10 Gbit/s photonic crystal fiber transmissions with 1.1 μm directly-modulated single-mode VCSEL

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Abstract: We demonstrate 10 Gbit/s transmission over a 5 km photonic crystal fiber (PCF) in the 1.1 μm band using a directly-modulated single-mode vertical cavity surface emitting laser (VCSEL). A combination of PCF and VCSEL enables us to achieve high-speed transmission at a low cost and with a simple configuration that does not employ optical modulators or amplifiers. Furthermore, the transmission distance was extended to 14 km by using an ytterbium-doped fiber amplifier (YDFA), and a power penalty-free transmission was successfully achieved.

Keywords: vertical cavity surface emitting laser (VCSEL), photonic crystal fiber (PCF), ytterbium-doped fiber amplifier (YDFA)

Classification: Fiber-optic communication

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1 Introduction

With the increasing demand for high-capacity optical networks, it is important to construct high-speed optical transmission system at low cost for fiber to the home (FTTH). To realize such a system, a combination of a directly-modulated vertical cavity surface emitting laser (VCSEL) and 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, which are difficult to achieve with a conventional step index fiber (SIF), by properly designing such aspects of the air-hole structure as the hole pitch Λ and the hole diameter d [3]. SIF that is single mode at shorter wavelength is more sensitive to bend loss and has larger dispersion compared with 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] were previously demonstrated. One difficulty with such a high-speed PCF transmission is the trade off between the loss and dispersion of the PCF. At such short wavelengths, a low dispersion PCF generally requires very small d and Λ values, which induce a large anomalous waveguide dispersion. In this way we can reduce the large normal dispersion caused by the material dispersion of the silica. However, the small d and Λ values inevitably lead to a loss increase. But, it is important to note that this trade off can be relaxed for a longer wavelength, as a lower waveguide dispersion is sufficient to eliminate the material dis-

persion. The 1.1 μm wavelength region is particularly interesting because a high-speed VCSEL and a wide-band optical amplifier (ytterbium-doped fiber amplifier: YDFA [6]) are 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, 8, 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 of 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 $\sim 3.6 \mu\text{m}$, 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 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

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

four PCFs as a transmission line. Table I shows the characteristics of each PCF, and Fig. 2 shows the dispersion characteristics, which were measured by the time-of-flight method [10]. 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

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

where α is the chirp parameter of our VCSEL (typically $\alpha = 3$ 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 I, 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.

Table I. PCF characteristics 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

Fig. 2. Dispersion characteristics of PCF.

3 10 Gbit/s transmission experiments in 1.1 μm band

Figure 3 shows the 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. 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. 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 launched into the transmission line. The optical power

Fig. 3. 10 Gbit/s PCF transmission experiments in 1.1 μm band. (a-1), (b-1): Experimental setup for 5 km and 14 km transmission. (a-2), (b-2): BER characteristics for 5 km and 14 km transmission with YDFA repeaters.

launched into the PCF was -3.5 dBm. We used two types of transmission line configuration as shown in Fig. 3 (a-1) and (b-1). In Fig. 3 (a-1), PCF-A with a length of 5 km was used because its loss is the lowest. Next, we combined all the PCFs which we possess, as shown in Table I, to extend the transmission distance. In Fig. 3 (b-1), 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 I. Then the signal was transmitted over a 10 km PCF which is composed of 3 km PCF-B and all other PCFs. The loss was 37 dB, but the signal can be received with a sufficient sensitivity by using a pre-amplifier. The YDFA was composed of a 15 m-long YDF with the Yb^{3+} concentration of 6000 ppm with a forward pumping at 980 nm. For a pump power of 280 mW, a gain of about 30 dB was obtained at 1070 nm, when the gain bandwidth was more than 30 nm and the noise figure (NF) was 4.5 dB. 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. 3 (b-1), a YDFA was inserted as a pre-amplifier together with a 1.0 nm optical band pass filter (OBPF).

Figure 3 (a-2) and (b-2) show the result of 5 and 14 km transmissions corresponding to Fig. 3 (a-1) and (b-1), respectively. Figure 3 (a-2) 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 3 (b-2) 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.

4 Conclusion

We have successfully demonstrated a 10 Gbit/s optical transmission at $1.1 \mu\text{m}$ 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.

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