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Modal dispersion compensation by using digital coherent receiver with adaptive equalization in multi-mode fiber transmission

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ABSTRACT

Modal dispersion compensation is demonstrated by using electrical adaptive equalization for a multi-mode fiber (MMF) transmission with multipath interference resulting from mode conversion caused by axial deviations in the transmission line. We reveal that we can realize a 20 km 50 μm-core GI-MMF transmission even if mode conversions are intentionally introduced by two 5 μm axial deviations in the transmission line.

1. Introduction

The explosive growth in Internet traffic is generating a demand for greater capacity. To realize a much higher transmission capacity, we need to avoid the nonlinear effects that occur in optical fiber and the optical fiber fuse phenomenon [1]. Enlarging the effective area (A_{eff}) of optical fibers is a practical way of reducing nonlinearity and increasing the fiber fuse threshold power. Optical fibers with W-shaped and trench refractive index profiles have already been proposed as a way of achieving a larger A_{eff} [2–4]. In addition, it has been reported that photonic crystal fiber (PCF) can realize an A_{eff} of 220 μm^2 with both single-mode operation and a low bending loss at 1460–1625 nm [5]. However, enlarging the A_{eff} makes it difficult to maintain the single-mode operation of the fiber at the signal wavelength. With multi-mode operation, modal dispersion causes serious signal degradation as a result of inter-symbol interference (ISI). If we can compensate for such signal degradation by modal dispersion, we can realize a much larger A_{eff} and expect to achieve a much higher transmission capacity. For example, if we assume a three-mode PCF described in [6], we can realize about two times larger A_{eff} of the single mode PCF described in [5]. In order to compare transmission performances of two different fibers, we can use Figure of Merits (FOM) which is a function of the effect of both nonlinearity and loss of the transmission fibers:

$$FOM\ [\mathrm{dB}] = 10\log_{10}\left(\frac{A_{eff1}}{A_{eff2}}\right) - (\alpha_1 - \alpha_2) \quad (1)$$

where A_{eff1}, A_{eff2} and α_1, α_2 are the A_{eff} and the transmission loss of the two different fibers, respectively [7]. If we can realize the three-mode fiber with same loss of the single-mode PCF, FOM is about 3 dB compared with the single-mode PCF. We can expect to increase the transmission capacity by 3 dB if we assume that FOM improvement directly reflect the capacity increase.

Two main approaches have been proposed for avoiding the signal degradation caused by modal dispersion. One is a center-launching technique where a signal light is launched into the center of the core of a multi-mode fiber (MMF) to prevent the occurrence of the higher-order mode (HOM) [8–12]. The other approach is a mode filtering method that removes the HOM in the receiver by using a mode filter [13,14]. However, for example, axial deviations in the transmission MMF, as shown Fig. 1, lead to multipath interference (MPI), which is caused by repeated mode conversion between the fundamental mode (FM) and HOM [15]. First, the HOM is excited at the axial deviation. Then, a mode delay occurs between the FM and the HOM during MMF transmission. Finally, the HOM couples with the FM at an axial deviation, and this signal degradation cannot be removed with an optical method.

Digital signal processing (DSP) with an electric adaptive equalizer has been proposed to compensate for signal degradation resulting from MPI induced modal dispersion [16,17]. However, signal recovery with the direct detection method is less accurate because it does not use phase information, and the maximum subcarrier frequency is limited to the electrical bandwidth in a subcarrier multiplexing (SCM) system. As a result, it is difficult to achieve a larger capacity and a longer transmission distance.

We investigated modal dispersion compensation by using a digital coherent receiver with an adaptive equalizer for MMF to realize a larger capacity transmission over a longer distance. In our

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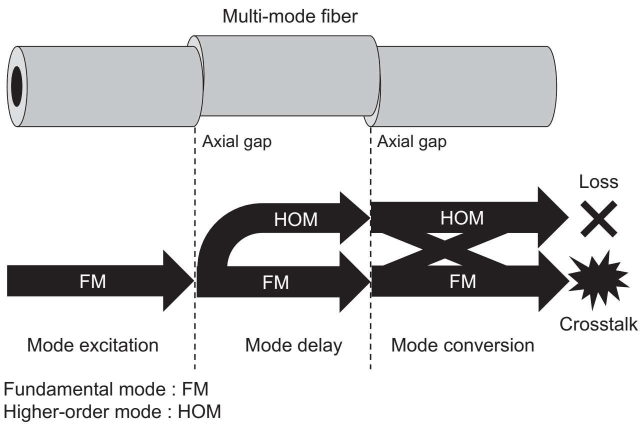

Fig. 1. Schematic of MPI in MMF.

previous work [18], we demonstrated that 10 Gbit/s BPSK data can be transmitted over 10 km of graded-index MMF (GI-MMF) with MPI caused by mode conversion to investigate the signal recovery under the worst conditions where exist a number of modes and mode conversion for multi-mode operation in the MMF transmission.

In this paper, we furnish further details of our modal dispersion compensation technique by using a digital coherent receiver with an adaptive equalizer. We also experimentally investigate the quality of the transmitted signal compensation in a severe situation where mode conversion is caused by axial deviations in the transmission line. We show that we can realize a 20 km 50 μm-core GI-MMF transmission even if mode conversions are intentionally introduced by two 5 μm axial deviations in the transmission line.

2. Modal dispersion compensation with adaptive equalizer

A communication channel model with an adaptive equalizer is shown in Fig. 2. An adaptive equalizer consists of an adaptive filter and an adaptive algorithm that controls the filter. First, the transmitted signal $x(n)$ passes through a transmission line, and becomes a received signal $y(n)$ distorted by ISI. Then, the received signal is compared with an already-known training sequence $d(n)$ and passed through the adaptive filter in the training mode as shown in Fig. 2. An adaptive algorithm minimizes the error signal $e(n)$ to optimize the adaptive filter coefficients $w(n)$. The error signal is given as

$$e(n) = d(n) - xr(n) \tag{2}$$

where $xr(n)$ is the output symbol from the adaptive filter as shown in the following equation:

$$xr(n) = y(n) * w(n) \tag{3}$$

The adaptation of the equalizer is driven by the error signal. The received signal $y(n)$ passes through the optimized adaptive filter $w(n)$, and is output as a recovered signal $xr(n)$.

Once the equalizer has converged it may move into a decision directed mode [19]. The decision-directed mode that updates the adaptive equalizer coefficients is effective in tracking slow variations in the channel response. Then, $e(n)$ in the decision-directed mode is given as

$$e(n) = xr_{\mathrm{d}}(n) - xr(n) \tag{4}$$

where $xr_{\mathrm{d}}(n)$ is the decided symbol from $xr(n)$.

We adopted a decision feedback equalizer (DFE) as an adaptive equalizer as shown schematically in Fig. 3. In channels with severe ISI, a DFE can adequately compensate for the ISI [19]. The DFE includes a feedforward (FF) filter, a decision unit, and a feedback (FB) filter. The filters are built up with multi-taps. Each tap consists of a delay unit, a multiply unit, and an adder unit. A signal that passes the FF filter $x_{\mathrm{bd}}(n)$ is inputted into the decision unit. The decided signal $x_{\mathrm{ad}}(n)$ is coupled into an FB filter. For example, with a BPSK signal, the decision unit output is 1 or -1 depending on the input signal. The restored signal is obtained as the sum of the output from the FB and FF filters as shown in the following equation:

$$xr(n) = \sum_{j=-N_{\mathrm{tapff}}+1}^{0} w(j + N_{\mathrm{tapff}})y(n-j) + \sum_{j=1}^{Ntapfb} w(j + N_{\mathrm{tapff}})x_{ad}(n-j) \tag{5}$$

where N_{tapff} and N_{tapfb} are the number of FF and FB filter taps, respectively. Because the DFE uses the restored signal after the decision, the restoration accuracy can be high for a signal with a large ISI. The adaptive algorithm controls the tap coefficients of the FF and FB filters. We use a recursive least squares (RLS) algorithm as the adaptive algorithm [20,21]. The tap coefficient $w(n)$ is optimized so that the error signal $e(n)$ takes its minimum value.

3. Modal dispersion compensation experimental setup

Fig. 4 shows the experimental setup we used for MPI compensation. In an MMF transmission, to consider signal recovery under the worst conditions where all the excited HOMs are changed into the FM, we emulated MPI by using the configuration shown in Fig. 4.

First, we intentionally excited HOMs by using a mode excitation unit (MEU) to degrade the signal with modal dispersion. The signal light emitted from the end of a single-mode fiber (SMF) passed through two optical lenses, and the light was coupled into a GI-MMF based on ITU-T G.651. The numerical aperture (NA) was 0.2. The focal length and NA of the lens on the SMF side were

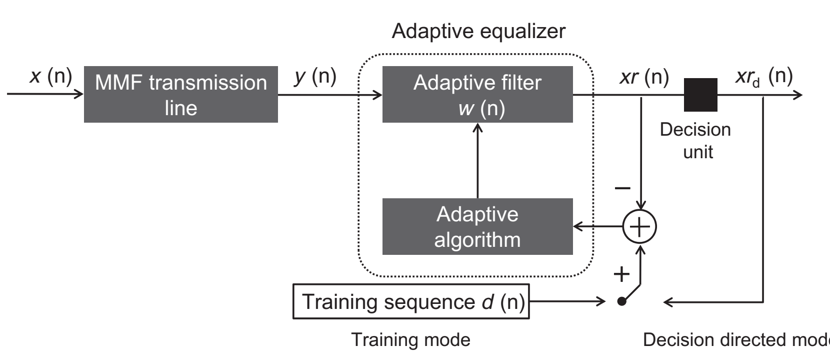

Fig. 2. Communication channel model with adaptive equalizer.