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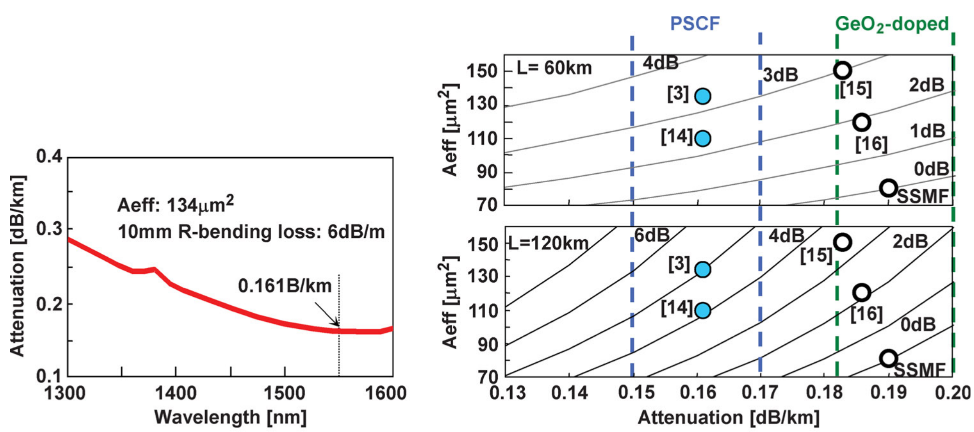

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Future of Transmission Fiber

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(Invited Paper)

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Abstract: In 2010, most high-capacity transmission experiments have been demonstrated over low-loss and/or low-nonlinearity dispersion unshifted fibers. Not only the research interest but the discussions of actual deployment of such linearity-enhanced fibers as well were starting to increase network capacity with systems based on greater than 100-Gb/s symbol rate. In addition, evolutional optical fibers that dramatically increase capacity in a single fiber, including multicore fibers and photonic crystal fibers, have been proposed.

Index Terms: Optical Transmission Fibers, Fiber Nonlinear Optical Effects.

Along with the rapid spread of bandwidth-hungry services, large volumes of data are required to be transmitted over a long reach. As a corollary, the demand for broadband Internet-traffic continues to increase at about 2 dB per year [1], and it is said that "capacity crunch" in the very near future will become a possible reality [2]. A straightforward way to keep up with the explosive traffic growth is to increase the transmission capacity per a single fiber, and therefore, there have been continuous and strong demands for advanced transmission fibers. The type of advanced fibers has been historically changing every several years along with the development of transmission systems and signal processing [3].

In 2010, the most advanced fiber for high-capacity long-haul transmission experiments completely changed to linearity-enhanced fibers, that is, low-loss and/or low-nonlinearity dispersion-unshifted fiber. Actually, this class of fibers has been utilized as the transmission line in 10 out of 11 high-capacity transmission experiments, which was presented as postdeadline paper in [4] and [5]. In addition, to further expand capacity over the coming decade, many different kinds of evolutional fibers have been proposed and fabricated.

Here, state-of-the-art linearity-enhanced fibers for long-haul systems will be described. Then, the required performance of transmission fibers for tomorrow's high-capacity long-haul systems will be discussed. In addition, some prospects of evolutional fibers, including photonic crystal fiber (PCF), multicore fiber (MCF), and multimode fiber (MMF), will be also described.

Recent capacity progress depends on the spectral efficiency increase using higher order signal formats with a coherent detection. Actually, 10-Tb/s transmission systems based on a 100-Gb/s symbol rate with quadrature phase shift keying (QPSK) are launching the service in 2010. In the digital coherent transmission systems, a digital signal processor (DSP) that can equalize for practically any amount of linear transmission impairments has been utilized [6]. In this system, accumulated chromatic and polarization-mode dispersions are no longer obstacles, and therefore, dispersion compensation in the transmission line has become unnecessary. In fact, the larger chromatic dispersion improves transmission capacity and distance [7]. With such electronic

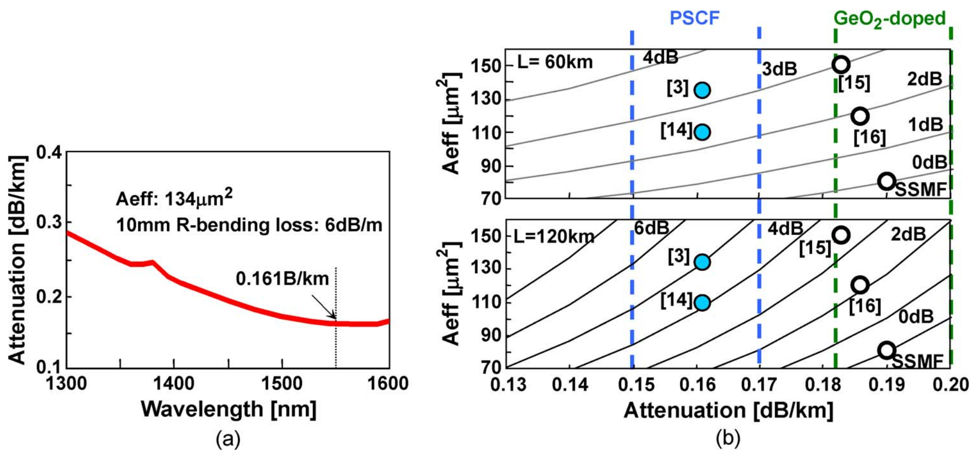

Fig. 1. (a) Attenuation spectra of pure-silica core fibers with A_{eff} of 134 μm^2 and the characteristics at 1550 nm and (b) contour map of relative FOM normalized to SSMF.

processing, required performances for optical system came to be simple, increasing the optical signal-to-noise ratio (OSNR) [8]. As for fiber properties, reduction of the attenuation and nonlinear coefficient (γ) are essential, because the lower fiber attenuation can directly increase the output power for a certain input power, and the lower γ can allow the higher input power managing the transmission impairment due to Kerr nonlinear effects accumulated in a fiber [9].

Pure-silica core fiber (PSCF) has an improved attenuation of 0.15 to 0.17 dB/km at 1550 nm [10], which is significantly lower than the attenuation around 0.19 dB/km of a standard single-mode fiber (SSMF) doped with GeO_2 in the core. In order to decrease the γ, reduction of the nonlinear refractive index of n_2 and enlargement of the effective area of A_{eff} are key issues, because the γ is defined as $\gamma = n_2/A_{eff} \times 2\pi/\lambda$, where λ is the lightwave wavelength. The n_2 is determined with the composing material, and a PSCF is about 10% lower (-0.3 dB) than that of a GeO_2-doped SSMF [11]. To decrease the γ, it is more important to enlarge the A_{eff}. The challenge is to cope with poor macro- and microbending loss performance by employing an appropriate refractive index profile and a low Young's modulus primary coating. Applying a trench-assisted profile, a fiber with the A_{eff} of 120 μm^2, which is 1.5 times larger than that of SSMF, and the better microbending loss performance than SSMF's, was demonstrated [12]. Another issue of large-A_{eff} fiber is the huge splicing loss to an existing SSMF because of a large amount of mismatching in mode-field diameters between fibers. Considering the splicing loss, we found that that the A_{eff} around 135 μm^2 would be the most suitable as a long-haul transmission fiber [13] and actually demonstrated PSCF with the A_{eff} of 134 μm^2 and low attenuation of 0.161 dB/km having the equivalent bending sensitivities to that of actually deployed fibers, as shown in Fig. 1(a) [3], [13].

A lot of high-capacity transmission experiments through linearity-enhanced fibers were presented in 2010 [14]–[17]. For example, the record-high total capacity of 69-Tb/s transmission over 240-km-long PSCF with the A_{eff} of 110 μm^2 and attenuation of 0.160 dB/km [14], and total capacity of 12.5 Tb/s transmission over 9360 km-long large A_{eff} fiber of 150 μm^2 with the attenuation of 0.183 dB/km [15], was demonstrated, respectively. Here, the question is, "which is the best fiber for high-capacity and long-haul transmission?" In a system with the span length of L [km], the figure of merit (FOM) for a fiber having the A_{eff} $[\mu\text{m}^2]$ and an attenuation of α [dB/km] will be described as [3], [18]

$$FOM\ [\text{dB}] = 10\log(A_{eff} \times \alpha) - \alpha \times L. \quad (1)$$

The first term means that the allowable signal launched power limited by Kerr nonlinearities is determined with a product of $A_{eff} \times \alpha$, and the second term represents the output power after L km-long fiber propagation. Therefore, the better ONSR a system has over a fiber with the higher FOM [9]. Providing an SSMF with the α of 0.19 dB/km and A_{eff} of 80 μm^2 as a reference, the relative

FOM can be calculated. Fig. 1(b) shows the contour map of the relative FOM as a function of A_{eff} and attenuation for span length L of 60 km and 120 km. As can be seen in Fig. 1(b), reported linearity-enhanced fibers have improved FOMs by 3 to 5 dB as a result of improvements to both A_{eff} and attenuation. It should be noted that the lower attenuation has the more advantageous impact on the FOM rather than the larger A_{eff} for the longer span length. In order to apply this class of linearity-enhanced fibers to a terrestrial transmission system, there are still things to be solved, including establishment of a unified standard and evaluation of mixability with various types of fibers that have actually been deployed [19].

To further decrease the nonlinearity, a PCF with dramatically enlarged A_{eff} of 220 μm^2 with practically low bend-induced loss was demonstrated [20]. However, its attenuation is as high as 1.2 dB/km, and it is expected that the attenuation of large-A_{eff} PCF will be able to be reduced to a comparable value with the lowest attenuation of a PCF ever reported (0.18 dB/km) [21].

In order to avoid the capacity crunch, the advent of some evolutional fibers is anticipated over the next decade, and new multiplexing schemes other than time and wavelength have been seriously considered [20]. MCF has several cores in a single fiber, and space-division multiplexing through the MCF is expected to dramatically increase the transmission capacity [21]. In order to apply a MCF to a long-haul transmission, the challenge is to reduce intercore crosstalk, and the efforts to manage the crosstalk were actively reported in 2010 [22]–[25]. We and Fini *et al.* independently revealed that the crosstalk is significantly affected by a bend in MCF and is a stochastic value, both with theoretical [22], [23] and experimental [22] evaluation. In 2011, it is promising that an MCF having negligible crosstalk will be demonstrated.

Propagation mode division multiplexing (MDM) using a multiple-input and multiple-output (MIMO) algorithm over MMF is also a hot topic, and transmission of two modes $\times$ 4 Gb/s over a 5 km-long MMF was demonstrated [26]. The transmission capacity and reach are still not very impressive compared with that in today's WDM systems, and the development of fiber structure suitable for the MDM and improvement of the MIMO algorithm are strongly expected.

In summary, advanced transmission fibers are strongly expected in order to keep up with explosive increase of traffic growth. Linearity-enhanced PSCFs would be promising because of the potential attenuation as low as 0.15 dB/km and A_{eff} as large as 135 μm^2. For the next decade, some "evolutional" fibers will be expected to prevent transmission capacity from crunch.

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