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An Improved Simulation Method of Supercontinuum Generated by Sub-nanosecond Pulse*

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Abstract: In this paper, a method of twice sampling based on split-step Fourier method was developed to analyze and simulate the supercontinuum generation in photonic crystal fiber pumped by sub-nanosecond laser pulse. Applying this method to generalized nonlinear Schrödinger equation, much operation time was saved in Supercontinuum simulation, and the simulated spectrum agrees well with the experimental result under the same conditions. Also, the slight dissimilarities between the simulated spectrum and the experimental one were discussed. The simulated supercontinuum with 1.15W power generated in 1.8 m Photonic Crystal Fiber and the evolution of spectrum by our work can give reference for improving further experiment setup.

Key words: Supercontinuum; Twice sampling; Split-step Fourier method; Sub-nanosecond pulse

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0 Introduction

SC (Supercontinuum) is of practical significance in spectrum analysis, optical metrology and optical communication, etc[1-3]. In recent years, SC generation has attracted lots of attention, and there have been many relevant reports[4-14], in which most researchers used femtosecond or picosecond incident laser pulse as pumping source[5-9], and just a few used nanosecond pulse or continuous wave laser source[10-12]. Femtosecond pulse can be spectrally broadened more easily than picosecond and nanosecond pulses through nonlinear fiber, but femtosecond laser is complex and very expensive, and its power output isn't high enough. There have been some reports about high SC power output by pumping the fiber with continuous light[10-11], and the highest out power achieves 29 W[15], but it's spectrum is narrow, and if we want to get broad SC spectrum, long fiber often more than one thousand meter needs to be used. So compared with the femtosecond and continuous light pumping, the picosecond and nanosecond pumping are economical and applicable to obtain SC with high power and broad spectrum, and the SC power under these pumping condition has achieved 7.2 W[16].

The symmetrical split-step Fourier method is a good way to study the mechanism of SC generation and the pulse evolution along the fiber. The numerical simulation of SC generation using femtosecond pulse has been studied well. But since the number of sample points need increase with incident pulse width, the simulation of SC generation using picosecond or nanosecond pulses is comparably difficult due to the very large number of sample points. For example, in order to simulate the SC generation by a pulse over 50 ps, 2^{17} sampling points needs to be chosen to cover the several hundreds nanometers of the SC spectrum, which is a very larger burden for personal computers. At present, people have two methods to deal with the problem. One is spending very long time (11-31 days)[12], the other is changing incident pulse width to reduce computing time[13]. But the reliability of the second method needs to be verified since the pulse width affects stimulation of nonlinear and dispersive effects very much. In this paper, we introduce an improved method to simulate the SC generation by a sub-nanosecond pulse. The stimulated results show that this method is very time saving and effective, the operation time is just 10 min, and the simulated result agrees well with experimental result.

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1 Theory Background

The propagation of pulse along the fiber could be described by generalized nonlinear Schrodinger equation which satisfies slowly varying approximation

$$\frac{\partial A}{\partial z}=(\hat{D}+\hat{N})A \tag{1}$$

$$\hat{D}=-\frac{i}{2}\beta_2\frac{\partial^2}{\partial T^2}+\frac{1}{6}\beta_3\frac{\partial^3}{\partial T^3}+\frac{i}{24}\beta_4\frac{\partial^4}{\partial T^4} \tag{2}$$

$$\hat{N}=i\gamma\left[|A|^2+\frac{i}{w_0}\frac{1}{A}\frac{\partial}{\partial T}(|A|^2A)-T_R\frac{\partial|A|^2}{\partial T}\right] \tag{3}$$

In the equations, $A(z, T)$ is the slowly varying pulse envelope, $\hat{D}$ is a differential operator, $\hat{N}$ is a nonlinear operator. The β_2, β_3, β_4 account respectively for the second, third and fourth order dispersion. T_R is the first moment of the nonlinear response function. As the fiber is short, we ignore the loss. In fact, when the pulse width is over 100 ps, the second and third items in Eq (3) could be ignored because of low nonlinearity[14], which is also confirmed in our simulation. We can get output intensity of spectrum by iterative differential operator and nonlinear operator along the fiber length z. The iterative order is

$$\begin{aligned}&A(z,T)\to F(A)\\&\to\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\\&\to F^{-1}\left(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\right)\\&\to\exp(h\hat{N})F^{-1}\left(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\right)\\&\to F\left(\exp(h\hat{N})F^{-1}\left(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\right)\right)\\&\to\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(\exp(h\hat{N})\cdot\\&F^{-1}\left(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\right))\\&\to F^{-1}(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(\exp(h\hat{N})\cdot\\&F^{-1}\left(\exp\left(\frac{h}{2}\hat{D}(iw)\right)F(A)\right)))\\&=A(z+h,T)\end{aligned} \tag{4}$$

The F represents Fourier Transformation, and F^{-1} represents Inverse Fourier Transformation. The process above is one step along the fiber, and h is the step size.

2 Twice Sampling Method

The number of sample points should increase with the pulse width in calculation, or else the sampling would not cover the expanded spectrum. We use the normalized parameters such as amplitude and time and fiber length so that it is convenient to calculate. The conversions between them are given by four stages

$$dt=T/N \tag{5}$$

Where T is the time window of sample, N is the elementary number of sample points, dt is time spacing.

$$dw=2\pi/dt/N \tag{6}$$

Where is frequency spacing.

$$w=dw[-N/2, N/2-1]=[-\pi N/T, \pi N/T-1] \tag{7}$$

Where w is normalized frequency, then the wavelength is

$$\lambda=2\pi c/(w/T_0+2\pi c/\lambda_0) \tag{8}$$

The T_0 represents incident pulse width of 342 ps (This is the half-width at 1/e-intensity points, the full width at half maximum (FWHM) abbreviated to 570 ps). The time window we choose is 1 710 ps (5 times of input pulse width). If we want the spectral coverage of sample to be from 400 nm to 2 000 nm, at least 2^{20} sample points need to be chosen from the equations above. However, the calculation is too time-consuming for personal computer. So, we adopt the method of Twice Sampling which is choosing a point every n points in the 2^{20} elementary sample points, then doing calculation with the points we second choose as the sample of time domain and frequency domain. This method keeps the incident pulse width and just increases the spacing of sampling, which avoids the influence of changing incident pulse width on SC generation and also saves much operation time. In 1.8 m fiber, the process could get result just for about 10 minutes when $n=2^7$ and normalized step size $h=3\times10^{-12}$.

We know that the spacing of sampling and step size along fiber length couldn't be too large or too little, large n and h will induce large error, but little n and h will take up long operation time. So, we should choose an optimal value which can keep a right spectral curve and take up shortest time. After many times of debugging, we find that the number of 2^7 and 3×10^{-12} for n and h respectively are optimal. We keep $h=3\times10^{-12}$ and change the n to observe the effect of n. The spectrum has been deformed when $n=2^8$ and the deformation becomes more serious as n is bigger; when we minish the value of n, the spectrum will be exactly accord with the spectrum from $n=2^7$, but the operation time become much longer and it cost over 30 minutes when $n=2^6$. Then we keep $n=2^7$ and change h, we get the same changing trend as above. When $h=4\times10^{-12}$ the spectrum has been deformed, when $h=2\times10^{-12}$ the spectrum accords with the spectrum from $h=3\times10^{-12}$ but the operation time is 34 minutes.

When $n=2^7$ and $h=3\times10^{-12}$, the number of sample points across an initial pulse width is up to 183 8, a step along fiber length is 0.14mm and the total number of steps is 13050, so the relative error of this method is still little. The results we got exactly agree with experiment by choosing suitable iterative step along the fiber length and the spacing of sample points.

3 Simulation Result and Analysis

3.1 Simulation of SC spectrum

We have simulated the SC spectrum of 1.15 w output power from 1.8 m PCF (Photonic Crystal Fiber) which has ZDW (Zero Dispersion Wavelength) at 1 040 nm. The second, third and fourth order dispersion of this PCF at 1 062 nm are respectively: $\beta_2=-2.543\,9$ ps^2/km, $\beta_3=7.143\,6\times10^{-2}$ ps^3/km, $\beta_4=-1.105\,0\times10^{-4}$ ps^4/km, and the nonlinear parameter is $\gamma=11$ W^{-1}km^{-1}.

Fig. 1 is the simulated spectrum smoothed by cubic spline interpolation and the experimental result with same parameters. We can find that the simulation exactly agrees with experimental result, their spectrum curves both have the highest peaks at the pump wavelength of 1 062 nm and cover the span from 745 nm to 1 550 nm. The two spectral peaks close to the peak pump wavelength, as marked by arrows in Fig. 1 are the outcome of maximum gain of MI (modulation instability). The long wavelength side has higher intensity than the short wavelength side.

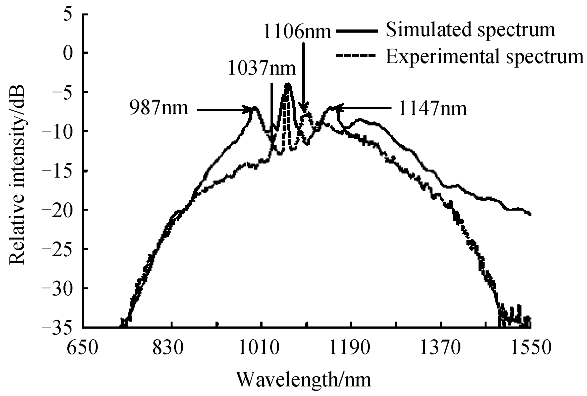

Fig. 1 Simulated spectrum and experimental spectrum from 1.8 m PCF with 1.15 W power output

The dissimilarities between results of simulation and experiment are: 1) the position and the relative intensity of maximum gains of MI are different. 2) the long wavelength is over 1 550 nm in simulation but under 1550nm in experiment. It′s because that:

First, in theory, the max gains of MI are given by

$$g_{\max}=g(\Omega_{\max})=\frac{1}{2}|\beta_2|\Omega_c^2=2\gamma P_0 \tag{9}$$

The distance from them to central frequency are given by

$$\Omega_{\max}=\pm\frac{\Omega_c}{\sqrt{2}}=\pm\left(\frac{2\gamma P_0}{|\beta_2|}\right)^{1/2} \tag{10}$$

The max gain peaks worked out locate at 987 nm and 1 147 nm, where nonlinear parameter $\gamma=11$ W^{-1}km^{-1}, peak power $P_0=2\,018$ w and $\beta_2=-2.543\,9$ ps^2/km. These calculated positions exactly agree with simulation, but they are 1 037 nm and 1 106 nm in experiment. It′s because that our simulation ignores the effect of loss for short fiber, but in fact the loss will reduce peak power gradually with the increase of propagation distance[14], which will decrease MI gain and augment the distance of frequency from gains to pump, so wavelengths at gains are closer to the pump wavelength. The effect of loss is given by

$$\Omega_{\max}^{l}=\Omega_{\max}\exp(-az/2) \tag{11}$$

Where a (the loss coefficient) we chose is 0.3 dB/m (300 dB/Km), $z=1.8$ m. The loss induce 24% frequency shift (wavelength shift is about 20 nm). Besides, the Raman effect could also cause the maximum peak shift[12]. The effect of Raman on peak shift is

$$\Omega_{\max}^{R}=\Omega_{\max}(1-f_R)^{1/2} \tag{12}$$

Where f_R is 0.18, the Raman effect cause about 9.9% peak shift (wavelength shift is about 8 nm).

Second, we assume the mode field diameter (MFD) is invariable to all wavelengths, but in fact the MFD is bigger for long wavelengths, which results in lower nonlinearity, so the nonlinear effect on long wavelength side in experiment is weaker than in simulation. Besides, we consider whether the loss also induces the discrepancy. The loss of the Photonic Crystal Fiber (PCF) in our experiment is less than 10 dB/Km under wavelength from 600 nm to 1 350 nm but more than 50 dB/Km around 1 440 nm (The PCF of 1 040 nm ZDW is from Crystal Fiber company in Denmark). To observe the effect of large loss on SC, we do another simulation with a 300 dB/Km wavelength-independent loss, for 1.8 m fiber the loss is 0.54 dB. In Fig. 2, we can observe the spectrum with high loss has no significantly change compared with the simulated result without loss. And it is seen that the large loss didn't induce the discrepancy at longer wavelength between experiment and simulation.

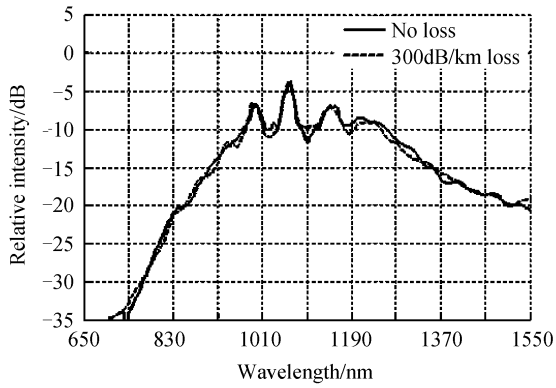

Fig. 2 Effect of large wavelength-independent loss on SC

3.2 Simulated evolution of SC spectrum

Fig. 3 shows spectral evolution along the fiber via Twice Sampling method. The $(w-w_0)T_0$ represents normalized frequency, and the intensity is linear and normalized. We can see that when the pulse propagates along the fiber, its spectrum is expanding continuously, and the intensity of pump wavelength is decreasing gradually for the transfer of its energy to other wavelength. Since the soliton order N is given by

$$N^2=\frac{L_D}{L_{NL}}=\frac{\gamma P_0 T_0^2}{|\beta_2|} \tag{13}$$

$$L_{NL}=\frac{1}{\gamma P_0} \tag{14}$$

$$L_D=\frac{T_0^2}{|\beta_2|} \tag{15}$$

In which L_{NL} is the nonlinear length, L_D is the dispersion length. The calculated value of L_{NL} and L_D are 0.045 m and 4.06×10^7 m, and N is far bigger than 1. We know that when L_{NL} and fiber length z are far less than L_D, the effect of nonlinearity will act significantly in expanding the spectrum compared with effect of GVD (Group-Velocity Dispersion), and the plus chirps generated by nonlinearity are far bigger than the minus chirps generated by GVD, so the spectrum could be expanded symmetrically and evenly[12]. At the same time, the soliton period is given by

$$L_S=\frac{\pi}{2}L_D=\frac{\pi}{2}\frac{T_0^2}{|\beta_2|} \tag{16}$$

The calculated L_S is 7.22×10^7 m, so the intensity of spectrum doesn't show periodic change along the 1.8 m fiber. All these verify that the simulations are effective, and we will find that longer fiber needs to be used to expand SC spectrum broader.

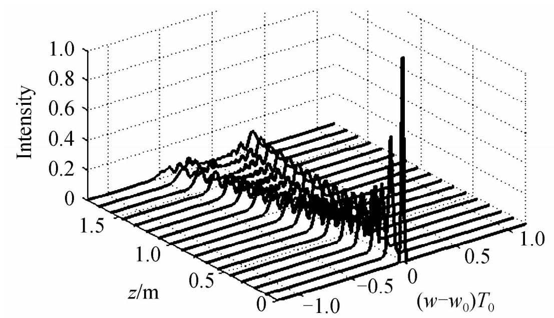

Fig. 3 Simulated evolution of spectrum along the fiber

4 Conclusion

We saved much operation time in simulation of SC generated by pumping 1.8 m PCF with sub-nanosecond pulse and come up with the spectrum which exactly agrees with experimental result via the method of Twice Sampling, and the process just spends ten minutes to simulate the SC. Referring to the simulated evolution of spectrum along the fiber length, we can improve further experiment setup.

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数值模拟亚纳秒脉冲产生超连续谱的一种改进方法

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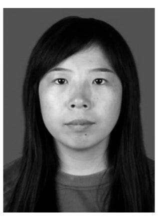
摘　要：提出了一种基于分步傅里叶方法的二次采样法，用以模拟和分析亚纳秒脉冲泵浦光子晶体光纤产生的超连续谱特性.通过此方法在广义非线性薛定谔方程上的应用，在超连续谱模拟中显著缩短了运算时间，模拟结果与实验符合很好.同时还对模拟光谱与实验结果间的细微差别做了讨论.通过此方法，模拟了1.8 m晶体光纤中产生的1.15 W续谱和光谱沿光纤长度的演化，为超连续谱实验研究的优化设计提供了依据.

关键词：超连续谱；二次采样法；分步傅里叶方法；亚纳秒脉冲



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