CSO/CTB/BER performances improvement in a bi-directional hybrid DWDM system

Hai-Han Lu (呂海涵), Hsu-Hung Huang (黃旭弘),
Ming-Chuan Wang (王明傳), and Heng-Sheng Su (蘇恆生)

Institute of Electro-Optical Engineering, National Taipei University of Technology, Taipei 10608

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Experimental verifications of the feasibility of using chirped fiber grating (CFG) as the dispersion compensation device in a bi-directional hybrid dense-wavelength-division-multiplexing (DWDM) system to reduce the dispersion and cross-phase modulation (XPM) induced crosstalk were proposed and demonstrated. Not only channel capacity was increased, but also good performances of carrier-to-noise ratio (CNR) ≥ 50 dB, composite second order (CSO) ≥ 72 dB, composite triple beat (CTB) ≥ 69 dB and low bit error rate (BER) $< 10^{-9}$ were achieved in our proposed system over a 50-km single-mode fiber (SMF) transport.

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A hybrid signal transport system could use dense-wavelength-division-multiplexing (DWDM) technique to increase channel capacity and upgrade optical network flexibility[1,2]. However, increasing channel capacity will lead to transmission quality degradation because of nonlinear distortions in the fiber[3,4]. One important nonlinear distortion which has recently attracted increased attention is cross-phase modulation (XPM), where the phase of each channel in DWDM systems is modulated by the overall power in all other channels[5]. In such systems, the nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of other channels. In DWDM transport systems over single-mode fiber (SMF), distortion induced by XPM emerges as an important limiting factor of the channel capacity. XPM interaction will dominate the DWDM systems' performance. It has been reported that systems' dispersion and XPM-induced crosstalk can be reduced by using chirped fiber grating (CFG) in a two-wavelength WDM transport system[6,7], however, CFG has not been used as the dispersion compensation device in a bi-directional hybrid DWDM transport system. In this letter, we proposed and demonstrated an architecture by using CFG as the dispersion compensation device to reduce the dispersion and XPM-induced crosstalk in a bi-directional hybrid DWDM system for CATV and telecommunication trunking. Compared with uni-directional transport, bi-directional transport over fiber span reduces the required number of fibers. Not only channel capacity was increased, but also good performances of carrier-to-noise ratio (CNR), composite second order (CSO), composite triple beat (CTB) and low bit error rate (BER) were achieved in our proposed system over a 50-km SMF transport.

Figure 1 shows our proposed a bi-directional hybrid DWDM system that use SMF as the transmission fiber and CFG as the dispersion compensation device. The bi-directional hybrid DWDM system consists of two externally modulated optical transmitters, two OC-48 digital optical transmitters, and two broadband erbium-doped fiber amplifiers (EDFAs). The four wavelengths of λ_1, λ_2, λ_3 and λ_4 for externally modulated AM-VSB analog video and OC-48 digital baseband signals are 1554.1, 1552.4, 1550.9 and 1549.3 nm, respectively. Input and output powers of the EDFA are ~ 3 and 20 dBm, respectively. The 4×1 DWDM multiplexer/demultiplexer (MUX/DEMUX) is used to launch the downstream wavelengths λ_1 and λ_3 (λ_2 and λ_4) into the fiber link and to receive the upstream wavelengths λ_2 and λ_4 (λ_1 and λ_3) simultaneously.

Channels $2-78$ ($55.25-547.25$ MHz) were fed into the two externally modulated optical transmitters (1554.1 and 1552.4 nm) with an optical modulation index (OMI) of $\sim 3.5\%$. The polarization controller (PC), at each analog transmitter output, is used to adjust the state of polarization of the transmitter signal. And further, a 2.5-Gb/s OC-48 pattern generator was fed into the two OC-48 digital optical transmitters (1550.9 and 1549.3 nm), respectively. The composite signals are now combination of two 77 AM-VSB video channels and two OC-48 digital baseband channels. The combined signals are sent to the receiving site by a 4×1 DWDM MUX, a 50-km SMF and a 1×4 DWDM DEMUX. System link with a transmission length of 50-km SMF (with an attenuation of 0.24 dB/km, and a dispersion of 17 ps/(nm·km)) consists of four CFGs in combination with four optical circulators (OCs). The dispersion compensation wavelength region of the CFG is $1520-1565$ nm, each CFG has a total insertion loss of ~ 3.8 dB and a total dispersion of about -1034 ps/nm. These four CFGs have central reflective wavelengths of 1554.1, 1552.4, 1550.9 and 1549.3 nm, respectively. Furthermore, the hybrid signals are detected using broadband analog optical receivers and digital optical receivers, respectively. The input powers at the two analog optical receivers are 0 dBm, and at the two digital optical receivers are -19.03 dBm. All CATV RF parameters were measured using an HP-8591C CATV analyzer over a 50-km SMF transport. The OC-48 signal was fed into an OC-48 error detector for BER analysis.

Figures 2(a) and (b) show the measured CNR, CSO and CTB values with and without CFG after aligning polarization for the lowest crosstalk. Due to high insertion loss (~ 3.8 dB) of CFG, the CNR value (≥ 50 dB) for system with CFG is degraded about 1 dB compared to the system without CFG. However, it still satisfies the fiber optical CATV CNR performance requirement

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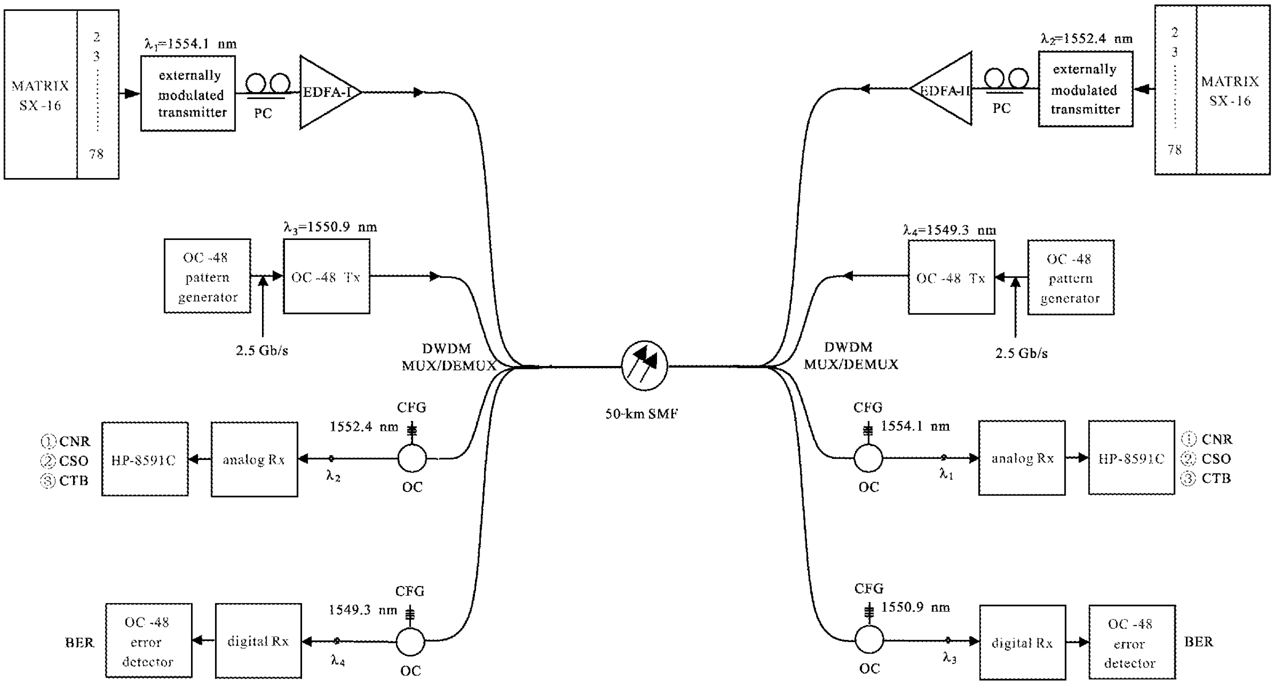

Fig. 1. The bi-directional hybrid DWDM system that use SMF as the transmission fiber and CFG as the dispersion compensation device.

($\geq$ 50 dB). As to the CSO/CTB performance, the CSO/CTB values ($\geq$ 72/69 dB) of system with CFG can be improved significantly. Improved results in the system can be attributed to the use of CFG as a dispersion compensation device. The CSO distortion can be obtained as[8]

$$\mathrm{CSO} = N_{\mathrm{CSO}} \cdot \left(\frac{m}{2}\frac{P_{\mathrm{in}}}{A_{\mathrm{eff}}}\frac{L-L_{\mathrm{eff}}}{\alpha}\beta_2 k n_2 m \Omega^2\right)^2, \qquad (1)$$

where N_{CSO} is the product count, m is the optical modulation index, P_{in} is the optical power launched into the fiber, A_{eff} is the effective fiber core area, L is the fiber length, $L_{\mathrm{eff}} = (1-\mathrm{e}^{-\alpha L})/\alpha$ is the effective nonlinear length, α is the fiber attenuation coefficient, $\beta_2 = -D\lambda^2/2\pi c$ is the second order dispersion coefficient (D is the dispersion coefficient), k is the wave number, n_2 is the nonlinear refractive index of the fiber, and Ω is the angular frequency. Introducing a CFG with the second order dispersion coefficient of β_g, after fiber link, then the CSO distortion Eq. (1) will be changed as

$$\mathrm{CSO} = N_{\mathrm{CSO}} \cdot \left(\frac{m}{2}\frac{P_{\mathrm{in}}}{A_{\mathrm{eff}}}\frac{L-L_{\mathrm{eff}}}{\alpha}(\beta_2+\beta_g) k n_2 \Omega^2\right)^2. \qquad (2)$$

The XPM-induced crosstalk can be expressed as[4]

$$\begin{aligned}&\text{Crosstalk (XPM)} = \\ &10\log\{(\frac{4\pi n_2 \beta_2 \Omega^2 P_{\mathrm{in}} \rho_{\mathrm{XPM}}}{\lambda A_{\mathrm{eff}}})^2 \\ &\cdot\{1+\mathrm{e}^{-2\alpha L} - 2\mathrm{e}^{-\alpha L}(1-\alpha L)\cos(d_{12}\Omega L) \\ &-2L[\alpha + d_{12}\Omega \mathrm{e}^{-\alpha L}\sin(d_{12}\Omega L)] + [\alpha^2 + (d_{12}\Omega)^2]L^2\} \\ &/[\alpha^2 + (d_{12}\Omega)^2]^2\}, \qquad (3)\end{aligned}$$

where ρ_{XPM} is the polarization overlap factor for the XPM, and d_{12} is the group velocity mismatch between WDM signals. Introducing a CFG after fiber link, then the crosstalk Eq. (3) will be changed as

$$\begin{aligned}&\text{Crosstalk (XPM)} = \\ &10\log\{(\frac{4\pi n_2 (\beta_2+\beta_g) \Omega^2 P_{\mathrm{in}} \rho_{\mathrm{XPM}}}{\lambda A_{\mathrm{eff}}})^2 \\ &\cdot\{1+\mathrm{e}^{-2\alpha L} - 2\mathrm{e}^{-\alpha L}(1-\alpha L)\cos(d_{12}\Omega L) \\ &-2L[\alpha + d_{12}\Omega \mathrm{e}^{-\alpha L}\sin(d_{12}\Omega L)] + [\alpha^2 + (d_{12}\Omega)^2]L^2\} \\ &/[\alpha^2 + (d_{12}\Omega)^2]^2\}. \qquad (4)\end{aligned}$$

By choosing β_2 and β_g with opposite sign, then systems' CSO distortion and XPM-induced crosstalk can be reduced. System link with a transmission length of 50-km SMF has a positive second order dispersion coefficient of β_2. In our proposed system, the dispersion compensator of CFG has a negative second order dispersion coefficient of β_g. Thus the CSO distortion and XPM-induced crosstalk will be reduced, and the CSO/CTB performance can be improved significantly.

Figure 3 shows the performance of the 2.5-Gb/s digital channel over a 50-km SMF transport with and without CFG. For the OC-48 channel, the sensitivity at BER of 10^{-9} with and without CFG are -34.1 and -33.5 dBm, respectively. The sensitivity improvement ($\sim$ 0.6 dB) is due to the use of CFG as the dispersion compensation device. The BER is given by[9]

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathrm{SNR}}{2}}\right), \qquad (5)$$

where SNR is systems' signal-to-noise ratio. SNR can be increased with employing CFG to reduce fluctuations caused by fiber dispersion. This SNR increase will lead to better BER performance, and finally result in receiver

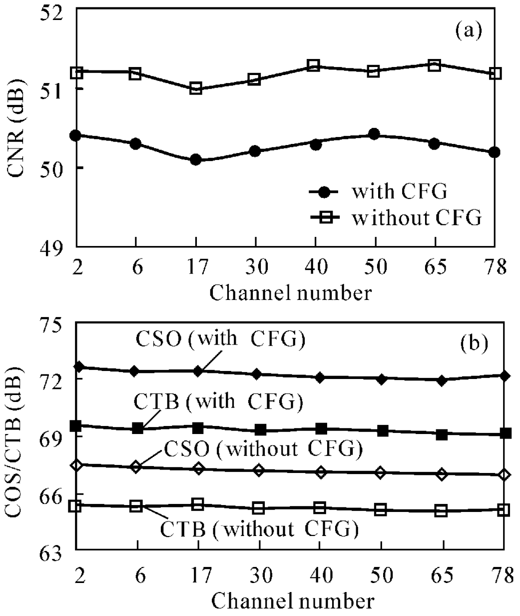

Fig. 2. (a) Measured CNR values with and without CFG after aligning polarization for the lowest crosstalk. (b) Measured CSO and CTB values with and without CFG after aligning polarization for the lowest crosstalk.

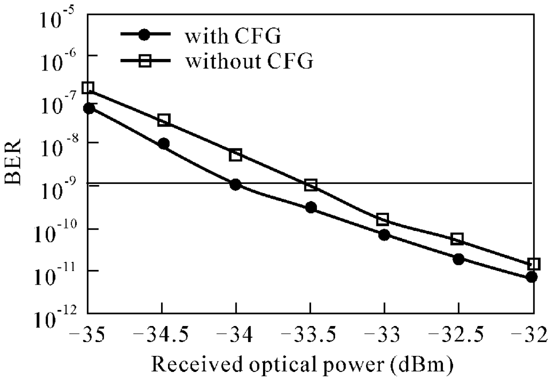

Fig. 3. The performance of the 2.5-Gb/s digital channel with and without CFG.

sensitivity improvement. The received optical powers for the digital optical receiver are −19.03 (with CFG) and −15.23 (without CFG) dBm, so we can easily obtain the BER $< 10^{-9}$ over a 50-km SMF transport. System link with a transmission length of 50-km SMF has a positive dispersion of 850 ps/nm (17 ps/(nm·km)·50 km). The dispersion compensator of the CFG has a negative dispersion of −1034 ps/nm, so systems' total dispersion can be reduced to 184 ps/nm ($|850$ ps/nm-1034 ps/nm$| = 184$ ps/nm). The lower total dispersion we obtain, the better CSO/CTB/BER performance we can achieve.

Experimental verifications of the feasibility of using CFG as the dispersion compensation device in a bidirectional hybrid DWDM system to reduce the dispersion and XPM-induced crosstalk were proposed and demonstrated. Not only channel capacity was increased, but also good performances of CNR, CSO, CTB and low BER were achieved in our proposed system over a 50-km SMF transport.

H.-H. Lu's e-mail address is hhlu@ntut.edu.tw.

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