The Physics Research of Optical Information Effect at Low Loss in Nonlinear Optical Fiber Transmission

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Abstract. Both nonlinear effects and dispersion are important factors that affect the transmission of optical pulses in optical fibres. In the anomalous dispersion region, the mutual balance of dispersion and nonlinear effects can achieve optical soliton transmission. Starting from the nonlinear Schrödinger equation of the optical pulse, under the condition of ignoring the dispersion, the nonlinear phase shift and frequency chirp of the Gaussian optical pulse under the nonlinear effect of self-phase modulation (SPM) are derived and simulated; the numerical simulation of the SPM the spectrum of Gaussian optical pulses with different maximum phase shifts without chirp and with positive chirp. The study found that the fusion loss of the fibre obtained by this algorithm is less than 0.11dB than that of the traditional single-mode fibre, and the additional bending loss caused by the wavelength range of 1460nm to 1625nm after winding 100 times on a 60mm cylinder is less than 0.02dB/km.

Keywords: Nonlinear optics; frequency domain transfer function; non-zero dispersion shifted fibre; dispersion slope; wavelength division multiplexing.

1. Introduction
Non-linear effects and dispersion are both important factors that affect the transmission of optical pulses in optical fibres, and the transmission of non-linear dispersion of light has always been an important topic of concern. In optical fibres, a typical nonlinear effect is self-phase modulation (SPM) related to the nonlinear optical Kerr effect of the fibre material. In the anomalous dispersion region, the mutual balance of this effect and dispersion can achieve optical soliton transmission. Yuguang Soliton Communication. This paper introduces the SPM in the pump wave channel [1]. In the theoretical analysis part, the frequency domain transfer function reflecting the cross-phase modulation (XPM) process is first derived and combined with the typical parameters of the system to simplify it, and then given when the pump The theoretical analysis method for determining the time-domain waveform of the probe wave when the input in the wave channel is an arbitrary signal; in the results and discussion part, the analysis results obtained are used to analyse the role of the pump wave SPM in the XPM process, and it is found that SPM is to a certain extent The frequency domain transfer function is increased, thereby enhancing the XPM function. The analytical results obtained and the numerical simulations are in good agreement under the premise of small signal analysis.
2. Transmission characteristics of single-mode fibre and nonlinear effects in the fibre

2.1. Single-mode working model performance and optical power distribution

The working mode of the single-mode fibre is the main mode $LP_{01}$ Mix columns, and the transverse electromagnetic field of the $LP_{01}$ mode is solved as follows:

$$ E_{11} = \frac{A}{J_0(U)} J_0 \left( \frac{U}{a} r \right), \quad r \leq a $$

$$ E_{22} = \frac{A}{K_0(W)} K_0 \left( \frac{W}{a} r \right), \quad r > a $$

$$ H_{11} = \frac{A_{n1}}{Z_0 J_0(U)} J_0 \left( \frac{U}{a} r \right), \quad r \leq a $$

$$ H_{22} = -\frac{A_{n2}}{Z_0 K_0(W)} K_0 \left( \frac{W}{a} r \right), \quad r > a $$

(1)

As for the weakly conductive fibre, the longitudinal field quantities $E_z$ and $H_z$ are much smaller than the transverse field quantities $E_x$ and $H_x$, so the longitudinal field quantity is omitted. We substitute $m=0$ into the characteristic equation of the LP mode to obtain the characteristic equation of the working mode: $UJ_0(U) = WK_0(W)$, where $U$ and $W$ satisfy the equation: $U^2 + W^2 = V^2 = k_0^2 a^2 (n_1^2 - n_2^2)$. In the range of $0 < V < 2.405$, the characteristic equation has only one set of solutions $U$ and $W$. This is the characteristic parameter of the main mode, which determines the distribution characteristics of the field in the radial direction [2]. The $LP_{01}$ mode transverse electromagnetic field solution is a transcendental equation, and only a numerical solution can be obtained.

2.2. Gaussian approximation of $LP_{01}$ mode in single-mode fibre

In step fibre, the field of mode $LP_{01}$ takes the form of a zero-order Bessel function in the core. Since the processing of Bessel functions is complicated and the Gaussian function is close to the Bessel function, people imagine whether the Gaussian function can be used to replace the Bessel function to simplify the analysis of the fundamental model. Assuming that we use a Gaussian field to excite the step single-mode fibre, the coupling coefficient between the $LP_{01}$ mode and the excitation field is:

$$ \rho = \left[ \frac{1}{2\pi} \int_0^{2\pi} \int_0^a E_x H_x r dr d\phi \right]^2 $$

(2)

In the formula, $H_x$ is the Gaussian distributed magnetic field given by the previous formula, and $E_x$ is the $LP_{01}$ mode electric field given by the previous field solution. Properly choose the constants $A_x$ and $A$ so that the total transmission power of the Gaussian field and the $LP_{01}$ mode is normalized, that is:

$$ \frac{1}{2\pi} \int_0^{2\pi} \int_0^a E_x H_x r dr d\phi = \frac{1}{2\pi} \int_0^{2\pi} \int_0^a E_{sg} H_{sg} r dr d\phi = 1 $$

(3)

Then the maximum value of the coupling coefficient given by the coupling coefficient formula is 1. When there is a big difference between $H_{sg}$ and the actual field volume $H_x$, $\rho$ will have a big difference compared to 1. It can be seen that $w_{opt} w_{sg}$ should be the value of $w$ that maximizes the coupling coefficient. The biggest limitation of using Gaussian field to equate accurate field is that it cannot be used to equate the field in the fibre cladding [3]. This is because the attenuation of the accurate field is slower than that of the Gaussian field. Therefore, the field in the cladding needs to find another approximation method. When $w / a \geq 2$, the field in the cladding can be approximated by the following formula:
We use the Gaussian approximation method to calculate the power distribution of the LP01 mode in the fibre. Under the Gaussian approximation, they have a simple form:

\[
\frac{P_{\text{core}}}{P_{\text{total}}} \approx 1 - \exp\left(-2\left(\frac{a}{\omega_{0}}\right)^{2}\right)
\]

\[
\frac{P_{a}}{P_{\text{total}}} \approx \exp\left(-2\left(\frac{a}{\omega_{0}}\right)^{2}\right)
\]

### 2.3. Dispersion coefficient of single-mode fibre

The optical signal propagates in the optical fibre at the group velocity. The group velocity is defined as:

\[
\tau = \frac{l}{V_{g}} = \frac{d\beta}{d\omega} = \frac{d\beta}{dk_{0}} \frac{dk_{0}}{d\omega} = \frac{l}{c} \frac{d\beta}{dk_{0}}
\]

You can use \(k_{0} = \frac{2\pi}{\lambda}\) again to convert the above formula to:

\[
\tau = \frac{1}{c} \frac{d\beta}{dk_{0}} = -\frac{\lambda^{2}}{2\pi c} \frac{d\beta}{d\lambda}
\]

Assuming that the spectral width of the optical signal is \(\Delta \lambda\), the group delay difference \(\Delta \tau\) is:

\[
\Delta \tau = \frac{d\tau}{d\lambda} \Delta \lambda + \frac{d^{2}\tau}{2d\lambda^{2}} \Delta \lambda^{2} + \frac{d^{3}\tau}{6d\lambda^{3}} \Delta \lambda^{3} + \ldots
\]

In \(\frac{\Delta \lambda}{\lambda} \ll 1\), only the first term of the above formula is enough, so there is:

\[
\Delta \tau = \frac{d}{d\lambda} \left(\frac{1}{c} \frac{d\beta}{dk_{0}}\right) \Delta \lambda = \frac{d}{d\lambda} \left(\frac{-\lambda^{2}}{2\pi c} \frac{d\beta}{d\lambda}\right) \Delta \lambda = -\frac{1}{2\pi c} \left(2\lambda \frac{d\beta}{d\lambda} + \lambda^{2} \frac{d^{2}\beta}{d\lambda^{2}}\right) \Delta \lambda
\]

Defining the dispersion coefficient as the group delay difference of the two frequency components with a unit wavelength interval in the optical fibre transmission unit length is the dispersion coefficient of the optical fibre, denoted by \(D(\lambda)\), and the unit is ps/(nm.km).

\[
D(\lambda) = -\frac{1}{2\pi c} \left(2\lambda \frac{d\beta}{d\lambda} + \lambda^{2} \frac{d^{2}\beta}{d\lambda^{2}}\right)
\]

Therefore, you can get:

\[
D(\lambda) = -\frac{1}{2\pi c} \left(2\lambda \frac{d\beta}{d\lambda} + \lambda^{2} \frac{d^{2}\beta}{d\lambda^{2}}\right) = \frac{2\pi}{c\lambda^{2}} \frac{d^{2}\beta}{dk_{0}^{2}}
\]
\[ b = \frac{W^2}{V^2} = \frac{\beta^2 - k_n^2}{k_o^2 (n_1^2 - n_2^2)} \Rightarrow \]

\[ \beta = k_o \left[ n_2^2 - \left( n_1^2 - n_2^2 \right)b \right]^{1/2} \approx k_o n_1 \left( 1 + \Delta b \right)^{1/2} = k_o n_1 (1 + \Delta b) \]

\[ \frac{d\beta}{dk_o} = \frac{d}{dk_o} \left[ k_o n_1 (1 + \Delta b) \right] = N_i (1 + \Delta b) + k_o \frac{dn_1}{dk_o} \frac{db}{dk_o} \]

\[ = N_i + (N_i - N_j) b + (n_1 - n_2) k_o \frac{db}{dk_o} \]

\( N_i \) and \( N_j \) are called the group refractive index of the core and cladding respectively, \( N_i \Delta = N_i \frac{n_i - n_2}{n_1} \approx n_1 - n_2 \approx N_i - N_2 \) is used in the derivation, and the dispersion term \( \frac{d\Delta}{dk_o} \) of the refractive index profile is ignored. Derivation of the normalized phase constant \( b \) with respect to \( k_0 \), we can get:

\[ \frac{db}{dk_0} = \frac{db}{dV} \frac{dV}{dk_0} = \frac{db}{dV} \frac{dV}{dk_0} \left[ k_o a (n_1^2 - n_2^2) \right]^{1/2} \approx \frac{db}{dV} \left[ a (n_1^2 - n_2^2) \right]^{1/2} = \frac{V}{k_0} \frac{db}{dV} \]

Bring into the pre-form, after getting the 9th round of Mix columns

\[ \frac{d\beta}{dk_0} = N_i + (N_i - N_j) b + (n_1 - n_2) k_o \frac{db}{dk_0} \]

\[ = N_i + (N_i - N_j) b + (n_1 - n_2) k_o \frac{db}{dk_0} \]

Derivative again to get:

\[ \frac{d^2 \beta}{dk_0^2} = \frac{d}{dk_0} \left( N_i + (N_i - N_j) \frac{db}{dV} \right) \]

\[ = \frac{dn_i}{dk_0} \left( N_i + (N_i - N_j) \frac{db}{dV} \right) + \left( N_i - N_j \right) \frac{V}{k_0} \frac{d^2 (bV)}{dV^2} \]

Ignore the second refractive index profile dispersion here, and get:

\[ \frac{d^2 \beta}{dk_0^2} = \frac{dn_i}{dk_0} + \left( N_i - N_j \right) \frac{V}{k_0} \frac{d^2 (bV)}{dV^2} \]

Substituting the previous formula, you can get:

\[ D(\lambda) = -\frac{2\pi}{c\lambda^2} \frac{d^2 \beta}{dk_o^2} = -\frac{2\pi}{c\lambda^2} \frac{dn_i}{dk_o} + \frac{2\pi}{c\lambda^2} \left( N_i - N_j \right) \frac{V}{k_0} \frac{d^2 (bV)}{dV^2} = D_{\omega}(\lambda) + D_{\omega}(\lambda) \]

It can be seen from the above formula that the first term is the material dispersion term, and the second term is related to the normalized propagation constant and the normalized frequency. Since, \((N_i - N_j) > 0\), in the wavelength range we are interested in, there is always \( 0 < \frac{d^2 (bV)}{dV^2} < 0 \), so the waveguide the dispersion coefficient \( D_{W}(\lambda) < 0 \).

3. Nonlinear effects in single-mode fibre

3.1. Stimulated Raman Scattering (SRS)

The strict description of the SRS process requires the use of quantum theory. In view of the fact that the incident light and scattered light are relatively strong in the range of interest, the electrostatic electromagnetic field theory can also be used for quantitative analysis [5]. At this time, we need to give a coupled wave equation describing the interaction between incident wave and Stokes’s wave in a nonlinear medium can prove:
In the above formula, $P_p, P_s$ is the power of pump light and Stokes light respectively, $\alpha_p, \alpha_s$ is the loss coefficient of light and pump Stokes wave respectively, and $g_s$ is the Raman gain coefficient, which represents the coupling of energy between the two waves. Intensity depends on the gain characteristic of the nonlinear medium, that is, the wavelength spacing, $k$ is the polarization-maintaining coefficient, when the polarization directions of the pump light and Stokes wave coincide, $k=1$, generally $1<k<2$, $\lambda_p$ is The interaction area of pump light and Stokes light is approximately the core area in a single-mode fibre. Early fibre Raman gain coefficients can be obtained by measuring the cross-sectional area of spontaneous Raman scattering [6]. The Raman gain coefficient is generally related to the core composition of the fibre, and the Raman gain coefficient varies greatly for different dopants. It can be seen from Figure 1 that for different pump wavelengths, the Raman gain coefficient is inversely proportional to the pump wavelength.

$$\alpha_p \frac{\partial P_p}{\partial z} + n_e \frac{\partial P_p}{\partial t} = - \frac{g_s}{kA_p} P_s P_p + \alpha_p P_p$$

$$\alpha_s \frac{\partial P_s}{\partial z} + n_e \frac{\partial P_s}{\partial t} = \frac{g_s}{kA_p} P_s P_p - \alpha_s P_s$$

(19)

In the above formula, $P_p, P_s$ is the power of pump light and Stokes light respectively, $\alpha_p, \alpha_s$ is the loss coefficient of light and pump Stokes wave respectively, and $g_s$ is the Raman gain coefficient, which represents the coupling of energy between the two waves. Intensity depends on the gain characteristic of the nonlinear medium, that is, the wavelength spacing, $k$ is the polarization-maintaining coefficient, when the polarization directions of the pump light and Stokes wave coincide, $k=1$, generally $1<k<2$, $\lambda_p$ is The interaction area of pump light and Stokes light is approximately the core area in a single-mode fibre. Early fibre Raman gain coefficients can be obtained by measuring the cross-sectional area of spontaneous Raman scattering [6]. The Raman gain coefficient is generally related to the core composition of the fibre, and the Raman gain coefficient varies greatly for different dopants. It can be seen from Figure 1 that for different pump wavelengths, the Raman gain coefficient is inversely proportional to the pump wavelength.

$$g_s(\gamma|\lambda_p) = \frac{1}{\lambda_p} g_s(\gamma|\lambda_{1.0})$$

(20)

Figure 1. Stimulated Raman scattering function

The figure shows the relationship between the Raman gain coefficient of the quartz fibre and the frequency shift when a certain pump light is used. The most notable feature of Raman gain in silica fibre is the wide bandwidth (up to 40THz) and a broad main peak near 13THz. These properties are due to the amorphous nature of silica glass.

3.2. Stimulated Brillouin scattering (SBS)

Considering the Stokes effect of the first-order SBS, we can get the coupling equation under steady-state conditions (that is, ignoring the pump light and Stokes’s light changes with time):

$$\alpha_p \frac{\partial P_p}{\partial z} = - \frac{g_s}{kA_p} P_s P_p + \alpha_p P_p$$

$$\alpha_s \frac{\partial P_s}{\partial z} = \frac{g_s}{kA_p} P_s P_p + \alpha_s P_s$$

(21)

$g_s$ is the Brillouin gain coefficient, other parameters are defined as above. The SBS gain spectrum width of the optical fibre is very narrow, and the spectrum width is related to the damping time of the sound wave or the lifetime of the phonon. The spectrum width can be expressed as: $\Delta \omega_p = \frac{1}{\lambda_p^2} \Delta \omega_p |_{\lambda=1.0}$.

The corresponding Brillouin gain coefficient $g_s$ is $g_s = 1.73 \times 10^{-6}$. The above formula is the Brillouin
gain coefficient for monochromatic pump light. When the pump fibre width increases, the Brillouin gain coefficient becomes 
\[ g_b = \frac{1.73 \times 10^{-9}}{k^3 \Delta \nu_p} \frac{\Delta \nu_p + \Delta \nu_d}{\Delta \nu_d}. \]

3.3. Nonlinear refractive index and related non-linear phenomena

In the field of optics and optical fibre transmission, the study of nonlinear phenomena will play a pivotal role in the development of optical information technology in the future. In the past, the non-linear problems we encountered in the fields of electromagnetics and optics were mainly harmonic distortion, cross-modulation, four-wave mixing, etc. These non-linear phenomena would all cause the distortion of electromagnetic signals, so we should try our best to avoid them.

For non-magnetic media, if there is an electromagnetic field, the media will be polarized. The electric polarization state is described by the electric field polarization intensity vector \( P \), its direction represents the polarization direction of the medium, that is, the average orientation of the electric dipole in the medium, and its mode represents the strength of the polarization. The relationship between the polarization intensity and the electric field in the medium is:

\[ P = \varepsilon_0 (\chi^{(1)} EE + \chi^{(3)} EEEE + \ldots) \]  

(22)

According to this formula, we only consider the second-order and third-order polarization intensities expressed as:

\[ P(t) = P_1(t) + P_2(t) = P_1(t) + P_2(t) + P_3(t) \]  

(23)

Due to the symmetrical structure of the quartz material molecules, the second-order nonlinear polarization intensity can be ignored, and only the third-order nonlinear polarization intensity needs to be considered. Assuming that the optical fibre is regarded as an isotropic medium, the polarization intensity in the optical fibre can be expressed as:

\[ P(t) = \varepsilon_0 \chi^{(1)} E(t) + \varepsilon_0 \chi^{(3)} E^3(t) \]  

(24)

Therefore, the electric displacement vector can be expressed as:

\[ D(t) = \varepsilon_0 E(t) + P(t) = \varepsilon_0 \left[ 1 + \chi^{(1)} E + \chi^{(3)} E^3 \right] E(t) = \varepsilon_0 n^2 E(t) \]  

(25)

In the formula: \( 1 + \chi^{(1)} E + \chi^{(3)} E^3 = n^2 \). Therefore, the refractive index can be expressed as:

\[ I + \chi^{(1)} E + \chi^{(3)} E^3 = n^2 = n_1 + n_2 E \]  

In the formula, \( n_1 \) and \( n_2 E \) are the linear and nonlinear parts of the refractive index. It can be seen that in addition to a linear part, the refractive index of the fibre also has a nonlinear correction term that is proportional to the applied light intensity.

4. Experimental simulation research

4.1. Comparison of analytical solutions and simulation results

In order to study the IM frequency domain transfer function that characterizes XPM, the sinusoidal modulation signal \( P_2(0) + 0.1P_2(0) \sin(\omega t) \) is input into the probe wave channel, where \( P_2(0) \) is the average power. Figure 2(a), (b) is the specific result, in which the solid line and the dashed line are obtained using equations (5)(9)(10) respectively, and the discrete points are the results of numerical simulations, which essentially reflect the impact of the transmission code rate on XPM. The difference between the line (obtained from equation (5)) and the dashed line (obtained from equations (9) and (10)) reflects the contribution of the pump wave SPM. Figure 2 shows that the simplified IM frequency domain transfer function still has a higher degree of approximation, and as predicted in section 2.2, when the modulation frequency \( \omega \) is low, \( H(\omega) \) is proportional to \( \omega^2 \) (see Figure 2(a)), and when \( \omega \) is high, \( H(\omega) \) appears extreme with \( \omega \). The fluctuation phenomenon of large and small alternating changes, and the fluctuation period is gradually reduced (see Figure 2(b)). The fluctuation reflected in Figure 2(b) reveals that in order to reduce the XPM effect, the system parameters should be reasonably selected so that the frequency domain transfer function value corresponding to the transmission code rate avoids the peak as much as possible, so this has a certain reference for system design.
Figure 2. Frequency change of the normalized frequency domain intensity modulation transfer function

4.2. Time domain results obtained by $H(\omega)$
In order to illustrate the problem vividly, the time domain results are given below. In the pump probe wave structure with a channel spacing of 0.4nm, the input of the probe wave channel is continuous wave (CW). Two conclusions can be drawn from Figure 3. First, except for the deviation of the output signal at the peak (high-frequency component), the two are in good agreement. In fact, the error between the analytical result and the simulation result is modulated by the pump wave. The depth and nonlinear effects increase because the derivation of equation (4) in the theoretical part is based on small signal analysis; second, when the pump wave input signal undergoes a "0" "1" jump, the maximum and minimum values of the signal will appear at the output of the probe wave. This is due to the relatively large phase change $d_1X_{PM}$ at the corresponding point of the probe wave channel when the optical power of the pump wave changes. The IM conversion has signal extremes at the output.

Figure 3. Time domain output power of sounding wave channel

5. Conclusion
In this paper, under the premise of small signal analysis, the optical signal transmission under the combined action of group velocity dispersion and nonlinearity in the pump probe wave structure is studied, and the combined effects of loss, dispersion, self-phase modulation and cross-phase modulation
are deduced, which can be used to reflect cross-phase modulation. Frequency domain transfer function of the phase modulation process. The analytical results obtained in this paper and the numerical simulations are in good agreement under the premise of small signal analysis, and have a certain reference effect for the design and analysis of the intensity modulation direct detection wavelength division multiplexing system.

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