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Limiting-amplified multiwavelength dispersion compensator incorporating chirped fiber gratings and optical amplifier for DWDM systems

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Abstract

An optical limiting-amplified multiwavelength dispersion compensator (LDC), incorporating multiple chirped fiber gratings and a common bidirectional erbium-doped fiber amplifier, for dense wavelength-division-multiplexing (DWDM) systems is proposed and demonstrated. The LDC provides simultaneous dispersion compensation and limiting amplification of multiple DWDM signals. A high constant channel output power of 16.4 dBm and a low power penalty of less than 0.3 dB over an input signal dynamic range of -17 to 0 dBm can be obtained for this LDC in a 10 Gb/s two-wavelength 80-km conventional single-mode fiber system. The LDC may facilitate easier DWDM system design flexibility and network implementation. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

Dispersion compensating techniques are important for high bit-rate transmission over long-distance conventional single-mode fiber (SMF) links. Addition of dispersion compensating fiber (DCF) [1,2], providing a large chromatic dispersion of opposite sign, in the 1.55-μm SMF span link is capable of compensating the SMF group velocity dispersion. However, utilization of DCFs as dispersion compensators (DCs) suffers from several problems such as long DCF length (several km long, about 1/4 of the SMF span length), relatively high fiber loss ($\alpha \sim 0.5$ dB/km), and enhanced nonlinear effects because of a relatively small mode diameter. On the other hand, chirped fiber grating (CFG) [3,4] is a promising option as a DC because it is compact, passive, simple to fabricate, low-loss, and can provide large differential group delay. In recent years, progress in the use of CFG-based compensation for ≥ 10 Gb/s transmissions has been rapid [5–7]. Because the compensated signal is back-reflected, an optical circulator (OC) is commonly required to separate the output from the input of the device. For CFG-compensated systems reported to date, the erbium-doped fiber amplifier (EDFA) used for compensating the span loss is always located in front of the OC and CFG. However, the insertion losses of both OC and CFG attenuate the compensated signal and thus result in a reduced system power budget and span link length.

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In this paper, we propose and demonstrate a high-power limiting-amplified multiwavelength DC for dense wavelength division multiplexing (DWDM) systems by placing a bidirectional EDFA sandwiched between the OC and multiple CFGs. Such an arrangement not only carries out dispersion compensation of the preceding SMF span, but also offers a high constant channel output power within a large input signal dynamic range to compensate link attenuation of the followed SMF span. The output power and dynamic range, as well as power penalty induced by this LDC, are investigated and also compared with the conventional configuration. The features and applications of the proposed LDC are also addressed.

2. Dispersion compensator configurations and experimental setup

The proposed limiting-amplified dispersion compensator (LDC), the conventional dispersion compensator (CDC) scheme, and experimental setup are shown in Fig. 1. For CDC, a dual-pumped conventional EDFA (C-EDFA) is used and followed with an OC, multiple CFGs, and an optical isolator (ISO). In contrast, for an LDC, a bidirectional EDFA (B-EDFA, because no built-in optical isolators are used) is inserted between the OC and multiple CFGs. The B-EDFA, employing bi-directionally dual-pumped scheme, consists of two 980-nm pump lasers, two 980/1550-nm WDM couplers, and a piece of EDF. Each pump laser has an output power of 120 mW. The EDF (Highwave Technology 741 type) with an optimal length of 15 m is used. The output powers of both C-EDFA and B-EDFA are the same, about 19.6 dBm. In the experiments, two apodized CFGs (CFG1 and CFG2) are used. The center wavelength and reflectivity of the CFG1 and CFG2 are 1552.52 nm, 67%, and 1550.92 nm, 87%, respectively. Fig. 2 illustrates the spectral reflectivity and group time delay characteristics of the 1552.52-nm apodized CFG. The 1552.52-nm CFG, providing a dispersion of about −1480 ps/nm, has a 3-dB bandwidth of 0.5 nm. The grating should thus be able to compensate for 87 km of the conventional SMF. The 3-dB bandwidth and dispersion of the 1550.92-nm CFG are almost the same as that of the 1552.52-nm CFG. The total insertion losses of the OC with CFG1, and the OC with CFG2 are 5.6 and 4.5 dB, respectively.

At the transmitter site, the CW output of each DFB laser (1550.92 and 1552.50 nm) is externally

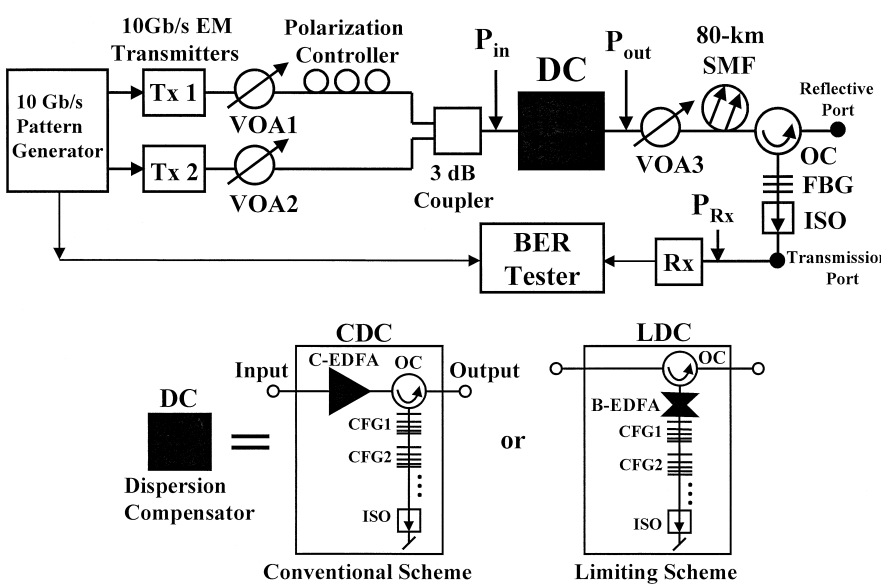

Fig. 1. The proposed limiting-amplified dispersion compensator (LDC), a conventional amplified dispersion compensator (CDC), and the experimental setup.

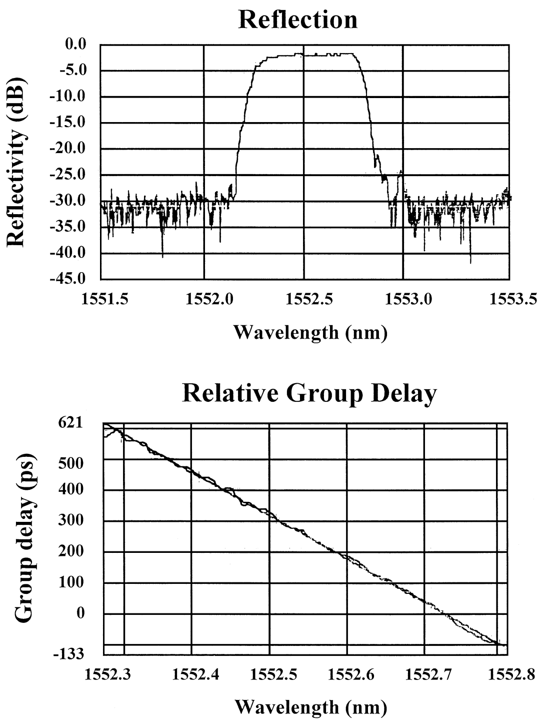

Fig. 2. Spectral reflectivity and group time delay characteristics of the 1552.52-nm apodized chirped fiber grating.

modulated at 10 Gb/s by a $LiNbO_3$ intensity modulator. The modulating data is an NRZ pseudorandom bit sequence with a length of $2^{23}-1$. The polarization controller is required for this experiment so as to avoid the four-wave mixing (FWM) effect occurring in such a high-power LDC module. However, this FWM effect can be eliminated and thus the polarization controllers can be removed when multiple wavelength signals (e.g., more than four WDM signal wavelengths) are fed into the LDC. The input signal power of each DC, P_{in}, was controlled by the variable optical attenuators (VOA1 and VOA2). The launched signal power into the 80-km link is controlled by the VOA3 therefore the fiber nonlinearities are excluded. The amplified compensated signal output power, P_{out}, is measured at the output port of the DC. At the receiver site, a conventional apodized fiber Bragg grating (FBG) with high reflectivity of $>99\%$ in combination with an OC and an optical isolator (ISO) is used as an optical demultiplexer. The FBG has a center wavelength of 1550.95 nm, a 3-dB bandwidth of 0.8 nm, and an adjacent channel isolation of >30 dB. The 1550.92-nm and 1552.50-nm channels were demultiplexed and detected at the reflective port and the transmission port, respectively. The receiver sensitivity of the PIN receiver, measured by the bit-error-rate (BER) tester, at a BER of 1×10^{-9} was -17 dBm.

3. Experimental results

Fig. 3 shows the compensated-signal output power and noise figure characteristics of LDC and CDC for the 1552.50-nm channel as a function of P_{in}. The noise figure of the CDC is about 4.5–6 dB, although for this 'soft-limiting' CDC, a low channel output power of ≥ 8 dBm is obtained within a 12-dB dynamic range (-17 to -5 dBm), which is defined as the 3-dB output-power compression, because the compensated signal is attenuated by the insertion loss of followed CFG and OC. In contrast, the LDC exhibits the very 'hard limiting' characteristic, and the dynamic range is ≥ 20 dB, namely, from -25 to greater than -5 dBm. Here, the arrangement of B-EDFA in the proposed LDC makes it not only act as a dispersion compensator, but also behave like an optical limiting amplifier [8–10]. The limiting amplification results from both narrowband filtering effect of each CFG and the deep saturation effect of the B-EDFA. The narrowband channel-filtering of each CFG not only selects the channel signal, but also eliminates most of the amplified spontaneous

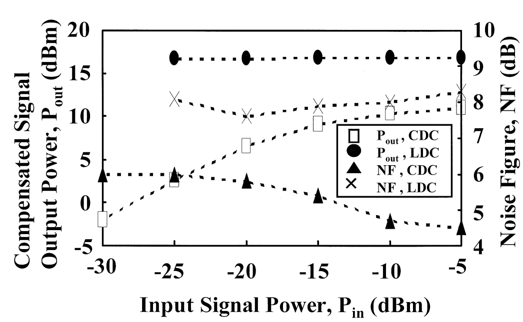

Fig. 3. Output power of the compensated signal, P_{out}, and noise figure characteristics of the proposed LDC and a conventional CDC for the 1552.52-nm channel as a function of the per-channel input signal power, P_{in}.

emission (ASE) noise generated in the first-pass amplification process. Deep saturation of B-EDFA results from the double-pass amplification process, where the large amplified input signal is reflected by the CFG, then launches into the B-EDFA, and therefore forces the amplifier to be deeply saturated. The channel output power is constantly ≥ 16.7 dBm within the >20-dB dynamic range at the expense of high noise figure of about 8 dB, which was measured by using the polarization nulling method [11]. The high noise figure is attributed to: (1) the high signal-spontaneous (s-sp) beat noise resulting from high ASE noise; and (2), the amplifier saturation effect at large input signal power. Similar 'hard-limiting' results with a constant channel output power of 16.3 dBm and a dynamic range of >20 dB can also be obtained for the 1550.92-nm channel. The peak output power difference between these two DWDM channels is only about 0.4 dB, and about 0.6 dB when CFG with a reflectivity of 87% is exchanged in front of another one. The insensitivity of peak power difference against the CFG reflectivities again results from the double-pass amplification of each DWDM channel.

Fig. 4 shows the power penalties of DCs in 80-km DWDM system link for the 1552.50-nm channel at a BER of 1×10^{-9} as a function of P_{in}. Note that power improvement of 0.7 dB, instead of power penalty, occurs when $P_{in}=-5$ dBm for both LDC and CDC cases. This is because each $LiNbO_3$ intensity modulator has a residual blue-shift chirp combining with the larger negative dispersive CFG. However, the power penalty increases to about 1 dB when $P_{in}=-20$ dBm for the LDC case. This is

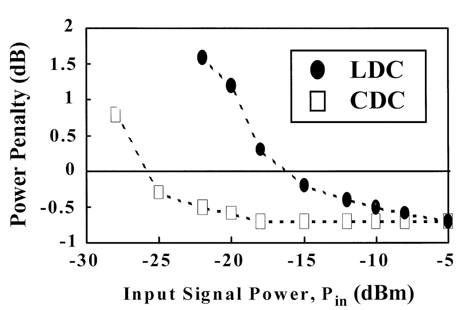

Fig. 4. Power penalty of the LDC and CDC in an 80-km system link for the 1552.50-nm channel at a BER of 10^{-9} as a function of the per-channel input signal power, P_{in}.

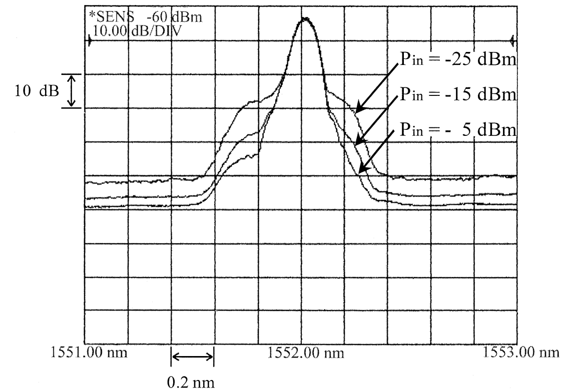

Fig. 5. Optical output spectra of the LDC for the 1552.52-nm channel with an input signal power of -5, -15, and -25 dBm.

mainly due to the worst optical signal-to-noise ratio and the increased s-sp beat noise. The ASE within the stopband of each CFG is detrimentally enhanced by the double-pass amplification process, especially for small P_{in}. The optical output spectra of the LDC at 1552.50 nm, corresponding to $P_{in}=-5$, -15, and -25 dBm, as illustrated in Fig. 5, confirm the power penalty evolution mentioned in Fig. 4. Assuming that the allowable power penalty is 0.3 dB, the minimum P_{in} per DWDM channel launched into the LDC is about -17 dBm, and thus the effective input signal range of the LDC can be from -17 to 0 dBm. Although P_{in} can be as small as -27 dBm for the CDC to keep power penalty to be less than 0.3 dB, the corresponding low output power of $+2$ dBm make it unable to provide sufficient power budget for the followed fiber span. In consequence, the experimental results confirm the feasibility of LDC, because the high ASE power was resulted from the enhancement of double-pass amplification process of the LDC. Thus, the ASE power can be reduced and the noise figure can be improved when multiple WDM channels are fed into the LDC. Therefore, the system power penalty of LDC can be further improved.

4. Discussion

The effect of nonideal dispersion and reflection characteristics of CFGs on the performance of 10 Gb/s nonreturn-to-zero transmission systems over standard fiber have recently been investigated [12]. It was found that for modulation periods (about 100 pm, i.e., 12.5 GHz) greater than the data bandwidth, the ripples had no effect on the eye-open (EO) penalty. In addition, for high frequency modulations (with a 10 pm period of modulation), 10 Gb/s NRZ data was extremely tolerant and peak-to-peak ripple amplitudes up to 1.67 dB in reflectivity and 170 ps in time delay could be tolerated for less than 1-dB EO-penalty, which was required for a good 10 Gb/s system performance. From the spectral reflectivity and time delay characteristics of both CFGs used in this experiment, as illustrated in Fig. 2, the period of ripples is in the range of 10 pm to about 100 pm, which may be due to the CFG imperfect process, and the peak-to-peak ripple amplitudes of the reflectivity and time delay are about 0.9 dB and 50 ps, respectively. Therefore, the nonideal dispersion and reflection characteristics of such 0.5-nm-stop-bandwidth apodized CFGs on the performance of this system are negligible. Furthermore, in this experiment, the interchannel crosstalk and the crosstalk induced by the edge dispersion, which is at frequencies close to but outside the stopband of CFGs, can be neglected due to the high channel isolation of 30 dB and the sharp edge characteristics (i.e., the -30 dB stop bandwidth of only 0.75 nm) of the used CFGs.

There are several advantages of the proposed LDC: (1) high constant channel output power with a large dynamic range; (2) less sensitive to CFG reflectivity and suitable for multiwavelength operation with no power/gain equalization required; (3) easy to design and fabricate the CFGs matching the ITU-T grid wavelengths with desired dispersions; and (4) low loss and potentially low cost. These features imply that the LDC allows the SMF span length to be extended and thus the quantity of required in-line EDFAs is reduced compared with a system employing the CDCs. For example, based on the experimental results, the allowable span power budget of the proposed LDC is about 33 dB, which is calculated by the per-channel amplified compensated signal output power ($+16.4$ dBm) minus the minimum per-channel input signal power (-17 dBm), for which the power penalty is <0.3 dB. Then, the SMF span length can be extended to be at least 120 km for this two-wavelength LDC when each CFG is designed to have a dispersion of about -2040 ps/nm. It is easy to design and fabricate such CFG with today's technology. Therefore, the LDC may facilitate easier DWDM system design flexibility with unequal span link lengths to accommodate geographical environment, and enhance system reliability while employing alternately with the LDC and CDC in the DWDM system.

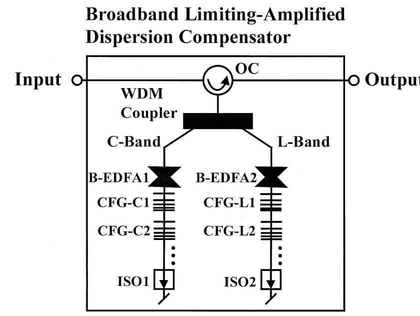

Fig. 6. Proposed broadband limiting-amplified dispersion compensator without need of power/gain equalization.

On the other hand, considering the attenuation of the 80-km SMF span of about 20 dB, when the minimum per-channel input signal power and the total signal output power of this LDC are -17 and $+19.6$ dBm, respectively, the amplified per-channel compensated-signal output power is about $+3$ dBm ($=20-17$), and thus the maximum number of DWDM channels allowed to be supported by this LDC can be at least 40 ($\leq 10^{(19.6-3)/10}$). Furthermore, by adopting the spectral split-band (C-band and L-band) WDM EDFA scheme, as shown in Fig. 6, the power and/or gain equalizations may not be required for the proposed broadband LDC to cover the full 80-nm (C-band of 1530–1565 nm and L-band of 1570–1610 nm) gain bandwidth.

5. Conclusions

We have proposed an optical limiting-amplified multiwavelength dispersion compensator (LDC), incorporating multiple chirped fiber gratings and a common bidirectional erbium-doped fiber amplifier. The LDC provides simultaneous dispersion compensation and limiting amplification of DWDM signals. A high constant channel output power of 16.4 dBm and a low power penalty of less than 0.3 dB have been achieved over an input signal dynamic range of 17 dB for this LDC in a 10 Gb/s two-wavelength 80-km SMF transmission system. In addition, the proposed LDC is less sensitive to CFG reflectivity and thus relaxes the requirement of CFG reflectivity. This potentially low-cost LDC may facilitate easier DWDM system design flexibility and network implementation.

References

[1] C. Lin, H. Kogelnik, L.G. Cohen, Opt. Lett. 5 (1980) 476.
[2] A.M. Vengsarkar, W.A. Reed, Opt. Lett. 19 (1993) 924.
[3] F. Ouellette, Opt. Lett. 12 (1987) 847.
[4] K.O. Hill, F. Bilodeau, B. Malo, T. Kitagawa, S. Theriault, D.C. Hohnson, J. Albert, Opt. Lett. 19 (1994) 1314.
[5] W.H. Loh, R.I. Laming, X. Gu, M.N. Zervas, M.J. Cole, T. Widdowson, A.D. Ellis, Electron. Lett. 31 (1995) 2203.
[6] W.H. Loh, R.I. Laming, A.D. Ellis, D. Atkinson, IEEE Photon. Technol. Lett. 8 (1996) 1258.
[7] A.H. Gnauck, L.D. Garrett, F. Forghieri, V. Gusmeroli, D. Scarano, IEEE Photon. Technol. Lett. 10 (1998) 1495.
[8] W.I. Way, T.H. Wu, A. Yi-Yan, M.J. Andrejco, C. Lin, J. Lightwave Technol. 10 (1992) 206.
[9] O.C. Graydon, M.N. Zervas, R.I. Laming, J. Lightwave Technol. 13 (1995) 732.
[10] Y.K. Chen, S.K. Liaw, W.Y. Guo, S. Chi, IEEE Photon. Technol. Lett. 8 (1996) 842.
[11] J. Aspell, J.F. Federici, B.M. Nyman, D.L. Wilson, D.S. Shenkl, 1992 Technical Dig. Opt. Fiber Commun. Conf. (OFC' 92), February 1992, paper ThA4.
[12] K. Ennser, M. Ibsen, M. Durkin, M.N. Zervas, R.I. Laming, IEEE Photon. Technol. Lett. 10 (1998) 1476.