Control of the amplification of large band amplitude modulated pulses in Nd-glass amplifier chain

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ABSTRACT

We study nonlinear effects in amplification of partially coherent pulses in a high power laser chain. We compare statistical models with experimental results for temporal and spatial effects. First we show the interplay between self-phase modulation which broadens spectrum bandwidth and gain narrowing which reduces output spectrum. Theoretical results are presented for spectral broadening and energy limitation in case of time-incoherent pulses. In a second part, we introduce spatial incoherence with a multimode optical fiber which provides a smoothed beam. We show with experimental results that spatial filter pinholes are responsible for additive energy losses in the amplification. We develop a statistical model which takes into account the deformation of the focused beam as a function of B integral. We estimate the energy transmission of the spatial filter pinholes and compare this model with experimental data. We find a good agreement between theory and experiments.

As a conclusion, we present an analogy between temporal and spatial effects with spectral broadening and spectral filter. Finally, we propose some solutions to control energy limitations in smoothed pulses amplification.

1. INTRODUCTION

The development of the coming generation of Megajoule-class laser requires optical smoothing to obtain both a focal spot large enough and a good uniformity. Different optical smoothing techniques have been proposed and experimented, such as Smoothing by Optical Fiber (SOF)[1] and Smoothing by Spectral Dispersion (SSD)[2]. SOF seems to be an efficient method when it deals with asymptotic contrast, shape and control of the focal spot, or smoothing of low spatial frequencies. But, earlier experiences with SOF technique have shown a strong limitation in term of the amplification performances[3]. Indeed, amplitude modulations involve nonlinear effects in time and spatial domains. We have studied both effects with theoretical models and compared them with experimental results on Phebus laser facility. We will see as a conclusion that we can have a symmetric approach for spatial domain and temporal domain.

2. DESCRIPTION OF THE LASER FACILITY USED FOR AMPLIFICATION EXPERIMENTS

We have carried out experiments on the backlighter beam of Phebus laser. We create a time-incoherent pulse at 1.053 μm with a spatially uniform profile by using a longitudinal multimode glass laser. The 14-ns output pulse has the characteristics of a Gaussian stationary statistical process and its spectral bandwidth is typically

1.2 nm FWHM which corresponds to a coherence time T_c of 1.1 ps. We can inject this pulse into a multimode optical fiber in order to create the spatial incoherence coupled with the time incoherence. The optical fiber used in our experiments provides 400 spatial modes and a total time delay of 9 ns. We have made experiments with and without the multimode optical fiber.

Before injecting pulses into the power chain, we use a slicer in order to obtain 1.3 ns pulses. The amplification is composed of Nd-doped phosphate glass rod and disk amplifiers which are able to deliver up to 1 kJ energy in coherent configuration. We measure the energy at the midchain and at the end of the laser which corresponds to an amplification gain of 10^3. Indeed, we have verified that there is no effective nonlinear effect before the midchain because of a low energy level.

3. STATISTICAL MODEL USED FOR TIME-INCOHERENT PULSES AMPLIFICATION

The broadband field is described using a statistical approach[4]. We consider plane waves and assume that the initial field propagating along the z axis is $E_0(t)\exp - i(\omega_0 t - k_0 z)$, ω_0 and k_0 are the carrier frequency and the corresponding wave vector, respectively. The envelope $E_0(t)$ is assumed to obey stationary Gaussian statistics with the following correlation function :

$$\langle E_0(t)E_0^*(t+T)\rangle = I_0 \exp\left(-T^2/2T_c^2\right) \tag{1}$$

T_c is the laser coherence time and the bracket is a statistical averaging with respect to the distribution of the envelope.

We assume in the amplification model that diffraction and group-velocity dispersion are negligible which is valid in our experimental conditions. Furthermore, we do not take into account the gain saturation in this part in order to only study the interplay between self-phase modulation and spectral gain. The set of equations for the normalized polarization P and the normalized field E is then simplified :

$$i\frac{\partial E}{\partial z} + \frac{k_0 n_2}{n_0}|E|^2 E = \frac{1}{2}P \tag{2}$$

$$T_2\frac{\partial P}{\partial t} + P = i\gamma E \tag{3}$$

n_0 is the unperturbed value of the index of refraction and n_2 is the Kerr constant that characterizes the nonlinear correction of the index. T_2 is the dephasing time of the two-level amplification system, $T_2 = \frac{2}{\Delta\omega_a}$ where $\Delta\omega_a$ is the spectrum gain bandwidth of the media. γ is the inverted population expressed in gain per unit length, we suppose that γ is a constant in this model.

We have obtained a closed-form expression for the correlation function $C(t,z) = \langle E(T,z)E^*(T+t,z)\rangle^4$:

$$C(t,z) = \frac{e^g I_0 \exp\left(-t^2/2T_c^2\right)}{\left\{1 + B^2\left[1 - \exp\left(-t^2/T_c^2\right)\right]\right\}^2} \tag{4}$$

I_0 is the initial averaged intensity and $g = \gamma z$. We assume that gain narrowing effect is negligible compared to spectral broadening. We also obtain an approximation for the spectral broadening :

$$\frac{\Delta\lambda_{output}}{\Delta\lambda_{input}} = \sqrt{1+2B^2} \tag{5}$$

B is the so called B integral : $B = k_0 n_2 I_0 \left(e^g - 1\right) / \left(2n_0 g\right)$

Self-phase modulation broadens the pulse spectrum during amplification following the growth of the B integral. However, the output intensity is reduced by gain narrowing effect : the gain of the amplifier medium has a finite bandwidth and the new frequencies which are created by temporal nonlinear effect are amplified with a lower gain. In case of small effect, we obtain an asymptotic expansion with respect to $\frac{T_2}{T_c}$ and find that the average field intensity I at position z is :

$$I(g,B) = e^g I_0 \left[1 - \left(\frac{T_2}{T_c}\right)^2 \left(g + 2B^2\right)\right] \tag{6}$$

The intensity reduction is divided in two terms. The first one depends on amplification gain and corresponds to gain narrowing effect. Because of spectral broadening, gain narrowing is enhanced with the second term which now depends on the B integral.

4. EXPERIMENTAL RESULTS OF LARGE BAND AMPLITUDE MODULATED PULSES

We have carried out experiments with the setup described in part II in order to validate the previous model. First experiments compare the amplification between monochromatic pulses and broadband pulses without smoothing. Figure .1 shows the experimental energy output as a function of midchain energy input. Squares correspond to the monochromatic case and triangles to the broadband one.

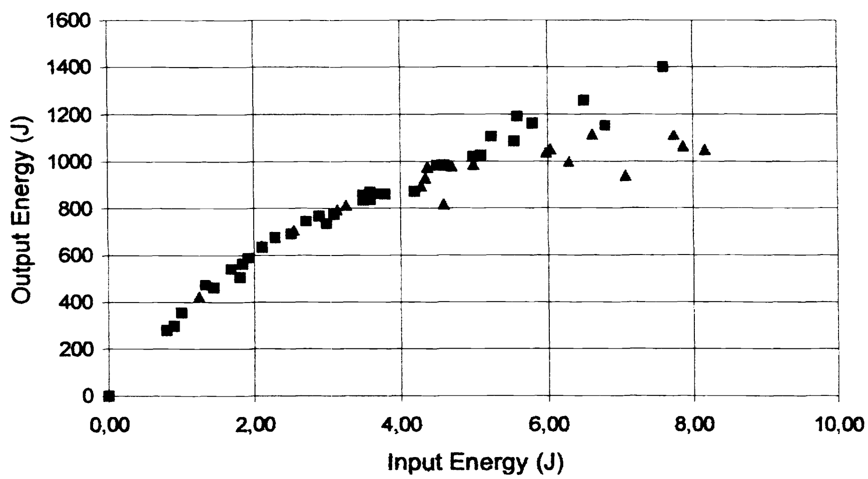

Fig.1 *Experimental energy output as a function of midchain energy input for a monochromatic pulse and for an incoherent pulse of bandwidth (FWHM) 1.2 nm*

We observe a limitation of the output energy decreased by 10 % when going from monochromatic to broadband pulses for high input energy. We assume that this saturation is related to the nonlinear effect discussed here above and we confirm this origin with spectra measurements. Figure 2 shows the spectral broadening in the chain, the narrow curve corresponding to the 1.2 nm input spectrum and the wide one to the output spectrum. The output energy was in this case 900 J and the output spectrum bandwidth 2.2 nm.

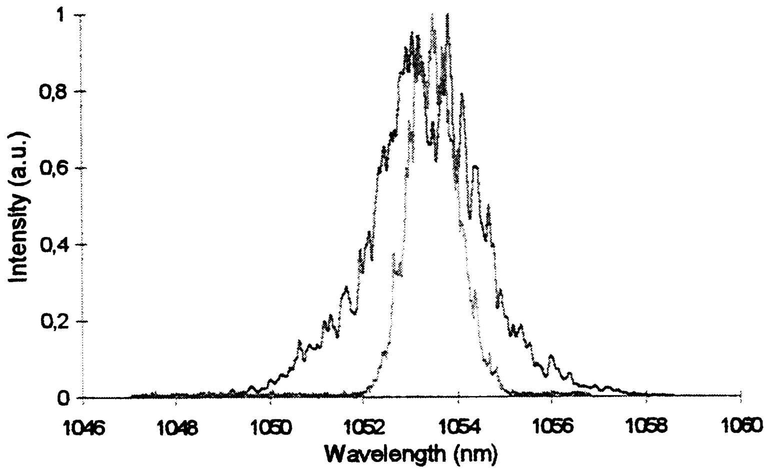

Fig.2 The input spectrum (narrow curve) has a FWHM of 1.2 nm and the output spectrum (wide curve) has a FWHM of 2.2 nm. It corresponds to an output energy of 900 J.

We measure the experimental broadening for each shot which allows to infer the B integral using the relation found in equation 5. Figure 3 shows the B integral deduced from experimental spectral broadening as a function of energy output. For high energy, we obtain values up to 1.5 rad which is in agreement with simulations using the code Miro.

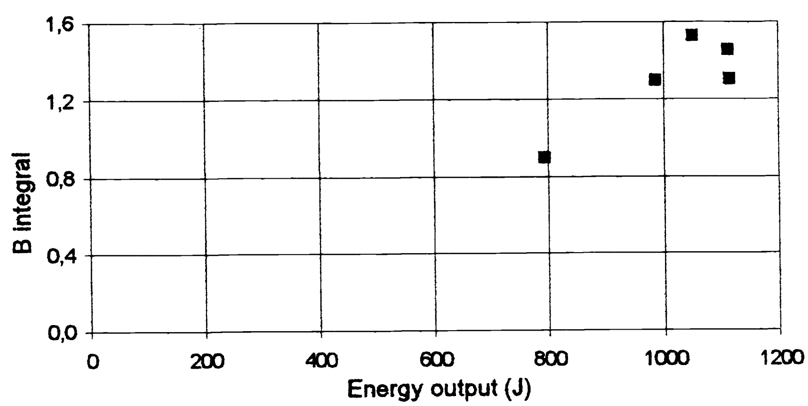

Fig. 3 B integral deduced from experimental spectral broadening as a function of energy output with an incident incoherent pulse of bandwidth (FWHM) 1.2 nm.

Using equation 6, we can estimate the output energy reduction when amplifying 1.2 nm broadband pulses. We find 8 % of losses compared to monochromatic case for highest energies which is close to the corresponding observed 10 % loss of energy.

5. AMPLIFICATION OF SMOOTHED PULSES IN PRESENCE OF FILTER PINHOLES

In this part, we study smoothed pulse amplification in the same laser chain. The input spectral bandwidth is always 1.2 nm at 1.053 μm. Figure 4 shows the energy output as a function of midchain energy input in the case of monochromatic pulse (squares), broadband pulse (triangles) and smoothed pulses (diamonds). All these experiments use the standard chain configuration with spatial filter pinholes.

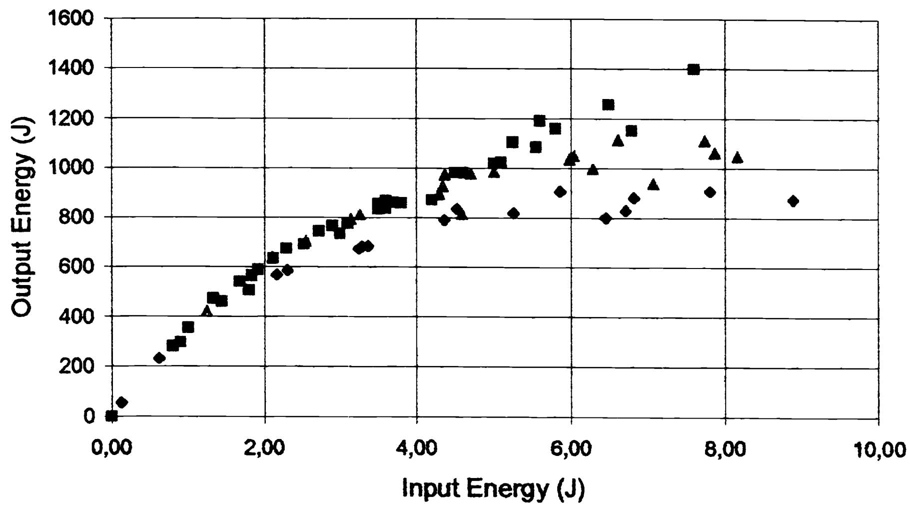

Fig. 4 Experimental energy output as a function of midchain energy input for monochromatic broadband and smoothed pulses in presence of filter pinholes.

We obtain an additional decrease of amplification when using SOF compared to only broadband pulses. This decrease is about 10 % and we observe a limit value for the output energy close to 900 J. This limit is obtained as soon as the input energy is greater than 5 J. This observation suggests a mechanism in the space domain which is the analogy of what is occurring in the time-spectral domain, namely the broadening of the k-spectrum by nonlinear effects and the cut-off due to pinholes in the spatial filters. Figure .5 shows smoothed pulse amplification with spatial filter pinholes (diamonds) and without (squares). The black curve represents the monochromatic pulse amplification which is our reference curve.

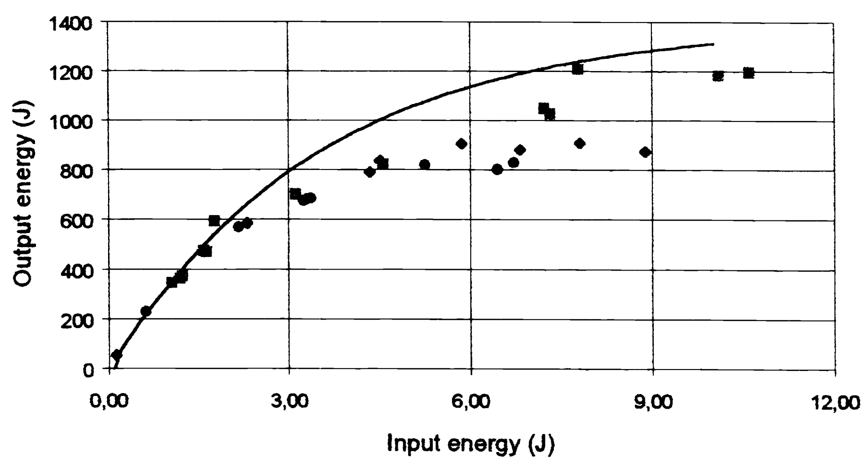

Fig.5 Experimental energy output as a function or midchain energy input for smoothed pulses with spatial filter pinholes (diamonds) and without (squares). The curve represents the monochromatic pulse amplification.

These results show that filter pinholes originate from energy losses. We recover the output energy when we remove pinholes and suppress the additional decrease compared to broadband pulses. In order to explain these results, we have developed a simple model of spatial filter pinhole for spatial incoherent pulses which is the analogy of what has been developed in the time domain. We assume that smoothed beams in near field are described in spatial domain with a statistical model because of many independent spatial modes. The initial spatial correlation function in our case is $C_0(x,y)=\left\langle E_0(X,Y)E_0^*(X+x,Y+y)\right\rangle$:

$$C_0(x,y)=2\frac{J_1(\pi r/r_c)}{\pi r/r_c} \qquad \text{with } r=\sqrt{x^2+y^2} \tag{7}$$

$2r_c$ is the diameter of the image of the fiber core at the pinhole position. E_0 is the near field which is imaged in amplifiers. The field at pinhole position is the Fourier Transform of E_0 and Wiener-Khintchine theorem[5] implies that :

$$I(k)=TF(C(x,y)) \tag{8}$$

I(k) is the far field envelope at pinhole position and *TF* is the Fourier Transform operator.

In presence of B integral, we deduce the correlation function of the near field (in agreement with the expression of Manassah[6]) :

$$C(x,y)=\frac{C_0(x,y)}{\left\{1+B^2\left[1-C_0^2(x,y)\right]\right\}^2} \tag{9}$$

Figure.6 shows the deduced far field envelop for different values of B, the initial correlation function is given by equation 7. Without B, the beam profile is a disk which corresponds to the unperturbed fiber image. When increasing B, the beam profile spreads with large wings.

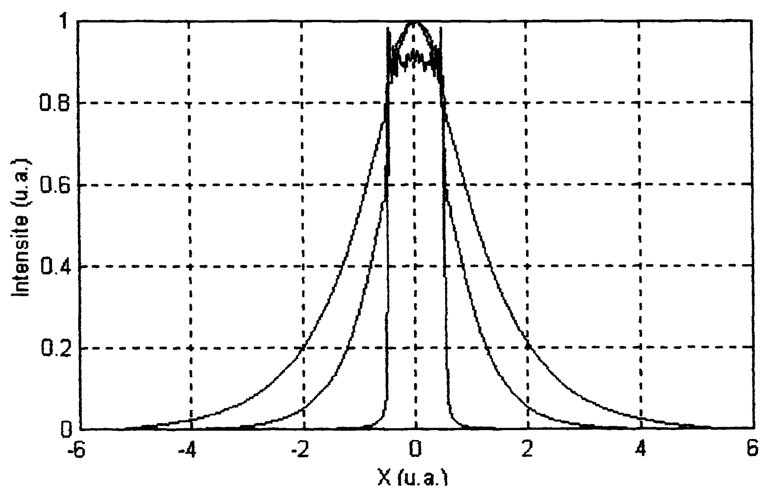

Fig.6 Beam profile for different values of B with arbitrary units. The larger curve corresponds to a B of 3.1 rad the intermediate one to a B of 1.8 rad and the narrower to a B of 0 (unperturbed beam).

Beams are cut by pinholes if the spreading effect is sufficient which induces energy losses. We have the transmission as a function of the B integral, the initial fiber diameter (d_c) and the pinhole diameter (d_t), using an empirical relation :

$$T\left(B,\frac{d_c}{d_t}\right)=\frac{1}{1+1.2B^2\left(\frac{d_c}{d_t}\right)^2} \qquad (10)$$

Relation 10 is valid only for small values of B (<3 rad) and large value of the ratio $\frac{d_t}{d_c}$ (>2).

In first approximation, the B integral is proportional to the output energy. So, the pinhole transmission is reduced when output energy is higher and a competition between amplification and pinhole transmission occurs for high energy level.

We have made simulations which take into account the pinhole transmission (equation 10) for smoothed pulses and the gain saturation in our chain. We omit here the gain narrowing in order to study only spatial effects. Figure 7 shows numerical simulations for output energy as a function of input energy on the experimental laser chain. We simulate only spatial effects with pinholes as spectral filter.

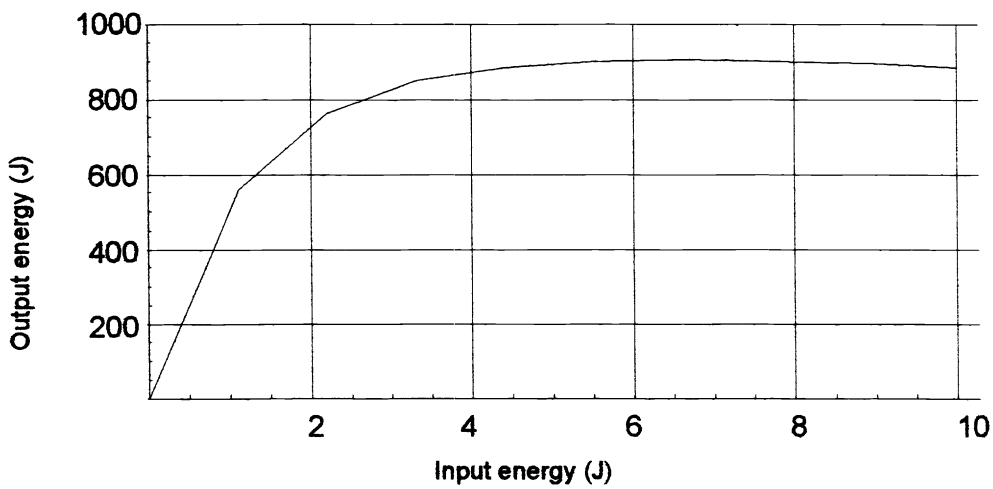

Fig.7 Simulated output energy as a function of input energy on our experimental power chain.

We observe an anomalous saturation which corresponds to a competition between amplification and losses in spatial filter pinholes. The value of energy level saturation is in good agreement with experimental data (diamonds in Figure .5).

6. DISCUSSIONS

We have shown that amplitude modulated pulses amplification involves nonlinear effects which can limit the energy output. We can notice the analogy between temporal and spatial effects : self-phase modulation broadens the spectrum bandwidth, while the spectral filter reduces energy transmission. In the spatial domain, the equivalent spectral filter is spatial filter pinhole. We have proposed theoretical models in both domains which take into account spectral broadening and spectral filter and give some simple relations for output spectrum and output energy. Different series of experiments confirm theoretical results with good agreement.

For LMJ design, we have to control these limitations in order to reach the required laser performances in term of output energy, focal spot shape and output spectrum. In temporal domain, we expect to control the gain narrowing limitation by starting with a narrower spectrum. The B integral should broaden the spectrum to the required value due to self-phase modulation. This solution should reduce the gain narrowing effect to a negligible value.

The major problem concerns the spatial domain. We could open the spatial filter pinholes which are responsible for energy limitation. But, the focal spot shape is damaged as we can see in Figure .6. Therefore, we expect to enhance the focal spot shape by reducing the B integral in the chain and using a mask at the front end which should compensate for the effect of the B in spatial domain.

7. ACKNOWLEDGMENTS

We acknowledge the initial input of Didier Véron to this study and we thank J.Paye and C.Sauteret for useful discussions. This research was performed under the auspices of the Laser Megajoule Program of Commissariat à l'Energie Atomique/Direction des Applications Militaires. We thank Phebus team for all experiments we have made on Phebus laser chain.

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