Dispersion compensation of wavelength-division multiplexed signals using waveband shift-free optical phase conjugators

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Abstract: Dispersion compensation performance of a waveband-shift-free optical phase conjugator (WBSF-OPC) on multi-span transmission of 20-Gbit/s quadrature phase-shift keying × 3-ch. WDM signals is numerically investigated. Provided that linear distortion owing to chromatic dispersion is considered, the middle channel of the WDM signals is perfectly compensated by WBSF-OPCs. Further, it is shown that the 3-channel WDM signals with a 2.2-THz optical frequency interval can be transmitted via a 640-km transmission fiber owing to the WBSF-OPCs, although their signal qualities degrade owing to residual dispersion.

Keywords: Optical phase conjugation, Chromatic dispersion compensation, Wavelength-division multiplexed signal transmission, Spectral efficiency, Optical signal processing

Classification: Fiber-optic transmission for communications

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1 Introduction

The optical phase conjugation (OPC) technique proposed in 1979 [1] has recently received attention because of its potential for optical linear and nonlinear distortion compensation. An OPC device is in the middle of a transmission fiber, and it generates a phase conjugated (PC) signal from an incoming optical signal distorted by the first half of the transmission fiber. The PC signal involves the inverse distortion of the incoming optical signal and is transmitted through the second half of the transmission fiber. The signal distortion is optically canceled out via the transmission and finally compensated, i.e., the OPC optically enables back-propagation. This contributes to the reduction in power consumption and latency in receiver-side digital signal processing (DSP) for the distortion compensation owing to the reduction in the calculation amount. However, conventional OPCs halve the spectral efficiency because the wavelength of the PC signals is shifted from that of the original signals, and a guard band is necessary for the generated PC signals. To address this challenge, several types of the waveband shift-free OPCs (WBSF-OPCs) have been proposed and studied [2–5]. The WBSF-OPCs can implement the spectral inversion of incoming wavelength-division multiplexed (WDM) signals without the guard band because spectral inversion is performed around the center optical frequency of the WDM signals. To the author’s knowledge, most studies on WBSF-OPCs have focused on optical nonlinear distortion compensation and employed chromatic dispersion (CD) compensation fibers. The question remains unanswered whether the WBSF-OPCs compensate for optical signal distortion due to CD, because the phase rotations from the CD are different before and after the WBSF-OPCs, excluding the center channel of the WDM signals.

In this study, the dispersion compensation of WDM signals by WBSF-OPCs is numerically investigated. The multi-relay transmission of 20-Gbit/s quadrature phase-shift keying (QPSK) × 3-ch. WDM signals with WBSF-OPCs is simulated. In addition, the received signals are evaluated using the eye-opening ratio. Finally, the transmittable distance of QPSK × 3-ch. WDM signals is numerically clarified.

2 Numerical simulations

2.1 Simulation model of multi-relay transmission with WBSF-OPCs
Figure 1 presents the simulation model of multi-relay transmission systems with WBSF-OPC, which comprises the transmitter, optical transmission, and receiver sections. In the transmitter, 20-Gbit/s quadrature phase-shift keying (QPSK) × 3-ch. WDM signals with an optical frequency interval \( \Delta \nu \) are generated. The optical frequency of the middle channel (M-ch.) \( \nu_M = 193.4 \text{ THz} \), while the low/high channels (L/H-ch.) are located at \( \nu_M - \Delta \nu \) and \( \nu_M + \Delta \nu \), respectively. The beams from laser diodes (LDs) in each transmitter are QPSK-modulated where phase noises in the LDs are ignored to evaluate waveform degradation owing to CD. Further, the QPSK-modulated signals are multiplexed, and the generated WDM signals are launched into the optical transmission section with 0-dBm optical power per channel. The optical transmission section comprises four transmission spans where one span includes an optical fiber and amplifier repeater, and the WBSF-OPC is placed at the middle point of the transmission spans. All fibers in transmission spans employ the following parameters: Fiber length \( L = 80 \text{ km} \), loss coefficient \( \alpha = 0.2 \text{ dB/km} \), dispersion \( D \) at \( \nu_M = 15 \text{ ps/nm/km} \), and dispersion slope \( D_s = 0.06 \text{ ps/nm}^2/\text{km} \). Amplifier repeaters achieve linear optical amplification with 0-dB noise figure. The nonlinear coefficient is \( \gamma = 0 \text{ /W/km} \) because this study focuses on waveform degradation due to CD. By solving the propagation equation, (the nonlinear Schrödinger equation when \( \gamma = 0 \text{ /W/km} \)), via the split-step Fourier method, the signal propagation in such fibers is calculated. The WDM signals are transmitted through the first half of the transmission spans and are distorted owing to the CD. The distorted WDM signals are input to the WBSF-OPC and the phase-conjugated (PC) signals, in which the spectra of L- and H-ch. were swapped as shown in the inset of Fig.1, are generated. The operation optical frequency of the WBSF-OPC is equal to the center optical frequency of the M-ch. signals, and the calculation of the WBSF-OPC is simply implemented by taking the complex conjugate of the electric field of the distorted WDM signals. The PC signals are transmitted through the second half, and the waveform degradation owing to CD emerging from the first half is compensated in the optical domain. This section is iterated by \( N = 1, 2, 3, \ldots \) times. Subsequently, the output signals of the \( N \)th transmission are launched into the receiver section. Every channel of the PC signal is detected by a coherent receiver. To focus on the CD compensation performance of the WBSF-OPC, digital CD compensation is not adopted, and the phase noise of the optical local oscillator, shot, and thermal noises in the coherent receiver are not considered. The detected signals are evaluated by the eye-opening ratio EOR to measure the degree of signal degradation. As shown in the eye pattern of Fig. 1,
EOR = $O_{\text{inner}}/O_{\text{outer}}$, where $O_{\text{inner}}$ and $O_{\text{outer}}$ are the inner and outer amplitudes, respectively.

### 2.2 Waveform degradation due to residual dispersion

Figure 2 presents the eye-opening ratio of each channel as a function of transmission distance, and the cases of $\Delta \nu = 200, 400, 800, 1200, 1600, \text{ and } 2000$ GHz are depicted. The case of without WBSF-OPCs is also plotted with a triangle marker in the upper left of Fig. 2 for comparison. It is evident from the upper left of Fig. 2 that WBSF-OPCs are effective for the CD compensation without DSP calculations. Regarding M-ch. signals, because the phase rotations due to CD from the first and second halves of the transmission spans are completely canceled out by each other; therefore, waveform degradation cannot be confirmed. Optical frequencies of the M-ch. signals, and its PC signals are equal to $\nu_M$, and the M-ch. signal after the first half, and its PC signals before the second half have $2\beta(\nu_M)L$ and $-2\beta(\nu_M)L$, respectively. Subsequently, the PC signals transmitted and phase-rotated by $+2\beta(\nu_M)L$. Accordingly, $2\beta(\nu_M)L-2\beta(\nu_M)L=0$, and the waveform degradation due to CD is perfectly compensated through the transmission of PC signals generated by the WBSF-OPC. Meanwhile, regarding L and H-ch., the EOR values linearly decrease as the transmission distance increases, owing to the residual dispersion originating from the first and second halves of the transmission span. Specifically, $2\beta(\nu_L)|L \neq 2\beta(\nu_H)|L$; therefore, $2\beta(\nu_L)-\beta(\nu_H)|L \neq 0$. This indicates that the degrees of the L and H-ch. signal degradation owing to the residual dispersion is identical as presented in Fig. 2, and EOR degrades as $\Delta \nu$ increases.
2.3 Transmittable distance on multi-relay systems with WBSF-OPCs

Transmittable distances of 20-Gbit/s QPSK × 3-ch. WDM signals on multi-relay systems with WBSF-OPCs were calculated and evaluated for L and H-ch. We

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**Fig. 2.** Eye opening ratio of received signals EOR as a function of transmission distance. Red, blue, and green dots indicate the L, H, and M-ch. cases, respectively. Optical frequency interval $\Delta \nu$ is altered and ranges from 200 GHz to 2000 GHz.

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**Fig. 3.** Transmittable distance of L- and H-ch. signals as a function of frequency interval $\Delta \nu$. Red and blue curves show the L- and H-ch. cases, respectively.
defined the transmittable distance $L_{\text{max}} = 4LN_{\text{max}}$, where $N_{\text{max}}$ is the maximum number of the optical transmission section satisfying $50\%$ EOR, and the transmittable distance as a function of frequency interval $\Delta \nu$ is presented in Fig. 3. The curves of L and H-ch. shown in Fig. 3 are overlapped, and the transmittable distance $L_{\text{max}}$ monotonically decreased as the frequency interval $\Delta \nu$ increased because of the residual dispersion. Figure 3 is also construed as the wavelength range in which 20-Gbit/s QPSK signals can be transmitted without the digital CD compensation with the assumption that tolerable EOR penalty is $50\%$. The doubled frequency interval $2\Delta \nu$ roughly interpreted as the wavelength range and increases sharply with decrease in the transmission distance. The results indicate that the WBSF-OPCs enable at least 640-km multi-relay transmission of 20-Gbit/s QPSK $\times$ 3-WDM signals without the digital CD compensation on noiseless and linear conditions and would contribute to implementing the low-latency optical networks by reducing the DSP calculations. For further extension of the transmission distance, the combination use of dispersion compensating fibers would be effective. WBSF-OPC-based multi-relay optical transmission systems in realistic conditions considering the optical noise and the optical Kerr effect should be investigated further, and the calculation cost of DSP on the systems should be quantitatively evaluated.

3 Conclusion
In this study, the CD compensation performance of WBSF-OPCs in multi-relay optical transmission systems was numerically investigated, and 20-Gbit/s QPSK $\times$ 3-ch. WDM signals were evaluated. The EOR penalty of received M-ch. signals was not confirmed because the WBSF-OPCs achieved perfect compensation of the CD on the M-ch. whose optical frequency was identified with the operation center optical frequency of the WBSF-OPCs. This indicated the WBSF-OPCs would be useful in the single carrier with high-baud rate systems because phase rotations due to CD are perfectly compensated when the center optical frequency of the WBSF-OPCs is equal to the optical carrier frequency. In the cases of L- and H-ch. signals with $\Delta \nu = 2.2\text{ THz}$ optical frequency interval, corresponding to the range of C-band, 640-km multi-relay transmission was successfully achieved by the WBSF-OPCs, although their EOR values decreased because of the residual dispersion. The case in which the nonlinearity of the transmission fiber is considered needs to be studied. This study dealt point-to-point optical transmission systems, and WBSF-OPCs had to be positioned at the middle of transmission fiber to receive the maximum benefits of OPCs, namely compensation of dispersion and optical nonlinear distortion. However, it seems difficult to apply the OPCs to flexible optical networks, and this should be studied further.

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