Simulation study of broadband long-pulsed amplification in high-power laser systems

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Accurately and efficiently predicting the fundamental-frequency temporal shape of broadband long-pulsed lasers is very important in research on the properties of high-power laser amplifiers. In this study, we first propose that analytic electric polarization in the temporal domain is applied to broadband long-pulsed pulse amplification. We first verify the accuracy of this algorithm in the dozens of picoseconds range and the results are consistent with Miro software. Then we simulate the broadband long-pulsed amplification. The simulation results indicate that the front edge of the output pulse is more enlarged than the end edge owing to saturation and that the gain narrowing induces severe amplitude modulation. Analytic electric polarization in the temporal domain is effective and precise for investigating the broadband pulse amplification in the time scale from dozens of picoseconds to nanoseconds, and the computation time can be decreased by at least 4 orders of magnitude.

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To ensure the expected output of the inertial confinement fusion (ICF) experiment, the laser performance operations model (LPOM)[1,2], which automates the setup of all the laser beams, accurately predicts the output parameters, and provides online equipment protection for the laser system has been developed. However, some problems, such as the accurate and quick prediction of the fundamental-frequency temporal shape of broadband long-pulsed lasers, must be studied in detail. In the high-power laser facility, the fundamental-frequency pulse width of thermonuclear ignition is approximately 1 to 10 ns[3] and can be classified as long-pulsed amplification. The fundamental-frequency laser spectrum is broadened through the phase-modulation module for the following reasons to avoid stimulated Brillouin scattering (SBS)[4–6] and to “smoothen” the final focal spot that reaches the target capsule. First, spectral broadening can reduce the maximum spectral power density below the SBS threshold at the end of the amplifier chain to protect large optical elements, improving the operation safety and reliability of the system. Second, nonuniformities in the laser irradiation may seed Rayleigh–Taylor hydrodynamic instability, which degrades target performance. Therefore, high spatial homogeneity[7] is desired for focal spots. Broadband pulses can reduce the near-field spatial coherence of laser beams and improve the space uniformity[8]. Combined with the smooth spectral dispersion (SSD) technique, the irradiation uniformity of focal spots can be significantly improved. Third, highly efficient broadband harmonic conversion technology has become the development bottleneck, and the laser facility urgently needs to develop third-harmonic conversion technology for broadband lasers[9–13]; however, broadband third-harmonic conversion requires broadband fundamental-frequency laser amplification. Therefore, investigating broadband long-pulsed amplification is a new development direction for future high-power laser systems.

Broadband long-pulsed beams have not yet been introduced for investigation and use in domestic high-power laser facilities. Fresnel and Prop92 software mainly use the Frantz–Nodvik[14] model and solve the transmission and amplification problems well for laser pulse widths of nanoseconds to subnanoseconds; however, they cannot calculate broadband laser pulse widths because the Frantz-Nodvik model is suitable for quasi-monochromatic waves. The national ignition facility (NIF) is in the stage of preliminary study and is not yet used in practical applications[15]. A new calculation model has been developed with Miro[16] software to treat the broadband effects involved in optical smoothing, and the model has been solved using the windowed Fourier transform (WFT). Thus, on one hand, Miro software analyzes only short pulses (dozens of picoseconds). On the other hand, WFT is very complex and time consuming. In this method, first, the appropriate time-frequency localization window function is selected. Then, this window function is moved to change the linear space from one dimension to two dimensions. Subsequently, the power spectra of different times are calculated. After that, the two dimensions are changed back to one. Finally, the space-time evolution of the signal is obtained. In order to expand the range of pulse widths to long pulses and to meet the high-efficiency requirement of LPOM, based on the numerical analysis of a nonstationary signal during the propagation of light pulses in a chirped-pulse amplification laser[17], this paper first proposes a new calculation method, analytic electric polarization in the temporal domain, to investigate broadband amplification. Compared with WFT, this method has the advantages of high efficiency and precision.

A numerical method has been developed because Miro's broadband calculation mode computes amplification by considering both saturation and gain narrowing. The broadband amplification equations for a homogeneous line are[16]

$$\begin{cases} \frac{\partial E(z,t)}{\partial z} = i\tilde{P}(z,t), \\ \frac{\partial \tilde{P}(z,t)}{\partial t} = i(w_A - w_L)\tilde{P}(z,t) - \frac{\tilde{P}(z,t)}{T_2}, \\ -i\frac{g(z,t)}{T_2}E(z,t), \\ \frac{\partial g(z,t)}{\partial t} = -g(z,t)\frac{|E(z,t)|^2}{F_{\text{sat}}}, \end{cases} \tag{1}$$

where $\tilde{P}(z,t) = P_{wL}/(2nc)$. Equation (1) is valid for a Nd-like medium with a four-level amplifier when the lifetime of the upper laser level is supposed to be infinite and that of the lower laser level is zero. Here, w_A is the resonance frequency of the gain medium, w_L is the laser frequency, P is the polarization density, and E is the electric field. Furthermore, g is the small-signal gain coefficient, c is the velocity of light in vacuum, and n is the linear index of refraction. F_{sat} is the saturation fluence, which is a constant characteristic of the amplifying medium; T_2 is the coherence time of the line, and $T_2 = 2/\Delta w_A$.

In the time domain, the expected electric-field output modulated by a phase-modulation module can be expressed as[8,16]

$$E(z,t) \equiv \bar{E}(z,t)\exp[i\varphi_m(t)], \tag{2}$$

where $\bar{E}(z,t)$ is the amplitude of the incident electric field and $\varphi_m(t)$ is the phase of the electric field.

The maximum difference between analytic electric polarization in the temporal domain and WFT is that the new algorithm aims to solve the signal property in the entire time domain. By following a previous report[17], we solve $P(z,t)$ in the Fourier domain and transform it back to the time domain through asymptotic expansions of the integrals. The basic assumption is that the pulse duration is much greater than the dephasing time of the gain medium, and the laser field is not sufficiently strong to create Rabi-frequency oscillations. With these two assumptions, we can obtain

$$P(z,t) = \frac{-igE}{1 + iT_2[\varphi'_m(t) + w_L - w_A)}, \tag{3}$$

where $\varphi'_m(t)$ is the instantaneous frequency, defined as the time derivative of the total light-field phase.

Finally, we simplify the broadband amplification of Eq. (1) to obtain

$$\begin{cases} \frac{\partial E(z,t)}{\partial z} = \varepsilon g(t)E(z,t), \\ \varepsilon = 1/[1 + iT_2(\varphi'_m(t) + w_L - w_A)], \\ \frac{\partial g(z,t)}{\partial t} = -g\frac{|E(z,t)|^2}{F_{\text{sat}}}. \end{cases} \tag{4}$$

The conventional mathematical method can solve Eq. (4) with stability and convergence.

Miro's[16] simulation parameters are as follows: $F_{\text{sat}} = 4.93\ \text{J/cm}^2$, $g = 3\ \text{dB/m}$, the bandwidth is 20 nm, the gain medium is N31 neodymium glass, the central wavelength of the emission spectrum is 1053 nm, and the broadband short-pulsed duration is 30 ps. We designed a double-pass amplifier, and we consider an initially sinusoidal phase-modulated pulse with a 500 GHz frequency of modulation and a 10 rad modulation depth. The equivalent thickness of the medium is 0.144 m, and the laser pulse beam output is radially symmetric. We introduce a Tukey window (the size parameter is 0.4) into the spatial distribution of the electric-field amplitude. The initial pulse distribution is satisfied with the equation[5,8]

$$E(z,t) = E_1(z,t)\exp[i\beta\sin(2\pi f_m t)], \tag{5}$$

where β is the phase-modulation depth of the electric field and f_m is the frequency of modulation.

To verify the accuracy of the new algorithm, Fig. 1 shows the temporal shape of a broadband short-pulsed laser after amplification using analytic electric polarization in the temporal domain and the WFT method. It can be concluded that the two pulse-peak-intensity distribution curves are fitted quite well. There are some subtle differences between two algorithms due to the different approximate treatment and deduction, respectively. The two algorithms were run on *HP–Z*800 workstations with the same configuration. WFT requires at least 8 h, whereas the new algorithm only requires 1.9 s. It can be seen that the new method has high computation efficiency and maintains the precision demand of the physics experiment.

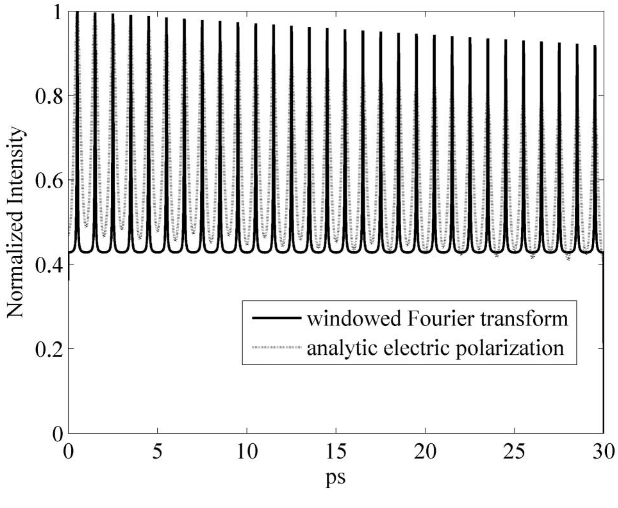

Fig. 1. Temporal shape of the output pulse (30 ps).

In order to improve the focus uniformity of the near and far field further, and to suppress the SBS of large optical elements, the high-power laser facility should develop fundamental-frequency broadband long-pulsed laser amplification. In addition, one of the preconditions of analytic electric polarization in the temporal domain is that the pulse duration should be much larger than the dephasing time. Therefore, expanding the range of pulse durations to long pulses can make the calculation results more accurate. In order to satisfy the development requirement for high-power laser drivers using the new algorithm, we calculate the broadband amplification for 0.3 and 3 ns pulse widths. The following parameters are almost consistent with the parameters required by physical experiment in the laser facility.

The parameters for the 0.3 ns pulse width are as follows: $f_m = 40$ GHz, $\beta = 20$ rad, and $g = 4$ dB/m. The rest of the parameters are the same as those for the 30 ps pulse width. The result for the 0.3 ns simulation is presented in Fig. 2. We observe that there is more gain at the front edge of the pulse than at the end edge, owing to the saturation effect. During this process of calculation, we also use the WFT method. Compared with analytic electric polarization in the temporal domain, WFT needs a large number of points for temporal sampling (we use 32768 points in Fig. 2). Further, it needs a process of increasing and decreasing dimensions: first, the dimensions are increased from 1×32768 vectors to 32768×32768 matrices; then, the dimensions are reduced from 32768×32768 matrices to 1×32768 vectors. However, such computation requires, in general, a large amount of memory and a duration of at least 12 h. Under the same conditions, the new method only needs approximately 2 s and can decrease the duration by at least 4 orders of magnitude.

The parameters of the 3 ns pulse width are as follows: $f_m = 10$ GHz, $\beta = 40$ rad, and $g = 5$ dB/m. The rest of the parameters are the same as those for the 30 ps pulse width. The result for the 3 ns simulation is presented in Fig. 3. From Figs. 2 and 3, we observe that more gain occurs at the front end of the pulse than at other parts, owing to the saturation effect. The gain narrowing induces an obvious modulation of the field amplitude, and a loss in the average amplification. The results of multiple simulations show that the phase-modulation depth has a significant influence on the amplitude modulation when β is high, and the strong amplitude modulation can seriously affect the laser pulse shaping ability. In order to reduce this modulation, an appropriately small phase-modulation depth should be chosen.

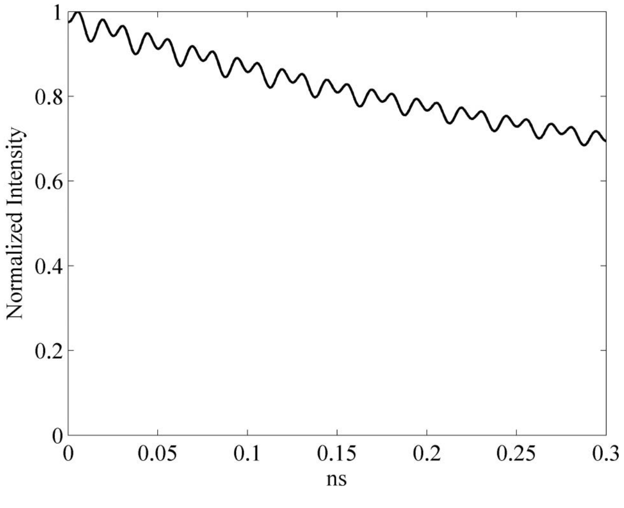

Fig. 2. Temporal shape of the output pulse (0.3 ns).

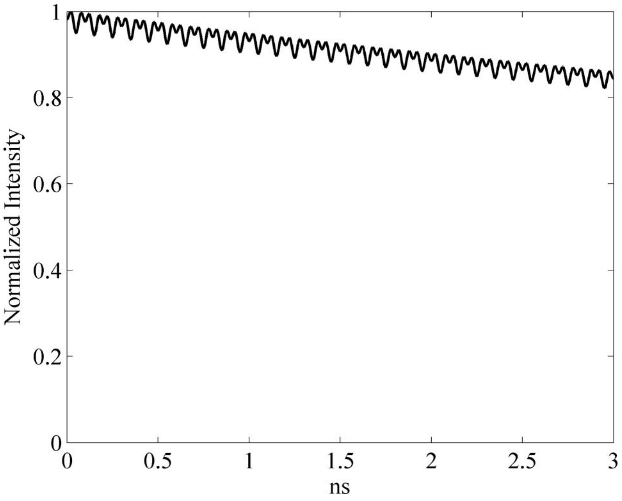

Fig. 3. Temporal shape of the output pulse (3 ns).

The amplifiers constitute the most critical part of the laser chains, determining the output ability and level of the laser device. Therefore, an accurate amplified-transmission model of laser pulses in amplifiers and a high-efficiency algorithm are prerequisites to ensure accurate prediction and feedback. Although a broadband short-pulsed mode has been developed inside the Laser Magajoule device in France, the efficiency of the algorithm is quite low, and it cannot meet the engineering requirements of LPOM. Under this condition, it will be very important to make full use of the advantages of analytic electric polarization in the temporal domain, such as the wide range of pulse widths from dozens of picoseconds to a few nanoseconds, high efficiency, and high precision. The purpose of this paper, on one hand, is to prepare a preliminary theory for the broadband long-pulsed amplification and transmission in the SG-II facility; on the other hand, the purpose is to provide an efficient method of guidance for the implementation of online laser control and feedback.

In conclusion, the conventional method is very complicated and time-consuming for solving the problems of broadband pulse transmission and amplification for time scales from dozens of picoseconds to nanoseconds. Analytic electric polarization in the temporal domain was found to be more effective and appropriate, especially for long-pulsed amplification, and the new method can fully meet the engineering requirements of LPOM.

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