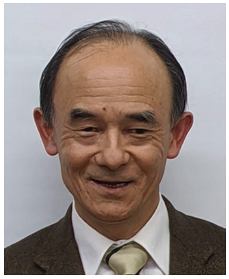

Yoshimichi Ohki

Development of Ultralow-Loss and Low-Crosstalk Four-Core Communication Fiber

In today's international society, a vast amount of information that no one could have imagined a while ago is circulating in the world. This trend is expected to be further accelerated in the "new normal" life with COVID-19, where online social activities have become commonplace. Although organic polymers are also used for short-distance in-equipment information-transmission optical fibers, only amorphous silica (SiO_2) is used for long distances. In other words, what supports the information society is the insulating material familiar to readers of this *IEEE Electrical Insulation Magazine*.

As Google announced in 2018, a private 250 Tbit/s 6,600-km transatlantic communication cable Dunant, named for Henry Dunant, connecting the United States (Virginia Beach) and France (Saint-Hilaire-de-Riez), began operating in 2020 [1]. In recent years, the amount of intercontinental information transmission has continued to increase at a tremendous pace. In this regard, the importance of an optical submarine cable system as an international data communication infrastructure, which realizes large-capacity communication, is increasing.

As mentioned earlier, it is necessary to increase the amount of international information transmission. The improvement of the transmission capacity of optical communication systems using conventional single-mode fiber is approaching a theoretical limit. In order to respond to such a situation, it is necessary to increase the number of optical fibers accommodated in an optical submarine cable. Space division multiplexing (SDM) technology is drawing attention as such a technology. One example of SDM technologies is a technology that arranges a large number of optical fibers, such as 6,912 cores, in an optical cable with the same outer diameter as existing ones, such as 29 mm, as introduced in the News from Japan column in the May/June 2021 issue of this magazine [2]. The mode-division multiplexing is another example of such a method.

However, with conventional SDM technology, there is a limit to the number of optical fibers that can be accommodated without changing the outer diameter of the optical fiber cable, which makes further increases in communication capacity difficult. Therefore, as another SDM technology, a multicore fiber (MCF), of which cladding has multiple cores that can work as independent lines, is considered. This short article introduces the first successful development of MCF conducted by a Japanese team consisting of KDDI Research, Tohoku University, Sumitomo Electric Industries, Furukawa Electric, NEC, and Optoquest by the research funded by the Ministry of Internal Affairs and Communications.

As shown in Figure 1, optical fiber has a cylindrical coaxial structure consisting of a central core, through which light propagates, and a surrounding cladding. The principle of light transmission is the well-known total internal reflection of light. At the interface of two media with different refractive indices, light partly reflects and travels through the original medium. The rest refracts and travels through the new medium according to Snell's law, as shown in Figure 2. However, when light travels from a medium with a high refractive index to a medium with a low refractive index, if the angle between the direction of light and the interface is smaller than the critical angle, the light cannot travel to the low-refractive-index medium. As a result, all the light reflects at the interface and travels through the original high-refractive-index medium. This is total internal reflection. In an optical fiber, as shown in Figure 1, a medium with a slightly higher refractive index, called a core, is placed in the center of a concentric structure through which light travels, and a medium with a slightly lower refractive index, called a cladding, surrounds it. This is the principle of the transmission of light by total reflection.

The MCF with a cladding diameter of 125 μm, the standard diameter of single-mode fiber, has attracted much attention from the viewpoint of practical applications because its use has a major advantage in that existing techniques can be used for cutting, connecting, and splicing fibers [3], [4]. Because a typical core is about 10 μm in diameter, it is geometrically possible to place four cores in a typical cladding with a diameter of about

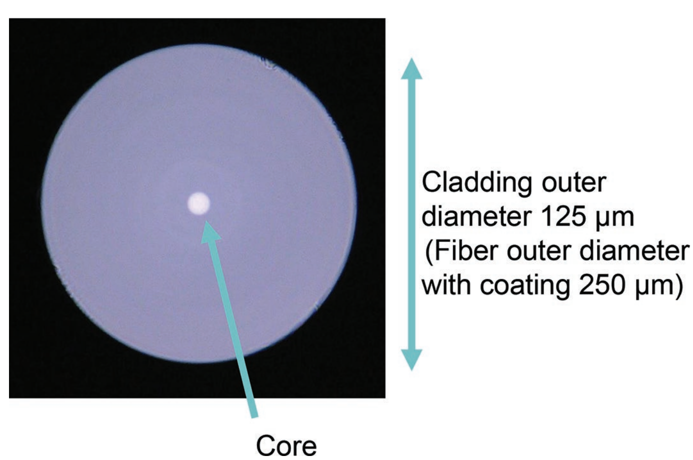

Figure 1. Cross section of a typical single-mode optical fiber.

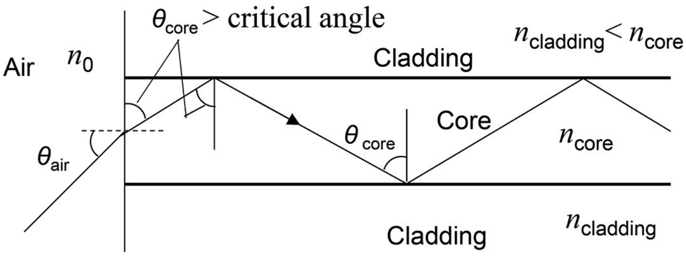

Figure 2. Principle of light propagation through a core in an optical fiber. n = refractive index, θ = injection angle of light.

125 µm. However, even if four cores with a higher refractive index than the cladding are simply placed in the cladding, crosstalk of information occurs between the cores. Crosstalk occurs because 100% of the light does not perfectly reflect, and some light leaks into the cladding despite the claim of total internal reflection. With this situation, the Japanese team has succeeded in preventing crosstalk by creating a region with an even lower refractive index in the cladding as shown in Figure 3.

In Japan, optical fibers are made by the vapor phase axial deposition method. In this method, soot-like SiO_2 is deposited by oxidizing $SiCl_4$ in an oxyhydrogen flame. Its chemical reaction formula is

$$SiCl_4 + 2H_2O \rightarrow SiO_2 + 4HCl.$$

Thin optical fiber can be obtained by heating and melting the base material with accumulated soot to vitrify it and then by drawing it.

The refractive index of SiO_2 is about 1.46. The addition of Ge to SiO_2 increases the refractive index, whereas the addition of F decreases the refractive index. Therefore, for example, it has already been confirmed that crosstalk in MCF was successfully prevented by arranging Ge-doped SiO_2 as a core at the center, non-doped SiO_2 as a cladding around it, and F-doped SiO_2 concentrically as the second cladding a little farther away. Crosstalk was also confirmed to be prevented by arranging undoped SiO_2 as a core, F-doped SiO_2 as a clad, and F-doped SiO_2 with an increased doping amount a little farther away as the second cladding. As a result, an uncoupled four-core optical fiber with a cross section shown in Figure 4 was developed by Furukawa Electric, one of the members of the Japanese team.

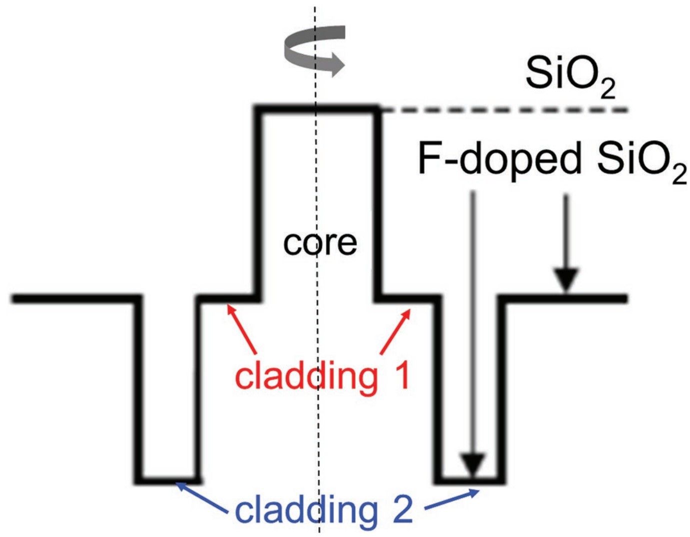

Figure 3. Example of refractive index distribution in a multi-core fiber (MCF).

The typical specifications and features of the MCF developed by Furukawa Electric are listed in Table 1 [5]. In addition,

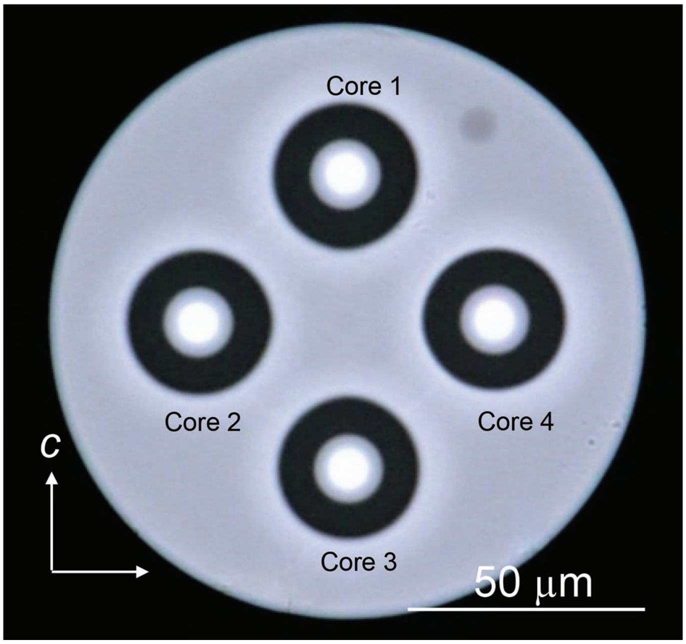

Figure 4. Cross section of the uncoupled four-core optical fiber developed by Furukawa Electric.

Table 1. Specifications and features of the uncoupled four-core optical fiber at 1550 nm developed by Furukawa Electric

Characteristic	Unit	Value
Cladding diameter	µm	125
Coating diameter	µm	245
Core pitch	µm	43.0
Effective area	µm2	87.1
Cut-off wavelength (22 m)	nm	1,539
Dispersion	ps/nm per km	22.6
Dispersion slope	ps/nm2 per km	0.06
Attenuation loss		
Core 1	dB/km	0.155
Core 2	dB/km	0.156
Core 3	dB/km	0.157
Core 4	dB/km	0.155
Intercore crosstalk		
Core 1–Core 2	dB/100 km	–63.8
Core 2–Core 3	dB/100 km	–60.7
Core 3–Core 4	dB/100 km	–62.7
Core 4–Core 1	dB/100 km	–61.8

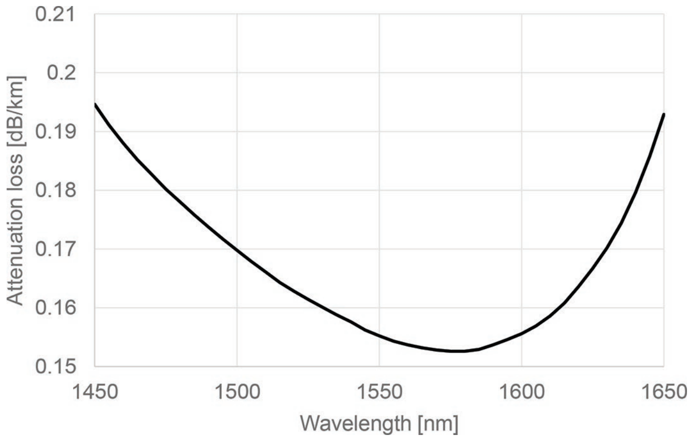

Figure 5. Attenuation loss spectrum of core 1 of the uncoupled four-core optical fiber developed by Furukawa Electric.

Figure 5 shows the attenuation loss spectrum of core 1 of the developed uncoupled four-core optical fiber.

The main features of the newly developed MCF are as follows: (1) It uses uncoupled four-core fiber, which has four times as many cores as the conventional single-core fiber cable. Therefore, it is possible to increase the transmission capacity significantly while maintaining the same fiber size. (2) Crosstalk between cores, which is a problem in MCF transmission, is suppressed to a low crosstalk of −60 dB/100 km or less while achieving the world's lowest transmission loss of 0.155 dB/km for MCF. (3) By applying the developed optical fiber, the team has demonstrated that it is possible to transmit optical signals of 56 terabits per second over 12,000 km in addition to being able to transmit ultra-high-capacity optical signals of 109 terabits per second over 3,120 km [6].

The submarine cable developed by the Japanese team can accommodate a maximum of 32 uncoupled four-core fibers, which makes possible optical transmission using 128 cores. As a whole, the Japanese team will construct a 3,000-km-class optical submarine cable system covering the Asian region, etc., consisting of optical submarine cables accommodating 32 cores (16 pairs) of four-core fibers, multi-function devices, and optical amplifiers. The team has confirmed the possibility of increasing the capacity of the cable to about 1.74 petabits per second using the developed submarine optical communication system [7].

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