

Demonstration of two-user, 10-Gbits/s optical code-division multiple-access system implemented by using cascaded long-period fiber gratings formed in dispersion-compensating fiber with inner-cladding structure

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Abstract. A two-user, 10-Gbits/s optical code-division multiple-access system implemented by using cascaded long-period fiber gratings formed in a dispersion-compensating fiber (DCF) is demonstrated. Our results show that the sensitivity of cladding modes to the refractive index change on the cladding surface is greatly reduced by utilizing the inner-cladding mode of the DCF. Two pairs of encoder/decoder are constructed and the performance is evaluated by measuring bit error rate (BER). With an interferer, a BER of 1.5×10^{-12} is measured at a received optical power of -6 dBm. © 2005 Society of Photo-Optical Instrumentation Engineers.
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1 Introduction

An optical code-division multiple-access (O-CDMA) system is very attractive owing to its high security and

multiple-access capability.¹ All-optical encoders/decoders based on fiber grating have been proposed as the devices having high cost-effectiveness and precision.²⁻⁵ Especially, the method based on cascaded long-period fiber gratings (C-LPGs) in Ref. 4 showed ultrahigh precision and high-speed coding capabilities because it used the mode coupling between a core mode and a copropagating cladding mode. However, the drawback of using the C-LPGs was the sensitivity of the cladding modes to environmental change. The propagation of cladding modes was easily affected or even lost by the refractive index change on the cladding surface. This problem has been one of the major limiting factors for the C-LPGs to be practically used.

In this letter, to mitigate the sensitivity of the cladding modes, a dispersion-compensating fiber (DCF) with an inner-cladding structure is used in this work to fabricate the C-LPGs and a 2×10 Gbits/s O-CDMA system implemented by using the C-LPGs is demonstrated.

An LPG is a well-known device for making the mode coupling between the core and copropagating cladding modes. A pair of LPGs can generate two identical, but separated in time, pulses using time delay between the two modes. Likewise, N C-LPGs will provide 2^{N-1} identical pulses. Thus, by adjusting the separations among LPGs, we can generate code patterns with a 2^{N-1} weight.

2 Experiment

First, a pair of LPGs having a separation of 25 cm was fabricated by exposing a KrF excimer laser beam on a hydrogen-loaded DCF made by KT Corp., Korea, through an amplitude mask having a periodicity of $700 \mu\text{m}$. The refractive index profile of the DCF is depicted in Fig. 1(a). The refractive index of the center core was about 2.5% higher than that of the outermost cladding of the fiber. The innercladding region consists of one raised-ring layer and one reduced-ring layer, located far from the outer cladding. Thus, if a mode is coupled and guided to and through the inner-cladding layer, it will not be easily affected by the variation of fiber surrounding material. This was verified by observing the variation in the transmission spectrum of a LPG pair while applying a series of index-matching oils on the fiber region between the LPGs. As shown in Fig. 1(b), although the index of matching oil was varied from 1 to 1.5, no significant change in the resonant peak was observed.

We fabricated two pairs of encoder/decoder, $C_{e1}:C_{d1}$ for a channel 1 and $C_{e2}:C_{d2}$ for a channel 2, where subscripts

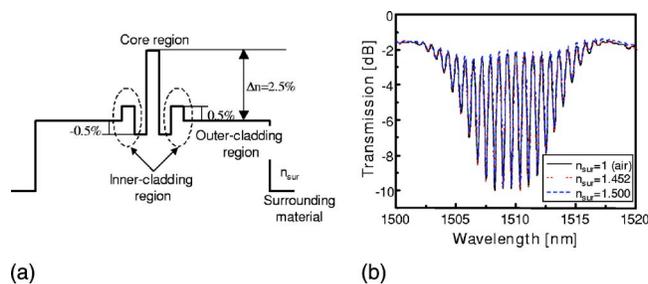


Fig. 1 (a) Refractive index profile of the DCF with an innercladding structure and (b) transmission spectrum of a pair of LPGs with a separation of 25 cm; n_{sur} represents the index applied on the surface of the fiber between the LPGs.

1 and 2 represent specific code patterns of (100100100100) and (1000010100001), respectively. A test LPG pair with a separation of 34.1 cm was fabricated using an amplitude mask with periodicity $780 \mu\text{m}$, which gave the resonant wavelength of C-LPGs at 1554 nm. Also, it was found that the differential effective group index (DEGI) of the DCF was 1.1×10^{-2} at 1554 nm.

Assume the chip spacing was 4.16 ps. To fabricate the C-LPGs $C_{e1}:C_{d1}$, three LPGs were cascaded with the separations of 34.1 and 68.2 cm. These separations correspond to the time delays of 12.48 and 24.96 ps, respectively. On the other hand, the separations for the C-LPGs $C_{e2}:C_{d2}$ were selected as 56.83 and 79.56 cm to provide the delays of 20.80 and 29.12 ps, respectively.

As shown in Fig. 2, a 10-GHz pulse source with a full width at half maximum of 1.5 ps was modulated using a LiNbO₃ external modulator at a 10-Gbits/s rate using a $2^{23}-1$ pseudorandom-bit-sequence pattern. The modulated signal was amplified, divided into two channels for encoding with C_{e1} and C_{e2} , and then fed into two decoders C_{d1} and C_{d2} at the same time. The output of decoder was sent to a dispersion-imbalanced nonlinear optical loop mirror (DI-NOLM) that was expected to act as an optical hard threshold. The DI-NOLM was composed of a single-mode fiber (SMF) of 150 m and a DCF of 25 m, whose chromatic dispersions were ± 2.5 ps/nm, respectively. The resultant signals coming from the DI-NOLM were received with a 45-GHz photodetector and amplified electrically with a 10-GHz limiting amplifier. The output was sent to a 10-Gbits/s error detector for bit error rate (BER) measurement.

3 Results

In Fig. 2, insets (i) to (iv) show the measured temporal responses for the four C-LPGs: C_{e1}, C_{e2}, C_{d1} , and C_{d2} , respectively. As the signal encoded with C_{e1} was fed to the decoder C_{d1} , the output gave a high intensity peak [inset (v)]. This was so because encoder C_{e1} was matched to decoder C_{d1} and the output corresponded to $C_{e1} * C_{d1}$, where the symbol $*$ represents the correlation notation. On the

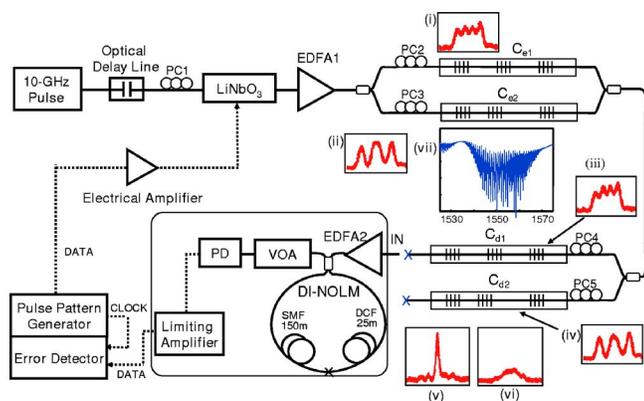


Fig. 2 Experimental setup: EDFA; erbium-doped fiber amplifier; PC, polarization controller; LiNbO₃, optical external modulator; VOA, variable optical attenuator; PD, 45-GHz photodetector; DI-NOLM, dispersion-imbalanced nonlinear optical loop mirror. Insets (i) to (iv): temporal responses of C-LPGs, C_{e1}, C_{e2}, C_{d1} , and C_{d2} ; inset (v): matched signal ($C_{e1} * C_{d1}$), inset (vi): unmatched signal ($C_{e2} * C_{d1}$), and inset (vii): transmission spectrum of C_{e2} .

contrary, the signal encoded with C_{e2} and decoded by decoder C_{d1} gave a time-spread waveform [inset (vi)] as the output. This was so because the pair was not matched. Similarly, the outputs of decoder C_{d2} for the input signals encoded with C_{e1} and C_{e2} gave the unmatched and matched signals, respectively. Inset (vii) shows the measured transmission spectrum of C_{e2} .

The BER curves of the system are shown in Fig. 3, where insets are the eye diagrams of the implemented two-user system. Without channel 2, i.e., $C_{e1} * C_{d1}$, the BER of channel 1 was 3×10^{-12} at a received optical power of -8 dBm. However, with channel 2 at the same time, i.e., $(C_{e1} + C_{e2}) * C_{d1}$, the BER of channel 1 could not be measured because of the appreciable interference noise originating from channel 2 [inset (i)]. Similarly, for the measurement of channel 2, the existence of channel 1 gave an interference noise [inset (ii)]. These interference noise terms could be suppressed by passing the signals through the DI-NOLM, which enabled us to have greatly enhanced signal contrasts [insets (iii) and (iv)]. For that case, the BER at both channels was below 1.5×10^{-12} at a received optical power of -6 dBm. Error-free performance was also observed for a higher received optical power. Even though there was some power penalty, we can see that the proposed O-CDMA system worked well.

4 Conclusion

We have demonstrated a two-user, 10-Gbits/s O-CDMA system using the C-LPGs encoder/decoder formed in a DCF. A system composed of two pairs of encoder/decoder was implemented and the performance was evaluated by measuring the BER. Even with an interferer, owing to the help of a DI-NOLM, error-free performance could be observed. At a received optical power of -6 dBm, a BER of 1.5×10^{-12} was measured. Using the inner-cladding mode of a DCF, we could achieve an LPGs whose spectral properties were not sensitive to environmental changes.

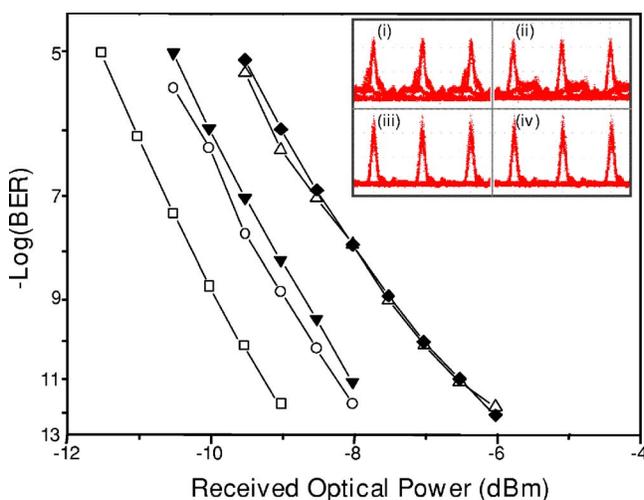


Fig. 3 BER curves: \square , original optical pulse source; \circ , channel 1 without channel 2; \triangle , channel 1 with channel 2 after DI-NOLM; ∇ , channel 2 without channel 1; \blacklozenge , channel 2 with channel 1 after DI-NOLM. Inset (i), eye diagram of channel 1 with channel 2; inset (ii), eye diagram of channel 2 with channel 1; inset (iii), eye diagram of channel 1 with channel 2 after DI-NOLM; and inset (iv), eye diagram of channel 2 with channel 1 after DI-NOLM.

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