Generation and Amplification of Temporally "Square" Optical Pulses for the FEL Photoelectric Injector

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ABSTRACT

We discuss the application of self-phase modulation and grating pulse compression to the generation of optical pulses suitable for controlling the electron beam emittance and energy spread in an FEL photoelectric injector. Pulse compression in a single-stage pulse compressor, with background reduction based on the nonlinear birefringence of the optical fiber, yields 5-10 ps Gaussian pulses. Temporally "square" pulses with 15-ps FWHM and 5-ps rise time have been obtained through self-phase modulation and group-velocity dispersion of the 5-ps pulses in a second fiber. Pulse shaping through the use of nonlinear birefringence in optical fibers is also discussed.

1. INTRODUCTION

The recent advent of the photoelectric injector - an electron injector design based on laser irradiated photocathode emitters incorporated in an RF cavity - has generated much interest because it offers electron beams with high current density, low transverse emittance and small energy spread. [1-5] This design also lends itself to controlling of the electron beam emittance and energy spread by programming the temporal and spatial formats of the modelocked laser pulses used to illuminate the photocathode. Theoretical simulations [6] predict that for a space-charge dominated electron beam, minimum beam emittance and energy spread are obtained if the electron bunch has uniform current density, both radially and axially. Thus, the ideal spatial and temporal pulse formats for illuminating the photocathode are flat tops with steep edges. Furthermore, for small energy spread, the laser pulses must be short enough to cover a small angular fraction of the RF cycle but not too short so as to introduce significant space charge in the electron bunch. In this paper, we describe methods to generate and amplify optically compressed 10-ps Gaussian pulses and ~20-ps "square" pulses from a Nd:YLF modelocked laser.

2. PULSE COMPRESSION WITH BACKGROUND REDUCTION

Using a fiber-grating pulse compression technique, [7, 8] we compressed the output of a cw modelocked Nd:YLF laser operating at 108.33 MHz (1/12th subharmonic of 1300 MHz) repetition rate from 40 ps to ~5-10 ps. The experimental setup is shown in Fig. 1.

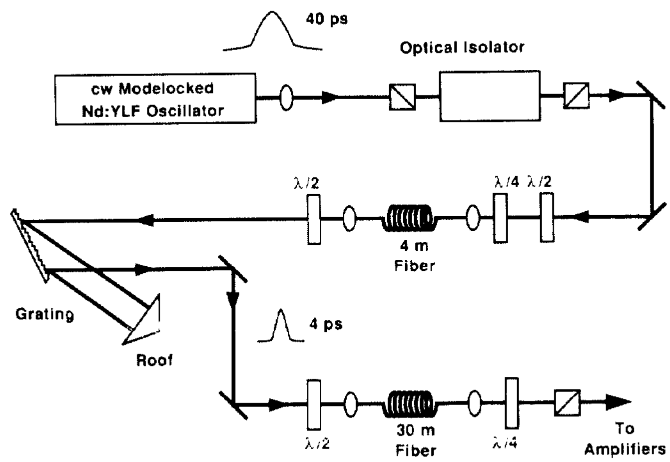

Figure 1. Experimental setup.

Through self-phase modulation (SPM) in the 1-m non-polarization preserving fiber (NRC F-SF with a 5 μ core diameter) and an average input power of ~5.5 W, the 40-ps input pulses developed a frequency spread of ~3 cm^{-1}. With this fiber length, the positive group velocity dispersion (GVD) of the fiber did not change the pulse width appreciably. The chirped pulses were compressed to ~8 ps FWHM in a double-pass grating arrangement with a 1700 grooves/mm diffraction grating. The compressed pulse width was measured with a non-collinear, background-free SHG autocorrelator.

For a Gaussian pulse shape, the transform- limited compressed pulse width is given by

$$\tau_{FWHM} = \frac{.44}{\Delta\nu_{FWHM}} \qquad (1)$$

where $\Delta\nu_{FWHM}$ is the frequency spread produced by SPM in the fiber. In the absence of positive GVD, $\Delta\nu$ can be approximated by

$$\Delta\nu = \frac{K\, L\, n_2\, \nu\, P}{c A_{eff}\, t_{FWHM}} \qquad (2)$$

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where

$K = 2(2\ln 2)^{1/2}\, e^{-1/2} \approx 1.428$ for Gaussian pulses

$n_2 = 6.2 \times 10^{-20}\ m^2/W\ (1.1 \times 10^{-13}$ esu)

$P = P_{av} / (1.12\, f_r\, t_{FWHM})$

and $A_{eff} = 1.26\, \pi\, D^2/4 = 2.5 \times 10^{-11}\ m^2$ for D=5 μm (fiber core diameter); L is the interaction length ~ the fiber length for short fiber. For P_{av} = 5.5 W, we calculated a frequency chirp of 3.2 cm^{-1}, in good agreement with the observed frequency chirp of 2.9 cm^{-1}. From the observed chirp, the calculated and observed pulse width are 5 and 8.8 ps (See Fig. 2).

The use of short fibers allows generation of compressed pulses with appreciable output power without the complication of stimulated Raman scattering. However, in the absence of positive GVD, the chirps produced in short fibers are nonlinear, resulting in pedestals and sidelobes in the background of the compressed pulses (Fig. 2a). These unwanted features can be reduced by a spectral windowing method which removes the offending frequencies. These are at the extremes of the frequency distribution and occur in time at the leading and trailing edges of the pulses. [10] Alternatively, the nonlinear birefringence of the fibers can be used to enhance the contrast ratio of the central part of the pulse with respect to the background. [11]

Using the fiber nonlinear birefringence to perform spectral filtering, we can reduce the background without introducing the sidelobes that result from the sharp edges of the spectral windows. If an elliptically polarized light is launched into a non-polarization preserving fiber at an angle whereby the nonlinear birefringence of the fiber is maximized, the major axes of the ellipse can rotate at an angle that depends on the light intensity, and hence give a time-dependent rotation. A small linear birefringence of the fiber also causes these background components to become linearly polarized. A second half-wave plate is used to rotate these components so that they are orthogonal to the p-polarization of the diffraction grating, and thus these components are rejected by the diffraction grating. The diffraction grating has a contrast ratio of better than 2 between the p- and s- polarizations and 4 diffraction passes increase the contrast ratio to >16. With a proper orientation of the entrance and exit half-wave plates, the low-intensity background of the chirped pulses is substantially reduced (Fig. 2b). The resulting compressed pulses are void of the pedestal or sidelobes, with a small penalty to pay: the peak power is reduced typically by a factor of ~2, although the average power is significantly reduced.

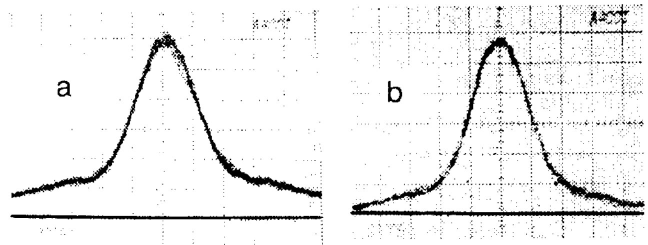

Figure 2. Autocorrelation of Gaussian pulses(a) without (b) with background reduction (3.5-ps division).

3. GENERATION OF SQUARE PULSES

For the "square" pulse generation, a longer - 4 m - fiber was used in the pulse compression step to provide the seed pulse . The output of the pulse compressor, 5-ps in width, ~1.5 W average power, was used to generate "square" pulses by propagation in a second, 30-m fiber where additional SPM increased the bandwidth of the pulses up to 80 cm^{-1}. With this combination of fiber length and bandwidth, GVD becomes significant, and the pulses stretch into a "square" pulse shape, as previously reported. [12] Figure 3 illustrates a background-free SHG cross- correlation trace of the square pulse with a 4-ps pulse. The cross-correlated pulse shape exhibits a flat-top of ~10 ps and good stability. This amplitude stability may be explained by the self-limiting nature of self-phase modulation in the presence of group velocity dispersion. The leading and trailing edges are rounded off due to the 4-ps width of the probe pulse. After correction for this probe pulse broadening, the "square" pulses have a ~5-ps rise time and a 15-ps FWHM.

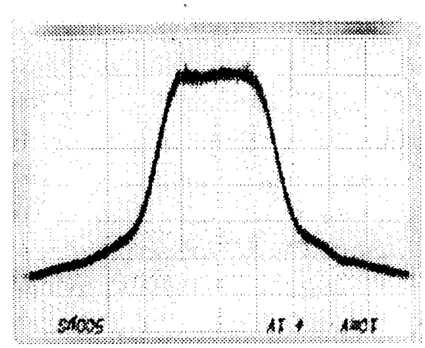

Figure 3. Cross correlation trace of square with 4-ps probe pulse (5-ps per division).

The above technique for square pulse generation has a disadvantage that the resulting bandwidth is too wide to be amplified by Nd ion in standard crystalline hosts. Alternative methods for generating programmable pulse shapes with smaller bandwidths in the output pulse have been reported. These techniques involve either calculating the Fourier transform of the desired pulse shape and applying suitable phase and amplitude masks in the frequency domain, [13-14] or using a rf-driven modulator to perform time domain masking of the chirped pulse prior to compression with the grating pair.[15] We show that temporal pulse shaping can also be done through the use of ellipse rotation in optical fibers .

If a plane-polarized Gaussian laser pulse is launched into an optical fiber sandwiched between two quarter- wave plates, as shown in Fig. 4, the transmission through the second polarizer as a function of laser intensity is given by

$$T(I) = P_1^2 P_2^2 \{1-(1-q^2)\sin^2(p_1^2\, q\, J)\} + p_1^4(1-q^2)\sin^2(p_1^2\, q\, J) \quad (3)$$

P_1^2 = transmission of output polarizer for the desired polarization
P_2^2 = transmission of output polarizer for the undesired polarization
q = $\sin(2\theta)$
θ = relative orientation of the quarter-wave plates
$J(t)$ = normalized intensity as a function of time
= $I(t)\, L/I_o$ (I_o = 150 GW/cm^2)

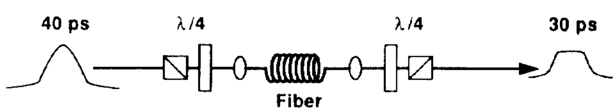

Figure 4. Pulse squaring via self-induced ellipse rotation

With a proper combination of quarter-wave plate orientations and fiber length, the pulse transmitted through the second polarizer can develop a "square" shape, as shown in Fig. 5. Note that the autocorrelation of a "square" pulse has a triangular shape.

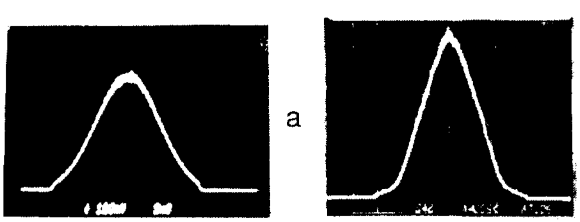

Figure 5. Autocorrelation of a) input gaussian pulse
b) output "square" pulse (5-ps per division)

We have performed amplification of the 9-ps, 3 cm^{-1} Gaussian pulse in a Nd:YLF amplifier which has a bandwidth of ~5 cm^{-1}. No significant loss of optical gain was detected for the 9-ps Gaussian pulse. However, amplification of the generated "square" pulses requires large bandwidth gain media such as Nd:glass, since gain narrowing of the amplifier bandwidth at high amplification can distort the pulse shape. Phosphate glass amplifiers are typically used for amplifying the Nd:YLF oscillator output, and silicate glass amplifiers are better matched to Nd:YAG oscillator.

4. CONCLUSION

A 10-ps Gaussian pulse and a temporally "square" 15-ps pulse have been obtained via self-phase modulation, grating compression and positive group velocity dispersion in a two-stage fiber-grating pulse compression and shaping technique. Amplifying the 10-ps Gaussian pulses can be achieved in Nd:YLF but the "square" pulses will require the use of large bandwidth gain media such as phosphate and silicate glasses as amplifiers. Alternative techniques for square pulse generation are being considered. Among them is a simple method involving a single optical fiber through the phenomenon of ellipse rotation. The new temporal pulse format applied to the photocathode could produce electron bunches which have more uniform space charge and thus have lower beam emittance and energy spread.

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