Study on Physical Effects of Optical Fiber Transmission Characteristics Under Nonlinear Optical Effects

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Abstract. Photonic crystal fiber has a special light guiding mechanism and structural tunability, which can produce singular dispersion characteristics and high nonlinearity, which provides new conditions for the research in the field of nonlinear fiber optics. Due to the combined action of a variety of nonlinear optical effects, photonic crystal fibres with different structural parameters and transmission characteristics can produce rich nonlinear spectra under different pump light pulse parameters. We use the photonic crystal fiber cladding section to conduct nonlinear optical experimental research, and obtain the broadband spectral output of soliton wave and dispersive wave. The theoretical analysis and experimentally measured spectra include blue-shifted dispersion waves in the visible light band near 0.5 μm, residual pump light in the 0.82 μm band, soliton waves in the 1.1 μm band, and red-shifted broadband dispersive waves near 2 μm. Corresponding to this, the formation and redshift of solitons can be clearly seen in the time domain, and there is no more oscillation secondary peak in the femtosecond transmission pulse.

Keywords: Nonlinear optical effects, optical fiber transmission characteristics, physical effects, structural parameters.

1. Introduction
With the enhancement of the emission power of semiconductor lasers and the widespread application of low-loss and small-core single-mode fibres, the core of single-mode fibres can be obtained and maintain a high optical power density over a long distance, making light and fiber media maintain strong interaction over long distances, thereby inducing various nonlinear optical effects, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), four-wave mixing (FWM), self-phase modulation (SPM) and cross-phase modulation (XPM) has affected the linearity of optical fiber communication systems, and the impact of SRS and SBS cannot be ignored. This article mainly discusses the influence of SBS on the power of the optical signal when the high-density wavelength division multiplexing system is used alone, and the influence on the power of the optical signal when the SRS and SBS work together in the high-density wavelength division multiplexing system.

We analyse and solve the nonlinear Schrödinger equation, analyse the relationship between the output spectrum of the PCF and the structural parameters and the input optical pulse parameters [1].
the PCF cladding section to conduct nonlinear optical experimental research, compare the theoretical analysis with the experimental measurement results, and find the physical principle of the nonlinear spectrum. Provide theoretical guidance for high nonlinear PCF structure design, preparation and application research.

2. Experimental system
The experimental system of femtosecond pulse transmission in the PCF is shown in Figure 1. The ultrashort pulse output by the titanium-sapphire laser system is coupled into the PCF by the microscope objective after the isolator, and the power meter and the power meter are connected to the exit of the fiber [2]. The spectrum analyser measures the output power and output spectrum. The light beam derived from the gold mirror in front of the microscope objective is measured by the spectrum analyser, autocorrelator and power meter to measure the spectrum, pulse width and power of the incident pulse.

The input pulse used in the experiment is Gaussian type, which is generated by the Kerr mode-locked Ti: Sapphire laser produced by Spectrophysics, the output pulse repetition frequency is 82MHz, the centre wavelength is adjustable from 780-820nm, the full width at half maximum of the pulse is 50fs, and the maximum average output power It is 400mW. The fiber core diameter is 2.3μm, the cladding air filling rate is greater than 90%, the zero-dispersion wavelength point λ₀=790nm, the dispersion (second-order dispersion) slope at the zero-dispersion point is 0.61ps/nm, the loss coefficient α≈90dB/km, non-linear the coefficient γ≈80W/km, and the length of the optical fiber used in the experiment is L=80cm.

![Figure 1. Experimental setup diagram](image)

3. Optical fiber transmission nonlinear effects

3.1. Optical fiber characteristics and optical power distribution
For the actual single-mode fiber, the normalized operating frequency should be selected in the range of 2.0-2.35, so that both single-mode transmission can be ensured, and most of the optical power is propagated in the fiber core [3]. The power intensity is the square of the electric field intensity, and the optical power intensity distribution in the fiber core can be obtained by using the previous electric field vector solution: $P(r) = \left| J_0(\frac{U_0}{a}) \right|^2$, $r \leq a$. Figure 2 shows the optical power distribution in the fiber core.
The figure uses the power $P_r(a)$ at the radius $r=a$ as a reference, indicating that the power ratio $R$ at different $r/a$ is:

$$R = \frac{P_r(r)}{P_r(a)} = \left(\frac{J_0\left(\frac{\xi}{a}\right)}{J_0(U)}\right)^2.$$

**Figure 2.** Optical power distribution in the core

Because there is considerable power transmission in the cladding, in order to obtain low attenuation, the single-mode fiber must have a sufficient thickness of the deposited inner cladding. The thickness of the inner cladding depends on the distribution of the field strength along the $r$ in the cladding and the structure of the section [4]. Similarly, according to the solution of the electric field vector, the electric field intensity in the cladding can be obtained as:

$$E_{az} = \frac{A}{K_e(W)} K_e\left(\frac{W_a}{a}\right), r > a$$

(1)

According to the approximate formula of the abnormal Bessel function

$$K_e(x) \approx \left(\frac{\pi}{2x}\right)^{\frac{3}{2}} e^{x}$$

(2)

The field strength ratio at the relative radial position $t=r/a$ and $r=a$ is:

$$\frac{E_{az}(t)}{E_{az}(1)} = \frac{1}{t} e^{\frac{1}{2} - \frac{1}{2t^2}}$$

(3)

The optical power intensity distribution in the cladding is:

$$P_r(r) \propto \left[\frac{K_0\left(\frac{aL}{a}\right)}{aL}\right]^2, r > a$$

(4)

The ratio of the power intensity at the relative radial position $t=r/a$ and $r=a$ is:

$$\frac{P_r(t)}{P_r(1)} = \frac{1}{t} e^{\frac{1}{2} - \frac{1}{2t^2}}$$

(5)

If the cladding thickness $r=6a$, the optical power density there is less than $10^{-8}$, and the total optical power outside this can be ignored.

The thickness of the electric field penetrating into the cladding layer is different when the value of $V$ is different. In the case of ensuring single-mode transmission, the larger the value of $V$, the better, and the value of $V$ is larger, and the thickness of the deposited inner cladding layer can be thinner.

### 3.2. Gaussian approximation in optical fiber

In step fiber, the field 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 [5]. The main mode field in the step fiber is qualitatively close to the Gaussian distribution. Therefore, the Gaussian function can be used to approximate the Bessel function distribution, which can simplify the pair distribution. In other words, the amount of electromagnetic field can be written as
2.2 \[ \frac{r}{w} \]

\[ EG \]

\[ XG \]

\[ 0 \]

\[ E A e \]

\[ A n \]

\[ H e \]

\[ \frac{Z}{Z} \]

\[ (6) \]

Where \( r \) is called the mode field radius. \( 2w \) is an important parameter of single-mode fiber. When the mode field diameter is \( r=w \), the field volume drops to \( \frac{1}{e} \) of the central axis. Because the coupling coefficient \( \rho \) calculated by the coupling coefficient formula is a function of the parameter \( w \), that is, \( \rho=\rho(w) \). Therefore, the optimal mode field radius should be the solution of the equation: 

\[ d\rho(w) \]

\[ \frac{d}{d\omega} \]

\[ \omega \]

\[ \sqrt{0.65 + 1.619W^2 + 2.879W^4} = 0.65 + 0.434(\frac{A}{L_a})^2 + 0.0149(\frac{A}{L_a})^4 \]

(7)

A simpler formula is 

\[ \frac{a_{opt}}{a} = 2.6 \frac{V}{c} \]

3.3. Polarization mode dispersion concept

The group delays per unit distance of the two mutually orthogonal polarization modes analysed in the fiber are:

\[ \tau_x, \tau_y = \frac{d\beta_x}{d\omega}, \frac{d\beta_y}{d\omega} \]

(8)

The resulting propagation delay or pulse broadening is: 

\[ \Delta \tau_p = \frac{d\omega}{c} \left( \beta_x - \beta_y \right) = \frac{d\Delta \beta}{d\omega} \]

For silica fiber, the second term is much smaller than the first term, so the pulse broadening caused by polarization mode dispersion:

\[ \Delta \tau_p = \frac{B}{c} \frac{\Delta \beta}{\omega} = \frac{1}{L_a\beta} \]

The birefringence parameter \( B \) of ordinary single-mode fiber is in the order of \( 10^{-6} \). For example, when \( B=10^{-6} \), the working wavelength is 1.5 microns, the beat length \( L_a = 1.5 \) meters, and the optical pulse broadening due to polarization mode dispersion is \( \Delta \tau_p = 3.3 \text{ps/km} \). This is equivalent to the pulse broadening caused by wavelength dispersion near the zero-dispersion wavelength of a single-mode fiber using a single longitudinal mode laser (with a spectral width of about 1 nm). However, due to the coupling effect between two orthogonal modes during long-distance transmission, the total dispersion or pulse broadening is not proportional to the distance, so compared with the wavelength dispersion, the polarization mode dispersion is secondary [6]. The low birefringence fiber produced by the rotating process can have a birefringence parameter \( B \) as low as \( 10^{-9} \). This kind of fiber can completely ignore the influence of polarization mode dispersion.

We choose a rectangular coordinate system so that the x-axis and y-axis coincide with these two directions respectively. Such a coordinate system can be called a spindle coordinate. Assuming that a linearly polarized wave is excited at the input end of the fiber, the angle between the electric field intensity vector and the x-axis of the above-mentioned coordinate system is \( \varphi \), which is called the input polarization angle. Suppose the electric field vector at the input terminal is:

\[ E_i = E_x e^{i\varphi}, E_y \]

After the transmission distance \( z \) in the optical fiber, the output electric field vector is:

\[ E_o = E_x e^{i\beta_x z} e^{i\varphi}, E_y = E_y e^{i\beta_y z} \]

(10)

Because of \( \beta \neq \beta' \), the above formula represents an elliptically polarized wave in general. This is because the two components of the electric field strength will have a \( (\beta_x - \beta_y)z \neq 0 \) phase difference. Since this phase difference is a function of \( z \), the polarization state of the field described by the above formula
will also change with \( z \). According to the polarization theory of plane electromagnetic waves, when the phase difference between these two components is \( n \pi \), it describes a linearly polarized wave, and when \( n \) is an even number, the polarization state of the field vector is the same as the initial polarization state. When the phase difference is \( n + \frac{\pi}{2} \) and \( E_x \neq E_y \), it describes a circularly polarized wave. If \( E_x \neq E_y \) is an elliptically polarized wave, the long and short axes of the ellipse coincide with the x and y axes, respectively. As mentioned above, when linearly polarized transmission in a single-mode fiber, due to the influence of birefringence, its polarization state will change with the transmission distance. Generally, two parameters, output polarization angle and polarization ellipticity can be used. The long axis of the elliptical polarization along the fiber generally does not coincide with the birefringence axis of the fiber. Set it to form an \( \Omega \) angle with the Ox axis. This angle is called Is the output polarization angle. Suppose the electric field amplitudes in the major and minor axis directions of the polarization ellipse are \( a_{\text{max}} \) and \( a_{\text{min}} \), the corresponding light intensities are \( I_{\text{max}} \) and \( I_{\text{min}} \), and the ellipse polarization is defined as

\[
P = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{a_{\text{max}}^2 - a_{\text{min}}^2}{a_{\text{max}}^2 + a_{\text{min}}^2}
\]

4. Discussion of Linear Relations

Nonlinear phenomena related to nonlinear refractive index Take two waves as examples to discuss the nonlinear phenomena related to nonlinear refractive index. Assuming that two light fields with the same polarization direction and different frequencies are input into the nonlinear medium at the same time, the combined light field is:

\[
E = \frac{1}{2} \sum_{m=1}^{2} E_m \exp \left[ j(\beta m z + \omega_m t) + \text{c.c.} \right]
\]

In the formula, c.c. is the conjugate term, then the nonlinear polarization rate is:

\[
P_{nl} = \frac{3}{8} \varepsilon_0 \chi^{(3)} \left[ \frac{1}{2} \sum_{m=1}^{2} E_m \exp \left[ j(\beta m z + \omega_m t) + \text{c.c.} \right] \right]^1
\]

\[
= \frac{3}{8} \varepsilon_0 \chi^{(3)} \times \{ (\omega_1) \{ E_1^2 + 2E_1^3 \} E_1 \exp \left[ j(\beta_1 z + \omega_1 t) \right] 
+ \frac{3}{8} \varepsilon_0 \chi^{(3)} \times \{ (\omega_2) \{ E_2^2 + 2E_2^3 \} E_2 \exp \left[ j(\beta_2 z + \omega_2 t) \right] 
+ \frac{1}{8} \varepsilon_0 \chi^{(3)} \times (3\omega_1) \exp \left[ j(\beta_1 z + \omega_1 t) \right] \}
+ \frac{3}{8} \varepsilon_0 \chi^{(3)} \times (3\omega_2) \exp \left[ j(\beta_2 z + \omega_2 t) \right] \}
+ \frac{1}{8} \varepsilon_0 \chi^{(3)} \times (3(\omega_1, \omega_2)) \exp \left[ j(\beta_1 z + \omega_1 t) \right] \}
+ \frac{3}{8} \varepsilon_0 \chi^{(3)} \times (2\omega_1, \omega_2) E_1 E_2 \exp \left[ j((\beta_1 + 2\beta_2) z + (\omega_1 + 2\omega_2) t) \right] \}
+ \frac{3}{8} \varepsilon_0 \chi^{(3)} \times (2\omega_2, \omega_1) E_1 E_2 \exp \left[ j((\beta_2 + 2\beta_1) z + (\omega_1 + 2\omega_2) t) \right] \}
+ \frac{1}{8} \varepsilon_0 \chi^{(3)} \times (2\omega_1, -\omega_2) E_1 E_2 \exp \left[ j((2\beta_1 - \beta_2) z + (2\omega_1 - \omega_2) t) \right] \}
+ \frac{1}{8} \varepsilon_0 \chi^{(3)} \times (2\omega_2, -\omega_1) E_1 E_2 \exp \left[ j((2\beta_2 - \beta_1) z + (2\omega_2 - \omega_1) t) \right] \}
\]

We compare the first and second terms in the above formula with the previous formula, we can get that the nonlinear refractive index corresponding to light field 1 and light field 2 are respectively

\[
n_{nl1} = n_{nl1} + n_{nl1}' = \frac{3}{4} n_n E_1^2 + \frac{3}{4} n_n 2E_1^3
\]

\[
n_{nl2} = n_{nl2} + n_{nl2}' = \frac{3}{4} n_n E_2^2 + \frac{3}{4} n_n 2E_2^3
\]

The first item is the change in refractive index due to the change in the intensity of the optical field itself. During the transmission of the optical signal, this change will cause the phase of the optical signal to be modulated, which results in the so-called self-phase modulation phenomenon. The second term is the change in refractive index due to changes in the intensity of other light fields. This change will also
modulate the transmitted signal, which is the so-called cross-phase modulation phenomenon. It can be seen from the formula that the latter is twice that of the former.

In addition, it can be seen from the above formula that new frequency components are generated in several other items, which are the so-called four-wave mixing items. But the appearance of the four-wave mixing term must meet the so-called phase matching condition. If the newly generated frequency component is used to represent the propagation constant of the newly generated frequency component, the phase matching condition is:

\[
\omega_n = \pm \omega_1 \pm \omega_2 \pm \omega_3 \\
\beta_n = \pm \beta_1 \pm \beta_2 \pm \beta_3
\]  

(15)

5. Experimental Design

5.1. Pumping at zero-dispersion wavelength

The evolution and broadening of the output spectrum of the femtosecond pulse with the centre frequency at the zero-dispersion wavelength under different powers is shown in Figure 3. The marked power P0 in the figure is the average power at the fiber exit. When the pulse is at a lower power (below 2mW), the spectrum is only slightly broadened. As the power continues to increase, a small peak is first separated on the right side of the spectrum, and then the small peak moves to the right and gradually widens, and new frequencies are generated on the left. The pumping power continues to increase, the new frequency components gradually expand, and the energy further increases [7]. During this period, the main peak of the output spectrum gradually shifts to the short-wavelength direction, and the energy gradually shifts to the new frequency. When the output power reaches 47mW, it exceeds the continuum covers 600-1000nm.

![Figure 3. The evolution of the output spectrum of a femtosecond pulse with the centre frequency at the zero-dispersion wavelength under different powers](image)

5.2. Pumping in the anomalous dispersion zone

Experiments have found that when the centre wavelength of the incident pump pulse is located on one side of the zero-dispersion wavelength, the broadening of the output spectrum is different from the result of the zero-dispersion wavelength pumping. Figure 4 shows the output spectrum of the centre frequency at 800 different powers. The spectrum in Figure 4 first moves to the long wave direction, and a small peak is first separated on the left side of the main peak. With the increase of power, the main peak and small peak gradually move to both sides, and the energy of the main peak is gradually divided by the new frequency components. Until the supercontinuum is generated, the centre frequency of the pump
pulse no longer has an advantage. The supercontinuum covers the wavelength range of 600-1100nm when pumping at 800nm, and the wavelength covers 550-1150nm when pumping at 820nm, and the width of the supercontinuum is up to 600nm.

![Figure 4](image)

**Figure 4.** The evolution of the output spectrum of a femtosecond pulse with a centre frequency of 800 nm under different power

6. Conclusion

We use a femtosecond pulse laser with tunable wavelength to study the evolution process and non-uniformity of the supercontinuum generated by the femtosecond pulse in the HNLPCF when pumping at the zero-dispersion wavelength and the anomalous dispersion region from both experimental and theoretical aspects. Linear transmission characteristics. During the transmission of the femtosecond pulse in the anomalous dispersion region, there is no interference oscillation spike in the time domain. The study also found that the anomalous dispersion region near the zero-dispersion wavelength is more likely to produce the FWM effect than the zero-dispersion wavelength point.

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