TOWARDS ACCELERATION OF HIGH-QUALITY ELECTRON BEAMS: MANIPULATION AND CHARACTERIZATION OF ULTRA-SHORT LASER PULSES

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Introduction

- Off-Axis Parabolic (OAP) mirrors play a crucial role in high-power laser facilities like the Intense Laser Irradiation Laboratory at CNR-INO [1], due to their achromaticity and ability to achieve high intensity without Fresnel losses.
- Despite their benefits, understanding the temporal and spatial electric field structure in OAPs' focal regions is essential, especially for ultra-short and ultra-intense laser pulses.
- This knowledge is vital for optimizing the quality of electron beams produced by laser-plasma interactions.
- Therefore, a preliminary study on the spatial and temporal profiles of non-monochromatic laser pulses based on the full Stratton-Chu vector diffraction theory [2] is presented.

Theoretical Framework

Consider an optical system's geometry, depicted in Figure 1. As can be seen, an incident laser pulse propagates in the Cartesian coordinate system $O'x'y'z'$ longitudinally in the direction negative to the z'-axis.

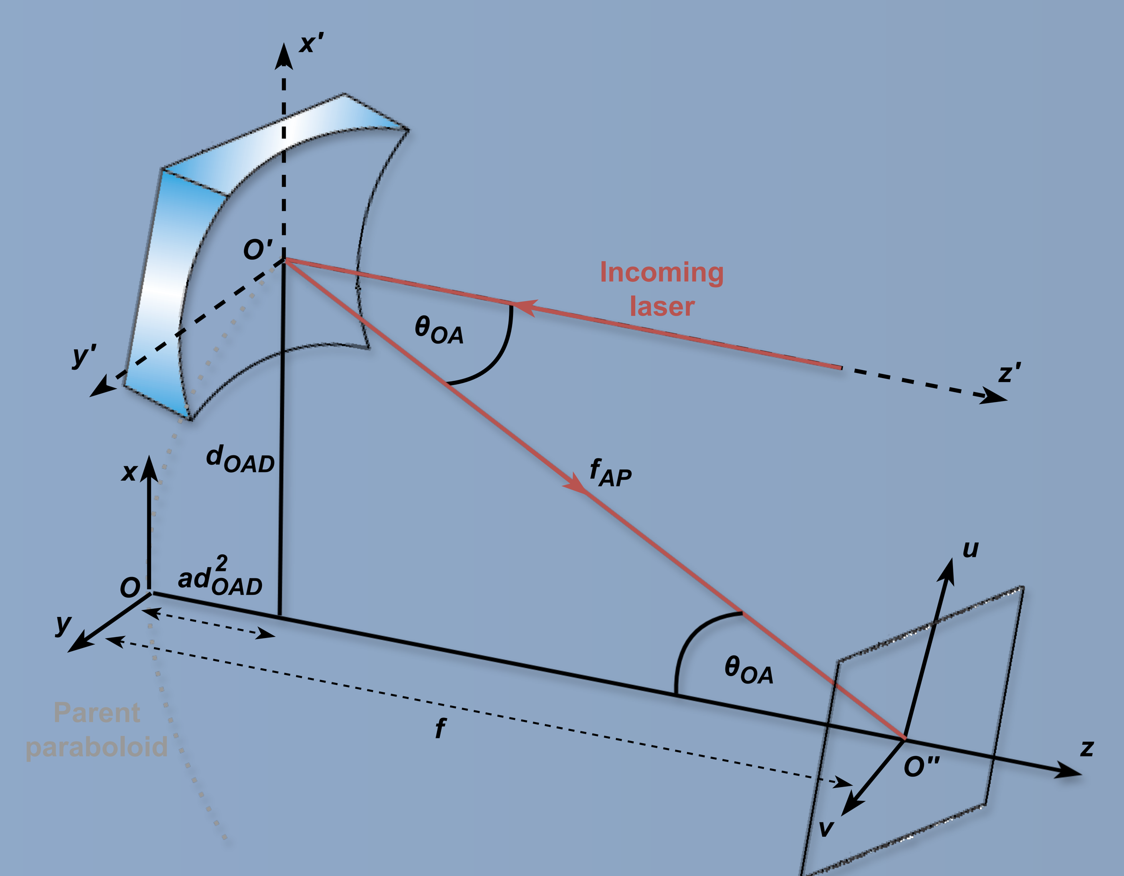

Figure 1: The sketches of coordinate systems used to derive diffraction integrals in Equation (2)

Let the amplitude of the laser pulse be defined as

$$A(x,y) = A_0 \exp\left(-\frac{1}{2}\left[\left(\frac{x-d_{\mathrm{OAD}}}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2\right]^n\right). \quad (1)$$

Based on these initial conditions and system geometry, a full Stratton-Chu vector diffraction theory [2] can be employed while taking advantage of the studies on this topic that were presented by L. Labate et al. [3], [4]. Corresponding diffraction integrals based on the theory and previously published studies are given as

$$E_j^{\mathrm{Re}}(\mathbf{x}_p) = -\frac{1}{\lambda}\int_{S_{\mathrm{OAP}}} A(x,y)\left[\cos(kv-\omega t)\mathrm{Im}\left\{g^{(Ej)}\right\} + \sin(kv-\omega t)\mathrm{Re}\left\{g^{(Ej)}\right\}\right]\mathrm{d}x\mathrm{d}y,$$
$$E_j^{\mathrm{Im}}(\mathbf{x}_p) = -\frac{1}{\lambda}\int_{S_{\mathrm{OAP}}} A(x,y)\left[\sin(kv-\omega t)\mathrm{Im}\left\{g^{(Ej)}\right\} - \cos(kv-\omega t)\mathrm{Re}\left\{g^{(Ej)}\right\}\right]\mathrm{d}x\mathrm{d}y, \quad (2)$$

where

$$g^{(E_x)} = \frac{1}{u}\cos\delta - \left(1-\frac{1}{iku}\right)\frac{1}{u^2}\left(\frac{x}{2f}\cos\delta + \frac{y}{2f}\sin\delta\right)(x-x_p),$$
$$g^{(E_y)} = \frac{1}{u}\sin\delta - \left(1-\frac{1}{iku}\right)\frac{1}{u^2}\left(\frac{x}{2f}\cos\delta + \frac{y}{2f}\sin\delta\right)(y-y_p), \quad (3)$$
$$g^{(E_z)} = \frac{1}{u}\left(\frac{x}{2f}\cos\delta + \frac{y}{2f}\sin\delta\right) - \left(1-\frac{1}{iku}\right)\frac{1}{u^2}\left(\frac{x}{2f}\cos\delta + \frac{y}{2f}\sin\delta\right)(z-z_p),$$

In the field of ultrashort pulse diagnostics, it is impossible to employ common methods, such as fast photodetectors, for direct pulse duration measurement. Instead, the spectral characteristics, such as $\Delta\lambda^{\mathrm{Int}}_{\mathrm{FWHM}}$, of the laser pulse are analyzed. Consequentially, due to its dependence on $\Delta\tau^{\mathrm{Int}}_{\mathrm{FWHM}}$ defined as

$$\Delta\tau^{\mathrm{Int}}_{\mathrm{FWHM}}\Delta\lambda^{\mathrm{Int}}_{\mathrm{FWHM}}\frac{c}{\lambda^2} = \mathrm{TBWP}, \quad (4)$$

where for Gaussian pulses, TBWP=0.441, it is possible to retrieve the pulse duration through the Fourier and inverse Fourier transform. Laser pulses that satisfy Equation (4) are referred to as bandwidth limited. Owing to the obtained spectral field $\left|\tilde{E}(\omega)\right|^2$ in the frequency domain and the use of an inverse Fourier transform, the temporal structure of this field in the time domain can be derived.

Preliminary Results

The radius of OAP mirror was set to $R = 76.2$ mm with $\theta_{\mathrm{OA}} = 6°$, the central wavelength λ_0 is 800 nm, $\sigma_\lambda = 30$ nm, and the wavelength spectrum is <618,1130> nm with an increment of 0.5 nm. The f-number f/# was picked arbitrarily, and the parent focal length f was derived from f/# $= f/3D$, where $D = 40$ mm is the FWHM of the laser pulse before focusing. Based on the θ_{OA} and Figure 1, it was possible to obtain parameter d and f_{AP}. Moreover, the super-Gaussian incident laser pulse is considered, with amplitude defined by Equation (1), where $n = 3$.

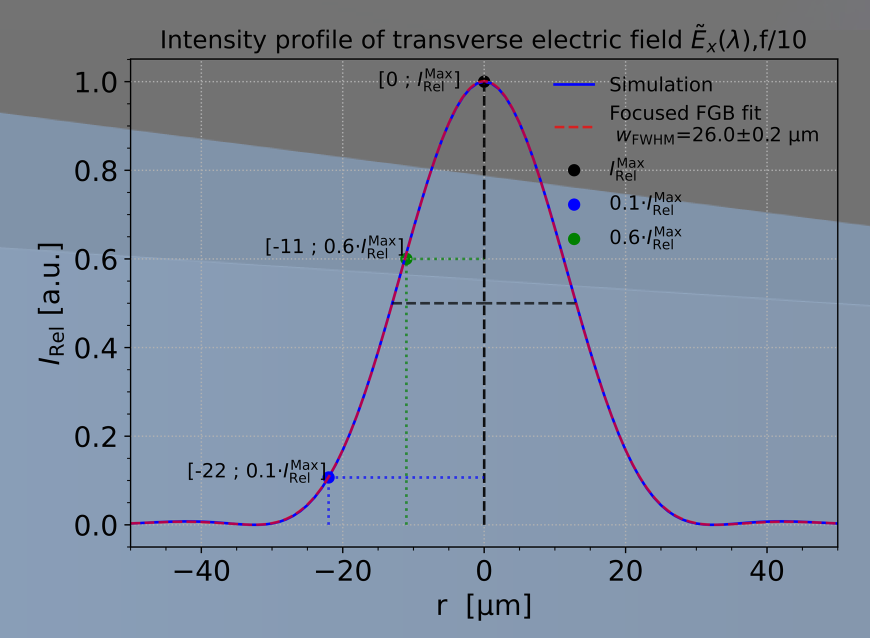

Figure 2: Intensity profile of transverse electric field $\tilde{E}(\lambda)$ for $f = 120$ cm, i.e., f/10.

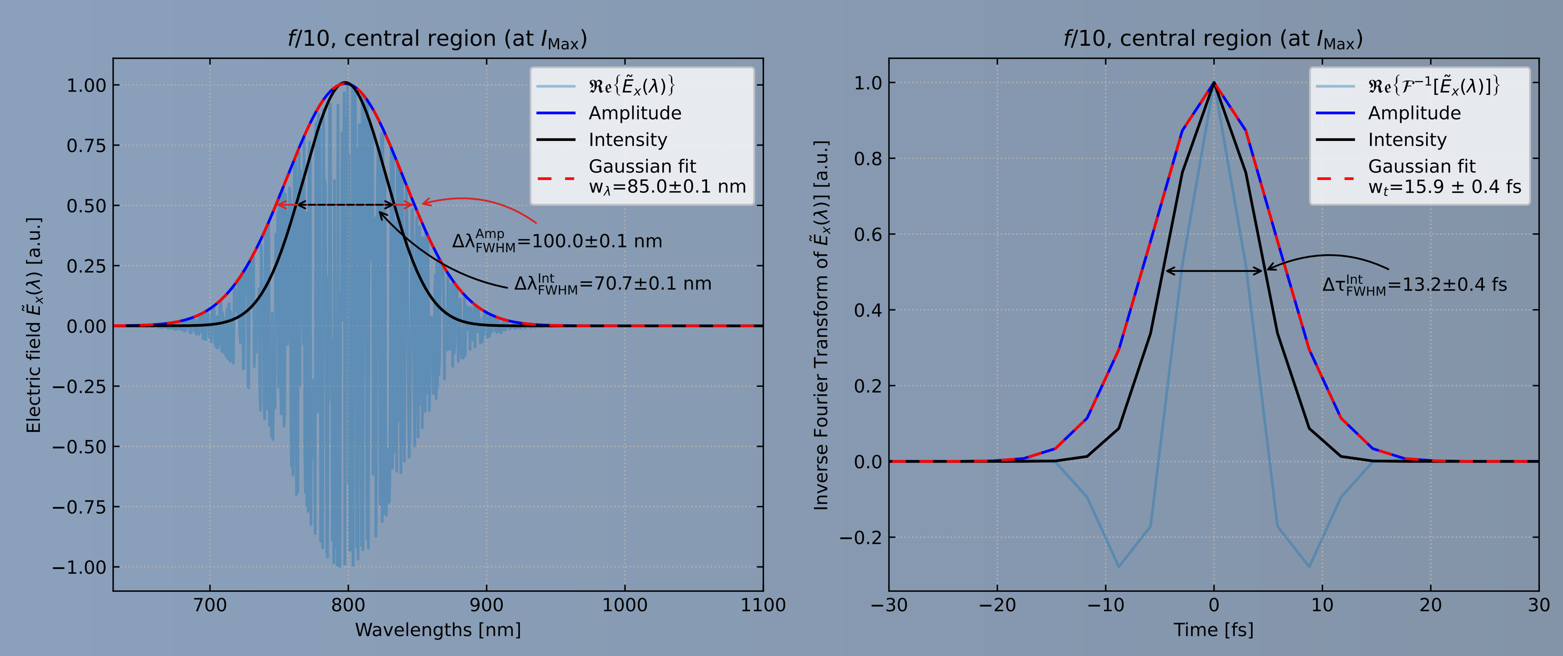

Figure 3: Corresponding transverse electric field observed in the central focal region, i.e. where I_{Max}.

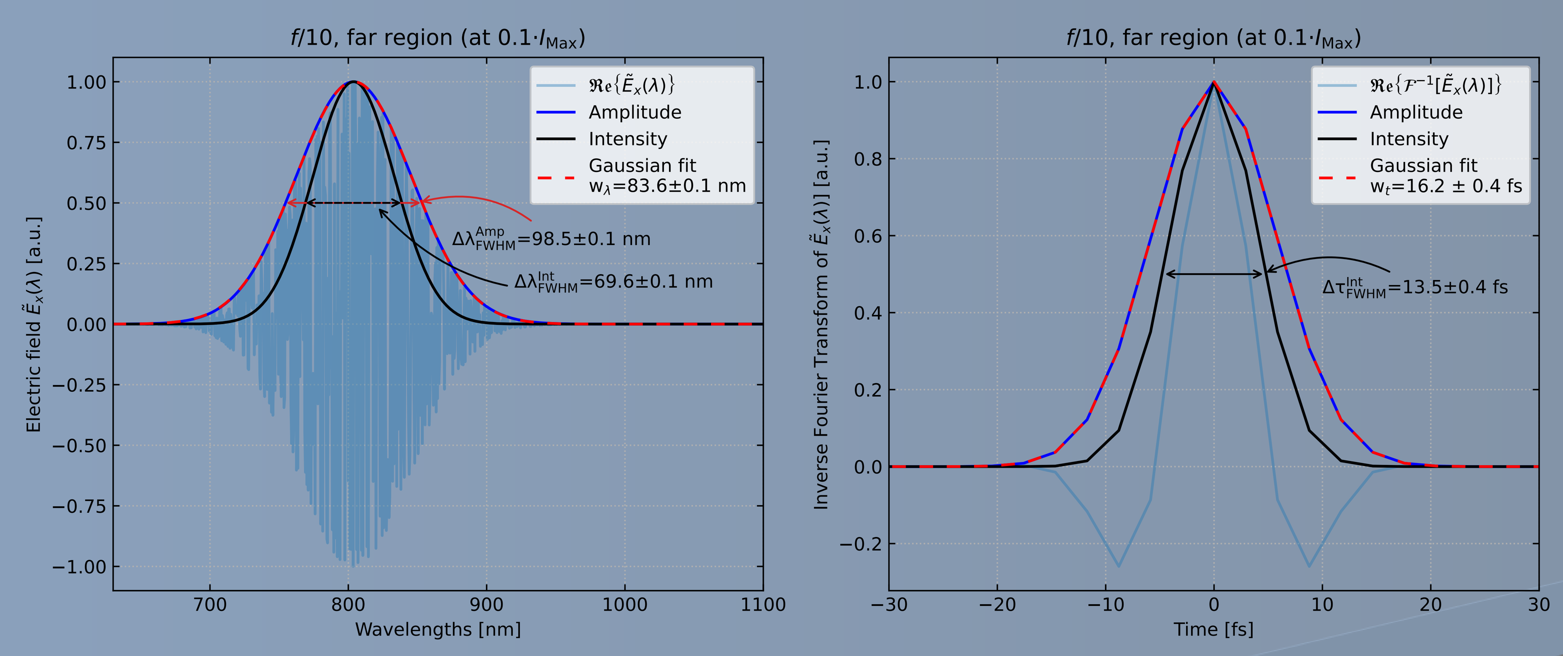

Figure 4: Corresponding transverse electric field observed in the central focal region, i.e. where $I_{\mathrm{Rel}} = 0.1 \cdot I^{\mathrm{Max}}_{\mathrm{Rel}}$.

Summary

- From Figure 4, the pulse duration stretching can be observed further from the central region of the focal plane, i.e., where $I_{\mathrm{Rel}} = 0.1 \cdot I^{\mathrm{Max}}_{\mathrm{Rel}}$. One of the preliminary reasons for this phenomenon can be linked to the different intensity distributions of focused laser pulses.
- Further studies assuming tight focusing conditions are currently being conducted.

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