Next-generation Optical Transmission Medium Technology

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Abstract

The research and development of the next generation of optical transmission media aims to provide a medium that exceeds the transmission speed and capacity of current optical fiber. In this article, we describe the latest work on photonic crystal fiber technology and an ultrahigh-speed optical signal monitoring technique that uses optical sampling technology.

1. Introduction

Communication networks are now being used for more diverse and advanced purposes such as multimedia services, video-on-demand, ubiquitous communication, and Web 2.0. Consequently, the functions and performance required of them are also increasing. In addition to higher speeds and capacities, networks must be more flexible and economical with respect to maintainability, operability, and service expansion. In particular, we believe that they will require a transmission medium that exceeds the speed and capacity of current optical fiber to cope with true peer-to-peer (P2P) communication, where large amounts of information will be transmitted bidirectionally. NTT Access Network Service Systems Laboratories is researching photonic crystal fiber (PCF), a new kind of optical fiber [1], and a new method of monitoring high-speed optical signals. In 2005, we introduced the features of PCF and our related activity [2]. In this article, we report our latest work on PCF transmission performance and describe new optical sampling techniques for ultrahigh-speed optical signal monitoring.

2. Transmission capabilities of PCF

PCF features a wavelength range for single-mode operation that extends from the infrared region to the visible region of the electromagnetic spectrum. This range, which is considerably wider than that of conventional single-mode optical fiber, enables ultrahigh-capacity transmission. In 2005, we reported the results of 19-wavelength wavelength division multiplexing (WDM) transmission experiments [2] conducted to test the feasibility of using wavelengths from 0.85 to 1.55 μm. Since then, there have been four technical advances.

The first advance includes opening up the 1-μm-band wavelength region and confirming the transmission performance of the 0.78- and 0.65-μm bands on the shorter wavelength side, with higher speeds attained for each wavelength. The 1-μm band is positioned midway between the 0.85-μm band, which is typical for silica-based multimode optical fiber, and the 1.3-μm band for single-mode optical fiber. This band has been attracting attention in relation to high-power Yb-doped fiber lasers and other such devices. We have focused our research on the 1-μm band as a promising wavelength region that holds the key to ultrahigh-capacity transmission. A transmission speed of 10 Gbit/s was achieved in experiments in September 2005 [3] and this was improved to 40 Gbit/s in March 2006 [4]. These experimental results show the applicability of the 1-μm band as a communication wavelength region for PCF.

On the other hand, the 0.78- and 0.65-μm bands are general wavelengths for multimode polymer optical fibers made primarily of polymethylmethacrylate (PMMA). In these wavelength bands, light sources, photodetectors, and other devices with a relatively low bit rate are commercially available. To clarify the

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high-speed transmission performance of PCF in these wavelength regions, we conducted experiments with higher speed devices. We reported the results of 1-Gbit/s transmission experiments in both bands in September 2006 [5].

We particularly focused on improving the transmission speed per wavelength in the conventional communication wavelength bands of 1.3 and 1.55 μm. Specifically, we attained higher transmission speed in PCF by raising the bit rate from 10 to 40 Gbit/s. That showed the feasibility of 40-Gbit/s transmission in both the 1.3- and 1.55-μm bands [6], [7]. Using an extremely broad wavelength range that extends for roughly 300 THz from the visible region into the infrared region (**Fig. 1**), we have been investigating the possibility of achieving ultrahigh-speed, high-capacity transmission through PCF.

The second advance relates to loss compensation techniques for various wavelength bands that are suitable for communication over a wide wavelength region. Distributed Raman amplification (DRA) techniques that use the stimulated Raman amplification effect in silica-based optical fiber have been studied and many reports have been published. However, there have been few such reports on PCF. It is difficult to obtain sufficient gain to compensate for the relatively large transmission loss of PCF. Using a new technique for fabricating long lengths of PCF with low loss, we achieved DRA in PCF for the first time. After reporting DRA in the 1.55-μm band in September 2004 [8], we attained a 1.6-dB improvement in the power penalty in DRA transmission in the 0.85-μm band in September 2005 [9]. These results suggest that it will be possible to make a long-distance DRA transmission system using PCF as with conventional single-mode optical fiber.

The third advance relates to the application of the flexible chromatic dispersion controllability of PCF to dispersion compensation in conventional optical fiber. With conventional single-mode optical fiber,

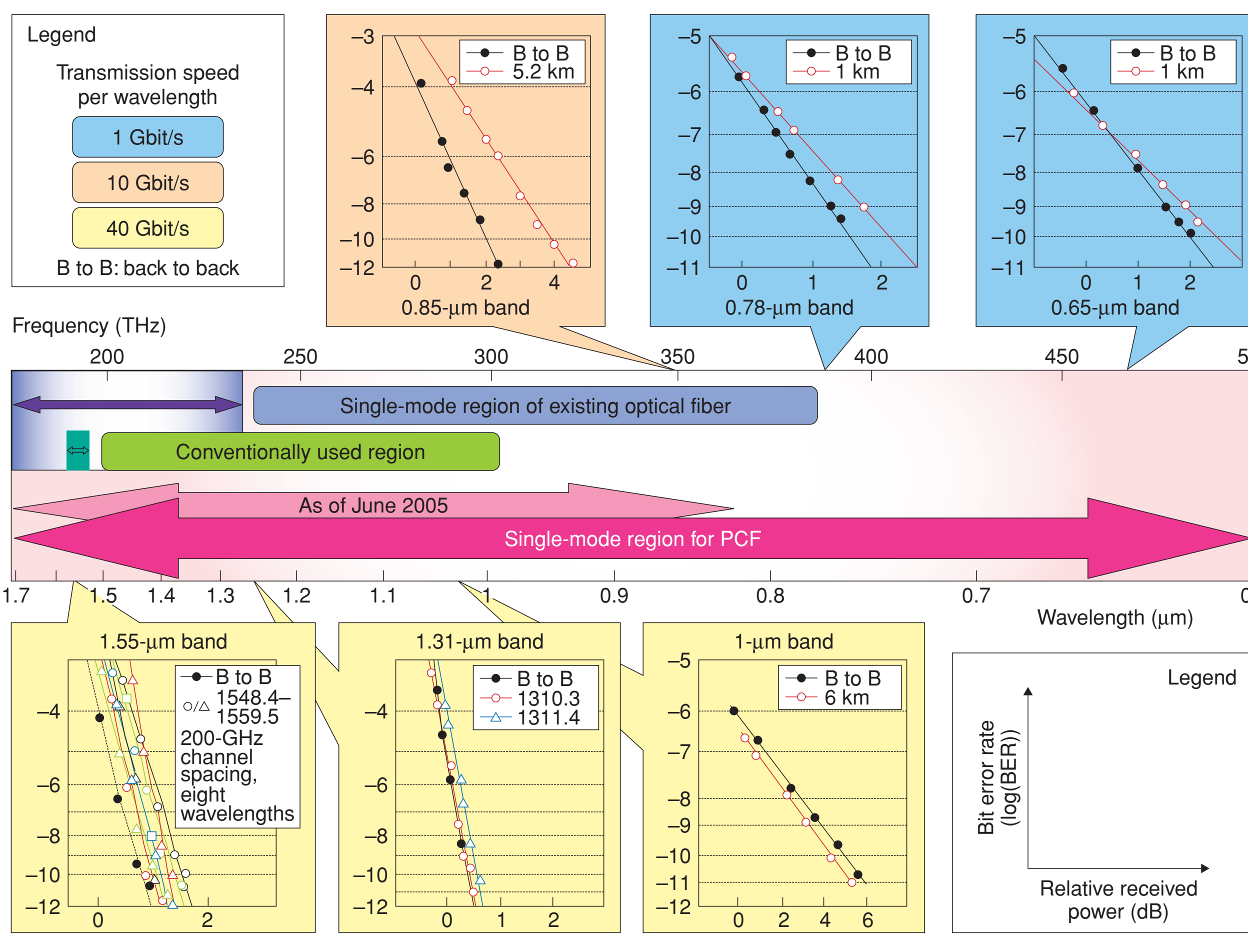

Fig. 1. Experiments on transmission through PCF.

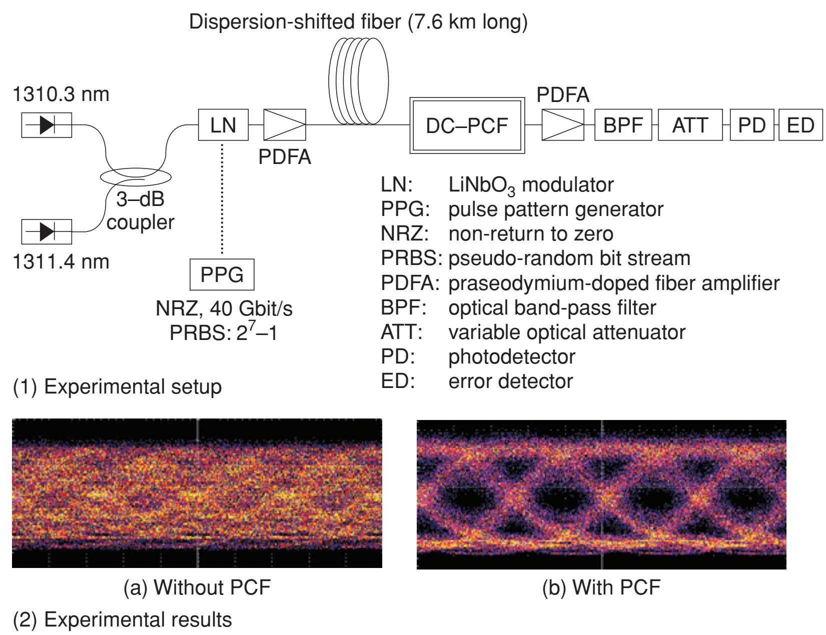

Fig. 2. Example of applying PCF to dispersion compensation.

signals faster than about 10 Gbit/s cannot be transmitted in certain wavelength regions because of cumulative chromatic dispersion. In 1.3-µm zero-dispersion fiber, the 1.55-µm wavelength band is unusable; for dispersion-shifted fiber, the 1.3-µm band is unusable. We demonstrated high-speed transmission through conventional fiber by compensating for the cumulative chromatic dispersion in various wavelength bands by using PCF. With dispersion-shifted fiber in particular, cumulative chromatic dispersion in the 1.3-µm band cannot be compensated for by conventional dispersion-compensating optical fiber technology. We confirmed the applicability of the dispersion compensation of the dispersion-shifted fiber by implementing the PCF as a dispersion-compensating medium [6] (**Fig. 2**).

The fourth advance is a new fiber structure that can flatten dispersion over a wide wavelength region. A reduction in chromatic dispersion is essential for high-speed transmission and PCF has a novel ability to control chromatic dispersion. With PCF having a uniform hole size, if the chromatic dispersion D from the 1.3-µm band to the 1.6-µm band, which is important for telecommunications, is designed to be within ±10 ps/nm/km, the effective area is several tens of square micrometers and the confinement loss reaches about 100 dB/km [10]. Generally, the former should be large to suppress non-linear optical effects and the latter should be small because the confinement loss directly corresponds to the transmission loss for the signal light. We have developed a flat-dispersion fiber with a double-cladding type PCF structure [11]. The inner cladding, formed by relatively small holes, controls the dispersion characteristics while maintaining a relatively large effective area and the outer cladding of large holes reduces the confinement loss. This structure makes it possible to control dispersion, improve the effective area, and reduce the confinement loss simultaneously (**Fig. 3**).

Because this double-cladding PCF structure can compensate for the dispersion of both 1.3-µm zero-dispersion fiber and dispersion-shifted fiber, it is expected to lead to new applications.

3. Waveform monitoring technology for high-speed optical signals

The speed of optical transmission systems is increasing, and we are currently studying the introduction of a 40-Gbit/s system. Waveform monitoring is becoming difficult because electrical oscilloscopes cannot keep up with the signal speed. Furthermore, differential phase shift keying (DPSK), differential quadratic phase shift keying (DQPSK), and other phase modulation methods are being studied for 40-Gbit/s systems, so waveform monitoring techniques that can detect changes in light phase are also needed. A linear optical sampling method, in which linear

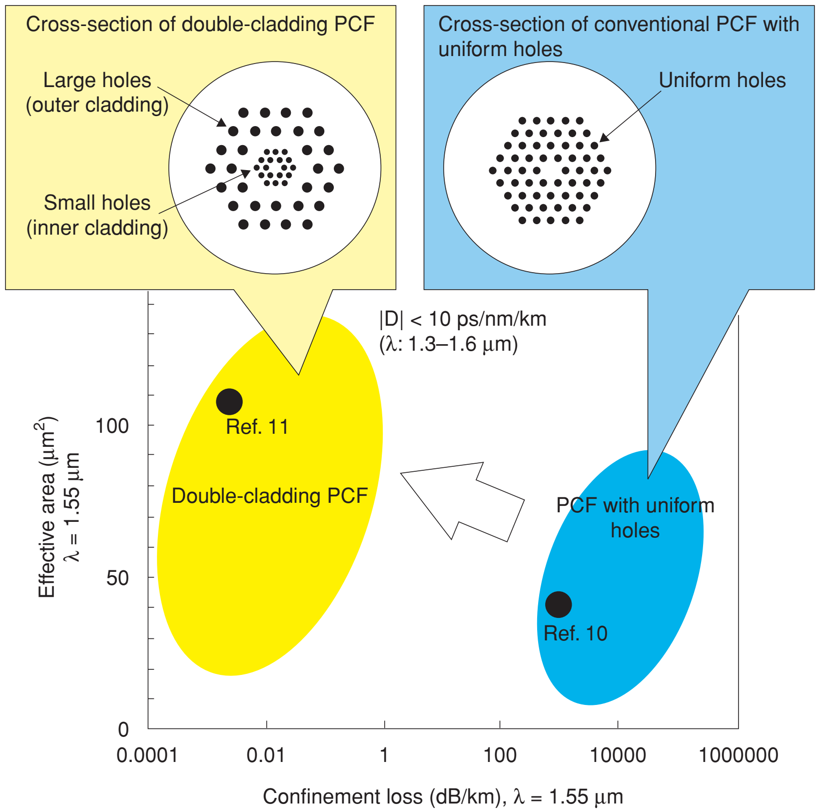

Fig. 3. Effect of double-cladding PCF on dispersion flattening.

cross-correlation (interference) between a sampling pulse and the signal light is observed, has been proposed as a new optical signal waveform monitoring technique, and research on this method is moving forward. This method has the following features, which make it a promising next-generation waveform observation technique.

- Potential for speeds in the terahertz bandwidth
- Possibility of monitoring phase modulation waveforms (or frequency modulation waveforms) as well as intensity modulation waveforms
- High sensitivity because only linear photodetectors are used

The linear optical sampling method is an application of detection technology in coherent light telecommunications. Here, we provide only a brief explanation of how it works. For more information on the principle and experimental apparatus, see references [12], [13].

If we combine the signal beam with a sampling pulse whose pulsewidth is sufficiently shorter than that of the signal light, the two waveforms interfere to create an interference fringe that can be detected by a low-speed photodetector (**Fig. 4**). The amplitude of the fringe is proportional to the instantaneous amplitude of the signal beam when the sampling pulse is present. This phenomenon can be used to detect the amplitude (intensity) of an ultrahigh-speed signal.

To detect the phase change of the signal beam, the signal beam and the sampling pulse are split into two beams and injected into a dual-channel interferometer. In the second interferometer channel, the injection of the sampling pulse is given a delay of $\Delta\tau$ relative to sample pulse injection in the first channel. The phase difference between the interference fringes of channels 1 and 2 corresponds to the change in the phase of the signal light over time $\Delta\tau$, so the phase modulation (or frequency modulation) waveform can thus be observed.

Using this principle, we succeeded in observing the waveform of a signal from a semiconductor laser. The results presented in **Fig. 5(a)** confirm that the frequency was reduced at the tail of the pulse. In contrast, in **Fig. 5(b)** the pulse of Fig. 5(a) passed through a dispersion compensating fiber, so the change in frequency was in the opposite direction. The linear sam-

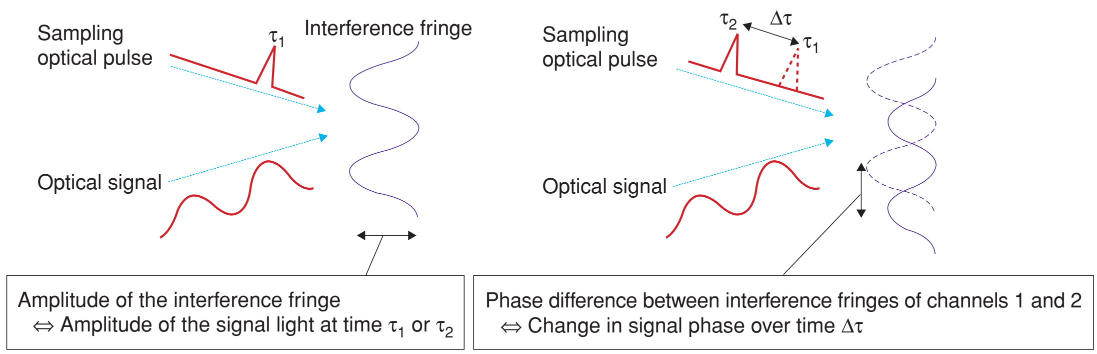

Fig. 4. Principle of linear optical sampling. The left figure is for channel 1 and the right figure is for channel 2.

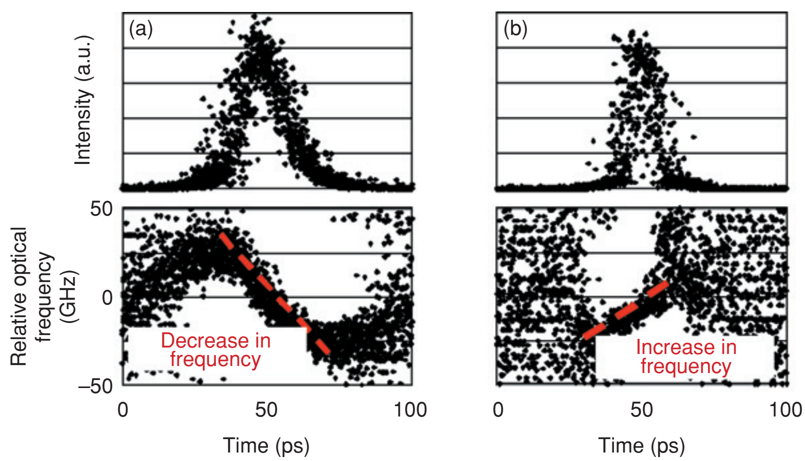

Fig. 5. Experimental results for linear optical sampling.

pling method thus makes it possible to monitor the change in phase (frequency) along with optical signal intensity.

4. Future plans

We will continue to research new optical communication medium technology to support telecommunication at even higher speeds and greater capacities to meet the expected future demands.

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