Letters

Photonic Crystal Fiber

Katsusuke Tajima, Kenji Kurokawa, Kazuhide Nakajima, and Izumi Sankawa†

Abstract

Photonic crystal fiber (PCF) is a promising candidate as a future transmission medium because it has unique features that are not available with conventional single-mode fiber. This article describes recent important progress on PCF.

1. Introduction

Optical fiber has become a vital element of the infrastructure supporting the continuously expanding IT (information technology) society. Although it has mainly been used in backbone networks, its application has now been extended to access networks. However, the optical characteristics of conventional single-mode fiber (SMF), where dopants are doped into silica glass to form a waveguide structure, limit the optical communication capacity at currently used wavelengths. There has been a strong need for a new type of fiber with which to construct more economical networks based on an ultrahigh-capacity backbone.

Recently, optical fibers called "holey fibers" have received increasing attention because they provide transmission characteristics that are superior to those of conventional single-mode fiber. One such holey fiber is index guiding photonic crystal fiber (PCF) [1], which has dozens of small air holes arranged like a crystal lattice, as shown in **Fig. 1**. As with conventional single-mode fiber, light can propagate along the fiber by a mechanism based on total internal reflection.

In this article, we outline recent progress on PCF especially for transmission purposes.

2. Unique features of PCF

PCF has several unique features that make it suitable for ultrawide-band and ultralong-distance trans-

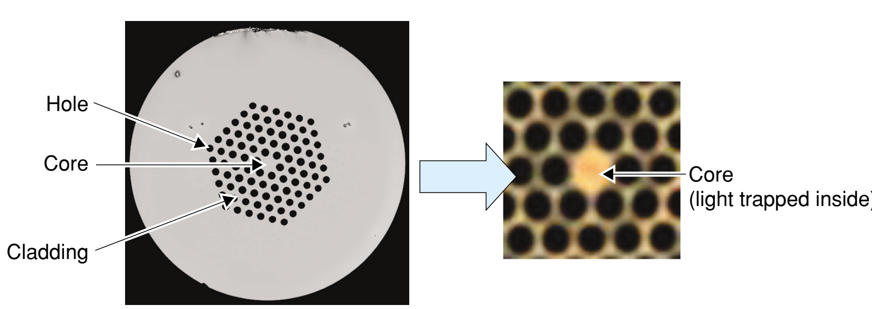


Fig. 1. Cross-sectional photograph of photonic crystal fiber.

† NTT Access Network Service Systems Laboratories
Tsukuba-shi, 305-0805 Japan
E-mail: sankawa@ansl.ntt.co.jp

mission. One of its most interesting properties is its endlessly single-mode characteristics, which could open a new optical transmission window ranging continuously from the visible to near-infrared wavelength regions. This particularly wide wavelength window cannot be obtained with conventional single-mode fiber. Therefore, it should be possible to greatly increase the transmission capacity of PCF.

In addition, the intrinsic loss of PCF is less than that of conventional single-mode fiber. This is because PCF is composed solely of pure silica glass without any dopants. This is an advantage because the use of dopants often increases the scattering loss. This feature makes PCF a promising candidate as a long-distance transmission medium. However, if we are to use it as a transmission medium, we must fabricate long lengths of low-loss PCF.

3. Low-loss and long-length PCF

The main loss factors for PCF are confinement loss, intrinsic silica loss due to scattering and absorption, and extrinsic loss caused by contamination and surface roughness. Unfortunately, the extrinsic loss dominates the optical attenuation of current PCF. Efforts to reduce attenuation are shown in **Fig. 2**. In March 2003, NTT Access Network Service Systems Laboratories established a world record of 0.37 dB/km at 1550 nm [2] and then broke this record six months later with a loss of 0.28 dB/km [3] by reducing the optical attenuation caused by surface roughness and OH absorption. As a result of these efforts, the loss now approaches the intrinsic loss of silica-based fiber (0.14 dB/km).

Until recently, the maximum available length of PCF was limited to a few kilometers, which meant that it would have been necessary to concatenate many segments to construct a long transmission line. Recent work on the fiber drawing process and the use of a large PCF preform led to the production of an approximately 10-km-long PCF in September 2003 [3] and a 100-km-long, low-loss (0.3 dB/km) PCF in March 2005 [4].

4. Mechanical reliability of PCF

A PCF cabling process is needed if PCF is to be used as a transmission medium. Therefore, high mechanical reliability is required. The fact that PCF contains air holes has led to the belief that its tensile strength must be lower than that of conventional single-mode fiber. However, it has been found that PCF with an optimized structure is actually stronger than conventional single-mode fiber [5]. The tensile strengths of a PCF with 90 holes and a conventional single-mode fiber are compared in **Fig. 3**. The tensile strength of the PCF is 62 N and that of the single-mode fiber is 58 N. The existence of the holes prevents cracks from growing. There appears to be an optimal hole size, hole pitch, and number of holes for

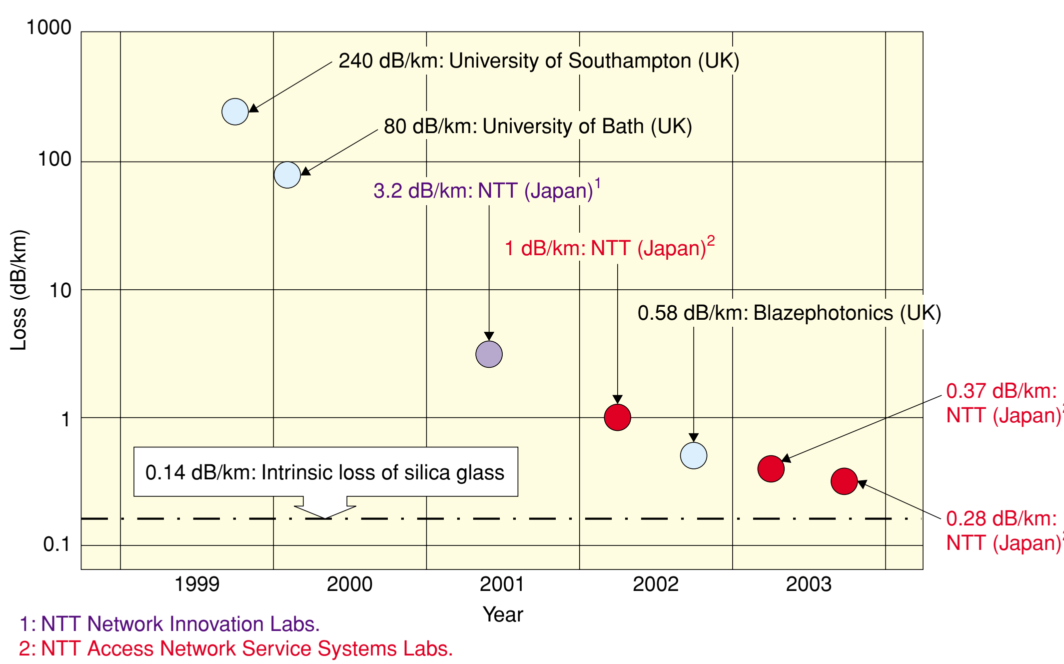


Fig. 2. Progress in reducing the loss of PCF.

higher-tensile-strength PCFs. However, before PCF can be employed as a practical transmission infrastructure, the long-term stability of its mechanical and optical characteristics must be studied.

5. Application as transmission medium

The new low-loss PCF has been tested in several transmission experiments. NTT Access Network Service Systems Laboratories performed the first successful 19-channel wavelength division multiplexing transmission experiment (190 Gbit/s) through a 5-km-long PCF in the 850–1550-nm wavelength region [6]. The measured bit error rate (BER) performance in the 850-, 1310-, and 1550-nm bands is shown in **Fig. 4**. There was no noticeable BER degradation in

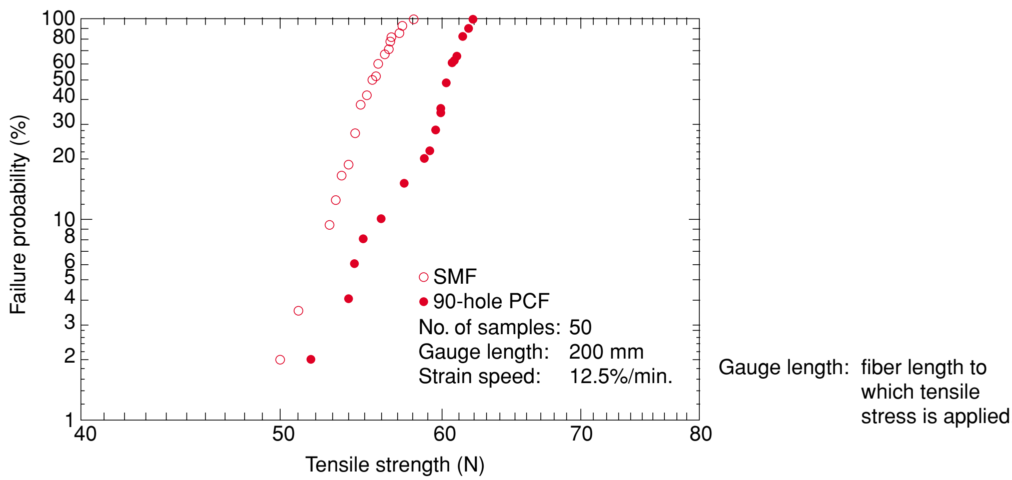


Fig. 3. Probability plot of tensile strength test.

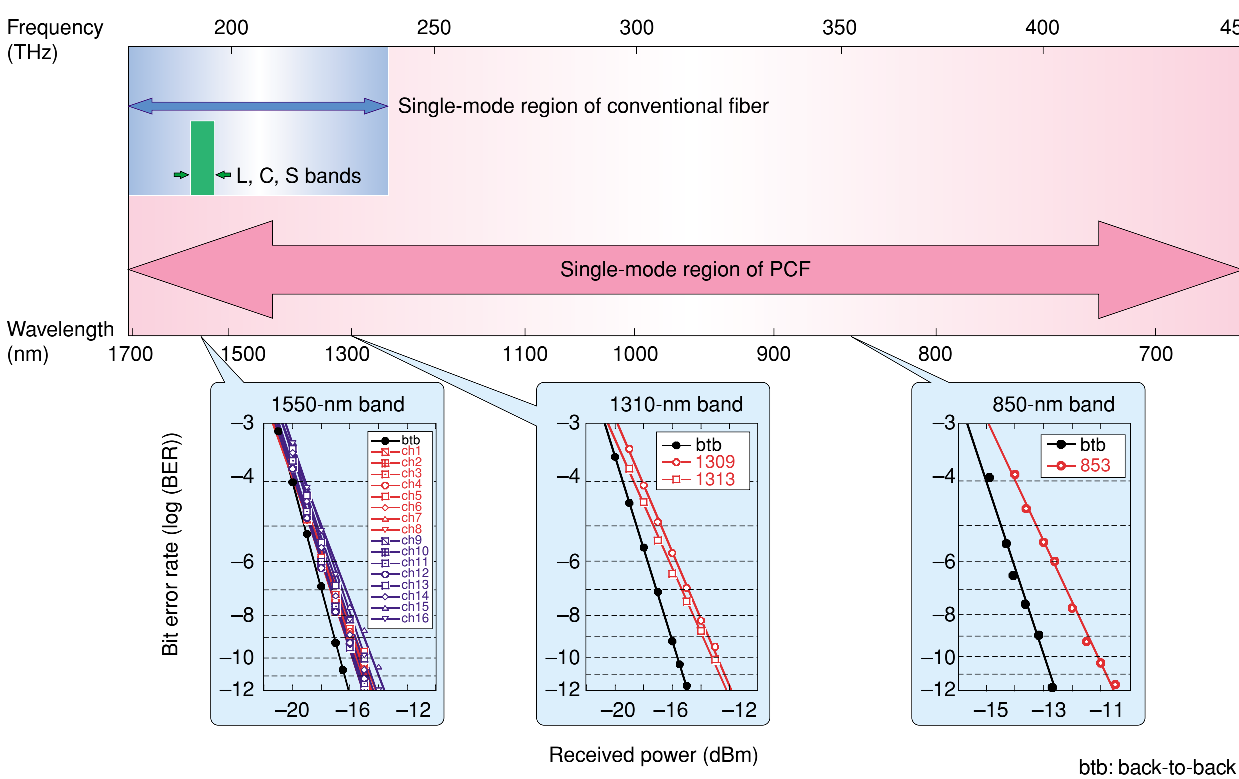


Fig. 4. Ultrawide-band transmission experiment.

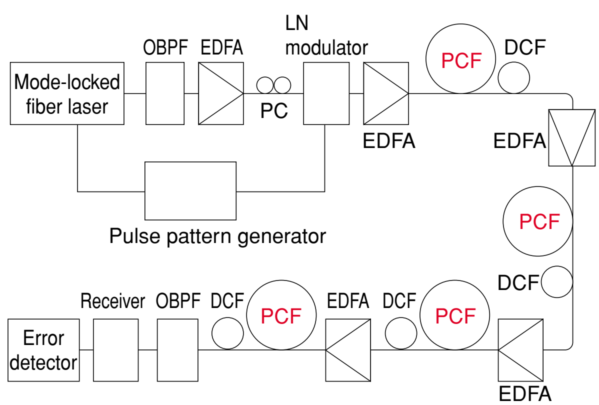
any of the transmission bands. These results show that the single-mode high-bit-rate transmission potential of PCF was confirmed experimentally over a wide wavelength range from 850 to 1550 nm, which corresponds to a bandwidth of 160 THz. We can expect that an endlessly single-mode PCF will provide an ultrawide band of several hundred terahertz for future optical communication systems with an ultralarge capacity on the petabit-per-second order.

Moreover, NTT Access Network Service Systems Laboratories has reported the first optical soliton transmission experiment with a 100-km-long and low-loss (0.3 dB/km) PCF at 10 Gbit/s [4]. The experimental setup, BER performance, and autocorrelation traces before and after the 100-km transmission are shown in **Fig. 5**. A BER of less than 10^{-11} was successfully obtained without any power penalty. The output pulse was slightly wider than the input pulse, but no BER degradation was observed because the output pulse width was much narrower than the bit slot. Thus, power-penalty-free dispersion-managed soliton transmission over 100 km was achieved.

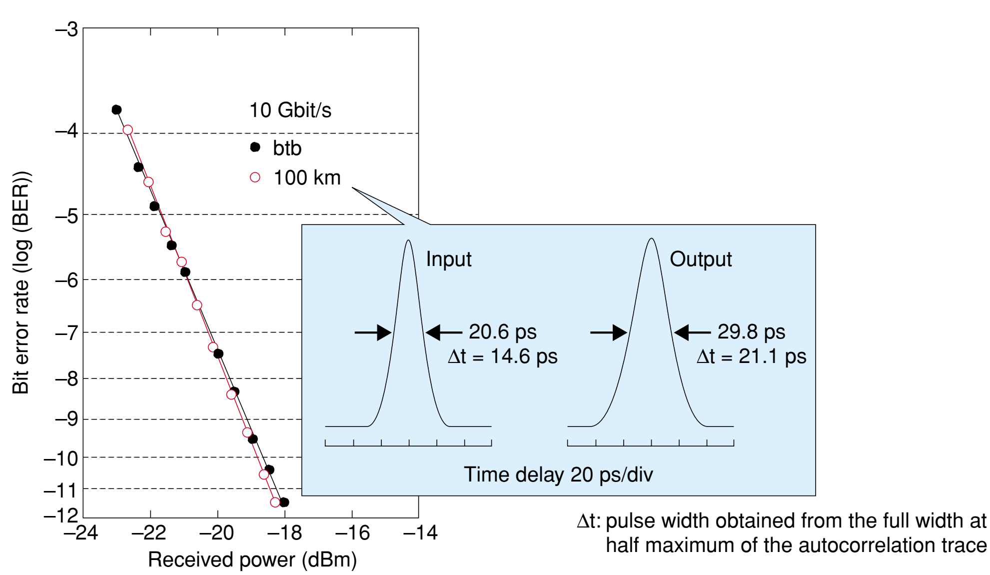
These experimental results show that low-loss PCF is a promising candidate as a long-distance transmission medium.

6. Future directions

Recent progress on PCF has shown its potential as a high-bit-rate, large-capacity, and long-distance



(a) Experimental setup



(b) Experimental results

Fig. 5. Long-distance and nonlinear optical transmission experiment.

transmission medium. From the practical point of view, several feasibility studies will be undertaken on PCF as a future communications medium. These will include investigating its transmission characteristics and reliability over wide wavelength regions and technologies for testing, connecting, and cabling it.

References

[1] "Research Advances Rapidly on a New Breed of Optical Fiber that Could Lead to Ultrahigh-capacity Communications and Cost Reductions," NTT Technical Review, Vol. 2, No. 2, pp. 89-90, 2004.

[2] K. Tajima, J. Zhou, K. Nakajima, and K. Sato, "Ultra low loss and long length photonic crystal fiber," Tech. Digest of OFC 2003, PD1.

[3] K. Tajima, J. Zhou, K. Kurokawa, and K. Nakajima, "Low water peak photonic crystal fibers," Tech. Digest of ECOC 2003, Th4.1.6.

[4] K. Kurokawa, K. Tajima, J. Zhou, K. Nakajima, T. Matsui, and I. Sankawa, "Penalty-free dispersion-managed soliton transmission over 100 km low loss PCF," Tech. Digest of OFC 2005, PDP21.

[5] J. Zhou, K. Tajima, K. Kurokawa, K. Nakajima, and I. Sankawa, "High tensile strength photonic crystal fiber," Tech. Digest of OFC 2004, WI2.

[6] K. Nakajima, J. Zhou, K. Tajima, K. Kurokawa, C. Fukai, and I. Sankawa, "Ultra wide band 190 Gbit/s WDM transmission over a long length and low loss PCF," Tech. Digest of OFC 2004, PDP23.

Katsusuke Tajima

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received the B.E. degree in electrical engineering from Science University of Tokyo, Tokyo in 1980 and the M.S. and Ph.D. degrees in electronics engineering from the University of Tokyo, Tokyo in 1982 and 1985, respectively. He joined NTT Ibaraki Electrical Communication Laboratory in 1985 and engaged in research on the transmission characteristics of optical fibers. His current research includes the design of optical fibers, new fiber materials especially for low-loss transmission media, and nonlinear effects in optical fibers. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Kenji Kurokawa

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received the B.S., M.S., and Ph.D. degrees in physics from the University of Tokyo, Tokyo in 1985, 1987, and 1997, respectively. He joined NTT Ibaraki Electrical Communication Laboratories in 1987 and has been engaged in research on ultrashort optical pulse generation and nonlinear effects in optical fibers. He is a member of IEICE, the Japan Society of Applied Physics (JSAP), and the Physical Society of Japan (JPS).

Kazuhide Nakajima

Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received the M.S. and Ph.D. degrees in electrical engineering from Nihon University, Chiba in 1994 and 2005, respectively. In 1994, he joined NTT Access Network Systems Laboratories, Tokai, Ibaraki, where he has been engaged in research on optical fiber design and related measurement techniques. He is a member of IEICE.

Izumi Sankawa

Group Leader, Senior Research Engineer, NTT Access Network Service Systems Laboratories.

He received the B.S. and Dr.Eng. degrees in electrical engineering from Waseda University, Tokyo in 1979 and 1991, respectively. He joined the Ibaraki Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation (now NTT), Ibaraki in 1979 and has been engaged in research on optical fiber splicing, testing technologies, and optical fiber measurement and surveillance systems. He is a member of IEICE, JSAP, and JPS.