3-5 Polarization-mode Dispersion and its Mitigation

MATSUMOTO Masayuki

Polarization-mode dispersion (PMD) is one of major factors limiting the performance of high-speed optical fiber transmission systems. This review paper describes basic mathematics and features of PMD, statistical properties of PMD of some installed systems, and principles of proposed methods of PMD mitigation.

Keywords
Polarization-mode dispersion, Optical fiber transmission system, Birefringence, Polarization-mode dispersion compensation, Signal regeneration

1 Introduction

In optical fiber transmission systems with transmission speeds exceeding 10 Gbps per channel, polarization-mode dispersion (PMD) is one of the major factors limiting system performance. Unlike other degenerating factors (such as chromatic dispersion and nonlinear effects), signal degeneration caused by PMD is time variable and random, which renders it difficult to deal with. Since the late 1980s, many studies have been conducted concerning clarification of the PMD phenomenon, its quantitative evaluation, and countermeasures to compensate for PMD. Recently, detailed PMD evaluation has also been conducted in installed fiber transmission systems in connection with the introduction of 40-Gbps transmission in practical systems. This article describes the basic characteristics of PMD, the statistical properties of PMD in some installed fiber transmission systems, and the principles of proposed methods of PMD compensation.

2 Basic characteristics of polarization-mode dispersion

The single-mode optical fiber used in long-haul transmission features slight birefringence due to the formation of an off-circular core and application of transverse stress in production, cable creation, and installation. The magnitude and the direction of this birefringence change randomly in the direction of transmission. This sort of optical fiber can be modeled by serially connected short birefringent fibers whose eigen axes rotate randomly. Assuming that the entire length of the fiber consists of n birefringent fibers, the input optical pulses are in general divided into 2^n components, each of which reaches the output end of the fiber at different moments. Consequently, the output waveform is distorted. This phenomenon is referred to as polarization-mode dispersion (PMD).

Let us consider input of a continuous monochromatic wave into such an optical fiber. If the polarization state of the input light is randomly selected and fixed, the polarization state of the output light changes periodically when the carrier wavelength of the input light is varied. However, if the input light is in particular polarization states, the polarization state of the output light does not change in first order even when the carrier wavelength of the input light is varied. There are two such input polarization states, which are orthogonal to each other. Each of these states is referred to as the input Principal State of Polarization (PSP)[1]. The output polarization state corresponding to the input PSP is referred to as the output PSP. The difference in the group delays between these two orthogonal PSPs is referred to as the Differential Group Delay (DGD). We note that this polarization behavior is the same as that seen when a continuous monochromatic wave is input into a linear birefringent fiber with a constant birefringence. In other words, a general single-mode optical fiber with slight, randomly changing birefringence behaves similarly to a linear birefringent fiber with constant birefringence. (See Fig. 1.) However, PSP is elliptically polarized in general, with PSP and DGD changing according to wavelength. A general single-mode optical fiber with slight, randomly changing birefringence can be modeled as a linear birefringent fiber with a constant birefringence only in a narrow band around each wavelength. The approximate value of the bandwidth is expressed as follows[2][3]:

$$\Delta\nu_{PSP} = 125\text{GHz}/\langle \text{DGD(ps)} \rangle . \quad (1)$$

Here, $\langle$DGD(ps)$\rangle$ is the average DGD, in picoseconds.

Let us now consider the input of monochromatic light featuring an arbitrary polarization state into the single-mode fiber introduced above. The polarization state is expressed as follows using two orthogonal input PSPs, $e_{in}^{+}(\omega_0)$ and $e_{in}^{-}(\omega_0)$, at the angular frequency of ω_0:

$$\mathbf{E}_{in} = c_1\mathbf{e}_{in}^{+}(\omega_0) + c_2\mathbf{e}_{in}^{-}(\omega_0) . \quad (2)$$

The electric field of the output signal is expressed as follows using the propagation constant $\beta(\omega)$ and the unitary matrix $\mathbf{U}(\omega) = \begin{bmatrix} u_1(\omega) & u_2(\omega) \\ -u_2^*(\omega) & u_1^*(\omega) \end{bmatrix}$, which describes the change in the polarization state[1][4]:

$$\begin{aligned} \mathbf{E}_{out}(\omega) &= \exp[i\beta(\omega)z]\mathbf{U}(\omega)\mathbf{E}_{in} \\ &\cong \exp[i\beta(\omega)z]\left[\mathbf{U}(\omega_0) + \frac{d\mathbf{U}}{d\omega}\Delta\omega\right] \\ &\quad [c_1\mathbf{e}_{in}^{+}(\omega_0) + c_2\mathbf{e}_{in}^{-}(\omega_0)]. \end{aligned} \quad (3)$$

The last line of the equation above expands U(ω) around ω_0 and omits the second- and higher-order terms. $\Delta\omega = \omega - \omega_0$ also holds. Here, the input PSP, $e_{in}^{\pm}(\omega_0)$, satisfies the eigenvalue equation,

$$-i\mathbf{U}^{+}\frac{d\mathbf{U}}{d\omega}\mathbf{e}_{in}^{\pm}(\omega_0) = k^{\pm}\mathbf{e}_{in}^{\pm}(\omega_0)$$

and the relationship $e_{out}^{\pm}(\omega_0) = U(\omega_0)e_{in}^{\pm}(\omega_0)$ holds between the output PSP and the input PSP. Based on these facts, Equation (3) is rewritten as follows:

$$\begin{aligned} \mathbf{E}_{out}(\omega) = \exp[i\beta(\omega)z]\big[&c_1\exp(ik^{+}\Delta\omega)\mathbf{e}_{out}^{+}(\omega_0) \\ &+ c_2\exp(ik^{-}\Delta\omega)\mathbf{e}_{out}^{-}(\omega_0)\big]. \end{aligned} \quad (4)$$

Here, the DGD, $\Delta\tau$, between the two PSP is given as follows:

$$\Delta\tau = k^{+} - k^{-} = 2\sqrt{|du_1/d\omega|^2 + |du_2/d\omega|^2} .$$

Using the output electric field (4), one can show that the Stokes vector S_{out} of the output light E_{out} satisfies the following equation:

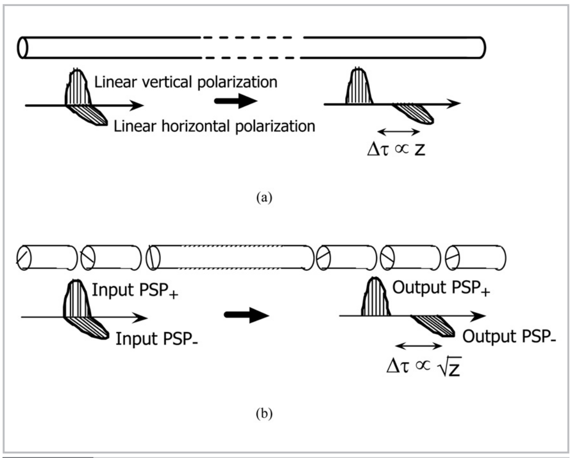

Fig.1 *Behavior of optical pulses propagating in (a) linear birefringent fiber (polarization-maintaining fiber) with a constant birefringence and (b) general single-mode optical fiber (non-polarization-maintaining fiber). (Despite the explanation in the main text, this figure illustrates pulses input to the fiber instead of a continuous wave.)*

$$\frac{\partial \mathbf{S}_{out}}{\partial \omega} = \mathbf{\Omega} \times \mathbf{S}_{out}. \quad (5)$$

Here, Ω is a vector in the Stokes space with the same magnitude as $\Delta\tau$ and the same direction as the Stokes vector corresponding to the output PSP, e_{out}^{+}. $\mathbf{\Omega}$ is a quantity that characterizes the polarization characteristics of this transmission line and is known as the polarization-mode dispersion vector.

Equation (5) expresses how the polarization state of the output light changes when the length of the transmission line and polarization state of the input light into the transmission line are fixed and the carrier frequency is varied. On the other hand, when the carrier frequency is fixed and the length of the transmission line is varied, the polarization state of the light output from the transmission line varies according to the following equation:

$$\frac{\partial \mathbf{S}_{out}}{\partial z} = \mathbf{W} \times \mathbf{S}_{out}. \quad (6)$$

Here, **W** is a vector that expresses the local birefringence of the transmission line and is known as the birefringence vector. For example, for a linear birefringent fiber with a magnitude of birefringence satisfying $\Delta\beta = \beta_x - \beta_y$ and an axis extending at angle θ from the x-axis, **W** is expressed as follows:

$$\mathbf{W} = [\Delta\beta\cos(2\theta), \Delta\beta\sin(2\theta), 0]^t. \quad (7)$$

Equations (5) and (6) combined yield an equation that expresses the spatial variation of the polarization-mode dispersion vector as follows[5]:

$$\frac{\partial \Omega}{\partial z} = \frac{\partial \mathbf{W}}{\partial \omega} + \mathbf{W} \times \Omega. \quad (8)$$

As discussed earlier, a general single-mode optical fiber can be modeled as serially connected short birefringent fibers with their eigen axes rotating in random directions. Solving Equation (8) for such a fiber using Equation (7) yields the polarization-mode dispersion vector $\mathbf{\Omega}$, which describes the polarization characteristics over the entire length of the fiber[6]. When the direction of the eigen axis of each birefringent fiber changes randomly, $\mathbf{\Omega}$ is also a random variable. The mean square of the magnitude of $\mathbf{\Omega}$ is calculated as follows:

$$\langle |\Omega|^2 \rangle = N(\Delta t)^2 \quad (9)$$

Here, N is the number of serially connected birefringent fibers, and Δt is the DGD of each birefringent fiber. Equation (9) expresses that the root mean square (rms) value of the DGD of a general single-mode optical fiber is proportional to the square of the distance. When N is sufficiently large, each component of $\mathbf{\Omega}$ is a random variable that follows a Gaussian distribution. In this case, the magnitude of $\mathbf{\Omega}$—in other words, the DGD—features a Maxwell distribution, and its probability density function is expressed as follows:

$$p_{DGD}(x) = \frac{32x^2}{\pi^2\langle|\Omega|\rangle^3}\exp\left(-\frac{4x^2}{\pi\langle|\Omega|\rangle^2}\right) \quad (10)$$

3 Polarization characteristics of installed optical fiber transmission lines

The DGD of a general single-mode optical fiber transmission line changes randomly with time according to the environment surrounding the transmission line. The DGD also changes when the carrier wavelength of the signal changes. When the frequency difference is approximately six times the frequency width given by Equation (1) or greater, the DGD behaviors of the two wavelengths are nearly independent[7]. When the DGD value exceeds the upper limit determined by the signal transmission speed and the modulation format, system outages occur. When designing high-speed transmission systems, it is important to know the extent to which the system failure rate due to PMD depends on transmission speed and modulation format, and the extent to which this failure rate can be reduced by PMD compensation.

Traditionally, when calculating the system failure rate due to PMD, the distribution of the DGD of the transmission line has in most cases been assumed to feature a Maxwell distribution, as discussed in Section **2**[8]. The individual channels of wavelength division multiplexing (WDM) systems are each also considered to exhibit the same failure characteristics. On the other hand, it has recently been pointed out that a number of practical installed transmission systems do not feature a Maxwell distribution within a specified time scale and that different wavelength channels of the WDM system may present different failure characteristics[9]-[11].

Figure 2 shows a model of such a transmission system. The transmission fiber between the transmitter and the receiver is buried underground in most sections. However, the fiber is drawn aboveground at a finite number of positions (for insertion of optical amplifiers and dispersion compensation modules and to carry the line over rivers). In sections where the transmission line is underground, the variation over time in the surrounding temperature is small, and the DGD and PSP values of these sections change little over long periods (of several weeks to several months). On the other hand, in sections where the transmission line is aboveground, the temperature around the fiber changes rapidly, on the order of hours or minutes. Accordingly, the polarization state of the transmitted light varies significantly. In other words, this sort of transmission fiber behaves as a finite number of birefringent fibers connected via variable polarization rotators. When the number of birefringent fibers constituting the transmission line is small, the statistical characteristics of the DGD deviate significantly from those described in terms of a Maxwell distribution.

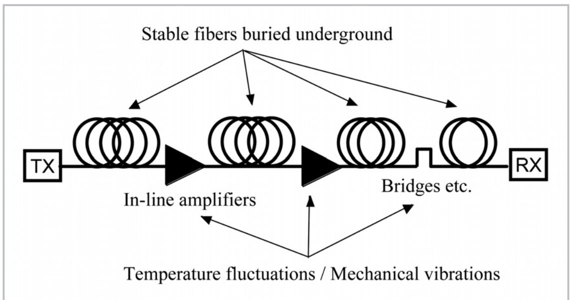

Fig.2 Model for installed transmission line

For example, let us consider a transmission line with an average DGD of 3 ps from the transmitter to the receiver. This transmission line is considered to consist of six sections of stable transmission lines and five polarization rotators that connect these sections. The DGD of each section takes a random value following the Maxwell distribution, with an average value of 3 ps/$\sqrt{6}$. Now let us consider two sets of DGD values for the six sections: Set A, with (0.93 ps, 0.82 ps, 1.17 ps, 1.62 ps, 1.14 ps, 0.55 ps); and Set B, with (1.37 ps, 0.77 ps, 1.94 ps, 1.47 ps, 1.70 ps, 2.43 ps)[11]. These two sets may be considered to comprise values for two different wavelength channels of a WDM system. Figure 3 shows probability density distributions for total DGD for Sets A and B calculated under the assumption that the polarization state of the polarization rotator placed in the nodes between the fiber sections are scattered uniformly and randomly on the Poincaré sphere. (The probability density function can be calculated analytically[12].) Figure 3 also shows the Maxwell distribution with an average of 3 ps. Figure 3 shows that the probability density function differs for each set of values and also differs from the Maxwell distribution. In particular, the chance of developing a large DGD that may cause system failure varies between the sets. These distributions continue for a relatively long period, until there is a change in the DGD value of either section. Thus, it is possible that during this period system failures will frequently occur in a given wavelength channel while they will occur only rarely (i.e., the probability of system failure is zero) in another wavelength channel. This result represents a significant difference in terms of system failure characteristics derived under the assumption that the DGD of every wavelength channel follows the same Maxwell distribution. System design policy and a PMD compensation strategy thus need to be revised accordingly.

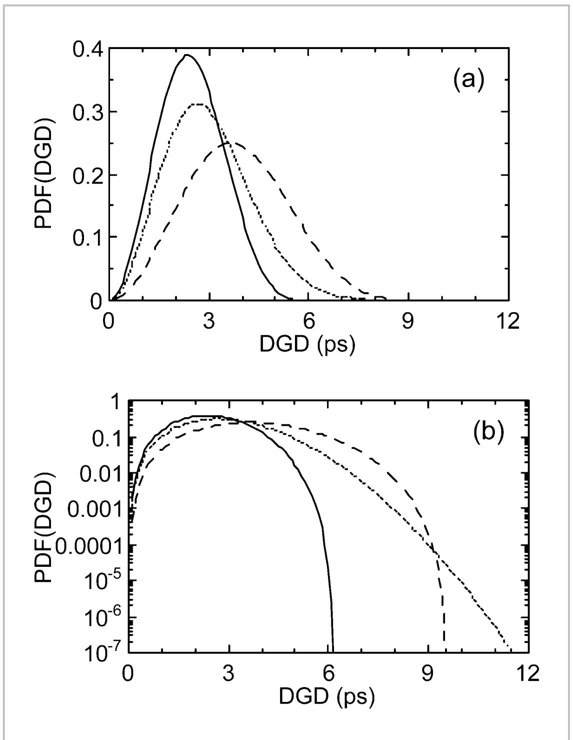

Fig.3 *Probability density function of total DGD for a transmission system consisting of six fibers with fixed DGD. The solid curve represents Set A, the dashed curve represents Set B, and the dotted curve represents the Maxwell distribution. The vertical axis is shown (a) in linear scale and (b) in logarithmic scale.*

4 Polarization-mode dispersion compensation

As discussed above, the polarization characteristics of an optical fiber transmission line change randomly with time. To avoid signal degradation and system failures caused by PMD, researchers have proposed and discussed a large number of methods. Two such methods, specifically aimed at reducing signal degradation caused by PMD, are (1) use of a modulation format with high resistance to PMD and (2) compensation in the optical or electrical domain.

For Method (1), it has been demonstrated that the RZ signal format offers higher resistance against PMD than the NRZ signal format. Electric power is more concentrated around the center of the bit slot in the RZ signal than in the NRZ signal, such that interference between symbols occurs less easily in the RZ signal, even when PMD should broaden the waveform. However, the RZ signal features a broader spectral width, so PMD compensation is less effective in the optical domain[13]. Recently, the use of multi-level modulation—which can reduce the symbol rate while maintaining the bit rate—has attracted attention as a means to avoid the degradation of transmission characteristics caused by PMD. In this context, the PMD resistance of the DQPSK (Differential Quadrature Phase-Shift Keying) transmission scheme has been studied in detail[14]. It is also known that the optical soliton transmission scheme, combined with a form of transmission control such as synchronous amplitude modulation, also offers high PMD resistance[15]. This transmission scheme is based on a type of all-optical 3R regeneration. 2R or 3R regeneration is effective in countering accumulated signal degradation from a variety of sources other than PMD, and these methods have also been demonstrated to be effective in PMD compensation[16][17]. Figure 4 shows an all-optical 2R signal regenerator with a simple configuration based on the nonlinear effects of the fiber. Self-phase modulation within the highly nonlinear fiber broadens the spectral width of the input signal, and an optical bandpass filter with a slight wavelength shift cuts out a part of this spectrum. This process provides reliable waveform shaping and noise reduction for the signal pulses[18]. Figure 5 shows the results of calculation of the extent to which eye-opening degradation due to PMD is suppressed if this regeneration device is inserted

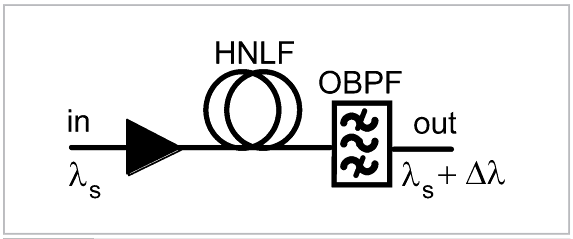

Fig.4 *All-optical 2R regenerator based on nonlinear effects of optical fibers. HNLF: highly nonlinear fiber; OBPF: optical bandpass filter*

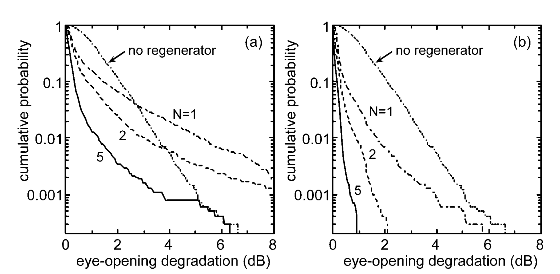

Fig.5 *PMD compensation effect produced by signal regenerator. Cumulative distribution of eye-opening degradation (a) when n sets of 2R regenerators are inserted into the transmission line and (b) when timing regeneration by synchronous modulation is combined with 2R regeneration*

in a 40-Gbps, 1,000-km transmission system (with PMD of 0.3 ps/km$^{1/2)}$ [16]. Though 2R regeneration alone cannot provide sufficient PMD compensation, combining this method with timing regeneration based on synchronous modulation significantly reduces signal degeneration.

As for Method (2), many reports over the past dozen years or so have addressed adaptive compensation in the optical domain[19]. One representative method involves transmitting signals using only one of the PSPs of the transmission lines, along with a polarization controller (which is controlled by the signal-quality-monitor signals fed back from the receiver) placed at the input end of the transmission line. Another method involves the insertion of a PMD compensator, consisting of a polarization controller and a delay line, at the receiver end of the transmission line. We note that the PMD compensation methods discussed here relate in principle to first-order PMD compensation. The spectral bandwidth subject to this compensation is narrow, and two or more compensators (often one for each channel) are required for PMD compensation in WDM systems. To minimize this problem, several methods have been proposed for sharing compensators between the WDM channels[20][21].

Waveform compensation by signal processing in the electrical domain after detection[22] (in particular when compensation is provided in each channel in a WDM system) also offers cost advantages. However, in this case it is difficult to provide accurate compensation including higher-order PMD, and it is also difficult to apply this compensation to high-speed transmission at 40 Gbps or higher.

5 Future problems for research

In order to solve the problem of signal degradation caused by PMD and to compensate for this phenomenon effectively, it is essential to be able to quantify both variation over time and randomness of the PMD. Several studies to date have measured the rate of variation in DGD or PSP over time. However, theoretical analysis has been rare[23]. In the future, it will be important to clarify, in a statistical manner, system downtime and other data. Discussions of operation speeds and optimization of the adaptive control algorithm in an adaptive PMD compensator are also rare. Quantitative clarification and control of the PMD phenomenon and the dynamic behavior of compensation are among the main research topics for the future in terms of polarization-mode dispersion. It is also important to find effective methods to avoid outage due to degradation in transmission caused by intermittent and probabilistic PMD, including control in the upper layers of optical networks.

Acknowledgment

Part of this report is drawn from the “Research and development on ultrahigh-speed backbone photonic network technologies” project of the National Institute of Information and Communications Technology. We would like to express our gratitude to the relevant individuals involved.

References

1 C. D. Poole and R. E. Wagner, "Phenomenological approach to polarisation dispersion in long single-mode fibres", Electron. Lett. Vol.22, pp. 102901030, 1986.

2 S. Betti, F. Curti, B. Daino, G. De Marchis, E. Iannone, and F. Matera, "Evolution of the bandwidth of the principal states of polarization in single-mode fibers", Opt. Lett. Vol. 16, pp. 467-469, 1991.

3 H. Kogelnik, R. M. Jopson, and L. E. Nelson, "Polarization-mode dispersion", Optical Fiber Telecommunications, IV B, System and Impairments, ch.15, Academic Press, San Diego,2002.

4 A. Hasegawa and M. Matsumoto, "Optical Solitons in Fibers, 3rd Ed.", ch.9, Springer, Berlin, 2002.

5 C. D. Poole, J. H. Winters, and J. A. Nagel, "Dynamical equation for polarization dispersion", Opt. Lett. Vol.16, pp. 372-374, 1999.

6 C. D. Poole and D. L. Favin, "Polarization-mode dispersion measurements based on transmission spectra through a polarizer", J. Lightwave Technol. Vol.12, pp. 917-929, 1994.

7 M. Karlsson and J. Brentel, "Autocorrelation function of the polarization-mode dispersion vector", Opt. Lett. Vol.24, pp. 939-941, 1999.

8 J. A. Nagel, M. W. Chbat, L. D. Garrett, J. P. Soigne, N. A. Weaver, B. M. Desthieux, H. Bülow, A. R. McCormick, and R. M. Derosier, "Long-term PMD mitigation at 10 Gb/s and time dynamics over high-PMD installed fiber", 2000 European Conference on Optical Communication, Vol.2, 31, 2000.

9 A. Mecozzi, C. Antonelli, M. Boroditsky, and M. Brodsky, "Characterization of the time dependence of polarization mode dispersion", Opt. Lett. Vol.29, pp. 2599-2601, 2004.

10 M. Boroditsky, and M. Brodsky, N. J. Frigo, P. Magill, C. Antonelli, and A. Mecozzi, "Outage probabilities for fiber routes with finite number of degrees of freedom", IEEE Photon. Technol. Lett. Vol.17, pp.345-347, 2005.

11 H. Kogelnik, P. J. Winzer, L. E. Nelson, R. M. Jopson, M. Boroditsky, and M. Brodsky, "First-order PMD outage for the hinge model", IEEE Photon. Technol. Lett. Vol.17, pp.1208-1210, 2005.

12 C. Antonelli and A. Mecozzi, "Statistics of the DGD in PMD emulators", IEEE Photon. Technol. Lett. Vol.16, pp.1840-1842, 2004.

13 H. Sunnerud, M. Karlsson, C. Xie, and P. A. Andrekson, "Polarization-mode dispersion in high-speed fiber-optic transmission systems", J. Lightwave Tech. Vol.20, pp. 2204-2219, 2002.

14 A. H. Gnauck, P. J. Winzer, C. Dorrer, and S. Chandrasekhar, "Linear and nonlinear performance of 42.7-Gb/s single-polarization RZ-DPSK format", IEEE Photon. Technol. Lett. Vol.18, pp.883-885, 2006.

15 M. Matsumoto, Y. Akagi, and A. Hasegawa, "Propagation of solitons in fibers with randomly-varying birefringence : Effects of soliton transmission control", J. Lightwave Technol. Vol. 15, pp. 584-589, 1997.

16 M. Matsumoto, "PMD mitigation by a fiber-based all-optical signal regenerator", 2003 IEEE/LEOS Summer Topical Meetings, Polarization Mode Dispersion, WB2.5, 2003.

17 Y. Akasaka, Z. Zhu, Z. Pan, and S. J. B. Yoo, "PMD mitigation application of MZI-SOA based optical 2R regeneration in the receiver", 2005 Optical Fiber Communication Conference, JWA22, 2005.

18 P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect", 1998 European Conference on Optical Communication, pp.475-476, 1998.

19 T. Takahashi, T. Imai, and M. Aiki, "Automatic compensation technique for timewise fluctuating polarisation mode dispersion in in-line amplifier systems", Electron. Lett. Vol.30, pp. 348-349, 1994.

20 R. Khosravani, S. A. Havstad, Y. W. Song, P. Ebrahimi, and A. E. Willner, "Polarization-mode dispersion compensation in WDM systems", IEEE Photon. Technol. Lett. Vol.13, pp.1370-1372, 2001.

21 M Boroditsky, C. Antonelli, and A. Mecozzi, “Broadband PMD mitigation using a mid-span polarization controller”, 2005 European Conference on Optical Communication, We1.3.5, 2005.
22 F. Buchali and H. Bülow, “Adaptive PMD compensation by electrical and optical techniques”, J. Lightwave Technol. Vol. 22, pp. 1116-1126, 2004.
23 C. Antonelli, A. Mecozzi, M. Brodsky, and M. Boroditsky, “A simple analytical model for PMD temporal evolution”, 2006 Optical Fiber Communication Conference, OWJ4, 2006.

***MATSUMOTO Masayuki**, Dr. Eng.*

Associate Professor, Graduate School of Engineering, Osaka University

Optical Fiber Communications, Nonlinear Optics