

INVESTIGATION AND EVALUATION ON PULSE STACKERS FOR TEMPORAL SHAPING OF LASER PULSES

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Abstract

A sophisticated research device such as an advanced photo-cathode injector for a high energy accelerator-based X-ray light source requires drive lasers with a flat-top shape both in time and space in order to generate high-quality short electron beam bunches. The practical methods for temporal shaping, in particular in the picosecond or femtosecond regime, are quite limited. One simple way to shape laser pulses is pulse stacking by birefringent crystals. While the method itself has the great advantage of simplicity, the overall performance depends on many factors. In this paper, we will present both calculation analysis and the recent experimental study

about important pulse shaping characteristics that, to our knowledge, have not been adequately explored before.

CALCULATION AND ANALYSIS

The basic principle of pulse stacking can be easily found in literature [1-5], we only present the calculation results in view of the page limitation. What should be pointed out is that we have included the phase and polarization of the electric field of the laser light wave, in contrast to the design method that only sums over intensity distribution which even if often shows good agreement with the measurement but may not be always correct in reality.

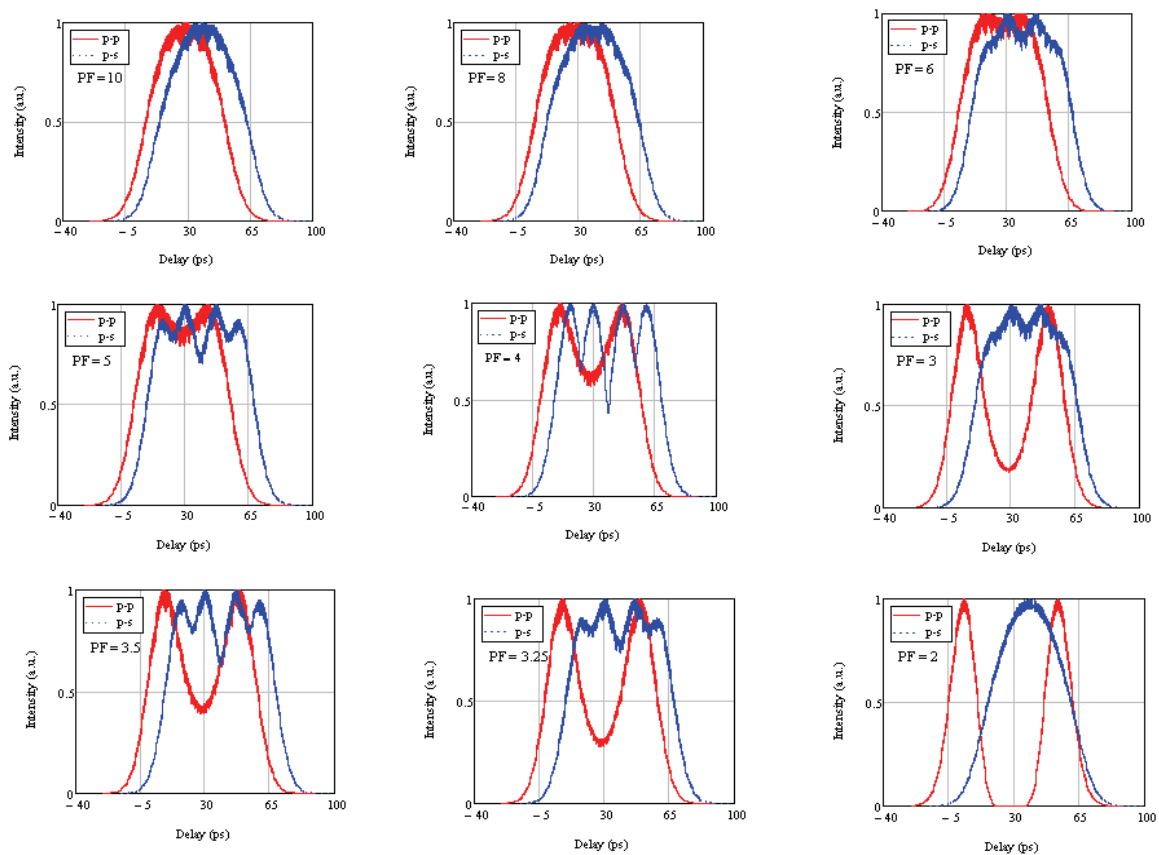


Figure 1: Intensity distributions of combined sub-pulses with different time delays and polarizations (p is horizontal and s is vertical). “p-p” refers to the same (here all s) polarization pulses. “p-s” refers to the case with alternating polarizations. Phase factor PF is explained in the text. Initial single sub-pulse has a Gaussian distribution and 20ps pulse width (FWHM).

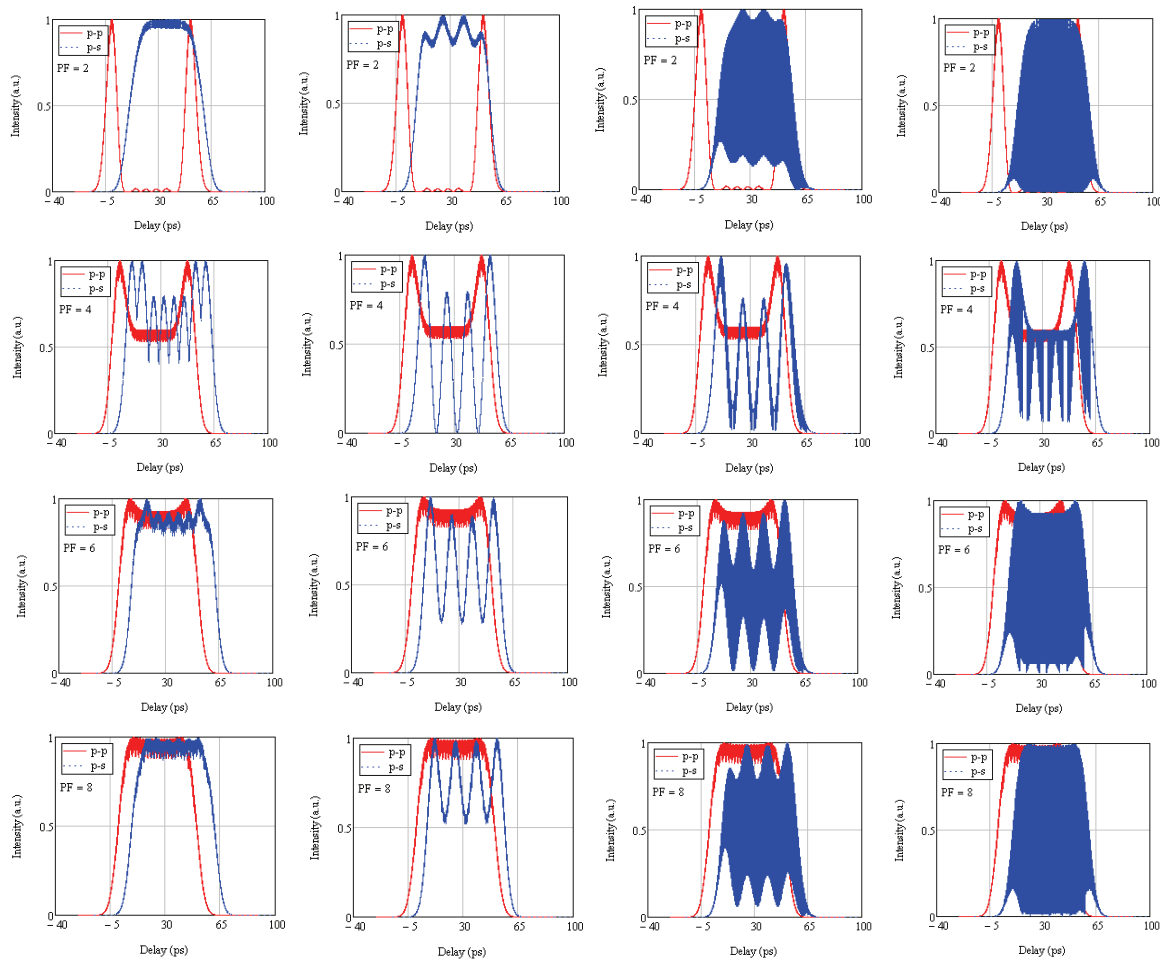


Figure 2: Projected Intensity distributions of combined 8 sub-pulses with different time delays and polarizations (p, s and PF have the same definition as in Figure 1). Initial pulse has a Gaussian distribution and 10ps pulse width (FWHM). From left, 1st column, no projection. 2nd column, projected to 0°. 3rd column, 22.5°. 4th column, 45°.

Figure 1 presents a group of calculation results for both single polarization and alternating polarization fields against phase differences introduced by the time delay. To simplify the graph, only the intensity envelop (without the fine oscillating structures) are plotted. The wavelength of each pulse is 1 micron and the initial pulse intensity distribution is Gaussian with 20ps FWHM duration. The delay between each pulse is set to 4000 field periods, or 13.33ps. The time delay T between adjacent pulses is expressed by $T = k\tau + \tau/PF$, where k is an integer and equal to 4000. τ is the period of the oscillating electric field of the light wave. The quantity τ/PF represents a fraction of the field oscillation period, therefore defining a phase difference between each pulse. When PF is relatively large, the shape of the combined pulses look very similar for both red and blue traces, close to a low-order super-Gaussian distribution. But dramatic shape change for the red ones occurs as the phase delay gets bigger as a result of the temporal interference between pulses. The combined pulses from the sub-pulses with the same polarization (red curves shown in Figure 1) present a strong sinking center and eventually a double pulse shape is formed when PF is close to 2, or a phase

difference of π . The destructive interference in the central part results in two individual pulses separated apart by approximately 38ps. Each pulse has shorter time duration than the original 20ps pulse. However, it is much lesser an effect on the blue curves for the pulse formed by pulses with alternating polarization directions (denoted by p-s). The alternating polarization pulses tends to wash out the large modulation over the envelop. It should be kept in mind that the combined pulse in blue colour has a varying polarization along its entire time duration.

For many applications, linearly polarized pulse is preferred or necessary in some cases. Experimentally it is easy to use a polarizer to select any desired polarization from the shaped pulse, but the associated pulse shape change may be a real concern even if the loss of efficiency can be tolerated. In Figure 2, the output pulses are projected at different angles with respect to the horizontal (denoted by p) axis. The original pulse duration of 10 ps is taken this time in order to get better time resolution and shaping effects. The delay between each pulse is 2000 electric field periods (or 6.67ps). The graphs in the 1st column are the results from the direct addition of all fields without projection to any axis. They bear

similarity to those in Figure 1. The graphs in the rest of the columns are the projection to the different angles ranging from 0° to 45° . As the angle of projection changes, the pulses (blue traces) formed by the sub-pulses with orthogonal polarizations varies to a great extent. The red traces remain unaffected due to the simple reason they are formed by sub-pulses with the same polarization.

There are other factors that may also affect the shaped pulse profiles, for example, the alignment of laser beam polarization angle with respect to the crystal axis. When the beam polarization is not exactly 45° degree, the o-ray and e-ray have different field amplitudes, which leads to the distortion of the overall pulse profile after passing through crystals. Based on the calculation shown in Figure 3, even 1° away from 45° would add fairly obvious changes on the top of the pulses. The final pulse profile also depends on the angle of the laser beam with respect to the propagation (longitudinal) axis or the transverse adjustment of the crystals, since they can easily change the optical path-length through the crystals or the phase difference between o-rays and e-rays. For the most available lasers, the wavelength is around 1 micron or less, it is not practical to have several crystals made with their length within sub-micron precision which unfortunately seems to be needed for such application. However, it is possible to achieve sub-micron optical path length variation inside crystals by tuning their opto-mechanical holders. To view from another perspective, this actually provides a simple way to obtain different pulse shapes and width without the need to change crystals.

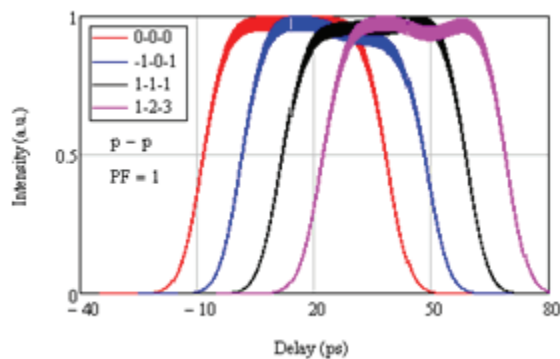


Figure 3: Intensity distributions vs. different angle deviation from expected 45° degree with respect to crystal axis. 0-0-0 means the pulse is perfectly aligned to all 3 crystals and all the deviation angles are 0° degree. 1-0-0 means the angle deviation is 1 degree on the 1st crystal and 0° for the 2nd and 3rd crystals. The beam passes through the crystals in the corresponding sequence as the crystals are numbered.

EXPERIMENT AND RESULTS

The pulse shaping section consists of several birefringent crystals with different lengths. As mentioned earlier, YVO₄ and α -BBO crystals are typically preferred birefringent materials for this application. Although

YVO₄ has much larger linear dispersion (~ 0.8 ps/mm) than α -BBO (~ 0.47 ps/mm) at 532nm, it also shows considerable absorption in the visible wave band and therefore may significantly reduce the transmission efficiency. The temporal profiles of the laser pulses could be characterized by the widely used cross-correlation technique, but it involves the complication of having an extra short probe pulse in addition to the difficult alignment. In our measurement, we used a Hamamatsu (FESCA) streak camera which has sub-ps time resolution from UV to IR.

Figure 4 is the result of a measurement for initial 4 pulse replicas, the calculated and the measured stacked pulses. In principle, two crystals are needed to split one initial pulse into 4 sub-pulses with proper delay. The crystals are all a-cut YVO₄. The first crystal is 15.5 mm long and the second one is 32.4mm long. The original goal is to stretch and shape the pulse to a 55ps flat-top for a specific application. The agreement between the prediction and the measurement appears to be fairly good. However, as mentioned before, it is possible to generate various pulse shapes with the same optical configuration simply by adjusting crystals' orientations. Figure 5(a) is a good example. The flat-top profiles with various pulse durations are produced by the same stacker assembly. The twin-peak (purple) trace represents the longest time duration (~ 55 ps as designed) or maximum delay the stacker can generate. During the experiment, we adjust the rotation, pitch and yaw of each crystal. It is not difficult to obtain a flat-top like profile, but it indeed requires careful adjustment on all the optics in order to minimize and clean up the large modulations on the top. Many fine tunes are needed along with the rotation of the waveplate. Usually an optimization has to be done later once the local temperature is stabilized. We found that the pitch and yaw can significantly affect the leading and falling edges while the rotation of the crystals and waveplate have more influence on the pulse shape and duration. We were even able to generate triangle-like pulses, as shown in Figure 5(b).

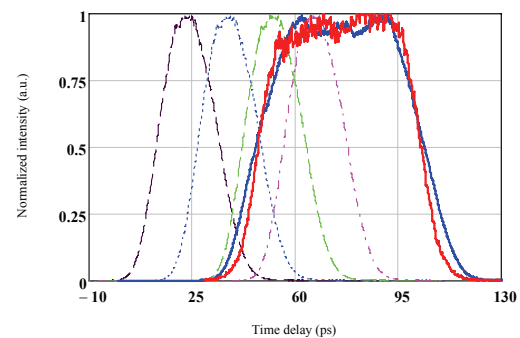


Figure 4: Typical pulse shapes of four initial sub-pulses (dashed lines), stacked pulse by calculation (blue solid line) and the measured (red solid line).

As the calculation indicated, the profile of the stacked pulse after the crystals is highly polarization-dependent. The combination of waveplate and the polarizer

(downstream of the stacker) serves as a polarization selector to produce linearly polarized beam required by some applications, and as a pulse profile selector as well. Figure 6 shows the pulse profiles at three different waveplate angles. The polarizer only allows horizontally-polarized beam pass through. Significant change occurs when the angle rotates. It is worth to mention that the actual efficiency of the stacker assembly can be as much as only 50% when using a polarizer to select linear polarized beam.

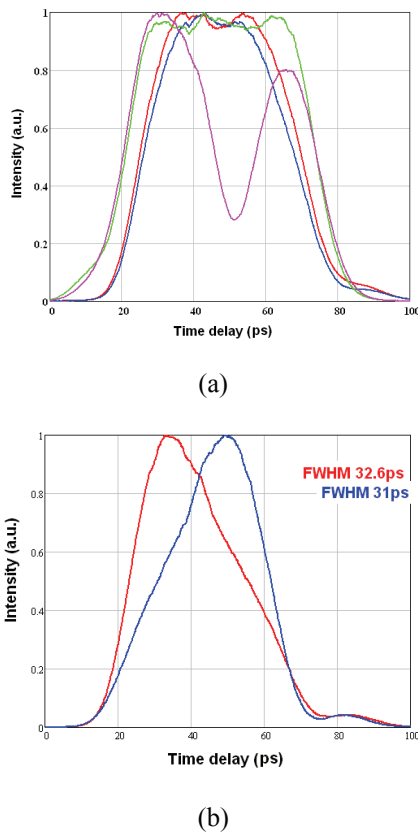


Figure 5: Various pulse shapes from the same crystals and configuration. (a) Flap-top pulses with different pulse duration. (b) Triangle pulses.

The stacked pulse shape is very sensitive to any changes that lead to the beam optical path variation on the order of the laser wavelength and angle deviation. While the magnitude of this kind of change is well manageable by the fine opto-mechanical parts, it does cause issue for application that needs high pulse stability. We did observation on the stability of the shaped pulse shape by the pulse stacker. The pulse shape slowly drifts away from where it was originally set up. The change occurs on the time scale of many hours and we seldom see immediate changes once the system is optimized. While sometimes a minor change can be seen after run the system for an entire day (more than 8 hours), it could also be dramatic sometimes. A typical state-of-the-art commercial laser like the one used here has a pointing stability around 10 to 20 micro-radian, the optical path

length variation is negligible in spite of the high refraction index of the crystal (>2). But the thermal optical coefficient is on the order of $10^{-6} \sim 10^{-5}$, it is easy to see several microns of optical path difference even with a tenth of a degree temperature fluctuation. In addition, due to the high absorption of laser power, a temperature gradient will be formed from the crystal center to the edge of the crystals which are mounted on adjusting holders. This will cause depolarization effect and can affect the pulse shaping in a destructive way. It is difficult to determine exactly how much each factor has contributed, but it is definitely a combined action from many known facts. This tells us on the other end, the stability may be substantially improved if we put all the crystals into temperature controlled cells. It is even possible to control the pulse shape by a precision temperature control. This will be an interesting topic for further research in future.

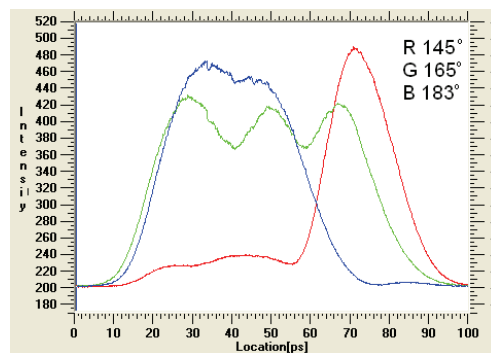


Figure 6: Pulse profiles with polarizer at three different rotation angles. Inlet is the angle reading of waveplate.

CONCLUSION

We presented both analysis and recent experimental study about important pulse shaping characteristics that have not been adequately explored so far. Our observation indicates, in spite of its simplicity, the stability of this shaping method needs improvement which may be accomplished by temperature control. It also shows the un-desired distortion effect can be used to produce various pulse shapes and time duration.

ACKNOWLEDGEMENT

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