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The improvement of composite triple-beat distortion induced by cross-phase-modulation in wavelength-division-multiplexing CATV transmission systems with chirped fiber grating compensator

C.C. Lee [a,b,*], S. Chi [b]

[a] *Chunghwa Telecom Labs., P.O. Box 6-1, Yang-Mei 326, Taoyuan, Taiwan*
[b] *Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan*

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Abstract

Composite triple-beat (CTB) distortion induced by cross-phase modulation (XPM) in a 1.55 μm wavelength-division-multiplexing (WDM) CATV transport system has been effectively improved, theoretically and experimentally, from -55.4 dBc to -60.8 dBc by using the chirped fiber grating to compensate the fiber dispersion. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Subcarrier-multiplexed (SCM) CATV fiber systems could use the wavelength-division-multiplexing (WDM) technique for both capacity upgrade and networking flexibility. However, recent studies showed that is severe crosstalk between optical channels in both 1.3 μm and 1.5 μm WDM–SCM CATV systems [1–3]. The channel crosstalk is confirmed mainly introduced by the stimulated Raman scattering (SRS) interaction and the cross-phase-modulation (XPM) effect. The crosstalk of the system with small channel spacing of <4 nm is dominated by the cross-phase-modulation effect [4]. The cross-phase-modulation-induced phase shift on WDM systems has been studied theoretically and experimentally [5,6]. As a result of FM–AM conversion due to fiber dispersion, cross-phase-modulation interaction between optical channels will introduce significant crosstalk in WDM–SCM systems. The cross-phase-modulation-induced crosstalk will be increased by decreasing the channel spacing because of more significant cross-phase-modulation interaction. The higher optical power level, the longer fiber link and the less group velocity mismatch between channels will worsen the cross-phase-modulation-induced channel crosstalk. By applying the 2 GHz dithering tone to the laser and proper polarization control in each optical channel, both the SRS- and cross-phase-modulation-induced crosstalk could be reduced [7].

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[*] Corresponding author. Fax: +886-3-424-4165; e-mail: chchl@ms.chttl.com.tw

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Cross-phase-modulation-induced penalty in digital transmission systems could be decreased with dispersion compensation in linear regime [8,9]. However, the dispersion compensation method for coping with the cross-phase-modulation in AM CATV transport systems has not yet been investigated. Chirped fiber gratings have many applications. In particular, the linearly chirped grating has been used as a dispersion-correcting and compensating device. This application has triggered the fabrication of ultralong, broad-bandwidth gratings for high bit-rate, long-distance or WDM transmission [10]. Some of the other applications include chirped pulse amplification [11], sensing [12], higher-order fiber dispersion compensation [13], and amplifier gain flattening [14]. The reflective chirped grating for dispersion compensation was originally suggested by Ouellette [15], and the designs of linearly chirped gratings have been reported [16]. In WDM–AM–CATV transport systems, the cross-phase-modulation-induced crosstalk will deteriorate the composite triple-beat (CTB) distortion. For practical system operation, composite triple-beat distortion should be less than −60 dBc. In this paper, we compensate the fiber dispersion by using the chirped fiber grating (CFG) to reduce the cross-phase-modulation-induced composite triple-beat distortion in WDM–CATV systems. Theoretically and experimentally, we will show that reduction of the cross-phase-modulation-induced composite triple-beat distortion to −60.8 dBc is possible to achieve.

2. Analysis

2.1. The intrinsic composite triple-beat distortion

We consider an analog optical link based on external modulation of the laser. The electrical signal to be transmitted, denoted V_m, drives an electro-optic modulator to produce optical intensity modulation. In general, we can express the optical intensity output of the modulator, I, as a function of the applied voltage, V, and input optical intensity, $I_0 : I = f(V) I_0$. If f is nonlinear in V, various nonlinear distortions will be generated. Let us assumed that the modulator is biased at a voltage V_b and also driven by the modulating voltage V_m for a total applied voltage of $V = V_b + V_m$. Anticipating that the modulating voltage $V_m \ll$ the minimum voltage swing V_s (the voltage to produce 100% modulation of the optical intensity), we can expand f in a Taylor series about V_b [17]. Then,

$$\frac{I}{I_0}(v) = f(v_b) + \left.\frac{\mathrm{d}f}{\mathrm{d}v}\right|_{v_b} v_m + \frac{1}{2!}\left.\frac{\mathrm{d}^2 f}{\mathrm{d}v^2}\right|_{v b} v_m^2 + \dots$$
$$= c_0 + c_1 v_m + c_2 v_m^2 + c_3 v_m^3 + \dots \tag{1}$$

where $v = V/V_s$, $v_m = V_m/V_s$, and $v_b = V_b/V_s$. To derive the intermodulation distortion, we consider to drive the modulator with a multi-channel CATV modulating signal consisting of N unmodulated carriers. The modulating voltage can be given by

$$V_m = \sum_{q=1}^{N} V_0 \cos(\omega_q t + \psi_q). \tag{2}$$

Substituting Eq. (2) into Eq. (1) under small modulating signal condition (that is, $V_m \ll V_s$, and the high-order terms of v_m in Eq. (1) are negligible) yields [17]

$$\frac{I}{I_0}(v) = c_0 + c_1 \sum_{q=1}^{N} \frac{V_0}{V_s}\cos(\omega_q t + \psi_q) + c_2 \left(\sum_{q=1}^{N} \frac{V_0}{V_s}\cos(\omega_q t + \psi_q) \right)^2 + c_3 \left(\sum_{q=1}^{N} \frac{V_0}{V_s}\cos(\omega_q t + \psi_q) \right)^3. \tag{3}$$

The term in c_1 is the linear desirable term, whereas the term in c_2 is the composite second-order component and the term in c_3 is the composite triple-beat component. The triple sum term, denoted $I^{(3)}$, is further trigonometrically expanded to yield [18]

$$I^{(3)} = c_3\left(\frac{V_0}{V_s}\right)^3\left(\sum_{q1=1}^{N}\sum_{q2=1}^{N}\sum_{q3=1}^{N}\cos(\omega_{q1}t+\psi_{q1})\cos(\omega_{q2}t+\psi_{q2})\cos(\omega_{q3}t+\psi_{q3})\right)$$
$$= \frac{c_3}{4}\left(\frac{V_0}{V_s}\right)^3\sum_{\pm}\sum_{q1=1}^{N}\sum_{q2=1}^{N}\sum_{q3=1}^{N}\cos\big((\omega_{q1}\pm\omega_{q2}\pm\omega_{q3})t+\psi_{q1}\pm\psi_{q2}\pm\psi_{q2}\big). \tag{4}$$

where '±' implies summation over all four possible pairs of signs. Since CATV channel plans usually contain large subsets of commensurate channel frequencies arranged on a grid of equidistant frequency values, many mixing products could potentially fall on the same beat frequency ω_b, a situation occurring whenever the three channel frequencies satisfy $\omega_b = \omega_{q1} \pm \omega_{q2} \pm \omega_{q3}$. When the light falls on a photodetector, the current produced is proportional to the light intensity. Hence, the electrical triple beat power detected in the receiver is the statistical average of the square of the optical beat signal. Therefore, the intrinsic composite triple-beat distortion $CTB_i(\omega_b)$ caused by modulator at a given channel of frequency ω_b is expressed as a summation over the individual beat powers with mixing frequencies falling on ω_b. Then,

$$CTB_i(\omega_b) = 10\log\left(\frac{\langle|I^{(3)}(\omega_b)|^2\rangle}{\langle|c_1(V_0/V_s)\cos(\omega_b t+\psi_b)|^2\rangle}\right)(\mathrm{dB}). \tag{5}$$

Since the composite triple-beat distortion has the same frequency with RF carrier, the composite triple-beat distortion often appears as horizontal streaks covering one or more lines of video.

2.2. The composite triple-beat distortion induced by the cross-phase-modulation effect

For analysis, we consider the simple case with two WDM channels, one for signal light and one for pump light, each modulated with one subcarrier. We have assumed that both optical carriers have the same average optical power P_i (W), and are modulated by the same subcarrier angular frequency ω (rad s^{-1}) with the same optical modulation index m. The optical modulation index m is defined by [17]

$$m \equiv \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \approx \left|\frac{c_1V_0}{c_0V_s}\right|. \tag{6}$$

By considering the cross-phase-modulation interaction between two WDM channels, the phase of the signal light has a component $\Delta\phi$ due to the cross-phase-modulation interaction with the pump light [5]:

$$\Delta\phi(L,t) = 2\gamma m\sqrt{\eta_{XPM}}\,L_{eff}\left(\frac{1}{3}P_{i\perp}+P_{i\parallel}\right)\cos(\omega t+\varphi) \tag{7}$$

where $P_{i\perp}$ and $P_{i\parallel}$ (W) are the fractions of power in signal channel that are orthogonal and parallel to the polarization of pump channel, $\gamma = 2\pi N_2/\lambda_p A_{eff}$ (m^{-1} W^{-1}) is the fiber nonlinearity coefficient, λ_p (m) is the wavelength of the pump light, N_2 (m^2 W^{-1}) is the Kerr nonlinear-index coefficient, A_{eff} (m^2) is the effective fiber core area, $L_{eff} = (1 - e^{-\alpha L})/\alpha$ (m) is the effective fiber length, L (m) is the fiber length, and α (Np m^{-1}) is the fiber attenuation coefficient. η_{XPM} is the cross-phase-modulation efficiency and is given by [5]

$$\eta_{XPM} = \frac{\alpha^2}{\omega^2 d_{12}^2+\alpha^2}\left[1+\frac{4\sin^2\left(\frac{\omega d_{12}L}{2}\right)e^{-\alpha L}}{(1-e^{-\alpha L})^2}\right] \tag{8}$$

where $d_{12} \approx D\Delta\lambda(\mathrm{s\ m}^{-1})$ is the walk-off parameter, D (s m^{-2}) is the dispersion coefficient, and $\Delta\lambda$ (m) is the wavelength separation between the two channels. φ is cross-phase-modulation phase retardation factor and can be expressed as [5]

$$\varphi = \cos^{-1}\frac{1-\mathrm{e}^{-\alpha L}\cos(\omega d_{12}L)}{\sqrt{(1-\mathrm{e}^{-\alpha L})^2 + 4\sin^2(\omega d_{12}L/2)\mathrm{e}^{-\alpha L}}} - \cos^{-1}\frac{\alpha}{\sqrt{\omega^2 d_{12}^2 + \alpha^2}}\,. \tag{9}$$

φ is important when phase shifts contributed from several sinusoidal components are added up. From this analysis, the cross-phase-modulation effect can be modeled as a phase modulator with inputs from the intensity of copropagating waves.

As a result of the FM–AM conversion due to fiber dispersion, the above phase modulation gives rise to the crosstalk after fiber distance z in signal channel. The crosstalk ratio $C(z)$ is defined as the ratio of crosstalk power and the signal power, and can be given by [19]:

$$C(z) = \frac{\left|\int_0^z -\beta_2 P_{\mathrm{i}}\frac{\partial^2\Delta\phi(L)}{\partial t^2}\mathrm{d}L\right|}{|mP_{\mathrm{i}}\cos(\omega t)|} = \left|\int_0^z \frac{\beta_2}{m}\omega^2|\Delta\phi(L)|\mathrm{d}L\right| \tag{10}$$

where β_2 (s^2 m^{-1}) is the second-order fiber dispersion coefficient for the signal light and is related to the dispersion D by $\beta_2 = -D\lambda^2/2\pi\mathrm{c}$.

Intermodulation distortion can be derived from the calculated crosstalk. Assume the two wavelength channels have power modulated by N subcarriers using external modulator [20]:

$$P_{\mathrm{A,B}}(t) = P_{\mathrm{i}}\left[1 + \sum_{q=1}^{N} m\cos(\omega_q t + \psi_q)\right] \tag{11}$$

where P_{A} and P_{B} are the powers of channel A and B. By considering both the intrinsic triple-beat and cross-phase-modulation effect with $m \ll 1$, the power of channel A at the output is

$$P_{\mathrm{A}}(t) = P_{\mathrm{i}}\mathrm{e}^{-\alpha L}\left[1 + \sum_{q=1}^{N} m\cos(\omega_q t + \psi_q) + \sum_{q=1}^{N} C(z,\omega_q)|m\cos(\omega_q t + \psi_q)| + I^{(3)}/c_0\right]. \tag{12}$$

In the worst case, the phases of the intrinsic triple beats CTB_{i} and crosstalk $C(z)$ are identical and added on an amplitude basis. Therefore, the effective composite triple-beat distortion CTB_{eff} at frequency ω_{b} can be expressed by

$$CTB_{\mathrm{eff}}(\omega_{\mathrm{b}}) = 10\log\left(\left(C(z,\omega_{\mathrm{b}}) + \left(\frac{|I^{(3)}(\omega_{\mathrm{b}})/c_0|}{|m\cos(\omega_{\mathrm{b}} + \psi_{\mathrm{b}})|}\right)\right)^2\right) = 20\log\left(10^{CTB_{\mathrm{i}}(\omega_{\mathrm{b}})/20} + C(z,\omega_{\mathrm{b}})\right). \tag{13}$$

2.3. The improvement of composite triple-beat distortion by using dispersion compensating method

When n optical channels (optical wavelength from λ_1 to λ_n) are modulated simultaneously by CATV signals with multiple subcarriers, the cross-phase-modulation induced phase modulation $\Delta\phi_{\mathrm{eff}}$ for a given frequency ω_{b} can be derived from Eq. (7) and expressed by

$$\begin{aligned}\Delta\phi_{\mathrm{eff}}(\lambda_j) &= \sum_{i=1,i\neq j}^{n}\Delta\phi(d_{ij}) = \sum_{i=1,i\neq j}^{n}|\Delta\phi(d_{ij})|\cos\left(\omega_b t + \varphi(d_{ij})_i\right)\\ &= \sqrt{\left(\sum_{i=1,i\neq j}^{n}|\Delta\phi(d_{ij})|\cos\left(\varphi(d_{ij})\right)\right)^2 + \left(\sum_{i=1,i\neq j}^{n}|\Delta\phi(d_{ij})|\sin\left(\varphi(d_{ij})\right)\right)^2}\cos(\omega_{\mathrm{b}}t + \theta)\end{aligned} \tag{14}$$

where θ is the effective cross-phase-modulation phase retardation factor and is given by

$$\theta=\tan^{-1}\frac{\sum\limits_{i=1,i\neq j}^{n}|\Delta\phi(d_{ij})|\sin\big(\varphi(d_{ij})\big)}{\sum\limits_{i=1,i\neq j}^{n}|\Delta\phi(d_{ij})|\cos\big(\varphi(d_{ij})\big)}. \tag{15}$$

Similarly, the effective composite triple-beat distortion at frequency ω_b in multi-wavelength WDM systems can be calculated by substituting Eq. (14) in Eqs. (10)–(13).

From Eq. (10), the crosstalk produced can be eliminated at a given frequency ω_b in the optical wavelength λ_j by using the proper dispersion-compensating device such as chirped fiber grating after the multi-wavelength WDM fiber link of length ℓ. Then,

$$C\big(\lambda_j,\ell+L_g\big)=\left|\int_0^{\ell}\frac{\beta_2}{m}\omega_b^2|\Delta\phi_{\rm eff}(\lambda_j,L)|{\rm d}L+\int_{\ell}^{\ell+L_g}\frac{\beta_g}{m}\omega_b^2|\Delta\phi_{\rm eff}(\lambda_j,\ell)|{\rm d}L\right|=0 \tag{16}$$

where β_g and L_g are the second-order dispersion coefficient and length of the chirped fiber grating, and $|\Delta\phi_{\rm eff}(\lambda_j,\ell)|$ is independent of L. Therefore, the optimal value of $(\beta_g L_g)_{\rm opt}$ can be expressed by

$$(\beta_g L_g)_{\rm opt}=\frac{\int_0^{\ell}-\beta_2|\Delta\phi_{\rm eff}(\lambda_i,L)|{\rm d}L}{|\Delta\phi_{\rm eff}(\lambda_i,\ell)|}. \tag{17}$$

The over-compensating or under-compensating chirped fiber grating can not eliminate the crosstalk produced by the cross-phase-modulation completely. If the over-compensating or under-compensating value is too high, the crosstalk will even worsen than the uncompensating case. If a chirped fiber grating has $\beta_g L_g=(\beta_g L_g)_{\rm opt}\pm\Delta$, where the '+' and '−' signs represent the over-compensating and under-compensating cases and Δ is the dispersion difference reference to the optimal value, then the crosstalk $C(\lambda_j,\ell+L_g)_{\text{non-opt}}$ for over-compensating and under-compensating cases can be given by

$$C\big(\lambda_j,\ell+L_g\big)_{\rm non-opt}=\left|\frac{\pm\Delta}{m}\omega_b^2|\Delta\phi_{\rm eff}(\lambda_j,\ell)|\right|. \tag{18}$$

Therefore, the higher modulation frequency and the larger effective amplitude of cross-phase-modulation-induced phase modulation will produce larger crosstalk (i.e. worse composite triple-beat distortion).

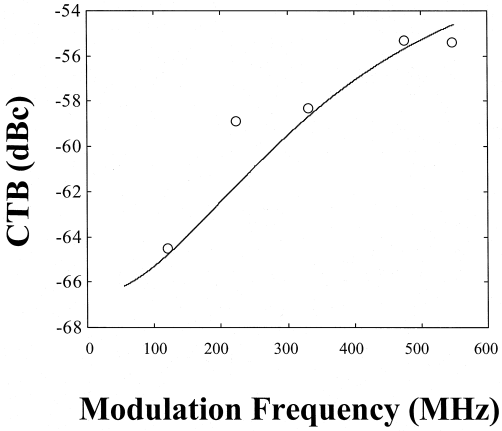

Fig. 1. Cross-phase-modulation-induced composite-triple-beat (CTB) distortion versus modulation frequency. System parameters: $\lambda_p=1553.7$ nm, $\alpha=0.2$ dB/km, $\Delta\lambda=2.4$ nm, $N_2=2.5\times10^{-20}$ m^2/W, $A_{\rm eff}=80$ μm^2, $m=0.038$, $D=17$ ps/nm km, $P_i=11$ dBm, and 40 km SMF.

For example, if the parameter values used for the two-wavelength WDM transmission system at 1.55 μm are: $\lambda_p = 1553.7$ nm, $\alpha = 0.2$ dB/km, $\Delta\lambda = 2.4$ nm, $N_2 = 2.5 \times 10^{-20}$ m^2/W, $A_{eff} = 80$ μm^2, $m = 0.038$, $D = 17$ ps/nm km, $P_i = 11$ dBm, $CTB_i = -66.6$ dBc, 40 km SMF and average polarization state, the dependence of the cross-phase-modulation-induced composite triple-beat distortion on modulation frequency is shown as the solid line in Fig. 1 by using Eq. (13). As seen in Fig. 1, the cross-phase-modulation-induced composite triple-beat distortion increases with modulation frequency, therefore the cross-phase-modulation-induced composite triple-beat distortion in the high-frequency RF channel will dominate the composite triple-beat performance. If a chirped fiber grating of -1275 ps/nm combined with a variable length of SMF are placed after 40 km SMF as a variable dispersion compensator, the amplitude $|\Delta\phi|$ of cross-phase-modulation-induced phase modulation and cross-phase-modulation-induced composite triple-beat distortion versus fiber length for $P_i = 8$, 11 and 14 dBm at the subcarrier frequency of 547.25 MHz are shown in Fig. 2(a) and Fig. 2(b). $|\Delta\phi|$ increases with the fiber length L in the regime of $L < 20$ km, decreases for 20 km $< L <$ 40 km due to walk-off effect, and keeps as a constant for $L > 40$ km. The cross-phase-modulation-induced composite triple-beat distortion increases with fiber length in the regime of $L < 40$ km due to the fiber dispersion, and decreases drastically at the $L = 40$ km point due to the high negative dispersion of chirped fiber grating (over-compensating). By adding SMF for reducing the over-compensating effect of the chirped fiber grating, the composite triple-beat distortion decreases with fiber length to the intrinsic composite triple-beat distortion at $L = 68$ km,

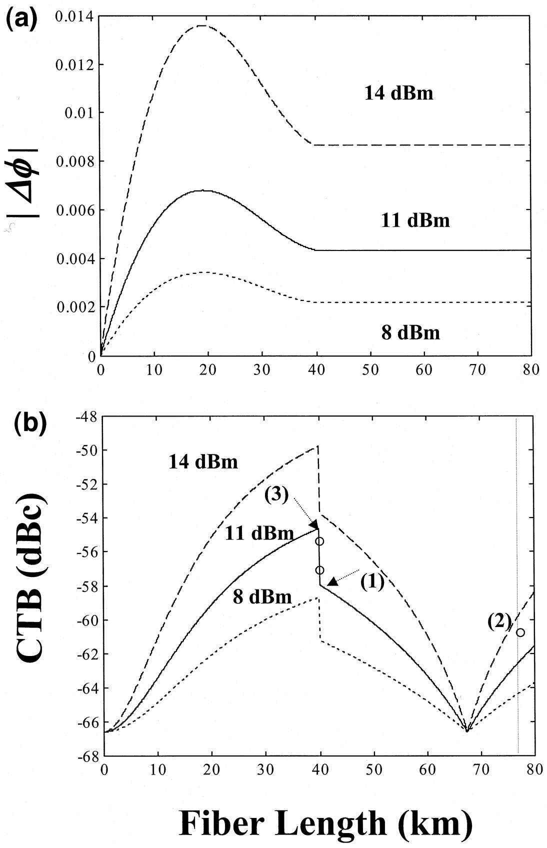

Fig. 2. The calculated and measured results of the parameters for the subcarrier frequency of 547.25 MHz: (a) the amplitude $|\Delta\phi|$ of cross-phase-modulation-induced phase modulation versus the fiber length L for $P_i = 8$, 11 and 14 dBm; and (b) the cross-phase-modulation-induced composite triple-beat distortion versus the fiber length L for $P_i = 8$, 11 and 14 dBm.

and then increases with fiber length again for $L > 68$ km. Both $|\Delta\phi|$ and composite triple-beat distortion are increased with optical power, and the optimal values of the compensating dispersion for $P_i = 8$, 11 and 14 dBm to retrieve the minimal composite triple-beat distortion are all the same with $\beta_g L_g = 1.03 \times 10^{-21}$ s^2 ($D_g L_g = -799$ ps/nm). Therefore, by proper adjusting the compensating dispersion, the cross-phase-modulation-induced composite triple-beat distortion can be improved to the value of the intrinsic composite triple-beat distortion in WDM AM–VSB CATV systems theoretically. If a non-optimal chirped fiber grating with $\beta_g L_g = 1.03 \times 10^{-21}$ s^2 ($D_g L_g = -637.5$ ps/nm) is used to reduce the crosstalk of the above system with $P_i = 11$ dBm, from Eqs. (13) and (18), the calculated composite triple-beat distortion at frequency of 547.25 MHz is -62.4 dBc, and 7.8 dB improvement is expected compared with the uncompensated case theoretically.

Assume that the parameter values used for the n-wavelength WDM transmission system at 1.55 μm are: $\alpha = 0.2$ dB/km, $N_2 = 2.5 \times 10^{-20}$ m^2/W, $A_{\text{eff}} = 80$ μm^2, $m = 0.038$, $D = 17$ ps/nm km, $P_i = 11$ dBm per channel, $CTB_i = -66.6$ dBc, 40 km SMF, average polarization state, and equal channel spacing $\Delta\lambda$. If the modulating RF signals are coherent and whenever the phases are identical, the composite triple-beat distortions in the longest or shortest wavelength channels versus channel spacing for $n = 2$, 8, 16 and 64 at the subcarrier frequency of 547.25 MHz are calculated as shown in Fig. 3. In practical, the conventional erbium-doped fiber amplifier can provide about 30 nm bandwidth (from 1530 to 1560 nm) for optical WDM signals. Therefore, the tolerable maximal channel spacing are about 30, 4.29, 2, and 0.48 nm for $n = 2$, 8, 16 and 64. From Fig. 3, it can be seen that increasing channel spacing decreases composite triple-beat distortion due to the walk-off effect, and increasing channel number increases composite triple-beat distortion. However, because the retardation factors contributed by different optical channels are not equal, and the larger wavelength difference due to the increasing channel number, the composite triple-beat distortion in high-channel-number regime will increase slowly with channel number. If the used channel spacing is 0.4 nm (50 GHz), the composite triple-beat distortions caused by cross-phase-modulation for $n = 2$, 8, 16 and 64 are -51.3, -38.6, -35.4 and -31.3 dB. Compared with -60 dB requirement of composite triple-beat distortion, the necessary improvements for $n = 2$, 8, 16 and 64 are 8.7, 21.4, 24.6 and 28.7 dB. From Eq. (17), the optimal $\beta_g L_g$ values of chirped fiber gratings for $n = 2$, 8, 16 and 64 are 5.7×10^{-22}, 7.3×10^{-22}, 7.7×10^{-22}, and 8.2×10^{-22} s^2. Therefore, the chirped fiber grating needs to be replaced by a new one with higher $\beta_g L_g$ value as the WDM channels are increased. Furthermore, the crosstalk produced by stimulated Raman scattering will also need to consider when the wavelength difference between channels is larger than 4 nm.

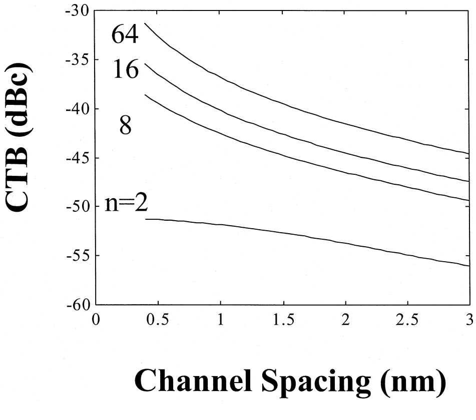

Fig. 3. The calculated results of the composite triple-beat distortion versus channel spacing in the longest or shortest wavelength channels for $n = 2$, 8, 16 and 64 at the subcarrier frequency of 547.25 MHz.

3. Experiments and results

The experimental setup is shown in Fig. 4, where two externally modulated transmitters, with wavelengths at 1553.7 nm and 1556.1 nm, respectively, were used. The stimulated Brillouin-scattering suppression ability of each transmitter was about 16 dBm. Each transmitter was modulated with 80 NTSC channels (55.25 to 547.25 MHz), generated by two multiple-frequency generators. The optical modulation index on each transmitter was about 3.8% per channel. The polarization controller, at each transmitter output, was used to adjust the state of polarization of the transmitter signal. After passing through a 980-nm-pumped erbium-doped fiber amplifier (EDFA) with a saturated output power of 16.5 dBm and an optical band-pass filter (OBPF), the two WDM signals were combined by a 3 dB coupler and launched into a 40 km SMF with 11 dBm optical power per channel. At the receiving end, four kinds of architectures were individually arranged in front of a commercial CATV receiver. They are: (1) a 1553.7 nm chirped fiber grating with 0.6 nm FWHM bandwidth, 83% reflectivity and dispersion coefficient = −1275 ps/nm, combined with an optical circulator (OC), an EDFA with 16 dBm saturated output power, an OBPF and an optical attenuator (ATT); (2) inserting a 37.5 km SMF in (1); (3) an OBPF with corresponding wavelength, an EDFA with 16 dBm saturated output power, an OBPF and an optical attenuator; and (4) inserting a 37.5 km SMF in (3). The optical attenuator is adjusted to keep 0 dBm input power of the CATV receiver. The selectivity are > 40 dB and > 50 dB for optical filter and chirped fiber grating, respectively.

We first measured the back-to-back transmission performance of the composite triple-beat distortion, composite second-order distortion, and carrier-to-noise-ratio on the 1553.7 nm channel for the optical transceiver connected with fiber jumper and −66.6 dBc, 65 dBc and 51.9 dB are retrieved, respectively. Using the architecture (3) in Fig. 4, we can measure the dependence of the cross-phase-modulation-induced composite triple-beat distortion (the circle '∘' sign) on the modulation frequency as shown in Fig. 1. The experimental measurements show good agreement with the theoretical calculation based on Eq. (13). We then measured the

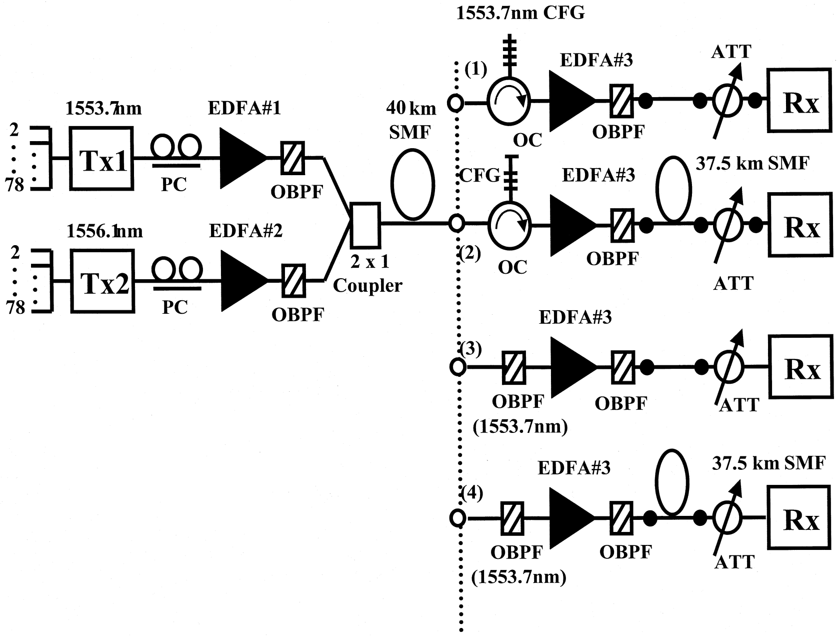

Fig. 4. The experimental setup.

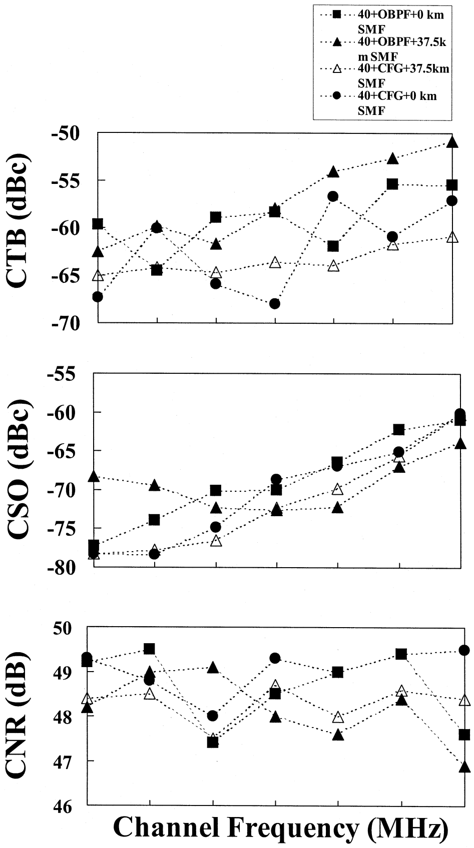

Fig. 5. Measured composite triple-beat (CTB), composite second-order (CSO), and carrier-to-noise ratio (CNR) versus channel frequencies for the architectures (1)–(4) in two-wavelength WDM transmission.

RF performances of the four different architectures after fiber on the 1553.7 nm channel. As can be seen in Fig. 5, the composite triple-beat distortions of the architectures (1)–(4) at 547.25 MHz channel are −57.1, −60.8, −55.4 and −50.8 dBc, respectively. Compared with the calculated cross-phase-modulation-induced composite triple-beat distortions in our analysis, the difference between measured and calculated results (the circle '*o*' sign and solid line, respectively) are −0.8, 0.8 and 1.6 dB for architectures of (3), (1) and (2) in Fig. 2. Using the chirped fiber grating combined with 37.5 km SMF (effective dispersion value = −637.5 ps/nm), the composite triple-beat distortion in all measured channels is improved to ≤ -60.8dBc by 5.4 dB improvement, which has 2.4 dB difference compared with calculated result (= 7.8 dB). The difference may be caused by the weak stimulated Raman scattering effect, polarization error or dispersion compensation in non-linear regime. Therefore, we have successfully reduced the cross-phase-modulation-induced composite triple-beat distortion below −60 dBc, and have minor effect to carrier-to-noise ratio and composite second-order distortions by using the compensating chirped fiber grating.

4. Conclusions

In summary, utilization of a chirped fiber grating combined with a proper length of SMF to compensate the fiber dispersion, we have successfully reduced the cross-phase-modulation-induced composite triple-beat distortion theoretically and experimentally. For two-wavelength WDM transmission with 2.4 nm channel-spacing and 11 dBm optical power per channel, the cross-phase-modulation-induced distortion can be improved from −55.4 to −60.8 dBc by using the compensating chirped fiber grating. This technique may benefit the deployment of WDM–SCM CATV transport systems and networks.

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