Analysis of a novel stimulated Brillouin scattering suppression mechanism through self phase modulation process in the high power short pulse fiber amplifier

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The automatic Stimulated Brillouin Scattering (SBS) suppression mechanism in low repetition rate, nanosecond level pulsed EDFA and passive fiber is analyzed in this paper .Both based on the Self Phase Modulation (SPM) caused frequency spectrum broadening which will decrease the SBS gain and increase the SBS threshold power in the main power amplifier stage of the Master Oscillator Power-Amplifier configuration. Using the Split step Fourier and Local error method (SSFM_LEM) to solve the modified nonlinear Shroedinger equation (NLSE) and our analysis data show that this method will suppress the SBS effectively.

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1. Introduction

The high power fiber short pulse amplifier with high peak power and narrow pulse width have been developed and researched widely for its important applications in many fields, for instance: laser radar, laser cutting, and space laser communication [1, 2]. The high peak power in the fiber pulse amplifier may lead to many nonlinear phenomena in the fiber such as SBS, SRS, and SPM. Among all the above, the SBS effect will be the first and easily simulated for it has the lowest threshold power, once the SBS occurred, it will transfer the energy from the signal to the backward stokes wave and consume the inverted population of the gain medium [3]. So it restrains the pulse energy and decreases the output signal power significantly, in addition SBS can cause the pulse distortion in the time domain, leading to the amplifier performance degradation [4]. As a result, the suppression of SBS becomes the main limiting factor especially in the high power pulse amplifier and the suppression of SBS is the main concern in the system design of the high power pulsed fiber amplifier.

The leading framework of high power fiber pulse amplifier called MOPA (Master Oscillator Power-Amplifier) as depicted in Fig.1, while the Master Oscillator part often include a seed laser source and one or two stage EDFA as the preamplifiers (Stage 1) to boost the power to several hundred milliwatt level, then the signal will go into the main Power-Amplifier part (Stage 2) to obtain the required power and pulse energy.

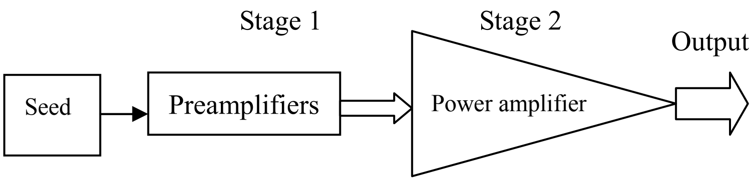

Fig.1 High power fiber amplifier based on MOPA configuration

There has been several effective choices to solve this problem: there will be considerable thermal gradients caused by heat generation because of the high pump power, this thermal gradients will broaden the Brillouin gain and increase the SBS threshold seriously [5-6]; by applying different temperature distributions along the fiber to change the Brillouin frequency downshift [7] or choosing the backward pump scheme for the fiber length experienced by high power pulses is significantly shorter [8]

In this paper, we present a novel automatic SBS suppression mechanism in the EDFA stage and the deeper suppression in the passive fiber both based on the SPM caused frequency spectrum broadening. According to the nonlinear fiber optics theory, The SPM will always occur as the optical pulse transmits along the fiber, the main effect of SPM is to broaden the frequency spectrum of the optical pulse, and the broadening extent is decided by the pulse peak power and fiber length. First, we use the optimized Split Step Fourier Method (SSFM) with error control method to analyze the variation of the pulse frequency spectrum in the EDFA by solving the modified NLSE with Fast Fourier Transform algorithm (FFT);then we analyze the further spectrum broaden in the passive fiber by solving the NLSE;at last we select the typical double clad Er-Yb co-doped fiber parameters to present the SBS suppression extent and show that this method is a useful and effective way to suppress the SBS when design the high power low repetition rate (10kb/s-30kb/s) pulsed amplifier.

2. Theory mechanism

As the seed optical pulse go through the EDFA stage the SPM effect will occur, in addition, pulse signal with narrow pulse width (ns) has a relative high peak power than the continuous signal, so the SPM will cause frequency spectrum broaden greatly and become useful to suppress the SBS effect that may happen in the next Power-amplifier stage for that the SBS gain coefficient depends on the signal frequency spectrum width. The well-known SBS gain coefficient can be described by the following: [9]

$$g_B = g_B' \frac{1}{1 + \Delta \upsilon_p / \Delta \upsilon_B} \tag{1}$$

Where g_B' is the maximum gain which is of the order of 5×10^{-11} m/W, $\Delta \upsilon_p$ is the pumping light frequency spectrum width and $\Delta \upsilon_B$ is the intrinsic linewidth of the Brillouin process range from 20MHz to 100MHz decided by the different fiber [10].

SBS has the threshold character, the estimate equation for the threshold input power is

$$g_B p_{cr} L_{eff} / A_{eff} \approx 19 \qquad (2),$$

and the factor 19 is used to replace the used approximated factor 21, because modern fibers have much lower loss than the fibers at that time [11].

Where p_{cr} is the peak power of the pump light, $Aeff$ is the effective area, in a single mode ,stedp-index fiber, the field of the fundamental mode can be approximated by a Gaussian function with the beam radius, so $Aeff = \pi w^2(\lambda)$, $2w(\lambda)$ is the mode field diameter(MFD)of the fiber at the wavelength λ [12]. $Leff$ is the effective fiber length, where $Leff = (1-\exp(-\alpha l))/\alpha$, l is the fiber length, α is the fiber loss.

Substitute Equ. (1) Into Equ. (2), we obtained the equation for the threshold input power

$$P_{th} = \frac{19 A_{eff} [1 + \Delta v_p / \Delta v_B]}{(g_B L_{eff})} \tag{3}$$

When the pump light is Polarization Independent totally the P_{th} will increase 50% [13], namely:

$$P_{th} = \frac{28.5 A_{eff} [1 + \Delta v_p / \Delta v_B]}{(g_B L_{eff})} \tag{4}$$

We can get the conclusion that if we can broaden the pump light linewidth properly, the P_{th} will increase to a considerable level and suppress the SBS effect. The common method to increase the $\Delta \upsilon_p$ is to add another high frequency carrier to increase the RF component oft the signal [14] or phase modulation using the additional phase modulator[15]. The main concept is to broaden the frequency spectrum of the signal and distribute the high peak power to a relative wider frequency spectrum, but they all have to use the extra energy input with the signal. Since the SPM effect can broaden the frequency spectrum automatically when the signal pulse transfers along the fiber, so it can suppress SBS itself when we choose the optimal fiber length without the extra energy.

The SPM effect in the EDFA transient model can be described by the modified nonlinear Shroedinger equation [16]:

$$\frac{\partial U}{\partial z} = -\frac{\alpha}{2}U - \frac{i}{2}\beta_2 \frac{\partial^2 U}{\partial T^2} + i8/9G(z)\gamma P_{cr} |U|^2 U \tag{5}$$

Where $U = A(z,T)/\sqrt{p_{cr}}$ is the normalized optical field, P_{cr} is the optical pulse peak power, γ is fiber nonlinear coefficient. , α is fiber absorption coefficient. $G(z)$ is the EDFA gain along the fiber length *z*.

3. Simulation and Analysis

Fig.2 is the EDFA transient gain versus EDF length using the Optisystem simulation environment : using the parameter EDF C600 produced by the Coractive company ;bidirectional pumping configuration with 200 mw and300mw pumping power at each end, signal wavelength is 1560nm ,the signal pulse width is 10ns, repetition rate 10kb/s and 30kb/s Gaussian pulse signal respectively . We can get the parameter in Equ. (5) $G(z)$ According to the Fig.2 .then we use the traditional and effective Split step Fourier method (SSFM) to solve the Equ .(5), further more and use the advanced step control method called Local Error Method (LEM) [17] for the sake of improving the precision and the speed of the SSFM. Finally, we use the FFT algorithm to analyze the variation of the frequency spectrum.

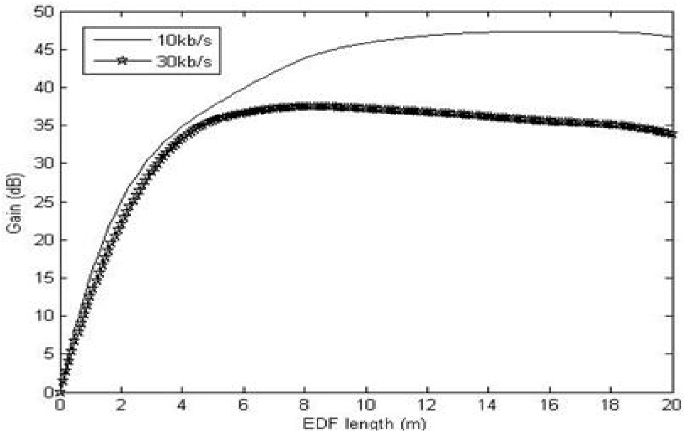

Fig.2 the EDFA transient gain versus EDF length

If we don't consider the frequency spectrum broadening, the P_{th} at the entry port of the main power amplifier stage is about 242w according to the Equ. (4) Using the double clad fiber parameter:

$$A_{eff} = 707\text{um}^2,\ L = 8\text{m},\quad L_{eff} = 7.68\text{m},\quad \Delta\upsilon_B = 20\text{MHz},\ \Delta\upsilon_p = 100\text{MHz}.$$

Now if we consider the SPM effect in the EDFA, Fig.3 is the peak power variety of the 2mw average power, 10kb/s, 10ns pulse width input signal versus the fiber length. We choose the fiber length 20m, the peak power increase from the origin 20w to the 950w when the signal passes along the EDFA, and the signal frequency spectrum will broaden to 1.4GHz, leading to the P_{th} increase to 8.79KW accordingly. Compared to the 242W above, the P_{th} has been boosted greatly.

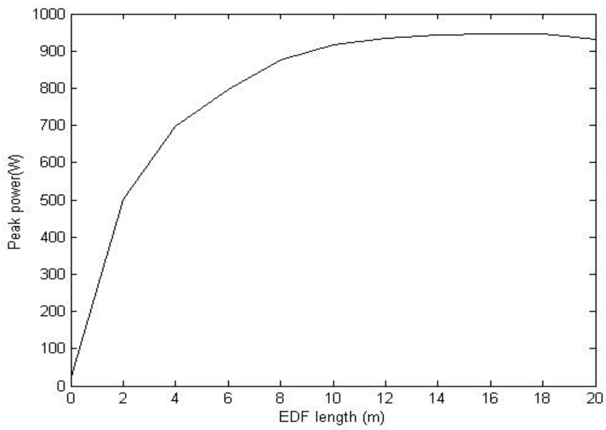

Fig. 3. Peak power variety versus EDF length

Further more, if the pulse power is too high, and the SPM effect caused frequency spectrum broadening during the EDFA stage suppress the SBS is not enough .We can add another standard single mode passive fiber between the first EDFA stage and the second double clad fiber stage to suppress the SBS deeply which will occur in the next high power amplifier stage. Since the optical pulse signal doesn't get the gain when it transfers along the passive fiber, we only considers the SPM effect, we can use the NLSE without the gain parameter:

$$\frac{\partial U}{\partial z} = -\frac{\alpha}{2}U - \frac{i}{2}\beta_2\frac{\partial^2 U}{\partial T^2} + i\gamma P_{cr}|U|^2 U \tag{6}$$

Also using the SSFM_LEM to solve the Equ. (6), and FFT to analyze the frequency spectrum broadening similarly as above.
Optical pulse signal wavelength 1560nm, the stand single mode fiber parameter we used:
g_B= 5×10^{-11} m/W. γ=2.5×10^{-3}(1/W.m) the peak power from the EDFA is 950W ,Fig.4 is the frequency spectrum broadening against the fiber length and Fig.5 is the wavelength broadening accordingly.

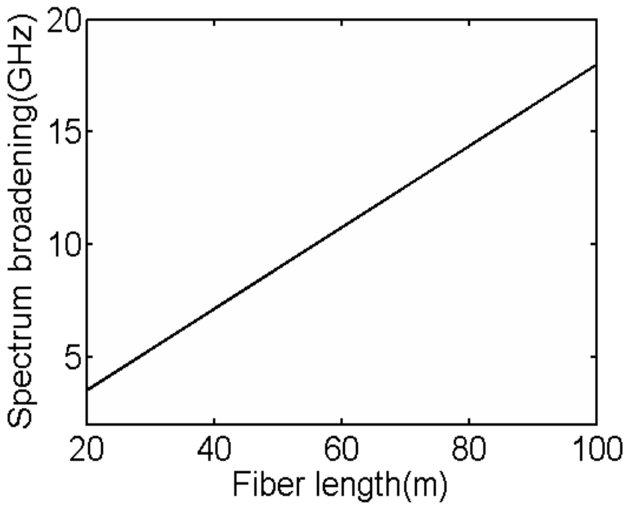

Fig. 4 signal frequency spectrum broadening against the fiber length

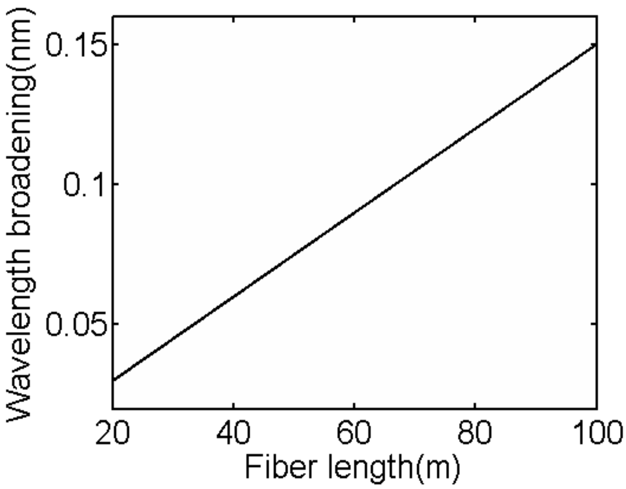

Fig.5 the wavelength broadening versus fiber length

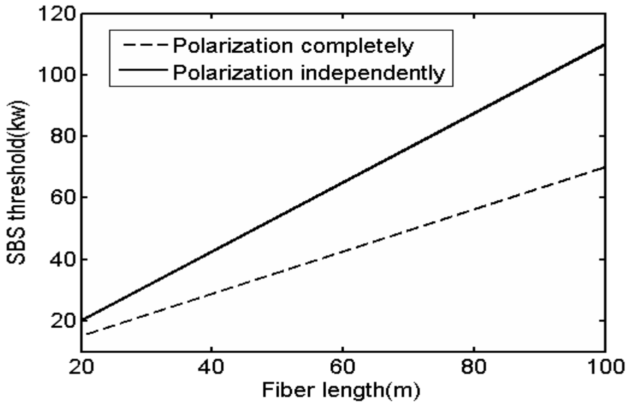

Fig. 6 SBS Pth increasing versus fiber length

We can see from Fig.4 that the frequency spectrum has broadened from 3.5GHz to 18GHz as the passive fiber length varied between 20m and 100m. At the same time, the signal wavelength only broadens from 0.025nm to 0.145nm in Fig.5; this minute change in the wavelength scale can be neglectable in many application environments. But we can see from Fig.6 that as the pumping light frequency spectrum broadens along the fiber the SBS P_{th} has increased tremendously from 20KW to 110KW (polarization independent) and 13KW to 70KW (Polarization completely).this high level SBS threshold power can suppress the SBS effect that will happen in the high power amplifier stage sufficiently . Even if the pulse peak power is very high, such high SBS effect threshold power can also prohibit it from stimulating or at least restrain the SBS power in an acceptable extent and won't influence the performance of the amplifier.

Just as the optical pulse signal transfer along the EDFA the frequency spectrum will be broadened, when the signal transfer in the main power amplification stage, its peak power is becoming higher and higher ,and the frequency spectrum will be broaden again also due to the SPM effect as the double clad fiber length increase, leading to the SBS threshold power increase more, as a result ,the SBS threshold power increase automatically as well, leading to the automatic SBS suppression again, if we select the fiber parameter carefully, the SBS in the high power pulse amplifier may be suppressed absolutely.

Table 1. Simulation parameters

Signal	Gaussian
Pulse width	10ns
Peak power	20w
Repetition rate	100kHz
Brillouin intrinsic linewidth	20MHz
Signal bandwidth(1)	20MHz
Signal bandwidth(2)	12.5GHz
Er-Yb co-doped Double clad fiber length	10m
Forward pump power at 915nm	100w
Core diameter	10 μm
Ytterbium concentration	$2.685e^{26}$ irons/m^3
Erbium concentration	$3.08e^{25}$ irons/m^3

We simulated the high power amplification account for the transient gain in the Er-Yb co-doped double clad fiber(DCF),the main DCF and the system parameters we used were showed in Table 1.the model which included the gain and the stokes wave power evolution we selected is according to [3].

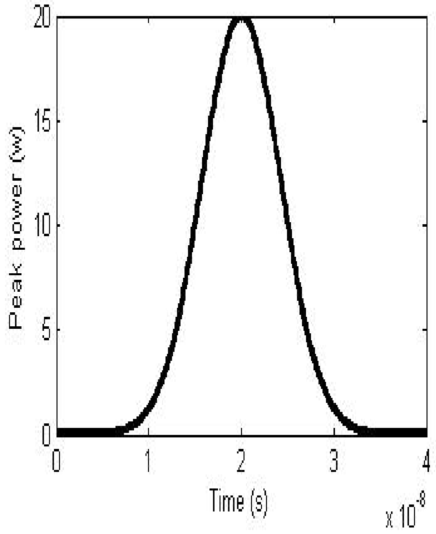

Fig. 7 Initial Gaussian pulse

The initial input Gaussian pulse with 20w peak power is showed in Fig.7, when we assuming its bandwidth is 20MHz, after it is amplified by the double clad fiber, the peak power is about 4kW as in Fig.8 (a), next, we consider the bandwidth is 12.5GHz, the peak power after amplifier is 8kW as in Fig.8 (b), the peak power increased very much as the spectrum broadening, namely, signal with 12.5GHz, increased the SBS threshold tremendously.

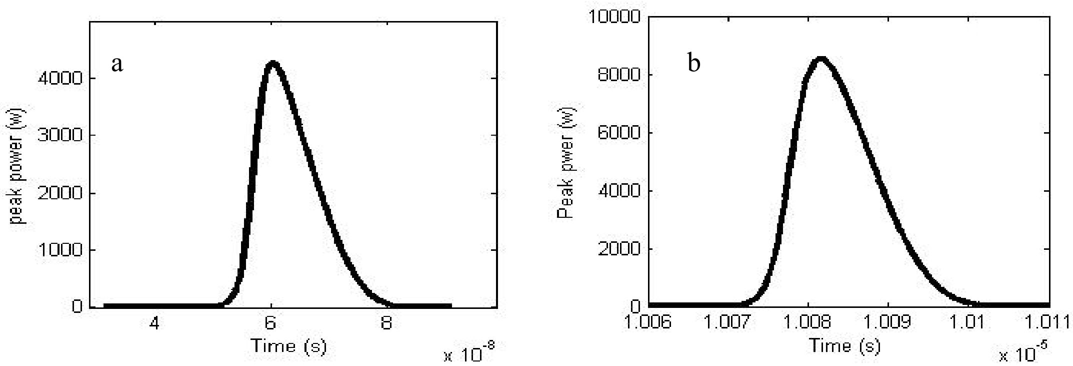

Fig.8 (a) output Gaussian pulse with bandwidth 20MHz

(b) output Gaussian pulse with bandwidth 12.5GHz

4. Conclusion

We have studied the novel SBS suppression mechanism in high power pulsed fiber amplifier based on the SPM caused frequency broadening. By solving the modified NLSE in the EDFA and NLSE in the passive fiber using the SSFM_LEM .Our simulation results show that this method will increase the P_{th} in the power amplification stage of the MOPA configuration to dozens of kilowatt though choosing the proper fiber length, such high level SBS threshold power can suppress the SBS sufficiently even completely . We use a model included the gain and SBS effect in the double clad fiber to simulated the Gaussian pulse amplifier, the result showed the spectrum broadening will increase the peak power greatly. Carefully selected the fiber parameters this method will lead to a very simple and easy way to suppress the SBS in the high power pulse amplifier.

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