Theoretical Investigation of 8 × 10-Gb/s WDM Signal Transmission Performance Based on Gain-Equalized SOAs Using Backward Raman Pumping at DCF

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***Abstract*—We have theoretically investigated 8 × 10-Gb/s wavelength-division multiplexing (WDM) signal transmission characteristics based on semiconductor optical amplifiers (SOAs) with equalized gain using discrete Raman amplification (DRA). Gain equalization and low noise figures have been obtained by adjusting the backward Raman pumping power and wavelength at a dispersion compensating fiber (DCF) for each span. Bit-error-rate characteristics were calculated for 8 × 10-Gb/s WDM signal transmission over 6 × 40-km single-mode fiber (SMF) + DCF links with gain-equalized SOAs using DRAs at DCF. Approximately a 2.5-dB improvement of the receiver sensitivity was achieved by using SOAs and DRAs with optimized Raman pumping. One can easily upgrade the transmission length of a link based on SOAs with an appropriate backward pump laser at each DCF.**

***Index Terms*—Optical communication, Raman amplifier, semiconductor optical amplifier (SOA), wavelength-division multiplexing (WDM).**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) are prospective devices for optical fiber transmission systems due to their compact size, ultrawideband gain spectrum, integration with other devices, and low cost. Many experimental results of SOAs as inline amplifiers [1], [2], optical preamplifiers to receiver [3], switch fabrics [4], and wavelength converters [5] have been reported. Recently, there has been interest in using SOAs as a booster amplifier for regional metro wavelength-division-multiplexed (WDM) networks due to their possible low cost. SOAs, however, have inferior characteristics compared with erbium-doped fiber amplifiers (EDFAs) as follows: fast gain dynamics give rise to a distortion of pulse shapes, and nonsymmetrical gain profiles lead to an unequal gain of each channel. SOAs themselves have relatively high noise figure (6∼8 dB). These inferior characteristics of SOAs can be improved using discrete Raman amplification (DRA) at dispersion compensating fiber (DCF) in the links.

Fiber Raman amplifiers can be used for improving optical signal-to-noise ratio (OSNR) and extending gain bandwidth [6]. Because WDM signals propagating a fiber experience gain tilts due to the energy transfer to longer wavelengths, the Raman process also can be used to compensate gain tilts in transmission links based on SOAs. The compensation amount of gain tilts can be adjusted by changing the Raman pumping power and wavelength. In WDM transmissions, the Raman stage can be easily implemented by inserting an appropriate pump laser diode to the DCF module placed at each span.

In our previous work [7], we theoretically reported the transmission performance of WDM signals in cascaded conventional SOAs. In this paper, we extend the work to equalize the gain of each channel and improve the noise figure using DRA. We numerically solve steady-state coupled Raman equations for the backward pumping for the single-mode fiber (SMF) + DCF configuration. Then, we calculate the transmission performance of 8 × 10-Gb/s WDM signals displaced the wavelengths of 30 and 50 nm from the gain peak of SOAs using cascaded SOAs up to 6 × 40-km SMF + DCF with a backward Raman pumping. At each span, we adjust the backward pump power and wavelength to achieve gain equalization and a low effective noise figure.

The rest of this paper is organized as follows. In Section II, we theoretically describe the numerical model of Raman amplifications. Section III shows the transmission performance of 8 × 10-Gb/s WDM signals with and without optimized Raman pumping for different wavelength displacements. For the best gain flatness and noise figure, optimum backward pumping conditions are obtained at each span. Finally, conclusions are given in Section IV.

II. Gain Equalization Using Raman Amplifier

We used the modified transfer matrix method (TMM) based on a dynamic SOA model [8] to calculate amplified optical pulse waveforms and chirping in SOAs by solving the pulse propagation equations and rate equation. Amplified spontaneous emission (ASE) noise power was obtained from [9], and the longitudinal variation of the α-parameter was considered in our simulation. However, we did not consider nonlinear effects such as the four-wave mixing (FWM) effect in SOAs, since there were negligible increases in the links [2].

The Raman amplifier model was included in the wavelength-dependent fiber attenuation, Rayleigh backscattering, stimulated Raman scattering with forward and backward propagating signals, spontaneous Raman scattering from forward and backward propagating signals [10] as in

$$\frac{dP_i^+}{dz} = -\alpha_i P_i^+ + \eta_i P_i^- + \sum_{j\neq i} g_{ij} \left[P_j^+ + P_j^-\right] P_i^+ \quad (1)$$

$$\frac{dP_i^-}{dz} = +\alpha_i P_i^- - \eta_i P_i^+ - \sum_{j\neq i} g_{ij} \left[P_j^+ + P_j^-\right] P_i^- \quad (2)$$

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TABLE I
MATERIAL PARAMETERS OF FIBER USED IN THE SIMULATION

	SMF	DCF
Attenuation (dB/km)	0.22	0.59
Dispersion (ps/nm·km)	17	-86.59
Dispersion slope (ps/nm^2·km)	0.05936	-0.135
Nonlinear index (m^2/W)	1.3×10^{-20}	2.69×10^{-20}
Effective core area (μ m^2)	78	35
Peak Raman gain (m/W)	0.5×10^{-13}	2.0×10^{-13}

$$\frac{dN_i^+}{dz} = -\alpha_i N_i^+ + \eta_i N_i^- + \sum_{j\neq i} g_{ij}\left[P_j^+ + P_j^-\right] N_i^+ + \sum_{j\neq i} g_{ij} n_{ij}\left[P_j^+ + P_j^-\right] \tag{3}$$

$$\frac{dN_i^-}{dz} = +\alpha_i N_i^- - \eta_i N_i^+ - \sum_{j\neq i} g_{ij}\left[P_j^+ + P_j^-\right] N_i^- - \sum_{j\neq i} g_{ij} n_{ij}\left[P_j^+ + P_j^-\right] \tag{4}$$

where P_i^+, P_i^-, N_i^+, N_i^-, α_i, and η_i are forward propagating signal power, backward propagating signal power, forward propagating noise power, backward propagating noise power, attenuation coefficient, and Rayleigh backscattering coefficient at the frequency i, respectively. g_{ij} is the Raman gain coefficient as a function of frequency shift. The Raman gain coefficient and attenuation coefficient (fiber loss) as a function of frequency were used for the experimentally measured data [11]. For all other frequencies j, g_{ij} can be obtained using the proportional relationship of pump frequency. n_{ij} is the noise factor [12] that considers the spectral properties of the spontaneous Raman scattering, and its temperature dependence can be expressed by

$$n_{ij} = n(f_j, f_i) = hf_i\delta f\left(1 + \frac{1}{\exp\left(h(f_j - f_i)/(kT)\right) - 1}\right) \tag{5}$$

where f_i is the signal frequency, f_j is the scattered wave frequency, h is Planck's constant, k is Boltzmann's constant, δf is the frequency resolution, and T is the fiber temperature.

We performed iterative calculations numerically to solve the coupled wave equations with the two-point boundary problem for signal power and noise power. After power analysis for forward signals and a backward pump was done, we solved the nonlinear Schrödinger equation with the split-step Fourier method [13] to consider dispersion and nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), and FWM in optical fibers. For solving the nonlinear Schrödinger equation, we also used the fixed power profiles calculated from the coupled wave equations. Relevant material parameters of fiber are given in Table I.

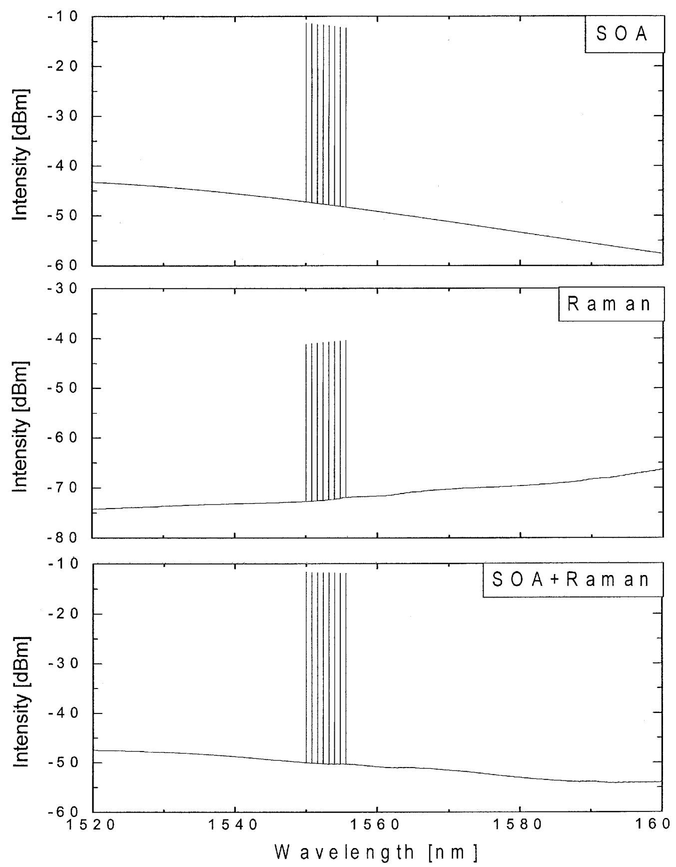

Fig. 1. Amplifier output spectra calculated from SOA, Raman amplifier, and SOA + Raman amplifier.

Fig. 1 shows amplifier output spectra calculated from each SOA, DRA, and SOA followed by DRA. Shorter wavelength channels transfer energy to the longer wavelength channels in DRA used 7.9-km DCF with the pump laser power of 150 mW at 1480 nm. The Stokes' shifts do not exist at about 13 THz where the peak exists in the Raman gain coefficient because it is not necessary for the Raman stage to amplify WDM channels. The spectrum from SOA + DRA shows that the Raman effects compensate gain tilts due to the SOA gain profile decreasing to the

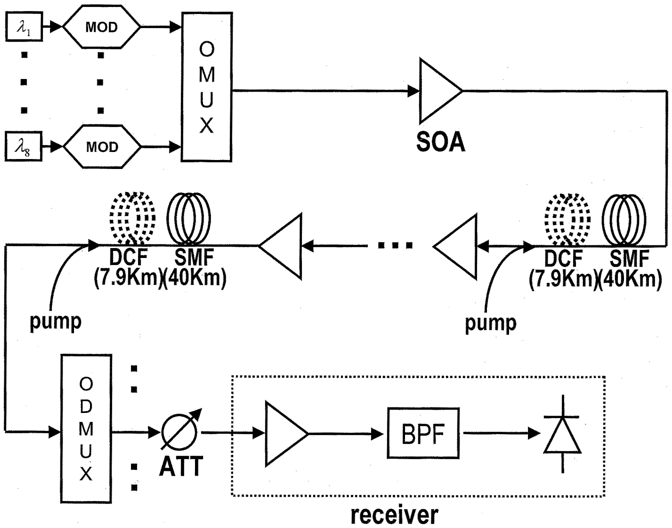

Fig. 2. 8 × 10-Gb/s transmission configuration using SOA + Raman amplification.

longer wavelength channels. The ASE noise power decreases about 5 dB compared with that of SOAs. The use of DRA gives rise to lower the noise figure and can enhance the transmission length. In addition, it is possible for DRA to use DCF as a gain medium to compensate for the chromatic dispersion from optical fiber transmissions.

III. Simulation Results and Discussions

We theoretically investigated 8 × 10-Gb/s WDM transmission characteristics using our developed simulation tools. After the SMF 40-km transmission using an SOA as booster amplifiers, a backward propagating pump laser diode is placed in a 7.9-km DCF that compensates both chromatic dispersion and gain tilt, as shown in Fig. 2. Eight distributed feedback (DFB) lasers in wavelengths from 1550 to 1556.4 nm with 100-GHz spacing were externally modulated by 10-Gb/s $LiNbO_3$ modulators with a nonreturn-to-zero (NRZ) bit stream of 2^7 length. Each channel had a 5-bit delay to decorrelate the bit pattern. The SOA used in this simulation has a gain peak at 1520 nm and an isolator at input and output stages. One span loss is about 13 dB, and this is compensated by the following SOAs. We used variable attenuators to make the input power of each SOA be −15 dBm per channel and fiber launching power be −2 dBm per channel. After the demultiplexer, the received power of each channel was the same to each other. At each span, the power and wavelength of the Raman pump were adjusted to achieve gain flatness and low noise figure. Gain flatness was able to adjust within 0.5 dB. The double Rayleigh backscattering in the Raman process was neglected due to the low Raman ON–OFF gain, and the parallel polarization states of each channel were assumed.

The receiver consisted of an optical preamplifier, a bandpass filter, and a pin photodiode. Bit error rate (BER) characteristics for each data bit were calculated including intersymbol interference (ISI), thermal noise, shot noise, signal–spontaneous beat noise, and spontaneous–spontaneous beat noise [13].

Fig. 3 shows received eye diagrams for the first channel after 6 × 40-km transmission based on SOAs using DRAs. The wavelength of 8-channel WDM signals were displaced at 30 and 50 nm from the fixed gain peak wavelength of SOAs. The pump laser had the output power of 250 mW with 1500-nm operating wavelength at each DCF. The Rayleigh backscattering coefficient of DCF was assumed to be −27 dB/km. As we expected, small wavelength displacement induces large amounts of crosstalk to signals from gain variations due to fast gain dynamics [14]. Rayleigh backscattered waves from a backward propagating pump at DCF, caused by refractive index variations due to random inhomogeneities during fiber manufacturing, also play a role in crosstalk to signals. Changing of the gain peak wavelength can mitigate crosstalk components from wavelength displacement. Rayleigh backscattered waves cannot be reduced due to their inherent characteristics. At the output of each DCF, Rayleigh backscattered pump power can be

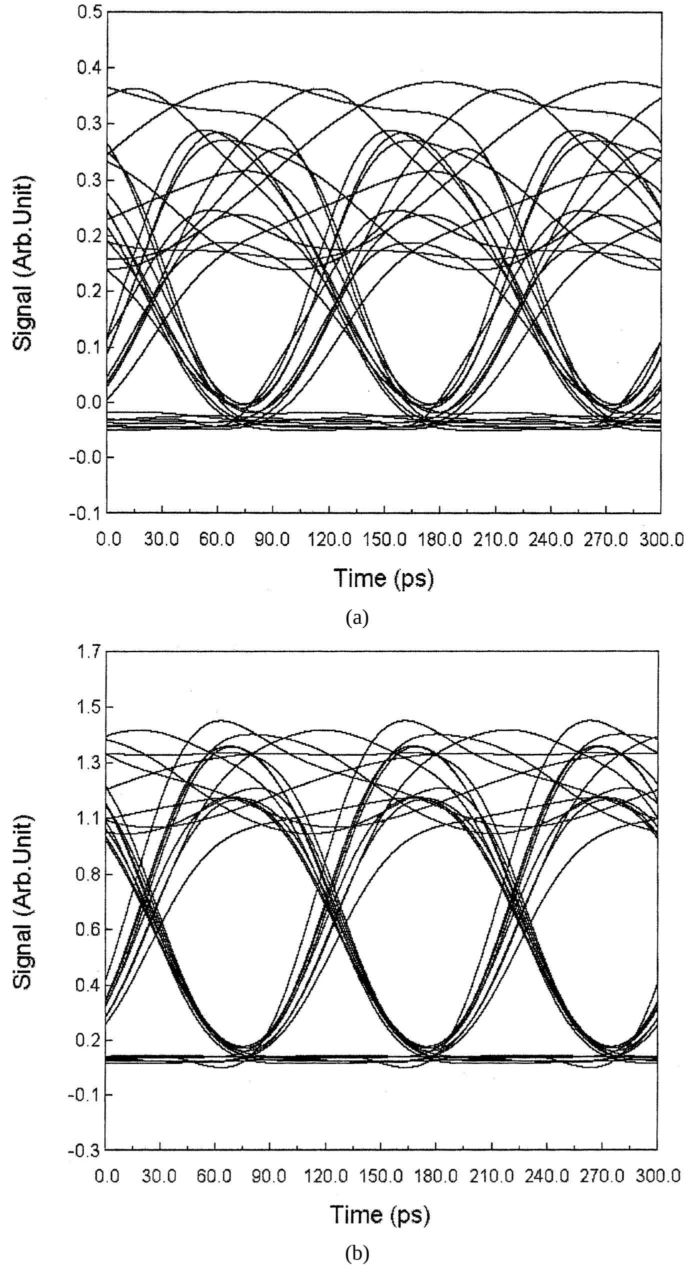

Fig. 3. Eye diagrams after 6 × 40-km transmission using SOA + Raman amplification: (a) 30- and (b) 50-nm wavelength displacement.

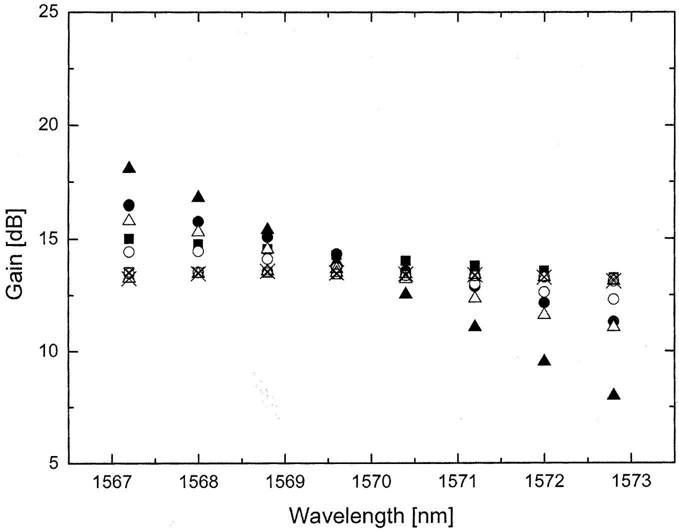

Fig. 4. Gain for SOA (closed symbols), SOA + Raman without optimization (open symbols), and SOA + Raman with optimization (open × symbols). Rectangles, circles, and triangles represent the calculated gains for the 1, 3, and 6 spans, respectively.

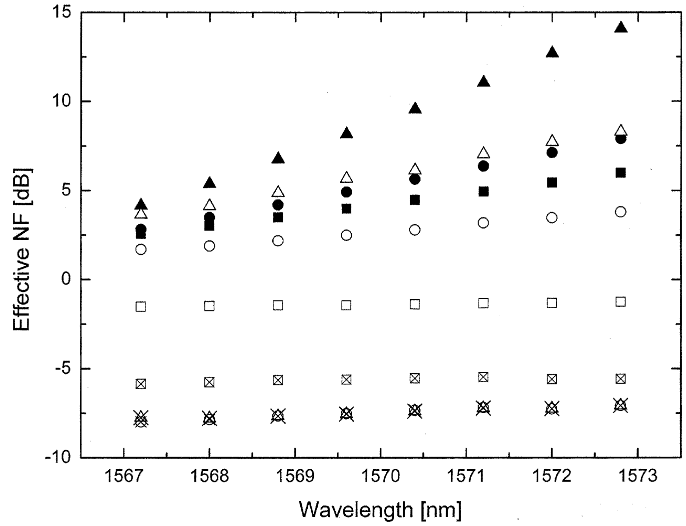

Fig. 5. Effective noise figure for SOA (closed symbols), SOA + Raman without optimization (open symbols), and SOA + Raman with optimization (open × symbols). Rectangles, circles, and triangles represent the calculated noise figures for the 1, 3, and 6 spans, respectively.

a reservoir channel for SOAs of the next span. These Rayliegh backscattered pump waves were removed from isolators.

Because the Raman gain does not perfectly compensate negative gain tilts at the 50-nm wavelength displacement from the SOA gain peak, it needs to optimize the power and wavelength of the pump laser at each span. According to the Raman gain dependence to the pump power [15], we first increased the power of each pump laser lasing at 1480 nm to achieve gain flatness. We could achieve optimum pump powers for the gain flatness at each span and the effective noise figure of 5 dB. However, the effective noise figure also must be minimized at the same time to achieve high transmission performance. After optimizing the gain flatness with changing pump powers, we then changed the pump wavelength to improve the effective noise figure. The 1480- and 1500-nm pump wavelengths were found to be effective in improving the effective noise figure for 30- and 50-nm wavelength displaced WDM signals, respectively.

The increase in the number of cascaded SOAs without DRAs pushes up negative gain tilts (closed symbols) as shown in Fig. 4. The use of the same pump power of 250 mW at each span without optimization reduces gain tilts (open symbols) from 10 to 5 dB after six span transmissions. Moreover, the adjustment of 250, 280, 290, 300, 300, and 300 mW for each pump power at each stage with optimization obtained gain tilts (open × symbols) smaller than 0.5 dB, even though WDM channels transmitted six spans using SOAs. Fig. 5 shows the calculated effective noise figures for cascaded SOAs without DRAs, SOAs + DRAs without optimization, and SOAs + DRAs with optimization. The effective noise figure was calculated by subtracting the output OSNR of DRAs from the input OSNR of SOAs within a span. Therefore, we could obtain a negative effective noise figure. With optimization of Raman pumping power and wavelength, the effective noise figure also remains a negative value in the decibel scale as the span length increases.

We examined the transmission performance of 8 × 10-Gb/s WDM signals over 3 × 40 km for 30- and 50-nm wavelength displacement from SOAs with and without optimized Raman pumping conditions to gain flatness and improved effective

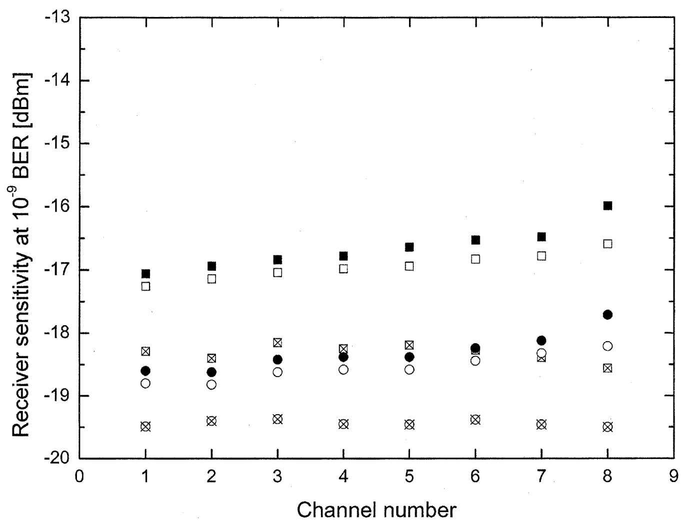

Fig. 6. Receiver sensitivities for 3 × 40 km using SOA (closed symbols), SOA + Raman without optimization (open symbols), and SOA + Raman with optimization (open × symbols). Rectangles and circles represent receiver sensitivities for 30- and 50-nm wavelength displacement, respectively.

noise figure. Fig. 6 shows the receiver sensitivities at 10^{-9} BER for each channel after 3 × 40-km transmissions. The larger wavelength displacement from the SOA gain peak brings better transmission performance, as expected. The signal-to-signal crosstalk components from wavelength displacement did not exist in the Raman process because the coupled Raman equations were solved in the steady state. Up to three spans, gain tilts are negligible for both links using SOAs and SOAs + DRAs without optimization. When the optimizations of Raman pumping are applied to each span, the receiver sensitivities remarkably improve due to the improvement of the effective noise figure.

The receiver sensitivities at 10^{-9} BER of 8 × 10-Gb/s WDM signals transmitted after 6 × 40 km are shown in Fig. 7. The signals were displaced 30 and 50 nm from the SOAs gain peak with and without optimized Raman pumping conditions to gain flatness and improved effective noise figure. The deteriorated receiver sensitivities are improved by using DRAs at each

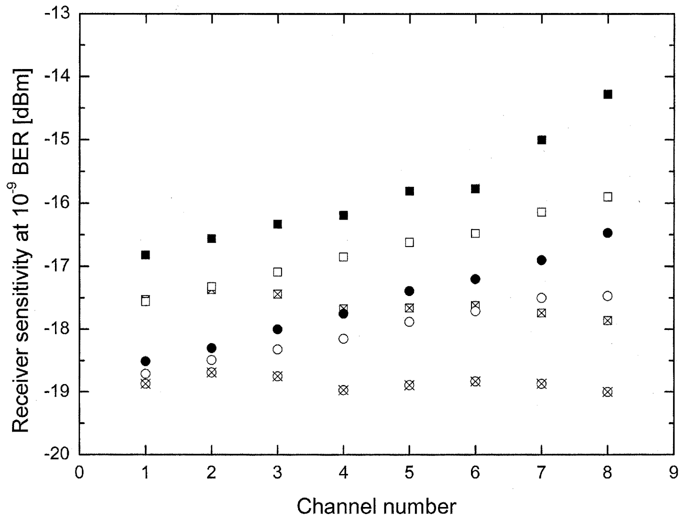

Fig. 7. Receiver sensitivities for 6 × 40 km using SOA (closed symbols), SOA + Raman without optimization (open symbols), and SOA + Raman with optimization (open × symbols). Rectangles and circles represent receiver sensitivities for 30- and 50-nm wavelength displacement, respectively.

span. Because the nonoptimized Raman pumping did not fully compensate the negative gain tilt from SOAs, there were degradations of transmission characteristics at longer wavelength channels, and accumulated noises dominantly influence the transmission performance. If the Raman pumping conditions for gain flatness and improved effective noise figure are used in DCF so that the reference wavelength exists in the center wavelength of WDM signals, only residual dispersions affect the transmission performance of each channel. Accumulated crosstalk components induced from Rayleigh backscattered waves also degrade the pulse shape. In the case of 50-nm wavelength displacement from SOAs over 6 × 40-km transmission, the receiver sensitivities of the last channel for SOAs + DRAs with optimized Raman pumping improved about 2.5 dB than that for SOAs without DRAs.

IV. Conclusion

We investigated the transmission performance of WDM signals using SOAs and Raman amplification at DCFs with a backward propagating pump. The numerical model of the Raman amplifier was made by calculating the steady-state coupled Raman equations with the iteration method. Using developed simulation models, the gain equalization was obtained by adjusting the Raman pumping power, and the effective noise figure was then improved changing the Raman pumping wavelength. Because the gain flatness and the minimum effective noise figure did not exist at the same time, we optimized pump power for gain flatness and wavelength for improved effective noise figure. With and without optimized conditions of the Raman pumping, we obtained the receiver sensitivities at 10^{-9} BER of 8 × 10 Gb/s differently than wavelength displaced WDM signals transmitted after 3 × 40 km and 6 × 40 km. With optimization of Raman pumping power and wavelength, we obtained better transmission performance about 2.5 dB of the receiver sensitivity than that of only SOAs without DRAs over a 6 × 40-km link. These results propose that one can easily upgrade the transmission length of the link based on SOAs by using an appropriate backward propagating pump at each DCF.

References

[1] H. K. Kim, S. Chandrasekhar, A. Srivastava, C. A. Burrus, and L. Buhl, "10Gbit/s based WDM signal transmission over 500km of NZDSF using semiconductor optical amplifier as the in-line amplifier," *Electron. Lett.*, vol. 37, pp. 185–187, Feb. 2001.

[2] L. H. Spiekman, J. M. Wiesenfeld, A. H. Gnauck, L. D. Garrett, G. N. Van Den Hoven, T. Van Dongen, M. J. H. Sander-Jochem, and J. J. M. Binsma, "Transmission of 8 DWDM channels at 20 Gb/s over 160 km of standard fiber using a cascade of semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 717–719, June 2000.

[3] E. S. Bjorlin, J. Geske, and J. E. Bowers, "Optically preamplified receiver at 10 Gbit/s using vertical-cavity SOA," *Electron. Lett.*, pp. 1474–1475, Nov. 2001.

[4] C. Schubert, J. Berger, S. Diez, H. J. Ehrke, R. Ludwig, U. Feiste, C. Schmidt, H. G. Weber, G. Toptchiyski, S. Randel, and K. Petermann, "Comparison of interferometric all-optical switches for demultiplexing applications in high-speed OTDM systems," *J. Lightwave Technol.*, vol. 20, pp. 618–624, Apr. 2002.

[5] T. Akiyama, H. Kuwatsuka, T. Simoyama, A. Sugawara, and H. Ishikawa, "Design optimization of SOA-integrated DFB laser wavelength converter," *Electron. Lett.*, vol. 38, pp. 239–241, Feb. 2002.

[6] M. N. Islam, "Raman amplifiers for telecommunications," *IEEE J. Select. Topics Quantum Electron.*, vol. 8, pp. 548–559, May/June 2002.

[7] W. Choi, S. Hur, J. Lee, Y. Kim, and J. Jeong, "Transmission performance analysis of 8 × 10 Gbps WDM signals using cascaded SOA's due to signal wavelength displacement," *J. Lightwave Technol.*, vol. 20, pp. 1350–1356, Aug. 2002.

[8] H. Lee, H. Yoon, Y. Kim, and J. Jeong, "Theoretical study of frequency chirping and extinction ratio of wavelength-converted optical signals by XGM and XPM using SOAs," *IEEE J. Quantum Electron.*, vol. 35, pp. 1213–1219, Aug. 1999.

[9] M. A. Summerfield and R. S. Tucker, "Frequency-domain model of multiwave mixing in bulk semiconductor optical amplifiers," *IEEE J. Select. Topics Quantum Electron.*, vol. 5, pp. 839–850, May/June 1993.

[10] J. Ko, S. Kim, J. Lee, S. Won, and J. Jeong, "Estimation of performance degradation of bidirectional WDM transmission systems due to Rayleigh backscattering and ASE noises using numerical and analytical models," *J. Lightwave Technol.*, vol. 21, pp. 938–946, Apr. 2003.

[11] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995.

[12] H. Kidorf, K. Rottwitt, M. Nissov, M. Ma, and E. Rabarijaona, "Pump interactions in a 100-nm bandwidth Raman amplifier," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 530–532, May 1999.

[13] S. K. Kim, O. Mizuhara, Y. K. Park, L. D. Tzeng, Y. S. Kim, and J. Jeong, "Theoretical and experimental study of 10Gbps transmission over 100km standard fiber using 1.55um $LiNbO_3$-based transmitters with adjustable extinction ratio and chirp," *J. Lightwave Technol.*, vol. 17, pp. 1320–1325, 1999.

[14] K. Inoue, "Crosstalk and its power penalty in multichannel transmission due to gain saturation in a semiconductor laser amplifier," *J. Lightwave Technol.*, vol. 7, pp. 1118–1124, July 1999.

[15] C. R. S. Fludger, V. Handerek, and R. J. Mears, "Ultra-wide bandwidth Raman amplifiers," in *Tech. Dig. Optical Fiber Communications Conf.*, 2002, Paper TuJ3, pp. 60–62.

Sub Hur, photograph and biography not available at the time of publication.

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