One-petabit-per-second Fiber Transmission over a Record Distance of 200 km—Paving the Way to Realizing 1000-km Inline Optical Amplified Transmission Systems within C Band Only

1. Introduction

NTT has demonstrated ultralarge capacity inline optical amplified transmission of 1 petabit (1000 terabits) per second (Pbit/s) over a 205.6-km length of 32-core optical fiber in collaboration with the Technical University of Denmark, Fujikura Ltd., Hokkaido University, the University of Southampton, and Coriant GmbH.

This sets a new world record for the transmission distance of 1-Pbit/s capacity over a single strand of optical fiber within a single optical amplifier bandwidth (C band), which is half the bandwidth used in the previous experiment (**Fig. 1**). The present achievement indicates that the transmission of 1 Pbit/s—a capacity equivalent to sending 5000 high-definition television videos each two hours long in a single second—is potentially possible over 1000 km, which is approximately the distance between major cities in both Japan and Europe.

Part of this research utilized results from the EU-Japan coordinated research and development project on Scalable And Flexible optical Architecture for Reconfigurable Infrastructure (SAFARI) [1] commissioned by the Ministry of Internal Affairs and Communications of Japan and EC Horizon 2020.

2. Experiment and results

The use of 32-core multi-core fiber (MCF), which we have successfully prototyped for a long length of over 50 km [2], a fan-in/fan-out (FI/FO) device to couple light into the MCF, and new digital coherent optical transmission technology made it possible to achieve the high-capacity optical transmission rate of 1 Pbit/s. We accomplished this by exploiting dense space and wavelength division multiplexing (DSDM and DWDM) over long distances. The 32-core MCF used in the experiment utilized a new arrangement of cores that greatly reduces inter-core light leakage that otherwise degrades performance [2]. In addition, we used the wave properties of light (phase and polarization) to apply multi-dimensional coding to polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) digital coherent technology to improve the long-distance transmission performance in each core.

The experimental results are shown in **Fig. 2**. We achieved 31.3-Tbit/s capacity per core (= 680 Gbit/s per wavelength x 46 wavelength channels), and using the 32-core MCF, we recirculated and amplified the signals over four spans of the 51.4-km fiber, demonstrating that signal transmission of an aggregate 1-Pbit/s capacity was possible over 205.6 km.

The Q-factor indicates the transmission quality of the PDM 16-QAM signals. Because the Q-factor was uniform, it showed that high quality transmission with small variations between cores and low error was possible. In 2012, we reported on an experiment in which we achieved a world-first 1-Pbit/s capacity over 52.4 km [3]. In comparison, these new results demonstrate a distance about four times longer at

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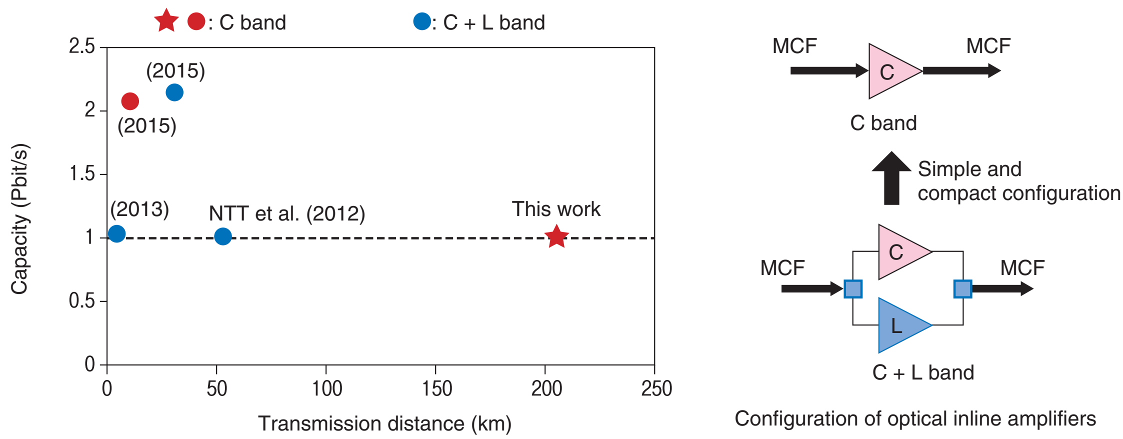

MCF: multi-core fiber

Fig. 1. The achievement in petabit-per-second-class transmission.

- All 1473 channels with a 680-Gbit/s PDM 16-QAM signal format were transmitted over 205.6 km without eight-dimensional coded modulation.
- Total capacity of 1 Pbit/s/fiber (= 32 cores x 46 wavelengths x 680 Gbit/s) was achieved.

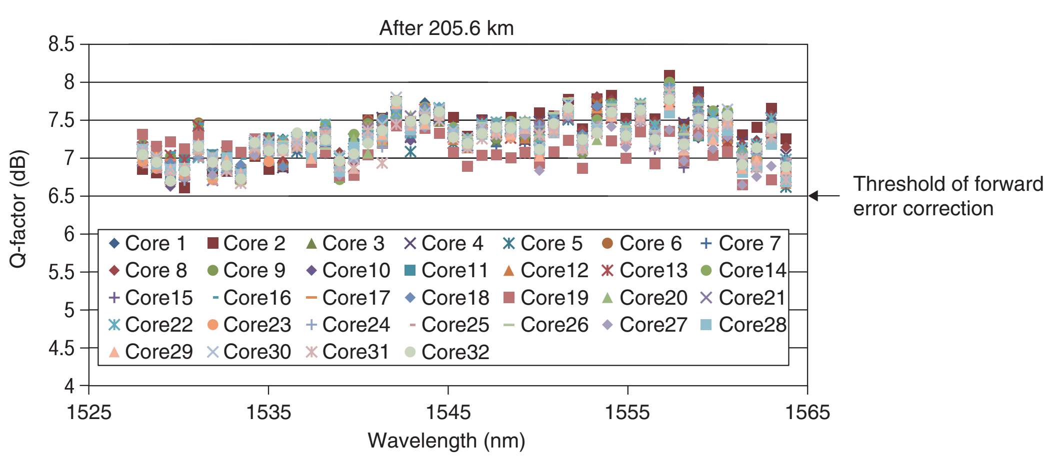

Fig. 2. Transmission performance of 1 Pbit/s over 205.6 km.

205.6 km, which is the world's longest distance for over petabit-per-second capacity transmission.

Moreover, by applying a digital signal processing technique called multi-dimensional coded modulation, the capacity per wavelength is reduced by 25% to 510 Gbit/s. Nevertheless, we demonstrated that the transmission distance can be increased to over 1000 km. As a result, with one optical fiber, we showed that there is a possibility for ultrahigh capacity equivalent to 0.75 Pbit/s using just the 5 THz bandwidth of the C band, and 1.5 Pbit/s using the 10 THz bandwidth provided by the combined C and L bands, with a potential transmission distance over 1000 km.

3. Technological features and roles

Here, we describe the technology that was applied to achieve the 1-Pbit/s transmission over a record distance.

3.1 Thirty-two-core MCF transmission line

The MCF we used in this experiment was jointly designed and prototyped by the Technical University of Denmark, Fujikura, and Hokkaido University. The fiber has a new structure (single-mode heterogeneous-core MCF) with 32 cores incorporating several types of cores, each with different properties [2]. The characteristic of this fiber is that two kinds of cores with slightly different refractive indices are arranged in a square lattice pattern. With this structure, even if the number of cores is increased to 30 or more, the crosstalk between adjacent cores can be greatly reduced [2], making it possible to realize long-distance DSDM transmission [4]. NTT and Coriant evaluated the long distance characteristics of the 51.4-km MCF transmission line with the 32-core MCF and FI/FO devices prototyped by Fujikura, the University of Southampton, and NTT. As a result, we confirmed that all cores had low crosstalk and low loss characteristics over the entire C band, which is a requirement for a 32-core MCF transmission line suitable for transmission over a 1000-km distance.

3.2 Multi-dimensional coded 16-QAM technique

In recent large-capacity optical communications, instead of the intensity modulation signal transmitted using binary states of either ON or OFF, a highly efficient PDM-QAM digital coherent signal has been used that realizes a large number of signal states created by using the wave properties (phase and polarization) of light. Such multi-level QAM signals can achieve a highly efficient ultrahigh speed optical signal by associating a plurality of bits of digital signals with a plurality of optical signal states encoded using the phase and polarization of light. However, the drawback is that when we increase transmission efficiency by increasing the number of multi-levels, the transmission distance sharply decreases. In addition, signal quality degrades by the crosstalk that arises in MCF transmission.

In this case, NTT reduced the number of multi-levels of the QAM signal from 32 in the conventional report [3] to 16 and applied a wideband digital-analog conversion technique [5] to the digital coherent signal using highly efficient error correction coding. As a result, we successfully transmitted a capacity of 680 Gbit/s per wavelength (1 Pbit/s per fiber) over a 205.6-km distance, the longest distance for petabit-per-second capacity transmission. Furthermore, by applying the eight-dimensional encoded 16-QAM technique [6] and by improving the allocation method of the digital signal and the optical signal state, the transmission quality can improve compared with the normal QAM code. With the same 16-level QAM, the transmission rate will be reduced to 510 Gbit/s per wavelength, but by doing this, we showed that it has the potential to extend the transmission distance to possibly over 1000 km.

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