a simple refractive index distribution and the trench-assisted (TA) type that forms a trench layer with a low refractive index around each core to strongly confine light and reduce crosstalk[1]. The number of cores that can be achieved in weakly coupled MCF is limited due to such crosstalk. In long-haul transmission, the upper limit is considered to be four cores in the case of a cladding diameter of 125 µm (standard diameter) the same as conventional single-mode optical fiber (SMF).

There are also coupled MCF and MMF as optical fiber for increasing space-division multiplicity. Both of these types of optical fiber allow for crosstalk between cores or propagation modes to increase space-division multiplicity. The generated crosstalk is removed by large-scale multi-input multi-output digital signal processing (MIMO DSP) installed in the receiver. In coupled MCF, space-division multiplicity at present is inferior to that of MMF, but propagation loss is low and inter-core deviation is small, so coupled MCF is expected to be mainly applied to long-haul transmission systems of 1,000 km or longer (terrestrial or submarine cables)[2]. On the other hand, MMF is being studied as a means of further increasing space-division multiplicity mainly in short- to medium-haul transmission systems up to 1,000 km (between data centers or in terrestrial links). In either coupled MCF or MMF, the implementation of large-scale MIMO DSP according to space-division multiplicity is a major issue.

To increase space-division multiplicity even further, there is also multi-mode multi-core fiber (MM-MCF) as a hybrid structure combining MCF and MMF. Transmission experiments exceeding 10 cores × 10 modes = 100 SDM have been reported[3, 4].

Figure 1: Categories of optical fiber for SDM transmission



2. Trends in Record High-capacity, Long-haul SDM Optical Transmission Experiments

A 138.9 Tb/s, 12,345 km transmission experiment using standard-diameter TA-4 core fiber has been reported as a high-capacity, long-haul transmission experiment using weakly coupled MCF[5]. To increase capacity, this experiment used the L-band and S-band wavelength bands in addition to the existing C-band. A 2.15 Pb/s, 31 km transmission experiment using TA-22-core fiber has also been reported as a high-capacity transmission experiment with many cores[6]. However, in many-core weakly coupled MCF, inter-core spacing must be kept above a certain value to suppress crosstalk, so in general, the fiber will not be of a standard diameter. Fiber with a large diameter can easily break, which means that there are issues here in terms of mechanical reliability[1]. Recently, with the aim of achieving early deployment, there has been much study on the extent to which a high-capacity, long-haul weakly coupled MCF transmission system can be achieved within the standard-diameter constraint[1]. This effort regarding standard-diameter weakly coupled MCF will be described later.

In studies of coupled MCF for increasing space-division multiplicity, there is standard-diameter coupled 19-core fiber as the maximum number of cores and 1.7 Pb/s, 63.5 km transmission has been reported with this fiber[7]. A 1.2 Tb/s, 7,280 km transmission experiment using coupled 12-core fiber has also been reported as a many-core, long-haul transmission experiment exploiting the features of coupled MCF[8]. In addition, a 50.4 Tb/s, 9,150 km transmission experiment using coupled 4-core fiber has been reported as a transmission experiment achieving both high-capacity and long-haul characteristics based on existing wavelength-division multiplexing (WDM) technology[9]. In the above ways, coupled MCF has characteristics applicable to long-haul transmission with small wavelength dependence while having broadband features, so it is expected to be applicable to terrestrial and submarine cable transmission systems that require high capacity and long-haul transmission. In addition, as a high-capacity transmission experiment using MMF, a 3.56 Pb/s transmission experiment using standard-diameter 55-mode fiber exceeding the data rate of coupled MCF with the maximum number of cores (19) has been reported[10]. Furthermore, 15-mode 273.6 Tb/s, 1,001 km transmission has been reported as a many-mode, long-haul transmission experiment[11].

However, in these reports on transmission experiments using coupled MCF and MMF, while using standard-diameter optical fiber, the fact that MIMO DSP can only be performed offline is a major issue.

As for MM-MCF combining MMF and MCF, the first 10-Pb/s ultra-high-capacity transmission experiment using 6-mode/19-core fiber for a space-division multiplicity greater than 100 (6 modes × 19 cores = 114 SDM) was reported in 2017[3], and a 22.9-Pb/s ultra-high-capacity transmission experiment based on expansion of the WDM wavelength band was reported in 2023[4]. However, since MM-MCF is not a standard-diameter type of fiber while also requiring MIMO DSP, it is considered to be a future technology for SDM transmission systems.

3. Initiatives toward Deployment of SDM Optical Transmission Systems

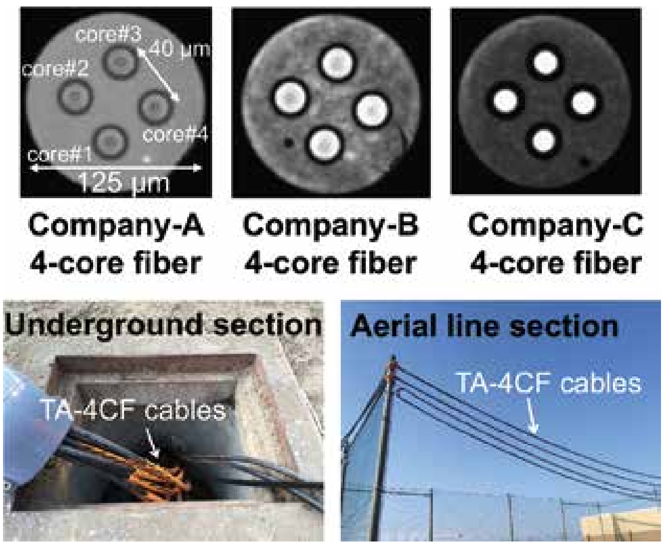
3.1 Standard-diameter SDM Optical Fiber/Cable

Standard-diameter weakly coupled MCF requiring no MIMO DSP and having high mechanical reliability is considered to be a promising technology for early deployment of SDM transmission systems. As a specific transmission application, the making of standard-diameter 4-core fiber into a cable with a view to terrestrial and submarine cable deployment has been reported, and it has been confirmed that there are no significant degradation of optical characteristics (caused by crosstalk, etc.) even in cable form[1, 12]. In addition, adopting a bidirectional core multiplexing transmission system that changes the direction of propagation between adjacent cores would make it possible to suppress crosstalk even further and extend transmission distance[13]. In 2023, Google announced the introduction of standard-diameter weakly coupled 2-core fiber in submarine cable[14].

3.2 Demonstrations in Cable Deployed Environments

Terrestrial transmission systems, in particular, include deployed environments containing much disturbance such as aerial line sections different from laboratory experiments. There are also many connections using splicing or connectors, so demonstrations of transmission performance in actual deployed environments are essential. In the city of L'Aquila, Italy, an evaluation was performed of polarization change speed and propagation delay fluctuations using standard-diameter weakly coupled 4-core fiber deployed in an underground tunnel in a metropolitan area[15]. In Japan, meanwhile, a transmission

Figure 2: Examples of weakly coupled 4-core-fiber cables deployed outdoors



experiment using standard-diameter 4-core fiber deployed in an underground cable tunnel was reported[1]. Similarly, from KDDI as well, an experiment using standard-diameter 4-core fiber in a nearly real environment was reported[16]. This experiment was performed in a disturbance-containing environment that included aerial lines, manholes, etc. and included interconnection loss between fibers from different vendors[16]. Photographs of 4-core-fiber cross-sections and cable deployed environments are shown in Figure 2. It was shown by this experiment that high-capacity and long-haul transmission at 63.5 Tb/s and 1,800 km could be achieved even when taking interconnection loss and increase in crosstalk into account.

4. Future Outlook for SDM Transmission Systems

4.1 Real-time MIMO DSP for Increasing Space-division Multiplicity

The maximum number of cores in standard-diameter weakly coupled MCF is limited due to crosstalk. To further increase space-division multiplicity, coupled MCF and MMF transmission technologies that assume removal of crosstalk by MIMO DSP are indispensable. It is therefore necessary to develop real-time MIMO DSP in the form of an application-specific integrated circuit (ASIC). In contrast to offline operations, real-time implementation must consider computational delays arising from large-scale MIMO calculations. Given the existence of such delay, a major study item here is whether real-time MIMO DSP can track the moment-by-moment changes in the coupling state between cores and between modes. In recent years, there have been implementations of real-time MIMO DSP using field-programmable gate arrays (FPGAs) and real-time transmission experiments. In 2015, a real-time transmission experiment using 60-km coupled 3-core fiber was reported for the first time[17], and in 2021, 7,200-km long-haul real-time transmission using coupled 4-core fiber was demonstrated[18]. The FPGA board implementing real-time MIMO DSP for coupled 4-core fiber in the latter experiment is shown in Figure 3. These were laboratory experiments, but a demonstration of tracking performance with respect to fiber laid in a harsher environment has been reported[15]. That experiment demonstrated tracking performance using coupled 4-core fiber deployed in the city of L'Aquila, Italy. Although change in the inter-core coupling state here was faster than that of interpolarization coupling in conventional SMF, it was shown that this speed of change fell into a range that could be tracked by MIMO DSP. In 2024, a specific ASIC design was reported for the first time[19]. Going forward, we can expect the deployment of high-capacity SDM transmission systems using coupled MCF and other technologies based on the development of MIMO DSP ASIC devices.

5. Conclusion

In this paper, we introduced record-setting high-capacity and long-haul SDM optical transmission experiments toward higher capacities. We also described demonstration experiments of standard-diameter weakly coupled MCF technology that shows promise for early deployment. Finally, we introduced the latest achievements in real-time DSP as the key to realizing MIMO-DSP-assisted high-capacity optical transmission technology for overcoming the upper limit in number of cores in weakly coupled MCF.

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■ Figure 3: Real-time MIMO DSP for coupled 4-core fiber