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A time-dependent ASE calculation for transient gain enhancement of picosecond pulses in a large-aperture KrF laser amplifier

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Abstract. In a large-aperture KrF laser amplifier, steady-state gain is heavily reduced by intra-cavity amplified spontaneous emission (ASE). However, the reduced gain can be transiently enhanced by temporally suppressing the ASE with an intense depleting short pulse. Previously, we reported the experimental observation of this transient gain enhancement and numerical calculations to explain the experimental results. However, a discrepancy was noticed between the experimental results and the calculated values, which was due to the neglect of the propagation time of laterally traveling ASE. In this paper, we present a novel time-dependent ASE code incorporating the lateral-ASE transit time and report the calculation results using the developed ASE code. The calculated values agreed with the experimental results.

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In a large-aperture KrF laser amplifier, steady-state gain is heavily depleted by intra-cavity amplified spontaneous emission (ASE). However, the depleted gain can be transiently enhanced by temporally suppressing the ASE by using a saturated depleting short pulse. In our previous experiments of amplifying 10-ps pulses in a 29-cm-diameter KrF amplifier, we observed a transient gain higher than that under constant ASE conditions [1], and thus experimentally confirmed the transient gain enhancement.

In order to explain the observed gain enhancement, we also performed a numerical calculation of the transient ASE and gain performances by using a one dimensional (1D) time-dependent ASE code [2]. The calculations produced a transiently enhanced gain and thus confirmed the observed phenomena qualitatively. However, there was a non-negligible discrepancy between the experimental results and the calculated values for the inter-pulse separations of less than 2 ns. It was due to the neglect of the propagation time of laterally traveling ASE photons in the calculation code.

In order to explain the experimental values, we developed a novel time-dependent ASE code modified from our previous one. This code deals with both axial and radial propagation times of ASE photons by assuming a simple ASE model. Also, reflection of ASE photons at the side wall in the laser cavity is incorporated as performed in the other ASE models [3, 4]. By using this ASE model, the experimental results are explained very well.

Initially, the modified time-dependent ASE code is briefly explained. Then the calculation results are compared with the experimental results of the two 10-ps pulse amplifications. Finally, the lateral ASE behavior is discussed in terms of its intensity and propagation time in the laser cavity.

1 ASE calculation

Some of the features of our new ASE code are described. It is essentially a 1D time-dependent ASE code that is modified from our previous model [2]. However, it can deal with the propagation times of laterally as well as axially traveling ASE photons in the cavity.

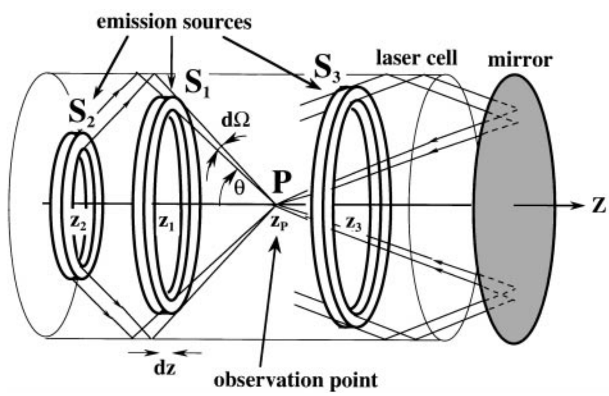

Fig. 1. Geometry used for the ASE calculation in a double-pass amplifier. The spontaneous emission sources S_1 to S_3 are assumed to have the form of an annulus. An observation point on the axis is shown as P

The geometry used for the ASE calculation is shown in Fig. 1. As in our previous code, the radial gain distribution is assumed to be uniform, and the intra-cavity ASE is treated as an energy fluence occupying each time step ($\mathrm{d}t = 33.3$ ps) or amplifier segment ($\mathrm{d}z = 1$ cm). The difference of the present model from our previous one is that spontaneous-emission sources depicted as $S_i (i = 1, 2, 3)$ in Fig. 1 are expressed in the form of an annulus of thickness $\mathrm{d}z$. From S_1, for example, emitted photons are transmitted along the conical surface making an angle θ to the axis, and the intensity is amplified to an observation point P having an elemental area on the axis. Also, the present code takes account of reflection of ASE at the side wall or foil surface. In this code, only the ASE photons that are reflected once are taken into account. Also the effective reflectance at the wall or foil surface is assumed to be 50% and no isotropic scattering is considered. From S_2, the emitted photons are reflected at the side wall and the ASE intensity reaching P from S_2 is reduced by the reflectance value. In the case of S_3, emitted photons are reflected by both the side wall and the rear mirror.

The ASE fluence reaching P from S_i is derived by modifying our previous equation and expressed as $\mathrm{d}\Phi$ normalized relative to the saturation energy density E_s given by

$$\mathrm{d}\Phi(z_p, t_p) = g(z_i, t_i)\frac{\mathrm{d}t}{\tau_u} A \,\mathrm{d}z \,\mathrm{d}\Omega \, G \,. \quad (1)$$

Here, $\mathrm{d}\Phi(z_p, t_p)$ is the value at P at a time t_p, and $g(z_i, t_i)$ is the local gain coefficient at S_i at a time t_i. The upper-state lifetime is expressed as τ_u, and A contains the factors related to the lifetimes and bandwidths (see [5] for details). $\mathrm{d}\Omega$ is the solid angle subtended by the annular area S_i as seen from P. G is the gain between S_i and P calculated with the local gains and times along the line with the angle θ. For each position of P, the angular position of S_i is changed by scanning θ from 0 to $\pi/2$ with an increment of $\pi/62$. Also for each θ, the axial position of S_i is incremented by $\mathrm{d}z$ until S_i hits the longitudinal end of the gain region or the radial limit increased due to the side-wall reflection. The ASE contributions are summed to get the total ASE intensity and the depleted gain at P.

In parallel with the ASE calculation at $P(z_p, t_p)$, amplification of two consecutive short pulses is performed if pulses exist at P. As conducted in [2], we calculated short-pulse amplifications under the following two ASE conditions, 1) steady-state ASE conditions, which is experimentally realized in a small-aperture beam path in a large-aperture cavity (small-aperture amplification), and 2) temporally changing ASE conditions, which is experienced by the beams fully covering the large-aperture gain medium (large-aperture amplification).

In the calculations to explain the experimental results using the 29-cm aperture amplifier [1], small-signal gain coefficient $g_0 = 8\,\%/\mathrm{cm}$ and gain-to-loss ratio $g_0/\alpha = 10$ (α : non-saturable absorption) are assumed. The calculated results are shown in Fig. 2 with the experimental values of the large-aperture amplification. The calculated fluences of the large-aperture output beams agreed with the experimental values within the experimental shot-to-shot fluctuations. Also in order to examine the possibility of a higher transient gain, we performed a calculation for a gain coefficient of $g_0 = 16\,\%/\mathrm{cm}$, which is twice as high as in the 29-cm aperture amplifier [6]. The result is shown in Fig. 3 for both the large-aperture and small-aperture beams. A transient gain higher than the steady-state value is noticed at the pulse separation of around 1.5 ns.

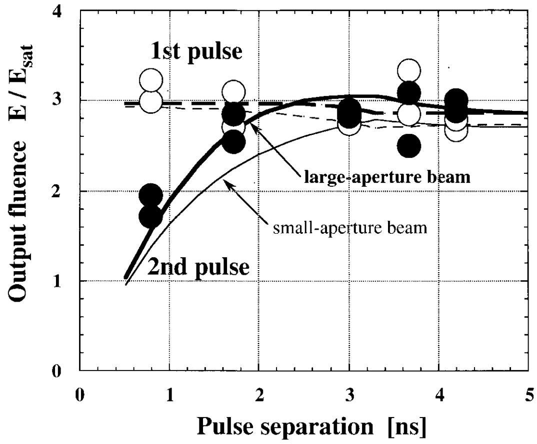

Fig. 2. Calculated and measured output fluences as a function of pulse separation. *Broken* and *solid lines* represent calculations for the first and second pulses, respectively. The *heavy lines* refer to the large-aperture amplification, and *fine lines* to the small-aperture amplification. In the calculation, small-signal gain coefficient $g_0 = 8\,\%/\mathrm{cm}$, gain-to-loss ratio $g_0/\alpha = 10$ (α : non-saturable absorption), and input fluences of $0.1E_{\mathrm{sat}}$ for both the first and second pulses are assumed. The other amplifier parameters for the calculation are shown in [2]. Measured fluences are shown as *open circles* and *solid dots* for the first and second pulses, respectively. Experimental points are from [1]

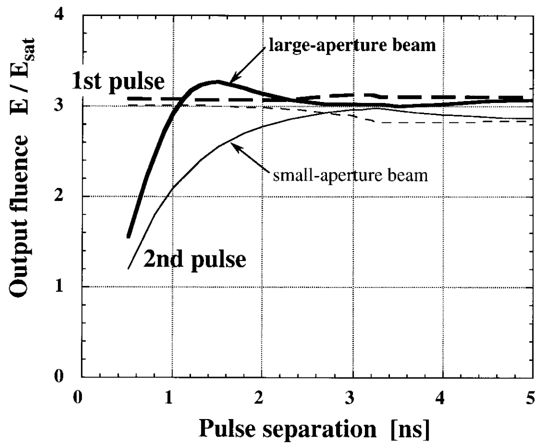

Fig. 3. Calculated output fluences for a higher gain coefficient, $g_0 = 16\,\%/\mathrm{cm}$, which is twice as high as in the 29-cm aperture amplifier. Other parameters and notations as in [2] and Fig. 2

2 Discussion

Based upon the agreement between the calculated values and the experimental results, the intensity and propagation time of the lateral ASE are discussed.

In our previous short-pulse calculations, the calculated second-pulse output fluences were smaller than the experimental values for the pulse separations of less than 2 ns. This was due to the neglect of the lateral-ASE transit time resulting in an underestimation of the gain values [2]. In the present calculations, however, the agreement is found between the experiment and calculation as seen in Fig. 2. The increased estimation of the gain values is considered to be due to the side-wall reflection model. In this model, the intensity of the lateral ASE reflected at the wall is comparable to that of the non-reflected components. On the other hand, the axial ASE components are not as increased in this model, since the beam size of the double-passed ASE is restricted by the amplifier aperture when they are transmitted via the rear mirror. Thus only the lateral-ASE components are estimated to be larger than before. Here, the increase in the ASE intensity due to the reflection is approximately 0.2 times the saturation intensity I_s, and thus the change in the gain coefficient is around 0.6 %/cm, which is within the experimental fluctuations. Thus the calculated gain values are consistent with those previously observed or calculated under the steady-state conditions [1, 5]. In conclusion, the agreement is brought about by the larger estimation of the lateral-ASE intensity and the transient suppression of those ASE photons.

In the present ASE model, the lateral transit time is also increased to a larger value than in our previous code due to the reflection at the side wall. In the amplifier considered, the propagation of the photons from the side wall to the axis is 0.5 ns. But the maximum propagation time in the radial direction is increased to 1.5 ns for the reflected ASE photons. As seen in Figs. 2 and 3, a transiently enhanced gain appears in the region of 1.5–2 ns. Thus the delay times of the measured or predicted gain enhancement are explained by the propagation time in this region.

As discussed previously, a larger transient gain is expected in a larger-aperture amplifier with a higher gain coefficient. It is due to a longer delay time for the lateral ASE and a faster rate of increase in the recovering gain [1]. This situation is considered to be realized in Fig. 3 for a gain coefficient of 16 %/cm. Whereas the amplifier aperture is limited to 30 cm in diameter, the enhanced gain is also considered to be due to the increased propagation time along the radius by the side-wall reflection.

In this ASE reflection model, some assumptions are made such as the reflectance value and number of reflections, while no consideration is given to scattering. In the real amplifier, in contrast, the wall reflectance will be smaller than the presently assumed value, and ASE photons will be reflected many times when they travel in the radial direction. Also, ASE photons will be isotropically scattered at the wall or foil surface. From the above results, however, the present reflection model can explain the experiment to a high degree. In other words, the real reflection conditions could be approximated by using the present ASE model to asses the transient gain enhancement in a large-aperture amplifier.

3 Summary

We have presented a time-dependent ASE code for short-pulse amplification in a large-aperture KrF laser amplifier. This 1D ASE code takes account of propagation times of laterally as well as axially traveling ASE photons and the reflection at the side wall in the laser cavity. The experimental results of 10-ps pulse amplification are explained by the calculations using this ASE model. The substantial suppression of the lateral ASE is found to be essential for the transient gain enhancement in terms of its intensity and propagation time.

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