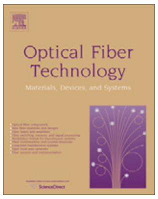
Optical Fiber Technology 17 (2011) 185–190

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte



Synthesis of fiber Bragg grating for gain-narrowing compensation in high-power Nd: Glass chirped pulse amplification system

Qiong Liu [a], Qing Ye [a,*], Zhengqing Pan [a], Aiping Luo [b], Haiwen Cai [a], Ronghui Qu [a,*], Zujie Fang [a]

[a] *Shanghai Key Laboratory of All Solid-State Laser and Applied Techniques, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[b] *Laboratory of Photonic Information Technology, School of Information and Optoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, China*

ARTICLE INFO

Article history:
Received 4 September 2010
Revised 18 January 2011
Available online 23 February 2011

Keywords:
Pulse shaping
Laser amplifiers
Fiber optics components

ABSTRACT

We propose and analyze theoretically a method to compensate gain-narrowing effect by using the spectral shaping technology based on superstructure fiber Bragg grating (SSFBG) in high-power Nd:glass chirped pulse amplification system. The target spectrum is firstly calculated from hundreds joules amplified chirped Gaussian or super-Gaussian pulse by an inverse engineering operation. A genetic algorithm is used to design the SSFBG and obtain the index modulation distribution of grating which can transform the initial seed pulse to the target spectrum. The numerically simulations show that the spectral narrowing effect of chirped pulse amplification will be reduced largely and the ideal pulse spectrum (Gaussian or super-Gaussian) is also obtained. It is believed that this proposed method will provide a theoretical direction for the following experiment. Moreover, it will also be useful and flexible for the spectral transform in other chirped pulse application areas.

1. Introduction

Ultrashort pulse amplification based on chirped pulse amplification can generate femtosecond duration pulses with peak powers ranging from a few hundred terawatts to several petawatts. Supporting technologies have developed rapidly in the past few decades [1,2]. This technology finds applications in large scale facilities for strong-field physics applications such as relativistic effects, particle acceleration [3], and inertial confinement fusion (ICF) [4,5]. Neodymium doped glass is usually used in extreme high-power laser system because a large-caliber Nd:glass can be fabricated. But the limited gain bandwidth of Nd:glass, which is limited typically to 20 nm, will reduce the spectral bandwidth of the amplified pulse and limit the minimal ultra-pulse duration. This phenomenon, which is known as gain narrowing [6,7], is introduced by the nonuniform gain in different parts of the spectrum. Gain saturation effect [7] is another limitation for the pulse quality. In the gain saturation regime, the leading edge of the pulse obtains a larger gain than the trailing edge of the pulse. To make sure the amplified pulse has enough spectral width and given pulse distribution, the input seed pulse should be pre-shaped to compensate the gain narrowing and the gain saturation. Currently, there have been many methods proposed to modify the spectrum of seed pulse. Barty used the thin-film polarizer [8] and Chambaret blue-shifted the seed pulse [9], but the former would add the dissipation of the amplifier and the latter had a limited compensation ability. Another useful method is using an acousto-optical programmable dispersive filter (AOPDF) [10], but AOPDF is fit for the broad bandwidth amplifier.

Recently, the fabrication technologies of fiber and related fiber devices have obtained huge advancements with the development of fiber communication and sensor technologies. The pulse shaping technology based on the fiber devices has also been proposed and drawn more and more attention. Several researchers have demonstrated that FBG can be used as spectral filter with controllable phase and amplitude [11,12]. The coupling between the fiber grating and the seed pulse from fiber mode-locked laser will be also more convenient than other volume optical devices. Moreover, FBG has many changeable structural parameters, such as period, apodization function, length and chirp, which make it more flexible for spectral shaping. Some inverse engineering algorithms, including Fourier transform method based on first-order Born approximation [12,13], solving Gel'fand–Levitan–Marchenko (GLM) integral equation [14], layer-peeling method [15] and genetic algorithm [16] and so on, have also been known and they can be implemented to obtain easily the eminent design of complex FBG.

In this paper, on the basis of the inverse engineering operation and the genetic algorithm, a SSFBG is proposed and synthesized theoretically to realize the spectral pre-shaping of input seed pulse, which may be used to compensate gain-narrowing effect in high-power Nd:glass chirped pulse amplification system. The target spectrum is firstly obtained from hundreds joules amplified

---

* Corresponding authors. Fax: +86 21 6991 8033.
E-mail addresses: yeqing@mail.siom.ac.cn (Q. Ye), rhqu@mail.siom.ac.cn (R. Qu).

1068-5200/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.yofte.2011.01.009

chirped Gaussian or super-Gaussian pulse by an inverse engineering operation. A SSFBG is designed by the genetic algorithm which can transform the initial seed pulse to the target spectrum. Using the proposed systemic scheme, we studied numerically a 20 μJ, 200 fs, 15 nm seed pulse is transformed to a 400 J, 8 nm optimal Gaussian or super-Gaussian (forth order and tenth order) chirped pulse in a high-power Nd:glass amplification system. The simulated results show that the spectral narrowing effect will be reduced largely and the ideal pulse spectrum (Gaussian or super-Gaussian) is also obtained.

2. Amplification of chirped pulse

Chirped pulse amplification technology was invented by Strickland and Mourou in 1980s [1] and it can effectively prevent the gain medium destruction from a high pulse peak intensity. In high-power amplification system, the seed pulse is generated by a mode-locked laser oscillator. Before passing through the gain medium, the seed pulse is chirped and temporally expanded to a long duration using a grating pair or other dispersion medium. This can reduce the peak intensity of the seed pulse and eliminate the detrimental effects in the gain medium. After amplification, the pulse is compressed by another reverse grating pair to obtain very short pulse duration (e.g. femtosecond pulse). The pulse propagation process in the gain medium is governed by the following equation [7]:

$$\frac{\partial E(z,t)}{\partial z} = g(\omega,t)E(z,t) + i\frac{\beta_2}{2}\frac{\partial^2 E(z,t)}{\partial t^2} - ik_0 n_2 |E(z,t)|^2 E(z,t) \qquad (1)$$

where β_2 is the group velocity dispersion constant of amplification medium, n_2 is the optical Kerr coefficient and $g(\omega,t)$ is the gain coefficient. For the chirped pulse amplification system, the compressor can effectively compensate the group velocity dispersion, so the group velocity dispersion will not be considered. The nonlinear effect may also be neglected due to the nanosecond chirped pulse. Then the gain coefficient $g(\omega,t)$ is described as:

$$g(\omega,t) = g_0 g'(t) g''(t) \qquad (2)$$

where g_0 is the small signal gain coefficient, $g'(t)$ is a coefficient to describe the gain saturation:

$$g'(t) = \exp[-\int_{-\infty}^{t} I(z,t')dt'/J_s] \qquad (3)$$

where J_s (=4.5 J/cm^2 for Nd:glass) is the saturation energy density of the gain medium. Gain saturation leads to pulse distortion because the leading edge of the pulse undergoes higher gain than the trailing edge due to the depletion of the population inversion. Gain narrowing is another primary limitation for the pulse quality, which is introduced by the nonuniform gain in different parts of the spectrum. For the Nd:glass system, the gain narrowing has a greater effect than the gain saturation on the performance of the amplified pulse due to the narrow gain bandwidth $\Delta\lambda$ (only 20 nm). Therefore, it will be studied specially and detailedly in this paper.

Usually, the Nd:glass gain can be approximately described by homogeneous theory [17] and the gain profile $g''(\omega)$ was assumed to have a Lorentzian shape centered at 1053 nm:

$$g''(\omega) = \frac{(\Delta\omega/2)^2}{(\omega-\omega_0)^2 + (\Delta\omega/2)^2} \qquad (4)$$

The gain narrowing is generally induced by the nonuniform gain for different parts of the spectrum, which leads to a reduction in the optical bandwidth of the amplification pulse and limits the pulse duration due to the Fourier transformation relation. Fig. 1 shows the effect of gain narrowing on sixth order super-Gaussian chirped pulse in a Nd:glass amplifier. The evolutive process of optical spectrum is displayed with normalized peak values in Fig. 1a. The input pulse has a 20 nm spectral width at 3 dB and a 100 dB amplification coefficient (10^{10} times) is implemented. It can be known from this figure that the pulse spectrum becomes narrower rapidly and the spectral waveform evolutes a Gaussian waveform from a super-Gaussian waveform. When the amplification is 400 times, the spectral bandwidth is about 8 nm. The corresponding value is 5.1 nm for 1.6 $\times 10^5$ times. The variation of bandwidth as a function of amplification times is shown in Fig. 1b.

3. Spectral shaping using SSFBG

3.1. Genetic algorithm

Genetic algorithm (GA) is a probabilistic parallel search algorithm to find exact or approximate solutions based on natural selection. The GA is categorized as global search heuristic and therefore it is more likely to find the global optimum solutions than local search approaches, such as the iterative layer-peeling algorithm. The GA in particular became popular through the work of Holland in the early 1990s [18], and was already used in FBG design [19]. GA uses a direct analogy of natural behavior. In nature, individuals compete with each other for limited resources. Broadly, those fittest individuals have better potential for survival and possibly have a large number of offspring. The GA usually starts from a population of randomly generated solutions (called individuals) in the solution domain. In most GA implementations, the solutions in a population are represented in strings of binary numbers or floating numbers. Then genetic algorithm uses some useful operations called genetic operations to search and optimize the solutions. A global optimum solution will be found at last. One of advantages

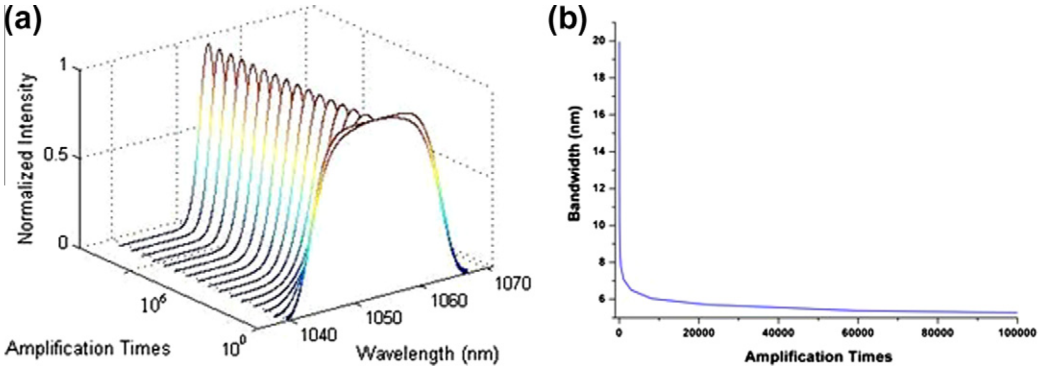


Fig. 1. The effect of gain narrowing on sixth order super-Gaussian chirped pulse in a Nd:glass amplifier: (a) The evolutive process of optical spectra and (b) the variation of bandwidth as a function of amplification times.