Temporal–space-transforming pulse-shaping system with a knife-edge apparatus for a high-energy laser facility

Lei Shen, Shaohe Chen, Xiaping Ge, Shizhong Xu, and Dianyuan Fan

For the first time to our knowledge, in a high-energy laser facility with an output energy of 454.37 J, by using a temporal–space-transforming pulse-shaping system with our own design of a knife-edge apparatus, we obtained a quasi-square laser pulse. © 2005 Optical Society of America

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1. Introduction

Temporal pulse shaping in a front-end system is important for inertial confinement fusion (ICF) experiments. With the development of ICF technology, it is necessary to develop advanced front-end pulse-shaping technology.[1] Various laser temporal pulse-shaping systems have been reported, including static variable impedance lines, such as devices implemented at the OMEGA laser[2,3] facility and low-voltage-programmable rf field-effect transistors coupled into striped lines at the National Ignition Facility.[4,5]

We report a new temporal pulse-shaping system, namely, temporal–space-transforming pulse-shaping system that contains a knife-edge apparatus. Using this new technology, we obtained a high-energy quasi-square laser pulse. The pulse meets the requirements for the physics experiments at the Shenguang-II upgrade facility located at the Shanghai Institute of Optics and Fine Mechanics. One of the main purposes of the upgrade is to achieve the capability of performing temporal-pulse shaping.

2. Theoretical Analysis

The temporal–space-transforming pulse-shaping system with the knife-edge apparatus is shown in Fig. 1. Lenses L1 and L2, which have the same focal length, comprise a $4f$ system. The distance between L1 and L2 is $2f$. We place $LiNbO_3$ crystals D1 and D2 on the front focal plane of L1 and the rear focal plane of L2, respectively. On spectral plane A of the $4f$ system we arrange the knife-edge apparatus as an adjustable-filter diaphragm. To improve the spatial quality of the pulse, we add two pairs of space filters (Ho and Hi) to filter the spatial diffraction. To analyze the performance of the temporal pulse-shaping system we use Fourier analysis.

In a Cartesian system, field $E_0(x', y', t)$ incident upon D1 is

$$E_0(x', y', t) = f_0(x', y')g(t). \tag{1}$$

When there is no voltage on D1, incident field $E_1(x, y, t)$ in the front face of the knife-edge apparatus is the Fourier translation of the field on D1. Then we have

$$E_1(x, y, t) = g(t)\mathscr{F}\{f_0(x', y')\} = g(t)f_1(x, y). \tag{2}$$

Here,

$$\mathscr{F}\{f_0(x', y')\} = \iint f_0(x', y')\exp\left[-2\pi i\left(\frac{x}{\lambda f}x' + \frac{y}{\lambda f}y'\right)\right]\mathrm{d}x'\mathrm{d}y' = f_1(x, y). \tag{3}$$

The intensity in the front face of the knife-edge apparatus is

The authors are with the National Laboratory for High Power Laser Physics, Shanghai 201800, China, and the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China. L. Shen's e-mail address is lshen@mail.shcnc.ac.cn.

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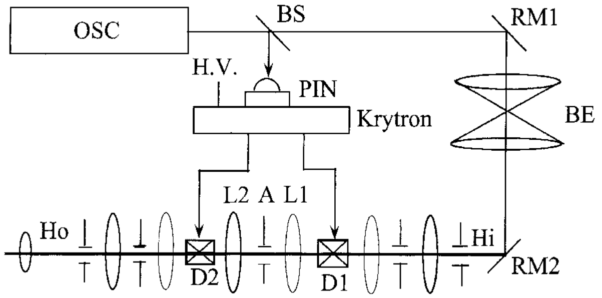


Fig. 1. Temporal–space-transform pulse-shaping system containing the knife-edge apparatus: OSC, oscillator; BS, beam splitter; RM1, RM2, reflecting mirrors; H. V., high voltage; PIN, p-i-n detector; BE, beam space filter; other abbreviations defined in text.

$$I_1'(x, y, t) = |E_1'(x, y, t)|^2 = G(t) I_1(x, y), \qquad (4)$$

where

$$G(t) = |g(t)|^2, \qquad I_1(x, y) = |f_1(x, y)|^2. \qquad (5)$$

$G(t)$ is the temporal distribution and $I(x, y)$ is the spatial distribution. When we add voltage on the deflectors along the y direction, the light scans at speed v along the y direction. The intensity in the rear face of the knife-edge apparatus is

$$\begin{aligned} I_2(t) &= G(t) \iint T(y) I_1(x, y - vt) \mathrm{d}x \mathrm{d}y \\ &= \mathrm{A}G(t) \mathscr{F}^{-1}\{[\mathscr{F}\{T(\eta)\}] \times [\mathscr{F}\{I_{1y}'(\eta)\}]\}. \end{aligned} \qquad (6)$$

The power in the rear face of the knife-edge apparatus is

$$\begin{aligned} P_2(t) &= \iint I_2(x, y, t) \mathrm{d}x \mathrm{d}y \\ &= \mathrm{A}G(t)[T(\eta) * I_{1y}'(\eta)]_{\eta = vt} \\ &= \mathrm{A}G(t) \mathscr{F}^{-1}\{[\mathscr{F}\{T(\eta)\}] \times [\mathscr{F}\{I_{1y}'(\eta)\}]\}, \end{aligned} \qquad (7)$$

where $T(y) = |t(y)|^2$ and the $*$ represents convolution. $t(y)$ is the transmissivity of the knife-edge apparatus. $A = \int_{+\infty}^{-\infty} I_{1x}'(x) \mathrm{d}x$ is a constant. Equation (7) shows that the temporal pulse shape is determined by $T(y)$. So by using the knife-edge apparatus as an adjustable-filter diaphragm, we can achieve temporal pulse shaping.

During amplification, the front of the pulse depletes the particles in the upper energy level first. After a pulse is amplified, the shape of the front becomes steeper. As the number of particles in the upper energy level decreases, the rear part of the pulse basically holds its original shape. So we should produce a special non-square-shaped pulse in a front-end system to get a square pulse in the terminal. To get this special temporal shaped pulse, we consider a theoretical model: Suppose that $f = 560$ mm and $v = 1$ mm/ns, with temporal and spatial characteristics of the input pulse all of the Gaussian type:

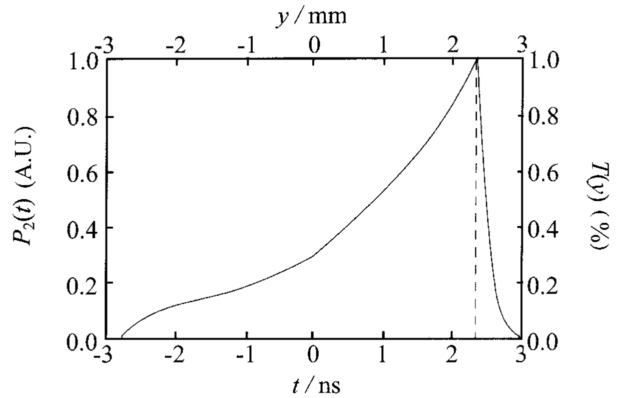


Fig. 2. Power in the rear of the aperture when we assume a special value of $T(y)$.

$$f_0(x', y') = \exp\left(-\frac{x'^2 + y'^2}{w^2}\right),$$

$$G(t) = \exp\left[-2\left(\frac{t}{\Delta t_0}\right)^2\right].$$

Here the size of beam w is 1 mm and the width of pulse Δt_0 is 20 ns.

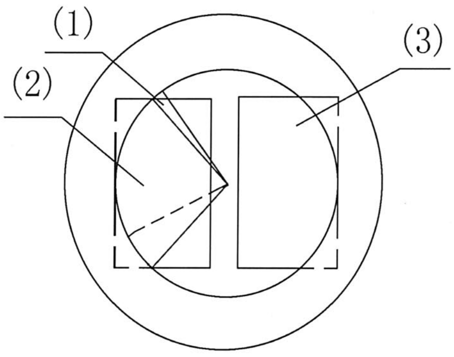
Suppose that

$$T(y) = \begin{cases} \exp\left(\dfrac{y - 2.5}{1.66}\right) & -2.5 \text{ mm} \le y \le 2.5 \text{ mm} \\ 0 & y > 2.5 \text{ mm}, \ y < -2.5 \text{ mm} \end{cases}.$$

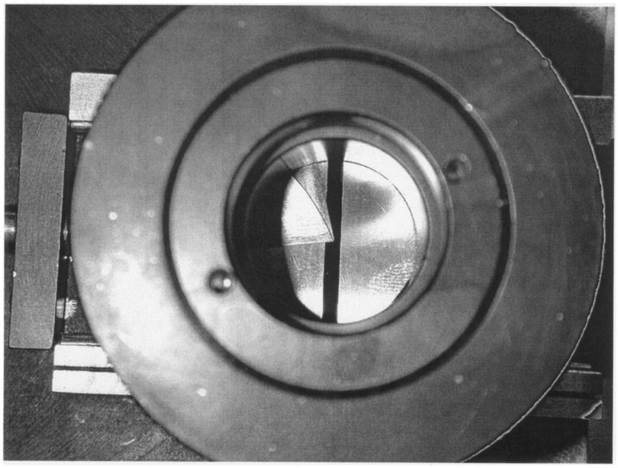
Then we obtain the shape of the output pulse shown in Fig. 2. This output pulse shape is the same as the result computed with the amplifier theoretical model.[6]

3. System Performance

In our pulse-shaping experiments, cascading avalanche photoelectric diodes were triggered by the laser output coming from a master oscillator. The master oscillator that we used was a 1053 nm single-longitudinal-mode Nd:YLF Q-switched laser with a pulse width of 20 ns and an amplitude fluctuation of less than 5%. An electric pulse coming from the cascading avalanche photoelectric diode was used to trigger a cold-cathode high-voltage pulse producer to generate a high-voltage pulse with an amplitude of ~10 kV. We made time-delay adjustments by changing the length of the transmission line. With this adjustment, high-voltage electric pulses with opposite voltage in two bulk $LiNbO_3$ crystals were synchronized with the output laser pulse of the master oscillator. The $LiNbO_3$ crystals act not only as Pockels cells to chop the pulse but also as deflectors to deflect the light. Because the same amplitude and the opposite voltage are added, these two deflectors have



(a)



(b)

Fig. 3. (a) Schematic of the knife-edge apparatus and (b) a photo of the knife-edge apparatus. In (a), (1) and (2) are two rotation knives and (3) is a vertical knife.

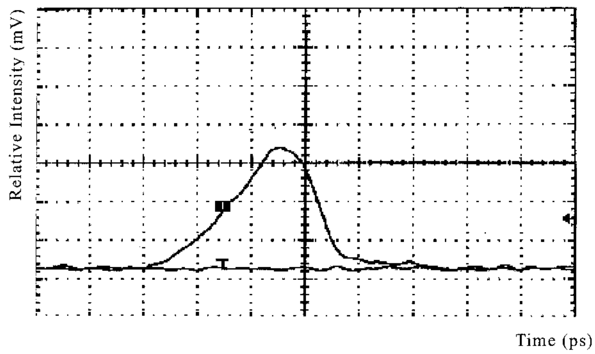


Fig. 4. Temporal waveform of the front end of a pulse formed by the AP measured with a Tektronix TDS694C digital storage oscilloscope. Each grid of the abscissa is 500 ps. The pulse width is 881.5 ps, the rise time is 845.4 ps, and the fall time is 408.7 ps.

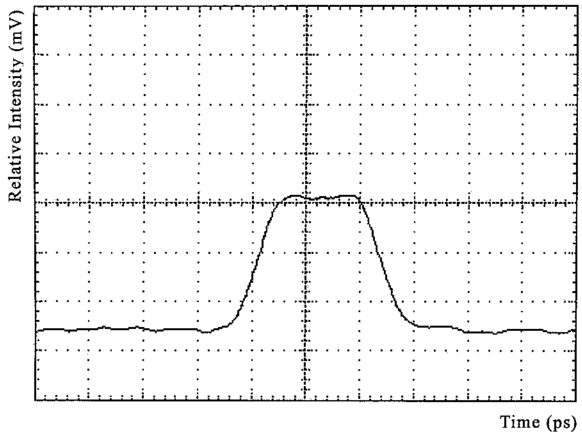


Fig. 5. Temporal waveform of the terminal laser pulse with an output energy of 454.35 J measured with a Tektronix TDS694C instrument. Each grid of the abscissa is 500 ps. The pulse width is 1.16 ns, the rise time is 337 ps, and the fall time is 360 ps.

oppositely deflected light-pulse directions. As a result, deflector D2 restores the deflected light of D1 to its original direction (the output beam is parallel to the input beam). By rotating the knife on the knife-edge apparatus to change the spatial distribution of the transmissivity of the knife-edge apparatus, we completely change the temporal waveform of the input pulse. To improve the spatial quality of the pulse, we place two pairs of space filters on each side of the knife-edge apparatus. Before the pulse shaping begins, the laser pulse is blocked off by the knife-edge apparatus to maintain a high signal-to-noise ratio. We can see the effect on the amplified pulse.

A schematic of the knife-edge apparatus designed by us and a photograph of it are shown in Figs. 3(a) and 3(b), respectively. Using this apparatus, we can study the temporal waveform of a laser pulse by adjusting the shape and size of the knife-edge apparatus as well as the scanning speed of the deflectors.

For our ICF system, after a pulse amplified by the gain system of the ICF facility, we get a square laser pulse with ~1 ns width in the target of the terminator. To achieve front-end pulse temporal shaping we change the shape and size of the knife-edge apparatus by adjusting the position of each knife. The temporal waveform of the front-end pulse after temporal shaping is shown in Fig. 4. The fluctuation of the front-end output was less than 10%. The shaped front-end pulse was amplified by the gain systems of the ICF facility. A terminal shaped pulse with an output energy of 454.35 J was obtained, and its temporal waveform is shown in Fig. 5. (The maximum terminal output energy of the system is >750 J. So, when we get 454.35 J, the amplifier system does not operate in the saturation area. Only when amplification makes the front of the pulse steeper can we get the expected pulse shape.) It can be seen from Fig. 4 that the terminal shaped pulse is a quasi-square laser pulse with 1.16 ns pulse width, 337 ps pulse rise time, and 360 ps pulse fall time. It meets the requirements of our ICF physics experiment. The shaped pulse in Fig. 5 has a high signal-to-noise ratio.

4. Conclusions

In conclusion, we have demonstrated a technique that possesses good optical pulse temporal shaping ability in the nanosecond domain by incorporating a new temporal space transform shaping system containing a knife-edge apparatus. After amplification by a gain system at the inertial confinement fusion facility, a quasi-square waveform larger-energy laser pulse was achieved, which well satisfies the requirements for physical experiments with ICF.

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