

Study on the suppression of IFWM in 40 Gb/s WDM systems

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Abstract The paper analyses the effects of intra-channel four-wave mixing (IFWM) on the high-speed optical fiber communication system. A new code format is developed with double 0 and double π phase separating 1 code; it can decrease the transmission penalty from fiber nonlinearity by counteracting the perturbation terms of IFWM. From the simulation of transmission of two classic code data “11011” and “11100”, we find that our proposed code format has a better suppression effect than the alternative modulation inversion (AMI) or the normal RZ format and supports a wider pulse mode. In a 40 Gbps system, the AMI format is 2 dB less than the RZ format, and our proposed format is 1 dB less than the AMI format when a 1 dB eye open penalty is taken as a meteward. Moreover, it can be realized as easily as the AMI format.

Keywords wavelength division multiplex (WDM), 40 Gb/s, intra-channel four-wave mixing (IFWM), nonlinear effect

1 Introduction

With the emergence of the 40 Gb/s transmission standard, commercialization connection and transceivers, practical 40 Gb/s optical transmission technology has become the key technology in the application of a 40 Gb/s WDM system. However, there are many physical limitations for the 40 Gb/s system in optical fiber transmission. In comparison with a 10 Gb/s optical fiber transmission system, a 40 Gb/s system requires higher signal-to-noise ratio, but has lower adaptation ability to the wave profile loss of signals such as dispersion and the nonlinear effect [1]. Meanwhile, the nonlinear effect in the channel has already substituted the nonlinear effect between the channels and become the most important

factor limiting the performance of 40 Gb/s optical transmission systems. The optical fiber nonlinear effect impacting a 10 Gb/s WDM system mainly includes self-phase modulation (SPM) of the pulse and four-wave-mixing (FWM) caused by pulse interaction between the channels and cross-phase modulation (XPM). In contrast, the optical fiber nonlinear effect impacting a 40 Gb/s WDM system is mainly between the channels due to the short distance between the pulses (25 ps) and wide signal spectral width (approximately 80 GHz) in the 40 Gb/s transmission systems [2–4]. After the signal is injected into the optical fiber, the optical pulse stretches fast as a result of the dispersion, and then adjacent pulses overlap seriously, thus producing a strong nonlinear function between the pulses — this is the main nonlinear effect in the 40 Gb/s system.

The main effect of nonlinear interaction between the pulses resulting from pulse overlapping within the same channel is cross-phase modulation between pulses (IXPM) and the four-wave mixing effect (IFWM). They will cause time vibration and power fluctuation of pulse signals separately and seriously affect the transmission performance of a 40 Gb/s system. At the same time, they are the main factor limiting transmission distance. Once nonlinearity occurs, it is very difficult to compensate and correct, so how to design a 40 Gb/s transmission system to reduce the impact of this effect is an important research task for 40 Gb/s system transmission technology.

At present, the emergence of many new technologies for 40 Gb/s systems is expected to improve adaptation ability to noise and nonlinearity; research on system modulation format is currently the popular focus for suppressing the nonlinear effect in the channel. Research on system modulation code includes not only designing a new modulation format, but also thoroughly studying the performance of proposed modulation formats. In recent years there have been many reports on this format. Conradi et al. made research on the nonlinear function of phase modulation NRZ modulation format between pulses in a 40 Gb/s system in 2002 [5]. Bell Labs

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conducted a 5200 km UltraWave optical fiber transmission in a 40 × 42.7 Gb/s DWDM system by using carrier suppression NRZ (CSRZ) in the same year [6]. Gill et al. from Lucent conducted research to improve the nonlinear adaptation ability of the ordinary OOK code in 40 Gb/s systems by using $\pi/2$ -AP OOK (alternating phase-shift keying switches) code in 2003 [7]. AMI code's suppression of the effect in the channel of 40 Gb/s systems proposed by Lucent's researchers in 2003 also attracted many researchers' attention [8,9]. This paper presents a new modulation format. It offers spacing by double 0 double π phase between 1-code to make IFWM disturbances mutually offsetting, which can obviously suppress the IFWM effect and the parasitic pulse.

2 Theory

The lumped-loss in dispersion management optical fiber and the evolution of transmission in dispersion compensation system of optical signals can be described as a nonlinear Schrodinger equation [10]:

$$i \frac{\partial u}{\partial z} + \frac{D(z)}{2} \frac{\partial^2 u}{\partial t^2} + g(z)|u|^2 u = 0, \quad (1)$$

where all quantities are expressed as dimensionless forms: $t = t_{\text{ret}}/t_*$, $z = z_{\text{lab}}/t_*$, $u = E/\sqrt{gP_*}$, characteristic parameter adds the angle sign *, z_{lab} , t_{ret} represent transmission distance and time delay respectively, and E represents the slowly varying envelop of light field. The characteristic parameter is chosen as $z_* = z_{\text{NL}} = 1/(vP_*)$ and v is a nonlinear coefficient. $D(z)$ and $g(z)$ are the non-dimensional functions describing fiber group velocity dispersion and attenuation of the optical power respectively.

When studying the evolution of the pulse located at $t = 0$ under the nonlinear function in the channel, u can be written as the pulse sum of each bit, with u_k indicating the pulse located at $t = kT$ and k is the integer, $u = \sum_{k=-\infty}^{\infty} u_k$. Substituted into Eq. (1), the nonlinear Schrodinger equation can be expressed as follows, where the pulse u_0 located at $t = 0$ is disturbed by nonlinear item $u_l u_m u_n^*$,

$$i \frac{\partial u_0}{\partial z} + \frac{D(z)}{2} \frac{\partial^2 u_0}{\partial t^2} + g(z)|u_0|^2 u_0 = F_0(z, t) = -g(z)u_l u_m u_n^*. \quad (2)$$

By phase matching condition, l, m, n should satisfy $n = l + m$. When $l = m = n = 0$, the item at right side of the formula is $|u_0|^2 u_0$, which expresses pulse u_0 own self-phase modulation. When $l = n \neq 0, m = 0$, this item is $|u_1|^2 u_0$, indicating cross phase modulation of pulse u_1 to u_0 , or

cross phase modulation in the channel (IXPM). For other situations, this item expresses four-wave mixing in the channel (IFWM).

It is clear that the self-phase modulation of the pulse and IXPM are unrelated to the phase of the pulse, while the IFWM is related with it. In addition, they interact among relatively close pulses and the interaction between 6 or 7 pulses can be neglected. More detailed calculation shows that IXPM will cause frequency offsetting of the pulse, which will result in time jittering that is due to group velocity dispersion and will increase linearly with increasing transmission distance. The IFWM will lead to the fluctuations in pulse rate, which results in a ghost pulse in the place without optical power of "0" code, reduces or increases the pulse rate representing "1" code and worsens the eye chart. IXPM cannot lead to a power exchange between pulses, but not for IFWM. The production mechanism of IFWM may be explained by chart 1. Taking pulse sequence "0110" as an example, the first line of the graph shows the energy distribution of a signal in time frequency plane, while the second line shows the time domain waveform. The first row shows the signal before transmission. After the group velocity dispersion, the signal gets into the condition as Fig. 1(b) shows, where the vertical distribution in the time frequency plane becomes inclined and an overlap of two pulses appears in one part of the time domain. As a result of four waves mixing, as the third row shows, there is four-wave mixing light in the place with equal spacing to the top and bottom. After the dispersion compensation, the signal shows as the fourth row in Fig. 1(d). Four waves mixing light originally in the place with equal frequency spacing moved into the place with equal spacing of time domain and produced a light pulse in the "0" code place.

It should be noted that each (l, m, n) group will have an IFWM item and corresponding parasitic pulse which can be expressed as follows [11]:

$$\frac{dA_0}{dz} = \sum_{l,m,n} D_{lmn} \gamma |A_l A_m A_n^*| F_{0 \leftarrow l+m-n}(z), \quad (3)$$

where A_k is the plural rate of pulse at $t = k$. When l, m, n are mutually different, $D_{lmn} = 2$, otherwise, $D_{lmn} = 1$. γ is the nonlinear coefficient of optical fiber, while $F_{0 \leftarrow l+m-n}(z)$ is the phase factor of disturbance. Assuming that each pulse is in Gaussian shape and is "0" code at $t = 0$, we can get a phase factor of four waves mixing disturbances of the pulse at the location of 0 ($n = l + m$), resulting from three pulses at l, m , and n separately.

$$F_{0 \leftarrow l+m-n}(z) = \exp\{i[\phi_l(0) + \phi_m(0) - \phi_n(0)] - i \frac{\pi c T^2}{\lambda D_{\text{accum}}(z)} (l^2 + m^2 - n^2)\}, \quad (4)$$

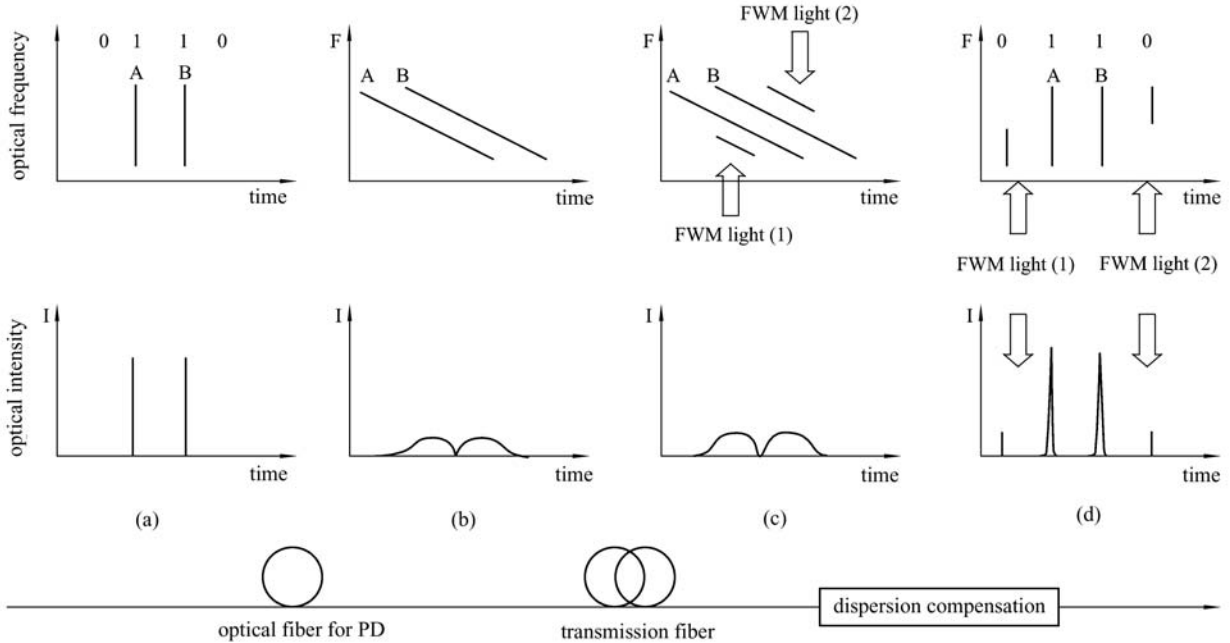


Fig. 1 Mechanism of IFWM generated

$\phi_k(0)$ is the initial phase of the k^{th} pulse in the center of pulse. $D_{\text{accum}}(z)$ is the accumulated dispersion. The second item of the index is the phase change caused by group velocity dispersion, which is related to dispersion configuration. With the transmission of a signal, the immediate dispersion quantity changes constantly and the second item also changes while the first item does not. The simulation shows that relative phase between parasitic pulses from IFWM is mainly decided by the initial phase. The second observation is that the changing phase changes unceasingly and is offset mutually with the accumulation of transmission distance. According to this characteristic, the disturbance of IFWM can be controlled by modifying pulse initial phase, enabling the mutual offset.

Because the IFWM effect is sensitive to the pulse phase, we can change the phase of the pulse sequence to make all simultaneous disturbances resulting from four waves mixing offsetting mutually, suppressing the IFWM effect and enhancing the transmission performance of the signal.

Several kinds of modulation formats are presented:

1) The traditional RZ code represents 1 with one light pulse and 0 with non-light pulse. For the ideal RZ signal, phases of all optical carriers are the same, i.e., there is no phase modulation or no chirp.

2) The carrier suppression return zero (CS-RZ) code, based on the traditional RZ code, adds the phase difference of π between the carriers of each adjacent symbol, regardless of 0 code or 1 code in the carrier. The phase difference of carrier π can be regarded as the signal, and the carrier does not change when adding a negative sign. The mean of the signal with both positive and negative polarity is zero. Therefore, there is no peak

resulting from δ function at zero frequency in its spectrum and correspondingly, there is no peak at carrier frequency after multiplying the carrier. Hence it is called “carrier suppression”.

3) For the AMI-RZ code, on the basis of traditional RZ code, whenever one 1 code appears, the phase of carrier increases (or is reduced) compared to the previous 1 code; regardless of the number of 0 codes, there are or there is no 0 code between two 1 codes. This format has no unified name in optical communication. It is also called Duobinary CS-RZ code because it may be regarded as the superposition of phase inversion modes of Duobinary code and CS-RZ code. It is also called Modified Duobinary in some documents. We call it AMI code in the paper for the sake of unification.

4) The modulation format proposed in the paper is shown as the code format at the bottom of Fig. 2. The phase is separated by two 0 and two π between 1 codes. We have explained its advantages in other papers: that the IFWM disturbance can offset mutually, thus suppressing the IFWM effect and formation of a parasitic pulse. We will analyze its performance through value simulation in the following experiment.

3 Numerical results

For evaluating the modulation format in the round, we have simulated the system transmission performance.

The transmission system is shown in Fig. 3. Each span is composed of 95 km NZDSF with $D = 7.06$ ps/(nm·km), 5 km DCF and EDFA. 30 spans are simulated and

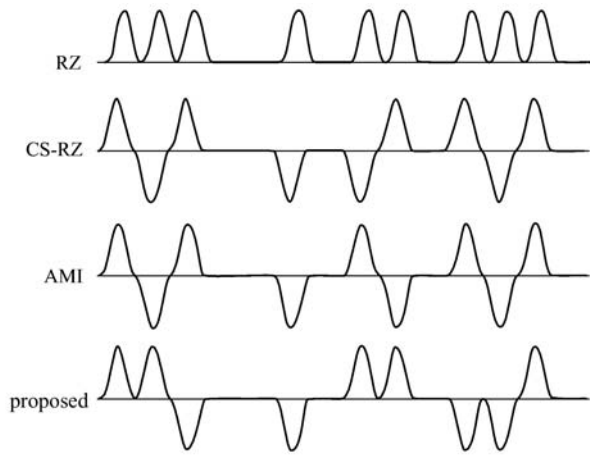


Fig. 2 Examples of several kinds of code formats

2^7-1 pseudo codes are used. Different modulation formats are implemented, including RZ, AMI and our new code. The input power changes from -1 to 6 dB and pre-dispersion is set to -410 ps/nm in all cases. In Fig. 4, the electrical signals are shown after data series “11011” and “11100” are transmitted with the three modulation formats. For evaluating the parasitical pulse amplitude, a logarithmic longitude coordinate is used and the maximal value is 0 dB. Obviously, for the left data code “11011”, the parasitical pulse appears at the central 0 code for the traditional RZ format, but is suppressed under AMI and our proposed format. For the right data series “11100”, the suppression effect on the left 0 code is very weak for the RZ and AMI formats, but our proposed code format obviously improves suppression. The eye open penalty of different code formats is shown in Fig. 5. As the input

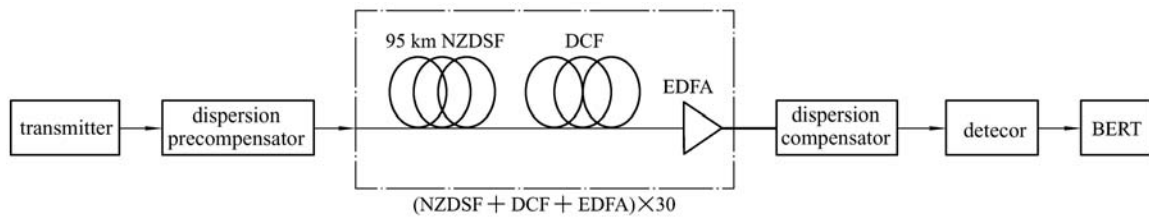


Fig. 3 Structure of the system in simulation

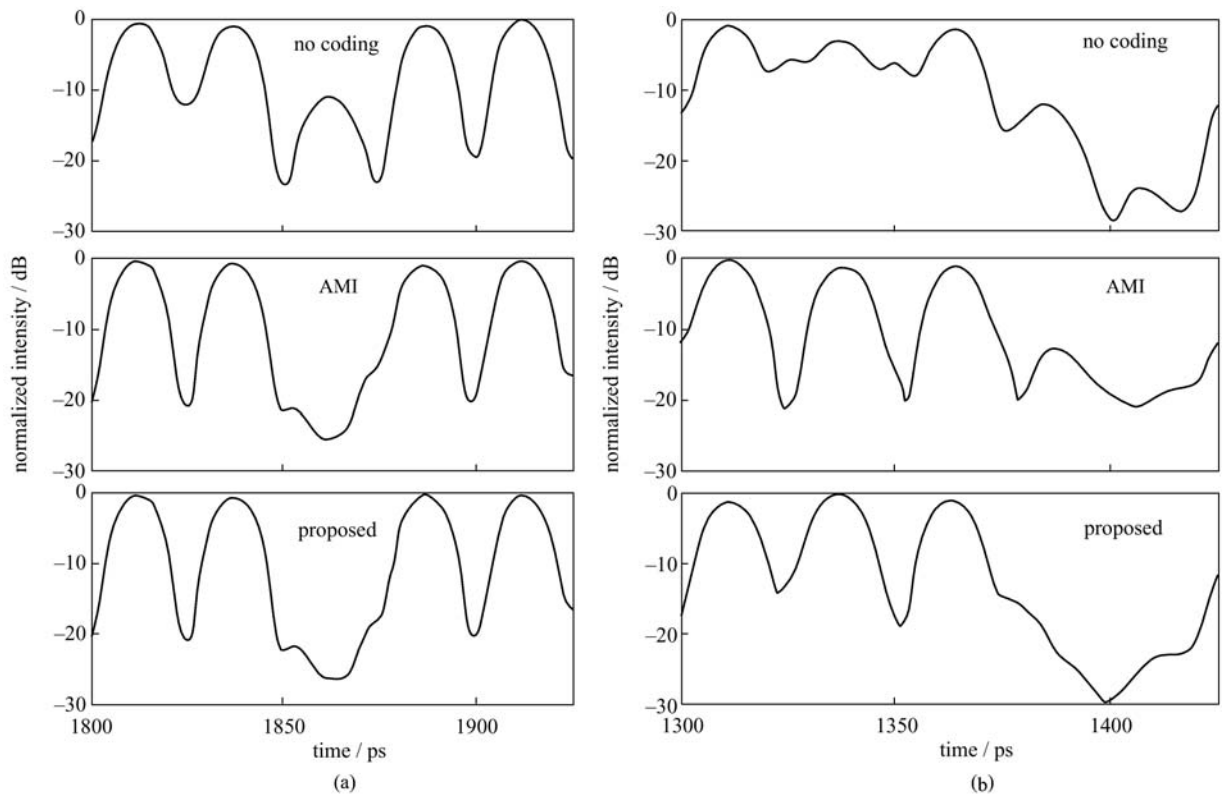


Fig. 4 “11011” and “11100” signal comparison of three code formats

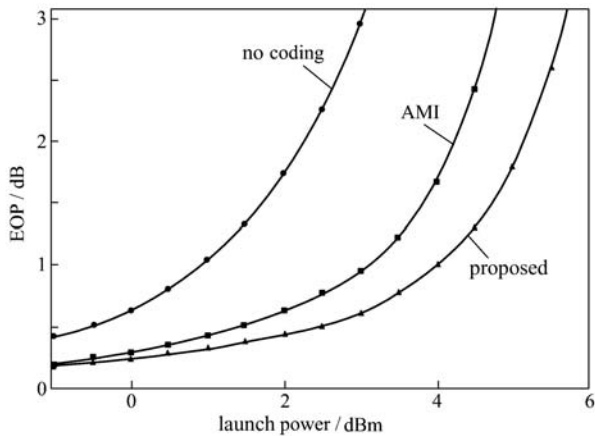


Fig. 5 Eye open penalty (EOP) of different code formats

power is small, the three formats give almost the same transmission performance, which shows that their performance difference is due to intra-channel nonlinear effects. RZ format transmission performance worsens first with increasing power, followed by the AMI format. Our proposed format offers good performance with 1 dB power penalty less than the AMI format does.

4 Conclusions

The IFWM principle of high speed optical fiber communication is analyzed. A new modulation format which can suppress the parasitical pulse with the nonlinear interaction length of less than 5 bit is then presented. The new format decreases the transmission penalty due to the counteraction of IFWM perturbation terms, and its performance is better than those of the RZ and AMI formats.

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