OWK3.pdf

10 Gbit/s Photonic Crystal Fiber Transmissions with 1.1 μm Directly-Modulated Single-Mode VCSEL

Kengo Koizumi, Masato Yoshida, Toshihiko Hirooka, and Masataka Nakazawa
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan
Tel: +81-22-217-5525, Fax: +81-22-217-5524, E-mail: k-kengo@riec.tohoku.ac.jp

Abstract: We demonstrate a 10-Gbit/s transmission over a 5-km photonic crystal fiber in the 1.1 μm band using a directly-modulated single-mode VCSEL. The transmission distance was extended to 14 km by using an ytterbium-doped fiber amplifier.

OCIS codes: (060.5295) Photonic crystal fibers; (060.2330) Fiber optics communications

1. Introduction

With the increasing demand for high-capacity optical networks, it is important to construct a high-speed optical transmission system at low cost such as fiber to the home (FTTH). To realize such a system, the combination of a directly-modulated vertical cavity surface emitting laser (VCSEL) and a photonic crystal fiber (PCF) is an attractive candidate. Single-mode, high-speed VCSELs that can be directly modulated at 10 Gbit/s have been developed at 0.8 μm [1] and more recently at 1.1 μm [2]. Furthermore, PCF enables us to realize single-mode operation and low dispersion at such short wavelengths [3], which are difficult to achieve with a conventional step index fiber (SIF). SIF that is single mode at shorter wavelengths is more sensitive to bending loss and has larger dispersion than PCF. This makes PCF a more attractive transmission medium for applications to high-speed LAN and FTTH. By taking advantage of these features, a 10 Gbit/s-2 km PCF transmission at 850 nm using a directly-modulated VCSEL and a Si-APD [4] and a 10 Gbit/s-1 km PCF transmission at 780 nm using a directly-modulated Fabry-Perot laser diode [5] have been demonstrated. The 1.1 μm wavelength region is particularly attractive because a high-speed VCSEL, low-loss PCF and a wide-band optical amplifier (ytterbium-doped fiber amplifier: YDFA [6]) are all available.

In this paper, we report a 10 Gbit/s-5 km PCF transmission at 1.1 μm with a directly-modulated VCSEL. We also demonstrate a 10 Gbit/s-14 km transmission using YDFAs to compensate for the transmission loss of the PCF. In previously reported 1.1 μm-band transmission experiments, mode-locked fiber or semiconductor lasers or the external modulation of DFB fiber lasers were used as light sources [7-9]. The directly-modulated VCSEL that we employ in the present work enables us to realize high-speed transmission at a low cost and with a much simpler configuration.

2. PCF characteristics in 1.1 μm band

When we apply PCF to a high-speed transmission, it is important to investigate the relationship between loss and dispersion. Figure 1 shows the numerical results for the PCF dispersion at 1.07 μm as a function of Λ and *d*/Λ. The measured transmission losses of PCFs are also plotted in this figure. The dashed line indicates the boundary between single-mode and multi-mode conditions. It can be seen that we can reduce the dispersion to zero and maintain the single-mode condition by reducing Λ to less than ~ 3.6 μm, but at the same time the loss increases significantly as Λ decreases. A large Λ is preferable for low loss but the dispersion cannot be reduced under the single-mode condition. Therefore, the optimum *d* and Λ must be chosen based on the signal-to-noise ratio (SNR) and dispersion limit requirements of the transmission system. For example, when we consider a 10 Gbit/s transmission over 5 ~ 15 km, the loss reduction realized by allowing a large dispersion is critical as shown by the shaded area in Fig. 1, where the dispersion length is sufficiently longer than the transmission length. In this experiment, we used four PCFs as a transmission line. Table 1 shows the parameters of each PCF. All the PCFs have a lower dispersion than a 1.1 μm single-mode step-index fiber (SIF). We also calculated the dispersion length L_D, which is defined as

$$L_D = \frac{\alpha + \sqrt{1+2\alpha^2}}{1+\alpha^2} \frac{\pi c T_0^{\,2}}{2\ln 2 \lambda^2 |D|} \tag{1}$$

where α is the chirp parameter of our VCSEL (typically α = 3 in the present case), D is the dispersion, λ is the wavelength, c is the velocity of light, and T_0 = 50 ps is the pulse width corresponding to 10 Gbit/s. As shown in Table 1, the L_D of the PCFs is sufficiently long, and therefore the influence of the dispersion is negligible if the transmission length is approximately 10 km.

OWK3.pdf

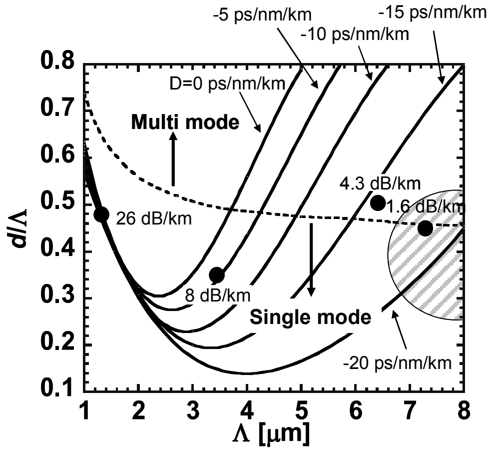


Fig. 1. Relationship between loss and dispersion of PCF at 1070 nm.

Table 1. PCF parameters at 1070 nm.

	PCF-A	PCF-B	PCF-C	PCF-D	SIF
Length (km)	5	7	1	1	-
MFD (μm)	6.1	4.9	9.2	7.7	6.2
Loss (dB/km)	1.4	8.0	1.6	4.3	1.5
Dispersion (ps/nm/km)	-14	-5	-19	-16	-36
L_D (km)	77	215	57	67	30

3. Experimental setup

Figure 2 shows our experimental setup for a 10 Gbit/s optical transmission in the 1.1 μm band. We used an InGaAs VCSEL as a light source. The VCSEL has a current confinement structure, and the oxide output aperture is 3.5 μm, which makes single transversal-mode operation possible by increasing the loss of the higher-order modes. The cavity length is 1.3 μm, which allows single longitudinal-mode oscillation. Figure 3(a) shows the optical output power characteristics of the VCSEL. The threshold current was 0.4 mA and the maximum output power was about 0.8 mW with an injection current of 5.0 mA. The slope efficiency at an injection current of 3.0 mA was 0.23 W/A. The oscillation wavelength was around 1.07 μm, and the side mode suppression ratio (SMSR) with the transverse higher-order mode was more than 50 dB, which indicates single-mode operation. Figure 3(b) shows the frequency response of the VCSEL. The 3 dB bandwidth was 7.2 GHz with an injection current of 3.0 mA. The capacitance C and resistance R of the VCSEL were 0.1 pF and 250 Ω, respectively. Therefore, the cutoff frequency f_p given by

$$f_p = \frac{1}{2\pi}\frac{1}{CR} \quad (2)$$

is calculated to be 7.1 GHz. The calculated value agrees well with the measured bandwidth, which is sufficient for 10 Gbit/s NRZ direct modulation.

The VCSEL was directly modulated with a 10 Gbit/s NRZ signal that had a 2^{31}-1 PRBS and then launched into the transmission line. The optical power launched into the PCF was -3.5 dBm. We used two transmission line configurations as shown in Fig. 2(a) and (b). In Fig. 2(a), a 5 km PCF-A was used because its loss is the lowest. Next, we combined all the PCFs shown in Table 1 to extend the transmission distance. In Fig. 2(b), the signal was first transmitted over two 2 km spans of PCF, whose loss was 16 dB and compensated for by in-line YDFAs. These spans are given by PCF-B, which has the largest loss, as shown in Table 1. Then the signal was transmitted over a 10

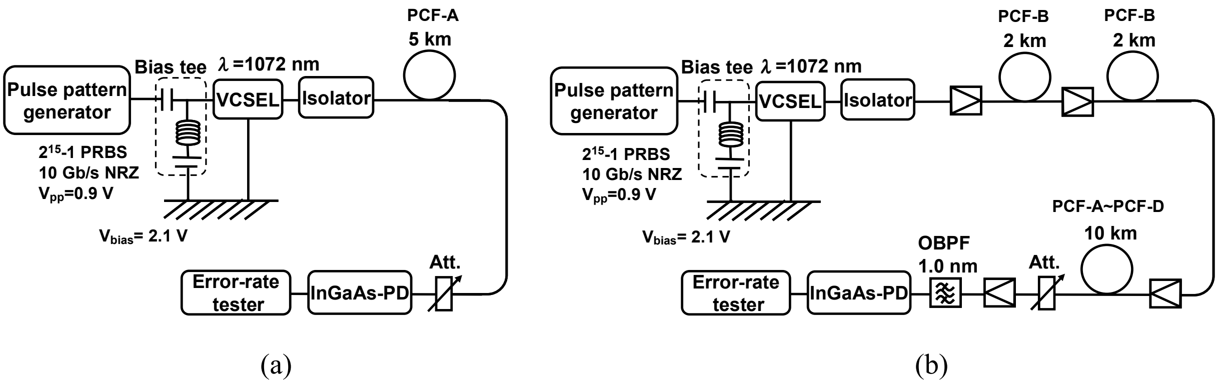
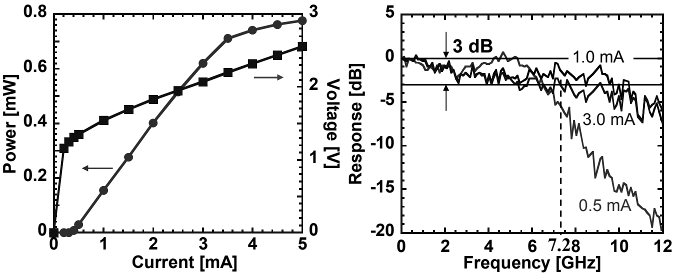


Fig. 2. Experimental setup for 10 Gbit/s-PCF transmissions at 1.1 μm. (a) 5 km and (b) 14 km transmission line.

km PCF, which was composed of a 3 km PCF-B and all the other PCFs. The loss was 37 dB, but the signal could be received with sufficient sensitivity by using a pre-amplifier. After the transmission, the data signal was received by an InGaAs-PD with an optical bandwidth of 10 GHz and a conversion efficiency of 0.3 A/W, and the bit error rate was measured. In Fig. 2(b), a YDFA was inserted as a pre-amplifier together with a 1.0 nm optical band pass filter (OBPF).

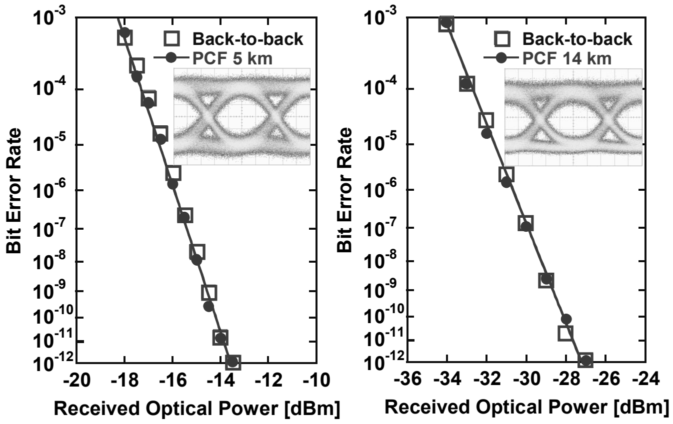


(a) (b)

Fig. 3. (a) Optical output power characteristics and (b) frequency response of VCSEL.

4. Transmission result

Figure 4 shows the results for 5 and 14 km transmissions corresponding to Fig. 2(a) and (b), respectively. Figure 4(a) shows the BER performance under a back-to-back condition and after a 5 km transmission. A clear eye opening was observed in the output signal after 5 km with an SMSR of 40 dB, and error-free transmission was achieved at a received optical power above -13.5 dBm with no power penalty. Figure 4(b) shows a 14 km transmission with YDFA repeaters. Error-free transmission was achieved without a power penalty at -27 dBm by using a YDFA as a pre-amplifier. The OSNR was 22 dB and clear eye opening was obtained. These results indicate that dispersion indeed has a negligible influence because of the sufficiently large L_D. By using a VCSEL with a higher output power, low-loss PCF, and a PD with a better sensitivity, the transmission distance may be further extended without employing optical amplifiers.



(a) (b)

Fig. 4. BER characteristics for 10 Gbit/s PCF transmissions. (a) 5 km transmission and (b) 14 km transmission with YDFA repeaters.

5. Conclusion

We have successfully demonstrated a 10 Gbit/s optical transmission at 1.1 μm using a directly-modulated VCSEL and PCF. As a result, we achieved a 5 km transmission without optical amplifiers. Moreover, the transmission length was extended to 14 km using a YDFA and a power penalty-free transmission was achieved.

References

[1] N. Ueki, A. Sakamoto, T, Nakamura, H. Nakayama, J. Sakurai, H. Otomo, Y. Miyamoto, M. Yoshikawa, and M. Fuse, “Single-transverse-mode 3.4-mW emission of oxide-confined 780-nm VCSELs,” IEEE Photon. Technol. Lett., **11**, pp. 1539-1541 (1999).

[2] T. Anan, N. Suzuki, K. Yashiki, K. Fukatsu, H. Hatakeyama, T. Akagawa, K. Tokutomo, and M. Tsuji, “High-speed 1.1-μm-range InGaAs VCSELs,” OFC2008, OThS5.

[3] J. C. Knight, J. Arriaga, T. A. Briks, A. Ortigosa-Blanch, W. J. Wadsworth, and P. S. J. Russell, “Anomalous dispersion in photonic crystal fiber,” IEEE Photon. Technol. Lett., **12**, pp. 807-809 (2000).

[4] H. Hasegawa, Y. Oikawa, and M. Nakazawa, “10 Gbit/s 2 km photonic crystal fiber transmission with 850 nm directly modulated singlemode VCSEL,” Electron. Lett., **43**, pp. 117-119 (2007).

[5] K. Kurokawa, K. Ieda, K.Tajime, K. Shiraki, and I. Sankawa, “Visible high-speed optical transmission over photonic crystal fiber,” Opt. Exp. **15**, pp. 397-401 (2007).

[6] R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, “Ytterbium-doped fiber amplifiers,” IEEE J. Quantum Electron., **33**, pp.1049-1056 (1997).

[7] K. Tsujikawa, K. Kurokawa, K. Tajima, K. Nakajima, T. Matsui, I. Sankawa, and K. Shiraki, “Application of a prechirp technique to 10-Gb/s transmission at 1064 nm through 24 km of photonic crystal fiber,” IEEE Photon. Technol. Lett., **18**, pp. 2026-2028 (2006).

[8] K. Kurokawa, T. Yamamoto, K. Tajima, A. Aratake, K. Suzuki, and T. Kurashima, “High capacity WDM transmission in 1.0 μm band over low loss PCF using supercontinuum source,” OFC2008, OMH5.

[9] N. Yamamoto, H. Sotobayashi, K. Akahane, M. Tsuchiya, K. Takashima, and H. Yokoyama, N. Yamamoto, H. Sotobayashi, K. Akahane, M. Tsuchiya, K. Takashima, and H. Yokoyama, “1-μm waveband 10-Gbit/s transmission over a 7-km single-mode hole assisted fiber using a harmonically mode-locked semiconductor laser,” CLEO2008, CTuLL4.