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Modulation Instability in Supercontinuum Generation Using the Photonic Crystal Fiber Pumped by Quasi-Continuum Wave*

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Abstract: A phenomenon experimentally emerging in super-continuum generation with a piece of photonic crystal fiber pumped by quasi-continuum wave is reported. According to the numerical simulation which contains using the gain spectrum theory of modulation instability and solving nonlinear Schrödinger equation, it is proved that this phenomenon is generated by modulation instability. After the results of the simulation and the experiment being contrasted and analyzed, it is found that the simulation result including two mentioned methods is in excellent agreement with the experiment result which the wavelength difference between the two spectrum lobes and the central wavelength are 27.08 nm and 32.72 nm respectively.

Key words: Supercontinuum generation; Generalized nonlinear Schrödinger equation; Modulation instability; Quasi-continuum wave
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0 Introduction

Recent years, there is growing interest in supercontinuum generation. Supercontinuum generation is a collection of the nonlinear effect which causes a very broad spectral bandwidth generation[1]. This collection is usually obtained by propagation of short laser impulses by strongly nonlinear devices. And the ultra-broadband light generated has a variety of potential applications, including in optical coherence tomography[2], optical communication[3], and frequency metrology[4]. Although the supercontinuum generation pumped CW was reported[5], majority experiments exhibit that supercontinuum generation was achieved with femto-second pulse, or several picoseconds pulse pumping the microstructure fiber, dispersion shift fiber[6] and tapered fiber[7] even SF6 soft glass photonic crystal fiber[8]. So supercontinuum generation had been defined to the phenomena generated by the pulse. Experimental and theoretical investigations on supercontinuum generation show that the interplay of many nonlinear effects takes an important role. This scenario is rich but not to be completely understood. However, modulation instability (MI) was numerically mentioned when the light pumped the fiber at abnormal dispersion region to generate supercontinuum. In the situation of supercontinuum generation pumped by the continuous wave or quasi-CW source, the important part is generation of the ultra-short pulse. At its generation progress, however, it is well known that with a proper choice of fiber length and the pump power, MI will pay an important role in the generation of a train of optical pulses whose repetition rate can be externally controlled[9-10]. And then the supercontinuum is generated under the interplay of some high-nonlinear effects. In ref [11], MI in photonic crystal fiber has been mentioned with numerical simulation, but the experiment character has not been presented.

In this manuscript, the sub-nanosecond pulse is adopted to pump the high nonlinear photonic crystal fiber for supercontinuum generation, and some nonlinear optical effects such as the MI / Four-Wave Mixing (FWM) were discussed and analyzed. At last we compared with the experimental and the simulation results, and found that the simulated results are excellent agreement with the experimental ones.

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1 Experiment setup and result

The experimental setup is based on a mode-locked Yb-fiber laser seeding a double-clad ytterbium-doped fiber that provided a 500 ps pulse train with a repetition frequency of 4 MHz and a central wavelength of 1 061 nm. The light average power which put out from the double-clad fiber end is 4 W, and then couple in the high nonlinear photonic crystal fiber which nonlinear coefficient is $\gamma = 11\ \mathrm{km}^{-1}/\mathrm{W}$ and the dispersion coefficient which provide by the manufacturer is given in the Fig 1. And after numerical calculation, we can receive the coefficient like $\beta_2 = -2.305\ \mathrm{ps}^2/\mathrm{km}$, $\beta_3 = 7.107\ \mathrm{ps}^3/\mathrm{km}$, $\beta_4 = -1.095\ \mathrm{ps}^4/\mathrm{km}$. From the dispersion curve the zero dispersion (ZDW) is conformed at 1 040 nm. This implies the pump light propagating in the anomalous dispersion region of the high nonlinear PCF.

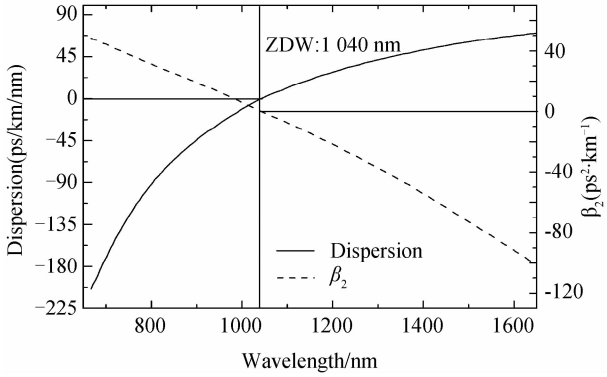

Fig. 1 Dispersion curve of nonlinear fiber provided by the manufacturer and the β_2 is calculate using the formula $D = -(2\pi c/\lambda^2) \times \beta_2$

After propagating the photonic crystal fiber, the light with the power measured by the fiber power meter is 1.1 W and the spectrum which measured by AQ-6315A optical spectrum analyzer is provided in Fig 2.

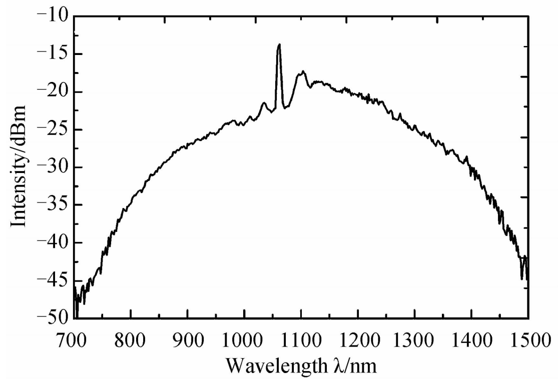

Fig. 2 Supercontinuum spectrum at the end of the high nonlinear photonic crystal fiber

In Fig 3, three peaks were exhibited and the wavelength difference between the wavelength corresponding to the two side spectrum peaks and the pump wavelength are almost equal. And the differences between the side peak and the central wavelength are 27.08 nm and 32.72 nm respectively.

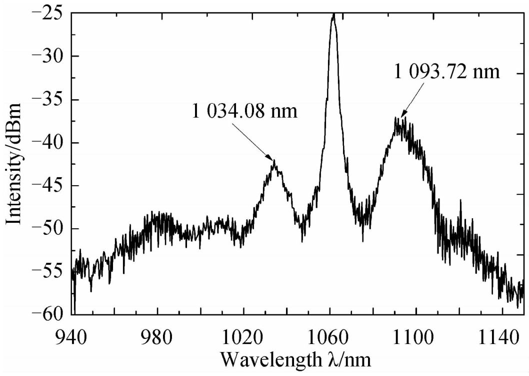

Fig. 3 Experiment spectrum of the 0.5 W supercontinuum

2 MI theory and simulation

It is well known that the gain spectrum of MI is obtained from the ref [11], and the expression is show as follows

$$g(\Omega) = |\beta_2\Omega|(\Omega_c^2 - \Omega)^{1/2} \tag{1}$$

where Ω: the frequency of perturbation, the $\Omega_c^2 = 4\gamma P_0/|\beta_2| = 4/(|\beta_2|L_{\mathrm{NL}})$, and the $L_{\mathrm{NL}} = 1/\gamma P_0$. The gain spectrum is symmetric with respect to $\Omega = 0$ such that g (Ω) vanishes at this point. The gain become maximum at two frequencies given by

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

where the P_0 is the peak power of the input pulse. From formula (3), we achieved that the position of the spectrum lobes exhibited in the light spectrum at the end of the nonlinear fiber are 1 017.65 nm and 1 106.11 nm respectively, and found that the position calculated by formula (3) is agreement with the spectrum received from the experiment.

MI is a well understood instability phenomenon of the nonlinear Schrödinger equation (NLS) which governs the underlying light wave propagation in an optical fiber in the presence of chromatic dispersion and self-phase modulation (SPM). In the anomalous dispersion region, the dominant unstable MI frequencies can be shown to be proportional to the CW amplitude and inversely proportional to the square root of the dispersion like the formula (2). Thus the modulation which grows on the CW field or the quasi-CW field is of increasing frequency as the group velocity dispersion (GVD) goes to zero. Even in the normal dispersion region, MI can occur due to third-order and fourth-order dispersion corrections. MI is responsible for initiating supercontinuum generation by destabilizing the launched CW light and the quasi-CW light[12].

In order to more clearly understand MI and the supercontinuum generation mechanisms, we have numerically solved the one-dimensional generalized nonlinear Schrödinger equation (GNLSE) by the standard split-step Fourier method. Assume that the pulse propagates along the z-axis. The general form of the NLSE for the slowly varying complex envelope $A(z,t)$ of a pulse centered at frequency ω_0 is given by

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A-\mathrm{i}\sum_{k=2}^{k_{\max}}\frac{i^k}{K!}\beta_k\frac{\partial^k A}{\partial t^k}=\mathrm{i}\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right) \\ \left(A(z,t)\int_0^{\infty}[R(t')|A(z,t-t')|^2]\mathrm{d}t'\right) \tag{3}$$

where $A(z,t)$ express the electric field envelope, β_k is the dispersion coefficients at the pump frequency ω_0 and γ is the nonlinear coefficient of the fiber. The $R(t)$ in the integral operator for nonlinear response of medium is taken from experiments in ref [13], it contains both electronic and vibrational (Raman) contributions. $R(t)$ can be expressed as

$$R(t)=(1-f_R)\delta(t)+f_R h(t)= \\ (1-f_R)\delta(t)+[f_R(\tau_1^2+\tau_2^2)/\tau_1\tau_2^2]\cdot \\ \exp(-t/\tau_2)\sin(t/\tau_1)\Theta(t) \tag{4}$$

where $f_R=0.18$ is the fractional contribution of the delayed Raman response, $\tau_1=1.22$ fs, and $\tau_2=32$ fs. $\Theta(t)$ is the Heaviside step function. Expansion of the dispersion operator into the Taylor series in the frequency is carried out to the terms $k_{\max}$, in this place we assume $k_{\max}=4$. The item in the right-hand side of GNLSE is responsible for numbers of nonlinear optical effects such as SPM, MI, stimulated Raman Scattering (SRS), four-wave mixing and so on.

The fiber and the pump source parameters in our experiment are adopted in the numerical simulation. Due to the fiber is too short, we neglected the fiber loss in our simulation. After the calculation of the GNLSE by the split-step Fourier method, the result which is the spectrum figure at the end of the photonic crystal fiber is exhibited in Fig. 4.

Fig. 4 is similar to the spectrum figure in Fig. 3, which is the experimental result. From Fig. 4, we also receive three peaks which are pump peak and two lobe peaks generated by MI respectively, and the wavelength difference $\Delta\lambda_1=38$ nm between the pump wavelength and the right spectrum lobe peak wavelength is larger than the difference between the pump peak wavelength and the left one $\Delta\lambda_2=33$ nm. However, because the other nonlinear effect such as soliton self-frequency shift (SSFS) and the dispersion affection are active but do not pay an important role in the experiment, the red-shift spectrum is larger and flatter than the blue-shift spectrum, which also is the cause which makes more energy distributing in the red-shift spectrum in the experiment result.

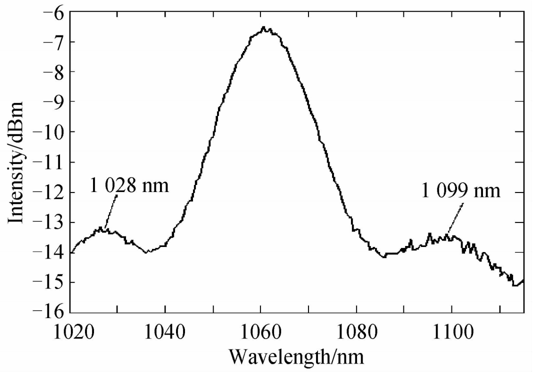

Fig. 4　Calculation spectrum of an initially Gaussian pulse

3　Conclusion

In a word, we experimentally reported the modulation instability in the supercontinuum generation pumped in abnormal dispersion region by the quasi-CW light. And then we utilized the modulation instability spectrum gain to prove the experiment spectrum which we got is modulation instability and solved the GNLSE to fit the experiment spectrum. After above contrast, we can make a conclusion that MI is an important nonlinear effect in the supercontinuum generation pumped by the quasi-CW light and the CW light. As mentioned before, the calculation results of modulation instability is excellent agreement with the experiment ones.

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孙喜文,王清月,胡明列,等.光子晶体光纤中调制不稳定性现象与超连续谱的产生[J].光子学报,2007,**36**(1):1-4.

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准连续光抽运光子晶体光纤产生超连续谱中的调制不稳定性

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摘 要:报道了应用准连续光抽运光子晶体光纤产生超连续谱时的一种现象,并根据调制不稳定和数值解薛定谔方程证明此现象为调制不稳定性.在实验中发现有两个波峰,与中心波长之间的距离分别为27.08 nm和32.72 nm,经过对比和分析数值结算和实验结果非常吻合,说明调制不稳定性在准连续光抽运光子晶体光纤产生超连续谱过程中起着重要的作用.

关键词:超连续谱的产生;广义的非线性薛定谔方程;调制不稳定性;准连续光

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