A Study on the Effects of Dispersion and Nonlinearity in Optical Fiber Communication Systems using DCF

Jing Niu 1, Jianqiao Shen * 2, Niu Yubing 3

1 School of information Science & Engineering, Lanzhou University
2 Department of COMPUTER & Information Science, City College of DongGuan University of Technology, DongGuan 523419, GuangDong, China
3 Zhuhai Radio & TV University, Zhuhai, 519000, China

* Corresponding author is Jianqiao Shen, email: 331096487@qq.com

Abstract --- In modern optical fiber communication systems, dispersion and nonlinear effect of optical fiber are the two main factors of decreasing communication quality, especially in Group Velocity Dispersion (GVD). In this paper, we use single-mode transmission fiber, Dispersion Compensation Fiber (DCF) and erbium-doped fiber amplifier (EDFA) to design a dispersion compensation optical fiber communication link. In optisys software, we simulate the 4QAM optical fiber communication system which based on this communication link. Through the diagram of constellation of receiving single, we study the influence of group velocity dispersion, nonlinear effect, amplify spontaneous emission (ASE) respectively, and their mutual effects to the quality of the signal in communication system. The results shows that dispersion compensation can only remove the influence of group velocity dispersion, but the nonlinear phase noise, which caused by the mutual effects of nonlinear effect and amplify spontaneous emission, will be accumulated as the increasing of fiber length and influencing the quality of 4QAM optical fiber communication system.

Keywords - Nonlinear Effect, Group Velocity Dispersion, Dispersion Compensation Fiber, Quadrature Amplitude Modulation, Nonlinear Phase Noise

I. INTRODUCTION

The influence to signal transmission quality in optical fiber communication systems is mainly caused by fiber loss, dispersion and nonlinear effect. However, with the development and usage of the Erbium Doped Fiber Amplifier (EDFA), optical fiber communication system changed further. Optical amplifier replaced traditional photoelectric repeater, and fiber loss has no longer become the main factor to limit fiber transmission length. As a result of that, dispersion and nonlinear effect become two hot spots for researchers, and the method to decrease the influence of this two factors become very important [1].

Dispersion will cause pulse broadening, results in the limit of the communication capacity (product of BL) of communication system, which will ultimately affect the quality of the signal transmission. For this characteristic, the researchers put forward many kinds of dispersion compensation technics. Finally the dispersion compensation fiber (DCF) is applied widely because of advantages such as the relatively matured technics, suitable for long distance transmission with controllable dispersion compensation amount, large bandwidth and transparent for transmission formats and bit rate. The method of dispersion compensation fiber is to add dispersion compensation fiber into optical fiber link, to make the total dispersion nearly zero, to decrease the influence of Group Velocity Dispersion (GVD) at least.

The nonlinear effect of the fiber is caused by the long transmission distance and the minimum cross-sectional area of light field. As a result, optical fiber material has obvious nonlinear effect although the quartz material itself does not have apparent nonlinear effect. Besides, nonlinear effect and amplifier spontaneous emission (ASE) noise will interact and cause nonlinear phase noise [2]. Although in the optical communication system of amplitude modulation, phase changes which caused by nonlinear effect has no effect on the signal of receiving end. But do very different in coherent optical communication system. The impact of the phase change is obvious. Currently, amplitude modulation communication system is still widely used because of its advantages of simple, easy to integrate etc. But it will be replaced by the coherent optical communication system in the future because of its limited single channel bandwidth. So the study on the Effects of Fiber Dispersion and Nonlinearity in 4QAM Dispersion Compensation Optical Fiber Communication System based on DCF has certain significance.

II. PRIOR KNOWLEDGE

A. Dispersion of Optical Fiber

1) The group velocity and its representation

In optical fiber transmission medium, optical signals includes many different frequency component, and different frequency component transfer in different velocities, so pulse broadening will caused in the process of pulse transmission. This phenomenon is called the group velocity dispersion. The group velocity dispersion is the dispersion of the second order effect, and the phase velocity dispersion is the first order effect. The results of the group velocity dispersion is pulse broadening and the limitation of the bit rate distance product (BL, communication capacity) in optical fiber communication system.
Normally dispersion comes from mode dispersion, material dispersion and waveguide dispersion.

Mode dispersion refers that the multimode fibers in different transfer mode cause different signals arrive at the end in different times.

Material dispersion is because there is a nonlinear relationship between the transmission wavelengths n and the refractive index of fiber core material λ. This makes the group velocity of a given pattern depends the wavelength.

The waveguide dispersion is because the fiber core and cladding has small refractive index. When the total reflection happens on the boundary surface, some light go into the cladding, this part of light go back into the core after the transmission in the cladding. This makes the different arrival times of different parts of light, which means pulse broadening.

Because there is only one transfer mode in single mode fiber, regardless of the mode dispersion, the two main sources of the group velocity dispersion are material dispersion and waveguide dispersion. Generally dispersion coefficient D(λ) is used to express the degree of group velocity dispersion (ps/nm/km). The parameter of dispersion can be represent as follows

\[ D = D_0 + D_\omega, \]

the group velocity dispersion usually represent as:

\[ \beta_2 = \frac{d^2 \beta}{d\omega^2}, \]

Among the formula above the β is the transmission constant.

The relationship between D and β2:

\[ \beta_2 = -\frac{D}{2\pi c}. \]

Group velocity dispersion is divided into the normal dispersion region (β2>0, D<0) and the abnormal dispersion region (β2<0, D>0) [3].

In the zero dispersion wavelength, Single-mode fiber dispersion did not disappear completely, there is still a high order dispersion β3:

\[ \beta_3 = \frac{d^3 \beta}{d\omega^3}, \]

Its value has a relationship with dispersion slop S [4,5]:

\[ S = \frac{dD}{d\lambda} = \frac{2\pi c}{\lambda^2} \beta_3 + \frac{4\pi}{\lambda^2} \beta_2. \]

2) The basic method and principle of the dispersion compensation

Many compensation method of fiber dispersion are put forward by researchers, such as dispersion compensation fiber (DCF), chirped fiber grating (CFG), dispersion supported transmission (DST), Spectral Inversion, Chirp and optical solution transmission technics [6]. Among these, dispersion compensation fiber is widely used because of its advantages such as, relatively mature and simple technology, transparent to transmission format and bitrate, stable performance and compatible with WDM.

Normally linear partial differential equation of optical pulse under the action of group velocity dispersion and high order dispersion:

\[ i \frac{\partial A}{\partial z} = \beta_2 \frac{\partial^2 A}{\partial T^2} + i \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3}. \]

General solution is obtained by Fourier change:

\[ A(L, t) = \frac{1}{2\pi} \int A(0, \omega) \exp \left( -i \omega^2 \beta_2 L - \frac{i}{6} \beta_3 \omega^3 \right) d\omega. \]

There into, L is the length of SMF, the term including β2 is the second order dispersion, the term including β3 is the third order dispersion. Compare with the influence caused by β2, the effect of β3 is not obvious. So in the paper, we only consider the influence of β2.

Positive dispersion is because that when light pulse into the material with high refractive index from the material with low refractive index, its velocity declines. When light pulse into the high refractive index material from the low one, its velocity increases. This is called negative dispersion [7].

In actual engineering, SMF has positive dispersion D, which means negative β2 and DCF has negative dispersion D, positive β3. If we insert a length of DCF in optical link, the dispersion effect of DCF will be imported.

In The formula above, an extra term of DCF second order dispersion will be added into the term which including SMF second order dispersion. The change is:

\[ \frac{L}{2} \frac{\partial^2 \beta_2 L_i}{\partial \omega^2} \frac{\partial A_L}{\partial \omega} \rightarrow \frac{i}{2} \omega^2 \beta_2 L_i + \frac{i}{2} \omega^2 \beta_3 L_i. \]

There into, L is the length of SMF, the term including β2 is the second order dispersion of SMF, the other term including β3 is the second order dispersion of DCF. If set the appropriate values to make the value of \( \beta_2 L_i + \beta_3 L_i \) zero, effect to signal amplitude A of second order dispersion can be removed. But in practical engineering, dispersion compensation can only according to certain experience to provide a general transmission distance dispersion compensation scope, and can't be precise compensation.

B. Nonlinear effects of optical fiber

1) The nonlinear effect of optical fiber

Fiber optical medium polarization P changes with nonlinear electric field intensity E changes. Just about this led to nonlinear effects. The minimum order nonlinear effects comes from the third-order electric susceptibility \( \chi^{(3)}. \)

Because the electric polarization intensity has nonlinear relationship \( p = eE \) with incident light instead of linear relationship:

\[ p = \epsilon \left( \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right). \]

Although the second order nonlinear polarization \( \chi^{(2)} \) can cause frequency doubling, sum frequency, difference frequency and optical rectification effect. But \( \chi^{(3)} \) is not zero only in the inversion symmetry molecular structure of medium, and molecular structure of SiO2 is symmetrical, therefore, second order nonlinear effect usually don’t shows in optical fiber communication system. The third order nonlinear polarization \( \chi^{(3)} \) will cause Kerr effect, the two-photon absorption, since the focal length, the phase modulation and stimulated Raman scattering and stimulated brillouin scattering etc.

There are two kinds of effects which have a great influence on quality of optical fiber communication system among various kinds: One is stimulated scattering, including
Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS). The other is the nonlinear refractive index modulation, including the self-phase modulation, cross phase modulation and four-wave mixing. In this paper, we mainly consider the phase modulation effect to the communication quality of system.

2) Self phase modulation

The nonlinear phase change which caused by the nonlinear effect of light field is called the self phase modulation of light field. Nonlinear refractive index and optical field influences each other in systems, as a result conductor transmission constant changes and an extra item is added:

\[ \beta' = \beta + \gamma P \]

In the formula, \( \beta \) is the transmission constant, \( P \) is the transmission power, \( \gamma \) is called the nonlinear factor:

\[ \gamma = \frac{k_n n_{20}}{A_{eff}} \]

Here, \( n_{20} \) is called the nonlinear refractive index, \( A_{eff} \) is the effective area.

After import the extra item of transmission constant, its phase will increase with the length by linear. Phase deviation deduce by transmission length \( L \) as follows:

\[ \phi_{NL} = \int_0^L (\beta' - \beta) dz = \int_0^L \gamma P(z) dz = \int_0^L e^{\gamma P} dz = \frac{k_n n_{20} L_{eff}}{A_{eff}} p_i \]

\( p_i \) is the power of incident light.

III. DISPERSION AND NONLINEAR EFFECTS IN
4QAM OPTICAL FIBER COMMUNICATION SYSTEM

A. Quadrature Amplitude Modulation (QAM) and Signal Constellation Diagram

Quadrature amplitude modulation: In the M scale digital modulation system, Maximum entropy for each symbol is \( \log M = \log(M) \). In a limited frequency band of the channel, \( M \) scale increases the information transmission rate, raises the utilization ratio of the frequency band.

MQAM is composed of two orthogonal carrier multilevel amplitude shift keying signal position. Two of the road of multilevel amplitude sequences are independent of each other. MQAM signal expression is as follows:

\[ S_{ MQAM}(t) = \sum_{i=1}^{M} a_i g_i(t) \cos \omega_0 t - a_i g_i(t) \sin \omega_0 t, i = 1 \sim M, 0 \leq t \leq T_s \]

\( a_i \) is a set of discrete level set. \( g_i(t) \) is the baseband shaping filter impulse response.

MQAM can be expressed as a linear combination of two normalized orthogonal basis functions:

\[ s_i(t) = s_{i1} f_1(t) + s_{i2} f_2(t) (i = 1 \sim M, 0 \leq t \leq T_s) \]

Two of the normalized orthogonal basis function is

\[ f_i(t) = \sqrt{\frac{2}{F_x}} g_i(t) \cos \omega_0 t, 0 \leq t \leq T_s \]

\( f_1(t) = - \frac{\sum_{i=1}^{M} g_i(t) \cos \omega_0 t}{F_x}, 0 \leq t \leq T_s \)

\( s_{i1} = \int_0^T s_i(t) f_1(t) dt = a_{i1} \sqrt{\frac{F_x}{2}}, i = 1 \sim M \)

\( s_{i2} = \int_0^T s_i(t) f_2(t) dt = a_{i2} \sqrt{\frac{F_x}{2}}, i = 1 \sim M \)

The signal waveform of the two-dimensional vector expressed as

\[ s_i = [s_{i1}, s_{i2}] = [a_{i1}, \sqrt{\frac{F_x}{2}}, a_{i2}, \sqrt{\frac{F_x}{2}}], i = 1 \sim M \]

\( E_i \) is the power of pulse \( g_i(t) \).

So the rectangular MQAM signal constellation diagram as Diagram 3.1 as right.

Diagram 3.1 the rectangular MQAM signal constellation diagram.

This paper uses 4QAM modulation format, so using the graph is \( M = 4 \) constellation diagram.

B. 4QAM optical fiber communication model based on dispersion compensation fiber

Normally, The dispersion compensation model based on optical fiber is divided into the front-end compensation, the back-end compensation and the mixed compensation. We choose the back-end compensation model as our example to found our 4QAM optical fiber communication system model. The optical link of model includes the simple model fiber, the back-end dispersion compensation fiber and the Erbium Doped Fiber Amplifier. Our 4QAM optical fiber communication system model structure as diagram 3.2 as bellow.

C. The research of the nonlinear effect and the group velocity dispersion in optical fiber

1) The influence before inserting dispersion compensation fiber

In the actual system, signal of output end(receiving end) has a little difference with the signal of input end. Based on diagram 3.2 model, we simulate the 4QAM optical fiber communication system in optisys software. Ignoring the nonlinear effect and the group velocity dispersion of optical fiber link respectively. We choose the 4QAM modulation mode, length 50km, \( P = 50mW \), bit rate=40gbit/s, loss=0.2db/km, gain=10db, at this time, the star map of the input and output end signals as diagrams 3.3 , 3.4 ,3.5 and
3.6 as bellow.

Diagram 3.2 Our 4QAM optical fiber communication.

Diagram 3.3 The star map of input end signal

Diagram 3.4 The star map of receiving end signal.

Diagram 3.5 The star map of receiving end signal.

Compare diagram 3.4 with diagram 3.5, we can see that before inserting DCF, only considered the effect of group velocity dispersion \( D = 16 \text{ (ps/nm·km)} \), the signal of the receiving end serious distorts and the original signal can not be distinguished.

When only considered the influence of the nonlinear effect \( A_{eff} = 80 \mu m^2 \), we can see that it caused the phase change of the signal. Compare with the original signal, the influenced signal changes \( \Phi \) in its phase.
2) The influence of the nonlinear effect and the group velocity dispersion after inserting DCF
In order to eliminate the receiving signal distortion caused by dispersion, dispersion compensation fiber be used insert to the system in the actual engineering. In our simulation, we insert the dispersion compensation fiber (length 10km dispersion=-80ps/nm/km effective area=80um² total length=60km), the impact of the dispersion in the system is basically eliminated. In the star map of diagram 3.7, we can see that after inserting DCF, the original signal (star map as diagram 3.4) be recovered, the phase and the amplitude of original signal can be distinguished clearly.

But when only considered the influence of the nonlinear effect, the output end signal still has a phase change (Diagram 3.8) compared with original signal after DCF compensation (Diagram 3.4). This means the phase shift caused by nonlinear effect can not be eliminated by inserting dispersion compensation fiber.

3) The accumulation of nonlinear phase noise
After the dispersion compensation, the output signal has basically recovered, see diagram 3.9. The signal distribution in their respective cluster is out of order, but different signal clusters have no influence with each other. Because of the nonlinear effect caused by the phase shift cannot be eliminated, In coherent optical communication system, it will cause the nonlinear phase noise by the interaction with Amplified Spontaneous Emission. The nonlinear phase noise will be increased with the accumulation of fiber length. Diagram 3.9—3.14 illustrate the situation of this process.
Through the star maps above, we can draw a conclusion: The nonlinear phase noise, which cannot be eliminated by inserting dispersion compensation fiber, accumulates slowly when the fiber is not long enough. But when the length increases, the distortion of signal increases and causes the crosstalk of different signals at last.

Diagram 3.10 The star map of receiving end signal dispersion and nonlinear effect, fiber length \( L = 120 \text{km} \)

Diagram 3.11 The star map of receiving end signal dispersion and nonlinear effect, fiber length \( L = 240 \text{km} \).

Diagram 3.12 The star map of receiving end signal dispersion and nonlinear effect, fiber length \( L = 360 \text{km} \).

Diagram 3.13 The star map of receiving end signal dispersion and nonlinear effect, fiber length \( L = 120 \text{km} \).
In this paper we based on the principle of the nonlinear effect and dispersion of the fiber, used optisys software as platform, built 4QAM dispersion compensation optical fiber communication simulation system on dispersion compensation fiber. And studied the nonlinear effect of the fiber (self phase modulation) and the dispersion effect (group velocity dispersion) of the signals in this system. We worked out the star maps of the receiving end in different situation, and drew the conclusion below through the compare of different star maps:

In 4QAM optical communication systems, the group velocity dispersion will cause distortion in transmission signal amplitude and the nonlinear effect can cause the signal phase change. The influence of group velocity can be eliminated by dispersion compensation fiber, but the phase change caused by nonlinear effect can not be recovered. Besides, nonlinear effect and Amplified Spontaneous Emission caused nonlinear phase noise by their interaction. The nonlinear phase noise will increase with the length of the fiber optic link and accumulated gradually, and affects the signal transmission in the coherent light modulation system eventually. For the optical fiber communication system of single amplitude modulation, the nonlinear effect doesn't affect the signal. But for the optical communication system of phase modulation, it is a very important factor to influence the communication quality. And in the future, coherent light modulation is bound to replace single amplitude modulation. So the research on the effects of nonlinear effects will be the hot of future research, and how to eliminate the influence of nonlinear effect caused by this problem will be the main direction of future research.

ACKNOWLEDGEMENT

This paper is supported by the Young Teachers' Development Fund Project, ID: 2015QJY0082

REFERENCES

[10] Liu Yan, Effect of four-wave mixing in DWDM system computer simulation research[D], Shandong university, 2004