Propagation Characteristics of Seven-core Fiber for Spatial and Wavelength Division Multiplexed 10-Gbit/s Channels

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Abstract: Propagation characteristics of seven-core fiber were investigated for multiplexed signals of spatial-division and wavelength-division. Effect of chromatic dispersion and inter-core crosstalk were evaluated for 5-km fiber by using 10-Gbit/s channels.

OCIS codes: (060.2300) Fiber measurements; (060.2330) Fiber optics communications.

1. Introduction

Multi-core fibers (MCFs) are attracting attention increasingly [1-7] due to their potentially large transmission capacity by means of spatial division multiplexing (SDM), since data transmission rate through conventional optical fibers is approaching to a practical limit imposed by the bandwidth of fiber amplifiers [8], fiber nonlinearity [9], and fiber fuse effect [10]. Reduction of fiber counts because of multiplication of several cores in a fiber is also reported to be desirable for passive optical network (PON) or local-area network applications [1,2]. Main concern of recent reports about MCF is inter-core crosstalk [3-7]. Present MCFs with kilometer lengths are inevitably subject to certain inter-core crosstalk induced by fiber bends.

In this report, we investigated propagation characteristics of an up-to-date heterogeneous seven-core MCF for spatial-division-multiplexed (SDM) and wavelength-division-multiplexed (WDM) optical signals. Also high-precision optical coupling device was developed to easily and stably realize SDM multiplexing and demultiplexing. Both dense WDM signals with 100-GHz spacing (DWDM) and coarse WDM signals over 9-THz spectral range (CWDM) were used respectively, regarding future large-scale transmission use. The aggregated data rate reached 700 Gbit/s (7 core×10 λ×10 Gbit/s) in the case of CWDM. This is the first SDM/WDM experiment using an MCF to the best of our knowledge.

2. Multi-core fiber

Fig. 1 shows a cross section of fabricated seven-core MCF and its core identification numbers. In order to reduce the crosstalk and avoid the crosstalk degradation due to fiber bend [3], we designed core diameters as 9.2 μm for center core (core 1), 10.7 μm for outer cores of even numbers, and 7.9 μm for outer cores of odd numbers, and core pitch as 34.0 μm, considering that the MCF was winded on a bobbin whose winding radius is 140 mm. Cladding diameter was designed as 141.7 μm. Propagation characteristics measured at a wavelength of 1550 nm are shown in Table 1. Attenuation less than 0.2 dB/km was successfully achieved in outer cores. Measured values of crosstalk at a wavelength of 1550 nm after 5-km propagation are shown in Fig. 2. A measurement setup and a crosstalk definition were the same as shown in ref [3]. Values of the crosstalk between center core and outer cores after 5-km propagation are about -20 dB, and the values among outer cores are around -45 dB. The latter values are smaller than the former values because the differences of core diameters, or effective indices, between neighboring cores are larger in the latter case.

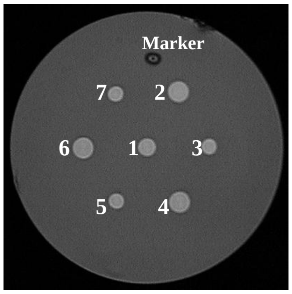

Fig. 1. A cross section of the fabricated fiber.

Table 1. Propagation characteristics.

	Core 1	Core 4	Core 5
Attenuation [dB/km]	0.212	0.199	0.194
Dispersion [ps/nm/km]	17.5	19.4	14.7
D. Slope [ps/nm^2/km]	0.056	0.058	0.054

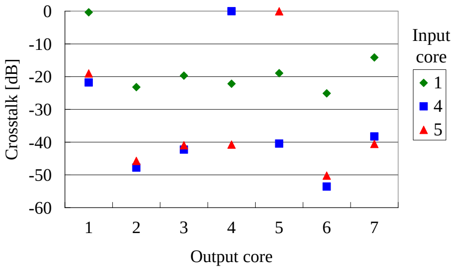

Fig. 2. Measured crosstalk after 5-km propagation.

3. High-precision optical coupling device (SDM Mux and Demux)

As a method of fan-out coupling between MCF and standard single mode fibers (SMFs), a free-space optical configuration using a set of lenses was adopted. Because the SMF diameter is larger than the core pitch of MCF, it is impossible to couple SMFs to every core of MCF at once by means of butt joint or splicing. However, it becomes possible to collect each beam from SMFs to the cores of MCF individually by using a set of lenses. The schematic drawing is shown in Fig. 3. The lights launched from the SMFs are collimated by using individual lenses (Lens-S). Light injected into the center core of MCF is passing through the principal axis of the aggregating lens (Lens-M) and collected along this axis, as same manner in conventional lens coupling. The beams injected into the outer cores of the MCF have an angle and position offset from the lens principal axis. The beams are focused parallel to the principal axis and coupled to the outer cores of the MCF. It is possible to realize optical systems without leakage between neighboring ports by using a single lens (Lens-M), as the beam from each core can be split seamlessly. Lenses with similar focal lengths were used for Lens-M and Lens-S, so that the lowest coupling loss is obtained when the mode field diameters (MFDs) of MCF cores match with the MFD of SMFs. The calculated coupling loss assuming the MFD of MCF core as 6~15 μm was smaller than 1.5 dB, and measured coupling loss for each MCF core was 0.6 dB ~ 1.1 dB when the MFDs of MCF and SMF are 8 μm and 10.5 μm, respectively.

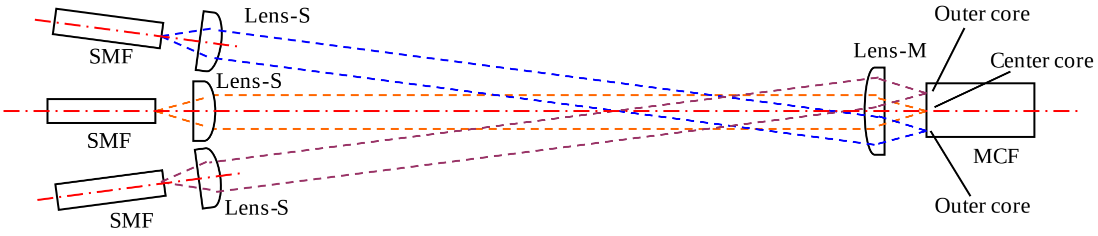

Fig. 3. Optics system for fiber coupling.

4. DWDM and CWDM experiment

In this study, we performed a (A): DWDM experiment with 8-channel, 100-GHz spacing signals (1563 to 1568 nm) and (B): CWDM experiment with 10-channel, 1-THz spacing signals (1534 to 1608 nm) to explore the capability of MCF as a high capacity transmission medium. The experimental setup is illustrated in Fig. 4(a). 10-Gb/s NRZ-OOK data signals of 2^{31}-1 PRBS patterns were generated using $LiNbO_3$ modulators. Tellurite-based EDFAs were used for broadband signal amplification. Fig. 4(b) shows the spectra of the DWDM signals before injected into the center and outer cores. The wavelengths of the signals into the center core and those into the outer cores were interleaved. Total DWDM signal power measured at each input port of the MCF coupling device was about +1.5 dBm/core. Signals through neighboring SDM channels were temporally decorrelated by using a 0.5-m delay fiber. Fig. 4(c) shows the spectrum of the signal after propagation through center core and amplification. As well as the spectral components injected into center core, crosstalk components from outer cores were observed in Fig. 4(c). We eliminated these crosstalk components using a 0.14-nm tunable band-pass filter before signal detection. Fig. 4(d) shows the spectra of

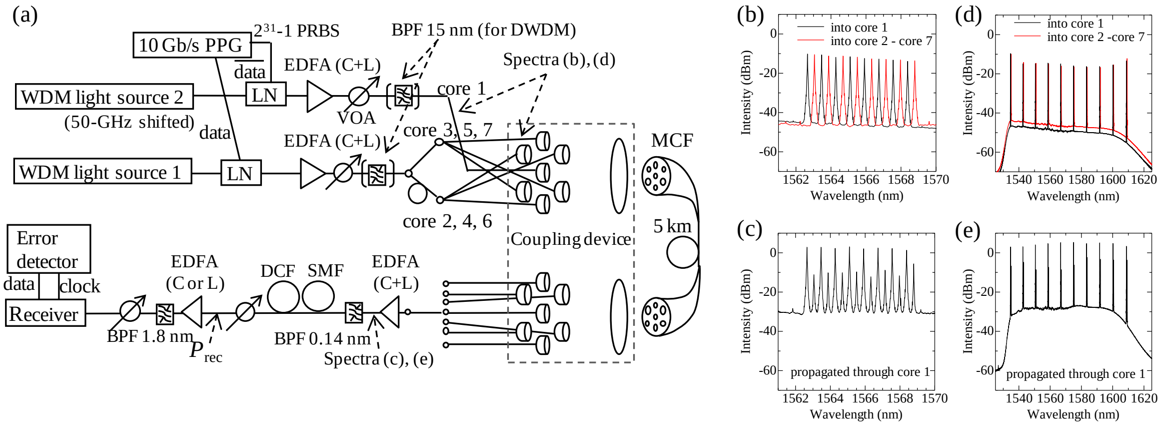

Fig. 4. WDM experiment. (a) Setup, spectrum of (b) DWDM signals before injection, (c) DWDM signals after propagation, (d) CWDM signals before MCF injection, (e) CWDM signals after propagation.

the CWDM signals injected into the MCF. Pre-emphasis was given to the channels near the edges of gain spectra of the EDFAs. Total CWDM signal power measured at each input port of the MCF coupling device was about +0.7 dBm/core. Accumulated dispersion of the 5-km MCF was roughly compensated by a dispersion compensation fiber and adequate set of SMFs for each WDM and SDM channels. Figs. 5(a) to 5(c) show eye diagrams of a single-channel signal (λ=1566.31 nm) before MCF propagation, after propagation through MCF outer core (5) without dispersion compensation, and after MCF propagation with dispersion compensation. Fig. 5(d) shows the eye diagram of the DWDM signal after MCF propagation and wavelength demultiplexing. Clear eye opening was observed.

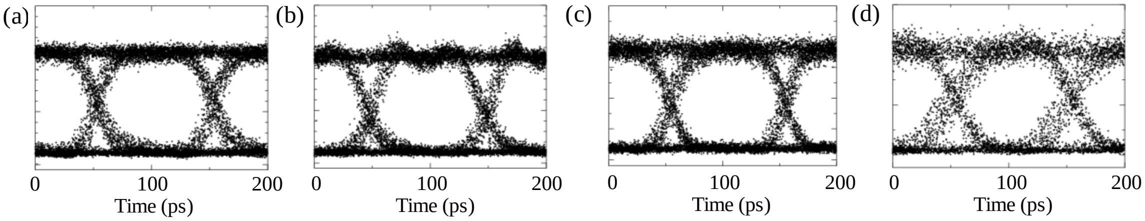

Fig. 5. Eye diagrams. (a) single channel (λ=1566.31 nm) before MCF, (b) through MCF core 5 without dispersion compensation (DC), (c) through MCF core 5 with DC, (d) through MCF core 5 with DC, DWDM Mux and Demux.

Figs. 6(a) to 6(c) show measured BERs of the DWDM signals for back-to-back, outer core (5) propagation, and center core propagation. While BER characteristics show some fluctuations among WDM channels, no significant degradation due to the MCF propagation was observed. This means that the crosstalk level of ~-45 dB between outer cores was sufficiently low for 10-Gbit/s base WDM transmission. Figs. 6(d) to 6(f) show the results for the CWDM signals. While signal power required for BER=10^{-9} showed certain wavelength dependence (~2 dB) due to the EDFAs, power penalties induced by the MCF propagation at each wavelength were typically small (typically less than 0.5 dB).

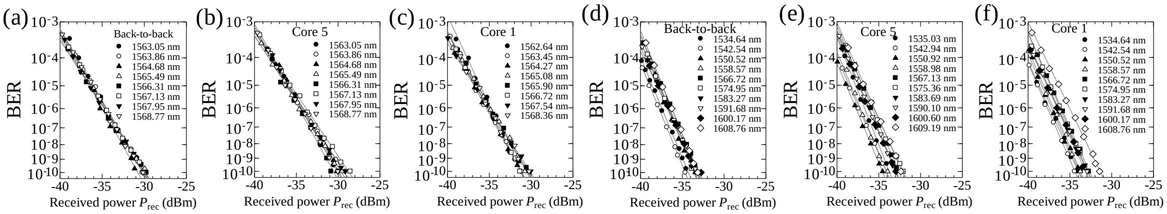

Fig. 6. BER vs. received signal power. (a) DWDM, back-to-back, (b) DWDM through outer core, (c) DWDM through center core, (d) CWDM, back-to-back, (e) CWDM through outer core, (f) CWDM through center core.

5. Conclusions

Propagation characteristics of 5-km seven-core fiber were investigated for SDM/WDM signals for the first time. In this study, experiments using DWDM signals with 100-GHz spacing and CWDM signals with 9-THz spectral range were performed respectively. The wavelengths of the signals into the center core and those into the outer cores were interleaved. Crosstalk of around -45 dB between outer cores caused no significant degradation on the BER performance. Thus high potential of MCFs regarding future large-scale data transmission was demonstrated. Further improvement of crosstalk between center core and outer cores is anticipated for increasing the spectral efficiency.

6. References

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