Leading-edge Optical Fiber Technologies :from ultra long haul to indoor wiring

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Various optical fibers are used for a wide range of applications from submarine cable transmission over 10,000 km to indoor wiring less than 1 m. It is therefore important to develop and commercialize novel fibers dedicated to each of these applications.

We have developed bend-insensitive fibers which have low bending losses. At a small bending radius, the bending loss of the bend-insensitive fibers is more than one order of magnitude smaller than that of a conventional single-mode fiber with a step-index profile. The application areas of bend-insensitive fibers are expanding, because they can avoid communication failure due to fiber bending during fiber installation.

Fujikura leads the development of multi-core fiber, in which multiple cores are embedded in the cladding. The multi-core fiber can make a breakthrough in the transmission capacity and thus has attracted much attention as a novel optical fiber for long haul optical communication.

1. Introduction

Optical fibers have low loss and are suitable for large capacity transmission, therefore they have spread remarkably. Submarine optical fiber cables have replaced communication satellites as means of inter-continental communication. FTTH and/or FTTX have started in many countries of the world. Fujikura, a leading optical fiber supplier in the world, develops new optical fibers dedicated to each of these applications.

In general, light leaks out of the core when an optical fiber is bent to a small radius. It is called bending loss. Higher bending loss is induced as the bending radius is decreased and the number of turns is increased. Bend-insensitive fiber can reduce the bending loss compared to that of a conventional fiber. This paper reviews several kinds of bend-insensitive fibers, which are now also finding applications outside FTTH.

Wireless communication speed and internet traffic have been increasing without end. The demand for a large capacity optical fiber network has been growing at a dramatic rate. Multi-core fiber, which possesses multiple cores in the cladding, can make a breakthrough in the transmission capacity and has attracted huge attention as a novel optical fiber for long distance optical communication. The progress of our development are reviewed.

1 Optics and Electronics Laboratory

2. Bend-insensitive fiber

2. 1. Recommendation of bend-insensitive fibers

Installation of FTTH system demands compact packaging of optical fiber cables. Figure 1 schemati-

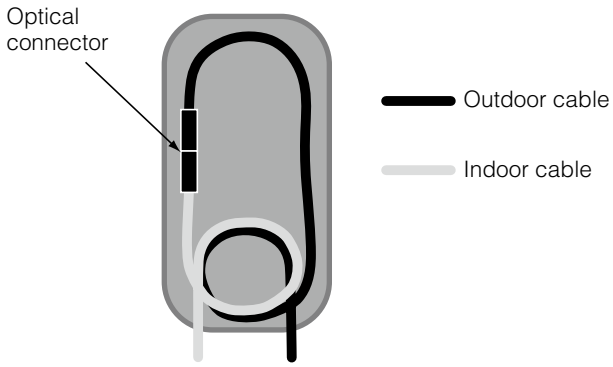

Fig. 1. Optical cables arrangement in a closure.

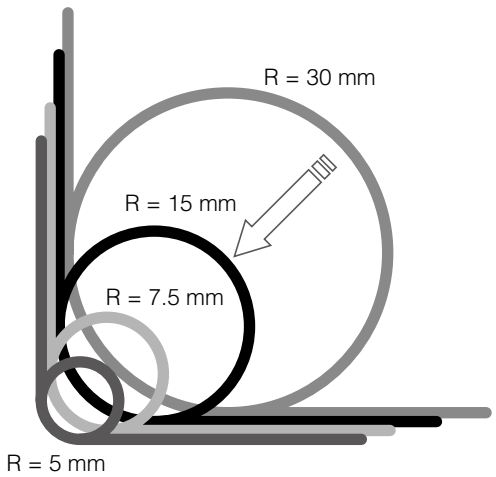

Fig. 2. Schematic of bending radii.

Abbreviations, Acronyms, and Terms.

FTTH—Fiber to the home
Optical access network format to connect a optical fiber to each home

FTTX—Fiber to the X
Optical access network format to connect a optical fiber to home, curb, node and so on

Multi-level modulation—Modulation format setting multiple value more than one bit on one signal

MIMO—Multiple-Input and Multiple-Output
Communication technology to enlarge capacity with multiple receivers and multiple transmitter

cally shows an optical outlet, which connects an outdoor and indoor cable. It is a general installation procedure that excess optical fibers are coiled for storage. Lower bending loss can allow a small diameter of the coils, and thus enables compact storage.

ITU-T (International Telecommunication Union's Telecommunication Standardization Sector) recommendation G.652 defines a conventional single-mode fiber whose minimum bending radius is 30 mm, therefore the fiber needs a minimum space of 60 mm (in diameter) for packaging. Table 1 shows the categories of ITU-T G.657 bend-insensitive fiber. Category A is fully compliant with G.652 fiber, i.e. meeting or exceeding the values specified in G.652. Category B is compatible with G.652 fiber - the fiber may not be compliant with G.652 but the system impairment or deployment issues are negligible. Sub-categories 1, 2 and 3 mean that the minimum bending radius is 15 mm, 7.5 mm and 5 mm, respectively.

2.2. *Performance and Application of FutureGuide®-BIS-B*

Figure 3 shows the refractive index profile of FutureGuide®-BIS-B (BIS-B) and that of G.652 conventional single-mode fiber. The low-index part surrounding the core is called a "trench". The trench strongly confines the electric field in the core and thus BIS-B exhibits low bending loss. Figure 4 displays the bending loss properties of BIS-B (at 1.55 μm) and those of G.657.A2 recommendation, showing the superior bending-loss performance of BIS-B. Trench technology can improve bending loss properties of optical fiber by modifying the refractive index profile.

BIS-B fiber can be applied to a wide variety of applications. This is because, even though the bending loss is reduced, the chromatic dispersion, mode field diameter and attenuation at 1383 nm are compliant with G.652 conventional single-mode fiber[1]. For example, BIS-B fiber can be used in a central office with optical exchanges and optical transmission devices. In a central office, cables might accidentally be bent to a small radius during maintenance and installation because the optical wirings are complex and crowded; the bend may cause a high bending loss and instantaneous communication interruption could occur. Adoption of BIS-B drastically reduces the probability of the interruption.

Table 1. Sub-category of ITU-T G.657.

Minimum bending radius	15 mm	7.5 mm	5 mm
Compliant with G.652.D	A1	A2	not defined
Not compliant with G.652.D	not defined	B2	B3

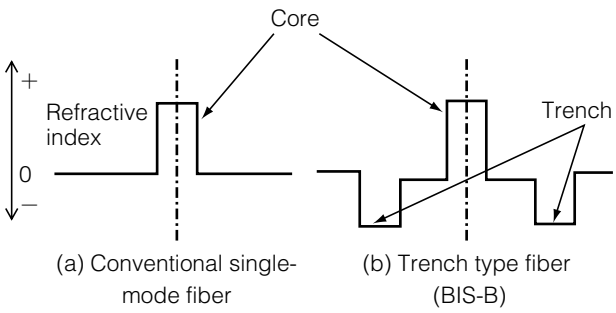

Fig. 3. Refractive index profile.

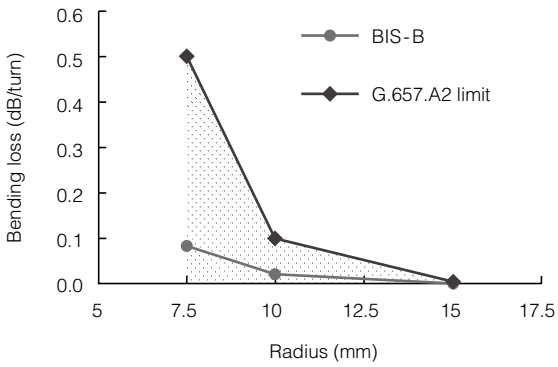

Fig. 4. Bending losses of BIS-B.

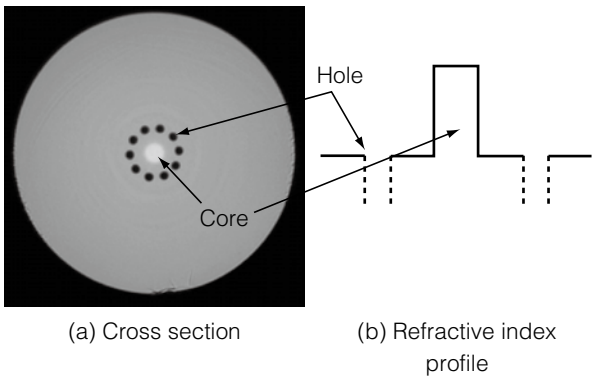

Fig. 5. Structure of HAF.

2.3. *Performance and Application of HAF*

Hole Assisted Fiber (HAF) is a bend-insensitive fiber with a bending loss lower than that of BIS-B[2]. The main feature of HAF is that the clad has multiple air holes whose refractive index is very low, nearly one. As a result, the effective refractive index of the glass near the holes is lowered. Figure 5 shows the cross sectional view and refractive index profile of our HAF.

Figure 6 shows the bending loss properties of the HAF at 1.55 μm. Also shown in the figure is G.657.B3 recommendation, which defines a bend insensitive fiber with a minimum bending radius of 5 mm. The figure suggests that the HAF shows extremely low bending losses. We have developed the HAF compliant with G.652 conventional single-mode fiber by adopting appropriate manufacturing conditions and design, even though B3 sub-category fiber is not necessarily compliant with G.652 recommendation.

HAF was commercialized as a fiber for an indoor cable and is expected to be applied for wiring in a central office and so on. Recent commercialization of an indoor cable for interspace wiring has enabled the installation of an optical fiber cable into a house through a gap between the door/window and the frame. HAF is used in this indoor cable in order to take full advantage of the bending loss properties; the minimum bending radius of the cable is 3 mm. Details of the cable structure and applications are provided in another article in this technical review.

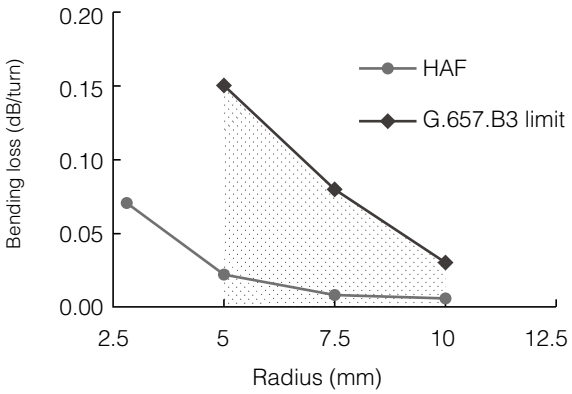

Fig. 6. Bending losses of HAF.

3. Multi-core fiber

3.1. *Transmission capacity of conventional fiber and multi-core fiber*

In accordance with the increasing traffic, the transmission capacity has increased by improvements in optical fibers and transmission systems. Figure 7 shows the transmission capacity records (using one fiber) reported in academic conferences and trend of internet traffic. 100 Tb/s transmission experiments have been reported using digital coherent technology with digital signal processing, multi-level modulation and MIMO (Multiple-Input Multiple-Output) technology.

In spite of developments in these technologies, the increasing rate of the transmission capacity has gradually lowered. It is estimated that maximum transmission capacity is about 100 Tb/s based on the existing transmission system with conventional fibers[3]. Further enlargement of the capacity needs new revolutionary technologies. We have been focusing on the development of multi-core fibers for space division multiplexing[4)~9)], which is one of the candidate technologies.

3.1. *Multi-core fiber's structure and requirement*

The cross sectional view of a typical multi-core fiber for space division multiplexing is shown in figure 8. Multiple cores are embedded in the cladding of one fiber, and each core transmits signals independently.

To enhance the transmission capacity of each core, crosstalk between the cores should be reduced as low as possible. In addition, to enlarge the transmission capacity of the entire fiber, a high core density and high core multiplicity are also effective. Furthermore,

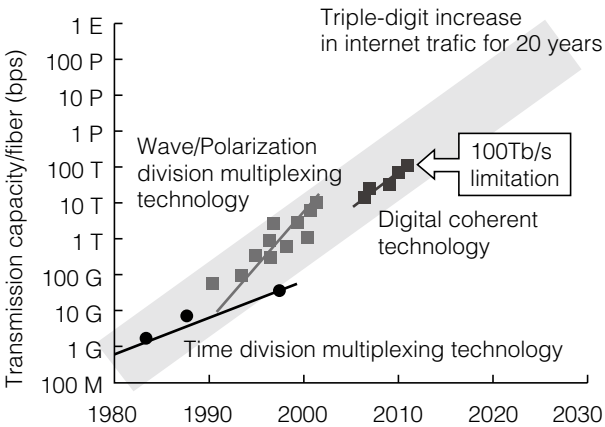

Fig. 7. Trend of transmission capacity per fiber

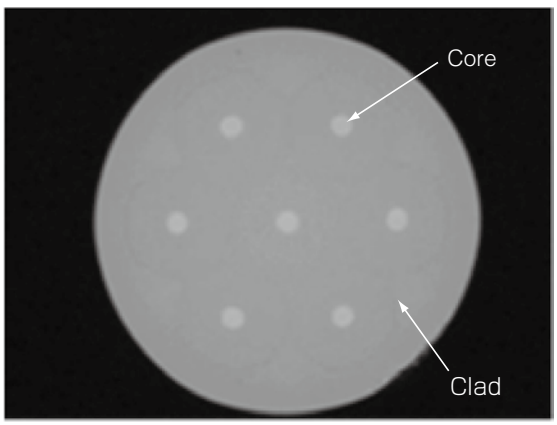

Fig. 8. Cross sectional view of a multi core fiber.

from viewpoints of interconnectivity and easiness of network design, multi-core fiber should have almost uniform optical properties, such as a mode field diameter, chromatic dispersion and so on. A large effective area of each core of the fiber is required to avoid degradation of transmission quality caused by non-linear effects[7].

3.3. High density layout of cores

Low crosstalk and high core multiplicity are requirements unique to a multi-core fiber, and there is a trade-off between them. To overcome the trade-off, we have proposed a multi-core fiber with trench technology[5]. Each of the cores has an index trench similar to that shown in Figure 3(b), and the overlap of electric fields between the cores is reduced. Figure 9 shows the cross section of the trench type multi-core fiber. Figure 10 shows the crosstalk values of two types of multi-core fibers (after 100 km transmission) as a function of core pitch. At the same core pitch, the crosstalk value of the trench type is improved by 20 dB compared to that of the step type (multi-core fiber without index trench). In order to achieve a same crosstalk value, the core pitch of the trench type can be reduced by 16 % compared to that of the step type.

In addition to the reduced crosstalk, the trench technology also enabled a large effective area of 110 μm^2.

3.4. High multiplicity of cores

One simple way to increase the number of cores is increasing the number of core layers. The number of cores is increased to 19 (from 7) if we add another layer of cores using the hexagonal lattice. The core pitch should be kept almost the same in order to keep the crosstalk to a low level. The diameter of a 19-core fiber therefore increases to 240 μm from 160 μm (7-core fiber), lowering the mechanical reliability of the fiber. We have designed a new fiber to maximize the product of effective area and the number of cores under the condition that the fiber diameter is about 200 μm.

A cross sectional view of the world's first 10-core fiber is shown in figure 11. The effective area of each core is from 116 to 125 μm^2. The crosstalk between adjacent outer cores is nearly -26 dB and the crosstalk between an outer core and an inner core is -56dB, which are low enough for stable transmission[8].

4. Conclusion

I reviewed bend-insensitive fibers and multi-core fibes, which attract much attention as optical fibers used for information communication. The bend-insensitive fiber plays a critical role for FTTH, and the multi-core fiber will be a transmission media for future long distance optical communication. Fujikura is also studying few-mode fibers which guide several propagation modes. For multi-core and few-mode fibers, the optical input-output system and amplification system have various technical issues to be solved, thus it may take longer than 10 years for these fibers to be practically used. We will continue our research and development

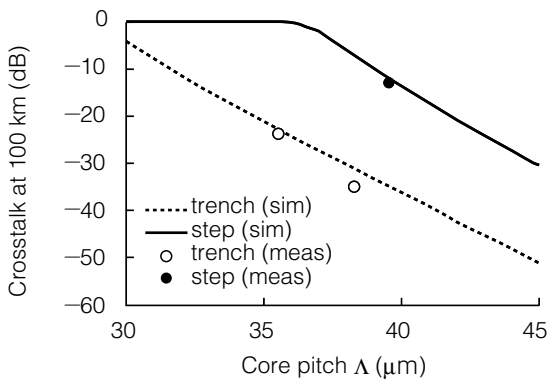

Fig. 10. Relationship between core pitch and crosstalk.

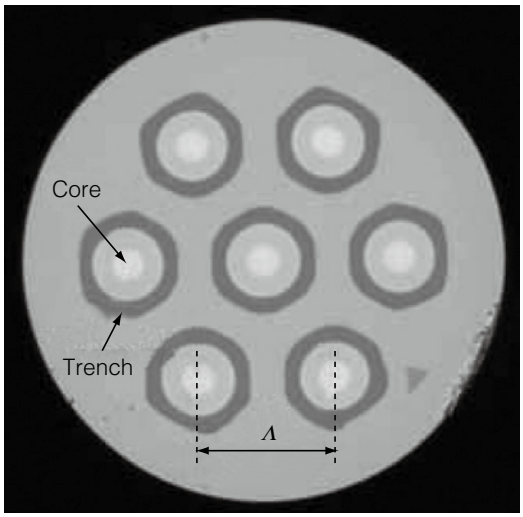

Fig. 9. Cross section of the trench-assisted multi-core fiber.

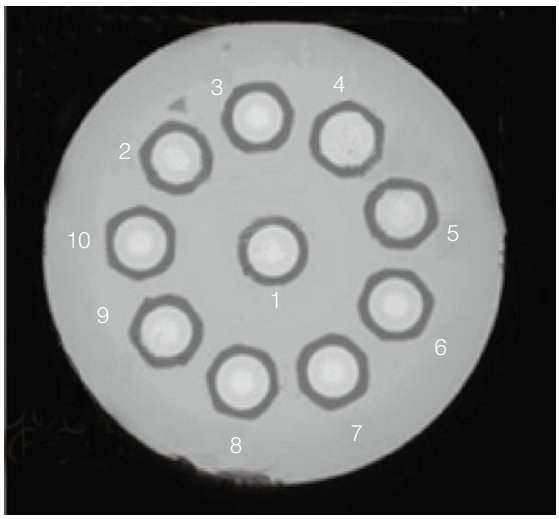

Fig. 11. Cross section of the 10-core fiber.

of optical fibers for the next generation optical transmission systems.

Our transmission experiment report[10] with Fujikura's multi-core fiber was adopted as a post-deadline paper in ECOC2012 (38th European Conference and Exhibition on Optical Communication) on from September 16th to 20th, 2012 at Amsterdam. The reported transmission capacity of I.01Pb/s set a world record.

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