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Composite second-order performance improvement in optical fibre CATV transmission system using chirped fibre grating*

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Theoretically, we analyse the dispersion compensation characteristics of the chirped fibre grating (CFG) in an optical fibre cable television (CATV) system and obtain the analytic expression of the composite second-order (CSO) distortion using the time-domain form of the field envelope wave equation. The obtained result is in good agreement with the numerical simulation result. Experimentally, we verify the result by making use of the tunable characteristics of CFG to change the dispersion compensation amount and obtain an optimal CSO performance in a 125km fibre transmission link. Both the theoretical and experimental results show that the CSO performance can be improved by properly choosing the dispersion compensation amount for a certain fibre transmission link.

Keywords: composite second order, CFG, optical fibre CATV transmission system
PACC: 4230Q, 4280M, 4281D

1. Introduction

Long-distance transmission by 1550nm external-modulation Amplitude Modulated Vestigial Sidebands (AM-VSB) CATV systems based on the conventional single-mode fibre (SMF) has become widespread throughout the cable industry because of its large number of distribution nodes and high video quality.[1,2] However, fibre dispersion is one of the most severe limiting factors in long fibre transmission link because it may generate a serious CSO distortion resulting from the combination of the self-phase modulation with the chirping of laser transmitter. Several compensation techniques have been brought forward to improve the system's CSO performance. The common technique is the use of an externally modulated transmitter because it has hardly any chirping, which can improve the system's CSO performance greatly. The others include the dispersion compensation fibre (DCF) and reverse dispersion fibre (RDF),[3,4] and the differential detection technique through two-fibres transmission to recombine the in-phase RF signals from the optical receiver.[5] However, due to the high insertion loss of these fibres, it is difficult to obtain good CSO and CTB performances.

In recent studies, chirped fibre gratings (CFG) have been used as a fibre dispersion compensation device in digital fibre communication and analogue subcarrier lightwave systems for a single-mode fibre transmission link,[6−10] and the experimental results show that the CFG can improve the system's CSO performance greatly. However, no good theory has been developed in the case so far. In this paper, we analyse the dispersion compensation theory of the CFG in an optical fibre CATV system and obtain the analytic expression of the CSO distortion. The analytic result shows that the theory agrees with the numerical simulation very well. At the same time, the result is also verified experimentally, where we make use of the tunable characteristics of CFG to change the dispersion compensation amount and obtain an

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optimal CSO performance for a 125km fibre transmission link. Both the theoretical and experimental results show that CSO performance can be improved greatly by properly choosing the dispersion compensation amount for a certain fibre transmission link.

2. Theoretical analysis

In a fibre transmission system, the propagating optical signal satisfies the nonlinear Schrödinger equation (NLSE)[11]

$$\frac{\partial A}{\partial z}+\beta_1\frac{\partial A}{\partial t}-\frac{\mathrm{i}\beta_2}{2}\frac{\partial^2 A}{\partial t^2}+\alpha A=-\mathrm{i}\gamma\left|A\right|^2A, \tag{1}$$

where α is the material loss, β_1 and β_2 are the first- and second-order dispersion coefficients in the frequency expansion, and γ is the nonlinear coefficient. Substituting the field envelope

$$A=\sqrt{x(z,t)}\exp[\mathrm{i}y(z,t)] \tag{2}$$

into the NLSE and letting both $x(z,t)$ and $y(z,t)$ be real and contain all the information about the intensity and the phase respectively, the corresponding equations for intensity and phase may be respectively written as

$$\frac{\partial x}{\partial z}+\beta_1\frac{\partial x}{\partial t}=-\beta_2\left(\frac{\partial x}{\partial t}\frac{\partial y}{\partial t}+x\frac{\partial^2 y}{\partial t^2}\right)-2\alpha x, \tag{3a}$$

$$\frac{\partial y}{\partial z}+\beta_1\frac{\partial y}{\partial t}=\beta_2\left[\frac{1}{2}\left(\frac{\partial y}{\partial t}\right)^2+\frac{1}{4x}\frac{\partial^2 x}{\partial t^2}-\frac{1}{8x^2}\left(\frac{\partial x}{\partial t}\right)^2\right]-\gamma x. \tag{3b}$$

Here we introduce a new variable $u=t-\beta_1 z$ and it is the standard change of variable for the wave equation: any function $h(u)$ of u describes a wave envelope that travels undistorted through the medium at a group velocity $v_{\mathrm{g}}=(\beta_1)^{-1}$. In practical applications, fibre grating may be considered as a passive component with low loss and low nonlinearity and high dispersion. Because its length is very short, the loss and nonlinear effect of CFG may be neglected, i.e. $\alpha=0$, $\gamma=0$. Equation (3) describing the optical signal propagation in fibre grating may be re-written as

$$\frac{\partial x}{\partial z}=-\beta_{\mathrm{g}}\left(\frac{\partial x}{\partial u}\frac{\partial y}{\partial u}+x\frac{\partial^2 y}{\partial u^2}\right), \tag{4a}$$

$$\frac{\partial y}{\partial z}=\beta_{\mathrm{g}}\left[\frac{1}{2}\left(\frac{\partial y}{\partial u}\right)^2+\frac{1}{4x}\frac{\partial^2 x}{\partial u^2}-\frac{1}{8x^2}\left(\frac{\partial x}{\partial u}\right)^2\right], \tag{4b}$$

where $\beta_{2\mathrm{g}}=\lambda^2 D_{\mathrm{g}}/(2\pi z_{\mathrm{eff}})$ is the second-order dispersion coefficient of CFG, D_{g} is the dispersion amount of CFG in ps/nm. z_{eff} is an effective length of CFG section corresponding to the signal line-width $\Delta\lambda$, and can be expressed as $z_{\mathrm{eff}}=\Delta\lambda/(\lambda_0\rho)$ with the grating chirping rate ρ. In Ref.[12], the external modulation with single-tone intensity and phase modulation was considered under the initial conditions of

$$x(0,u)=P_0[1+m\cos\omega u], \tag{5a}$$

$$y(0,u)=\phi, \tag{5b}$$

where m is the intensity modulation index, ϕ is the initial phase, ω and P_0 are the angular frequency and the light power, respectively. When the modulation signal passes through a single mode fibre with a length of z_l, the intensity and phase changes can be described as a series of the modulation frequency ω.[11,12]

$$x(z_l,u)=x_0+x_1\cos\omega u+x_2\cos 2\omega u+\cdots, \tag{6a}$$

$$y(z_l,u)=y_0+y_1\cos\omega u+y\cos 2\omega u+\cdots, \tag{6b}$$

where we neglect the third-order and high-order frequencies. x_i and y_i are coefficients of the intensity and phase, respectively, and the corresponding expressions are as follows:

$$x_0=P_0\mathrm{e}^{-z_l\alpha}, \tag{7a}$$

$$x_1=\frac{mP_0\mathrm{e}^{-z_l\alpha}}{\alpha^2}[\alpha^2-(\mathrm{e}^{-z_l\alpha}-1+z_l\alpha)\gamma\omega^2P_0\beta_2], \tag{7b}$$

$$x_2=\frac{m^2\gamma\omega^2P_0^2\beta_2\mathrm{e}^{-z_l\alpha}}{\alpha^2}(\mathrm{e}^{-z_l\alpha}-1+z_l\alpha), \tag{7c}$$

$$y_0=\frac{(1-\mathrm{e}^{-z_l\alpha})\gamma P_0}{\alpha}, \tag{7d}$$

$$y_1=\frac{(1-\mathrm{e}^{-z_l\alpha})m\gamma P_0}{\alpha}, \tag{7e}$$

$$y_2=0. \tag{7f}$$

Now let us analyse the dispersion compensation theory of CFG in an optical fibre CATV system. The signal output from the fibre is input into the fibre grating, so it may be considered as the initial input signal of the fibre grating and satisfies the propagation equation (4). The corresponding electric field envelope is assumed to be by reflecting of CFG

$$A=\sqrt{X(z_{\mathrm{eff}},u)}\exp[\mathrm{i}Y(z_{\mathrm{eff}},u)]. \tag{8}$$

Solving Eq.(4) for intensity and phase deviations by using iterative method, the intensity and phase parts may be respectively described by use of a power series in z with u-dependent coefficients as its trial solution,

$$\begin{aligned}X=&X_0+X_1+X_2+\cdots\\=&x(z_l,u)+g_1z+g_2z^2+\cdots,\end{aligned} \tag{9a}$$

$$\begin{aligned}Y=&Y_0+Y_1+Y_2+\cdots\\=&y(z_l,u)+h_1z+h_2z^2+\cdots,\end{aligned} \tag{9b}$$

where $X_0 = x(z_l, u)$ and $Y_0 = y(z_l, u)$ are the initial input signals. Making use of the expressions of (6) and (7), we may obtain the intensity expression finally with the high order frequency terms neglected:

$$X = I_0 + I_1 \cos(\omega u) + I_2 \cos(2\omega u). \tag{10}$$

The corresponding coefficient expressions are

$$I_0 = P_0 \mathrm{e}^{-z_l \alpha}, \tag{11a}$$

$$I_1 = \frac{1}{\alpha^2} P_0 \mathrm{e}^{-z_l \alpha} [-m(\mathrm{e}^{-z_l \alpha} - 1 + z_l \alpha)\gamma \omega^2 P_0 \beta_2 + \alpha(m\alpha + (\mathrm{e}^{-z_l \alpha} - 1) m z_{\mathrm{eff}} \gamma \omega^2 P_0 \beta_{\mathrm{g}})], \tag{11b}$$

$$I_2 = \frac{1}{\alpha^3} \omega^2 P_0 \mathrm{e}^{-z_l \alpha} [(\mathrm{e}^{-z_l \alpha} - 1) m^2 z_{\mathrm{eff}} \alpha^2 \gamma P_0 \beta_{\mathrm{g}} - m(\mathrm{e}^{-z_l \alpha} - 1 + z_l \alpha)\gamma P_0 \beta_2 (m\alpha + (\mathrm{e}^{-z_l \alpha} - 1) \times m z_{\mathrm{eff}} \gamma \omega^2 P_0 \beta_{\mathrm{g}})]. \tag{11c}$$

The total 2HD second-harmonic distortion caused by the fibre and the fibre grating becomes

$$\mathrm{2HD} = \frac{\omega^2}{\alpha^3} [(\mathrm{e}^{-z_l \alpha} - 1) m z_{\mathrm{eff}} \alpha^2 \gamma P_0 \beta_{\mathrm{g}} - (\mathrm{e}^{-z_l \alpha} - 1 + z_l \alpha)\gamma P_0 \beta_2 (m\alpha + (\mathrm{e}^{-z_l \alpha} - 1) \times m z \gamma \omega^2 P_0 \beta_{\mathrm{g}})]. \tag{12}$$

When the fibre transmission link is long enough, i.e. $z_l > 50$km, the attenuation term $\mathrm{e}^{-z_0 \alpha}$ is very small compared with 1, and may be neglected. So the 2HD expression can be simplified into the following form:

$$\mathrm{2HD} = \frac{\omega^2}{\alpha^3} [-m z \alpha^2 z_{\mathrm{eff}} \gamma P_0 \beta_{\mathrm{g}} - (-1 + z_l \alpha) \times \gamma P_0 \beta_2 (m\alpha - m z_{\mathrm{eff}} \gamma \omega^2 P_0 \beta_{\mathrm{g}})]. \tag{13}$$

From the expression of (13), we know that, when the dispersion of the fibre link is compensated by the fibre grating completely, the second-harmonic distortion is small enough and the corresponding fibre grating dispersion compensation amount is

$$\beta_{\mathrm{g}} z_{\mathrm{eff}} = \frac{-\alpha(-1 + z_l \alpha)\beta_2}{\alpha^2 + \gamma \omega^2 P_0 \beta_2 - z_l \alpha \gamma \omega^2 P_0 \beta_2}. \tag{14}$$

To illustrate the preceding expressions, in the following simulation, we assume that the corresponding parameters are ω=543.25MHz, m = 0.04, α = 0.2dB/km, P_0=40mW, γ=3W^{-1}·km^{-1}, β_2=25ps^2/km, β_{g}=-10^7ps^2/km and z_l=60km, the variation of CSO distortion with the dispersion amount of CFG is shown in Fig.1. From the figure, the theoretical result from Eq.(13) is in good agreement with the numerical simulation. At the same time, when the dispersion amount of CFG satisfies expression (14), the CSO performance of the system is optimal and may be considered to have almost no CSO distortion existing in a practical system (< -75dBc). Or the system may appear in the case of over-compensation or under-compensation, either case will deteriorate CSO performance.

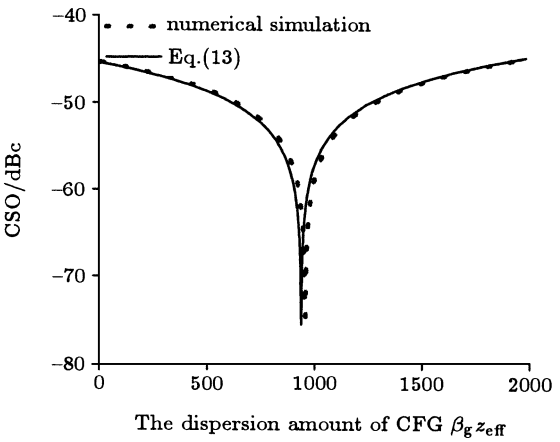


Fig.1. The CSO distortion vs the dispersion compensation amount of CFG with z_l=60km.

Figure 2 shows the variation of CSO distortion with the dispersion amounts of the fibre link and CFG. With the fibre propagation link increasing, the accumulated dispersion amount increases and the dispersion compensation amount of CFG should also increase in order to keep an optimal CSO performance. For a different fibre transmission link, the optimal dispersion compensation amount is also different.

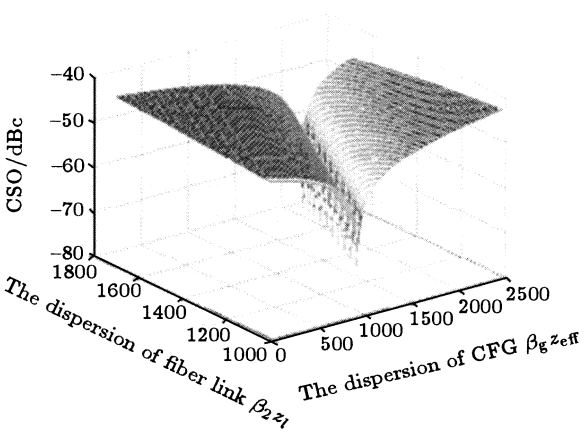


Fig.2. The CSO distortion vs the dispersion amounts of CFG and fibre transmission link.

3. Experimental setup and results

Figure 3 shows our experimental setup of an optical CATV transmission system with 59-channel (PAL-D) fully loading externally modulated signals by using tunable CFG as a fibre dispersion compensation

device in order to change the dispersion compensation amount. RF sub-carriers are generated from an RF carrier signal generator and are fed into an externally modulated transmitter with a light modulation index (OMI) of ~4%. The launched light power into the fibre is kept at <17dBm by using a variable optical attenuator (VOA) to avoid degradation caused by the SBS effect. The system link with a transmission length of 125km consists of two SMF spans (50+75km, with an attenuation of 0.24dB/km and a dispersion coefficient of 17ps/km/nm). The light power is amplified by two stages of EDFAs to transmit a light signal. The light power input to an optical receiver is adjusted to about 1.0dBm using a VOA. All CATV RF parameters are measured using an HP RF-Spectrum Analyser after a 125km fibre span transmission.

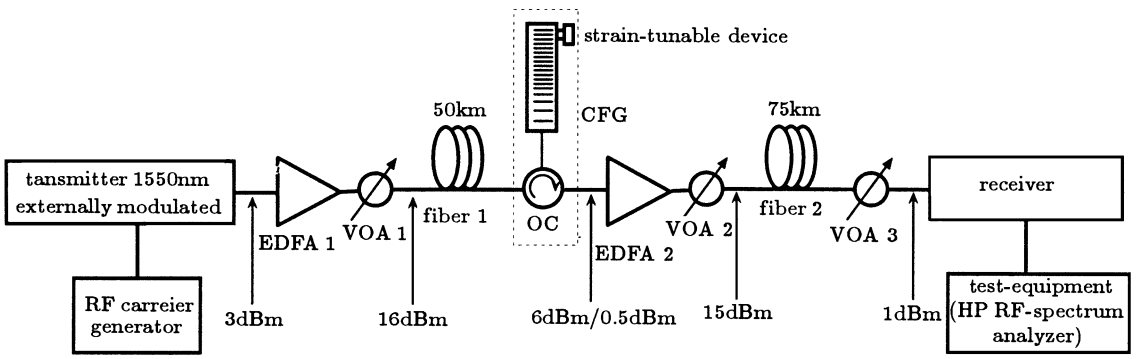


Fig.3. Externally modulated fibre transmission system using CFG as a tunable dispersion compensation device.

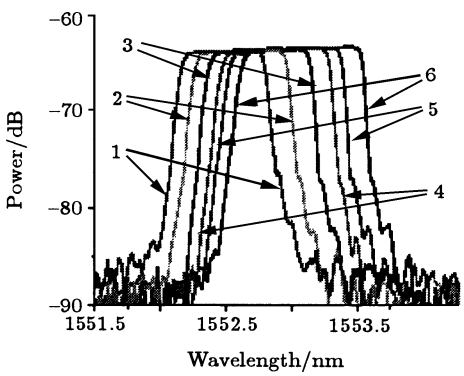


Fig.4. Reflection spectra of the CFG by adjusting the strain-tuning device.

A 10cm long CFG is fabricated by UV imprinting. Its 1-dB line-width is about 0.97nm and the corresponding original dispersion compensation amount is about 1000ps/nm before tuning. The wavelength of CFG should match that of the transmitter. To adjust the dispersion amount of the CFG, it is fixed on an aluminium cantilever beam. By adjusting the displacement of the beam free-end, the CFG bandwidth can be changed and the corresponding dispersion compensation amount is also changed. Figure 4 shows the CFG reflection spectrum by adjusting the strain device. The CFG is connected to the fibre link by a optical circulator in front of the second EDFA to obtain a better compensation effect.

Figure 5 shows the measured CSO RF spectra of the channel 22 (CH-22) after the 125km SMF link. The central frequency is 543.256MHz and the span is 8MHz. Figure 5 (a) is the transmission spectrum without dispersion compensation. The CSO distortion appears at 544.516MHz (the mark of Fig.5) and its value is 50.9dB, which does not satisfy the requirement for the fibre optical CATV CSO performance (>60dB) obviously. Figure 5 (b) shows the optimal result of the dispersion compensation effects by adjusting the CFG's strain-tuning device to obtain the optimal dispersion compensation amount. The CSO at 544.516MHz (the mark of Fig.5) is improved, reaching about 17.2dB up to 68.1dB. The result is a little worse than the theoretical result (Fig.2), which is due to the fact that the other mechanisms, such as polarization mode dispersions of fibre and CFG, the group delay ripple of CFG and so on, have not been taken into consideration in the above theory, however, they are included in the experimental result.

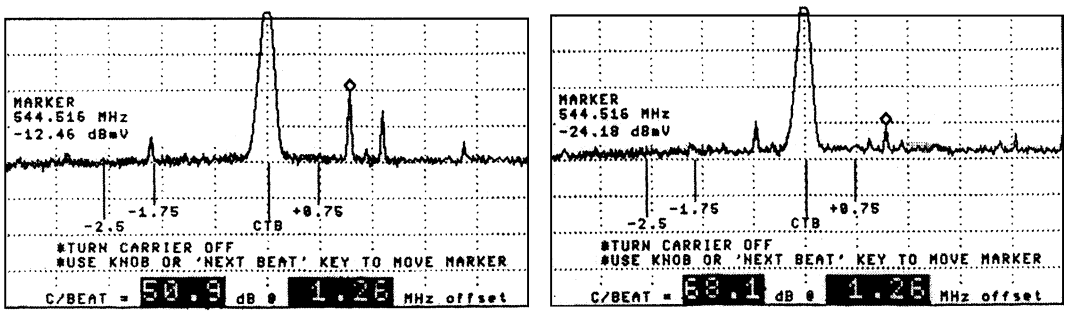


Fig.5. Optical spectra of the 125km SMF link (a) without dispersion compensation; (b) with dispersion compensation.

4. Conclusions

We analyse the dispersion compensation theory of the CFG in an optical fibre CATV system and obtain the analytic expression of the CSO distortion after the dispersion compensation of the CFG. The theoretical result is in good agreement with the numerical simulation. At the same time, the result is also verified by the experiment, in which we use the tunable characteristics of CFG to change the dispersion compensation amount and obtain a good CSO performance in a 125km fibre transmission link. Both the theoretical and experimental results show that the CSO performance can be improved by properly choosing the dispersion compensation amount for a certain fibre transmission link.

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