# 40-Gb/s RZ Transmission over a Transoceanic Distance in a Dispersion Managed Standard Fiber Using a Modified Inline Synchronous Modulation Method

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***Abstract*—This paper analyzes in detail numerically a 40-Gb/s return-to-zero (RZ) transmission system over a transoceanic distance in a strongly dispersion managed line composed of standard single-mode fiber (SMF) and dispersion compensation fiber (DCF). We derived a periodically steady-state pulse (a DM soliton) in a DM line. Since the pulse width of a steady-state pulse is too broad for a 40 Gb/s system, the conventional in-line synchronous modulation technique cannot greatly improve the transmission quality. However, we found that the modified inline synchronous modulation technique, which is reported as the black-box optical regenerator [1], can effectively extend the transmission distance even in such a strongly DM line. We discuss the mechanism of the modified synchronous modulation technique with respect to a steady-state pulse in a transmission line, and show that a 40-Gb/s RZ signal can be transmitted over 20 000 km.**

***Index Terms*—Dispersion managed (DM) soliton, 40 Gb/s, optical soliton, optical transmission, soliton control, standard fiber, transoceanic system.**

## I. Introduction

OPTICAL transmission using a dispersion managed (DM) transmission line composed of standard (nondispersion shifted) fiber (SMF) and dispersion compensation fiber (DCF) is very important in terms of developing high-speed time division multiplexed (TDM) and wavelength division multiplexed (WDM) systems. High-capacity WDM transmission over 1 Tb/s [2], WDM transmission over transoceanic distances [3], and single channel 40 Gb/s transmission over 1000 km [4] have already been reported in a DM line that used SMF and DCF. Single channel 40-Gb/s transmission over 10 000 km has also been reported in a dispersion managed (DM) line composed of dispersion shifted fiber (DSF) and DCF [5]. However, it seems difficult to transmit a single channel 40-Gb/s signal over transoceanic distances with SMF and DCF, because the nonlinear interaction (pulse overlapping) between adjacent pulses is large and limits the transmission distance [6].

The technique of soliton control, especially in-line synchronous modulation, is a very powerful way of extending the transmission distance [7], [8]. Recently, an inline synchronous modulation technique for a DM line composed of DSF and DCF has been proposed [1], [9]. This approach is called "black-box" optical regeneration (BBOR). A similar technique has already been used to stabilize the soliton energy in WDM soliton transmission with DSF [10]. Here, we extend the modified soliton control method (BBOR) to a strongly DM line composed of SMF and DCF. In this paper, we show numerically that 40-Gb/s RZ pulses can be transmitted over more than 20 000 km through a DM line using this modified soliton control method. To our knowledge, this is the first 40-Gb/s RZ transmission system over transoceanic distances in a DM line with SMF and DCF.

In Section II, we show the method we used for the numerical simulation. In Section III, we describe the characteristics of a 40-Gb/s RZ transmission system in a DM line composed of SMF without in-line synchronous modulation. We calculate a steady-state pulse in a DM line (a DM soliton) and show that a 40-Gb/s RZ signal cannot become a steady-state pulse through transmission. In Section IV, we describe the characteristics of a 40-Gb/s transmission system in a strongly DM line with conventional in-line synchronous modulation. We show that the conventional synchronous modulation technique cannot greatly improve the transmission quality in a strongly DM line. In Section V, we show that the modified synchronous modulation technique can effectively extend the transmission distance, and that a 40-Gb/s RZ signal can be transmitted in a strongly DM line with SMF over a transoceanic distance using the modified synchronous modulation technique. We discuss the mechanism of the modified synchronous modulation technique with respect to a steady-state pulse in a DM line. We analyze the dispersion tolerance and the power margin, and show that the optimization of a length of highly nonlinear fiber (HNF) can improve the robustness of the system design.

## II. System Performance Evaluation Method

We consider a single channel 40-Gb/s system composed of standard fiber (nondispersion-shifted fiber, SMF) and dispersion compensation fiber (DCF). We used the split step Fourier method to calculate the nonlinear Schrödinger equation [11]. This equation expresses the propagation of a pulse in a fiber,

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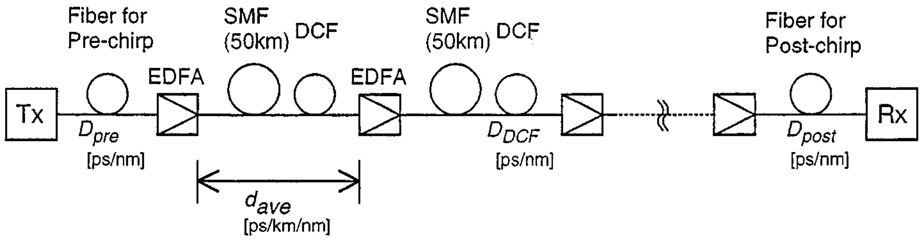



Fig. 1. The configuration of a 40-Gb/s RZ system in a DM line composed of SMF and DC.

and includes the effects of fiber loss and third order dispersion. Fig. 1 shows the configuration of a system in a strongly DM line composed of SMF and DCF. The 40-Gb/s pulse train was generated at the transmitter (Tx). The pulse was sech-shaped or Gaussian-shaped with a full-width at half-maximum (FWHM) of 5 ps, and the pseudorandom bit sequence (PRBS) length was $2^7 - 1$. The generated pulse was chirped by a fiber with a dispersion $D_{\rm pre}$ installed after the transmitter (prechirp). The SMF was 50 km long with a dispersion of 16 ps/km/nm. The fiber loss, third order dispersion, nonlinear Kerr coefficient and effective mode area of the SMF were 0.25 dB/km, 0.07 ps/km/nm$^2$, $2.24 \times 10^{-20}$ m$^2$/W and 78 $\mu$m$^2$, respectively. A dispersion compensation fiber (DCF) was installed after every SMF. We considered only the dispersion effect of the DCF and disregarded the nonlinear effect, third-order dispersion, and loss of DCF, because a dispersion compensation unit can be employed instead of DCF. The average dispersion $d_{\rm ave}$ is given by

$$d_{\rm ave} = (16 \times 50 + D_{\rm DCF})/50 \tag{1}$$

where $D_{\rm DCF}$ is the DCF dispersion in ps/nm units. The noise figure of the erbium doped fiber amplifier (EDFA) was 6 dB, and an optical filter was installed after every EDFA. The chirp of the transmitted pulse was compensated for by a fiber with a dispersion $D_{\rm post}$ installed before the receiver (postchirp). The optical signal was detected by an ideal photodiode (quadratic detector) and filtered with a second-order Butterworth type low-pass electrical filter with a bandwidth of 26 GHz. We used the $Q$-factor to evaluate the quality of the received data [12], [13]. We defined the transmission distance as the distance at which the $Q$-factor is greater than 7, and we calculated this distance for various conditions such as EDFA output power and average dispersion.

## III. RZ Transmission System in a Dispersion Managed Line

### *A. Solution of a steady-state Pulse (DM Soliton)*

A periodically steady-state pulse, in which the dispersion effect is balanced with the nonlinear effect, can exist in a dispersion managed transmission line, and is called a dispersion managed (DM) soliton [14]–[19]. The solution of a DM soliton can be obtained numerically by the split step Fourier method [15], [16], and by the variational method [17], [18], [20]. In this section, we calculate the solution of a DM soliton in a system as shown in Fig. 1.

A DM soliton is Gaussian-shaped with dips at the pulse tail [21], which is expressed by a set of Hermite–Gaussian orthogonal functions [22], [23]. We approximate a DM soliton as a chirped Gaussian function to simplify our analysis. This chirped Gaussian function is expressed by

$$u(t) = A_1 \exp\left(-(1 + iC)\frac{t^2}{2T^2}\right). \tag{2}$$

We use the following expression instead of (2) [18]:

$$u(t) = A_1 \exp\left(-\frac{1 + iD_{\rm Chirp}W^2}{1/W^2 + D_{\rm Chirp}^2 W^2}\frac{t^2}{2}\right) \tag{3}$$

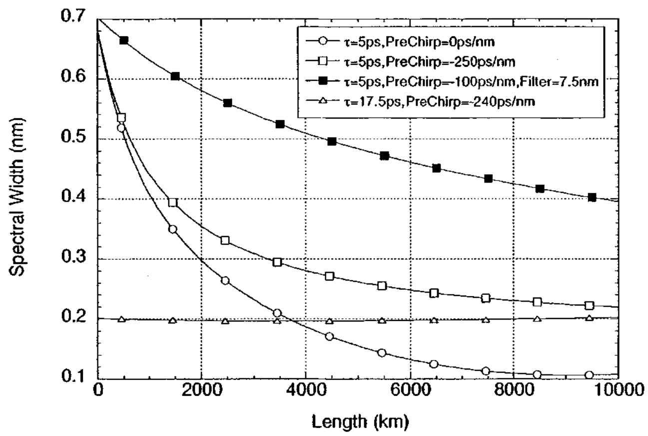
$$\Delta W = 2\sqrt{\ln 2}W. \tag{4}$$

Here, $\Delta W$ is spectral width FWHM and $D_{\rm Chirp}$ is the dispersion that is related to chirp. $W^2$ and $D_{\rm Chirp}$ correspond to $\gamma$ and $C$ in [18]. When this pulse is transmitted through a fiber with a dispersion of $-D_{\rm Chirp}$, a transform-limited pulse with a FWHM of $\Delta T$ is obtained as follows:

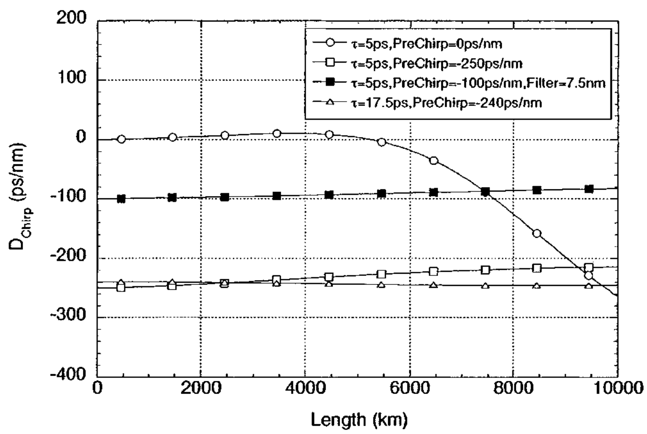
$$u(t) = A_2 \exp\left(-\frac{1}{1/W^2}\frac{t^2}{2}\right) \tag{5}$$

$$\Delta T = 2\sqrt{\ln 2}\frac{1}{W} \cong \frac{0.441}{\Delta W}. \tag{6}$$

Fig. 2 shows the evolution of the spectral width and $D_{\rm Chirp}$ measured at every EDFA, when a single pulse is transmitted in a DM line as shown in Fig. 1. We estimate $D_{\rm Chirp}$ from the amount of dispersion necessary to compensate optimally for the chirp of the pulse, i.e., the dispersion which minimizes the root-mean-square (rms) pulse width. The $D_{\rm Chirp}$ at the first EDFA corresponds to $D_{\rm pre}$. We calculated the evolution for a pulse energy of 53 fJ, and an average dispersion $(d_{\rm ave})$ of zero. We set the optical filter bandwidth at 3 nm. When the spectral width at the transmitter $(\Delta W_0)$ and $D_{\rm pre}$ were 0.7 nm and 0 ps/nm, respectively, the spectral width decreased rapidly with propagation (open circles). A spectral width of 0.7 nm corresponds to an FWHM of 5 ps. When $D_{\rm pre}$ was changed to $-250$ ps/nm, the spectral narrowing was slightly suppressed (open squares). When the optical filter bandwidth was changed to 7.5 nm and $D_{\rm pre}$ was set at $-100$ ps/nm, the spectral width narrowed slowly (filled squares). However, when the $\Delta W_0, D_{\rm pre}$, and optical filter bandwidth were 0.2 nm, $-240$ ps/nm and 3 nm, respectively, we observed no variation in the spectral width or $D_{\rm Chirp}$ with propagation (open triangles). That means that a steady-state pulse is transmitted under this condition, and these $\Delta W_0$ and $D_{\rm pre}$ values are the solution of a DM soliton. A spectral width of 0.2 nm corresponds to an FWHM of 17.5 ps. When the initial spectral width was 0.7 nm, the pulse approached a steady-state pulse with propagation, thus the spectral width approached 0.2 nm. This indicates that the pulse broadens when

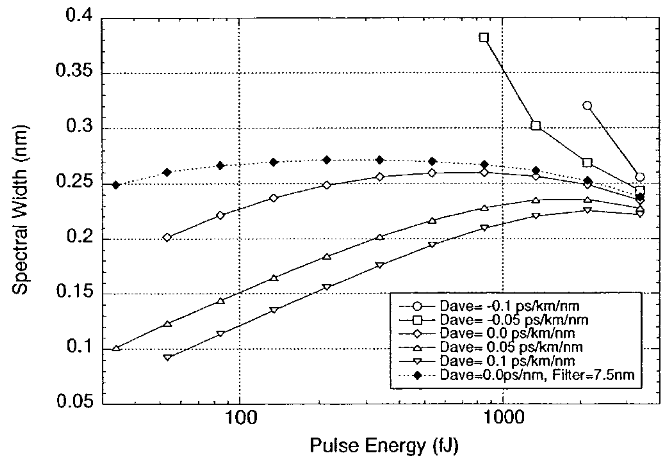



(a)




(b)

Fig. 2. The evolution of spectral width and $D_{\rm chirp}$ measured at EDFA. (a) Spectral width, (b) $D_{\rm Chirp}$. ○: $\tau$ (Initial pulse width) $= 5$ ps, $D_{\rm pre}$ (Prechirp dispersion) $= 0$ ps/nm, $\Delta\lambda_f$ (Optical filter bandwidth) $= 3$ nm. □: $\tau = 5$ ps, $D_{\rm pre} = -250$ ps/nm, $\Delta\lambda_f = 3$ nm. ■: $\tau = 5$ ps, $D_{\rm pre} = -100$ ps/nm, $\Delta\lambda_f = 7.5$ nm. △: $\tau = 17.5$ ps, $D_{\rm pre} = -240$ ps/nm, $\Delta\lambda_f = 3$ nm.

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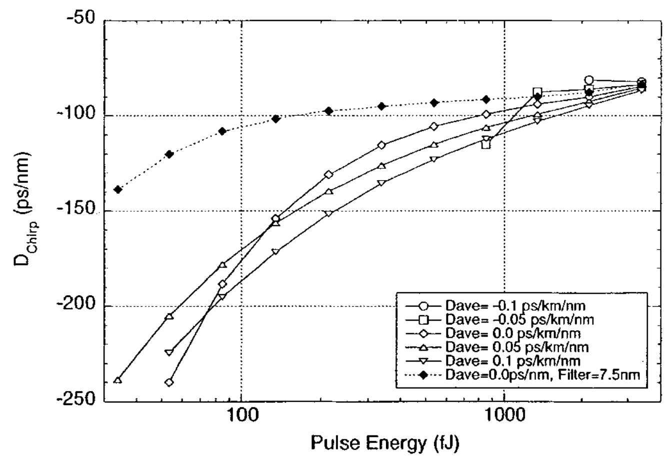



(b)

Fig. 3. The spectral width and $D_{\rm chirp}$ of a DM soliton measured at an EDFA as a function of pulse energy. (a) Spectral width, (b) $D_{\rm chirp}$. ○: $d_{\rm ave}$ (average dispersion) $= -0.1$ ps/km/nm. □: $d_{\rm ave} = -0.05$ ps/km/nm. ◇: $d_{\rm ave} = 0$ ps/km/nm. △: $d_{\rm ave} = 0.05$ ps/km/nm. ▽: $d_{\rm ave} = 0.1$ ps/km/nm. ◇: $d_{\rm ave} = 0$ ps/km/nm. The optical filter bandwidth is 3 nm for ○□◇△▽, and 7.5 nm for ▽.

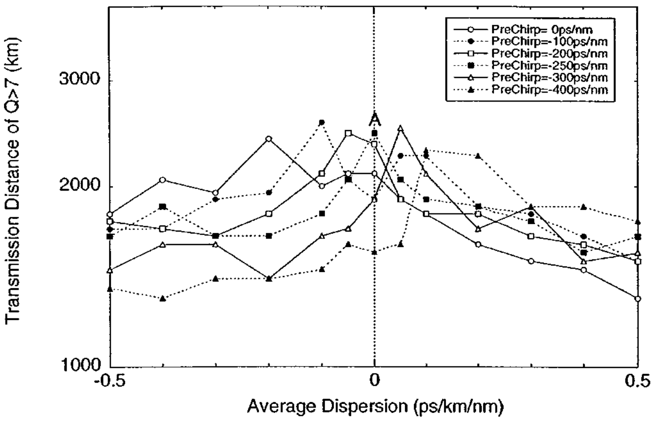
a pulse with an FWHM of 5 ps is launched into a strongly DM line.

Fig. 3 shows the spectral width and $D_{\rm Chirp}$ of a DM soliton measured at an EDFA as a function of pulse energy and the average dispersion. When the average dispersion is anomalous or zero, the spectral width of a DM soliton is narrower than 0.27 nm. This indicates that there is no solution of a DM soliton shorter than an FWHM of 13 ps. When we evaluate the present transmission system using a $Q$-factor, the FWHM of a Gaussian-shaped pulse must be shorter than about half a bit slot time for a high $Q$-factor. This means we cannot obtain a high $Q$-factor in a 40-Gb/s system by using the solution of a DM soliton in a D line composed of SMF and DCF. When the average dispersion is normal, we can obtain a DM soliton with a spectral width of 0.38 nm, hence with an FWHM of 9.2 ps. However, the energy of this solution is large and it causes a large nonlinear interaction with adjacent pulses.

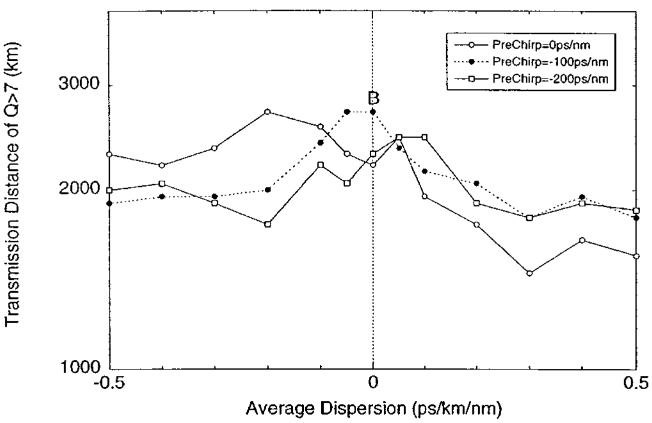
### *B. Transmission Characteristics of a 40-Gb/s System*

When we used the solution of a DM soliton as the initial pulse in a 40-Gb/s system in a DM line as shown in Fig. 1, we were unable to obtain a transmission distance of more than several hundred kilometers, because the pulse width was too broad. Thus, we used an initial pulse with an FWHM of 5 ps in the following analysis.

Fig. 4 shows the transmission characteristics in a 40-Gb/s system in a DM line composed of SMF, as shown in Fig. 1. This figure shows the transmission distance over which the $Q$-factor is more than 7 as a function of average dispersion. We optimized the EDFA output power to maximize the transmission distance. We used a Gaussian shaped pulse with an FWHM of 5 ps at the transmitter. We calculated the transmission distances with various pre-chirp dispersions $(D_{\rm pre})$ and we optimized the postchirp dispersion $(D_{\rm post})$ to maximize the transmission distance. Fig. 4(a) shows the transmission distance when the optical filter bandwidth was 3 nm. When the average dispersion is zero, the optimum $D_{\rm pre}$ value for maximizing the transmission distance is $-250$ ps/nm "A" in Fig. 4(a). The EDFA output power is 0 dBm, and the $D_{\rm post}$ is 250 ps/nm. Under these conditions, we can achieve a transmission distance of about 2 500 km. Fig. 4(a) shows that a transmission distance of more than 2000 km can be achieved by optimizing $D_{\rm pre}$, even when the average dispersion varies between $-0.2$ and 0.2 ps/km/nm.




(a)




(b)

Fig. 4. The transmission distance over which the $Q$-factor is more than 7 in a 40-Gb/s system in a DM line composed of SMF. The optical filter bandwidth is 3 nm in (a), and 7.5 nm in (b). ○: $D_{\rm pre}$ (prechirp dispersion) $= 0$ ps/nm. •: $D_{\rm pre} = -100$ ps/nm. □: $D_{\rm pre} = -200$ ps/nm. ■: $D_{\rm pre} = -250$ ps/nm. △: $D_{\rm pre} = -300$ ps/nm. △: $D_{\rm pre} = -400$ ps/nm.

Next, we optimized the optical filter bandwidth. The optimum bandwidth is defined as the bandwidth at which the maximum transmission distance is obtained. Fig. 4(b) shows the transmission distance when the optical filter bandwidth is 7.5 nm, which is the optimum bandwidth of the optical filter in this case. When the average dispersion is zero, the optimum $D_{\rm pre}$ for maximizing the transmission distance is $-100$ ps/nm "B" in Fig. 4(b). The EDFA output power is 0 dBm and the $D_{\rm post}$ is 100 ps/nm. Under these conditions, we can obtain a transmission distance of about 2700 km. Fig. 4(b) shows that a transmission distance of more than 2000 km is possible if we optimize the $D_{\rm pre}$, even when the average dispersion varies between $-0.5$ and 0.1 ps/km/nm.

In a 40-Gb/s system, the factors which limit the transmission distance are nonlinear pulse broadening and nonlinear pulse interaction (interaction is described in the next section), and these effects can be reduced by optimizing the pre-chirp dispersion [6]. We can obtain a transmission distance of approximately 2700 km by optimizing the prechirp dispersion. The evolutions of spectral widths under the conditions marked with "A" and "B" in Fig. 4 are shown by the open and filled squares in Fig. 2(a). Even under these conditions, the spectral widths become narrower, indicating that the pulsewidths broaden with propagation. This reveals that the optimum condition for maximizing the transmission distance is not a steady-state pulse for a 40-Gb/s system in a strongly DM line composed of SMF.

## IV. RZ Transmission System with Conventional Synchronous Modulation

### *A. The Conventional Synchronous Modulation Method*

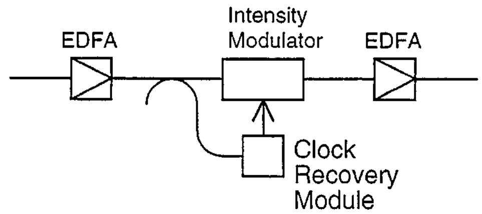
The inline synchronous modulation technique was developed to extend the transmission distance considerably in a soliton line, in which the dispersion is uniform over the transmission line [7], or in a weakly DM soliton line, in which the cumulative dispersion is small [24]. In this section, we analyze the transmission characteristics in a strongly DM line composed of SMF using the above technique. Fig. 5 shows the configurations for the conventional in-line synchronous modulation technique employed in a DM line. Fig. 5(a) shows the configuration of the synchronous modulator. The transmitted pulse is modulated in an intensity modulator by a baseband clock signal extracted from a part of the transmitted pulses. Fig. 5(b) shows the transmission system in a DM line composed of SMF that uses an inline synchronous modulator. In our present analysis, the synchronous modulator is installed every five repeaters (250 km). The modulation function we used is

$$T(t) = \frac{1 + \cos(\pi/2(1 + \cos Bt))}{2} \tag{7}$$

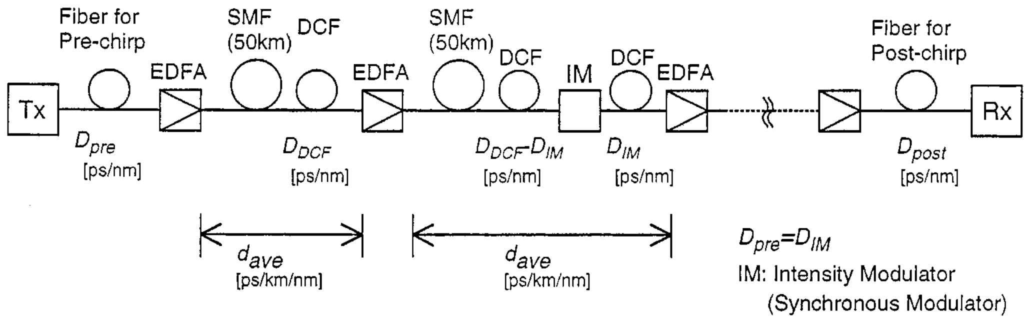
where $B$ is the bit rate. A synchronous modulator is installed in the middle of the DCF. We set the cumulative dispersion of the DCF before and after each synchronous modulator at $D_{\rm DCF} - D_{\rm IM}$ and $D_{\rm IM}$ ps/nm, respectively. We set the $D_{\rm pre}$ (pre-chirp dispersion) at $D_{\rm IM}$ ps/nm, so that $D_{\rm Chirp}$ at the intensity modulator approaches zero. If $D_{\rm Chirp}$ is far from zero, some of the pulse energy leaks into adjacent bit slots by the intensity modulator. Moreover, if the transmission distance were to be over 20 000 km, the pulse would become a periodically steady-state pulse. We assume that $D_{\rm Chirp}$ at the intensity modulator of the steady-state pulse is close to zero for the same reason. We calculated the transmission distance with the synchronous modulator at various positions, that is $D_{\rm IM}$, and we optimized $D_{\rm post}$ (postchirp dispersion) to maximize the transmission distance. We used a Gaussian-shaped pulse with an FWHM of 5 ps at the transmitter. A narrowband optical filter is indispensable for stabilizing the energy of the pulses in the soliton system with the synchronous modulator, however the pulse energy can be stabilized without any narrowband optical filters when a synchronous modulator is installed in the middle of the DCF in a DM soliton system [25]. Thus, we calculated the transmission distance using optical filters with various bandwidths.

### *B. Transmission Characteristics of a 40-Gb/s System with Conventional Synchronous Modulation*

Fig. 6 shows the transmission distance for which the $Q$ factor is more than 7 in a 40 Gb/s system with conventional synchronous modulation as shown in Fig. 5. The initial pulse is Gaussian-shaped with an FWHM of 5 ps. The transmission distance is slightly longer when the optical filter bandwidth




(a)




(b)

Fig. 5. The configuration of a 40-Gb/s RZ system using the conventional inline synchronous modulation technique. (a) The configuration of the synchronous modulator. (b) The configuration of the system with the synchronous modulator.

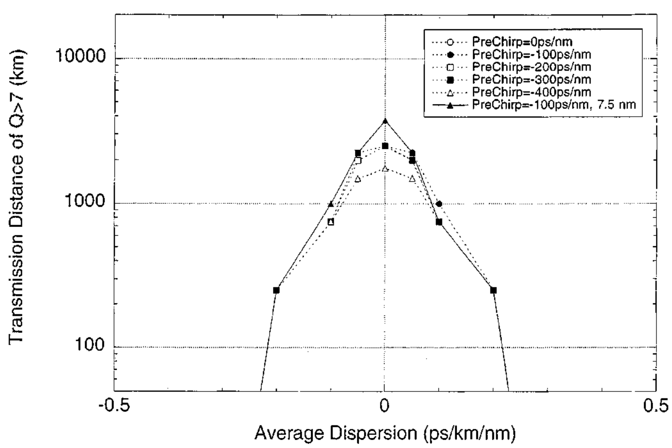



Fig. 6. The transmission distance over which the $Q$-factor is more than 7 in a 40 Gb/s system in a DM line with conventional synchronous modulation. ○: $D_{\rm pre}$ (prechirp dispersion) $=$ 0 ps/nm. •: $D_{\rm pre}$ $=$ $-100$ ps/nm. □: $D_{\rm pre}$ $=$ $-200$ ps/nm. ■: $D_{\rm pre}$ $=$ $-300$ ps/nm. △: $D_{\rm pre}$ $=$ $-400$ ps/nm. ▽: $D_{\rm pre}$ $=$ $-100$ ps/nm. The optical filter bandwidth is 1.5 nm for ○ • □■△, and 7.5 nm for ▽.

is 7.5 nm than when it is 1.5 nm. A maximum transmission distance of 3 750 km can be achieved when the average dispersion, EDFA output power, prechirp dispersion, postchirp dispersion, and optical filter bandwidth are 0.0 ps/km/nm, 0 dBm, $-100$ ps/nm, 100 ps/nm, and 7.5 nm, respectively. The increase in the transmission distance is approximately 1000 km, however, the synchronous modulation technique cannot extend the transmission distance to more than 10 000 km in a strongly DM line.

The reason is described below. Fig. 7 shows the pulse waveform evolution when a single pulse or a pair of pulses is transmitted in a DM line. Fig. 7(a) and (b) show the waveforms in a DM line without any synchronous modulation, and Fig. 7(c) and (d) show the waveforms in a DM line with synchronous modulation. The average dispersion is zero, and the EDFA output power is 0 dBm. The pre-chirp dispersion is zero, and the postchirp dispersion is zero. Fig. 7(a) shows that a pulse is broadened by transmission over 1 000 km when it is transmitted in a strongly DM line. This is the result of spectral broadening, which is described in the previous section. In Fig. 7(b), we see that there is interaction between adjacent pulses when a pair of pulses is transmitted in a DM line. Fig. 7(c) shows that synchronous modulation removes the tail of a broadened pulse. However, we find that a small amount of pulse energy escapes to the adjacent bit slots. Fig. 7(d) shows that a larger amount of the pulse energy leaks to adjacent bit slots when a pair of pulses is transmitted than when a single pulse is transmitted. In summary, when the pulses are transmitted in a strongly DM line with synchronous modulation, the pulse energy leaks to the adjacent bit slots because of the nonlinear pulse broadening and nonlinear pulse interaction. This escaped energy causes bit error in a transmission system.

The synchronous modulation technique can suppress the small amount of energy that leaks into adjacent bit slots through the nonlinear effect in a uniform or weakly DM soliton line [26]. However, the nonlinear effect is weak in a DM soliton line, and synchronous modulation cannot sufficiently suppress leaked energy. This is why the conventional synchronous modulation technique only provides a small increase in the transmission distance in a strongly DM line.

## V. RZ Transmission System with Modified Synchronous Modulation

### A. The Modified Synchronous Modulation Technique

With the modified synchronous modulation technique highly nonlinear fiber (HNF) is added to the conventional synchronous modulation technique to improve the transmission quality of a system in a strongly DM line. This principle is the same as the BBOR approach reported in [1]. A similar adoption of HNF is reported in [10]. In this section, we show how the transmission

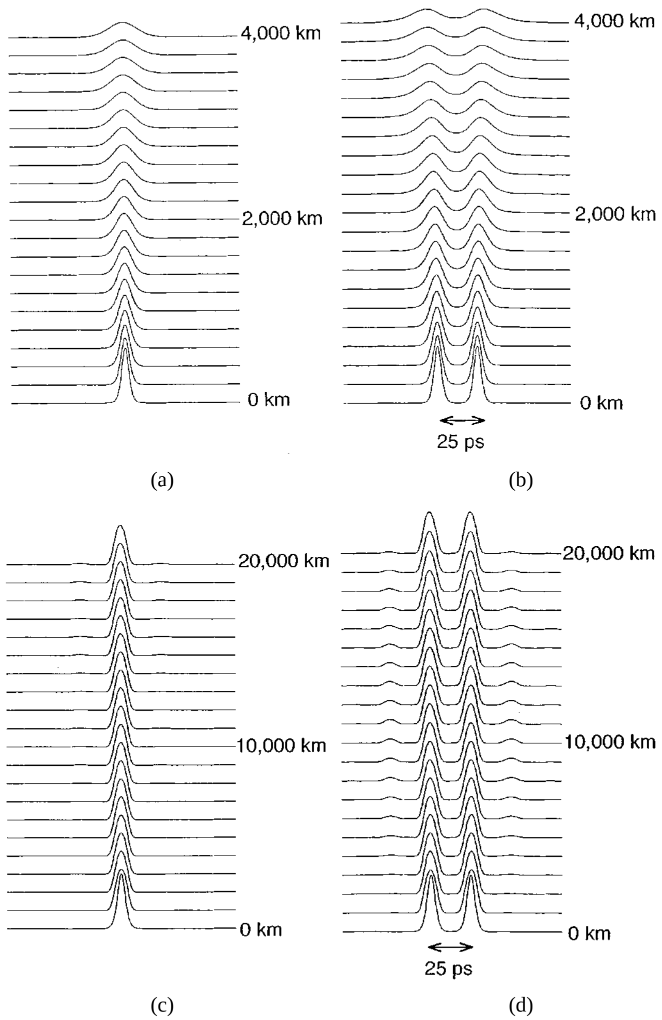



Fig. 7. The pulse waveform evolution. (a) A single pulse transmission in a DM line without synchronous modulation. (b) Two pulses transmission in a DM line without synchronous modulation. (c) A single pulse transmission in a DM line with synchronous modulation. (d) Two pulses transmission in a DM line with synchronous modulation.

distance can be extended to a transoceanic distance in a strongly DM line composed of SMF using the modified synchronous modulation technique.

Fig. 8 shows the configuration of a system in a DM line with the modified synchronous modulation technique. An HNF [27] is installed after a synchronous modulator. We set the energy of the transmitted pulse in the HNF at

$$E = \ln(\sqrt{2}+1)\frac{\lambda^3}{\pi^2 n_2 c}\frac{d_{\mathrm{HNF}}}{\tau_{\mathrm{in}}}A_{\mathrm{eff}} = 0.881\frac{\lambda^3}{\pi^2 n_2 c}\frac{d_{\mathrm{HNF}}}{\tau_{\mathrm{in}}}A_{\mathrm{eff}} \quad (8)$$

where $d_{\mathrm{HNF}}$ is the HNF dispersion and $\tau_{\mathrm{in}}$ is the FWHM of an initial pulse. This equation means that a fundamental soliton with an energy $E$ and an FWHM $\tau_{\mathrm{in}}$ can be transmitted in a HNF. The average dispersion $d_{\mathrm{ave}}$ is defined as (1), from which the HNF dispersion is excluded. In our analysis, we installed a synchronous modulator every five repeaters (250 km). The initial pulse was sech-shaped with a 5-ps FWHM. We did not use Gaussian shaped pulses because this system is considered to be a soliton transmission system that is perturbed by a DM line with conventional synchronous modulation. We set the optical filter bandwidth at 1.5 nm. The HNF dispersion, effective mode area of the HNF and energy of the pulse in the HNF was 1.8 ps/km/nm, 13 $\mu$m$^2$, and 6 dBm, respectively. Under these conditions, a fundamental soliton with an FWHM of 5 ps can be transmitted in HNF, and the soliton period is 5.2 km. We disregarded the loss and the third order dispersion of the HNF.

### *B. Transmission Characteristics of a 40-Gb/s System with Modified Synchronous Modulation*

Fig. 9 shows the transmission distance over which the $Q$-factor is more than 7 in a 40-Gb/s system in a DM line with modified synchronous modulation. We set the HNF length at 5.2 km (1 soliton period). The open circles show the transmission distance in a 40-Gb/s system without a synchronous modulator. The filled circles show the transmission distance in a 40-Gb/s system with conventional synchronous modulation. The open squares show the transmission distance in a 40-Gb/s system with the modified synchronous modulator. The initial pulse is sech-shaped with an FWHM of 5 ps. Fig. 9 shows that the modified synchronous modulation technique can extend the transmission distance to over 20 000 km even in a strongly DM line. This is achieved when the average dispersion is around zero. The dispersion tolerance, for which the transmission distance is over 20 000 km, is 0.02 ps/km/nm.

Modified synchronous modulation can extend the transmission distance for the reason described below. Fig. 10 shows the change in the pulse width (FWHM), spectral width and $D_{\mathrm{Chirp}}$ around 10 000 km when a single pulse is transmitted in a DM line with modified synchronous modulation. The average dispersion is zero and the EDFA output power is 0 dBm. Under these conditions, a transmission distance of over 20 000 km can be achieved. The pulse is transformed into a periodically steady-state pulse through transmission, and these figures show the periodical change of this steady-state pulse. When the pulse is transmitted in a DM line composed of SMF and DCF, the spectral width is narrowed and the pulse width is broadened, because the pulse approaches a steady-state in a DM line. When the pulse is transmitted through a synchronous modulator, the FWHM of the pulse decreases slightly. When the pulse is transmitted through HNF, the FWHM of the pulse decreases and the spectral width broadens. The cumulative dispersion of the HNF is about 9 ps/nm, however, the $D_{\mathrm{Chirp}}$ is almost unchanged. This indicates that the pulse is nonlinearly compressed as it passes through the HNF. In other words, the pulse approaches a steady-state in the HNF forming a pure soliton with an FWHM of 5 ps. Thus, the nonlinear pulse broadening in a DM line can be suppressed by the pulse compression in the HNF.

In the previous section, we described how the pulse is degraded by nonlinear pulse broadening and nonlinear interaction with adjacent pulses as it passes through a DM line. The nonlinear pulse broadening is compensated for by the HNF, and the nonlinear interaction is compensated for by the synchronous modulator. Moreover, the small amount of energy that leaks to adjacent bit slots can be suppressed by soliton control [24], provided by an HNF and a synchronous modulator. Thus, both HNF

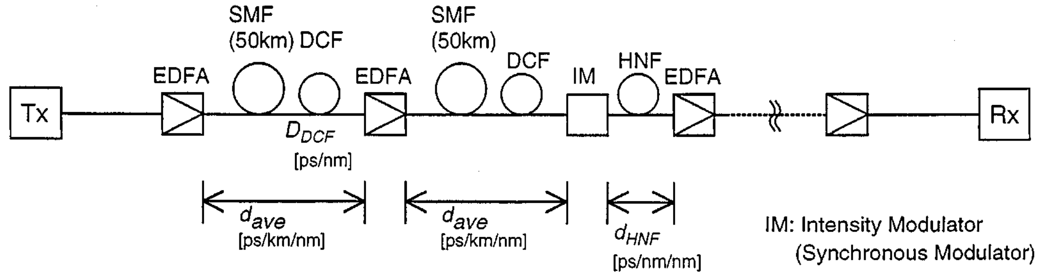



Fig. 8. The configuration of a 40-Gb/s RZ system using the modified inline synchronous modulation technique.

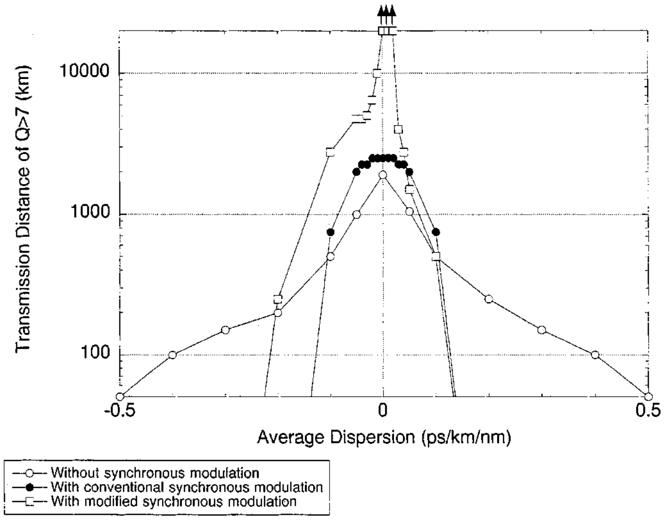



Fig. 9. The transmission distance over which the $Q$-factor is more than 7 in a 40-Gb/s system in a DM line. ○: Without synchronous modulation. •: With conventional synchronous modulation. □: With modified synchronous modulation. The initial pulse width is 5 ps, and the prechirp dispersion is 0 ps/nm. The optical filter bandwidth is 3 nm for ○, and 1.5 nm for •□.

and a synchronous modulator are indispensable if we wish to extend the transmission distance in a strongly DM line.

Fig. 11 shows the pulse waveform evolution when a single pulse and a pair of pulses are transmitted in a DM line with modified synchronous modulation. The average dispersion is zero, and the EDFA output power is 0 dBm. Fig. 11(a) shows that the pulse broadening can be suppressed when a single pulse is transmitted in a DM line with modified synchronous modulation. Fig. 11(b) shows that the pulse broadening and nonlinear interaction can be suppressed when a pair of pulses is transmitted in a DM line with modified synchronous modulation. We did not observe any escape of the pulse energy into adjacent bit slots. The small amount of energy that escapes to adjacent bit slots can be suppressed by the soliton control mechanism [26].

It has been reported that the main benefit of BBOR is to recover the efficiency of the pulse energy stabilization [1], [28]. Here, we discuss the stabilization of pulse energy in a strongly DM line with modified synchronous modulation. Fig. 12 shows the evolution of the pulse energy when pulses with various energies are launched into a strongly DM line with conventional and modified synchronous modulation. We calculate the pulse propagation under the conditions used in Fig. 7(c) (conventional synchronous modulation) and Fig. 11(a) (modified synchronous modulation), except that the EDFA gain is constant. We set the

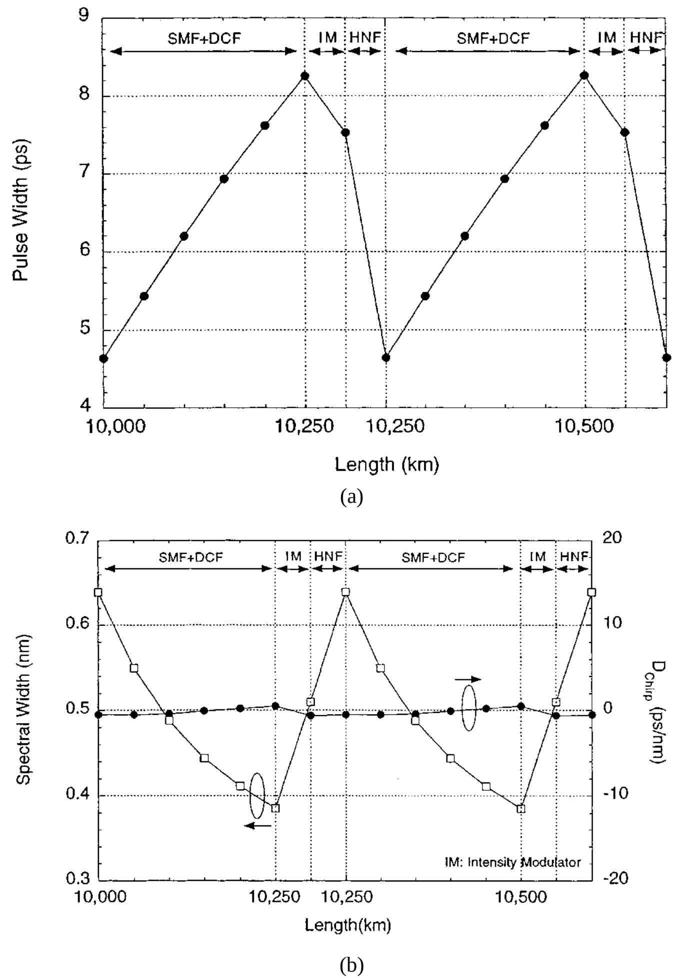
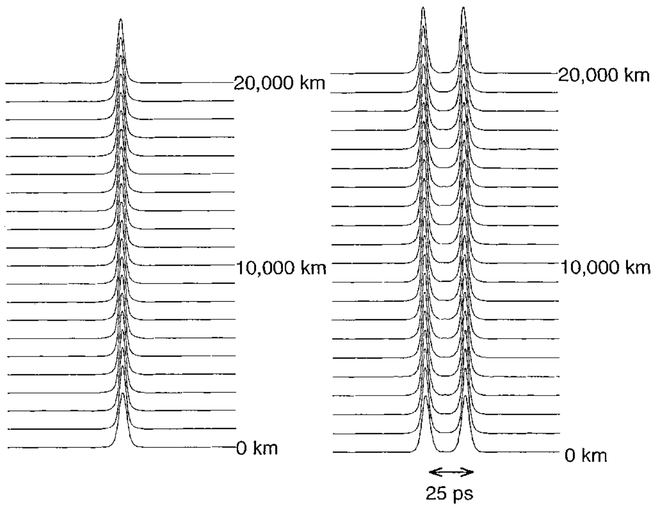



Fig. 10. The evolution of the pulsewidth, spectral width, and $D_{\rm chirp}$ when a single pulse is transmitted in a DM line with modified synchronous modulation. (a) Pulsewidth. (b) Spectral width and $D_{\rm chirp}$.

EDFA gain at the value found around 20 000 km in the analysis in Figs. 7(c) and 11(a). The dotted line shows the energy evolution when conventional synchronous modulation is employed. The solid line shows the energy evolution when modified synchronous modulation is used. The pulse energy is not stabilized in a DM line with conventional synchronous modulation, however, the pulse energy can be stabilized in a DM line with modified synchronous modulation. Thus, HNF is effective in stabilizing the pulse energy in a strongly DM line.

Thus, a 40-Gb/s RZ signal can be transmitted over 20 000 km in a strongly DM line composed of SMF using the modified synchronous modulation technique.




(a) (b)

Fig. 11. The pulse waveform evolution in a DM line with conventional synchronous modulation. (a) Single-pulse transmission. (b) Two-pulse transmission.

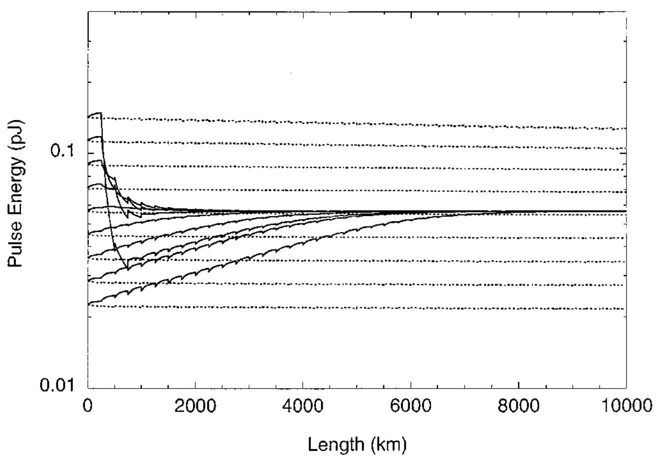



Fig. 12. The pulse energy evolution when pulses with various energies are launched. Dotted line: with conventional synchronous modulation. Solid line: with modified synchronous modulation.

## C. The Effect of the Length and Position of HNF

Fig. 13 shows the dispersion tolerance and power margin in a 40-Gb/s system in a DM line with modified synchronous modulation. These figures show contour plots of the $Q$-factor at 20 000 km as functions of average dispersion and EDFA output power. The HNF is 5.2 km (1 soliton period) in Fig. 13(a), and 15.6 km (3 soliton periods) in Fig. 13(b). When the HNF length is 1 soliton period, the power margin is 6 dB, and the dispersion tolerance is 0.02 ps/km/nm. When the HNF length is 3 soliton periods, the power margin can be improved to 10 dB, and the dispersion tolerance to 0.09 ps/km/nm.

The power margin can be improved with the longer HNF for the following reason. When the EDFA output power is too small, the signal-to-noise ratio (SNR) becomes low. When the EDFA output power is too large, nonlinear pulse interactions with adjacent pulses degrade the pulse quality. When the average dispersion is too far from zero, a larger amount of energy leaks to adjacent bit slots, because the pulse is greatly broadened at the synchronous modulator owing to residual dispersion. When the

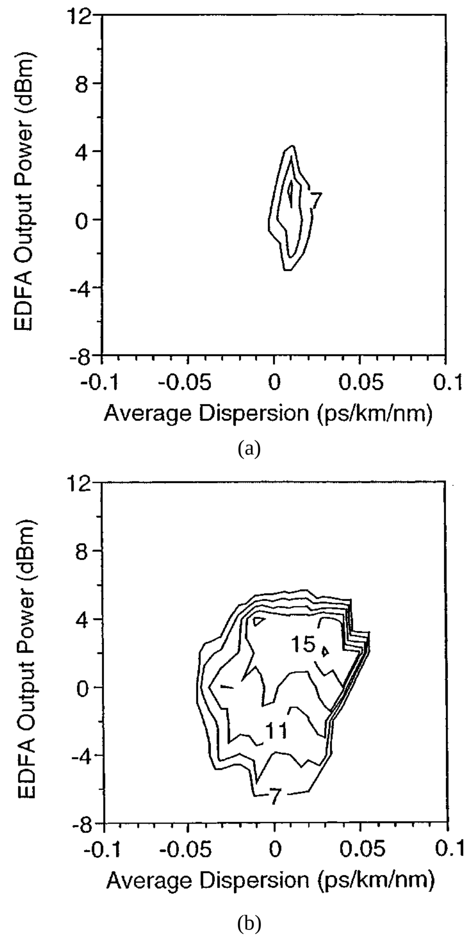



Fig. 13. A contour plot of the $Q$-factor at 20 000 km as functions of the average dispersion and EDFA output power (launched power into SMF). (a) The HNF is 5.2 km (1 soliton period) adn (b) 15.6 km (3 soliton periods).

HNF is longer, the pulse is stabilized more strongly, and this improves the power margin and dispersion tolerance.

We can consider a DM line with modified synchronous modulation to be a soliton transmission line composed of HNF with synchronous modulation that is perturbed by the DM line. Under this assumption, a longer HNF means a longer modulator spacing, and this worsens the transmission quality. Thus, there is an optimum HNF length with which to obtain the best transmission quality. Fig. 14(a) shows contour plots of the $Q$-factor at 20 000 km as functions of EDFA output power and HNF length. The average dispersion is zero. When the HNF length is about 2 to 3 soliton periods, the largest power margin and the highest $Q$-value are obtained.

With the modified synchronous modulation technique, we install the HNF after the synchronous modulator, while the HNF is installed before the synchronous modulator in the BBOR. We install the HNF after the synchronous modulator because this improves the transmission quality. Fig. 14(b) shows the transmission quality when the HNF is installed before the synchronous modulator (BBOR configuration). This figure shows contour plots of the $Q$-factor at 20 000 km as functions of EDFA output power and HNF length. The transmission quality is slightly worse compared with Fig. 14(a) (our configuration), and this is particularly noticeable in the high EDFA output power region (+4 dBm). This difference

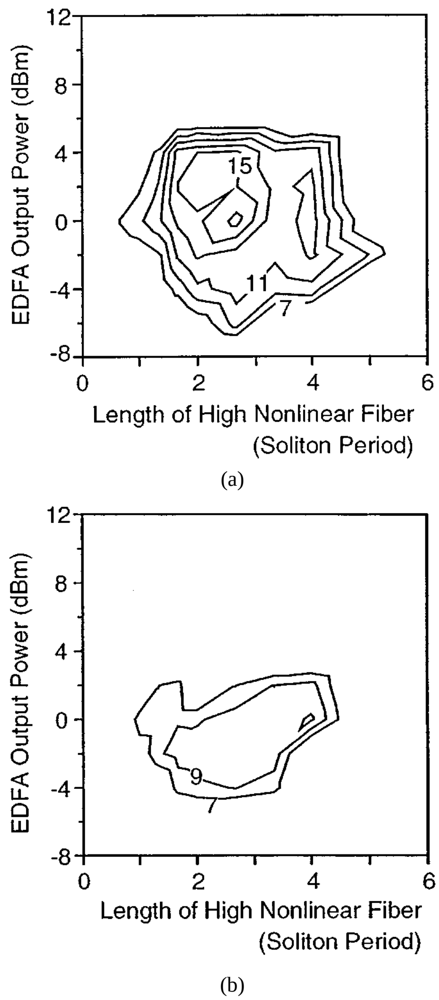



Fig. 14. A contour plot of the $Q$-factor at 20 000 km as functions of HNF length and EDFA output power (launched power into SMF). (a) The HNF is installed after a synchronous modulator and (b) before a synchronous modulator.

is mainly due to the difference in the timing jitter. That is, the timing jitter is suppressed more strongly in our configuration than in the BBOR configuration. We believe this to be for the following reason. The timing jitter is induced when the pulse is transmitted in the DM line, and it is suppressed by the synchronous modulator. However, when the pulse is transmitted in the HNF, the pulse interacts nonlinearly with the adjacent pulses, and more timing jitter is induced. The nonlinear interaction in HNF is greatly affected by the pulse tail, and the synchronous modulator eliminates the pulse tail energy. Thus, when the HNF is installed before a synchronous modulator, the tails of pulses transmitted in the HNF have considerable energy, and the timing jitter is more induced more strongly. In contrast, when the HNF is installed after the synchronous modulator, this energy becomes small, and so the nonlinear interaction between adjacent pulses is reduced. Therefore, the timing jitter is more strongly suppressed and better transmission quality is obtained in our configuration.

## VI. Conclusion

We undertook a detailed numerical analysis of a 40-Gb/s RZ transmission system over a transoceanic distance in a strongly DM line composed of SMF and DCF. We derived a periodically stable pulse (DM soliton) in the DM line. The pulsewidth of a steady-state pulse is too broad for a 40-Gb/s system. This means a 40-Gb/s RZ signal cannot be transformed into a stable short pulse through propagation, and the effectiveness of the conventional in-line synchronous modulation technique is insufficient to improve the transmission quality. However, the modified inline synchronous modulation technique can effectively extend the transmission distance even in such a strongly DM line. By using modified synchronous modulation, a steady-state pulse with a shorter pulse-width can be transmitted, because the broadened pulse in a strongly DM line can be compressed as it propagates in HNF. We found that it is possible to transmit a 40-Gb/s RZ signal over 20 000 km in a DM line composed of SMF using the modified synchronous modulation technique.

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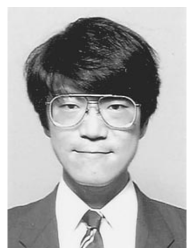

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